Nuclear Proliferation and Safeguards: Appendix Volume II, Part One

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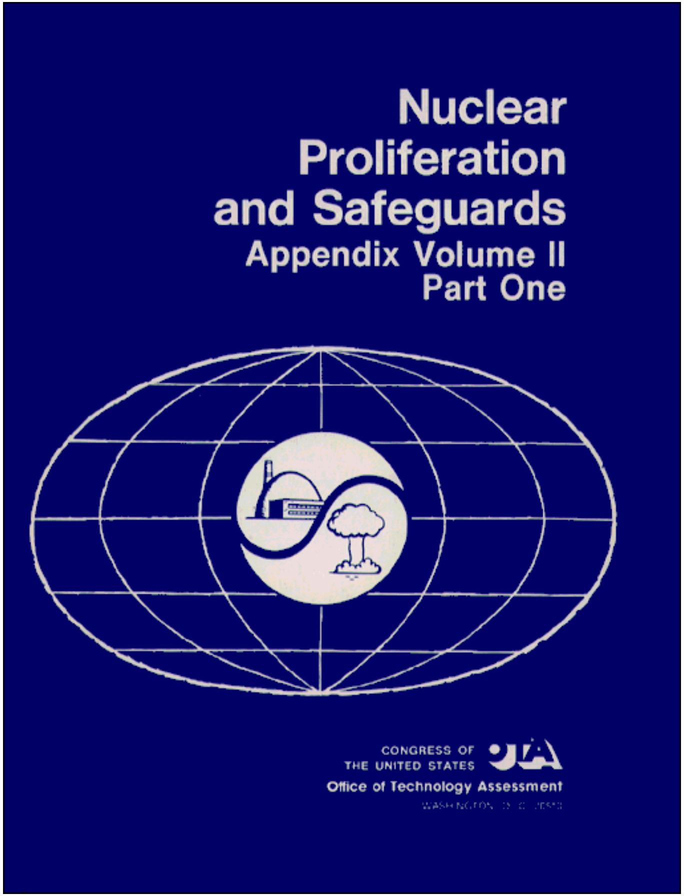

Nuclear Proliferation and Safeguards
Appendix Volume II
Part One

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FOREWORD

This volume contains the appendixes to the report “Nuclear Proliferation and Safeguards,” issued by the Office of Technology Assessment in June 1977. These appendixes are published in two parts; Part One includes appendixes I through V, and Part Two contains appendixes VI through IX. The appendixes were prepared for OTA by contractors and consultants, but several have been revised by OTA as noted. They were commissioned in order to collect and develop the information needed for the analysis presented in the OTA report.

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Incentives/Disincentives

Appendix I

Incentives/Disincentives

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MAJOR Nth COUNTRIES

Iran

1. Background

Iran is a country of 34 million people located to the south of the USSR, to the west of Pakistan, and to the east of Turkey and Iraq. It is governed by a hereditary monarch, the Shah, who holds most decisions on foreign and military policy very closely. There is no legal political opposition, but leftist guerrilla groups are active.

Apart from the "extractive" industries of oil and natural gas, which earn the bulk of foreign exchange, the major products of the Iranian economy are agricultural, including wheat and cotton.

While Iran is still a relatively underdeveloped country, its position as a prominent oil-exporting member of OPEC has brought it an enormous windfall of foreign currency holdings since 1973. This sudden currency inflow has brought about the intriguing problem of how to pass such prosperity forward, so that it will produce lasting well-being for Iranians into the next century. While some of this "petrodollar!' income can be invested profitably abroad, much of it is to be spent directly on development of the Iranian economy, including an ambitious program for the generation of electricity with nuclear reactors. Because of the relatively small infrastructure of trained scientific and engineering personnel in Iran, such investments will rely heavily on foreign technology and manpower for another decade or two. Most projects will take the form of "turnkey" packages purchased from abroad.

The nuclear projects strike some observers as incredibly ambitious, calling for the installation of perhaps twenty 1000 megawatt reactors by the end of the 1980's, more than doubling existing electric power capacity in the country. In some cases, reactors will be installed at locations which at this moment have no electricity of any kind.

With memories of a Soviet occupation of northern Iran during and after World War 11, the Iranian government has felt itself confronted with a continuing defense and deterrence problem. The insurance against a Soviet invasion has stemmed in part from American conventional or nuclear commitments, and more recently has been the justification offered for heavy Iranian purchases of conventional military equipment. While relations between Iran and the USSR are currently good, with the USSR purchasing piped natural gas from Iran, there is still evidence of suspicion about Soviet intentions on the part of the Shah and his government.

Justification for recent Iranian weapons purchases has also been based on Iran’s regional politico-military role. Iran’s relations with Iraq have been characterized by frequent disputes, although currently relations are improved. Iran has also sought to influence events in the Persian Gulf and on the Arabian peninsula. In 1971, Iranian troops landed on two strategically important islands in the Gulf vacated by the British. Iran has also been involved in combatting rebellions in Oman and other Gulf states at the request of the local regimes. In the aftermath of the Indian intervention in East Pakistan, the Shah is reported to have warned India against any military moves against West Pakistan as well. Whether the focus is the defense of Iran itself, or the projection of Iranian influence out into the surrounding region, the Shah has tended to emphasize the significance of armed forces. Already Iran is the dominant military power in the Persian Gulf region and is amassing hardware and constructing bases on a scale commensurate with a NATO country. Iran is rapidly becoming one of the world’s stronger military powers.

Although Iran has signed and ratified the Nuclear Non-Proliferation Treaty, it has nonetheless become suspect on proliferation. This may be attributed, in part, to the absence of public debate or a real legislative Process preceding Iran's ratification. This meant that no overt public opinion developed that would feel particularly committed to or bound by the treaty. The NPT also came before the windfall of OPEC, i.e., before Iran acquired the currency holdings facilitating major nuclear investments.

Further doubt followed the Indian detonation of a nuclear explosive in 1974, and a press interview with the Shah (immediately denied) in which he was quoted as saying that Iran might soon follow suit.

On the more positive side, the Shah and his government have presented some general proposals for a Middle East Nuclear Free Zone. While the boundaries remain to be defined, they clearly include Pakistan, Israel, Egypt and all the Arab states. They just as clearly do not include the Soviet Union or India, and thus do not depend on any nuclear-weapons-renunciation by states already having them. The proposal is in need of further definition, but can be seen as an offer by Iran to forgo nuclear explosives as long as the other Middle Eastern states cited do the same. If seriously pursued, this proposal could be a significant contribution to non-proliferation in the region.

Further clouding all predictions about Iranian policy is the special role of the Shah. Lower–ranking officials are discouraged from staking out positions on policy issued, or developing policy alternatives. If the Shah's regime were to fall suddenly a vacuum of policy direction might follow in which all things could become possible.

2. Incentives for the Acquisition of Nuclear Weapons

To purchase some additional insurance against Soviet invasion, in light of doubts about the continuing credibility of American commitments.

To acquire a counter to Indian political and military nuclear leverage, and to reassure Pakistan of meaningful Iranian support.

To acquire substantial global prestige and influence for the Shah and his country.

3. Disincentives to the Acquisition of Nuclear Weapons

The danger of antagonizing the United States, possibly resulting in the termination of American security commitments.

The risk of a slowdown or cutoff of European and American technological inputs to Iranian economic development.

The danger of antagonizing the Soviet Union, raising the spectre of preemptive military action.

The likely emulation of an Iranian nuclear weapon initiative by other Middle Eastern states thus clouding the vision of a prosperous twenty-first century Iran with a costly nuclear arms race and the risk of a regional nuclear conflict. Also, the acquisition of nuclear weapons by other countries in the region would tend to nullify Iran’s conventional arms superiority.

The unsuitability of nuclear weapons to the sort of regional military police actions in which Iran is likely to be involved.

The vulnerability of the Iranian nuclear power program to a cutoff of overseas inputs of technology and uranium fuel.

4. Technical Capabilities

Iran has placed firm orders for four light water power reactors to be supplied by France and Germany. The first two of these reactors are scheduled for completion in the early 1980’s. The power reactors will all be “turnkey” projects and many years may elapse before they can be manned entirely by indigenous Iranian personnel. This reliance on foreign technicians can amount to a check on proliferation. While much of the mineral wealth of Iran may yet be discovered, no large quantities of uranium have been uncovered, so that fuel requirements for the complex must be met abroad. Enriched uranium fuel will be supplied by France under an arrangement in which Iran has agreed to lend the French Atomic Authority $1 billion for the Eurodif enrichment plant under construction at Tricastin, giving Iran 10% ownership in the plant and entitling it to 10% of the output. Iran also has a 25% share of a second European enrichment facility, Coredif.

The Iranian nuclear electric complex, when it is finished, will be quite large, thereby generating substantial quantities of plutonium as well as electricity. While some interest has been shown in a plutonium reprocessing plant, no purchases have yet been negotiated, and strong outside disapproval has been communicated to Iran.

Recently, the former head of the Argentinian nuclear program, Admiral Quihillalt, was hired as a consultant to the Iranian Atomic Energy Commission. In addition, half of the foreign staff of the IAEC is from Argentina. To those outside observers who are given to looking for signs of a nascent Iranian nuclear weapons program, this was read as a signal that Iran would soon seek facilities applicable to a nuclear weapons program, following the path Argentina has taken. This would include the purchase of natural uranium fueled reactors instead of the more cost effective light water reactors Iran has ordered to date. This type of switch in orientation has not yet occurred and the presence of Argentinian technicians in Iran may simply reflect the more favorable employment conditions there.[1]

Iran’s venture into nuclear power looks like very much of a “great leap forward”. As such, it is likely to encounter disappointments of one sort or another. The schedules proposed by foreign manufacturers have in the Past been prone to slippage. The likely cost inflation in such reactor projects may similarly eat into Iran’s foreign cash reserves. A proliferation problem is clearly emerging in the Iranian projects, but there is every reason to assume that it will appear later than formerly anticipated.

Given its substantial foreign currency holdings, and its reliance on foreign technicians in other areas, it is always possible that an Iranian government might seek to hire foreign bomb-designers on a “mercenary” basis.

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10 George H. Quester, “The Shah, and the Bomb”, Policy Sciences 8 (1977) p. 25.

This is an avenue to nuclear explosives that no one else has tested yet, and is full of pitfalls.

5. Net Assessment-

The disincentives will outweigh the incentives for a considerable time into the future. The technical capability for manufacturing nuclear weapons will be compromised by the reliance on foreign technicians, foreign equipment, and uranium fuel. The military need for a nuclear weapon is not imminent, since relations with the USSR are relatively stable for the moment. The likely alienation of the outside world after a nuclear explosives decision might slow down or endanger the inputs of western material goods that make for Iranian prosperity. Iran is unlikely to jeopardize a major investment in nuclear electric power by overtly or covertly diverting fissile material to nuclear weapons production. Furthermore, a decision to make nuclear weapons would render the Shah’s nuclear-free-zone proposal, irrelevant, and indeed might speed up the nuclear-weapons decisions of Israel and the Arab states and Pakistan.

We perhaps know less than we would like to know about the exact plans and world-vision of the Shah. There is every reason to believe that he would like to go into history as the man who brought prosperity to his country. While this may be very consistent with a program of investments in nuclear electricity it is not so clear that it would fit with a program of nuclear weapons. The Shah’s proposals for a nuclear–free-zone, and his earlier decision to ratify the NPT, suggest that he may see this in the same way.

6. circumstances that Might Alter the Relationship between Incentives and Disincentives.

Among the circumstances that could shift the relationship between incentives and disincentives in favor of the former are the following:

A marked decline in the visible American inclination to support Iran against attack.

A marked increase in Soviet hostility toward the existing regime.

An assertion of new prerogatives in the region by India on the basis of the nuclear explosives it possesses?

The fall of Pakistan to outside invasion or domestic disintegration

The detonation of nuclear explosives somewhere else in the Middle East.

An outright rejection by Middle Eastern states of the proposal for a nuclear-free-zone,

A marked erosion of the domestic political prestige and support enjoyed by the regime -- an erosion which might be alleviated by a dramatic initiative like the acquisition of nuclear weapons.

Israel

1. Background

Israel is a small country of 3.3 million people who live mostly in urban or suburban areas in the northern part of the country. It is a constitutional democracy, in which the executive power rests with a Prime Minister and Cabinet based on a majority within a one-house parliament. Representation is through a number of political parties and elections are free and regularly held.

Although it may be characterized as a small industrial and commercial power that lacks heavy industry, Israel possesses a high degree of advanced technical skills and scientific accomplishment. An aircraft industry, electronics precision instruments and tools, and a first-class ordnance industry mark the exceptional nature of the Israel economy in comparison to other countries in the Middle East.

Israel borders on Egypt, Jordan, and Syria, with whom it has fought four major wars in the past thirty years. These countries as well as other Arab countries remain in a juridical state of war with Israel. Israel is without allies in the region and its population of only a little over 3 million people has repeatedly faced, in war, countries with combined populations of 100 million people. While Israel has been adept in converting foreign military equipment to its own tactical purposes, it, like the other countries in the region, is dependent on foreign suppliers for its military equipment. While the population of Israel is prosperous and fully employed, enjoying a relatively high standard of living, the burden of a very large defense budget has been felt in the form of an annual inflation rate in excess of 30 percent. The enormous costs of Israel’s many wars have been borne in part by contributions from sympathizers living abroad as well as through military assistance provided directly by the United States.

Israel’s dependence on U.S. military supplies and economic support makes it highly sensitive to changes in American attitudes and policies. Recent moves towards “even-handedness” in the region, the sale of U.S. military equipment to Egypt, increasing American dependence on Arab oil and U.S. concern with limiting the arms trade all add to Israeli fears and insecurities. One major result is an emphasis on increased military self-reliance.

Israeli nuclear weapons policy has not been the subject of intense public debate, although in recent years, the number of articles on the subject in the Israeli press had increased significantly. Articles in the foreign press concerning Israel's nuclear capability are often reprinted, and political leaders have made general statements concerning the utility or disutility of nuclear weapons in the Arab-Israeli context. The general public, however, apparently considers this subject to be a matter of national security, best left to political and military leaders.

While Israel's military forces have been successful in defending the country in short wars, the 1973 war witnessed the first military setback to Israel when Egyptian forces crossed the Suez Canal and managed to secure the eastern bank. Among the consequences was the loss of some Israeli territory gained in the 1967 war, and more importantly, a loss of confidence in the ability of the Israeli Defense Forces to stem any Arab attack on the state. Shaken confidence, continuing threats of war, the rising burden of defense costs, and fear that U.S. support is weakening may increase the attractiveness of nuclear weapons deployment as a means of restoring certitude to Israel's defense capability.

Israel has not detonated a nuclear weapon, nor declared herself a nuclear power, but there are a number of credible reports of the existence of an advanced nuclear weapons program. Israel is now generally credited with the potential of assembling, delivering, and successfully detonating a nuclear weapon on short notice. As a result, Israel should not be considered as simply another Nth country with a future potential for developing nuclear weapons, but neither is Israel a nuclear weapons state in the sense of India, because India has demonstrated its nuclear capability with its 1974 detonation. The crucial questions for Israel concern the incentives and disincentives for demonstrating its nuclear capability with a test detonation and deployment of nuclear weapons.

2. Incentives for the Testing and Deployment of Nuclear Weapons

- Calculation that the more overt the nuclear weapons capability, the more credible the deterrent. Thus, a clear capability might deter major Arab attacks, at least on Israeli population centers, whereas an ambiguous nuclear potential might not be as effective.

- Growing Western dependence on Arab oil may render U.S. support for Israel's security increasingly less and the need for a purely Israeli deterrent more compelling.
- Limitations on Israel's ability to develop and perfect a nuclear weapon force without actual testing.
- Belief that an overt capability will force the world community, including the Arabs, to acknowledge the reality and permanence of Israel's existence.
- The disparity between the size of Israel's armed forces and those of the neighboring Arab states is likely to grow over time, thereby diminishing Israel's ability to deter attack. An overt nuclear capability could arrest this trend.
- anxiety that Israel's defensive position is being and will continue to be eroded by diplomatic pressure aimed at achieving peace in the Middle East.
- Belief that the overt threat of the use of nuclear weapons on Arab oil fields will force the industrialized world to restrain the Arabs.

3. Disincentives to the Testing and Deployment of Nuclear Weapons

- The desire to preserve the present situation which permits Israel to gain the benefits of threshold nuclear weapons status but pay few of the costs associated with an overt weapons capability.
- The prospect that overt acquisition of weapons by Israel would cause one or more of its Arab adversaries to acquire a comparable capability resulting in the possible nuclearization of future wars.
- Fear that testing of nuclear weapons by Israel would alienate its supporters abroad and stop weapons supplies from the United States.
- Desire to maintain the moral principles and respectability of the Zionist and Israeli ideology.
- Fear that the possession of an overt (and vulnerable) nuclear force would make Israel a target for a pre-emptive nuclear or conventional attack.
- Overt nuclear weapons facilities and storage areas would probably become high priority terrorist targets.
- Deployment of nuclear weapons could increase the likelihood of their unauthorized or accidental use.

4. Technical Capabilities

Israel unquestionably has the scientific and technical know-how to fabricate nuclear weapons. Its reactor at Dimona appears to have had the purpose in part of the production of plutonium and it is generally assumed that Israel has the capability to separate plutonium from spent fuel. Research in the country, the possession of precision machining capabilities, the aviation and avionics industry, and the first-rate ordnance industry leave little doubt of Israel's competence to fabricate nuclear weapons and delivery systems. Israeli scientists have studied in Western universities and scientific institutes, while scientists from the U.S. and Western Europe have probably carried to Israel whatever techniques Israel may have at one time lacked.

Evidence suggests that Israeli scientists have long ago conducted the research necessary to the fabrication of weapons from available fissile material.

5. Net Assessment

Israel's clear capability to fabricate nuclear arms along with the obvious weight of the incentives to do so, make it impossible to rule out the existence of Israeli nuclear weapons. Certainly, Israel is widely perceived as already possessing such a capability although there is no conclusive evidence in support of this assumption. As a result of its ambiguous status, Israel enjoys many of the advantages of an overt weapon capability, including deterrence, while avoiding many of the costs, including precipitating an Arab nuclear arms program and antagonizing the United States. Consequently, the interaction between incentives and disincentives favors not crossing the nuclear threshold overtly. This is particularly true as long as the United States continues to provide adequate conventional weapons and credible security guarantees.

6. Circumstances That Might Alter the Relationship Between Incentives and Disincentives.

- The incentives for an overt Program of construction and deployment of nuclear weapons will be strengthened if there is a substantive weakening of U.S. support for Israel.
- The materialization of a situation in which Israel's existence as a state is in serious jeopardy or its population centers clearly threatened.

- The new Likud government may feel that the time has come to demonstrate Israel’s military strength by displaying a nuclear weapons capability.
- The acquisition of nuclear weapons by one of the Arab states.
- The coming to power in the Israeli. parliament of a party that assumes accommodation with the Arabs is the optimal way to achieve peace in the middle East and protect Israel’s security.

Two features distinguish the Israeli case. First, Israel is, and has been since its inception, in a state of belligerency with nations that surround it. The very existence of the state has been under constant challenge. Consequently, it requires no great imagination to conceive a scenario under which Israel would actually use any nuclear weapons it possessed. Second, Israeli position vis-a-vis proliferation is unique in that the suspicion that it has and will use nuclear weapons is seen to be of greater utility than an overt revelation that it really does possess them. It is quite possible that this strategy will be followed by other Nth countries including South Africa, South Korea, and Taiwan.

Brazil

1. Background

Brazil is a country of 110 million people, with a territory spread over a large portion of South America. It has been governed by a military regime since President Goulart was ousted from power in 1964. While the regime has used severe measures to repress domestic dissidence, including reported instances of torture, it has also achieved a substantial level of economic growth, and has thereby won some acceptance from the Brazilian populace.

Brazil has no significant border disputes with any neighbors. The South American continent as a whole has been generally free of military threats for many years. An old and continuing rivalry with Argentina is a significant factor in Brazilian policy formation and the growth of Argentina's nuclear capabilities and facilities may have had an impact on Brazil's nuclear policy. While Brazilian statements have hinted at an interest in peaceful nuclear explosives, allegedly for use in some massive river-dredging projects, there has been no official public speculation about any need for nuclear weapons. The armed forces of Brazil and its neighbors have over time assumed more of a domestic than an external function, and major weapons systems have become primarily symbols of national prestige. The continent has, however, recently seen a dramatic upswing in the quality and costs of the military equipment procured.

While plagued with unsolved problems of poverty, income maldistribution, and the movement of population from the countryside to overcrowded cities, Brazil has nonetheless achieved substantial economic development. The Brazilian economic "miracle" is based in part on an encouragement of foreign investment. The boom is thus dependent on infusions of American technology, and is likely to need continued infusions far into the future. Despite considerable industrial development, agriculture still accounts for roughly two-thirds of Brazil's foreign exchange earnings. Coffee, soybeans, and iron ore are the principal exports.

While the Brazilian regime is committed to replacing-an agricultural economy with a diversified industrial structure, it has been hard hit by the increase in oil prices, since Brazil must import virtually all of its petroleum. This has clearly increased the attractiveness of nuclear power. An additional factor which explains at least part of the interest in nuclear industry is the existence of significant hydroelectric potential at remote locations in the Brazilian jungle. To try to transmit electricity from these waterfalls by wire to the Brazilian industrial cities would be extremely wasteful of power. An alternative would be to -use the hydroelectric power at the site where it is available to enrichuranium, and then to transport the enriched uranium to power reactors close to the factories. The net result would be electrical power production exceeding that available from hydroelectric sources alone.

Brazil has shown interest in being recognized as a major power, and perhaps the preeninent power in Latin America. Signs of this include statements by government leaders, encouragement of domestic population growth (when many nations around the globe are trying to reduce their birth rate), the claim to territory in Antarctica, and the expression of interest in peaceful nuclear explosives. The use of PNE's has been mentioned in connection with proposals for excavating oil shale, for linking a number of rivers into an integrated network, and for the excavation of ports.[1]

While the government of President Goulart, the last popularly-elected

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[1] H. Jon Rosebaum, "Brazil's Nuclear Aspirations", in Nuclear prolifera- tion and the Near Nuclear Countries, 0. Marwah and Schulz, eds., Ballinger, 1975).

chief executive, played a significant role in the initiation of the Latin American Nuclear Free Zone Treaty, succeeding regimes have worked mainly to water it down, and signed it only after clauses were attached making it non-binding on Brazil unless all the world's nuclear-weapons states had adhered to various protocols. Brazil has refused to sign the Nuclear Non-Proliferation Treaty and has issued a number of statements attacking that treaty. Brazil is legally obligated to accept inspection and forego explosives manufacture on a project-by-project basis, as part of the sales contracts it signs with the United States or other suppliers, but it is not presently bound by any general treaty renouncing nuclear weapons. This hesitation to sign the NPT is not necessarily an indication of a Brazilian program to develop nuclear weapons, but rather appears to signify a reluctance to renounce the option to initiate such a program in the future.

The position of the regime in Brazil is such as to allow it to produce nuclear explosives without first securing popular consent. Some public opinion polls have been taken which seem to show enthusiasm for the government's stand in favor of the peaceful nuclear explosives option, but such polls were conducted in an atmosphere which would make it difficult for contrary opinion to emerge.

2. Incentives for the Acquisition of Nuclear Weapons

Desire to obtain prestige and great-power recognition for Brazil in the outside world.

Belief that such prestige would augment popular support for the regime at home.

Rivalry with Argentina, which has tended to be slightly ahead of Brazil in the nuclear field and which may be perceived as embarking on a weapons program.

3. Discentives to the Acquisition of Nuclear Weapons

Belief that United States and European inputs to the Brazilian economy, both nuclear and non-nuclear, might be less forthcoming if a move toward nuclear explosives became evident.

Concern that any Brazilian nuclear explosives acquisition would stimulate similar action by Argentina. The end result could be a costly nuclear arms race in Latin America to the detriment of all concerned.

Concern for the hostile reaction of other Latin American countries, a number of which have become parties to the Latin American Nuclear Free Zone Treaty, including Mexico, Chile and Venezuela

Fear that a nuclear weapons arsenal may become the focus of coup attempts by military factions.

Fear that nuclear explosives might be used by domestic dissidents in a terrorist action.

4. Technical Capabilities

As part of its general drive to industrialize, Brazil is accumulating an infrastructure of trained people in the nuclear field. The nuclear facilities operating in Brazil for the forseeable future will nonetheless be imported from sources such as the United States and Germany.

The first major power reactor obtained by Brazil was an enriched-uranium fueled reactor (LWR) purchased from Westinghouse; this was inherently less proliferation-prone than the natural uranium fueled reactor (CANDU) which Argentina selected. This was seen by many as a sign that Brazil was putting commercial considerations of cost effectiveness in electricity production ahead of thoughts of a weapons option. Proposals concerning the second round of purchases, however, have caused a great deal of attention to be directed towards Brazil. In 1975, West Germany and Brazil signed a multibillion dollar agreement which will entail Brazilian acquisition of the entire fuel cycle from West Germany including as many as eight power reactors, a jet nozzle uranium enrichment capability, a fuel fabrication plant, and a plutonium reprocessing facility. This agreement has resulted in U.S. protests to Germany and Brazil because of the potential use of these. facilities for nuclear weapons.

It will almost certainly be a decade before any of these facilities are in operation, and the sales agreements, as with the American supplied reactors, call for IAEA safeguards. This agreement reaffirms the principle of nuclear nonproliferation and specifies that German approval must be obtained prior to re-export of any materials, facilities or technology provided by Germany. It also includes a Brazilian commitment not to use any of these items for the production of nuclear explosives. Nonetheless, Brazilian scientists and industry will gain extensive experience in handling nuclear material and concern has been expressed that Brazil might be able to duplicate such facilities in an indigenous construction effort. Brazil may also achieve fuel cycle independence which would allow a unilateral abrogation of safeguards without major penalties to its nuclear energy program.

Brazil has as yet not found any significant quantities of uranium on its territory, but extensive prospecting is underway A more certainly available natural resource is the waterfalls at remote locations, whose electric potential can most easily be “transmitted” by use of uranium enrichment.

While Brazil (like Argentina) has signed “nuclear cooperation” agreements with India, these agreements seem to be innocent, since they specifically exclude “classified” matters, and all the Indian work on nuclear explosives is classified.

5. Net Assessment

Incentives seem to be somewhat outweighed by disincentives for the short-run and possibly for the middle term. The Brazilian government has an internal pro–bomb lobby in the military, but it also has an anti-bomb faction. While officials of the Foreign Ministry are prone to tout the advantages of “peaceful nuclear explosives’; officials responsible for economic growth tend to be against such projects, for fear of alienating the outside participation in Brazil’s economy that may be crucial to continued growth. Since growth is the major source of support for the regime, this is not a consideration that can be dismissed lightly.

It will be at least a decade before any weapon program can easily be undertaken using purely indigenous means. Any gains from acquiring such weapons will tend to be offset by U.S. displeasure and possible retaliation, by the likelihood that Argentina would move to acquire a bomb, and by the resentment of other Latin American states. Already U.S.-Brazilian relations have been severely strained by the planned Brazilian purchase of German enrichment and reprocessing facilities.

6. Circumstances that might Alter the Relationship between Incentives and Discentives

Much will depend on how the Brazilian economy grows and on how much such growth continues to be interlocked with American investment and technology. If such growth remains the continuing base of public acceptance for the regime, this may be a lever that can discourage proliferation well into the future.

Brazilian interest in a nuclear explosive will rise sharply, however, if Argentina takes steps to acquire the bomb.

South Africa

1. Background

South Africa is a country of 26 million people of which 4½ million are of European descent and 22 million are of African or mixed African and European descent. It is a federal republic with a President elected for a term of seven years, but the powers of government are exercised by a prime minister and cabinet chosen by the majority party in the two-house legislature. A number of political parties exist and elections are regularly held but the franchise and other rights of citizenship are enjoyed only by the white, European, portion of the population.

South Africa is the most advanced industrial nation in Africa and is well endowed with minerals and agricultural produce, from which it derives most of its foreign currency. The fruits of industrialization and trade have supplied the European population with a high standard of living and the amenities of a modern industrial state. South Africa depends on the export of its products and resources, including large quantities of uranium, to obtain those articles of heavy machinery and armaments which it is not yet capable of producing itself. South Africa's abundant coal reserves provide for most of its energy needs.

Apartheid policies have resulted in a situation in which friendly relations have only been maintained with Rhodesia, a bordering country with an even smaller proportion of European to African population than South Africa’s, and with Botswana which abuts South Africa along the Transvaal frontier. The eastern land border is with Mozambique, a former Portuguese colony and the northwest border is with Namibia, the former mandated territory of Southwest Africa presently under South African control.

In addition to increasingly violent internal opposition to white minority rule, African nationalist movements in Mozambique, Rhodesia (Zimbabwe), Namibia, and Angola, all work to surround South Africa with a number of hostile regions and insurgent movements which threaten its existence.

At the same time, South Africa’s position at the southern tip of Africa makes its fate a matter of concern to the maritime powers of the world whose ships pass the Cape of Good Hope. South Africa is pictured by its government and its white citizens as the representative of West European strategic interests in southern Africa and as the leading anti-Communist force in Africa. This view is reinforced by the presence of Soviet or Cuban military personnel in Angola and to a lesser extent, Mozambique. Its apartheid policies have made South Africa the target of economic boycott and recrimination by the Third World nations and to a lesser degree, by Western Europe and the United States. On the other hand, Western investment in South Africa and South Africa’s rich mineral resources and strategic position foster an ambivalence on the part of Western countries toward the regime.

White fear of the impact of political equality limits the possibilities for a voluntary and peaceful transition to majority rule while the desire to employ Africans and Cape Coloureds to maintain the economy and services limits the possibilities for a complete political separation between African and European populations. Strong racial prejudices make any progress toward integration difficult.

The outlook for stability in South Africa is poor. Failure of the white majority to bring Africans into the political process and to promote black education has been increasing disaffection among the politically fragmented black population. The likelihood that any Western nation would commit itself to defense of the white minority against an uprising by the black majority population or against attack from surrounding African nations is small. This leaves the white population alienated from the world community, fearing extermination, expulsion or at least the loss of property and political rights. Every criticism of South Africa’s internal policies from abroad and every successful terrorist raid serves to increase feelings of isolation.

Such conditions of isolation and desperation have led to speculation that South Africa may be considering the development of nuclear weapons. While the Prime Minister has stated that South Africa’s interest in nuclear power extends only to peaceful applications, he and members of his cabinet have made reference to the possibility of “mounting a nuclear defense” if the existence of the regime is threatened. The republic of South Africa has neither signed nor ratified the Nuclear Non-Proliferation Treaty and seems unlikely to do so.

The South African government has the legislative and administrative power to develop nuclear weapons without submitting the question to public opinion.

2. Incentives for the Acquisition of Nuclear Weapons.

The hope that the possession of nuclear weapons will discourage hostile external intervention (including that of USSR and Cuba) into South African domestic affairs.

The belief that technical superiority in armaments can compensate for the numerical inferiority of the white population.

The hope that by acquiring nuclear weapons, South Africa would raise the potential cost of a conflict to such a high level that black Africans, either on their own or at the behest of the superpowers, will agree to an accommodation acceptable to the white population.

The knowledge that South Africa is diplomatically and spiritually isolated from the West and is unlikely to receive any outside assistance against threats to its security.

3. Disincentives to the Acquisition of Nuclear Powers.

Doubts about the utility of nuclear weapons in fighting the kind of war that South Africa is likely to face.

The possibility that construction of nuclear weapons would impel one or more of the Black African states to acquire a nuclear capability of its own. At a minimum, a South African weapon would seem likely to further exacerbate the relationship with Black Africa.

Fear that the acquisition of nuclear weapons would result in the complete rupture of economic and technical relations with the West.

The hope that the West may yet help the white regime if it is faced with a Soviet supplied and Cuban led invasion, but that this slim possibility is muted if South Africa were to become a nuclear power.

4. Technical Capabilities.

South Africa was one of the early sources of uranium for the post World War II era and the country has remained an important supplier in the world uranium market ever since. It has a long history of uranium extraction technology and is capable of producing nuclear grade material. In the early 1970’s South Africa announced that it would mount a major effort to develop an enrichment capability. By enriching uranium prior to export, South Africa hopes to earn $500,000,000 annually in foreign exchange beginning in the mid-1980’s. While the specific enrichment technique and any other details on it remained secret for many years, information now available suggests that the method is a variant form of the aerodynamic nozzel. Indications are that South African industry has provided some 90% of the technology and support for this process, the remaining coming from foreign sources, available in “normal channels”. Intentions are that a commercial enrichment plant will be in operation in 1984 and full capacity of 10,000 metric tons SWU/ year 1) will be attained by 1986. A major portion of this output will almost certainly enter the world market to supply the growing number of LWR's.

South Africa sees itself as a supplier of nuclear fuel and has indicated that its needs are for export earnings rather than atomic weapons. It must be recognized, however, that imbedded within these commercial steps is the potential for a weapons program. According to recent reports, the pilot plant at Valindaba can enrich uranium to weapons grade levels.

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1) metric ton = 1,000 kilograms

In addition, South Africa has made a major investment in nuclear power research and development projects. The American designed Safari-1 research reactor has been in operation since 1964 and although American supplied enriched uranium fuel has been necessary for operating the reactor, South Africa is or soon will be capable of independent fuel production and reactor operation. In 1981, the first of several French supplied commercial nuclear power reactors are expected to begin operation. While these reactors will add little directly to South African nuclear weapons capability, they provide added experience in handling nuclear material and facilities and are a possible source of plutonium. The U.S. is committed to supply enriched uranium to fuel these reactors between 1981 and 1984 during which time U.S. safeguards will apply. But given South Africa's projected nuclear independence by the mid-1980's, safeguards may become moot.

The state of technology and industry is such that there is no barrier from that quarter to development of nuclear weapons. Since its nuclear weapons potential is based on uranium enrichment, rather that plutonium separation, South Africa faces fewer technical difficulties in the fabrication of a weapon than do other countries. Uranium weapons are more easily constructed and detonated than plutonium weapons. A minimal supply of highly enriched uranium sufficient for a single weapon may have already been produced during the development and prototype operation of the enrichment process.

5. Net Assessment.

At present the incentives for South Africa to acquire an overt nuclear weapons capability are probably insufficient to outweigh the very real disincentives. Nuclear weapons would be of little use in fighting a war against insurgents or in suppressing a domestic revolt. A South African weapon would place immense pressure on Black African states to acquire a countervailing capability or at least a nuclear guarantee. An expanded war in which both sides have access to nuclear weapons would place South Africa, with its predominantly urban population, at a disadvantage.

On the other hand, the pressure on South Africa by the African nationalists, the general strategic and diplomatic isolation of South Africa and the difficulties in maintaining internal stability all place the country in a desperate situation in which it may feel that it has little to lose in overtly “going nuclear”. Events in Rhodesia as that country is subject to increasing attack supported by the Soviet Union and its allies tends to strengthen the South African view that its position will become increasingly precarious. Nuclear weapons may be viewed as a means of keeping the Soviet Union and Cuban forces at a distance.

Given these considerations, South Africa may conclude that its interests are best served by remaining poised at the nuclear threshold. This posture based on a clear technical capability to fabricate nuclear explosives may enable South Africa to maximize its bargaining power with the U.S. and the Black African nations without incurring the liabilities associated with the overt acquisition of a weapon. The implicit threat to assemble and detonate a nuclear weapon is more useful to South Africa than the demonstration of nuclear capability through a test detonation.

Consequently, South Africa may become a second country following the path ascribed to Israel above, collecting the potential for deploying nuclear weapons on short notice, letting rumors and speculation leak out that such a weapons arsenal has been readied, but never detonating such a warhead in a test, or explicitly confirming possession of nuclear explosives in any public statement.

6. Circumstances that might alter the relationship between incentives and disincentives.

Among the circumstances that could alter the relationship between incentives and disincentives are the following:

An increase or diminution in Soviet activity in Southern Africa

Changes in the perceived orientation of U.S. policy toward the conflict between whites and blacks in Southern Africa;

Incentives could be strengthened by the fall of white rule in Rhodesia and the intensification of guerrilla operations within South African territory.

An attempt to impose a great power settlement on South Africa to bring about majority rule would strengthen incentives.

A Great Power guarantee of a political settlement acceptable to the white minority would strengthen disincentives.

In the event of an accommodation between whites and blacks in South Africa, any incentives for the development of nuclear weapons would largely disappear.

A black revolt within South Africa that forced the European government out of power before it could complete development of nuclear weapons would reader the entire question moot.

South Korea

1. Background

South Korea is a country of 35 million people, located south of the 39th parallel on the Korean Peninsula. Its government is headed by an elected president who rules through a premier and a cabinet with the assent of a national assembly. The assembly is composed principally of the President’s party, the Democratic Republic Party although other parties are represented as well.

The South Korean constitution vests strong executive authority in the President acting through a premier and cabinet that is responsible to the President rather than to the popularly elected National Assembly. While the President must, in theory, maintain enough popular support to gain periodic re-election and while opposition parties exist, the South Korean government has become increasingly repressive forcibly suppressing dissent and opposition. A policy favored by the President will generally be adopted and implemented by a Presidentially-led bureaucracy and military. That means that a presidential decision to acquire nuclear weapons need not be publicly debated nor even become public knowledge.

South Korea is a moderately industrialized nation whose population is employed in mining, agriculture and industries manufacturing light consumer goods for home consumption and export. It is a relatively prosperous country with a high rate of literacy amongst the population and is engaged in mining, agriculture, and industries manufacturing light consumer goods for home consumption and export. It is a relatively prosperous country with a high rate of literacy amongst the population and is in the process of developing steel and machinery products.

South Korea is abutted by the Democratic Republic of North Korea at the 38th Parallel, with the Soviet Union and the People's Republic of China in close proximity. Japan, along with the U.S., the principal trading partner of Korea, lies offshore. The Soviet Union and the Peoples's Republic of China maintain strong military, naval and air forces capable of quick and direct intervention in the Korean Peninsula. Some forty thousand American personnel are still stationed in Korea providing combat ground and air forces to guarantee the security of the country and the integrity of the demilitarized zone at the 38th parallel.

Both the Republic of Korea and the Democratic Peoples's Republic of Korea claim to be the legitimate rulers of the Korean Peninsula and seek the reunification of that peninsula under a single government. The intractable problem of the reunification of the two Koreas is constantly at the forefront of both North and South Korean policy.

A constant fear of a North Korean invasion, backed by China or the Soviet Union has made South Korea highly dependent on United States military assistance. The declining ability of South Korea to persuasively present its case for continued support to the U.S. public, however, strengthens the government's inclination to increase its capability to defend itself. The South Korean cause has been steadily losing support in the U.S. due in large part to the increasingly dictatorial nature of the Park regime, the persecution of opposition party leaders, and the activities of the Korean Central Intelligence Agency in the U.S.

Meanwhile, the withdrawal of the U.S. from South Vietnam and Cambodia and the removal of military units from Taiwan has increased South Korean fears concerning the strength of U.S. support. The announced intention of the Carter Administration to withdraw U.S. ground forces from the Peninsula will probably reinforce that insecurity. Despite whatever security guarantees that may accompany it, such a withdrawal will probably stimulate South Korea's interest in acquiring nuclear weapons. In South Korea, it is assumed that withdrawal of U.S. forces will be followed by a North Korean invasion of the South. Whether or not that assumption is well-founded, it is the premise upon which the present government in South Korea operates and North Korean propaganda has done little to counter it. Nuclear weapons may be seen as a deterrent to invasion, as an important defensive weapon in the event of such an invasion, and as a means of deterring the Soviet Union or China from assisting North Korea.

South Korea has signed the nuclear Non-Proliferation Treaty but has not yet ratified it. Whether the signing of the treaty was in response to U.S. pressures or to a genuine concern about nonproliferation is not clear. If it was a consequence of the former, any perceived weakening of the U.S. security guarantee would weaken South Korea's commitment to the Treaty. At the same time, any hint that South Korea had set out to acquire nuclear weapons would bring forth condemnation for the U.S., the U.S.S.R. , the PRC and many of South Korea's Asian and European trading partners and would strengthen the view of those who already view the regime with distaste. Proliferation, or the hint of it, could be expected to strain the already fragile security guarantees by the United States and hasten the dissolution of that arrangement. This fact constitutes an inhibition against overt South Korean proliferation as long as there is some chance that the U.S. security guarantee will be honored. In addition, any restraints that the Soviet Union and China may have placed on North Korea could be weakened by an overt South Korean nuclear weapons program. The development of nuclear weapons may be viewed as a preclude to a South Korean attempt to reunify Korea by force.

2. Incentives for the Acquisition of Nuclear Weapons

- Fear that North Korea will once again attempt to unify Korea by force.
- Uncertainty regarding a continued U.S. military presence in the Far East and the viability of U.S. security guarantees.
- Necessity to offset North Korea’s military support from China and the Soviet Union.
- Desire to establish South Korea’s standing as an independent nation commanding international attention and respect.
- Possibility that a South Korean nuclear weapon capability would make a new Korean conflict so dangerous as to compel superpower intervention to preserve the status quo.
- Belief that nuclear weapons would bolster the confidence of the South Korean population in the country’s future.
- Desire to demonstrate South Korea’s industrial and technical superiority over North Korea.

3. Disincentives to the Acquisition of Nuclear Weapons

- Prospect that proliferation would alienate the United States sufficiently to cause a withdrawal of all U.S. forces (including air forces) form the Peninsula and an end to all U.S. military assistance.
- Likelihood that Japan would be sufficiently concerned by proliferation to take diplomatic and economic measures against South Korea. The most direct effect might be upon the 26% of total South Korean exports that go to Japan and the Japanese assistance to Korean industrial development.
- Fear that proliferation would harden the attitudes of China and the Soviet Union in support of North Korea.
- Fear that a nuclear armaments would be discovered by the North Koreans prior to actual completion of any weapons and precipitate on a preemptive attack from the North.
- South Korean nuclear arms may induce North Korea to seek its own nuclear weapons capability.

4. Technical Capabilities

South Korea is a rapidly industrializing nation that has already begun the construction of two nuclear power plants near Pusan. Long range plans call for the construction of 25 plants by the year 2000. While Korea has the technical engineering personnel for the development of nuclear weapons, it is entirely dependent on foreign sources for fuel, fuel reprocessing and reactor components. Acquisition of the facilities for the development of nuclear weapons is not beyond the financial reach of South Korea, but the expense would require a major re-allocation of existing resources that are presently devoted to industrialization.

The first Korean power reactor is scheduled to begin operation in 1977, and is fueled with enriched uranium. In 1975, Korea signed an agreement for the purchase of a CANDU reactor which is fueled with natural uranium and is more conducive to the production of weapons grade plutonium than light water reactors. The reactor is covered by Canadian restrictions on the use of the technology or materials for development of explosive devices. Two research reactors, furnished by the United States, a TRIGA Mark II and a TRIGA Mark III, are operated by the Korean Atomic Energy Research Institute. These reactores are not suitable for plutonium production and there is no evidence of fuel reprocessing, or plutonium production, even on a laboratory scale.

Given South Korea’s lack of separation or fuel reprocessing facilities and of a nuclear reactor designed chiefly for plutonium productions it is unlikely that it could develop nuclear weapons in less than five years even with some outside assistance. Under strong U.S. pressure, South Korea abandoned efforts to purchase a French designed reprocessing plant. Without any outside assistance, it appears unlikely that South Korea could acquire a nuclear device in less than ten years. A significant arsenal of nuclear weapons would require an even longer time.

5. Net Assessment

At present incentives and disincentives appear to be closely balanced with the latter slightly preponderant. The obstacles to proliferation are chiefly political, technical and administrative. It would be difficult for the Korean government to initiate a clandestine program given its dependence on foreign suppliers for equipment and material and with the presence of U.S. military forces in Korea. Open pursuit of a nuclear weapons program would raise intense objections by the superpowers and other nations, like Japan, strongly opposed to proliferation.

On the other hand, fear of a North Korean invasion and declining support from the U.S. provide strong incentives for a South Korean nuclear weapons program.

In sum, South Korea has considerable political-military incentive to “go nuclear” but lacks the material means to do so. The strength of the incentives to proliferate will be primarily dependent on the presence or withdrawal of the American commitment to the defense of South Korea.

6. Circumstances that might alter the relationship between incentives and disincentives

Among the circumstances that could alter the relationship between incentives and disincentives are the following:

- The incentives would be greatly strengthened by a withdrawal of all U.S. forces from South Korea.
- A rapprochement between the Soviet Union and the People’s Republic of China would increase the fear of North Korean attack and strengthen the incentive to proliferate.
- A Japan, U.S., and South Korean alliance guaranteeing the status quo in the Korean Peninsula would strengthen the disincentives to proliferation.

Japanese acquisition of nuclear weapons would tend to strengthen the incentive to proliferation.

Changes in the relationship among North Korea, the Soviet Union and the Peoples’s Republic of China can strengthen or weaken the South Korean requirement for nuclear weapons.

The Federal Republic of Germany

1. The Security Perspective of the Federal Republic of Germany

Since its creation as an independent state following the Allied Occupation at the end of World War II, the FRG has been presented with a unique set of security problems. In their most acute form, these problems have revolved around the need to deter a Soviet ground assault in the heart of Europe. In view of the enormity of this task, as well as the firm European and Soviet opposition to independent German rearmament, German security perspectives have been dominated by the alliance relationship with the United States and NATO. At the same time, as a defeated power whose reentry into European politics was a cause Of considerable controversy within the ranks of the NATO allies, the FRG has feared that it would be relegated to the position of a junior partner within the Alliance, and has since struggled for equal status.

2. The Nuclear Debate

With various exceptions, the Bonn regime has found that the best mix of solutions for these problems has been to renounce any German possession or control over nuclear weapons, while asking the United States to remain committed to the use of its own nuclear weapons if a Soviet attack should ever come. Such a mix would work to deter Soviet attack, while not panicking Moscow or Paris or Bruxelles with the prospect of a German nuclear force.

While renouncing any right to produce nuclear weapons in one of the several treaties associated with the ending of the Allied occupation in 1954-55, the FRG was nevertheless anxious to obtain modern weapon systems, including nuclear capable systems, lest it be perceived as a second class power within the NATO hierarchy. At the same time, the Soviet Union began to reach a level of strategic parity with the Us. As a result, doubts concerning the reliability of the U.S. nuclear commitment to Europe’s defense began to surface on the continent. FRG officials grew increasingly uneasy; this unease stimulated FRG desires for a “Finger on NATO nuclear trigger,” as Franz Joseph Strauss and the CDU party put it. No leading West German political leader, however, has ever seriously suggested that Germany consider acquiring nuclear weapons of its own; and when German efforts to gain a direct and acknowledged share in the NATO nuclear decision-making process in the MLF proposal produced sharply unfavorable reactions throughout Western Europe, even that objective was abandoned.

Given West Germany’s industrial power and technical ability, it has the clear capability to develop nuclear weapons, should it ever choose to do so. Germany has made a major commitment to nuclear power and supports a large nuclear energy research and development program, including breeder reactor research. German scientists and industry have developed the jet nozzle uranium enrichment process, which has been sold to Brazil, and were active in the development of the gas centrifuge process to be used to enrich uranium in Europe.

German scientists, however, are led by a group which signed a pledge in 1957 not to participate in any research of military value, and the Germany Defense Ministry has few ties with nuclear research. While W. Germany is capable of developing an independent closed fuel cycle (with the exception of the initial uranium supply), it will acquire enriched uranium through URENCO, a European consortium and its small fuel reprocessing laboratory is tied to France. By becoming involved in multilateral nuclear fuel facilities, W. Germany has sought to allay fears of a covert nuclear weapons program based on nuclear power plants. Furthermore, all German reactors use slightly enriched uranium fuel, which is less than optimal for the production of weapons grade plutonium. A covert German nuclear weapons program would run the risk of exposure by Eastern. agents who have succeeded in penetrating the German security system on numerous occasions, and revelation of such a program theoretically could result in the loss of W. Germany sovereignty.

West Germany signed the NPT in 1969, but ratification was delayed until 1974. This five-year delay was a result of misgivings and divisions within Germany concerning the effect of the NPT, although it should not be taken as an indication of a desire for a German nuclear weapons development program. Germany’s continuing moral debt, public and scientific opposition, certain retaliation from both East and West, the cost, and low utility of a small German nuclear force all weigh against such a desire.

Initial German hesitation to sign the NPT was based on an uneasiness about the intentions of the Soviet Union, which was at that time still seen as a major threat to national sovereignty; on the fear that Germany ratification of the NPT could disrupt European integration; and a more general fear that the NPT would interfere with the development of industrial nuclear facilities. When Winy Brandt became Prime Minister and initiated the Ostpolitik policy, he signed the NPT and when safeguards agreements between Euratom and the IAEA were negotiated, the NPT was ratified. In addition, by that time, renunciation of nuclear weapons was not seen as resulting in an inevitable relegation to the level of a third-rate power and loss of international status.

Japan

1. The Security Perspective

Since Japan has a highly developed island economy deficient in indigenous resources, the import of resources and the export of semiprocessed and manufactured goods is essential for the maintenance of a high level of output and continued growth.[1] Thus, to foster and maintain Japan’s economic well-being, access to foreign sources of raw materials and other commodities, open routes of transportation, and unimpeded access to export markets are essential. Although the security of the sea-lanes has traditionally been viewed as a significant consideration, the energy crises of 1973-74 demonstrated the vulnerability of some of the other factors which are essential for Japan’s economic well-being.[2]

The military threat to Japan is considered less acute than the economic threat. Japan is not likely to be confronted with a major invasion of its islands by conventional forces, but would be vulnerable to nuclear weapon strikes delivered by USSR or PRC missiles or aircraft.

2. The Nuclear Debate

The strong moral aversion to nuclear weapons voiced by the Japanese public may have decreased somewhat in recent years, but a large segment of the population remains opposed to the acquisition of nuclear arms by their country.

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[1] Yuan-li Wu, U.S. Policy and Stra Interests in the Western pacific, p. 102 (New York: Crane, Russak & Company, Inc., 1975).

[2] Ibid.

One U.S. scholar has observed that the Japanese “nuclear allergy” has perhaps been overrated or taken too much for granted since 1945.[3] George Quester acknowledges a great deal of sincere Japanese revulsion to nuclear weapons in the aftermath of Hiroshima and Nagasaki. But he is also of the opinion that there has been a conscious exploitation by the Japanese of the guilt feelings of the United States and other nations with regard to the first and only use of these weapons. Manifesting an aversion to nuclear weapons contributed to Japan’s goal of reacquiring respectability in the aftermath of World War II.

The Atomic Energy Basic Law, enacted in 1955, explicitly prohibits Japan from developing nuclear weapons or applying nuclear technologies for military purposes. Constitutionally, “defensive” nuclear weapons are permissible to Japan, but this provision is subject to grave difficulties in interpretation and application. A credible nuclear deterrent today assumes possession of a second-strike capability, which, in turn, implies deployment of SLBMS. These missiles, by current Japanese definition, must be considered offensive weapons. Thus, although the possession of nuclear weapons is theoretically permitted under the Japanese Constitution, the types permitted are so limited as to make their acquisition impracticable under current circumstances. Nevertheless, this appears to be a surmountable barrier. If conditions appear to call for a Japanese nuclear deterrent, the government could simply "clarify" the meaning of “defensive” as it applies to nuclear weapons. A 1970 Defense white paper stated the official view that the development of tactical nuclear weapons would not violate the Japanese constitution.[4]

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[3] George H. Quester, The Politics of Nuclear proliferation, p. 111 (Baltimore: Johns Hopkins University Press, 1973).

[4] Yoshiyasu Sato9 “Japan’s Response to Nuclear Developments: Beyond ‘Nuclear Allergy’”, in O. Marwah and Schulz, Nuclear Weapons and the Near Nuclear Countries, (Cambridge, Mass.: Ballinger, 1975 p. 229)

While a few Japanese defense analysts have advocated keeping a more "open mind" on whether Japan might not be better off with nuclear weapons in its arsenal, most have been firmly opposed to such a development.

One of their principal arguments is the claim that nuclear weapons, the badge of strength and prestige for over two decades, are now of little military value in an era in which diplomacy is the key to security in a multipolar setting. Another argument is advanced on the premise that, although nuclear weapons might prevent a major war, they cannot prevent small conflicts.[5] It is further postulated that any Japanese nuclear force would be too small for deterrence and irrelevant for local wars.

The scientific elite of Japan has similarly been staunchly opposed to such possibilities, steering junior colleagues away from any "open-mindedness". One might note that this has been in marked contrast with the senior scientists of France and India, or indeed at times of Australia Germany, and Argentina. Due to the strong hierarchical structure of Japanese university life it is difficult for junior scientists to hold independent views which are at odds with those of the "establishment". Thus scant tolerance has been extended to any junior scientists voicing "open-minded" opinions on nuclear weapons for Japan. This anonaly has implications for any clandestine efforts to develop nuclear weapons because of its impact on the ability to recruit covertly the essential minimum number of scientists that would be required for developing a nuclear weapons program.

To be meaningful a Japanese nuclear force posture would have to possess an assured second-strike capability. If China is postulated

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[5] Fred Greene, Stresses in U.S. - Japanese Security Relations, P. 93 (Washington, D.C.: Brookings Institution, 1975).

as a potential enemy, it is noteworthy that the largest 1,000 Chinese settlements hold only 12 percent of the population, and China has an extensive civil defense program. There is a vast asymmetry in the vulnerability of densely populated, insular Japan vis-a-vis the People’s Republic of China. About 32 percent of Japan’s total population is concentrated in three circular areas with radii of about 30 miles each, centered on the cities of Tokyo, Nagaya, and Osaka.[6] Thus the cost of an assured second-strike capability would appear to be prohibitive. Any smaller Japanese nuclear weapons capability could leave Japan more vulnerable than it is now, for the development of any Japanese nuclear force is likely to lead to a withdrawal of U.S. security guarantees provided under the U.S.-Japan Security Treaty.

While it is assumed that Japan is under the “U.S. Nuclear Umbrella,” detente between the U.S. and the Soviet Union, normalization of U.S.-Chinese relations, reduction of U.S. military power in the Far East, the proximity of Soviet naval and air power to Japan, and Peking’s growing nuclear arsenal casts Japan’s future position in doubt. The desire for an″ ‘autonomous diplomacy’ [7] is frustrated by the sensitivity of its foreign trade to international political issues and by its military weakness. The simple issue of Japanese fishing rights in its own waters has remained largely unsettled since before World War 11 and has become increasingly critical with the growth of the Soviet fishing industry.

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[6] Adelphi Paper No. 92, East Asia and the World System: Part II: The Regional Powers. Papers from the Ste. Adele (Quebec) Conference, (London: The Institute of Strategic Studies, Nov., 1972), p. 24.

[7] Asian peace and Japanese Diplomacy,’l Senkai (Tokyo), August 1970; and “Rogers Statement. . . Should Counter with Autonomous Diplomacy Argument,” Yomiuri (Tokyo), August 13, 1972.

Japan’s military and naval forces are not adequate to the defense of the home islands nor for providing security to Japan’s maritime traffic. Japan is therefore dependent on the good will of its neighbors, the validity of the U.S. security treaty, and the continued orderly operation of the world’s commercial arteries.

While eschewing nuclear weapons development, Japan has invested heavily in nuclear power generating facilities. Japanese technology is highly advanced, and the increasing demand for electric power, coupled with the lack of domestic energy sources, has led to a growing reliance on nuclear power. Japanese scientists have gained a great deal of experience handling nuclear materials, and there are apparently no significant technical barriers to the development of nuclear weapons in Japan. At the same time, however, it must be noted that Japan has relied solely on light water reactors for power production and has not as yet constructed a fuel reprocessing plant. A major nuclear weapons program would require an entirely new set of nuclear reactors suitable for the production of weapons grade plutonium and a plutonium separation plant. Any such program would place Japan’s energy production system in jeopardy, however, as Japan is dependent on outside sources of uranium and enrichment services which might be cut off were Japan to develop nuclear weapons. This would then jeopardize the entire Japanese economy.

Japan is a party to the Non-proliferation Treaty, having signed it in 1970, and having ratified it six years later. The long interval between signature and ratification indicated serious misgivings on the part of some Japanese towards the treaty. The nuclear industry had first successfully opposed the treaty, fearing a competive disadvantage due to the safeguards system. By 1975, however, the industry realized that further delay would actually hurt the growth of nuclear power in Japan, and supported the NTP. The remaining opponents of ratification were unwilling to give up Japan's nuclear weapons option. Eventual Japanese ratification signified the importance attached to economic rather than military uses of nuclear technology. After six years of discussion and debate, the Japanese understanding of and commitment to the NPT and its provisions is among the strongest of the non-nuclear states.

3* Special Circumstances

Nuclear weapons may hold some attraction to Japan as a deterrent and badge of great-power status. The offsetting disadvantages are, however, overwhelming. In addition to public resistance at home, a Japanese nuclear force could be expected to intensify accusations abroad concerning the "remilitarization" of Japan and might even precipitate a movement to form an anti-Japanese military alliance among nations which suffered Japanese occupation in World War II. Tokyo has to be sensitive to world opinion because of the vulnerability of its trade, and a wide spread anti-Japanese movement could result in economic discrimination, closing of vital waterways, or similar problems.

Sweden

1. Security Perspective

Neutrality in World War II enabled Sweden to emerge from the conflagration as politically stable, economically unscarred, and militarily capable. Thus, the country had every incentive to maintain a credible form of armed neutrality in the late 1940s. Sweden's experience differed from the other Nordic powers, all of which had suffered military defeat.[1]

Throughout the postwar era, Swedish foreign policy has sought to chart an independent neutral course between NATO and the Warsaw pact. It is recognized, of course, that Sweden would be unable to withstand an attack by either coalition. The concept behind the organization of Swedish defenses is that any attack on the country could be so costly in terms of lives and equipment because of the resistance offered that any invader would consider the effort unworthy of return.[2] Accordingly, the Swedish government has provided deep shelter for important industries, protected military communications centers, maintained modern well-equipped forces, constructed extensive combat fortifications, and instituted a system of universal military training.

2. The Nuclear Debate[3]

The way in which the Swedish nuclear power program was established reflected an official desire to keep the nuclear weapons option open. A.B. Atomenergi, the semi-private corporation charged with nuclear development, opted for domestically designed and produced natural uranium reactors. This decision was apparently motivated by an

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[1] Egil Ulstein, Nordic Security, Adelphi "Paper No. 81 (London: The International Institute for Strategic Studies, 1971), pp.6-7.

[2] "In Defense of Sweden", International Defense Review, Vol. 111, No. 4 (December 1970), p. 395.

[3] The section on the nuclear debate is summarized from Jerome Garris, "Sweden's Debate on the Proliferation of Nuclear Weapons," Cooperation and Conflict, Vol. VIII (1973), pp. 189-208.

intention not to commit scarce resources to the development of an enrichment process. It also meant that Sweden would be able to produce materials needed to support a weapons program without reliance on an external source of supply.

At the same time, the leadership of the ruling Social Democrats was uncomfortable with the prospect of acquiring nuclear weapons, and--for over a decade--resisted efforts by the military and their Conservative Party allies to force a decision to begin nuclear weapons development.

While the option remained open, advocates of a nuclear capability based their arguments on the need for tactical nuclear weapons deployed defensively to maintain Sweden’s neutrality. As popular opinion began to shift in favor of non-acquisition, the military-Conservative coalition scaled down its demands, and urged a military research program which might keep the option open. The Social Democrats and their allies of the Liberal and Center parties continued to delay a decision and, in the meantime, pursued an active policy of supporting international efforts at disarmament and arms control. By the late 1960s, opponents of a national nuclear force were clearly ascendant: The Swedish <u>Riksdag</u> ratified the NPT in December 1968, with little debate and no opposition.

Several factors appear to have contributed to the decision to refrain from exercising the nuclear option:

- The Social Democrats exercised great restraint in resisting early pressures to proliferate.
- The government undertook a commitment to the goals of international disarmament and arms control.
- The nature of Swedish coalition politics, which makes compromise easy but decisions on controversial issues difficult, militated against the coalition supporting the acquisition of nuclear weapons.
- The Swedish public witnessed a real debate over the issue that spanned over a decade.
- Some military personnel concluded that increased conventional forces were more useful to Sweden than nuclear weapons.
- The perceived threat emanating from the East receded with the first stirrings of U.S.-Soviet detente.

3. Special Circumstances

The waning Swedish interest in acquiring nuclear weapons can be traced to several strategic developments in the 20 years between the creation of A.B. Atomenergi and ratification of the NPT. The first was the enormous growth of the U.S. and Soviet nuclear arsenals and the growth of the two great military pacts. The kind of armed neutrality that Sweden could seriously entertain in the late 1940s and early 1950s simply became less credible as the Cold War went on and as NATO and Warsaw Pact capabilities grew. The national defense burden also increased with the growing cost and complexity of modem arms and equipment. By the early 1970s, the Swedes openly admitted that there would be no follow-on to the Viggen fighter-bomber, the pride of the Air Force.

As the relevance of Swedish military forces shrank it became evident to the leadership in Stockholm that Swedish security interests were best served by striving to reduce East-West tensions, thereby minimizing the risk of confrontation and conflict in Europe. It is probably that the Swedes see their continued neutrality as a potential assest in mediating disputes between Washington and Moscow.

Conclusion

Japan, Sweden and the Federal Republic of Germany have each refrained from proliferation despite the technical and industrial capability that places nuclear weapons easily within reach of those countries. All three countries have extensive civilian nuclear power programs and each faces potential adversaries whose military strength and strategic position are threats to their independence.

Japan is party to a security treaty with the United States which is intended to deter strategic nuclear attack; the Federal Republic of Germany is a member of the North Atlantic Treaty Organization that is pledged to assist any of its members who are attacked; and Sweden is neutral, although it is assumed within Swedish defense circles that a Soviet attack on Sweden would be part of a general attack on NATO and that therefore NATO would in fact become an ally of Sweden under those circumstances.

The considerations that dictate nonproliferation for the three countries are chiefly political. Each eschews nuclear weapons, in part, because of their intrinsic qualities and because of the disapprobation that such weapons elicit among their citizenry. For Japan and Germany, there is the additional consideration that any nuclear weapons program would carry overtones of militarism reminiscent of the time when both countries were bent on conquest. Sweden on the other hand, cherishes a role as a neutral and an advocate of peace and reconciliation, a position that would be compromised by possession of nuclear weapons. Beyond that, the military utility of national nuclear forces for each of the three countries is problematical. Japan and Germany are allied to nuclear powers, implying that nuclear weapons would be available for their defense in the event of war, while none of the three countries can reasonably hope to deploy nuclear forces sufficiently adequate to defend against a determined attack by its potential adversaries. None of the three countries wishes to challenge its nuclear-armed adversaries, and both Japan and Germany are careful to respect the nonproliferation policy for their ally, the United States.

For the three refrainers examined here, the acquisition of nuclear weapons within the current context on international affairs would bring unwarranted changes on their circumstances in the international community without strengthening commensurately their respective defensive capabilities. Such is not the case with some other nuclear-capable countries.

Apppendix II. Peaceful Nuclear Explosions

by Barbara G. Levi

Appendix II

Peaceful Nuclear Explosions

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APPENDIX II

Peaceful Nuclear Explosions

The potential of nuclear explosions for both destructive and beneficial uses has posed a persistent arms-control dilemma: What measures can be taken to deny nuclear weapons to a nation without also denying it the possible benefits of peaceful nuclear explosions? A happy solution seemed to have been found in the Non Proliferation Treaty (NPT) , which forbids non-nuclear weapons states to develop nuclear devices of any type, but which simultaneously promises these nations any benefits from peaceful nuclear explosions (PNE's) on a non-discriminatory, low-as-possible cost basis. Hence, the non-weapons states would never have to develop the technology to produce nuclear explosives, which is essentially identical to the technology for producing nuclear weapons.

Since the signing of the NPT, however, the hopes for benefits from PNE's have continued to fade while the concern over their abuse has continued to intensify. India underscored this concern in 1974 by detonating a nuclear blast which she claimed was for peaceful purposes. Other nations have noticed that India suffered very few repercussions for her actions. Nations who are parties to the NPT are of course constrained from following India's example. Nevertheless, they could potentially feel disappointed that none of the promised wonders of PNE's have been made theirs, and resentment has been expressed over the discriminatory approach of the NPT. These factors could put an additional strain on nations' willingness to abide by the NPT.

The present dilemma might then be rephrased: What measures can be taken to prevent PNE's from being used as either an excuse or an incentive for weapons development? Suggested solutions range from a complete ban on PNE’s to an international regime that would provide them to all nations. The selection of any solution should be made only after a study of what hopes the various nations have placed on PNE’s and whether these aspirations are well founded.

Historical Background

The promotion of the peaceful nuclear applications of nuclear power began in the 1950’s, with President Eisenhower’s “Atoms for peace” speech in 1953 perhaps symbolizing the start of the era. Scientists at the Lawrence Livermore Laboratory (LLL) helped initiate the government sponsored Plowshare Program in 1957 to research commercial and civil engineering projects that could be undertaken with nuclear explosions. Some critics now feel these scientists may have been too committed to their work in nuclear explosives to take a sufficiently dispassionate view of PNE’s.[1] No matter what the motive, however, there clearly were legitimate reasons for exploring the idea that nuclear bombs could create as well as destroy.

The optimism of the early researchers was reflected in their presentations at various international conferences from the late ‘50’s to the early ‘70’s. Peaceful nuclear explosions were first mentioned at the second of four Conferences on the Peaceful Uses of Atomic Energy (1955, 1958, 1964, 1971) sponsored jointly by the U.N. and the IAEA, and were further described in the last two of these conferences. The U.S. conducted four symposia (1957, 1959, 1964, 1970) as part of the Plowshare Program. At all these meetings the various nations in attendance were stimulated to dream of grandiose nuclear engineering projects that might develop their domestic resources at a low cost.

These high expectations for PNE's had to be recognized when the NPT was drafted. The Treaty allowed non-nuclear weapons states to receive the benefits of PNE's even though they would not be permitted to develop their own nuclear explosions. Any nation that was truly serious about its plans to use PNE's should have welcomed this provision of the NPT, for most non-weapons states lack the sophisticated nuclear technology to develop an explosive with the stringent requirements of one intended for domestic applications. Such devices must be manageable small, yield minimal amounts of radiation and bear a low price tag.

Provisions of Article V

The specific provisions for peaceful applications of nuclear explosions are contained in Article V of the NPT, which reads as follows:

> "Each Party to the Treaty undertakes to take appropriate measures to ensure that, in accordance with this Treaty, under appropriate international observation and through appropriate international procedures, potential benefits from any peaceful applications of nuclear explosions will be made available to non-nuclear-weapons States Party to the Treaty on a nondiscriminatory basis and that the charge to such Parties for the explosives used will be as low as possible and exclude any charge for research and development. Non-nuclear-weapons States Party to the Treaty shall be able to obtain such benefits, pursuant to a special international body with adequate representation of non-nuclear-weapons States. Negotiations on this subject shall commence as soon as possible after the Treaty enters into force. Non-nuclear-weapon States Party to the Treaty so desiring may also obtain such benefits pursuant to bilateral agreements."

The wording of Article V of the NPT has created some problems with subsequent interpretation. From the start, the U.S. was concerned over what it viewed as an open-ended commitment implied in the Article.[2] To what extent does it obligate the nuclear powers to provide the peaceful benefits of nuclear explosions? Should they be actively developing and promoting the applications of PNE's or more passively providing the PNE's only if their benefits are unambiguously determined? It is also unclear whether a nuclear power must provide PNE's to a nation when they are either hazardous, uneconomic or in some way inappropriate to the job proposed.

A second uncertainty about Article V concerns the exact nature of the "special international agreements" and the identity of the "appropriate international body". Some may have envisioned that an agency would be promptly established to provide nuclear explosives and services for any peaceful domestic projects. The actual implementation of Article V, however, seems to be evolving slowly. perhaps because of the continued uncertainty over the relative merits and demerits of PNE's.

The International Atomic Energy Agency (IAEA) was perhaps the natural candidate to be the "appropriate international body" mentioned in the NPT. In 1971, the U.N. Secretariat asked the IAEA to "exercise the functions of an international service for nuclear explosions for peaceful purposes". The statement did not clearly define what those functions would be and suggested that the IAEA study the ways and means to carry out this task.

So far the IAEA seems to have defined its role as a fairly limited one. It has developed procedures for the international observation of peaceful nuclear explosions, as called for in Article V. It has further sought to gather and disseminate technical information about the nonmilitary application of nuclear devices. It has done so through the sponsorship of a series of international technical meetings (1970, 1971, 1972, 1975, 1976), through participation in the International Nuclear Information System and most recently through the establishment of an office to handle the information exchange and service requests.

In 1974 the IAEA developed procedures for responding to requests for PNE-related services. The services envisioned to date are assistance with preliminary, pre-feasibility and feasibility studies. In fact, a team from

IAEA, at the request of Egypt in 1976, did conduct a preliminary review of the possible use of nuclear explosions in connection with the construction of a canal from the Mediterranean Sea to the Qatarra Depression. No procedures have been defined for responding to requests for services beyond the feasibility-study stage , Such longer-range plans will be on the agenda of the Ad Hoc Advisory Group on Nuclear Explosions for Peaceful Purposes, created by IAEA in 1975. One of the tasks of this group is to advise the Board of Governors on the question of an international service for PNE’s as well as on the structure and content of the “international agreements” mentioned in Article V“.

In general, the IAEA seems to see its role as that of an intermediary - facilitating exchange of information and providing a liaison between those nations requesting PNE services and those nations willing to provide consultation or actual explosive devices.

Effect of PNE’s on Test Ban Treaties

PNE’s have complicated negotiations for test ban treaties. The only test bans that have been negotiated between the U.S. and the U.S.S.R. are the 1974 Threshold Test Ban (TTB) Treaty and its associated 1976 Treaty on Underground Explosions for Peaceful Purposes (the so-called PNE Treaty, which is till not ratified but which was a prerequisite for implementation of the TTBT). Both have been criticized for blocking rather than paving the way toward a comprehensive test ban.

The major objection to the Threshold Test Ban Treaty is that is poses very little hindrance to weapons tests: the upper limit of 150 kton is 10 times the size of the bomb dropped on Hiroshima. The PNE Treaty places the same limit on the size of nuclear explosions for peaceful applications as the TTB does on nuclear weapons tests. This provision was necessary because both sides admitted during the negotiations that no one can verify that PNE’s are not being used for weapons development--even with the on-site observations that constitute a unique feature of the PNE Treaty.

The unfortunate aspect of the PNE Treaty is that it is a separate treaty. It was negotiated separately largely in deference to the Soviets, who claim an active interest in a PNE program. (Ironically enough, it was the Soviets who, thirteen years earlier, had opposed U.S. efforts to exclude PNE’s from the Limited Test Ban Treaty.) The existence of a PNE Treaty legitimatizes a separate status for such peaceful nuclear devices and invites other nations such as Brazil to use the same excuse for nuclear weapons development as India did. Furthermore, the PNE Treaty will complicate any attempts to reduce the upper limit on tests set in the TTB. Because the treaties have recognized the indistinguishability of weapons and PNE tests, no reduction in weapons tests is likely as long as interest remains in larger PNE tests.

In view of these complications in arms control introduced by the concept of beneficial applications of nuclear devices, it is necessary to examine whether any of the potential benefits are worth this price.

U.S. Program on PNE's

In the nearly twenty years since the start of the Plowshare Program, many beneficial applications of nuclear explosions have been extensively studied in the U.S. Despite the initial enthusiasm over the Program, most of the recent reports manifest decreased optimism. The U.S. budget for PNE's reflects the same trend: After having spent $160 million on PNE experiments, the U.S. currently has alloted about $1 million per year for PNE's. Of that, $300,000 is earmarked for research on using PNE's to create storage cavities for radioactive wastes. The remaining funds are for the purposes of fulfilling the obligations of the NPT.

The Plowshare Program investigated both of the two general categories of nuclear explosions for peaceful purposes: excavation projects and contained explosions. (See Table I for a chronology of the Plowshare Program.) One of the more prominent excavation projects--the construction by nuclear means of a sea level canal to supplement the Panama Canal--was studied by the Atlantic–Pacific Interoceanic Canal Study Commission, appointed in 1965. In its final report in 1970, the Commission gave the concept a rather negative assessment. A major finding was that the technology of nuclear excavation was not yet sufficiently advanced. In addition, the necessity of locating the canal route far from population centers to avoid seismic and radiation damage raised costs above those estimated for construction with conventional explosions.

Although there are some locations where the economics are more favorable for nuclear excavation projects, the other factors that hindered the isthmian canal project are still present. The technology knowledge does not yet allow precise predictions of crater depth and width or of crater lip stability. Furthermore, the trough created by a given nuclear explosion must be accepted as is, for the area is too radioactively hot to permit immediate modifications, as is possible with conventional explosions. Even if these technical problems could be surmounted, the health and environmental problems still remain Seismic effects. air blast and radiation from a nuclear detonation are severe enough to necessitate evacuation of the local population, often for extended periods of time. Research on bomb design has resulted in "cleaner" bombs--ones that shield the neutrons and that have a large thermonuclear component to minimize the production of biologically significant fission products. The research has resulted in order-of-magnitude decreases in radiation, but some radioactivity is released.

The radiation releases constitute a political as well as a health constraint on excavation applications. The Limited Test Ban Treaty of 1963 forbids any nuclear explosion for any purpose that would spread radioactive debris beyond the border of the nation conducting the explosion. Wishing to abide by this treaty and discouraged by the many negative factors of nuclear excavation projects, the U.S. halted this phase of PNE research in 1969.

Contained Applications: General Factors

Although hopes for nuclear excavations are dead in the U.S. , interest in contained nuclear explosions is still alive. One reason is that nuclear explosions have a far greater energy density than conventional chemical explosions. Thus, the size and weight of a nuclear explosive can be about 1/10,000 of the size or weight of a chemical explosive that would accomplish the same job. This logistic advantage also leads to an economic advantage:

The cost of a nuclear device has been estimated to be about 1/10 that of a comparable chemical device, for those with a yield of 10 kt or higher (these estimates are somewhat speculative). In addition, the cost of the nuclear explosion does not increase much as the yield goes up. A 1,000 kt device costs little more than a 100 kt device. This fact tends to favor applications with large yields.[5]

The exact pricetag on a nuclear explosive is technically a military secret. Current estimates are that it would be somewhere between $400,000 and $1,000,000.[6] The costs associated with its use - such as device emplacement, monitoring, evacuation - roughly double the cost of the device.[7] None of these costs reflects the research and development expense, most of which has been covered by the weapons program[8] and the AEC Plowshare Program.

Some additional interest in PNE's has been stimulated recently by the energy crisis. The emphasis on decreasing our reliance on foreign sources of petroleum products and the increased cost of such energy sources has made it worthwhile to develop domestic reserves that were previously ignored. It is hoped that nuclear explosions might stimulate production from tight gas formations, assist in retorting oil shale <u>in situ</u> or perhaps create underground storage caverns for oil, gas or liquified natural gas (LNG).

A detailed evaluation of these and other possible applications of nuclear explosions in the U.S. was completed by the Gulf Universities Research Consortium (GURC) in 1975.[9] Their task, commissioned by the Arms Control and Disarmament Agency, was explicitly to project the use of PNE technology up to the year 1990. They found that the technical uncertainties surrounding most of the proposed projects were so large as to preclude any economic analysis except a range of cost estimates. Nevertheless, even with the most optimistic assumptions, the GURC study concluded that any PNE application before 1990 was highly unlikely. Their report underscores some general factors that all PNE applications have in common:

"1. Technical uncertainties. The impact of a nuclear explosion in particular circumstances can not yet be accurately predicted and the results vary with such factors as the type of rock, depth and size of explosive. Technical uncertainties also surround the non-nuclear aspects of most of the proposed applications. Finally, the quantity, quality and properties of the resource to be exploited are rarely known with great certainty.

2. Economic uncertainties. Until the technical questions are fully answered, firm cost estimates of various applications are difficult to make. The GURC report could make economic predictions only by assuming success for each of the various development stages. On this hypothetical basis the report found that some applications of nuclear explosives might be commercially competitive.

3. Regulatory Questions. A major factor in preventing or at least retarding the application of PNE's is the public opposition to it. Already two restrictions loom as handwriting on the wall, especially against the background of resistance that has been faced by the nuclear power industry. One of these restrictions is a state constitutional amendment that was passed in Colorado in 1974 to ban the conduct of any nuclear tests unless approved by a statewide referendum. (Colorado was the site of two contained

nuclear experiments and possesses considerable quantities of gas and oil shale that are being proposed for development by PNE’s.) Separately, Congress in 1974 passed a provision in the ERDA budget that prohibits funds from being used for PNE tests. If further public resistance developed to any attempt to accelerate the PNE program, it would produce considerable delays and would raise the costs.

4. Supply of PNE’s. Nuclear explosives are necessarily a government monopoly and would have to be supplied to the industry by the government if an actual PNE program developed. Some of the proposed applications envision several hundred PNE’s per year, and the industry would have to be assured of a reliable supply. The government would presumably have to establish a production line to provide the required number at a reasonable cost. Close coordination with the intended user would have to be maintained, especially in the early phases of production start-up. Another problem could conceivably be the competition of the PNE program with the Defense Department and the nuclear power industry for a supply of nuclear fuels.[10]

5* Environmental Effects. Seismic damage is a limiting factor for most contained PNE applications. The damage to buildings and necessity of evacuation restricts the use of such techniques to areas of low population density. Repeated detonations in the same area might also cause appreciable ground rise and additional damage to structures. While the radiation from a contained explosion is not released in large quantities into the air, as with an excavation, small amounts of radioactivity can still find their way out: Some might be vented to the air, some can seep into the ground water and some might be mixed with the product being mined or extracted. Finally, the ever present though small risk of accident becomes multiplied by the large number of explosions required for most of the PNE uses.

6. Success of Competing Technology. Almost every task proposed for PNE's can be accomplished by other techniques. Often the alternative is either more costly or in an early stage of development, but research on less controversial techniques may advance more quickly.

Increased Production of Gas Resources

A look at the most frequently discussed PNE proposals gives insight into how all these general factors operate in particular circumstances. One application that has received considerable attention is the stimulation of tight gas formations. These formations are regions where the permeability is too low to allow the gas to flow into wells at sufficiently fast rates. If the permeability could be increased by using a nuclear explosion to fracture the rock, the rate of recovery might be appreciably improved. A series of three such explosions were conducted in the Rocky Mountain states. The first two - Gasbuggy (a 29 kt explosion in 1967) and Rulison (43 kt in 1969) - produced some positive increases in gas flow. The third one - Rio Blanco (three devices of 30 kt each in 1973) - was a disappointment and has been one cause of general disillusionment with PNE's. The objective of the Rio Blanco test was to connect three lenticular regions by exploding three blasts simultaneously at different depths. Tests indicate the chambers did not connect as planned and gas yield was lower than expected. A fourth planned test of gas stimulation has not been scheduled.

The Rio Blanco test failure illustrates the lack of knowledge of critical parameters. The permeability of the rock and the amount of gas may not have been well enough known. The effect of the blast on the rock evidently were not predicted correctly. The unknown effects include the height of the chimney (perhaps underestimated in this case), the fracture patterns and the rate of healing of the fractures, which would slow production over a period of time.

Even if the technology did succeed, this application of PNE's would face some environmental problems. The gas produced might have some radioactive contamination (albeit at a low level) that might affect its marketability. This application also calls for a larger annual number of PNE's (as many as 450 per year)[11] than most other proposals.

The major competitor to PNE's for gas stimulation is the technique of massive hydraulic fracturing (MHF). A mixture of sand and water at high pressure is pumped into the rock to fracture it. The sand prevents any healing of the fractures. Estimates are that PNE's are cheaper than MHF for the stimulation of gas reserves but by a margin that is less than the range of uncertainty in the estimates.[12]

Stimulation of Oil Wells

The use of nuclear explosions to stimulate production from oil reservoirs is less promising than gas stimulation. There is virtually no interest in this application in the U.S. Many fear it might result in long-term damage to the reservoir, and several alternatives for enhanced oil recovery are available.[13]

Extraction of Oil from Shale

A third potential use for nuclear explosions is to assist in the recovery of oil from the shales in the Rocky Mountain Basin. The amount of oil that might be ultimately recoverable exceeds the cumulative domestic production of crude oil up to 1974.[14] The recovery of this large resource poses equally large problems. The petroleum is present in the shale in the form of an organic compound called kerogen which must be heated to 8 800 F before it turns into a fluid that can be extracted.

The best known method for extracting the shale oil is open-pit mining and above ground retorting. A perhaps preferable variation is to replace the open-pit mines with underground mines. Still both methods have severe problems. The above ground retorting requires large amounts of water whereas the surrounding areas are typically quite arid.[15] It also results in an accumulation of depleted shale above ground which presents a disposal problem. Finally, it requires relatively high quality shale.

To avoid these problems of above ground retorting, several in-situ techniques are being studied. In the Garrett process, an underground cavity is mined. A conventional explosion is detonated in this cavity to create a rubble-filled chimney. A combustion front is then started at the top of the chimney and continues to advance downward as air is fed in. The liquid product, similar to crude oil, forms in a pool at the bottom and is pumped to the surface. Gaseous products are also collected. The low Btu liquid usually requires further processing at the surface.

An alternative to the Garrett process is to use a nuclear device to create the rubble-filled chimney. This application may require explosives ranging from 30 to 130 kt for depths of detonation from 900 feet to 1900 feet.[fi] Perhaps 100 PNE's per year might be required if this application became fully developed.[17]

Many problems plague both in-situ retorting processes. Some features that need to be researched are the percentage of oil that might be recovered (optimistic estimates are 60%), the extent to which the void space in the rubble might be closed by such phenomena as exfoliation of the rock, and the pressure drop through the length of the chimney (the pressure drop affects a critical cost element - compression of the air). Some experimental data is being provided by an experimental 150-foot retort created by non-nuclear techniques and operated by the Bureau of Mines. However, it is not clear how one should extrapolate these data to the much higher chimneys and perhaps different rubble-size distribution to be created by a nuclear explosion.

The behavior of the shale following a nuclear explosion is a major uncertainty as PNE's have never been tested in this unique medium. It is critical to predict accurately parameters such as the chimney height, void space (now estimated at 12½%), and rubble size.[18]

As in other PNE applications there would be some radiation and seismic effects. The surface rise might be appreciable and could affect such high-investment structures as processing plants for the shale oil.[19]

The application of nuclear explosions to recovering oil shale is restricted to a limited portion of the shale region by several siting requirements. The explosives must be used in beds with an overburden of at least

1000 feet to avoid venting of radiation. They must be spaced far enough apart to avoid a blow-by, in which the chimney created by one explosion interferes with that from another. This latter spacing requirement may mean that only 25% of the oil shale in a given region may be fractured by PNE's.[20] The retorting process in turn can extract at most 60% of the oil in the fractured shale, further reducing the yield.[21]

Prospects for above ground retorting now appear poor because of unfavorable economics and environmental impacts. In situ retorting using conventional explosives appears better on both counts, but is in a substantially earlier stage of development. If oil shale is to be exploited, one or both of these techniques will be utilized well before the PNE concept can be realized.[22]

Creation of Storage Cavities

The furthest developed application of PNE's is the creation of underground storage cavities. The first contained Plowshare explosion, dubbed Gnome, was a 3.1 kt blast in a salt formation that produced a cavern with few cracks and glazed walls. Such a volume could be used for storage of gas, oil, liquefied natural gas or even for permanent storage of chemical or radioactive wastes. Salt domes or salt formations are probably the best media for such cavities, although other rocks such as clay, clay shale or some sandstone may also be quite adequate. Hard rock tends to fracture into large cracks when subjected to nuclear explosions.

The usefulness of nuclear explosions for creating such storage chambers will depend in part upon the number of locations that can be found with just the right combination of circumstances: salt domes situated far from population centers but near strategic points with respect for the marketing or transportation of oil and gas. These requirements frequently conflict with one another.[24]

One alternative to nuclear-created storage cavities is to construct above ground containers of steel or concrete, but these are often more expensive than underground vaults created by nuclear means. Solution-washed salt cavities may be cheaper but they are limited to regions near salt water for washing and the ocean for disposal.[25] Perhaps the least costly alternative for storage is to use abandoned mines or aquifers. There may be enough of these at appropriate locations to eliminate the need to carve new caverns with nuclear explosions.[26]

Leaching of Copper Ore

A fifth beneficial application of nuclear explosions might be to assist in the mining of copper deposits. A nuclear blast could be used to fracture the copper ore to facilitate a leaching process. The ore is leached with water that is saturated with oxygen in order to convert the insoluble copper sulfides to soluble sulfates. The problem is to have the temperature high enough (around 200°F) and the circulation rapid enough for the sulfate to remain in solution long enough to be extracted. Research on using PNE's for this technique began in 1967 with Project Sloop and is now being conducted jointly by LLL and the Kennecott Copper Company.[27]

As in the case of in situ retorting of oil shale, uncertainties must be resolved concerning the non-nuclear as well as the nuclear aspects of the copper leaching technique. Some of the unknowns include the degree of oxygen saturation required, the temperature gradient (because of the reaction rate is a function of temperature) and the composition of the ore itself. Once these questions are answered one must determine the size and distribution of the rubble created in the ore by the nuclear explosion, which in turn affect the reaction rate and the speed of fluid flow.[28]

The seismic damage may rule out some applications of this technique because significant copper deposits are located quite near to populated areas.[29] Further restrictions might result from possible contamination of the copper with small amounts of ruthenium-106, an element with a half life of about one year. A final factor limiting the use of PNE's is that the economics will remain quite marginal unless the prices of copper rise.

These five applications for PNE’s are only a few in a long list of proposals, but the others have received considerably less attention. No application is close to being realized in the U.S. In all cases there appear to be viable alternatives, but in some cases, PNE’s seem to offer substantial cost savings. As illustrated above, however, a great many uncertainties must be resolved before commercial use can be contemplated.

USSR Program on PNE’s

The Soviet interest in beneficial applications of nuclear explosions was increasing as that in the U.S. was declining. Some observers feel that the USSR may now be going through a period of questioning with regard to PNE’s similar to that experienced by the U.S. ten years ago. Some representatives of the USSR over the past few years have expressed serious doubts about the prospects of PNE’s.[30] Experiments are continuing, however, and at the August 1976 Conference on Complete Disarmament the Soviet delegate declared that “nuclear explosions for peaceful purposes represent one of the new and very promising avenues of the use of nuclear energy.”

The outcome of any deliberations over engineering applications of nuclear explosions in the Soviet Union will depend upon the same types of factors as those in the U.S. but these factors may operate in different ways. The U.S.S.R. is unlikely to face severe public opposition to PNE's although environmental groups do exist (Such a group succeeded recently in changing the development plans for Lake Baikal.). The concern over the seismic damage and the radiation releases is not as great because the U.S.S.R. has vast unpopulated regions in which it envisions many of the proposed applications. The economics are difficult to evaluate as the U.S.S.R. has not published any studies and the accounting procedures may be very different.

The technical aspect of PNE's have as many uncertainties in the U.S.S.R. as in the U.S.[31] The Soviets do have an active experimental program and are investigating a wide variety of applications and types of geological materials. From 1965 through November 1973, the Soviets conducted 16 nuclear explosions which they claimed were for industrial or experimental purposes. (See Table 2.) An additional 17 seismic events have been identified (by either ERDA or by the Stockholm International Peace Research Institute) as nuclear explosions outside the normal weapons test areas; these events are classified as probable PNE tests.[32] Two such tests were monitored in 1976, the more recent being a blast in Central Siberia on November 5.[33]

U.S.S.R. Excavations

One of the applications of PNE's that has received much attention is the construction of a canal to link the north-flowing Pechora River with the south-flowing Kana River. The goal is to increase the water flow into the Caspian Sea, whose level has dropped in recent years because of dry weather and heavy water demand. The Soviets have proposed the use of nuclear explosives to dig a 65-km section of the 112.5-km canal that traverses the most mountainous terrain. This application calls for 250 explosives of up to 150 kt each. (See Table 3.) They have tested three 15 kt explosions in the water-saturated alluvium soil that forms part of the canal route. (The effect of nuclear blasts on the rocky portions are believed to be better understood.) The tests resulted in a crater that is perhaps shallower and smaller in cross section than planned, but the Soviets claim it is adequate for their canal.[34]

Another excavation project for nuclear explosions in the U.S.S.R. is the creation of water-storage reservoirs, especially in the Central Asiatic Republic.[35] One such reservoir was created by a nuclear blast of more than 100 kt that was set off adjacent to a river bed. The crater lip formed a dam across the river and a reservoir behind it. A canal was subsequently dug to connect the crater with this reservoir. In this test and others, the crater lip tended to slump following the explosions, creating a wider but shallower crater, but was stable thereafter.[36] The Soviets seemed pleased with this project but later let the water drain.[37]

A final excavation proposal is to remove the overburden from large deposits of non-ferrous metals. It is estimated that perhaps more than half of the deposit can be made accessible by nuclear techniques at a savings of over one billion rubles.[38] The area is described as being similar to the far north but with high seismicity and frequent earthquakes.[39]

These three plans for excavation experiments in the U.S.S.R. are remarkable if only because the U.S. has long since discontinued its excavation projects to comply with the Limited Test Ban Treaty. Indeed, the crater lip dam did produce fallout that travelled beyond the boundaries of the U.S.S.R.[40] The Soviets claim that the radiation releases fall below standards for radiation protection, but the limit set by the Treaty is zero. This risk is inherent to excavation projects. Continued Soviet violations may put a severe strain on the treaty.

USSR: Contained Applications

The Soviets are investigating several uses of contained nuclear explosions in the category of resource recovery. They have claimed success in increasing the production of two oil fields by a series of explosions of 8 kt or less (See Table 2.) They presented too little data for their claims to be verified,[41] but several U.S. observers feel that it is not clear that the production increases were the direct result of the nuclear explosions.[42]

The U.S.S.R. plans to use PNE’s to simulate gas production as well. Although they claim to have conducted a test of this application, no details have been forthcoming.[43] The application of the fracturing properties of nuclear explosions to the breaking of ores is also being studied.[44]

As in the U.S., the application that is the most developed is the creation of underground storage chambers. The first cavity tested (created by 1.1 kt device exploded in a salt dome) leaked water and radioactivity. A second (25 kt in a salt dome) proved to have satisfactory storage properties. The third cavity (15 kt in salt formation) is now in industrial use for the storage of gas condensate.[45]

A proven but limited use for nuclear explosions that was developed in the U.S.S.R. is the sealing of runaway gas well fires. A 30 kt device sealed a fire that had been out of control for three years; a 40 kt explosions extinguished a flame in an adjacent well.[46] No other methods had been feasible or effective.

In the descriptions of all their various programs, the Soviets seem optimistic, but close examination reveals that few of the PNE uses (except perhaps the control of runaway gas well fires) are really proven both technologically and economically.

The intensity of Soviet interest in its PNE program is difficult to assess, especially as divergent voices are still expressed within the scientific community.

Most of the applications are being promoted more by technocrats than politicians. Which would win out if the U.S.S.R. ever had to decide whether it would forego the benefits of peaceful nuclear explosions in order to gain a comprehensive test ban? A very remote possibility is that the PNE program is being kept alive simply as an excuse not to enter into a complete test ban.

PNE Interest in Other Nations

Among the nuclear weapons states, the U.S. and the U.S.S.R. have by far the most active programs. France has expressed some interest in underground storage, especially under the ocean, and in the stimulation of hydrocarbon resources. However, she is limited from extensive PNE applications by her dense population. Great Britain faces similar limitations and has virtually no plans to use PNE's.[47] The plans of China are not known.

Although India claimed her nuclear detonation was a test for peaceful purposes, she has never elaborated in detail what her hopes for PNE's are. The Indian delegate to the IAEA technical meeting in 1975 spoke only vaguely about interest in stimulating production from oil wells (an application that is nearly rejected in the U.S.) and in the mining of non-ferrous metals.[48]

Among the non-nuclear nations, the most publicized peaceful applications of nuclear explosions are excavation projects. Perhaps these nations cannot think in terms of contained applications, which frequently would require hundreds of explosives per year and necessitate a reliable source of PNE's. Three canal-building proposals are summarized in Table 3. The Columbian project was considered the most favorable route evaluated by the Atlantic-Pacific Interoceanic Canal Study Commission. Little mention of it is made in recent literature.

Both Venezuela and Thailand have proposed canals that are estimated to be cheaper with nuclear than conventional explosions by significant margins” The Venezuelan plans involve smaller devices but would require the evacuation of two villages.[49] The Thailand project calls for very large blasts and would certainly spread radioactive debris to its neighbors. In addition, it requires the evacuation of 200,000 Thais for up to 16 months.[50] The feasibility study was financed privately under a previous government and the new government has adopted a very cautious attitude toward the canal project.[51]

The Egyptians have been investigating the use of nuclear explosions to help excavate 68 km of a canal that would link the Mediterranean Sea with the Qatarra depression. Water flowing from the sea into the depression could drive a 300 MWe (1200 Mwe peak) hydroelectric plant. The plans require some 213 explosions and evacuation of less than 25,000 people within 80 km of the route. Use of the nuclear explosions is estimated to reduce the total project cost by almost a factor of three.[52]

The likelihood of these or any other PNE proposals for non-nuclear nations depends strongly upon the resolution of technical uncertainties by research in the U.S. and U.S.S.R.[53] It also depends upon the need for the particular application, the availability of alternatives, the socioeconomic effect treaty provisions and the environmental impact.[54] If these factors were all resolved in favor of PNE’s, then institutional questions would arise regarding the source, cost and conditions of the nuclear explosives. 35 The suppliers of PNE’s are likely to be either the U.S. or the U.S.S.R., as they can presently manufacture the type and quantity of explosives required. However, other nuclear weapons states could quickly develop the technology to produce them as well.[56]

Conclusions

None of the proposed applications of nuclear explosions has been unambiguously determined to provide net benefits. Even the most optimistic estimates do not envision large scale applications in the near future. At the same time, few applications have yet been disproven. In the face of such ambivalence the present course has been to proceed with a low level of research on major uses of PNE's and move only slowly and cautiously toward providing PNE services to NPT signers.

One danger of this course is that the separate status accorded PNE's hinders progress towards a comprehensive test ban. The present course also provides justification for non-nuclear weapons states to develop nuclear explosives. Several seeds of discontent have been sown by PNE's: Many nations feel disappointed that earlier promises of PNE's have not yet been fulfilled. They also resent the reluctant pace at which provision for PNE services has been moving. For a nation such as Egypt, which has not ratified the NPT and which has proposed a PNE application, these feelings may contribute to a decision not to enter into the Treaty. Nonsigners may conclude they have more to lose than to gain by signing. Even if PNE's are not the real motive they might at least be the excuse for a nation to remain outside the NPT and even to develop their own nuclear weapon, as India has done.

One step out of the present course would be to call for a temporary ban on the conduct of all nuclear explosions for peaceful purposes.[57] Such a moratorium might be palatable in light of the findings of the GURC report that few applications of PNE's are likely to be feasible before 1980. Research on PNE's need not be halted along with the tests themselves because many non-nuclear aspects of each application need to be fully investigated.

The moratorium could be conditional upon either an unambiguous demonstration of a beneficial and viable application of PNE’s or upon the outcome of an international conference to assess the practicality of PNE technology at that future date. Other international conferences have dealt with various aspects of PNE technology but none has tried critically to evaluate and balance all factors--technical, economical, sociological, environmental and political.[58,59]

A permanent ban on PNE’s is a more drastic and perhaps premature step. The Soviets would be unlikely to accept it, even as a price for obtaining a comprehensive test ban, given their current announced interest in beneficial applications of nuclear explosions. Non-nuclear nations who have been led to believe in the real promise of PNE’s, may also object to such a proposal. They might justifiably claim it violates Article V of the NPT. Even in the U.S., industry seems to want to keep open the door for some possible far-future development of peaceful explosions.

A step in the opposite direction but aimed at the same result is to establish an international service to provide nuclear explosions for peaceful purposes to all nations, regardless of membership in the NPT.[60,61] This action might prevent non-NPT nations from developing nuclear weapons and labeling them peaceful devices. With an international service to provide PNE’s cheaply, no nation need make its own. Opponents of this plan argue that it is premature and that any sanctioned nuclear explosions makes a CTBT very difficult to achieve. The danger exists that such an institution as an international PNE service might be tempted to develop and promote various beneficial applications to justify its existence.

Any new course undertaken to deal with PNE’s must be charted to steer away from the three major dangers they now present: Hindering progress towards a CTB, retarding membership in the NPT and providing excuses for nations to test their own nuclear bombs. The present course runs into all three dangers. Each of the alternate routes avoids primarily one of the dangers. The proposed temporary ban on PNE’s would eliminate an obstacle to a CTB, while a provision for PNE services would remove the possibility that PNE’s could be used as an excuse. A decision between either of these courses then depends upon the area of greatest concern as well as upon the probable effectiveness and possible negative side effects of each action. The choice is not clear.

Footnotes

1. William Epstein, -The Last Chance, (The Free Press, 1976), p. 172.
2. Ibid., p. 174
3. Ibid., p. 173
4. Program on Science, Technology and Society, Cornell University, An Analysis of the Economic Feasibility, Technical Significance and Time Scale for Applications of Peaceful Nuclear Explosions in the U.S. , with Special Reference to the GURC Report Thereon, April 1975, p. 201.
5* Ibid., pp. 3, 4.
6. Gulf Universities Research Consortium, Peaceful Nuclear Explosion Activety projections for Arms Control planning, ACDA/PAB-253, April 1975, Volume II, p. 201.
7. Program on Science, Technology and Society, pp. 3, 4.
8. Herbert Scoville, Jr., Peaceful Nuclear Explosions - An Invitation ‘° proliferation, ed. Anne W. Marks, NPT: Paradoxes and Problems, Washington, D.C., 1975, p. 50.
9. GURC, Volume I.
10. GURC, Volume II, p. 202.
110 GURC, Volume I, p. 145.
12. Ibid., p. 80.
13. Ibid., p. 131.
14. Ibid., p. 45.
15. Frank A. Long, Peaceful Nuclear Explosions, Bulletin of the Atomic Scientist, October 1976, p. 23.
16. A. E. Lewis, Nuclear In Situ Recovery of Oil from Oil Shale, paper IAEA - TC-1-4/2, Proceedings of a Technical Meeting, Peaceful Nuclear Explosions IV, 20-24 January 1975, IAEA, Vienna, 1975 p. 170
17. GURC, Volume I, p. 145.
18. Program on Science, Technology and Society, Cornell University, p. 18.
19. GURC, Volume 11, p. 22.
20. Program on Science, Technology and Society, Cornell University, p. 18.
21. GURC Volume 1, p. 71.
22. Program on Science, Technology and Society, Cornell University, p. 19.
23. GURC, Volume I, p. 197.
24. Ibid., p. 105.
25. Ibid.
26. Program on Science, Technology and Society Cornell University, p. 190
27. GURC, Volume I, p. 126.
28. Ibid., p. 127.
29. Frank A. Long, p. 27.
300 V. S. Emelyanov, “On the Peaceful Use of Nuclear Explosions”, Stockholm International Peace Research Institute, Nuclear Proliferation Problems, MIT Press, Cambridge, Mass., 1974, pp. 215 - 224, and William Epstein, p" 177.
31. GURC, Volume I, p. 181.
32. Milo Nordyke, “A Review of Soviet Data on the Peaceful Uses of Nuclear Explosions,” Annals of Nuclear Energy, Volume II, Pergammon Press, 1975, p. 671.
33. W.K. Benson, Energy Research and Development Administration. Personnel communication, November 9, 1976.
34. Milo Nordyke, p. 661.

35. Energy Research and Development Administration, Peaceful Nuclear Explosions, ERDA-44, April 1975, p. 18.

36. Milo Nordyke, p. 659.

37. Herbert Scoville, Jr., p. 48.

38. Milo Nordyke, p. 663.

39. Ibid., p. 662.

40. Herbert Scoville, Jr., p. 48.

41. Milo Nordyke, p. 666.

42. GURC, Volume II, pp. 129-135.

43. Milo Nordyke, p. 667.

44. Ibid., p. 669.

45. Ibid., p. 667.

46. Ibid., p. 663.

47. Technology Committee Proceedings, IAEA, Peaceful Nuclear Explosions IV. January 20-24, 1975.

48. Ibid.

49. ERDA-44, p. 23.

50. Ibid., p. 25.

51. Technology Committee Proceedings, IAEA.

52. Harry Otway, IAEA Interoffice Memorandum to the Director General, Report of Project Qatarra Fact Finding Mission, Egypt, April 25 to May 2, 1976.

53. GURC, Volume I, p. 179.

54. Ibid., p. 178.

55. Ibid., p. 179.

56. W.K. Benson

57. Herbert Scoville, Jr., p. 50.

58. Herbert Scoville, Jr., p. 54.

59. William Epstein, "The Proliferation of Nuclear Weapons," Scientific American, April 1975, p. 18.

60. William Epstein, The Last Chance, p. 172.

61. William Epstein, "The Proliferation of Nuclear Weapons," p. 18.

TABLE I

PLOWSHARE CHRONOLOGY

L Program Milestones

Date	Event
Nov. 26, 1956	Commission approved in-house conference on peaceful uses of nuclear explosives. Lawrence Radiation Laboratory, Livermore (LRL-L), had been informally studying the question during previous years. (Staff Paper 81 1/4)
February 1957	First Plowshare Symposium held at LRL to discuss Industrial Uses of Nuclear Explosives.”
June 27, 1957	Commission approved the establishment of a program in the Division of Military Applications to investigate nonmilitary uses of nuclear explosives. (Staff Paper 811/6, dated June 13, 1957)
July 1957	LRLL-L formally establish Project Plowshare to investigate the nonmilitary applications of nuclear weapons.
September-1957	Project Rainier, the first US underground detonation of a nuclear explosive. A chimney of featured rock was formed which provided data on possible” underground engineering applications of nuclear explosions.
October 1957	The US Corps of Engineers agreed to supply support services for the Plowshare Program.
Dec. 10, **1957**	‘General Advisory Committee to AEC recommended that a study group be formed to investigate peaceful uses of nuclear explosives for the production of isotopes and for large earth-moving projects.
March 31, 1958	Responsibilities for operations and industrial contacts delegated to San Francisco Operations Office (SAN). SAN established Special Projects Group to oversee program.
July 1, 1958	Plowshare support efforts established at Albuquerque Operations Office (ALOO) and Oak Ridge Operations Office (OROO). “
Aug. i5, !958	US Geological Survey agreed to conduct support studies for Plowshare Program.
Sept. 9, 1958	US Bureau of Mines agreed to cooperate on Plowshare Program.
October 1958	US began voluntary moratorium on all nuclear testing.
Dec. 15,1958	Formation of Peaceful Nuclear Explosives Branch in DMA to supervise Plowshare Program.
January 1959	Joint AEC/Bureau of Mines Oil Shale Symposium at Dallas, Texas. Presented material on use of nuclear explosions to recover oil from oil shale.
May 13–15, 1959	The Second Symposium on the Plowshare Program was held in San Francisco, California, with 495 attendees. The symposium was open to the public including international participation.
November 1959	Sandia Laboratories Plowshare research and development effort established.
January 1960	In 1960 the Panama Canal Company reviewed and updated the 1947 studies in collaboration with the AEC.
August 1961	The Plowshare “Program was removed from DMA and the Division of Peaceful Nuclear Explosives established to administer the program.
September 1961	The US voluntary test moratorium of two years and 11 months duration was ended.
Dec. 10, 1961	Project Gnome, the first Plowshare experiment was conducted December 10, 1961. near Carlsbad, New Mexico. The explosive yield of this multipurpose experiment was 3.1 kt.
1962	US Corps of Engineers established Nuclear Cratering Group at LRL to cooperate with AEC on (1) projects concerning collateral high explosive experiments. (2) the development of engineering concepts relating to construction in fracture zones, and (3) studies of slope stability and related engineering considerations.
April 1962	The President requested the AEC and Corps of Engineers to jointly assess the feasibility of using nuclear excavation for canal construction. This led to the 1964 card studies.
July 1962	Savannah River Operations Office initiated support studies for Plowshare Program.
Sept.-Oct. 1963	Team of Australian scientists visited US to review Plowshare Program and study the scientific. engineering and safety aspects of nuclear explosives.
October 1963	The Limited Test Ban Treaty was ratified by the President, with consent of the Senate. The treaty prohibits nuclear explosions in the atmosphere, in outer space and under water.

from “PNE Activity Projections for Arms Control Planning” ACDA/PAB-2531 prepared for US ACDA by GURC.

	also prohibits any underground explosion "which causes radioactive debris to be present outside the territorial of the limits of the state under whose jurisdiction or control the explosion is conducted."
April 21-23, 1964	The Third Plowshare Symposium, "Engineering with Nuclear Explosives," was held at the University of California, Davis, California. Several hundred visitors including representatives from the United Kingdom, France, Australia, Canada, Mexico, Switzerland, South Africa, Israel and the International Atomic Energy Agency attended.
May 1964	The US Atomic Energy Commission released a policy statement and projected charges for Plowshare thermonuclear explosives for use by industry in conducting studies of economic and technical feasibility: 10 Kilotons-S 350,000 2 Megatons-S600,000
Sept. 22, 1964	Public Law 88-609 was signed by the President "to provide for an investigation and study to determine a site for the construction of a sea-level canal connecting the Atlantic and Pacific Oceans," and authorized establishment of a Commission to carry out provisions of . the Act. The Atlantic-Pacific interoceanic Canal Study Commission was established on April 18, 1965, to study sites for construction of a sea-level isthmian canal connecting the Atlantic and Pacific Oceans, and methods of construction. Studies included the feasibility of excavating a sea-level canal with nuclear explosives.
Feb. 14, 1967	Treaty for the prohibition of nuclear weapons in Latin America was signed in Mexico City. The treaty establishes Latin America as an area in which the participating nations will not manufacture or otherwise acquire nuclear weapons (explosives), but permits these nations to collaborate with third parties such as the US for the purpose of carrying out nuclear explosions for peaceful purposes.
Dec. 10, 1967	Project Gasbuggy, the first cooperative industry-government experiment, was conducted on December 10, to investigate the use of a nuclear explosion to stimulate a *low* producing gas field. The nuclear explosion of approximately 29 kt., which occurred 4,240 feet [1,292 meters] beneath the earth's surface, created a chimney about 335 feet [102 meters] high and 160 feet [49 meters] in diameter.
March 8, 1968	The Commission assigned the technical direction for Project Rulison to Los Alamos Scientific Laboratory.
March 12, 1968	Project Buggy. the first nuclear row charge experiment. The explosion. which involved the simultaneous detonation of five, 1.1 kt. explosives placed 150 feet [45.7 meters] apart at a depth of 135 feet (41.1 meters], created a ditch 855 feet [261 meters] long, 254 feet (77.4 meters] wide and 65 feet [19.8 meters] deep.
April 14–16, 1969	The first of a series of US/USSR bilateral technical talks took place in Vienna, Austria, on "Peaceful Applications of Nuclear Explosions."
Jan. 14– 16, 1970	An "Engineering with Nuclear Explosives" symposium sponsored by the American Nuclear Society was held in Las Vegas, Nevada. Sixteen foreign countries participated or attended. France, for the first time, presented technical data on their "Plowshare" Program.
Feb. 11-17, 1970	The second US/USSR bilateral technical talks took place in Moscow on "Peaceful Uses of Nuclear Explosions." The talks, just as those in April 1969, were restricted to technical aspects.
March 5, 1970	The Nonproliferation Treaty was put into force. Article V of the Treaty pertains to making available to non-nuclear-weapons states any benefits from peaceful uses of nuclear explosions.
March 2-6, 1970	An IAEA panel meeting on the peaceful uses of nuclear explosives was held in Vienna, Austria. The participants included France, Japan, Sweden, Australia, India. USSR, United Kingdom, and the US. At this meeting the Soviets, for the first time in public, discussed the USSR "Plowshare" Program which goes by the title, Nuclear Explosives for the National Economy,"
March 16. 1970	The Rulison Court decision, by the US District Court *for* the District of Colorado (Judge Alfred A. Arraj) ruled that: the flag phase of Project Rulison does not present a threat to public health and safety: the AEC has planned its activities and is curry in: them out with all due regard for health and safety: and radiation dose from flaring will be within radiation Standards.

Dec. 1, 1970 The Atlantic-Pacific interoceanic Canal Study Commission transmitted to the President its find report on December 1, 1970, and stated: "... although we are confident that someday nuclear explosions will be used in a wide variety of massive earth-moving projects, no current decision on US canal policy should be made in the expectation that nuclear excavation technology will be available for canal construction. . ." It was recommended that ". . . the US pursue development of the nuclear excavation technology, but not postpone Isthmian Canal policy decisions because of the possible establishment of feasibility y of nuclear excavation at some later date."

11. Contained Experiments and Study Projects Related to Industrial Applications

Date	Project or Study
September 1957	Rainier-The first US underground detonation of a nuclear explosive. This weapons test formed a chimney of broken rock which provided data on possible underground engineering applications of nuclear explosives.
August 1960	Pinot-HE experiment in oil shale near Rifle. Colorado.
Nov. 5,1964	Handcar-Plowshare nuclear explosion experiment Yield–12 kt. Depth of Burial-1,320 ft [402.3 m]. Medium-dolomite (carbonate rock) Site–Nevada Test Site Chimney dimensions-radius 69 ft (21 m]; height 233 ft [71 m] Objective-Study effects of nuclear explosions in carbonate rock.
Dec. 6,1966	Project Dragon Trail Study–Joint natural gas stimulation experiment proposed by Continental Oil Company and CER Geonuclear. In May of 1969, Continental advised the AEC that they did not plan to move forward in this project because of the added expense of drilling to greater depths than they planned. Also they felt the information from Gasbuggy and Rulison would answer many of their questions.
August 1967	Project Ketch Study–A joint feasibility study begun in 1965 was completed by the Columbia Gas System Service Corp., US Bureau of Mines, Lawrence Radiation Laboratory, and the San Francisco Operations Office-AEC to study uses of nuclear explosives to create underground natural gas storage reservoirs. The study was followed by a proposal from Columbia Gas to the AEC to conduct a joint experiment to further investigate this application. However, in 1968 Columbia withdrew the request for state land in Pennsylvania to look for other sites. It is informally understood that the Company has decided to defer further action.
Oct. 24, 1967	Project Bronco Study–A joint feasibility study begun in 1966 was completed by CER Geonuclear, representing some 20 oil companies, the Lawrence Radiation Laboratory, the US Bureau of Mines, and the San Francisco Operations Office to study the use of nuclear explosions to fracture oil shale for subsequent recovery of the oil by an *in situ* retorting process. The study resulted in a proposal from CER on behalf of the oil companies to conduct a joint experiment to test this concept. Although a contract was negotiated in 1968, it was not accepted by the oil companies. No further action is anticipated regarding this particular project although studies respecting nuclear application with oil shale continue.
Dec. 10, 1967	Project Gasbuggy-A first Plowshare joint government-industry nuclear experiment to test out an industrial application. Participants-El Paso Natural Gas Company, Department of interior, Atomic Energy Commission Technical Director-Lawrence Radiation Laboratory Yield–29 kt. Depth of Burial-4,240 ft [1,292 m]. Medium–Sandstone, gas bearing formation Chimney dimensions-height 335 ft [102 m], radius 80 ft [24.4 m] Site San Juan Basin, New Mexico

Objective-To investigate the feasibility of using nuclear explosives to stimulate a low producing gas field.

Sept. 10, 1969 Project Rulison - A joint government-industry gas stimulation experiment
Participants Austral Oil Company. CER Geonuclear Corporation (program manager). Department of Interior. Atomic Energy Commission
Technical Director Los Alamos Scientific Laboratory
Yield 40kt.
Depth of Burial 8,425.5 ft [2.568, lm]
Medium Sandstone, gas bearing formation
Chimney dimensions --height 270 ft [82.3 m], radius 70 ft [21.3 m]
Site -Garfield County, Colorado
Objective- To investigate the feasibility of using nuclear explosives to stimulate a low-producing gas field.

Proposed Experiments

Oct. 25, 1967 Reject Sloop-A joint feasibility study begun in 1965 by the Kennecott Copper Corporation, US Bureau of Mines, Lawrence Radiation Laboratory, and the San Francisco Operations Office-AEC to consider the overall feasibility of using nuclear explosives for fracturing low-grade copper ore bodies for subsequent recovery of copper by conventional *in situ* leaching methods was completed. Upon completion of the study. Kennecott-Copper Corporation proposed a joint experiment to the AEC to test this concept. The company is re-evaluating the project with regard to the current price of copper vs. the lack of available funds in both government and industry.

Jan. 24.1968 Wagon Wheel–This is a Plowshare gas stimulation project in the Pinedale area of Wyoming to demonstrate stimulation of formation at depths of 10,000 to 18,000 feet [about 3,000 to 5,500 meters] . meters]. The industrial sponsor, El Paso Natural Gas Co., has entered into the project definition stage. Execution is planned in late 1972 or early 1973.

July 30, 1969 WASP- A joint venture of companies and individuals interested in a Plowshare gas stimulation project in the Pinedale area of Wyoming. Oil and Gas Futures, Inc., of Bellaire, Texas, is the operating company for this group. The project is currently in the project definition stage. The project execution date is not expected before 1973 or 1974.

Dec. 18.1970 Rio Blanco-The feasibility study prepared by the industrial sponsor (CER Geonuclear, who is using lands obtained under joint venture agreement with the Equity Oil Co.) was accepted as a basis for entering into joint project definition activities with CER. This is to be a gas stimulation project in western Colorado, possibly using two or more nuclear explosives in the same emplacement hole. Execution is planned for late 1972.

TABLE II

Soviet excavation PNE applications.

Water Resource Development:		
1003	1-1 kt	Cratering shot in siltstone.
1004	125 kt	crater in river produced two lakes, 1° 6 x 10^7 m (13, 000 acre-ft) “Proven "Proven Technology”.
Proposed reservoir	Two 150-kt	To form 3 x 10^7 m^{s}(24, 000 acre-ft) reservoir.
T-1	***0-2*** kt	Cratering shot in sandstone calibration for T-2.
T-2	Three 0-2-kt	Row-charge cratering shot “model of Pechora-Kama”.
Proposed Pechora-Kama Canal	250 explosives	Divert Pechora River into Kama River and *thence* to Caspian Sea.
Pechora-Kama row crater	Three 15-kt	Experiment at southern **end** of Pechora-Kama Canal alignment to gain data on cratering characteristics and stability in saturated, alluvial medium.
Overburden Removal:		
Proposed mining project	-1-Mt row charge	Will remove 900,000 m^3 of overburden at 5 kopecks/m^3

Soviet contained PNE applications.

Application	Explosives	Comments
Control of Runaway Wells:		
Urtabulak	.30 kt	$75 million lost over 3 years
Nearby gas field	40 kt	“Proven Technology”
Oil Stimulation:		
Field A	Two 2-3-kt + ore 8-kt	26% internal rate of return in **U.S.**
Field B	Two 8 kt	“Proven Technology”
Proposed Field C	Three 20-30 kt	Designed to break barrier so underlying water will push oil out
Gas Stimulation:		
Underscribed	.	Statement that such an application was carried out
Proposed gas condensate field	Three 40-kt	Expect increase from 7-5 x 106 to 100 x 106 ft 3/day
Underground Storage of Oil or Gas:		
Salt Dome A	1-1 kt	Salt dome - leaked water and radioactivity
Salt Dome B	25 kt	106 -bbl storage at 1/6 surface gas storage and 1/3 washed cavities cost
Unidentified cavity		Tested with oil and gas at 6 MPa (50 atm)
Gas condensate storage facility	15 kt	300, 000-bbl storage facility in industrial use at a gas condensate deposit -- working pressure 8 MPa (80 atm)
Proposed - layered salt	TwO 35-kt	Require 2 x 10^6-bbl storage for gas condensate
Proposed - tuff uncle? permafrost	Three 40-lit	Require 2-5 x 10^9 ft^3 storage for gas at **7** MPa (70 atm)
Mineral Development:		
“Granddaddy Shot”	1 kt	Granite shot similar to Hardhat
Proposed ore breaking	1-8 kt	-Will break -10^6 m^{s} of ore in situ

“A Review of Soviet Data on the Peaceful Uses of Nuclear Explosions” by Milo Nordyke (LLL), Ann. Nucl. Energy Vol. *2, pp. 657-673, Pergamon* Press 1975.

Appendix III

Non-State Adversaries

Appendix III

NON-STATE ADVERSARIES

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APPENDIX III-A

THE POTENTIAL NUCLEAR NON-STATE ADVERSARY

The RAND Corporation
Brian Michael Jenkins
Joseph L. Krofcheck

I. INTRODUCTION

This report discusses the potential nuclear non-State adversary. This somewhat awkward term is meant to emcompass any individuals or nongovernment groups who seek to acquire a nuclear capability -- a nuclear explosive or dispersal device -- and those who might help them. Nuclear non-State adversaries include those who might attempt to steal a nuclear weapon; to pilfer or steal nuclear material to sell, ransom, or use to make a nuclear explosive or dispersal device; to illegally purchase, fence, or smuggle nuclear material or otherwise participate in a nuclear black market; or who claim to possess nuclear devices to extort concessions or cause alarm. The Office of Technology Assessment, for the purpose of this report, has also included in the definition of the nuclear non-State adversary those who might undertake malevolent actions against nuclear facilities. This would include those who might threaten or actually attempt to sabotage a nuclear reactor or other nuclear facility or transport vehicle, or who might seize temporary control of a nuclear facility. Appropriately we should limit this to serious sabotage resulting in the potential release of toxic radiological materials and exclude token acts of violence and minor incidents of vandalism or sabotage that do not imperil the public, although we want to examine the latter for indications of trends in the direction of more serious sabotage.

These adversaries are often referred to collectively as criminals and terrorists although all are criminals in that their actions violate an existing law -- for example, against arson, theft, extortion. The term criminal, however, generally implies a purely profit motive while the term terrorist implies political objectives. The spectrum of potential adversaries who might somehow participate in the actions described above actually is much broader. It may include:

a. criminals, who are considered to be primarily profit-motivated and theoretically apolitical. They may or may not be part of organized crime, and they are more likely to be interested in theft than sabotage. They are likely to avoid publicity. They are skilled burglars and armed robbers. They are willing to use armed force, but try to avoid taking too many risks of armed confrontation and capture.

b. terrorists, who are considered to be primarily politically, not profit-motivated. They may be interested in sabotage of facilities or the theft of SNM to build bombs or dispersal devices and to do or threaten damage. They are probably more interested in using nuclear terror to obtain concessions than in causing destruction for its own sake. They might seize political hostages at a facility or engage in extortion. They desire publicity. Their capabilities include knowledge of tactical operations, weapons, and explosives. They are probably not as skilled in the techniques of theft as professional criminals, but are likely to be more heavily armed and more willing to take risks and to engage in gunplay.

c. "eco-guerrillas," whose desire would be to halt nuclear programs or construction at specific sites by demonstrating inadequacies of security, threatening damage, or carrying out low-level acts of sabotage.

d. disgruntled employees, who might be a potential danger during periods of labor strife,

e. lunatics, who are those individuals with personal motives of revenge, for example, of saving the world, or following God's instructions. A bomb threat or nuclear hoax is the most likely form or action.

f. foreign agents and saboteurs, who might become an adversary in anticipation of war or during wartime. In peacetime, they are more likely to be concerned with intelligence than sabotage. On the other hand, they conceivably might secretly instigate terrorist or criminal groups to engage in acts of sabotage to disrupt nuclear power programs or turn nuclear weapons into political liabilities.

g. political factions within government, who are included for the sake of completeness. This category of adversary really approaches the level of diversion by a government.

The non-State spectrum of potential actions ranges from simple hoaxes to the construction and detonation of a homemade nuclear explosive device which could kill thousands of people.

At the low end of this spectrum are bomb threat calls, hoaxes, token acts of violence not aimed at producing serious casualties or damage, but which, if publicized, could disrupt essential routines, alarm the public, and discredit nuclear programs and safeguards measures. However, these actions pose little direct danger to public safety.

Further up the scale are actions that could result in serious damage, perhaps the disabling of a nuclear facility, and could endanger on-site personnel, although they would not necessarily pose a threat to public safety.

At the high end of the spectrum are actions, the ultimate consequences of which could be civilian casualties and significant material damage and radioactive contamination. It is the latter we are most concerned with here.

The threat posed by the non-State adversary has become an issue of considerable discussion and debate. Many see it as the principal argument against increased reliance on nuclear energy in the United States and the spread of nuclear technology abroad. Others counter that the danger of criminals or terrorists going nuclear is grossly exaggerated, and that adequate safeguards can be provided. Much of this debate is theological. Arguments are advanced about the inherent malevolence of Man or the perfectibility of social institutions. Whatever position one adopts must be accepted largely on faith for there is virtually no evidence.

Apart from a handful of low-level incidents, none of them involving any deaths, no incidents of nuclear terrorism have occurred. No nuclear facilities have been seriously sabotaged to the point that public safety was in peril (in France two nuclear reactors were damaged by bombs in 1975, and in 1973 in Argentina a reactor under construction was briefly occupied by urban guerrillas), no overt thefts of nuclear weapons or of weapons grade material have occurred, and insofar as anyone knows, no amounts of special nuclear material are known to have been secretly diverted, although large quantities are unaccounted for. But this is negative evidence; the lack of a history of incidents does not allow the inference that no such event will occur, especially in light of the increased level of violent crime and political violence and increased public attention to nuclear issues.

This report examines some of the reasons **why,** despite the lack of any serious incidents, the threat posed by the non-State adversary has in recent years become a topic of increasing public concern. It looks at the worldwide increase in terrorism and explores the various reasons why political extremists might be attracted to nuclear targets or use nuclear material as well as at some of the disincentives. The report then looks at the incidents that have occurred thus far involving nuclear facilities or material as well as at nuclear hoaxes. The report identified current schools of thought on the subject, the areas of apparent consensus, and the areas of continuing debate. It discusses the specific problems of employee surveillance and response planning and concludes with general observations on the potentiality of nuclear actions by non-state adversaries.

II. CAUSES OF INCREASED CONCERN ABOUT THE POTENTIAL NUCLEAR NON-STATE ADVERSARY

If there is an unwritten law of human behavior that no serious preventive measures will be taken until after the first catastrophe occurs, that law does not apply in the area of nuclear safeguards. Concern about the potential non-State adversary grew in the late 1960s although no criminal or politically-motivated terrorist had ever carried out any action against nuclear programs or involving nuclear material. Concern has continued to grow, although, apart from a handful of minor incidents, no serious action has occurred. Judging by the number of hearings, studies, reports, and articles on the topic, and by the increased security measures, the possibility that terrorists or criminals might carry out some action is being taken seriously. This is not to say that security measures are adequate. Nor is it to say that all those in government agencies and the private components of the nuclear industry equally accept the notion that there is a real threat, or that they have enthusiastically supported measures to improve security. They have been embarrassed by some obvious deficiencies that have been revealed, and in some cases they have been forced to adopt new security measures. Many, however, still view their problem as one of compliance, not one of security against a threat they are not convinced exists. Asked what he regarded as the biggest threat to his nuclear facility, one director of security replied, “A dedicated and determined band of NRC inspectors.”

The fear that some subnational group or private individual might “go nuclear” is not a new one, as Roberta Wohlstetter pointed out in her recent article in *Survival.* “In a memorandum to President Truman of 25 April 1945, Henry Stimson predicted that ‘the future may see a time when such a weapon may be constructed in secret and used suddenly and effectively with devastating power by a willful nation or group against an unsuspecting nation or group of much greater size and material power."[1]

The current concern seems to result from a confluence of several developments in the late 1960's and early 1970's. Foremost among these is the rapid growth, actual and projected> of nuclear power plants and the attendant fuel-making, reprocessing and nuclear waste disposal facilities. Increased demands for energy, the impact of the Arab oil embargo in 1973, the rapid rise in oil prices, all have given impetus to developing nuclear power as an alternative source of energy. In the United States, at the end of 1974, it was anticipated that there would be over 1000 nuclear reactors in the country by the end of the century. The 1975 OECD and IAEA projections anticipated over 2000 nuclear reactors world wide by the year 2000. (See Volume 1, Chapter X, page 244).

Reactors produce plutonium as a by-product. With the increase in the number of reactors will come an increase in the worldwide production of plutonium, the stuff atomic bombs are made of. In 1975, the annual worldwide production of plutonium was 20,000 kilograms. By 1983, it has been estimated that annual production will reach 70,000 kilograms (plus or minus 15-20 percent to provide for uncertainties).[2] By the year 2000, annual plutonium production may reach 400,000 kilograms, a quantity roughly sufficient for 40,000 bombs. The proliferation of nuclear facilities with the increasing availability of and traffic in plutonium will, it is feared, provide numerous opportunities for sabotage and theft.

Although diversion of plutonium by a government for military purposes may be more likely than diversion or theft by a non-State, it is the latter which may be perceived as the more worrisome problem by the general public. That Argentina or Pakistan may eventually acquire a nuclear weapon does not seem to cause great alarm (except perhaps to citizens of neighboring countries). People have come to accept the presence of nuclear weapons and have grown accustomed to living with the possibility of nuclear war. One nation more or less with nuclear weapons does not seem to make a lot of difference. In contrast, the possibility that some band of criminals or terrorists may acquire a nuclear capability causes a great deal of anxiety. This is no matter of remote debate by military deterrence strategists. Crime and terrorism affect people very personally at a daily-life level. They come to us nightly in the form of human dramas on our television screens in which the audience participates as vicarious victims.

Concurrent with the expansion of nuclear power, the environmentalist movement gained strength and was something new. The word "environmentalist" does not even appear in dictionaries that are ten years old. "Environmentalists," although they were not called that, have always existed in America primarily as a local phenomenon to preserve a specific piece of landscape. A national environmental movement is a relatively recent development and represents a new and powerful voice in modern society. Environmentalists have challenged some of the basic tenets of modern society: continuous economic growth, industrial expansion, the concept of progress itself which had somehow come to be synonymous with technological advance. Although at first nuclear power seemed to be a solution to environmentalists concerns about the pollution resulting from the use of fossil fuels, many began to question the effects of nuclear power on the environment. They worried about thermal pollution, the amount of radiation emitted during normal operations or that might accidently be released, the disposal of radioactive wastes. The initial focus on the adverse side effects of nuclear energy shifted to concern about accidents. How safe were nuclear reactors? What would happen if the system designed to meet emergencies failed? Later, they gave increasing attention to the possibilities and consequences of deliberate malevolent actions by terrorists or criminals. Man's malevolence became a major philosophical premise of the foes of nuclear energy, or, as David Comey put it, "No longer is one calculating the chances of malfunctioning machines; one is guessing the probability of malfunctioning human beings. One does not have to be a psychiatrist to realize that probability is high: one need only read the newspaper.[113] Nuclear power is bad because man is bad.

This struck a responsive chord in the public mind. There is undeniably a degree of anxiety in the mind of the public concerning nuclear power. Nuclear power is guilty of original sin. The nuclear age began with a bomb not a power plant, and the word “nuclear” recalls Hiroshima not Indian Point. Nuclear power is the most potent, and to many the most sinister, force known to man. However, nuclear power plants (light water reactors) are not nuclear bombs. Successful sabotage could theoretically result in a release of radioactive material, but a reactor cannot be turned into a nuclear bomb. Only recently has some of the public come to understand this point.

If people are already uneasy about nuclear power and worried about terrorists, it is not difficult to frighten them with a forecast of some kind of nuclear action by terrorists. The mere proximity of the words “terrorist” and “nuclear” induce fear.

If there was any doubt about man’s maliciousness, it could be dispelled by reading the newspapers or turning on the television -- news or drama. There is no convincing evidence that violence on television or in the movies causes people to be violent, but it may affect one’s view of the world. Those who are regularly exposed to violence on the screen tend to see the real world as a more violent place.[4]

It is, however, not simply the portrayal of violence that altered perceptions in the 1960s. Crime, particularly violent crime, often random, needlessly violent crime,increased by epidemic proportions. Political violence in the form of international terrorism also increased in the late 1960s and by the early 1970s had become a serious worldwide problem. Assassins, kidnappers, and bombers were no longer remote figures associated with the Russian Revolution and wartime serials. They regularly kidnapped government officials and businessmen, hijacked airliners, gunned down passengers in airline terminals, murdered Olympic athletes, set bombs off in restaurants and railroad stations. Their violence was no longer confined to guerrilla struggles in remote colonies or insurgences in Third World countries. Terrorists crossed national borders to carry out their attacks on virtually every continent. No country was neutral, no citizen safe.

Events of the past fifteen years also have made it difficult not to have lost some confidence in our social, political, and economic institutions. Social mores were challenged. Basic lifestyles were changing. Within 13 years, five men have held the office of president: one was assassinated, one virtually abdicated, one resigned in disgrace, and one was not elected. In addition to one successful assassination of a president, there were two more attempts against a president’s life, and two presidential candidates were shot, one fatally. American military involvement in the war in Indochina led ultimately to disaster. At home, news from Indochina triggered and provided the rationale for violent protests, bombings, and ultimately the appearance of genuine domestic terrorist groups. For the first time, it seemed (though not in reality for the first time) that there was political violence in the United States. Looking back, the passage to America’s third century was a very rough ride.

This turbulence was not a uniquely American phenomenon. Japan and the nations of Western Europe suffered from bad cases of political scandal and upheaval, and also from domestic political violence unprecedented since the thirties. Corporations too were shown to have lied, misled, bribed, and yielded to blackmail.

Such revelations do not inspire confidence in claims by government or industry that nuclear safeguards are adequate now, or that the increased measures of security considered necessary to protect nuclear programs would not be abused or that governments indeed would be able to prevent diversion or theft or protect their citizens against nuclear terrorists. There was and is reason for doubt and fear. Doubt and fear are selling well anyway. There seems to be a popular market for doom, whether the “light doom” of, for instance, the Club of Rome, or the “heavy doom” of those who warn people to have a year’s supply of food and a shotgun at home, or the religious groups who firmly believe that Armageddon is just around the corner.

III. GROWTH OF INTERNATIONAL TERRORISM

Terrorism can be described as the use of actual or threatened violence to gain attention and to create fear and alarm, which in turn will cause people to exaggerate the strength of the terrorists and the importance of their cause. Since groups that use terrorist tactics are typically small and weak, the violence they practice must be deliberately shocking.

Repeatedly, during the last few years, small groups of extremists have demonstrated that by using terrorist tactics they can achieve disproportionate effects. They attract worldwide attention to themselves and their causes; they arouse worldwise alarm, and can create international incidents that national governments are compelled to deal with, often before a worldwide audience.

Terrorism has in recent years become an international phenomenon. Modern jet air travel provides terrorists with worldwide mobility and convenient targets. Mass communications give them access to worldwide audiences through the almost instantaneous broadcasting of the violent dramas they create. New weapons have increased their capacity for violence, while society has become increasingly vulnerable because of growing dependence on complex systems and often fragile technology (civil aviation is an example) or technology, such as nuclear energy, that is potentially dangerous if exploited malevolently.

International terrorism is simply terrorism that has clear international consequences. It includes incidents in which terrorists go abroad to strike their targets (as in the Lod Airport massacre), or select victims or targets because of their connections to a foreign state (as in the assassination or kidnapping of a diplomat), or attack international lines of communication and commerce (as in the hijacking of an airliner).

International terrorism took a sharp upswing in the late 1960s. Latin American guerrillas moved into the cities and adopted terrorist tactics as a means of gaining international attention; the Palestinians initiated an international campaign of terrorism against Israel; and small terrorist groups appeared in Japan, Western Europe, and the United States. Once the utility of terrorist tactics was demonstrated, new groups –- South Moluccans, right-wing Cubans, etc. -- were inspired t. employ them and instructed how.

The following figures illustrate this increase. The first, reprinted from an unclassified CIA report "International Terrorism: Diagnosis and Prognosis," shows the total number of international terrorist incidents that occurred between 1965 and 1975.[5] The second is based on figures compiled by The Rand Corporation: using slightly different criteria from those of the CIA, which accounts for the slight difference in totals, it shows the total number of international incidents by year from 1968 to the end of September, 1976. Both figures show a peak in the years 1973 and 1974, a decline in 1975, and an increase again in the first nine months of 1976.

The third figure, a record of the casualties incurred in these incidents, shows a similar increase to the year 1974, a decline in 1975, and a rise again in 1976.

These are incidents of international terrorism only. Local incidents of terrorism -- the murder of Irishmen by Irish extremists in Northern Ireland, for example -- are not included (although incidents in which IRA extremists planted bombs in London were arbitrarily counted; although not international, they did represent an effort to carry out the Irish struggle "overseas") .

To respond to the concern that these increases did not reflect an increase in international terrorism but only improved reporting of a continuing phenomenon as governments became more disturbed about the problem, the following graph of "major incidents" of international terrorism was compiled (Figure 4). The criteria for inclusion as a major incident were that the incident resulted in at least one fatality, if a hostage incident that it involved a government official or diplomat, or if a hijacking that the hijacker demanded more than simply changing the destination of the airplane. These criteria excluded the numerous

INTERNATIONAL AND TRANSNATIONAL TERRORIST INCIDENTS

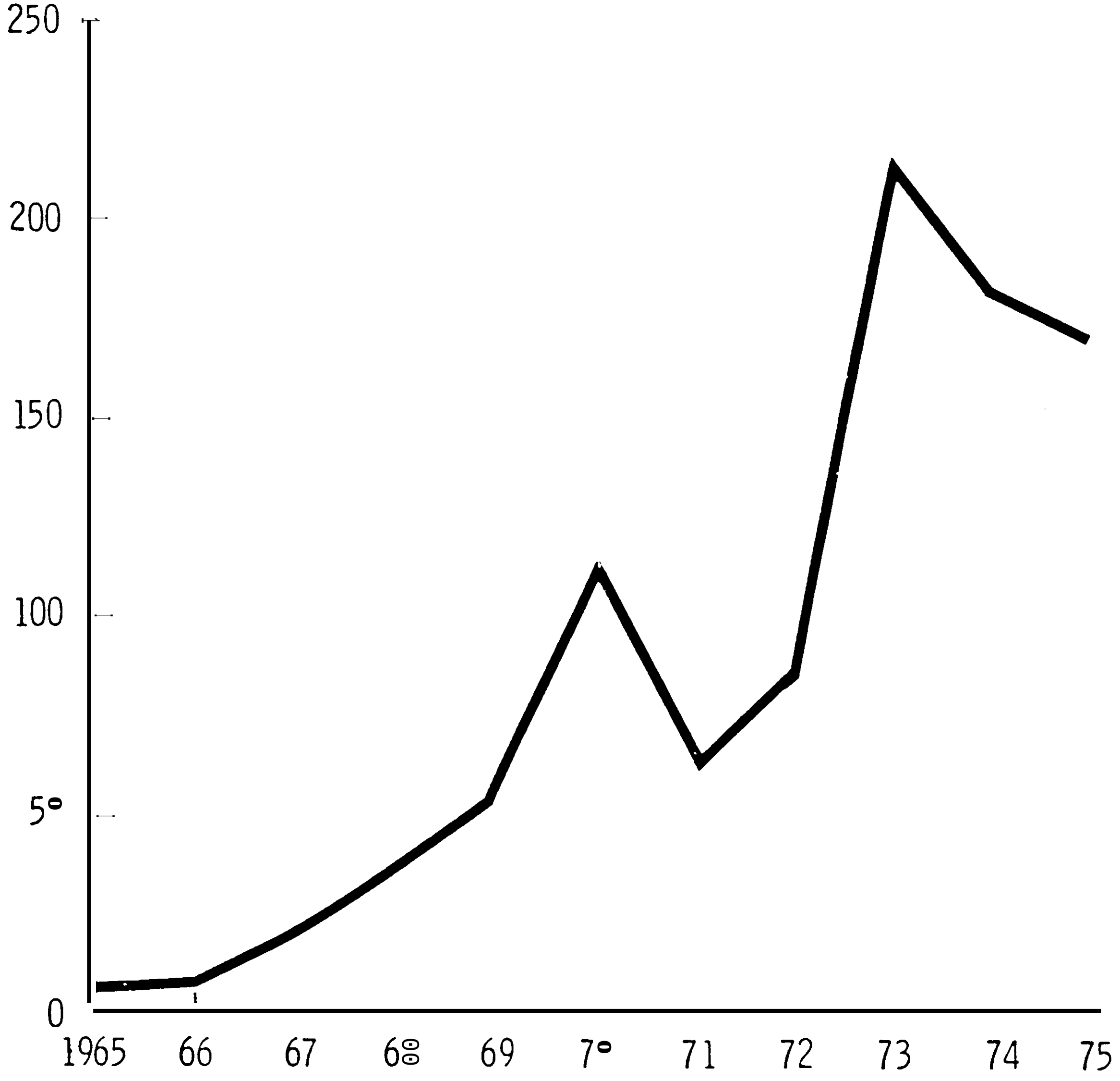


Fig. 1

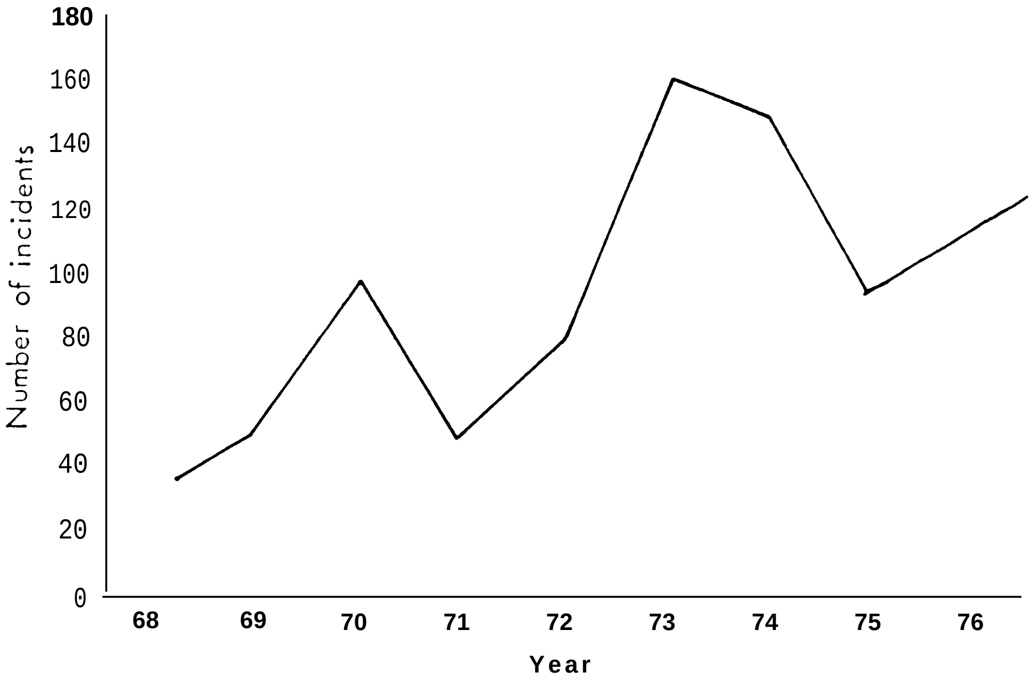


Fig.2 —Total number of incidents of international terrorism

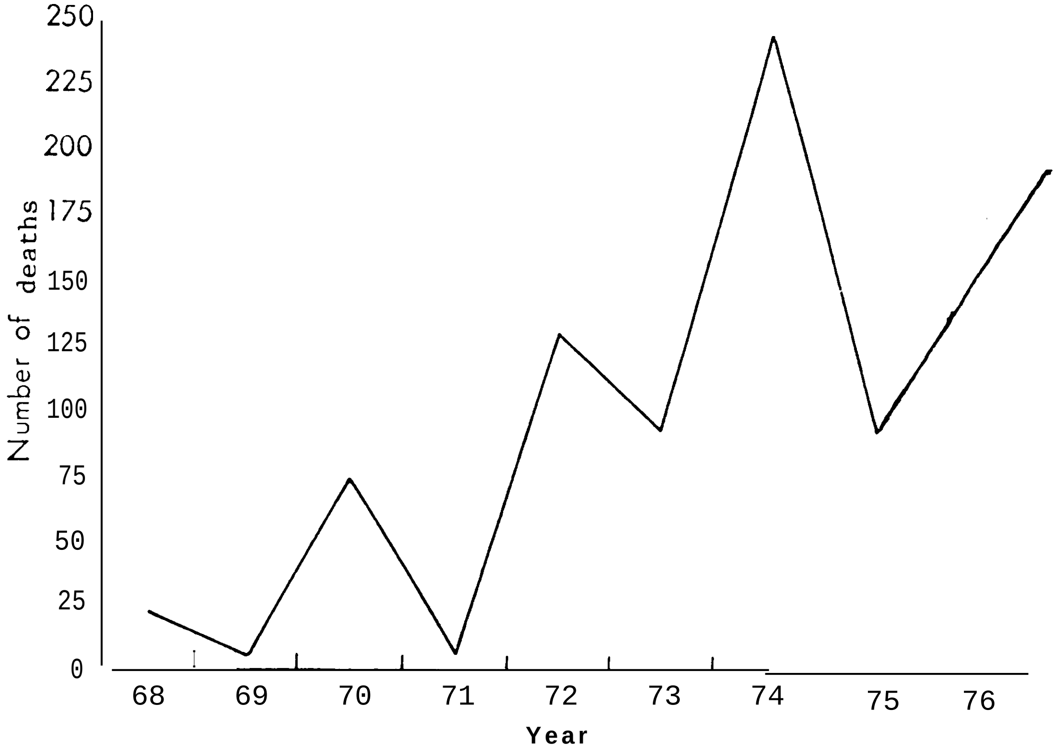


Fig. 3 -- Total number of deaths in incidents of international terrorism

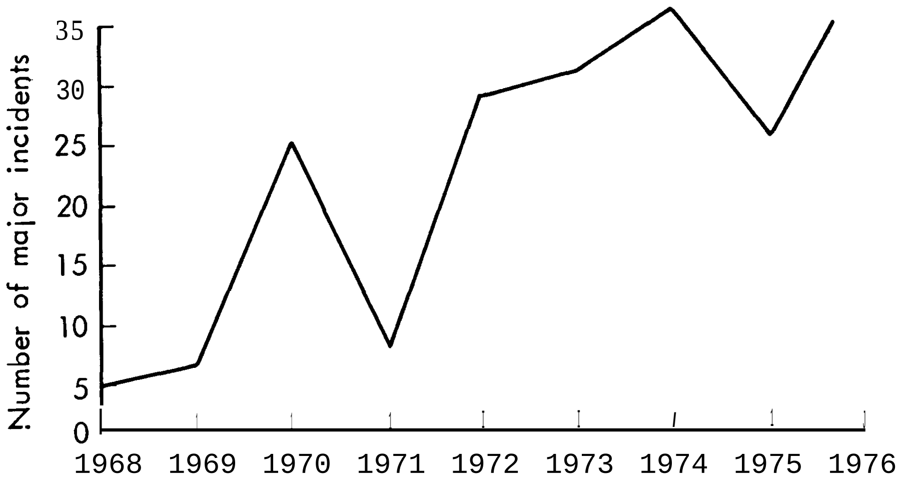


Fig. 4 — Major international terrorist incidents

token acts of violence -- little bombs planted in front of embassies, numerous kidnappings of business executives, and a lot of hijackings to Havana. Even by thus excluding most bombings, the category which has shown the greatest increase, the overall trend is still upward.

Some observers have found encouragement in an apparent decline of international terrorism in the last year. Judging from the figures presented here, however, it would be dangerous to conclude that international terrorism has leveled off or might even be declining; the data for 1976 show no such decline. If decrease there was, it is in the eyes of the audience, for terrorism is largely a matter of perceptions. It is not measured solely by the number of incidents or body counts. Neither sum accurately reflects the amount of terrorism, which comprises not only the actions of terrorists but also the effects -- the publicity, the shock, the terror -- that these actions generate.

To illustrate the point, fewer incidents of international terrorism occurred in 1972 than in 1970; however, two particularly shocking episodes in 1972, the Lod Airport massacre in May and the Munich incident in September, appalled the world and provoked many governments to undertake serious measures to combat terrorism. In the United States, it led to the creation of the Cabinet Committee to Combat Terrorism.

Similarly, many people labeled 1975 as the “year of the terrorist.” Certainly, 1975 seemed to surpass previous years in the number of dramatic and shocking episodes, particularly in Western Europe, and thus closer to us. Two attempts to shoot down airliners at Orly Field in Paris, the kidnapping of a candidate for mayor of West Berlin, the seizure of embassies in Stockholm, Kuala Lumpur, and Madrid, the IRA bombing campaign in London, the assassination of Turkish ambassadors in Austria and France, the hijacking of a train in The Netherlands, the takeover of the Indonesian consulate in Amsterdam, and the seizure of the OPEC oil ministers in Vienna, all combined to produce a spectacular effect. However, measured by the number of incidents and by the number of casualties, international terrorism had, in fact, declined in 1975. Fewer incidents of terrorism occurred than in 1973 or 1974, and fewer persons were killed than in 1974.

To repeat, there were no fewer incidents of international terrorism in 1976 than in 1975, and 1976 was no less bloody. The primary difference was that 1976 saw more assassinations and murders and fewer hostage incidents. A hijacking, kidnapping, or other kind of hostage incident may be in the news for days, even weeks; murder is usually in the news for a day. Probably more people recall that Croatian terrorists hijacked an airliner on which no one was killed than recall that Cuban extremists planted a bomb abroad an airliner that killed 73 passengers.

The actual amount of terrorist violence overall has been exaggerated -- evidence of its success in gaining worldwide attention. Measured against the world volume of violence, terrorist violence is trivial. About a thousand persons have died in international terrorist incidents since 1968; another two thousand have been injured. If we add the casualties of domestic political violence (as in Belfast or Buenos Aires), the total number of deaths may ascend to ten thousand at the most. More than twice that many are murdered every year in the United States. Since 1968, six million people in the world have died in 13 wars.

But terrorism is more appropriately measured by the amount of attention it receives, by its ability to create national and international crises, by the enormous costs of protection against terrorist attacks, by the alarm it creates, and the consequences these have for society. Terrorist tactics are calculated to rivet attention and create alarm. In this they succeed. This point is important when examining the incentives and disincentives to nuclear action by terrorists.

While any forecasts about terrorism in the future are conjectural, some trends are discernible. Although few terrorists have reached their stated long-range goals, and in that respect terrorism is a failure, terrorism has proved useful in getting publicity and occasionally obtaining some political concessions. These limited tactical successes may encourage terrorists, who are typically short-sighted politically, to continue to use terrorist tactics. Terrorism is likely to persist and perhaps increase as a mode of political expression.

Terrorists will remain highly mobile, able to strike targets anywhere in the world. Recent developments in explosives, small arms, and sophisticated man-portable weapons will provide terrorists with an increased capacity for violence. They appear to be getting more sophisticated in their tactics, their weapons, and their exploitation of the media. they will continue to emulate each other’s tactics, especially those that win international publicity. Terrorist groups appear to be strengthening their links with each other, forming alliances, and providing mutual assistance. One result is the emergence of multinational freelance terrorist groups that are willing to carry out attacks on behalf of causes with which they are sympathetic, or to undertake specific operations or campaigns of terrorism on commission from client groups or governments. Nations or groups unable or unwilling to mount a serious challenge on the battlefield may employ such groups or adopt terrorist tactics as a means of surrogate warfare against their opponents. The problem of terrorism will continue to require a major diversion of resources to internal security functions. We have already witnessed this development in the area of civil aviation, and we are now seeing the same thing in the nuclear industry.

IV. WILL TERRORISTS GO NUCLEAR?

There is no discernible trend in the direction of nuclear action. To date, no terrorist group has demonstrated that they possess nuclear weapons material or radioactive wastes, or has claimed they have such material to extort concessions. Apart from a few incidents of sabotage in France, political extremists have not attacked nuclear facilities, and there is no evidence that they have sought to acquire special nuclear material. In attempting to predict whether in the future terrorists will go nuclear, we must consider a spectrum of potential nuclear actions that terrorists could carry out. We can then discuss these in terms of capabilities and intentions.

Only a telephone call or a postcard are needed to carry out a nuclear hoax. An individual can do it. Acts of saborage can be carried out by one person but success requires some limited technical knowledge and involves some risks. The seizure of a control room or other portion of a nuclear facility could conceivably be carried out by one man, but is more likely to involve several. Seizures of embassies or other buildings, which we have seen terrorists do, seem to require a minimum of three men to guard any hostages, maintain a lookout, negotiate, sleep, etc. The operation also requires reconnaissance, some planning, the acquisition of weapons, and the penetration of the security apparatus. But it still would be within the range of many small groups, for example, a group the size of the "Symbionese Liberation Army." The overt theft of a nuclear weapon or special nuclear material would require a small armed assault, quite possibly the use of automatic weapons and explosives, a means of escape, and possibly a hideout. While such an operation could conceivably be carried out by a small group - say, a half-dozen people -- it is likely to require more in various supporting roles.

The manufacture (as opposed to the design) of a nuclear bomb is a complex operation demanding considerable effort and continued success through a number of difficult steps. It would require the accumulation of sufficient fissionable material (either by diverting small amounts over a long period of time in order to avoid detection or by overt thefts), the acquisition of convention explosives, a means of moving the radioactive material and storing it, a place to manufacture the bomb without mishap, its delivery, and its detonation. It would take weeks or months to do and the entire task would require a number of people, including a few with technical knowledge. (See Chapter VI of Volume I).

Acquiring sufficient fissionable material is seen as the principal obstacle to fabricating a clandestine nuclear explosive device. With sufficient material, there is a consensus that a crude explosive device can be made. For plutonium and uranium-233 about 5-10 kilograms are needed; for U-235 about 15-30 kilograms. Light water reactor fuel, which is 3 percent enriched uranium-235, cannot be made into a fission explosive device.

Plutonium and fully enriched uranium-235 are the most practical materials for the clandestine fabrication of a bomb. (Uranium-233 is a by-product of high temperature, gas-cooled reactors which have not yet come into widespread use.) Highly enriched 235_U can be found in government weapons programs and also is used as fuel for research reactors and nuclear-powered naval vessels. Plutonium is also found in the present nuclear fuel cycle, although it is currently not being commercially separated in the United Stat-es (it is in several countries in Europe and Japan), and is available in larger quantities than either 233_U or 235_U.

It has been asserted that commercial plutonium is useless for making bombs. This is not correct. See Chapter VI of Volume I for a discussion of the design and construction of Nuclear Fission Explosive Weapons.

The notion that someone outside of government programs can design and build a crude nuclear explosive is much more plausible now. In the beginning, the secrets of fission were closely guarded. However, much of the requisite technical knowledge has gradually come into the public domain. A growing number of technically competent people understand this material, and, even without detailed knowledge of nuclear weapons design, theoretically could design and fabricate a nuclear explosive. Its detonation and performance would be uncertain. Its yield would be low, probably in the tenths of a kilotan range.

A former designer of nuclear weapons asserts that "under conceivable circumstances, a few persons, possibly one person working alone who possessed about 10 kilograms of plutonium and a substantial amount of high explosive, could, within several weeks design and build a crude fission bomb."6 Three noted scientists, in a statement to the National Council of Churches, maintained that it was impossible for a single person to make a bomb. "At least six persons, highly skilled in very different technologies, would be required to do so, even for a crude weapon."[7] They may put it beyond the grasp of any "bright lunatic," but the perimeters of the debate are still significantly limited. It could be done. <u>See the conclusions of Chapter VI, Volume I</u>.

For a dispersal device, the technical and material requirements are less. Some plutonium, or a quantity of some other available radioactive material, spent fuel for example, and a mechanism for dispersal would suffice.

Assuming for the moment that it could be done; that there exist in the world today groups that possess or could acquire the resources necessary to carry our the actions described, we are left with the question of motivations and intentions.

A nuclear capability would give terrorists unprecedented destructive power. The detonation of even a crude nuclear device in a populated area would kill tens of thousands of persons. This is orders of magnitude greater than the casualties involved in the largest terrorist” incidents to date. Deliberate attempts, outside of war, to kill large numbers of people in a single act are rare, and instances in which politically motivated terrorists have deliberately attempted to kill large numbers of people are very rare. In no single incident in the past half century have terrorists killed more than 150 persons and incidents involving more than 20 deaths are extremely rare.

If we exclude acts that took place during wars, battles with or raids by guerrilla groups which produced heavy casualties, or instances of mass executions of government collaborators by revolutionaries or of suspected enemies of the state by governments, then in the past half century there have been perhaps fewer than a dozen instances in which terrorists have deliberately sought to kill a large number of civilians (that is, something approaching a hundred). Such incidents would include the detonation of a bomb at the Sofia Cathedral in Bulgaria in 1925 which killed 128 and wounded 323; the bomb planted by the Irgun at the King David Hotel in Jerusalem in 1946 in which more than 200 were killed or injured (although there is some evidence that the terrorists made an attempt to have the hotel evacuated before the explosion); the bombs placed aboard an aircraft in which 47 were killed one time and 88 another, the Lod Airport massacre in 1972 in which 25 were killed and 76 were wounded; and some of the bombings in the United Kingdom in which large numbers were injured but few were killed. The most recent incident of "mass murder" occurred on October 6, 1976, when a bomb placed aboard a Cubana Airlines jet exploded causing the airliner to crash; 73 persons were killed. Anti-Castro Cubans claimed credit for the act.

Apart from these rare incidents, the record of modern international terrorism shows that terrorists have, for the most part, not sought to carry out mass murder. Of 861 incidents of international terrorism that occurred between 1968 and October 1976, 178 (or 21 percent of them) involved one or more deaths. The rest were token acts of violence, for example, small bombs planted outside embassies, or hijackings without casualties, or other acts that did not result in any deaths. Of the 178 incidents in which one or more persons were killed, more than half (95 of them) involved one death; 26 resulted in two deaths. Approximately 11 percent of the incidents with deaths, or about two percent of the total number of incidents of international terrorism, involved 10 or more deaths, many of these the result of shoot-outs between terrorists and members of security forces, both of whom are included in these totals. Figure 5 illustrates the number of incidents with deaths and the number of deaths.

To repeat, these are incidents of international terrorism. Local contests could be more bloody, but a preliminary examination of politically-motivated violence in places like Argentina, Northern Ireland, and in the United States shows little evidence that terrorism equals mass murder. The vast majority of the incidents involve none or one or two casualties.

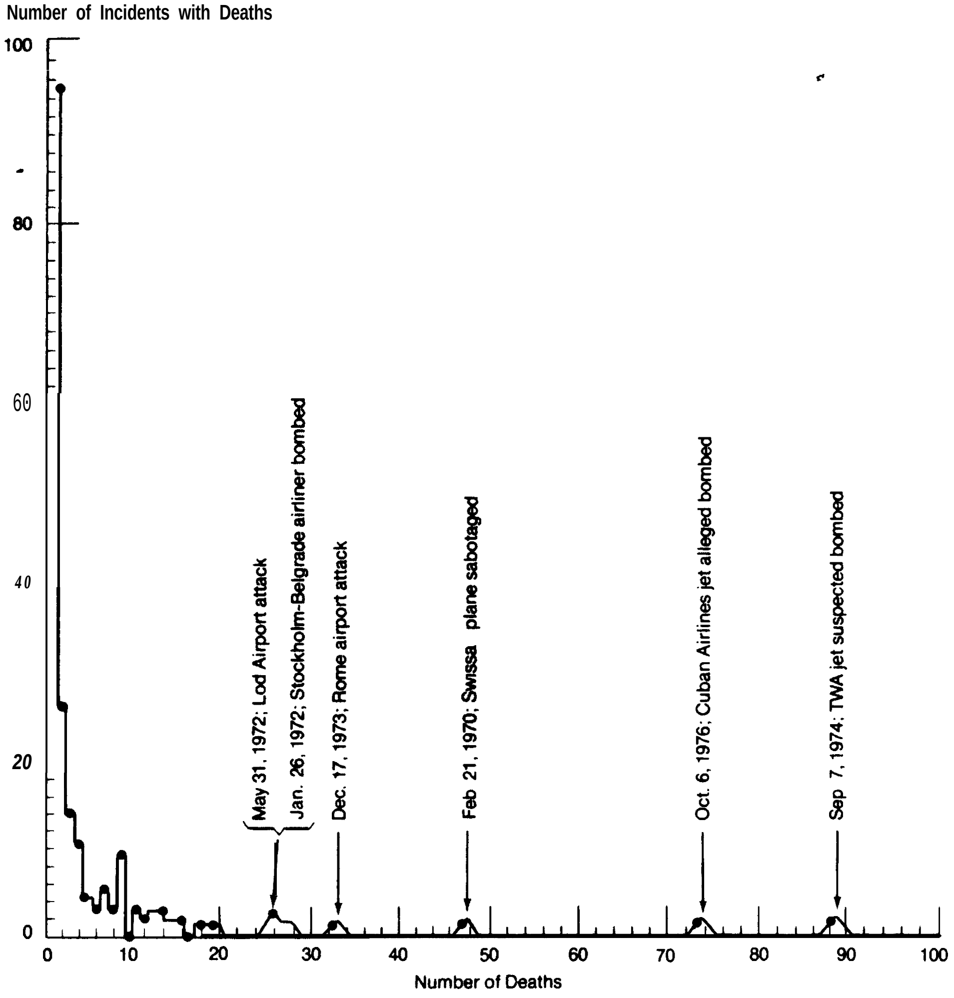
It is apparent that if any of several large known terrorist groups had wanted to kill hundreds or even thousands using chemical, biological weapons, or simply conventional explosives, they could have done so. If we were to examine all past incidents aimed deliberately at causing widespread casualties -- such as attempts to poison water supplies -- we would probably discover the perpetrators for the most part to be deranged individuals or tiny groups sharing serious mental problems. As an example, two youths were arrested by police in Chicago in 1972. They had planned to poison the city’s drinking water with typhoid bacteria. The youths were organizers of a “group” which planned to inoculate its own members against the disease “to form the basis for a new master race” after the rest of the population had been wiped out. It is noteworthy that the police discovered the plot after being tipped off by a person whom the boys attempted to recruit.

Mass murder may be considered counterproductive for terrorists. It could alienate sympathizers and potential supporters, provoke

Figure 5

Figure V-3.

Number of Deaths per Incident of Terrorism Involving Any Deaths 1966-1976 (October 6)



(See appendix II I-A for more information on the death Incidents)

Based upon data supplied by the RAND Cup

(See Annex to Appendix III-A for information on the high-death incidents.)

severe crackdowns that public opinion would demand and support, and threaten the survival of the organization itself. For these reasons, any scheme of this type is likely to create disagreement and dissention within the organization contemplating it, thus exposing the operation and the organization to betrayal. In sum, mass murder appears unlikely to be contemplated by groups capable of making elementary political judgments.

While we cannot rule out the possibility of a “large-scale Led,” the wanton killing of large numbers of civilians, the detonation of a nuclear device in a populated area appears unlikely, at least on the basis of the historical record. And the reasons cannot be explained in terms of limited capabilities. Political extortion based on some type of nuclear threats, a real one or a clever fabrication, seems more attractive to terrorists. possessing a nuclear device, it seems terrorists could demand anything. But the idea of nuclear blackmail has some weaknesses.

The whole area of motivations, incentives, demands and conceivably negotiations in the area of nuclear blackmail by non-State adversaries merits systematic examination, which it has not received. At present, we can do no more than speculate about the types of demands non-State adversaries can, cannot, and are most likely to make. It does not seem logical that non–State adversaries would resort to nuclear means to make demands that they have a good chance of achieving without escalating the threat to that level or making the investment and taking the risks necessary to obtain SNM and fabricate a nuclear device. If current tactics are successful most of the time they are unlikely to alter them. If there is an easier way, they will take it. If they can fabricate a nuclear threat without fabricating a nuclear device, they will prefer it. Therefore, nuclear blackmail to obtain a few million dollars ransom or spring a few prisoners does not seem likely. If they really possess a nuclear capability, it seems reasonable that they would certainly ask for something more than they can get now by less difficult means.

However, it is not entirely clear how the enormous capacity for destruction associated with a nuclear weapon could be converted into commensurate political gains. Even with a nuclear device, terrorists could not make impossible demands. They probably could not permanently alter national policy or compel other changes in national behavior. To do so would require at a minimum that they maintain the threat. It is not clear under what conditions and how long they could do so without being discovered. They could not creat a homeland, at least not without at the same time offering the victims of the blackmail a set of hostages of their own. The probably could not persuade a government to liquidate itself. To carry out a coup d'etat with a nuclear bomb still requires that the conspirators at some time surface to take control. Then they become vulnerable. They could not realistically expect to be given more nuclear weapons by claiming or even demonstrating that they had at least one. What then could they demand?

They might be able to deter certain acts by threatening nuclear action. As a hypothetical example, Palestinian leftists, with a credible nuclear capability, conceivably might have been able to deter Syria from invading Lebanon.

We must also consider bizarre demands such as the release of all prisoners in Oklahoma or the distribution of food to the poor. It is difficult to see how the satisfaction of these demands would be seen to contribute to the achievement of the threatening group's goals. However, they could be operating within a mind-set that is totally alien to our own. No one would deny that such individuals, conceivably even some small groups whose members share these characteristics, do exist in the world. However, we are now dealing with the lunatic fringe, not the large terrorist groups who are conceived to have the capability for nuclear theft and the fabrication of nuclear weapons.

Indeed, there seems to be an inverse relationship between intentions and capabilities. At the one end are those who in the same of some bizarre cause, are willing to threaten or cause mass casualties. Individuals or groups that make universal appeals--in the name of "brotherhood," "economic justice," or "world peace"--generally lack any real constituency. Such a group would not necessarily be constrained by fears of alienating world opinion. The group's members would place themselves above world opinion. An essential ingredient of such a group's philosophy would permit the negation of existing human values, allowing widespread and indiscriminate murder. They might claim divine inspiration (or at least tacit approval by God) to destroy the wicked or the weak--’’the good will survive”--or might adhere to a racist ideology that would permit genocide. We are describing here the authors of most hoaxes, and of the few mass murder schemes that are known to have occurred. Individuals with mental or emotional disorders, and a certain charisma, have on occasion managed to become heads of state––Adolph Hitler––or at least of gangs--Cl]arl(~s Manson. Fortunately, most such individuals usually lack the capability to successfully carry out their intentions.

At the other end, we have the large political organizations who probably can muster the resources to carry out such operations but who must carefully weigh the benefits and risks: they are compelled to make political judgments that impose constraints. The same is true of large criminal organizations which must make economic judgments.

There is some theoretical crossover point where intentions meet capabilities. As the opportunities for nuclear theft increase, that point may move toward the lunatics. This perhaps is the most frightening consequence of nuclear proliferation.

The primary attraction to terrorists in “going nuclear” may not be that nuclear sabotage or possession of nuclear devices would enable terrorists to cause mass casualties, but rather that almost any nuclear action by terrorists would attract widespread attention and cause widespread alarm. The words “nuclear” and “terrorist” in close proximity achieve a synergistic effect. A terrorist group might threaten to start fires in highrise office buildings and send authorities a set of blueprints and a book of matches to demonstrate its capability. But a terrorist believed to have a nuclear device is automatically a successful terrorist.

It would not be necessary for terrorists to take risks and make the investment necessary to steal SNM and fabricate a nuclear explosive or dispersal device to create an alarming situation. With a degree of imagination and intelligence, terrorists could do things that demand less technical skill and less risk on their part but still achieve the desired publicity or intended coercive effect. A well-publicized hoax could be as alarming as if the terrorists actually possessed a real weapon, provided that there is no way of verifying that it is a hoax.

Terrorists who seized control of a nuclear weapons storage site or a nuclear power reactor might present little threat to public safety but the situation would be frightening. Despite the assurance of scientists and engineers (who in such a situation can be relied on to disagree with each other), few would want to test their capabilities. The same would be true of terrorists who claimed to possess a nuclear device bolstered their credibility with the enclosure of a small sample of SNM. It might be their entire stash; they might not be able to fabricate a weapon; the device might not work, but again, few would want to run the test.

If we were to lay all of the potential scenarios of malevolent acts involving nuclear facilities or nuclear material out in order of increasing consequences (see Figure *6),* the curve representing potential casualties and destruction would sweep up sharply as we move through the list. This curve would begin with the hoax which would directly endanger no one but which if publicized might cause panic, move through the seizure of hostages at a nuclear facility which might directly endanger the hostages but probably would not result in widespread casualties, through contamination scenarios which might jeopardize the health of hundreds of people, and finally end with the manufacture and detonation of a nuclear explosive device which potentially could kill thousands. Terrorists typically have operated at the lower

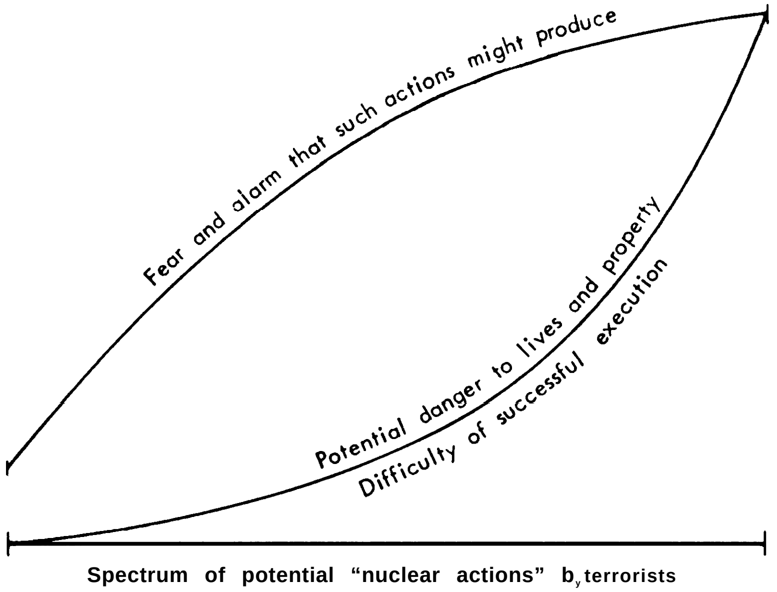


Figure 6

end of the spectrum where the actual number of casualties is low, but the dramatic impact, the fear and alarm they create is high.

In sum, the possibility of low-level but alarming incidents in which nuclear facilities or nuclear material figure as the backdrop or prop for terrorist action certainly exists. The possibility also exists for some alarming mass hostage situations in which there is considerable uncertainty about the capabilities and willingness of the authors of the threats to carry them out. Mass murder schemes still seem to be the product of individual lunatics.

V. ORGANIZED CRIME AS A POTENTIAL NON-STATE ADVERSARY

Ten years ago, the members of the Lumb Panel examining nuclear safeguards for the Atomic Energy Commission identified organized criminal as well as terrorist groups as potential threats to nuclear programs. In discussing criminal adversaries, they had in mind the thefts and illegal diversions that take place in other internationally-traded commodities. If whole shiploads of wheat could be diverted, why not nuclear material? The members of the Panel no doubt also had in mind the theft of the fuel rods from the Bradwell nuclear plant in England, which took place in 1966. A report on the incident is listed in the bibliography of the Panel's own report.

Whether organized crime should be counted among the potential subnational nuclear threats remains a matter of some debate. Organized crime here is defined as an organization dedicated to illegal activities; its existence transcends any single act; the organization survives its members. It is more like a business corporation than a gang. Organized crime should be distinguished from individual groups of criminals that organized themselves to carry out specific crimes. In the United States organized crime is generally considered to be a nationwide alliance of twenty-some "families" of criminals (not all of the members of the families are actually related). The families are variously referred to as the Mafia, the Mob, Cosa Nostra, or "the syndicate." In addition to the Mafia families, there are non-Mafia criminal syndicates, though by comparison these appear to be of lesser importance. The Mafia families are linked to each other and to non-Mafia syndicates by understandings, agreements, and treaties, and by mutual deference to a "Commission" made up of the leaders of the most powerful families.

Members of organized crime allegedly "control all but a tiny part of illegal gambling in the United States. They are the principal. loan sharks. They are the principal importers and wholesalers of narcotics. They have infiltrated certain labor unions. . .have a virtutal monopoly on some legitimate enterprises, such as cigarette vending machines and boxes. They own a wide variety of retail firms, restaurants and bars, construction companies, trucking companies, food companies meat packing companies, laundries, linen-supply houses, garbage collection routes, and factories. They are alleged to own or indirectly control a large share of the legal gambling in Las Vegas. More recently, they have moved into the manufacture and wholesale distribution of pornography. They also reportedly control a large share of prostitution. The annual take from these enterprises is estimated to be in the area of $50 billion with about half of that as net profit.

In addition to organized crime in the United States, there are, of course, similar criminal syndicates in other countries and these to varying degrees have connections with each other and with organized crime in the United States. There are also “families” of smugglers who each tend to specialize in certain commodities, and there are illegal international arms traders who conceivably could become involved in the transfer of intact nuclear weapons or SNM. All of these organizations collectively could be considered as part of vaster intimation network of organized crime. There is, however, no known central directorate.

Although some of the most spectacular criminal capers, the Great Train Robbery in England, the Brinks Robbery in Boston, were not carried out by members of organized crime as described above, it is generally thought that only organized crime, with its vast resources and connections, has the organization, capital, access to the skills, and international connections necessary to steal, fence, smuggle special nuclear material, organize and operate an international black market. in stolen nuclear material, or acquire the material and fabricate its own weapon. Or, it is believed that at least at some point, even a band of independent thieves would have to seek organized crime’s approval for a nuclear heist, fence the stolen material to organized crime, or seek the assistance of organized crime in some manner. This presumption is challengeable.

At issue is not the capability of organized crime to steal nuclear material or fabricate 3 nuclear device, but their interest in doing so. L. Douglas DeNike suggests, “Armed with plutonium or high level waste in storage, organized crime might demand federal assurances of non-interference with their operations. Punishment for non-cooperation might be the loss of Washington, D. C., as a habitable center. Nuclear thieves could demand large sums of cash, control over policy or special concessions from national governments."[10] Willrich and Taylor offer a similar view:

> ... .possession of a few fission explosives or radiological weapons might place a criminal group rather effectively beyond the reach of law enforcement authorities. A criminal organization might use the threat of nuclear violence against an urban population to deter police action directed against its nuclear theft operations. The organization might also use nuclear threats to extort from the government a tacit or explicit relaxation of law enforcement activities directed against a broad range of other lucrative criminal operations.[11]

Willrich and Taylor, however, go on to point out that "criminal groups primarily interested in money are likely to be politically conservative, and that they would not develop a black market in a commodity such as nuclear material which could have revolutionary political implications. Moreover, a large nuclear theft might prompt a massive governmental crackdown and lead to a widespread public outcry, whereas the continued existence of organized crime on a large scale might depend on the susceptibility of some government officials to corruption and on a degree of public indifference."[12]

Jenkins agrees that:

> Extortion is a classic crime and nuclear programs certainly open new avenues for extortion. Plutonium and certain other fissionable materials would be highly marketable commodities raising the possibility of a profitable black market traffic in these items. . however, one should be cautious about overestimating the attractiveness of engaging in nuclear extortion or trafficking in fissionable material to the criminal underworld, especially to organized crime. . . organized crime is a conservative service–oriented industry. It provides gambling, prostitution, and narcotics, The profits from the provision of these services are good and, perhaps more important, steady.. There is a willing market for such services, and despite the social harm they cause , they may not be perceived by the public as a direct threat to individual or collective security. Indeed , the

> existence of organized crime depends a great deal on tacit public acceptance or at least indifference and therefore it has tended to avoid criminal ventures--for example, in this country kidnappings for huge ransoms--that are likely to arouse public anger. Nuclear blackmail would bring tremendous heat on the organization and provoke crackdowns that could interrupt the flow of large steady profits from socially more acceptable crimes.[13]

James E. Lovett is very skeptical of the likelihood of organized crime involving itself in nuclear diversion.

> Organized crime will attempt nuclear diversion under one and only one condition, that it will bring more money. Organized crime has no use for nuclear material either as a blackmail threat or as a potential defensive or offensive weapon system. Nuclear material is of value to it only if it has a buyer.[14]

Lovett, however, concedes that a non-weapon State or a terrorist group might employ an organized crime syndicate to divert nuclear materials in return for financial payment. But a non-weapon State or wealthy enough terrorist group would not necessarily have to rely on *organized* crime. The could also recruit a band of independents.

In 1969, the Atomic Energy Commission asked Wright, Long & Company to study the possibility of nuclear cargoes being hijacked by the Mafia and other organized groups. Since the researchers were likely to have little direct contact with members of the Mafia, they used an indirect approach, interviewing police chiefs. The study itself is classified but speaking before a meeting in Los Alamos, New Mexico, one of the investigators said that “the Mafia appeared more interested in cigarettes and television sets than in uranium and plutonium.” He noted, however, “It is possible. . . that some foreign tyrant might offer a deal of some kind to any racketeer who would divert enriched uranium.” Hijacking trucks was something organized crime is skilled at. Ominously the researcher told the audience that “on a list of 735 so-called Mafia members, 12 are or were owners of trucking firms, two are truck drivers and at least nine were union officials."[15]

In private discussions with Jenkins, law enforcement officials generally found it hard to imagine organized crime going into nuclear extortion or theft. "It would bring too much heat on them." "They work with the people in power not against them." "In a case of nuclear theft or nuclear blackmail, judges are likely to become rather liberal in authorizing wiretaps, searches, and arrests. They wouldn't like that." "Their annual take is in the billions. What do they need nuclear for?" If not nuclear extortion or theft, would organized crime fence stolen nuclear material? If there was a market for it, possibly they would so long as it was not likely to be used where they lived.

The authors of the 1975 study by the Mitre Corporation, seven of the twelve of whom were former FBI officials disagree that organized crime's alleged conservatism in politics or business would dissuade it from action involving nuclear material. In a florid style that characterizes the entire report, its authors concluded:

> A veritable army of criminals and hoodlums in this country is waiting and willing to undertake any activity, including murder, if the profit justifies it. Their ruthlessness and sophisticated techniques and methods have been convincingly demonstrated in thousands of skillfully executed crimes. ...They have corrupted and compromised men in all walks of life. They have links with many foreign countries. Their greed knows no bounds.
>
> . . . .They are interested solely in acquiring more money and power for themselves and there is no evidence that they have or ever had any motivation such as patriotism. . . . There is little question that, for a sufficient amount of money, members of organized crime would take a contract to acquire special nuclear material for another party.
>
> .*..Organized crime shows little interest in its public image and would not be likely to be deterred from stealing nuclear material because the public might be outraged.

If there is any area of consensus within the debate, it is that no one who has commented on the topic seriously believes that organized crime lacks the resources, skills, patience and force necessary to steal special nuclear material or engage in an illicit international trade of the commodity. Putting it another way, no one views current safeguards as sufficient to deter or prevent nuclear theft by organized crime. The deterrents, if there are any, lie elsewhere in fears by the leaders of organized crime that such actions would provoke public outrage and lead to severe responses that would seriously damage organized crime’s other profitable enterprises. The idea that organized crime would attempt to deter such countermeasures with a nuclear threat is apparently accepted by only DeNike. Willrich and Taylor point out that “like nuclear war between nations, if the deterrent failed and a criminal group either used nuclear weapons or failed to use them, the group itself would probably not survive the crisis as an organization." .[17]

At the same time, even those who believe that the risks to organized crime of involvement in nuclear theft or nuclear extortion probably exceed the perceived benefits appear unconvinced that if a worldwide market for nuclear material develops, and if the price is right, organized crime, without becoming directly involved in the theft of nuclear material might act as a “fence” or broker for the stolen goods.

It seems not surprising that the attraction of nuclear material to organized crime is its intrinsic monetary value as a commodity, not its strategic attribute, which only increases the handling risks. Thus, the possible involvement of organized crime in nuclear theft or illicit trade in nuclear material would seem contingent upon (1) the continued expansion of the nuclear industry worldwide-–a seeming certainty; (2) a restricted market in special nuclear material, which will keep the value of the commodity high; (3) the consequent necessity and profitability of an illicit trade; (4) a sufficient number of suppliers and buyers to sustain a market as opposed to an occasional one-shot deal; and (5) sufficient laxness in the area of security and safeguards to allow a sufficient seepage of material for trade.

If the deterrents to nuclear theft or other nuclear action by organized crime lie in its natural concern about its other investments and its own survival, that may be an approach to explore. The question might be asked, apart from increasing security and safeguards, which many at present consider to be woefully inadequate measured against the capabilities attributed to organized crime, what could be done to insure that the leaders of organized crime fully understand that any involvement in nuclear action, like an armed attack upon the nation itself, would inevitably provoke an unprecedented attack on organized crime which it would not survive.

VI. THE RECORD OF NUCLEAR INCIDENTS

Between 1969 and 1975, there were 288 recorded threats or incidents of violence at nuclear facilities in the United States. This figure does not include nuclear hoaxes. The vast majority of these (240) were bomb threats against government or licensed nuclear facilities. Twenty-two were incidents of arson, attempted arson, or suspicious fires. Most of the arson incidents occurred in office buildings where the Atomic Energy Commission rented space, or were directed against university research facilities such as the Lawrence Radiation Laboratory at Berkeley, California. Ten of the arson incidents took place at this location. The same facility also received five bomb threats. Investigators believed the perpetrator or perpetrators to have been an individual, perhaps a former employee with a personal grievance, or militant students.

The most serious incident of arson occurred at Consolidated Edison's nuclear generating plant at Indian Point, New York. On November 4, 1971, a fire caused $10 million in damage to the facility, but did not affect the reactor. Later, in a letter to the New York Times, a group calling itself "Project: Achilles' Heel" claimed that "Indian Point guerrillas" were responsible for the incident. The letter implied that the action had been motivated by concern for the environment; however, the arsonist who was later apprehended turned out to be a former employee of the company who was undergoing psychiatric treatment at a local veterans' hospital. The fire delayed the plant's opening for three months.

There were four incidents in which bombs or explosives were found at nuclear facilities. Again, research facilities were the principal target. There were 10 actual bombings. Eight of the bombs exploded at federal office buildings or university research facilities, and it is not clear in all cases that nuclear programs were the target. (One, for example, exploded at the High School in Oak Ridge, Tennessee; it is not at all clear why this incident is included in the government's list of incidents other than the school's proximity to the government's research facilities at Oak Ridge.)

However, in two episodes, the targets clearly were nuclear. On December 7, 1971, two bombs exploded near the experimental linear accelerator at Stanford University in California causing heavy damage to the electronics equipment that controls the facility. A caller later claimed credit for the explosions, but no manifesto were issued and no suspects were ever arrested. It was, however, a period of student unrest and there had been other incidents of violence on campus by student militants.

The other action was carried out by an avowed foe of nuclear power. On February 22, 1974, a 400-ft. meteorological instrument tower at a proposed nuclear power plant site in Montague Center, Massachusetts, was toppled by a saboteur who simply loosened the turnbolts on the tower. The perpetrator, who turned himself in to the police, claimed in a written statement that his action was motivated by opposition to the future construction of a nuclear power plant at the site and t-o the danger this would impose on the community. "I held no malice toward the tower itself. . . ," he wrote. "Symbolically, however, it represented the most horrendous development this community could imagine."

The remaining incidents consist of forced entries and intrusions, shots fired at guards or at transmission towers, or deliberate breaches of security. In one incident, a student with a record for doing odd things cut through a fence to gain access to the area around a university research reactor simply to prove that it could be done.

The only known diversion of nuclear material in the United States occurred at the Kerr-McGee fuel. fabrication plant in Oklahoma. On November 5, 1974, a plant employee who had previously complained that working conditions at the plant were unsafe, was found to have been contaminated with plutonium. Put on administrative duties the following day, she was, when routinely checked, found again to be contaminated. A further check of her apartment, 25 miles from the plant, revealed some contamination, and her roommate. was also found to have a low level of contamination on her body. Urine and fecal samples taken after the first contamination also revealed contamination but not at levels consistent with that found later during an autopsy.

She was killed in an automobile crash eight days after the first incident while on her way to a meeting with a union official and newspaper reporter. Her death left numerous questions unanswered and the episode was investigated by the Nuclear Regulatory Commission and the Government Accounting Office.

A month later at the same facility, uranium dioxide pellets (containing low-enriched uranium) were found on the grounds Of the Plant outside the production area. There was no way they could have gotten there accidentally. The perpetrator was suspected to be a plant employee who wished to embarrass the company. While neither incident involved more than minute quantities of nuclear material, they did raise serious questions about the security of the facility and the possibilities of a more serious diversion.

None of these incidents, with the exception of the fire at the Lawrence Radiation Laboratory, the fire at Indian Point, the bombing of the Stanford linear accelerator, and possibly the removal of nuclear material from the Kerr-McGee facility could be called “serious.” There were no casualties; public safety was not imperiled. (Douglas DeNike in “Radioactive Malevolence” states that in August 1971 an intruder entered the grounds of the Vermont Yankee nuclear power plant and fled after wounding the night watchman.[18] This would be the only casualty. Curiously, the incident is not included in the lists released to the public by the Energy Research and Development Administration and the Nuclear Regulatory Commission.) With the exception of the Indian Point, Lawrence Laboratory, and Stanford incidents, all could be classified as minor incidents -- bomb threats, token acts of violence, low-level sabotage, etc. Many are nuclear incidents only in the administrative sense, for example, office buildings, campus science buildings.

There is no evidence that such incidents are occurring with increasing frequency. They go up sharply in 1970, probably due to better reporting, and remain relatively steady until 1975 when the total number of incidents again increases, again perhaps due to better reporting. (Figures for 1976 are not yet available.) They tell us that the nuclear industry is not immune to the bomb threats that have become commonplace in all businesses and industry, to arson, to incidents of low-level sabotage, and to an occasional bombing. The Bank of America and Safeway Stores fare no better.

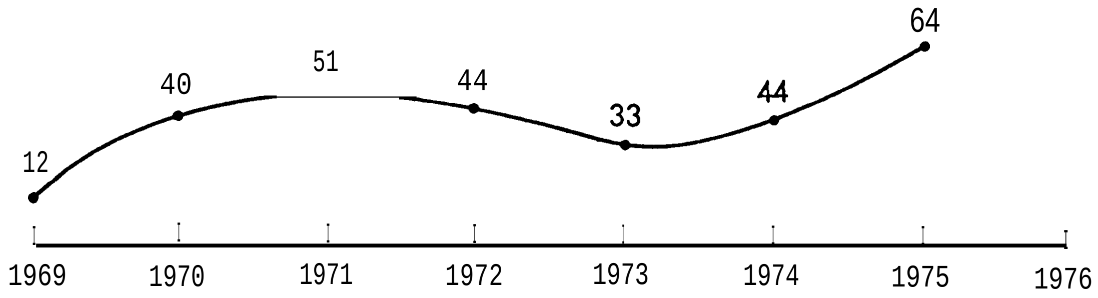


Fig.1 —Threats and incidents at nuclear facilities in the United States

The government list is not complete. It is unbelievable that no incidents of any type took place before 1969. There is the omission of the Vermont incident referred to by DeNike. During the summer of 1974 there were some incidents of low-level sabotage at the Zion nuclear power plant in Illinois which are not included in the list. They appear to have been the work of angry employees. There were also several bomb threats reported at the Zion plant in 1974, but the list mentioned only one that year. It appears that not all bomb threats are reported. The list makes no mention of several known thefts of radioactive material. (Not all such threats come under NRC or ERDA jurisdiction.)

In August 1973, 21 capsules of radioactive Iodine-131 were stolen from a hospital in California. In June 1974, a device was stolen containing strontium-90 which is used to measure the density of roadbeds. The thief, who was never apprehended, was in clear danger because prolonged exposure to strontium-90 can be fatal. In August 1974, nine radioactive radium needles were stolen from a hospital in California. This theft was carried out by a night porter who worked at the hospital. He was later apprehended. In September 1974, approximately 100 radioactive copper plates were stolen from the Lawrence Radiation Laboratory. They had just been removed from the laboratory's cyclotron. No perpetrators were apprehended. In December 1974, two cesi~um-137 gauges were stolen from a plant in New Jersey. These were found in damaged condition after an anonymous phone call led to their location. Other such thefts are known. Often it is reported that burglars involved in these thefts may not always know what they are stealing and may ditch the instruments or material when they are found not to be marketable.

Several more serious incidents of theft have occurred abroad. In November 1966, twenty uranium fuel elements in canisters were stolen from the Bradwell nuclear power station in the United Kingdom. The theft was carried out by two men, one of whom worked at the plant. Both were later arrested and the fuel elements were recovered. They said that a man in London had offered them "twenty quid" for the elements. The London connection was never identified. The rods contained only low-enriched uranium and could not have been used to make a bomb.

In April 1974, a uranium smuggling operation was uncovered in India. All of the details of the incident are not available, but it appears from the rather sketchy press accounts that uranium was being removed from the Jaduguda plant in Bihar, India, and was being smuggled to Nepal. From Nepal, it was smuggled to Hong Kong where reportedly Chinese or Pakistani agents took delivery. It is believed that as much as $2.5 million worth of uranium may have been involved. The plot came to public attention when five persons involved in the operation were arrested in India and 3.5 kilograms of low-enriched uranium were recovered. In October of the previous year, a scientist attached to the plant disappeared. It was speculated that his disappearance had something to do with the smuggling ring. Another man believed somehow connected with the operation was killed near Katmandu. The episode is extremely interesting for it reveals the possible existence of an embryonic international black market for nuclear material.

There are no complete chronologies of incidents involving nuclear facilities or material elsewhere in the world. From the reports of the incidents that are known, they do not differ markedly from those in the United States and consist mainly of bomb threats, hoaxes, incidents of vandalism and low-level sabotage. In the last few years, however, a few more serious incidents have occurred in Europe.

Several serious incidents of sabotage occurred in France in the last two years. On May 3, 1975, two bombs exploded at a nuclear power station under construction in Fessenheim, France. The explosions started a fire which damaged a nonoperative area of the nuclear reactor complex. The reactor itself did not contain fissionable material. In the months preceding the bombings there had been some local opposition to the construction of nuclear power stations in the area. The bombings, however, could also have been politically motivated. Shortly before the bombs exploded, a caller identifying himself as a member of the "Meinhof-Puig Antich Group" warned everyone at the site to evacuate the area. The "Meinhof-Puig Antich Group" had never been heard of before. Ulrike Meinhof was one of the leaders of the anarchist Baader-Meinhof Gang in West Germany. Puig Antich was an anarchist executed by the Spanish government. It is possible that anti-nuclear extremists used the cover of political extremism to gain publicity for their act.

Two more bombs were detonated at French nuclear facilities in June. A group calling itself the "Garmendia-Angelo Luther Commando," also previously unheard of, claimed credit for the incident. Again, the group may have been a political cover for foes of nuclear power. One bomb was placed at Framatome’s main computer center in Courbevoir, France; it destroyed half of the input terminals. The second bomb was planted at Framatome’s workship in Argenteuil and caused some damage at the valve testing shops.

In August 1975, two bombs exploded at a nuclear power plant at Mt. D'Arree in Brittany, France. The bombs caused minor damage to an inlet for cooling water for the reactor and to an air vent on the building in the power station. The reactor itself was not damaged, but it was ordered shut down pending an investigation. No one claimed responsibility for the attack, but police suspected that the attack had been carried out by a Breton separatist group responsible for other acts of sabotage in the area.

In early November 1976, a bomb exploded at the Paris offices of Cerca, a manufacturer of nuclear fuel elements. The blast caused heavy damage but no casualties. Responsibility for the attack was claimed by a man identifying himself as a member of the "Commando of Opposition by Explosives to the Self-Destruction of the Universe" -- COPEAU.

Less than a week after the Paris blast, two bombs were detonated at the Margnac Uranium Mine in Southwestern France. The bombs destroyed four pump compressors causing an estimated $2 million damage. The mine would have been flooded had not workers been able to get emergency pumps working within three hours. At any rate, the mine, which accounts for about one-eighth of France's annual production, was put out of action for about two months. COPEAU claimed credit and warned of further action.

Further incidents of violence against nuclear programs in Europe may be anticipated. Demonstrations against the construction of new nuclear power stations in West Germany, where anti-nuclear forces appear to have merged with extremist political movements, have resulted in violent confrontations with police. (We are not quite sure here whether political radicals have adopted the anti-nuclear cause, or political radicals and anti-nuclear forces overlap in membership or what the nature of the leadership of the demonstrations is, if any.) On one occasion, police used water guns and tear gas to prevent some 3000 demonstrators armed with clubs, rocks, and Molotov cocktails from storming the construction site. A number of people were arrested and injured.

In Sweden, where nuclear power has met similar resistance, a bomb containing 44 pounds of dynamite was found next to a nuclear power station at Ringhals in November 1976. A note to a local newspaper told police where to locate the device. The note, which was signed “M,” said, “This is the last warning. Next time we will level the station to the ground.” The bomb, which was defused by police, would have damaged transformers but not the two reactors.

There have been two incidents involving the use of radioactive material as contaminants. On April 16, 1974, an anonymous caller in Austria calling himself a “justice guerrilla” warned that certain train coaches had been deliberately contaminated with radioactive material. Investigators found strong but not lethal traces of radioactive material of a type normally used for medical diagnosis (Iodine-131). The episode attracted widespread publicity in Austria and provoked a number of hoax calls and threats. The “justice guerrilla” who was later arrested, turned out not to be a member of any extremist group as was first feared, but rather an individual with a history of insanity. He intended his actions to be a protest against the treatment of the mentally disturbed in Austria.

In October 1974, Italian government officials announced that they had discovered a plot by rightwing terrorists to poison Italy’s aqueducts with radioactive waste material stolen from a nuclear research center in Northern Italy. The alleged threat was associated with revelations of a planned assassination and political coup by rightwing elements. An engineer at the research center was named as a conspirator, but the allegations were never substantiated and the case became tangled in legal technicalities. Whether the alleged plot, which received widespread publicity in Italy, was real has never been determined.

A single incident is known to have occurred in Latin America. On March 25, 1973, fifteen members of the People’s Revolutionary Army, a Trotskyist urban guerrilla group in Argentina, occupied an atomic power plant under construction at Atucha, 62 miles north of Buenos Aires. They overpowered the guards, painted slogans on the walls, raised their own flag over the facility, and stole weapons, but they made no demands for the release of hostages and did not attempt to enter the reactor area or damage the facility itself.

What can we conclude from these incidents? For the most part, they were not serious: only one incident involved a minute quantity of plutonium (the Kerr-McGee episode); public safety was not imperiled. Most were low-level incidents -- vandalism, token acts of violence, low-level sabotage, minor thefts. We can safely predict more of such incidents as the nuclear industry continues to expand. The publicity surrounding the incidents was not that extensive. In only a few incidents did the incident attract international attention. The perpetrators were diverse. They included disgruntled employees, common thieves, political extremists, foes of nuclear power, and a few authentic lunatics. Their motives included protest, greed, revenge, or desire for attention. The perpetrators included insiders, external groups, and combinations of confederates.

For the most part, however, the perpetrators were probably individuals; a few were small groups. The smuggling ring in India with contacts in at least three countries shows the most organization.

The combination of anti-nuclear elements with political extremists, as in France and Germany, seems to be the most dangerous combination, that is, the one most likely to lead to violence. Further violence and perhaps some escalation seems possible, particularly in Europe. On the other hand, there is no evidence in these incidents that any criminal or terrorist group has made any attempt to acquire special nuclear material or radioactive waste for use in an explosive or dispersal device. And no individual or group has demonstrated such a capacity.

VII. NUCLEAR HOAXES

> "On 27 October 1970, the Orlando Police Department received a note threatening the City of Orlando, Florida, with destruction by a 'hydrogen bomb.' The note was accompanied by a diagram of the bomb. The anonymous author of the threat demanded $1 million in cash and a guarantee of safe passage out of the country. The city was given 24 hours to comply -- or risk annihilation. Authorities judged the threat to be a hoax, and police later apprehended a 10th grade student who admitted authorship. There was no nuclear device." 19

This threat and others, including those made in other parts of the world, exemplify that portion of the spectrum of adversary actions classified as hoaxes. For the purpose of this report a nuclear hoax is defined as a threat to cause harm by detonation of either a radiologic dispersal device, a homemade atomic bomb, or a nuclear weapon, but where the threatener lacks the capacity of which he boasts or the dedication necessary to carry out the threatened action. Although persons have made threats alleging that they indeed had a nuclear capability, there is no evidence to date that any of them actually possessed such a capability. While it is theoretically possible that someone had a nuclear device, but for some reason changed his mind and decided not to follow through with the threatened action, there is no basis in fact to believe that this has been the case. None of the threats to use nuclear material studied to date have proven credible. Therefore, they have all been classified as nuclear hoaxes.

Nuclear hoaxes have been seen in the form of extortions containing a range of demands from political concessions to $40 million in cash. However, the threat was not always coupled with a demand. In some cases it was in the form of a warning that damage would be done using a nuclear capability. Excluding the cases of extortion for money, justifications for the threatened damage were often given (such as opposition to nuclear development or testing and protest against U.S. participation in the Vietnam war). Other reasons *or* justifications given were vague, irrational, or poorly developed, and in a few cases no reason was given.

Whether the threat was an extortion device or a warning, the apparent intent of the perpetrators could be generally categorized under one of three major headings: expressive, disruptive, or coercive. Some threats appeared to be poorly thought out, nonspecific, and often irrational and confused. It was as if the author of the threat was struggling with an intrapersonal problem which he externalized and which took the form of a threat to cause harm, using the fantastically devastating force of a nuclear bomb. The delivery of such a threat especially if it lacked provision for communication between the adversary and the recipient of the threat seems to have been for the purpose of expressing a strong feeling? making a political statement, or eliciting some sort of reaction.

The second category of hoaxes is made for *disruptive* purposes. These hoaxes, as a group, were more organized than the first type in design, rationale, and content. They specified targets, dates, nature of the action threatened, nuclear capability, time frame (how much time t-he recipient had to comply with the demands), and if demands were made, t-hey were more carefully described. Since the adversary committing a hoax lacks the capability to follow through with his threat, one cannot be certain of his level of dedication. Even a hoax, however, inflicts a certain cost on a sector of society in the form of investigation, public anxiety, work stoppage, etc. There is a similarity between this type of hoax and a “conventional” bomb scare in that both threats are structured to force a response by the recipient which usually results in disruption of the normal state of affairs for persons involved with the threat-.

The third type of hoax may be described as coercive in that the perpetrator is serious in his intent to carry out an extortion using a nuclear threat as the means for coercive compliance to his demands. Since he lacks the capability stated in his threat, the perpetrator must rely upon the way he has structured his message and implemented the threat to “con” the “extortionee” into compliance. Since his intent is to have his demands met, provision is usually made for communication with the extortioner to ensure compliance. The major problem faced by the perpetrator who is “conning” the extortioner is to convince the extortioner that he, the perpetrator, has the nuclear capability and level of dedication necessary to carry out the threat if his demands are not met.

It is difficult to determine the motivation for making a nuclear threat. Without direct observation and study of perpetrators who engaged in nuclear threats, one must be cautious about attributing motives to these adversaries. Those who would engage in nuclear threats may be different from, or a special subset of, non-State adversaries. An assumption prevalent in the literature is that the non-State adversary would use nuclear capability if it were available to him, based mainly upon the logic that any adversary might utilize new technical advances for his purposes. The advantages and constraints associated with a nuclear capability are more complex than just increased destructive capability and the adversary who would contemplate the use of this level of force may have completely different perceptions of the world and different values or political objectives than have been demonstrated by adversaries thus far. It is sufficient for this section to raise questions about “nuclear” motivation and insert a caution against projecting the use of a nuclear capability by what are generally regarded as non-State adversaries. (The foregoing is not meant. to imply that there are not persons who would carry out a nuclear threat if the means to do so were available to them.)

Based upon a study of nuclear hoaxes, apparent motivation can, like apparent intent, be classified into three categories: political, criminal, psychotic. A careful reading of threat messages and study of the related circumstances indicates mixed motivation in most of the cases studied. In addition to the likely presence of more than one motive in a given hoax, there is also the possibility that the initial motivation will change as the event unfolds. Existing data do not permit the conclusion that a nuclear hoax extortion, which initially appeared to be politically inspired, was in fact just that and not of criminal origin. For classification purposes, a political motive was ascribed to the perpetrator when he demanded that certain political actions be taken or concessions made. In cases of political extortion, the coercion was directed against the U.S. Government (except for a couple of instances when certain foreign governments were cited to share with the U.S. the possible consequences if the threat demands were not met). There were no instances of a threat made against one government where compliance was demanded from a second government.

Demands for money, with or without safe passage to a foreign country, were assessed as a criminal motivation (personal gain) especially if there were no associated political demands. However, some of these cases had threat messages that demonstrated disordered thinking by the author.

A significant percentage of the nuclear hoax messages were disorganized in content, contained irrelevant statements or had other bizarre features. This group was evaluated as having a *psychotic* motivation. Some of these threats were implemented in such a way that the identity of the perpetrator was not difficult to establish--several of the perpetrators identified had a history of diagnosed major mental illness or hospitalization.

An interesting question for which there is not yet a good answer is, does the adversary perpetrate a hoax because he has *no* nuclear capability? If he had the capability to carry out a nuclear threat, would he choose to make a “real threat” rather than a hoax? Interpretation of available data is that there are those who would carry out a real nuclear threat if they had the capability. For example, in August of 1974, a large explosion at the Los Angeles International Airport killed three persons and wounded thirty seven others. Shortly thereafter, the Los Angeles Police Department received a taped message listing a series of demands which were to have been met or further bombings would occur. Demands ranged from easing restrictions on U.S. immigration laws to liberalization of sex laws. Because he was attempting to draw attention to injustices suffered by immigrants, the selected list of targets spelled out the word ALIEN, the first target, an airport corresponding to the letter “A.” He was subsequently named the “Alphabet Bomber” by the press.

It was later learned that prior to the airport bombing he had placed an incendiary bomb in the car of a police commissioner and set fire to his home. There were additional acts of fire bombing that he committed which served to demonstrate his dedication to carry out his threats. He had access to all of the ingredients to make nerve gas at the time he was arrested by the Los Angeles Police Department. There is little doubt in this author’s mind that he would have used it or any other capability which could cause much destruction if it had been available to him.

These hoaxes demonstrate that persons are at least thinking seriously about using nuclear material as the coercive basis of a threat. It also appears that while the psychotic individual a. more attracted to a nuclear threat than the politically or criminally motivated person, his ability to acquire SNM and carry out such a threat is greatly compromised. However, there have been instances (such as the Alphabet Bomber) when a person, although basically psychotic, has had the knowledge and skill to use materials available to him in a rather spectacular and destructive manner.

To date, it would appear that those who are dedicated enough to carry out a real nuclear threat have not been able to gain access or to acquire the necessary nuclear material . The nuclear hoax offers an alternate way for this type Of person to pursue his objectives still within the context of a nuclear threat. Neurologic or bacteriologic agents as the basis of a “massive threat” have not been popular thus far, although more easily available than nuclear material. Why the threatened use of nuclear material rather than these other agents as a basis for threat is an interesting question that should be studied. It is important to note that the hoaxes studied were all threats to use nuclear material. However, it is interesting that none of these were double threats--that is, threats to use nuclear material against a nuclear target. If a future threat is made to use nuclear material against a nuclear target, it would represent a significantly different type of threat.

It is obvious and logical that if the intent of an adversary is to damage or destroy a target that he would alert the target only in those instances when he was so confident of his capability to cause such damage that an alert could not neutralize his action. Therefore a warning-type threat is either a hoax or the perpetrator has laid his plans in such a manner that even with prior notification he believes no measures can be taken to stop his action. An extortion threat includes prior notification and the implication that the target cannot protect itself because the adversary has successfully placed at risk something highly valued (such as human life). In addition, the threat is created to be dramatic and cause high levels of fear in those associated with the target. Placing human life in the balance or causing terror are *tactics* used by adversaries. In both cases, the terrorist (especially the political terrorist) and the perpetrator of a hoax, as initiators Of these acts, have limited resources compared to the level of possible consequences. The use of tactics which terrorize tend to compensate for the lack of resources and maximize the capability possessed by the adversary, The observations about the types of adversaries who have made nuclear hoaxes, their motivations and objectives, strongly suggest that hoaxes will continue to be used by individuals who lack sufficient capability to mount real threats, but who wish to carry out an action within the means available to them.

It is a serious and often a difficult problem to assess the credibility of nuclear threats and to distinguish a real threat from a hoax.

In December 1976, the Canberra Police Department investigated “.. .a threat to explode nuclear devices in Australia’s two largest cities as a protest against continued mining and export of uranium.” “The bomb threat was contained in letters to Prime Minister Malcolm Fraser and Labor opposition leader Gough Whitlam. . . from a group of environmentalists calling themselves the Group of Six.” The messages “further threatened to contaminate water supplies in the two cities if attempts to explode nuclear devices failed.” The police states: “We have no option but to take it seriously.”20

The development of procedures and techniques to assess credibility and differentiate a real threat from a hoax have been and continue to be the responsibility of ERDA and NRC. The FBI by federal statutes is the lead investigative agency in all cases where threats are made involving radioactive material. The nuclear aspects of threat assessment have been delegated to the Energy Research and Development Administration (ERDA).

Current assessment of a nuclear threat consists of both a technical evaluation of all information related to the alleged nuclear device by ERDA nuclear scientists and a psychological evaluation of the threat message and the context in which it originated by the FBI backed up by ERDA capability.

ERDA is currently involved in augmenting and enlarging its capability for nuclear threat assessment and increasing the parameters for evaluation. This will also be available for direct support, at the field level, of the FBI’s investigative responsibilities of an incident and of the deactivation of any device by explosive ordnance disposal teams which may be associated with a threat.

As part of the total threat assessment process, an inventory of SNM is carried out, when relevant; however, there is some question as to the significance of a finding that "all SNM is accounted for." Because of the problem of measurement and checking SNM or any other substance, an unavoidable error is introduced into the accounting procedure. This error produces a calculation which is referred to as the "MUF" factor (material unaccounted for). Only a very small percentage of the total material is reflected in this measurement error. If, however, that material is special nuclear material, that small amount "unaccounted for" could be extremely significant. The inference is drawn that the adversary does *not* have the nuclear capability of which he boasts if the inventory check shows that all SNM is accounted for. This appears to have been the case thus far.

In any event, the usual approach has been to rule out the possibility of a *credible* threat. If the assessment found that the threat was *not* credible, an assumption was usually made that it was a hoax. Positive criteria for diagnosing a hoax are being developed. When this has been accomplished, the "default" approach (i.e., if the threat is not found credible, it must be a hoax) will be replaced by specific criteria for establishing that a threat is in fact a hoax.

Because of the diversity of motives and objectives attributed to perpetrators, it is not useful to identify any particular hoax as typical of the group. However, there are certain characteristics shared by nuclear hoaxes which can provide a basis for a composite hoax:

> *Targets* identified in the various hoaxes ranged from capitals of several countries, including the United States, to major U.S. cities. Federal buildings and certain large corporations and banks were also named as targets. Some hoaxes specifically identified the target while others made general references to "a big city in the U.S.," for example. Multiple targets were spelled out in a small percentage of the cases.
>
> Associated with the demand was usually an explanation or *justification* for the threatened action and ranged from concise specific statements to long and rambling diatribes. A few hoaxes specifically made reference to nuclear matters as being the cause of the perpetrator's concern.

Representatives of the news media and law enforcement agencies and certain major political figures were the most frequent *recipients* of threat messages.

The U.S. Mail Service was the most frequently used means for delivery of the message. In a few instances the threat was made via telephone and on one occasion the caller was apprehended while still talking to the recipient of his threat in a distant state.

In a little over two-thirds of the cases studied, the perpetrators alleged an *identity* and two-thirds of these claimed to be a group.

The amount of time granted by the perpetrator for compliance with his demands or before the alleged device would be detonated ranged from one day to several months with two to 15 days the most frequently mentioned period.

The perpetrator did not *validate* his allegations of possessing a nuclear capability by sending a sample of his SNM or by demonstration by detonation. However, he usually attempted, in some way, to convince authorities that he did in fact possess the alleged device. In a few instances, crude drawings of the device were included with the threat message which were easily assessed by experts as not capable of fission.

In a few of the cases, the *media* carried stories dealing with things nuclear within a two-week period prior to receipt of the threat. In one instance, the diagram of the alleged nuclear device included with a threat was similar to the diagram of an atomic bomb contained in an article of a national news magazine. The perpetrators who seemed to be set off by media stories about nuclear matters demonstrated a significant degree of disorganization and confusion in the content of their hoax message. Some of these individuals had a history of mental illness.

The cost of evaluating, investigating and reacting to nuclear threats is not insignificant. An increasing number of persons are acquiring information and technical expertise in nuclear matters as a result of the growth of the nuclear industry. If one such person were to initiate a hoax, it would be difficult to negate its credibility from a technical and behavioral assessment only. In instances of non-nuclear extortion, where the perpetrator did in fact possess the capability or valued commodity (such as a kidnapped victim or prized painting) which was the basis for his coercive threat, the extortionist usually did provide evidence of that fact and thereby removed all questions as to whether the basis for coercion was real.

In those cases, the question of the adversary's determination to carry out the threat, should his demands not be met, became a critical aspect of threat assessment. If we are unfortunate enough to encounter an adversary who demonstrates that he actually has the capability which he describes and his threat is therefore verified as credible, then the ability to assess motivation, intent and dedication will become essential in order to conduct successful communications or negotiations--should that prove necessary.

At this time, we are still concerned with distinguishing between real threats and hoaxes. A great deal of emphasis is placed upon evaluating technical aspects of the threat and accounting for current supplies of SNM. Even if it were possible to rely heavily on inventory methods and ignore the problems of "MUF," we still have the problem of a possible foreign source of SNM being used in a threat mounted in the U.S. The emphasis of U.S. nuclear security has been on nuclear materials under direct control of the U.S. at home and abroad. The production of SNM or high-level wastes by foreign governments potentially constitutes a source of supply of nuclear material to the non-State adversary of both the domestic and foreign variety. An effective security system must deal with the possibility of a foreign source of nuclear material and any comprehensive system of nuclear threat assessment must also recognize that even if all U.S. sources of nuclear material are accounted for, the adversary could have imported material from abroad,

In a spectrum of adversary actions, hoaxes can be viewed as entry level acts used by the emerging or relatively unsophisticated adversary. However, this does not mean that a hoaxer will graduate to a perpetrator of a real nuclear threat. Just as symbolic bombing is used by adversaries because it is easy to do, does not require a high degree of exposure or risk of death or capture (except in the assembly, transport and placement of the explosive), allows a wide range of target selection, multiplies limited capabilities into large payoffs in terms of publicity, and is very difficult for law enforcement to prevent, so too nuclear hoaxes allow an adversary with limited capability to levy a cost on the social system in excess of what his real capacity is (see Figure 6). If one were to project the gradual increase of sophistication and capability in adversary capability which has been observed over time in other situations, we can assume a similar learning curve in the production and use of hoaxes as weapons to create high levels of fear in the public or to attempt to disrupt growth or development of the nuclear industry.

To date, no adversary in the U.S. has been successful in using the media to escalate the public's fear or alarm associated with a nuclear hoax. It is not difficult to conceive how the media could be compelled to inform the general public of a nuclear threat and thereby increase the amount of fear and disruption. Cooperation of the media with law enforcement in this regard is an essential part of a reasoned response to a nuclear threat. The alleged purpose of a nuclear threat is to cause harm to a large number of people, destroy cities or render large areas of land unusable; however, some of those things can be done without the use of atomic devices. It seems then that the choice of a nuclear capability with which to threaten harm has an added dimension which other capabilities lack; that is, the culpability to instill fear and terror in the general population who may not be the direct target of the adversary threat.

Relationship of Effectiveness of a hoax wit-h its Purpose

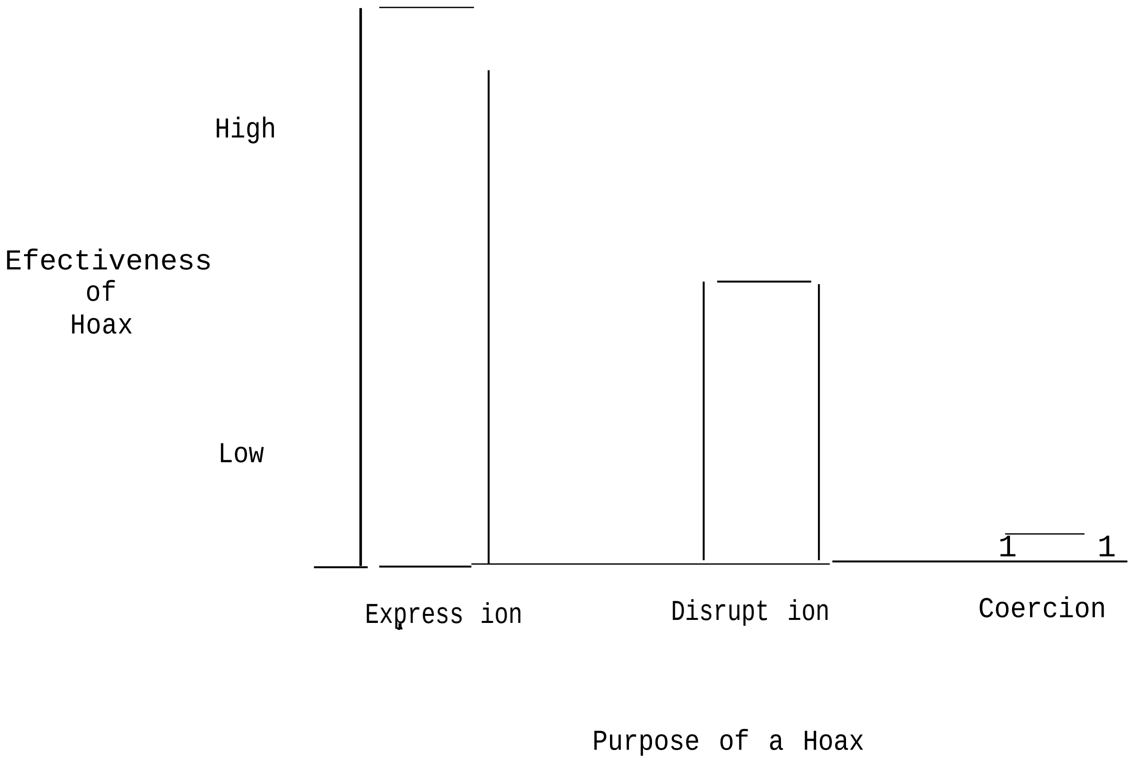


Figure 7

While it may be possible to anticipate adversaries who would use nuclear terror as a means of coercing a political response from a nation or as a means of obtaining large sums of money, it would be extremely difficult to predict what psychotic person may be attracted to nuclear power as a capability for widespread damage whatever his irrational beliefs. It seems that the attractiveness of a nuclear threat (real or hoax) for an adversary with political or criminal motivation is use as a tactic of terror rather than terrible destruction.

VIII. RESPONSE PLANNING FOR THREATS

A major problem area not addressed by the literature surveyed for this report is response planning for a nuclear extortion or nuclear warning threat. Other facets of adversary actions are discussed but the problems associated with threats to cause damage using nuclear material have not received adequate attention, at least in the open literature. A nuclear extortion or a nuclear warning is that threat where an adversary claims to have the nuclear means to cause great damage either by detonation or dispersal of nuclear material. The significance for this section on Response Planning is that an adversary *claims* to have a capability to inflict damage and not whether his threat is credible or a hoax. The determination of validity of a nuclear threat is discussed in the section on nuclear hoaxes (section VII).

An element common to both these types of threats is notification prior to the threatened act, but only in the case of extortion is it theoretically possible to avoid the destruction alleged by the adversary. The situation where an adversary claims responsibility for a nuclear act already carried out is not discussed here. However, because of the magnitude of possible destruction and disruption, the motivation for initiating such an act, its purpose, and post-event consequences warrant careful study.

The focus of this section is on extortion (those threatened acts where prior notification is given and the opportunity exists to exercise options either to neutralize the threat or to take damage-limiting action). Obviously, if the threat is a hoax, it is extremely important to assess it as such before protective measures, for example massive searches or wide scale evacuations, are implemented.

Preemptive action directed at potential nuclear non-State adversaries does not appear to be a feasible approach for protection of the public at this time. Although there is little disagreement that it would be better to stop an adversary before he can make a threat or take action, it is difficult to acquire the information about such potential adversaries. The problems associated with identifying individuals or small closed cells of adversaries operating within society but not necessarily having the dominant values and beliefs of that society and the problems associated with conducting an investigation without violating laws protecting personal privacy create real barriers to developing the option of preemptive action. The arguments for rights of personal privacy versus the rights of society to be protected from harm should be balanced by an assessment of the availability of plutonium and other SNM in a world economy increasingly in need of energy. Another possibility which should not be overlooked is the use of a foreign source of nuclear material to launch an adversary’s threat in the U.S. (The author is not addressing those debates dealing with societal risks where the location of nuclear power facilities near population centers is postulated as a threat.)

In addition to preemptive action, another general category of response planning is the prevention or deterrence of adversary actions to steal, by force or guile, SNM or to sabotage facilities (SNM in transit is recognized as a target with peculiar characteristics). The emphasis in this category of response planning appears to be placed upon defensive capability and tactics designed to defeat, contain, or delay an adversary once an action has started to allow time for additional assistance (response forces) from local law enforcement to arrive at the scene. One aspect of response planning as it relates to nuclear extortion is to consider including nuclear threats--both extortions or warnings--in the *Atomic Weapons and Special Nuclear Materials Rewards Act* (Public Law 93-377; 88 Stat. 472). Currently, the legal basis for prosecuting a person who perpetrated a nuclear threat rests mainly upon whether an extortion has been committed. PL 93-377 does “not” contain a provision for payment of a reward to assist in dealing with nuclear threats. It is beyond the scope of this section to deal with legal issues; however, the usefulness to law enforcement of including nuclear threats in the *Atomic Weapons and Special Nuclear Materials Rewards Act* should be considered, if it has not already been done.

A third category of response planning, which is the primary concern of this section, is the response to a threat to use nuclear material as part of an adversary action. The capability to assess whether a nuclear threat is real or a hoax is extremely important to the development of a response plan for these types of threats. Deployment of special search teams or the evacuation of even a very limited area within a city, such as a multi-story office building, is both costly and disruptive. The initiation of damage-limiting procedures in response to a threat is in itself a major decision, potentially containing serious consequences.

If a nuclear extortion threat is assessed as credible and not a hoax and the target is identified as a large U.S. city, decisionmakers could be faced with a mass extortion/mass hostage situation. Although the adversary may not directly restrain any citizen from leaving the city, an adversary who threatens to detonate a nuclear device in a large city, for all practical purposes, has created a mass hostage situation. The task of carrying out an orderly evacuation of a major U.S. city is laden with numerous problems.

There are those who believe that successful evacuation of a large urban area as a means for protecting its citizens from consequences of nuclear mishap is not realistic when all facets of the problem are examined. David D. Comey discusses various problems associated with evacuation and cites specific instances where there has been lack of compliance to established guidelines for evacuation procedures and where mock drills revealed gaps and breakdowns in carrying out simulated evacuation exercises.[21]

Because of the problems associated with evacuating citizens from a large city, a nuclear threat assessed as credible does potentially hold captive tens of thousands of people and could require hostage negotiations at a level not yet seen. The general area of negotiating or bargaining for large numbers of persons who are held as virtual hostages is a topic about which there is little information. Part of the response planning for nuclear threats should include development of policy and *guidelines* for deciding whether to implement evacuation plans. The planning work to date has dealt mostly with clarifying areas of responsibility and points of communication.

Questions which should be addressed are:

- What are the criteria for deciding to evacuate a large building or large urban area in the face of a nuclear threat?
- What is the extent of the liability of public officials if they do initiate evacuation procedures and under what circumstances can they force citizens to comply?
- What risk does a public official take if he fails to order an evacuation and some untoward event occurs?
- What is applicable to mass hostage situations of what we already know about hostage negotiations?
- What are the similarities and dissimilarities between the perpetrators of kidnap/hostage situations (where one or two persons are involved) and mass hostage situations?
- If large numbers of residents evacuate their homes and are relocated in adjacent counties, who provides such things as food, shelter, medical support, etc. , and who pays the bill?

A response plan for dealing with nuclear blackmail or threat has recently been developed for the State of California. Its purpose is "to summarize federal, state and local responsibilities in the event of attempted [nuclear] blackmail, threats, attacks involving radioactive materials, or nuclear weapons." It also attempts to provide planning assumptions and guidelines for local agencies to develop operation plans and SOPS for responding to a nuclear threat; and to protect tile Public health and safety in the event a nuclear threat is carried out.[22] This plan focuses on delineating responsibilities and establishing lines of authority and coordination but does not deal with policy issues. It was developed with the participation of a wide range of agencies, each representing its own particular area of jurisdiction and responsibility.

Shortly before the first meeting of various agencies engaged in developing the plan, a nuclear threat was made against a major corporate facility, located in the Southern California area. The threat was forwarded to the FBI which has primary jurisdiction for investigation of nuclear threats. Their evaluation of the threat and the technical assessment made by ERDA (which provides, at the request of the FBI, technical assessment of nuclear bomb and radiologic dispersion threats) was that the perpetrator lacked the alleged nuclear capability. It could not be ruled out, however, that the perpetrator might have planted high explosives at the target facility. Management of the corporation was understandably concerned with this threat and requested assistance from the local police department. The Nuclear Emergency Search Team (NEST) of ERDA was activated at the request of the FBI and was deployed to conduct a search of the target area with special monitoring equipment. The deployment of NEST provided an opportunity to test its response capability in coordination with activities of law enforcement under actual field conditions. While the operation and performance of the scientific instruments was satisfactory, the interaction between various agencies raised numerous questions.

One controversy, at that time, was jurisdictional. The FBI conducted the investigation but who would gather and retain evidence and who would handle the prosecution should the adversary be identified? The event occurred within the city limits, but the sheriff had previously been assigned a central coordination role for emergencies throughout the county. Although the FBI was conducting the investigation, the mayor of the city looked to his chief of police to keep him completely informed since the event could have widespread effects upon the health and safety of his constituents. The information, if any, that should be given to the media and who should make press releases when, could have been more of a problem than it was. These and many other issues regarding questions of jurisdiction and authority surfaced as the incident unfolded. The problems which arose were handled well because of the experience and professional attitude of the participants rather than because of any established policy or guidelines. (The California response plan had not yet been developed.)

The experience of having recently dealt with a nuclear threat in vivo was of great assistance to this group when they convened to draft the response plan for California. They had successfully faced an anxiety-provoking reality and now they were making plans to deal more effectively should it happen again. Because of the low probability of a nuclear threat being made and because of the potential large scale destruction and disruption which could attend execution of such a threat, there is a tendency on the part of some persons faced with planning for this problem to feel that nothing can be done to prevent or limit damage caused by such an act. With this mind-set, damage-limiting options and responses to conserve resources are not appealing and often planning this type of major emergency or disaster response is not attended to or completed. This was not the case of the group that developed the California plan. Because of their experience, the awesome reality for which they were developing a response plan could not be denied. This experience served to keep the group focused on the task and may be one reason why some potentially difficult jurisdictional problems were resolved (this is in no way meant to detract from those who led the work meetings and the manner in which differences were resolved). This group's experience with a real event may be useful to others who are developing response plans for devastating events which they believe highly unlikely and from which there is a natural tendency to shy away.

Because the incident was a hoax, operational issues of a greater magnitude were not encountered, such as, if large numbers of residents had to evacuate their homes and be transported to adjacent counties, who would provide transportation, food, shelter, and medical support? While it is necessary to work out procedures for such logistics, it is also necessary to develop guidelines for making these decisions in the first place.

The identification of issues operating at regional levels and for which responses must also be planned at regional levels is critical because until now, most response planning has been done by local or more traditional geopolitical levels of government. However, the consequences from a nuclear detonation pose complex problems which include jurisdictional questions crossing traditional boundaries of many agencies and city and county governments. In a way, the Tennessee Valley Authority had to deal with similar inter-agency and inter-regional issues because the “river of concern” impacts numerous geopolitical entities. It was clearly not a concern solely for the Federal Government or any single local government. A moving body of water represents a good analogy for visualizing the impact that a nuclear detonation could have on various levels of government and various local governing bodies. The extent of the “area of concern” will change in both magnitude and direction; it will not be bound by geopolitical considerations within a locale and may even impact several states. The decisions made by one group confronting the threat (equivalent to the source of this “river of concern”) may be made on data relevant to their immediate situation but the consequences of their decision may adversely impact another group of persons at a different location and at a later time (equivalent to introduction of contaminants upstream from a population center supplied by water from the “river of concern”). A regional approach to the response planning for nuclear emergencies should involve all entities who potentially would be harmed, in the development of information, discussion and selection of damage–limiting options. A strong impetus for establishment of the TVA was a real river; the possibility of devastating outcomes from a threat not yet made may not be sufficient to coerce similar action to organize regionally for response to threats or to limit damage associated with nuclear emergencies.

Disaster planning in peace time usually involves preparation for serious damage which is widespread or for extreme damage to a limited area. The requirements to deal with either of these forms of disaster can usually be met by some form of material assistance; namely, food, clothing, shelter and economic assistance.

Tile consequences of nuclear damage introduce new dimensions for crisis management which must respond with knowledge, skills, and equipment, some of which are highly specialized and of limited availability. In addition to the need for specialized and scarce resources, a unique management system is necessary to assure that timely communication will occur between those who must share information for appropriate decision-making and implementation. One such system is “Crisis Management.” Although not an entirely new concept, crisis management principles could be applied to a regional approach for dealing with the untoward consequences of nuclear threats. A discussion of crisis management, especially as applied to national (and international) issues and dealing with large natural disasters can be found in Science, Volume 187, by Robert H. Kupperman, et al. The emphasis of timely and damage-limiting actions, the ordering of competing objectives, and the use of computers to assist in the analysis of data and communication of information are a few of the ideas which could find application in a *regional management system* to deal with the nuclear consequences discussed in this section.

IX. APPROACHES TO THE STUDY AND ANALYSIS OF THE NON-STATE ADVERSARY

Various approaches have been taken with regard to analysis of the potential non-State adversary. A number of the reports and articles have taken for granted that an adversary exists--profit-motivated criminal., politically-motivated terrorist, demented individual--and have recommended security measures be increased accordingly. The report of the Lumb Panel is an example. According to this school of thought the identity of the potential burglar or his possible motivations matter little in the design of bank vaults. His existence is assumed; his objective is presumed (to get in, remove something of value, and escape); and the problem is prevention or apprehension.

A large portion of the reports and studies are descriptive catalogues of potential adversaries and the possible adversarial actions. These show the existence of a potential threat; some then recommend counter-measures. The Mitre Study of *The Threat to Licensed Nuclear Facilities* is an example. Some of Theodore Taylor's work also would fall in this category. So would most of the clearly anti-nuclear pieces and most of the journalistic pieces. Some of these begin with bits of history--the 14 year old boy in Orlando, a real hijacking--and then proceed to the possible nuclear actions.

Scenarios have been projected to show possible modes of action by different adversaries and reveal possible deficiencies in safeguards and security measures. Some of Theodore Taylor's classified and unclassified work and the Rosenbaum report provide scenarios. "Adversarial simulation" or "black hatting" is taking scenarios one step further. Safeguards and security measures are tested by setting a team of adversaries (scientists, engineers, security specialists) against them. Playing the role of the bad guys, or "wearing black hats," the adversary team actually tries to bypass barriers, pick locks, and so on. Of course, the actual use of armed force in a contest is not possible; so the "black hats" present their detailed plan of operations or scenario. The plan is then tested against the defenses, settling the outcome of hypothetical combat between guards and adversaries, if the plan calls for the use of armed force, by computerized models. “Black hatting” is probably one of the most useful approaches in actually testing safeguard and security measures. However, it is not always clear that the specialists who make up the “black hat” team, although usually very knowledgeable about nuclear facilities and material, are always that knowledgeable about the thinking and planning characteristics of burglaries, armed robberies, and sabotage. Second, the composition and skills given to the “black hats” must be derived from some actual data. Do the “black hats” have too few or too many members, are they given too much or too little time to carry out their action, etc.? Finally, the engagements tend to be restricted by the rules of the game. The “black hats” are not always allowed to give free rein to their imagination. They are sometimes compelled to do rather stereotyped things. Nonetheless, “black hatting” is probably the surest way of testing security hardware.

Another approach to identifying possible vulnerabilities is by surveying persons engaged in nuclear monitories activities. They are asked questions about possible nuclear thefts, much like asking bank security officers about how their banks might be robbed. The results of one such survey are contained in L. H. Rappoport and J. H. Pettinelli, “Social Psychological Studies of the Safeguards Problem,” in *Preventing Nuclear Theft.*[2.3] Confidence in the results of such surveys is somewhat limited because nuclear security personnel usually lack a general understanding of criminal operations. (Given the highly technical nature of the target, nuclear security personnel at the management level, as opposed to the rank and file guards, generally have nuclear industry backgrounds rather than criminological or law enforcement backgrounds. It would appear that they are drawn from management of the industry rather than recruited from the outside. Safeguards were initially viewed as a technical problem of detecting and preventing diversion by insiders, not criminal or politically motivated threats from the outside. This is not to say that those with engineering backgrounds are necessarily less effective than those with law enforcement backgrounds.)

Studying analogous; events is yet another approach. Several of the studies have sought to infer knowledge about possible adversaries of nuclear programs by examining non-nuclear events that are somehow analogous to possible nuclear actions. For example, although no known thefts of nuclear material have occurred, crimes are committed in which adversaries by means of stealth or force of arms penetrate well-protected and well–guarded facilities to remove valuable commodities. Thus, major thefts may provide insights about the capabilities and methods of operation of criminals. Several studies have taken this approach. In "Details of Criminological Investigations of Large-Valued Thefts Related to Nuclear Materials," a study carried out for the National Science Foundation, Leachman and Cornella examine major thefts of narcotics, data, precious metals and gems, objects of art, and weapons.[24] The McCullogh study examines the history of industrial sabotage an an analog to possible sabotage against the nuclear industry.[25] A study completed by the Historical Evaluation and Research Organization compiled a chronology of some 4,000 incidents of political violence and the record of one major terrorist group (the FLN in Algeria) to extract inferences regarding possible nuclear actions by terrorists. The BDM study of threats to licensed facilities looks at several thousand bombing incidents.[26] A study currently Underway by the Rand Corporation is looking at several categories of analogous events including major thefts and burglaries, assaults by terrorists, incidents of industrial sabotage, symbolic bombings, incidents the objective of which has been to cause mass casualties or widespread damage, and incidents of large scale extortion. While such an approach is based on "real life" data, it is sometimes a breathtaking inferential leap from non-nuclear to potential nuclear actions. Studies of analogous events provide a useful basis for scenario formulation and "black hat" testing.

A somewhat different approach is that of the "design basis threat" in which a hypothetical adversary is arbitrarily assigned certain strengths and capabilities which become the basis for designing protective measures. The shortcomings of this approach to adversary analysis is that it tends to become a matter of straightforward assaults, because these are the easiest to evaluate. The adversaries are accorded little ingenuity or imagination. The "design basis threat" also tends to lead to a somewhat sterile debate about numbers. Never the less, design basis threats do provide a reference point for setting and justifying security requirements and for measuring performance.

A combination of analog study plus “black hatting” may offer the surest way of developing a clear idea of the capabilities of adversaries as well as providing for testing these against security systems.

Little attention has been devoted to the subject of motivations and intentions. Although the motives of adversaries may be considered trivial once an action is initiated, such studies would be helpful in assessing the overall threat and in possible measures to deter would-be adversaries.

X. HOW MANY ATTACKERS -- HOW MANY DEFENDERS?

How much security is enough? Assuming for the moment that someone wants to sabotage a nuclear reactor or steal nuclear material, the answer to that question depends on the capabilities of the potential adversary. How many might participate in an act of sabotage or theft? How will they be armed? Will they possess explosives? What special equipment will they have? What level of criminal or military skills (the circumvention of alarm systems, the use of explosives, elementary tactics) will they possess? How knowledgeable will they be about the layout of the target, operating procedures, obstacles they are likely to encounter? How willing are they to risk capture or death?

Of all of the attributes of the potential adversary, numbers has received the most attention. How many external attackers are likely to participate in an act of sabotage or theft? Possibly this is because the number of possible assailants is the easiest attribute to deal with in designing a security system. An estimate of how many is also considered to lead directly to the answer to the question: How many guards are required?

It is this connection which makes the size of a potential attacking force a topic of some debate. Guards at government facilities must be paid for by the government, or in the case of licensed facilities, by private industry which tends to view the guard force solely in terms of added costs. An estimate of a large potential attacking force, if imposed on government programs or on the nuclear industry as a performance requirement, means means guards, which costs more money. A requirement to maintain a large guard force could even shut down some facilities, which would not be able to pay the costs and remain profitable. Naturally, arguments are made for a smaller or more “reasonable” estimate. To increase the design basis threat from three or six to 12 attackers probably would bring considerable protest from the nuclear industry. although it has been calculated that the costs of tile added security necessary to meet such a threat would represent a miniscule increase in the overall cost of energy. Determined foes of nuclear energy recognize this as a vulnerability of the nuclear industry and tend to argue for a larger estimate of the potential attacking force, hoping thereby to make the industry shut down because it simply cannot meet the requirements, or because it cannot profitably remain in business if so many guards are required. The debate thus tends to reflect, in part, motives that have little to do with the actual. determination of the threat size. By using different data bases, it is possible to reach different conclusions.

The first public study to mention the number of potential attackers was the Rosenbaum report written in 1974. Its authors estimated that “the maximum credible threat to any facility or element of transportation handling special nuclear materials is 15 highly trained men, no more than three of whom work within the facility or transportation company from which the material is to be taken.” Presumably, the authors meant any facility or element of transportation in the United States. An estimate of the number of assailants who might be assembled for an assault in Argentina or Lebanon under recent or current political conditions in those countries, of course, might be considerably more than that in the United States. It is not clear what evidence the authors of the Rosenbaum report used to arrive at their estimate of 15 or 12 outsiders and three insiders. They admitted that their estimate was “both subjective and imprecise” but they also believed it to be “informed and conservative.” “It was arrived at,” they wrote, “after informal discussions with the FBI and CIA . . . and [also based] on prior relevant experiences of the members of this study.[27]

Looking at the historical record, the Nuclear Regulatory Commission made a lower estimate of the threat size. Testifying before the House Subcommittees on Energy and the Environment of the Committee on Interior and Insular Affairs, the Director of the Office of Nuclear Material Safety and Safeguards said, “Historical data on the size of terrorist groups indicates that terrorist assault groups larger than six persons are not likely to be formed. We have examined over 4,000 incidents of terrorism and other anti-social behavior and were able to find 1,271 cases where the number of perpetrators could be identified. The number of incidents involving groups of more than six persons account for only about 2.5 percent of the cases. Groups with as many as 12 persons have been very rare. By far, the largest percentage -- 86 percent -- involved groups of three persons or fewer."[28]

The 4,000 incidents to which the director referred were compiled by the Historical Evaluation and Research Organization and comprise an exhaustive chronology of acts of sabotage and political violence going back to 1870. The chronology includes assassinations of presidents and other public officials, as well as many other acts which are of questionable relevance to assaults on nuclear facilities and may distort the impression of group size.

The BDM Corporation, under contract to the NRC, conducted a survey of 1,204 incidents of "worldwide terrorism and antisocial behavior" which took place between 1965 and 1975.[29] These included incidents of arson, armed attacks, bombings, hijackings, kidnappings, "psychological terrorism" (sic), and theft. U.S. bomb data, which had been collected in the course of previous studies by BDM, were deliberately excluded in order to avoid "the high number of unknowns associated with the U.S. bomb data base." In 702 of the incidents examined, the size of the attacking force was unknown, leaving 502 to be analyzed. Of these, 247 were hijacking of aircraft (and a small number of truck hijackings), 77 were bombings, and 5 were incidents of arson. Since many airline hijackings were carried out by lone hijackers, and arsonists and bombers tend to work alone, although bombers may be members of a larger group, one could argue that such a data base is not entirely relevant. And since such acts make up better than 65 percent of the data base, their inclusion would tend to skew findings toward smaller numbers.

The study includes no breakdown of the number of perpetrators by category of action and thus does not allow this possibility to be examined; however, one of the figures in the study does plot type of target with group size. It shows that in 128 of the cases in which "aircraft" were the target (i.e., hijackings), only one perpetrator was involved. Further figures show that individuals acting alone account for almost half (240) of the incidents in which the number of perpetrators was known.

At the same time, the data base used by BDM includes some incidents in which large groups were involved, but which took place in a political context that is not comparable to conditions in the United States today. Among these would be a number of attacks on rural garrisons and other targets by guerrillas in Argentina, or against rural villages in Israel by Palestinian Commandos. In both places, guerrilla warfare has been going on for a number of years and large guerrilla organizations comprising thousands of members have developed. Such conditions do not prevail in the United States today. However, these constitute so few incidents of the total that they probably would not warp the findings. Noting that some of the incidents, particularly some of the larger ones, took place in environments that do not apply to political conditions prevailing in the United States, the authors estimate that if these were eliminated, there would be a less than 1-2 percent total probability for an attack by a group of seven or more.

The study concludes that very few incidents, less than 5 percent, involve more, than six attackers and less then 1 percent involve more than 12 attackers. Oddly, this point is emphasized as a refutation of "those who maintain that terrorists are likely to attack in 10--12 men groups. '[30] It is not clear who, if anyone, ever asserted that terrorists are likely to attack in 10–12 person groups. Rather it was generally stated that 10-12 person groups represented somewhere near the maximum' threat.

The BDM report includes a reference to material compiled by The Rand Corporation which is offered as confirmation of its conclusions. The material consists of chronologies of incidents of international terrorism that occurred between 1968 and 1974. It includes 422 incidents; in 110 of these the number of perpetrators was known. It shows a similar sharp decline in incidents where the group size approaches six. The authors of the Rand work, however, for reasons already mentioned, would argue that this data base includes many bombings, airline hijackings, and other incidents which are not pertinent, and which tend to push the group size estimate down.

Current research at The Rand Corporation which involves a selected number of events that are more closely analogous to potential nuclear theft or sabotage shows that groups of 3 to 6 are common, that larger groups do appear, that a group size of 12 does appear to be somewhat of an upper boundary although there are a few cases in modern industrialized societies (United Kingdom, France, and United States) in which larger groups have been involved. More importantly, the Rand researchers argue that one must be extremely cautious in interpreting historical data regarding the number of attackers since the figures represent for the most part what the perpetrators, criminals or terrorists, perceived to be necessary to accomplish their mission, and in most cases what turned out to be sufficient. In other words, they came with as many as they needed to do the job, and no more. The fact that most came with a handful of persons, 3 to 6, thus does not represent an upper limit on their capacity to mobilize people.

Although the historical data are useful as a guide, an estimate of the number of attackers is inescapably a matter of judgment. Without speaking in terms of a “maximum” threat, a dozen or so attackers would seem to be a prudent estimate. The term “a dozen or so” has been chosen deliberately. We are not talking about a precise figure, but rather a range of anywhere from 7 or 8 to about 15. To be more precise would imply *some* type of actuarial chart based upon concrete data that simply does not exist, and a false sense of precision. That is not to say that no group of adversaries could not muster more persons if needed, or even that this many would be needed to accomplish the task. “Prudent” is the key word here.

Although that many (that is, 7-15) are rarely needed in a robbery or terrorist assault, there are incidents of both types involving that many persons. Again, although it is judgmental, military men and law enforcement officials would argue that more than that number might even be counterproductive. It is no mere coincidence that after 5,000 years of military history, the smallest operational unit of almost all armies is a squad composed of 9 to 13 men. It is difficult to maintain direct control over more than that in a fight. Of course, an attacking force could be composed of several Squads. Theoretically, it could be composed of several battalions. But a multi-squad attack force suggests a military or paramilitary operation. In the mountains of Argentina or the streets of Beirut yes, but under present political conditions in the United States, it seems a bit far-fetched. Even to come up with 10 or 12 attackers would stretch to the limit the capacity of most known violent political extremist groups in this country, most of whom comprise 8 to 12 dedicated “bombers and shooters,” a police term to describe those willing to participate in acts of violence. And bombers (who may plant bombs with little risk to themselves) are not necessarily shooters willing to engage in a gunfight. Moreover, although no one has attempted to determine precisely how many persons must be in a conspiracy to commit a serious crime before it is no longer a secret, the probability of discovery must increase rapidly in the higher ranges. The fear of leaks appears to be a principal consideration and constraint in assembling the personnel for a task force crime.

Current rules for licensed nuclear facilities postulate an external attack force of three persons who may be assisted by one inside confederate. (The use of “current” here poses some dangers as the security requirements are currently being reviewed and will probably be increased. This was as of January, 1977.)* ERDA has not picked a design basis threat. It has sought to improve security at its nuclear facilities without declaring that its security pains anticipate an attacking force of any particular number. There has been some debate about the ability of all nuclear facilities to defeat a determined, well-armed force of three external attackers, especially if they are assisted by an inside confederate. In some cases it may be possible for an insider to gain access

Note: See Volume I, Chapter 8 for some information on proposed increased physical security requirements.

to the central alarm station to immobilize those present, neutralize the alarms, and divert the remaining guards, thus facilitating the task of the external attack force. Even without inside assistance, a well-armed attack force of three persons might be able to overwhelm a small, lightly-armed civilian guard force. NRC officials concede that attackers may be armed with automatic. weapons, hand grenades, and possibly even anti-tank weapons. Civilian guard forces are armed with pistols, shotguns, and in some cases, semi-automatic rifles. Thus, they are clearly outgunned. (Guards at ERDA facilities may be armed with automatic weapons and at some facilities may also have armored cars.)

The performance standards may be increased to six external attackers with one insider. One technique calculates that a minimum of 11 guards must be on duty at all times to defeat an attack force of six persons. The primary basis for the calculations are Manchester equations, mathematical models developed during World War I to predict the outcome of major battles given the number of attackers and defenders and their respective armaments. Attempts were made during the Vietnam War to apply Lanchester equations to engagements between smaller units. The applicability of the mathematical model was restricted to skirmishes in which surprise was not a factor. However, the relevance of such mathematical models to engagements between a band of armed robbers or terrorists and civilian guards in which surprise is very likely to be a factor is extremely questionable.

Too much emphasis has been placed on the question of how many attackers. Although the size of a potential attacking force is certainly not an irrelevant consideration in determining the size of the guard force that is necessary to protect a facility, it has tended often to be used as a single determinant in a rather simple-minded fashion. As a result, it conjures a rather simple-minded and therefore unlikely adversary. The use of mathematical models to determine the outcome of firefights between guards and attackers suggests armed frontal assaults by potential attackers which may be a common mode of combat but not of armed robbery or even of very many terrorist assaults.

Armed robbers seldom “assault” their target. They employ stealth, deception, diversion and other techniques to gain access. Often they are inside or close upon the guards before displaying arms and revealing their intentions. Surprise is likely to play a major role.

A design basis threat also suggests that all facilities are equally attractive to potential adversaries and merit the same level of protection. This is not apparent. Those facilities where fissionable material is readily available in strategic quantities and in a form that can be handled easily may require greater protection. Moreover, the emphasis on attackers tends to level the differences inherent in different kinds of facilities and in different facilities of the same kind, Some are physically large and would require a major investment to breach; some are small buildings. Some are large complexes of hundreds of employees; others have only a handful. Some are located near population centers, and near reinforcements; others are remote where the assembly of a small group of attackers might arouse immediate suspicion. The number of guards, indeed the adequacy of security, is a judgment that may well have to be made after an examination of each specific site. The analysis has tended to turn the question around. We are not asked, as we ought to, what will it take to protect this specific facility against all conceivable actions -- burglary, armed robbery, sabotage, armed assault, standoff attacks, etc. Rather, it has become solely a question of estimating or guessing the number of armed attackers and the number of guards required to counter their potential assaults.

Much reliance is placed on the arrival of reaction forces to help fend off or prevent the escape of nuclear thieves. Indeed, some propose that on-site guards be no more than watchmen to sound the alarm leaving the armed response to local law enforcement officials. This idea merits scrutiny. It is approved by industry officials who wish to avoid the expense of maintaining large, unproductive, on-site guard contingents and by those who fear the social. consequences of the proliferation of private or federal nuclear guard forces. It must be noted that a majority of nuclear facilities for very good reasons are not located in the heart of metropolitan areas where police response could be swift. Most are located in remote rural areas where the capacity of local law enforcement is limited. Most armed robberies take only a few minutes. Even operations involving the penetration of barriers and setting of explosives, or seizing control of the facility are not likely to take more than a few minutes. The idea that an outside reaction force can be summoned in time to defend the facility again relates to the unlikely situation of a sustained military assault by the attacking force. If they do not achieve their objective in a few minutes, they are likely to flee, certainly not to hang around and shoot it out as Indians circling a wagon train. Moreover, the idea that the local police are going to arrive in strength is not always valid. In many cases, the first arrival, five to fifteen minutes after the alarm is received, is likely to be one man in a patrol car. Reinforcements in strength may take a half hour. By then the attackers are inside, or they have been defeated. Finally, we should draw some lessons from our recent military experience in Indochina. It is not probable that an adversary will be unaware of the local availability of reaction forces and the time it takes to get there. If they present an obstacle, and the adversary is determined nonetheless to seize the target, the first arrivals may be ambushed, not a difficult task given that many of the sites are in remote areas. Or as has been the case in several armed robberies, the reaction forces may be diverted beforehand by the adversary.

In sum, it appears that reaction forces that cannot arrive in strength at a facility in a few minutes, probably less than ten, certainly less than fifteen, are largely irrelevant, except for pursuit. The adversary will then have accomplished the mission or will have abandoned the attack. Local forces available after that might better attempt to seal off a wider area to prevent escape than concentrate at the scene of the incident.

XI. EMPLOYEE SURVEILLANCE AND RELIABILITY IN RELATIONSHIP TO THE POTENTIAL NUCLEAR NON-STATE ADVERSARY

Why Employee Surveillance and Reliability?

One potential mode of adversary action. previously identified is the penetration of a nuclear facility's safeguard system by subverting or coercing an employee to assist in the theft or diversion of nuclear material or in the sabotage of a nuclear facility. Employee surveillance and reliability programs contribute an approach to the defense against this type of adversary action.

Subversion is defined here as any action which seeks to manipulate, influence, or otherwise change the values, beliefs or allegiance of an employee and which could ultimately draw the employee into collaboration with the adversary. In this sense, an employee who was "successfully subverted" would be a conscious and willing participant in the scheme of the adversary. A distinction should be made between the employee who is acting as a result of having been subverted by an adversary and the employee who unknowingly takes harmful action because of disguised or misrepresented circumstances produced by the guile or cunning of an adversary. The former is willfully participating in the adversary's schemes; the latter believes he is carrying out his employee role in good faith and may only inadvertently initiate actions which benefit the adversary and harm the system.

Coercion is defined as the use of physical force, the threat of violence, extortion, or blackmail directed at an employee (or his family) for the purpose of obtaining compliance to the demands of the adversary. In this case, the employee succumbs to the pressure of the adversary and undertakes an action which he would normally resist.

An adversary action carried out over an extended period of time such as the diversion of SNM using an insider, as opposed to an armed assault for the purpose of stealing SNM, would be best served by using subversion to recruit the insider rather than coercion. The reason is that the adversary must maintain a sufficient level of coercive force to ensure employee compliance over an extended period of time during which the employee might change his mind about cooperating and might disclose to security or law enforcement the scheme of which he was a part.

Having an employee who was ideologically dedicated to the adversary operation would be much more effective in maintaining the security of the operation and would therefore probably be the preferred course of influencing an employee to participate in an adversarial action which extended over time.

Between the two modes of obtaining compliance [subversion and coercion) coercion may be more appealing to an adversary because it would require much less time to obtain the employee's cooperation than would a prolonged campaign of subversion. Coercion may also be the choice for obtaining inside assistance for an operation of relatively short duration, such as an armed attack to steal nuclear material. There would not be a need in this instance to maintain the coercive force for very long and therefore the probability is high that the employee who cooperates with the adversary under these circumstances would not betray the operation.

An employee surveillance and reliability program should consider as an objective the identification of employees who might be vulnerable or susceptible to subversion and take steps to correct that vulnerability or at least to limit any damage resulting from an exploitation of that vulnerability. How such a task might be approached will be discussed under the heading Monitoring Existing Employees.

Screening of New Employees

While it is possible that a nuclear non-state adversary could pose as a legitimate applicant for employment with the intent of gaining access to a nuclear facility, the difficulties of preplanning and providing the lead time necessary to infiltrate a facility and work into a strategic position would create a major obstacle. The long-term process of infiltrating a system is more the style of the traditional espionage agent than that of a non-state adversary who pursues an operation with more immediately achievable goals.

However, screening new employees at a nuclear facility can create a barrier to infiltration of the system by both the more traditional espionage agent and the non-state adversary. This initial screening process could be part of a comprehensive clearance procedure designed to identify those applicants who may present an increased security risk if employed in positions giving them direct access to SNM, control of accounting procedures, knowledge of security systems, etc.

The development of specific criteria to identify such applicants which could serve to alert those conducting a screening program, is not without problems. Leon Rappoport and J.D. Pettinelli touch briefly on "Identification of Criminal Topologies as They Might Apply to the Nuclear Industry. . . it (1) and point out a distortion in developing criminal typologies results from using criminals who are caught, when the worry should be instead about the criminals who are smart enough not to be caught. With respect to experience in the selection of employees for nuclear facilities, Frederick Forscher (a consulting engineer) tried to get assistance in hiring emotionally stable people. "After talking to several consultants about techniques to screen out emotionally imbalance people, he came to the conclusion that none could provide meaningful advice, a conclusion that Rappoport did not find surprising." The problems associated with selecting of appropriate personnel to fill a particular position or identifying particular people who should not fill specific positions are difficult In the early years of the Peace Corps the author was involved with the training and selection of Peace Corps Volunteers for overseas assignments. A Civil Service background check was made. In addition the trainee was evaluated during his three-month training period. Criteria were developed for the selection process which resulted in a very low rate of premature return from overseas assignments for other than reasons of compassion (i.e. death in the family). Other studies have identified stressful experiences or conditions in one's life which if present have a high degree of correlation with the development of mental health problems or physical symptoms.

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(1) Leon Rappoport and J.D. Pettinelli in preventing Nuclear Theft: Guidelines for Industry and Government, edited by Robert B. Lcachman and Philip Althoff (New York: Pracger Publishers, 1972), pp. 173-189.

(2) Ibid.

The point is that a specific criterion for deselecting applicants through a screening process does not exist; however, from experience to date, it seems likely that criteria could be developed which could alert those responsible for security matters to be especially attentive to a particular applicant because of a higher possibility of his becoming a security problem. Some possible categories of potential problem areas are:

- immaturity and instability
- mental illness
- asocial, anti-social personality
- vulnerability to blackmail
- strongly identifying with revolutionary political ideologies

Individuals who demonstrate signs of excessive anxiety, worry or depression, drinking, gambling, or who abuse drugs should also be subject to a finer level of scrutiny than those not showing such behavioral traits.

The issue of morality as a criterion is valid if done in a broad perspective of determining how the person relates to others rather than a microscopic examination of his private life.

Monitoring Existing Employees

Just as it is necessary to screen new employees to present a barrier to direct penetration of a nuclear facility by an adversary via the channel of employment and to exclude those who are unstable, mentally ill, or vulnerable to blackmail or subversion, so too is it necessary to monitor certain selected personnel who are in sensitive positions to assure that they do not move from a stable low-risk employee population to a population characterized by instability and a potentially high risk of being influenced by an adversary. Many of the criteria used to evaluate the existing employee will be the same as those for new employees. One major difference will be in how the data are generated. In addition to repeating a background check, as in the case of a new hire, the person who is currently employed could be evaluated in terms of behavior demonstrated on the job. For example, access to particularly sensitive areas could be controlled to require random dialog of a predetermined nature with an access control operator who could use psychologic stress evaluation (PSE) techniques to assess whether there had been any changes in that particular employee's established pattern. In addition to the use of PSE to identify changes in an employee's normal behavioral pattern which may be indicative of stress and would warrant closer evaluation, a psycho-linguistic analysis of speech content could also be made to look for evidence of changing parameters of word usage, thought content or mood.

Research would have to be done to develop or apply the appropriate methods for evaluation and assessment for both screening new employees and monitoring existing employees. Experience with reliability programs of SAC crews, and operators of missile bases, and atomic submarine crews should provide relevant data.

Societal Risk and Civil Liberties

In addition to the problems of developing a data base and evaluation criteria for ‘the purpose of screening and monitoring of employees, the problem of infringing on the personal and civil liberties of those employees in pursuit of the above is not easy to resolve. The Security Agency Study (NUREG-0015) (1) discusses full-field background investigations as they relate to guard applicants and points out that “such a requirement could impact the rights of free speech, association, and privacy. Interviews with references, neighbors, employees, and others regarding background and life-style could inhibit the exercise of free speech and association rights of . . . applicants. I*4 “Various court rulings in recent years have been favorable to the protection of individual privacy and of individual right-to-work. These rulings have made it difficult to make a personal background check of an individual in commercial activities to assure with high probability that he is trustworthy and, hence, potentially acceptable as a steward for the protection of plutonium.” (3)*

From a legal perspective and as it relates to constraints on what can and cannot be done to screen or monitor employees “. . . the ultimate question is whether the courts will perceive the dangers of plutonium to be so overwhelming as to allow them to . . . hold that the new statute authorizes the AEC to restrict the civil rights of plutonium workers in the interests of national security. h)+ Although the Ayres references deal with plutonium specifically, the tenor of concern of the courts would probably be relevant for those employees dealing with all forms of SNM or high-level wastes.

See also Appendix III-C of this volume for a discussion of the civil liberties implications of safeguards programs.

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(1) Security Agency Study, Report to the Congress on the Need for, and Feasibility of, Establishing a Security Agency Within the Office of Nuclear Material Safety and Safeguards, PB-256 962 (NUREG-0015), U.S. Nuclear Regulatory Commission, August, 1976.

(2) Ibid., p. IV-19.

(3) Russell W. Ayres, “Policing Plutonium: The Civil Liberties Fallout,” Harvard Civil Rights-Civil Liberties Law Review, Vol. 10 (Spring, 1975), Footnote 92, p. 388.

(4) Ibid., p. 399.

Impact of Surveillance on People.

Aside from considerations of the impact of surveillance on an individual's civil liberties-personal privacy or his qualifications for certain kinds of employment, we might well ask the question, “What happens to people who work under conditions of surveillance?” There is a rich history of various types of employment which are conducted under varying levels of scrutiny. In some post offices, postal employees are under surveillance of supervisory personnel during their entire shift and are aware of it. In the military there is close monitoring of crews that man missile silos. Astronauts on space flights are monitored not only for behavior but also for physiologic changes. In their confined quarters they are under keen surveillance and have essentially no privacy for the duration of their mission. Although not exactly under surveillance, famous persons are often in the public eye a significant part of the time and the intimate details of their private life are the basis of numerous widely distributed articles. Their response often is protective of their privacy but not necessarily pathologically suspicious or ‘paranoid. A good example of an environment under close surveillance is that of gambling casinos in Las Vegas. There both employee and customer are viewed directly and electronically. Judging by the level of activity in these casinos, it does not seem that surveillance per se is bad for business. In this author’s opinion, surveillance as an industrial safety measure is no more stressful than being closely supervised or being required to use protective equipment for certain industrial procedures.

Some individuals will feel constrained and stressed; others will have no reaction, but there is no stress inherent in exposure to a high surveillance environment which would lead to a particular behavioral syndrome--such as a distrustful and suspicious attitude.

The Ex-Employee

Certain ex-employees may be potentially useful to the adversary because of their technical knowledge or information they have about security procedures in a specific facility. Granted that the value of such an employee to the adversary may not have a long half-life; however, it would seem prudent to conduct exit interviews (in addition to security debriefings) with certain employees with special knowledge or skill to determine their mental state and attitude at the time of separation. Further, it might be advisable with selected members of this population to maintain periodic contact until it is determined that the transitional period after leaving employment with the facility has ended. This could be defined as the time when the individual has regained a stable life style and is possibly less vulnerable to malevolent manipulation.

The Insider Problem (1)

At the beginning of this section Surveillance and Reliability were approached from the perspective that the adversary would attempt to penetrate a facility directly or by subversion or coercion force an employee to assist him in carrying out his scheme. For the sake of completeness we should identify the situation of an employee who becomes disenchanted for any of several reasons and who initiates contact with an adversary group to assist him in carrying out some scheme he has developed.

The nuclear non-state adversary sees himself as an opposing force from the beginning but the ‘employee” adversary identified above may never have viewed himself as such. Because he is basically operating on his own or with outside assistance (rather than being an inside man for an outside group) his use of complex schemes, designed to deceive and cover up his actions may be the hardest of all “adversary actions” to identify. In fact his analogue, the “white collar” criminal, merits special attention and study to develop specific methods to deal with the "true" insider threat as opposed to the “adversary-induced” insider threat. It is fairly well conceded that some of the white collar crime of industry is never detected. In the nuclear industry a positive but delayed identification of an “insider” may have unacceptable consequences. He is extremely dangerous because he has opportunity, the key element in addition to motivation and capability, which the nuclear non-state adversary will probably not have.

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(1) See also The White Collar Challenge to Nuclear Safeguards (l?UREG-0156 January, 1977), Herbert Edelhertz and Marilyn Walsh, Battelle human Affairs Research Centers, Seattle, Washington 98105.

XII. CONCLUSIONS ON THE NATURE OF THE NUCLEAR THREAT OF THE NON-STATE ADVERSARY

First: The threat is real. The notion that someone outside of government programs can design and build a crude nuclear bomb is a good deal more plausible now than in the past. In the beginning, the secrets of fission were closely guarded. Now much of the requisite technical knowledge has come into the public domain. There also are a growing number of technically competent people in society who understand this material, and who, without detailed knowledge of nuclear weapons design, theoretically could design and fabricate a nuclear bomb. It would involve considerable risks for the builders. Its detonation and performance would be uncertain. Its yield would be low, probably in the tenths of a kiloton range.

For a dispersal device, some plutonium, or a quantity of some other available radioactive material, spent fuel for example, and a mechanism for dispersal would suffice. The principal impediment to building a nuclear bomb or filling a dispersal device is acquisition of the nuclear material. Should this prove insurmountable, a nuclear reactor could still probably be sabotaged, though the difficulty of causing damage or release of sufficient radioactive material to endanger the public remains unresolved.

The frequent use of reflective grammar -- for example, it could be done -- is deliberate. There is a great difference between theoretical feasibility and someone actually attempting to carry out one of the actions described.

Second: There are political extremists and criminal groups at large today that possess or could acquire the resources necessary to carry out any of the nuclear actions mentioned: sabotage a reactor, steal fissionable material and build a dispersal device or possibly even a crude nuclear explosive device. Some of the larger terrorist groups might undertake such actions with or without the assistance or complicity of a national government, and organized crime, at least theoretically have the option of acquiring a nuclear capability. There is general consensus on this. Arguments arise not so much in the area of theoretical capabilities, but rather in the area of intentions.

Third: The historical record provides no evidence that any criminal or terrorist group has ever made any attempt to acquire fissionable nuclear material or other radioactive material for use in an explosive or dispersal device. Apart from a few incidents of sabotage in France and one incident in Argentina, political extremists have not attacked nuclear facilities. No criminal or terrorist group has demonstrated or claimed that it possesses fissionable material. If members of any such groups have ever discussed the option of going nuclear, the present authors know of no such report. There have been bomb threats against nuclear facilities. There have been low-level incidents involving nuclear facilities or nuclear material -- vandalism, token acts of violence, low-level sabotage, minor thefts of nonfissionable material. There have been nuclear hoaxes most of which could easily be discarded as not credible. In sum, there is no direct historical evidence of any intentions on the part of the potential adversaries to carry out the actions of which they are theoretically capable. However, one ought to take little comfort in this fact. The lack of intelligence or of visible evidence does not mean that the option has not been discussed. Some group might move in this direction without providing clues or warning. We could first. know about it when it arrives.

Fourth: There is, however, no inexorable linear progression that takes one easily from the currently identified spectrum of potential subnational nuclear terrorists to actual subnational nuclear terrorists, or from the nuclear incidents that have occurred thus far to nuclear actions of greater consequence. Terrorist groups, as we know them now, might be among future nuclear terrorists, but their acquisition of a nuclear capability would not be a simple escalation of what has been demonstrated in terrorist actions thus far. We can only say that terrorists have been active in the recent past, that there is an apparent increase in their technical sophistication, that they have demonstrated a degree of imagination in their choice of targets, that nuclear facilities and material theoretically could provide them with a dramatic backdrop or prop for any action, and that terrorists have shown a flair for theoretical actions. On the other hand, terrorists generally have not attacked well-guarded targets. They have generally relied on relatively simple weapons -- submachine guns and dynamite -- and the number of casualties normally associated with the detonation of even a crude nuclear device, or the dispersal of toxic radioactive material is many times greater than the casualties that have occurred in any single terrorist incident. Terrorists have not yet gone to the limit of their existing nonnuclear capabilities. Acquiring a nuclear capability would represent a quantum jump, and upon close examination it is simply not clear what purpose taking that jump would serve.

It is an equally long conceptual jump from the present activities of organized crime to the notion of organized crime acquiring a nuclear capability. It would mean in effect that its leaders have decided to directly challenge the sovereignty of the nations in which organized crime’s normal--and highly profitable--activities take place. This would require a fundamental change in the objectives of organized crime, whose members have sought to make money and to acquire political influence to protect their investments, but not to acquire direct political authority at higher levels or to invoke public or political reaction.

It is somewhat easier to imagine organized crime engaged in the theft of or illegal trafficking in fissionable material without seeking to acquire a nuclear capability. The annals of crime are filled with successful penetrations of well-protected targets to obtain precious commodities. Enriched uranium and plutonium certainly are precious commodities. For the immediate future, however, highly enriched uranium or plutonium are unlikely to be stolen for their intrinsic monetary value but rather for their strategic value as bombmaking material. They do not have the same marketability that gold or other precious metals have, and their theft is likely to be regarded in a totally different light by authorities. The loss of fissionable material probably would be viewed by government as a potential threat to the security of the nation, not simply as an economic loss. It would provoke a different level of response, perhaps applied in a state of national emergency, which could pose a serious threat to the very existence of organized crime as presently organized. It would require on the part of its leaders a change in their goals and an acceptance of new kinds of risks.

That leaves the category of psychotic individuals operating alone usually, or occasionally in groups. “Nuts” are probably responsible for many of the low-level incidents and nuclear hoaxes that have occurred thus far, but most would not try anything more serious than causing disruption. On the other hand, a few, if they had somehow acquired a nuclear capability, might use it. Lunatics have been the designers of many known schemes of mass murder. Thus, in terms of intentions alone, psychotics are potential nuclear terrorists. In terms of capabilities, they probably are the farthest away from being able to acquire a nuclear weapon. To do so would require an enormous increase in their own capabilities or an external change that made the task much easier.

The authors of nuclear hoaxes have manifested desires of becoming nuclear non-State adversaries but none have demonstrated the required capabilities, and it is not certain that all hoaxers, even if they had access to nuclear material, would be anything more than hoaxers, anymore than one can say that people who call in bomb threats if they had the opportunity (which in fact they do) would go out and buy dynamite and make a bomb. Hoaxes suggest more hoaxes, not necessarily genuine nuclear adversaries.

In sum, the history of the nuclear incidents to date provides no convincing evidence of the really serious events--the theft of a nuclear weapon or the detonation of a crude nuclear explosive device.

Fifth: Whether any of the current potential nuclear terrorists will decide to actually go nuclear remains an unanswerable question. We can identify potential adversaries and describe their objectives, their capabilities, and the likely modes of operation if they decide to go nuclear, but we cannot predict with any confidence whether any will ever make that decision. This leaves a vast area of uncertainty between what “can be done” and someone deciding to do it.

The primary attraction to terrorists in going nuclear may not necessarily be the fact that nuclear weapons would enable terrorists to cause mass casualties, but rather that almost any terrorist action associated with the words “atomic” or “nuclear” automatically generates fear in the mind of the public. Drawing attention to themselves and their causes, creating alarm, and thereby gaining some political leverage--which have been typical objectives of terrorists--could be achieved by undertaking relatively unsophisticated actions with a nuclear backdrop to add drama to the episode. Terrorists seem more likely to do those things that demand less technical skill and risk on their part and also are less dangerous to public safety, instead of attempting some of the more complex and riskier operations which potentially could endanger thousands of people.

Nuclear terrorism seems more attractive as a threat than as an action. Possessing a nuclear device, it seems terrorists could demand anything. But the idea of nuclear blackmail. has some weaknesses. It is not entirely clear how the enormous capacity for destruction associated with a nuclear weapon could be converted into commensurate political gains. Even with a nuclear device, terrorists could not make impossible demands. They probably could not permanently alter national policy or compel other changes in national behavior. To do so would require at a minimum that they maintain the threat and it is not clear how long this could be done without discovery or betrayal.

Sixth: The nuclear terrorists of the future may not arise from those candidates currently identified. There may be or appear individuals or new kinds of groups that have not yet been identified who might be more likely to use nuclear means to achieve their objectives. Threats to nuclear facilities or involving the malevolent use of nuclear materials may emerge on a different organizational or mental plane. Ten years ago, the members of the Lumb Panel examining nuclear safeguards for the Atomic Energy Commission, identified “terrorists” as a potential threat to nuclear programs. They did not specify who or what they meant by the term “terrorist,” and it is a little difficult to imagine today who or what they had in mind in 1967 since their report preceded the recent increase in terrorist violence. But in retrospect, their report was prophetic, for in the following decade terrorists in well-organized groups that operated internationally did become a significant problem. They are a new entity that has emerged as a major threat in the past decade, and although they have as yet given no indication of going nuclear, they potentially could. It is difficult to say now what new entities may emerge in the coming decade.

The final conclusion is that the origin, level and nature of the threat may change. Some individual or group may acquire a nuclear capability and successfully carry out some scheme of extortion or destruction that will inspire imitation. The probability of a second incident occurring, especially after a “success” would seem to be greater than than probability of the first. A terrorist group with the capabilities for acquiring a nuclear capability may be placed in a desperate situation that will begin to erode the political arguments against nuclear action. The political context may change. A war may occur in which nuclear weapons are used, inviting further use by nations and subnational groups. Plutonium could become more widely and easily obtainable owing to lack of adequate safeguards. New low technology enrichment techniques could emerge, making the production of fissionable material much easier, giving more entities the capability of producing weapons material. At some point in the future, the opportunity anti capacity for serious nuclear violence could reach those willing to take advantage of it. We do not know where that point is or how close we may be to it.

FOOTNOTES

1. Roberta Wohlstetter, "Terror on a Grand Scale," *Survival,* May/June 1976, pp. 98-104, citing Grodzins and Rabinowitch, *The Atomic Age* (New'' York: Basic Books, 1963), p. 33.

2. According to calculations of Dr. Kenneth Solomon, Rand nuclear engineer.

3. David D. Comey, "The Perfect Trojan Horse," *Bulletin of Atomic Scientists,* June 1976, pp. 33-34.

4. George Comstock, The *Evidence on Television Violence, The* Rand Corporation, P-5730, October 1976, 14 pp.

5. David L. Milbank, *Research Study: International and Transnational Terrorism: Diagnosis and Prognosis,* Office of Political Research, Central Intelligence Agency, PR 76 10030, Washington, D.C., April 1976.

6. Mason Willrich and Theodore Taylor, *Nuclear Theft: Risks and Safeguards,* Ballinger Publishing Company, Cambridge, Massachusetts, 1974, pp. 20-21.

7. Bernard Cohen et al., *Statement Before the National Council of Churches,* February 1976.

8. Ralph Lumb, et al., *Report of the Advisory Panel on Safeguarding Special Nuclear Material,* unpublished, Washington, D.C. 1967"

9. Donald R. Cressey, *Theft* of *the Nation: The Structure and Opera*tions of Organized *Crime in America, ColoPhen Books, Harper and* Row, New York, 1969.

10. Douglas DeNike, "Radioactive Malevolence," *Bulletin* of Atomic *Scientists,* February 1974, p. 18.

11. Mason Willrich and Theodore Taylor, op. cit., p. 112.

12. Ibid.

13. Brian M. Jenkins, *Will Terrorists Go Nuclear?,* California Seminar on Arms Control and Foreign Policy, Santa Monica, California, 1975 p. 10.

14. James Lovett, "Who are the Enemy," in Leachman and Althoff (eds.), *Preventing Nuclear Theft: Guidelines for Industry and Government,* Praeger, New York, 1972, p. 215.

15. Deborah Shapely, "Plutonium: Reactor Proliferation Threatens a Nuclear Black Market," *Science, 1972,* April 9, 1971, p. 146.

16. S. Burnham, et al., *The Threat to Licensed Nuclear Facilities,The* Mitre Corporation, McLean, Virginia, 1975.

17. Willrich and Taylor, op. cit., p. 112.

18. DeNike, op. cit., p. 16.

19. Jenkins, op. cit., p. 1.

20. The Japan Times, December 3, 1976.

21. David D. Comey, "Do Not go Gentle into That Radiation Zone," *The Bulletin* of *the Atomic Scientists,* November 1975.

22. State of California, Office of Emergency Services, *Nuclear Blackmail or Nuclear Threat Emergency Response Plan for the State of California,* December 1976.

23. Leon Rappoport and J. D. Pettinelli, "Social Psychological Studies of the Safeguards Problem," in Leachman and Althoff (eds.), op. cit., pp. 173-189.

24. R. B. Leachman and A. P. Cornella, *Details of Criminological Investigations of Large-Valued Thefts Related to Nuclear Material, KSU/Ds-20,* Kansas State University, under contract to National Science Foundation, June 1972,

25. C. Rogers McCullough, et al., *An Appraisal of the Potential Hazard of Industrial Sabotage in Nuclear Power Plants,* Southern Nuclear Engineering, Inc., Dunedin, Florida, July 1968.

26. The BDM Corporation, *Analysis of the Terrorist Threat to the Commercial Nuclear Industry, Vienna, Virginia, 1975.*

27. D. M. Rosenbaum, et al., *Special Safeguards Study,* U.S. Atomic Energy Commission, April 1974.

28. Testimony of Kenneth Chapman, Director, NRC, Office of Nuclear Material Safety and Safeguards, *Hearings* before the Subcommittee on Energy and the Environment of the Committee on Interior and Insular Affairs, February 26-27, 1976, pp. 145-146.

29. The BDM Corporation, *Analysis of Group Size*, Vienna, Virginia, 1975.

30. Ibid., p. 8.

BIBLIOGRAPHIC NOTES

The literature on terrorism is abundant. Government-commissioned reports, journal and newspaper articles have proliferated particularly during the last decade. Among the major analytical works referred to in this report are those described below. These do not, of course, represent a complete list.

In July 1966, the Atomic Energy Commission appointed a special advisory panel of persons outside the government to review its policies and procedures for safeguarding special nuclear material.. The seven-man panel was headed by Dr. Ralph F. Lumb, Director of Western New York Nuclear Research Center. The 121-page report of the Lumb panel, issued in March 1967, states that “Safeguards programs should also be designed in recognition of the problems of terrorist or criminal groups clandestinely acquiring nuclear weapons or material useful therein.”

Ralph F. Lumb, et al., Report of the *Advisory Panel on* Safeguarding *Special Nuclear Material,* unpublished, Washington, D.C. *1967.*

Dr. Theodore B. Taylor is a former designer of nuclear weapons. His early work for the Department of Defense identified potential non-national nuclear threats. In *1968,* Stanford Research Institute published Taylor’s Preliminary Survey of Non-National *Nuclear Threats, an* unclassified report. Much of Taylor’s subsequent reports are classified.

However, in December 1.973 Taylor’s views gained national attention through a series of three interview articles by John McPhee ("The Curve of Binding Energy," The New Yorker, December 3, 10, and 17, 1973).

McPhee’s articles were later published in a book, The Curve of Binding Energy, Farrar, Straus, and Giroux, New York, 1973.

Mason Willrich and Theodore B. Taylor, *Nuclear Theft: Risks and Safeguards,* Ballinger Publishing Company, Cambridge, Massachusetts, 1974.

Robert B. Leachman and Phillip Althoff, eds., *Preventing Nuclear Theft: Guidelines for Industry and Government*, Praeger Publishers, New York, 1972.

D. M. Rosenbaum, et al. , *Special Safeguards Study, U.S. Atomic Energy* Commission, April 1974.

The BDM Corporation, *Analysis of the Terrorist Threat to the Commercial Nuclear Industry,* Vienna, Virginia, 1975.

S. Burnham, et al., *The Threat to Licensed Nuclear Facilities,* The Mitre Corporation, Mitre Technical Report, MTR-7022, McLean, Virginia, 1975.

Annex to Appendix III-A

INCIDENTS INVOLVING LARGE NUMBER OF DEATHS 1968-1976

(Refer to Figure 5 on Page 22 of Appendix III-A)

October 6, 1976	Caribbean -- A Cuban Airlines DC-8 jetliner carrying 73 persons crashed off the coast of Barbados, killing all 73 persons aboard. The Venezuelan Government pointed an accus--finger at Cuban exiles. [Two men carrying Venezuelan passports were arrested in Trinidad. One of them allegedly confessed to having placed a bomb in the baggage compartment of the Cuban airliner. This led to the arrest of a dozen more Cuban exiles.]
September 7, 1974	Greece -- A Trans World Airlines jet bound for the United States with 88 persons aboard crashed in the Ionian Sea off Greece. The Organization of Arab Nationalist Youth for the Liberation of Palestine (ANYO) claimed responsibility for the suspected bombing which killed all persons aboard.
December 17, 1973	Italy-- At least 32 people were killed and 18 wounded at the Rome airport when five Arab guerillas attacked a Middle East-bound Pan American World Airways jet airliner, spraying it with bombs and machinegun fire, hurling hand grenades into it and setting it on fire.
May 31, 1972	Israel -- Three Japanese gunmen attacked passengers at Tel Aviv’s Lod Airport with machineguns and hand grenades, killing 25 persons and wounding 76. The gunmen were members of the URA of Japan who had been recruited by the PFLP for the assault. The PFLP claimed credit for the attack, saying that the three terrorists belonged to the Squad of the Martyr Patrick Arguello.
January 26, 1972	Sweden -- Croatian emigres claimed responsibility for the bombing of a Stockholm-to-Belgrade airliner which crashed, killing 26 persons.
February 21, 1970	Switzerland -- A sabotaged Swissair plane en route to Tel Aviv crashed on takeoff, killing all 47 passengers. The PFLP was responsible.

April 11, 1974

Israel -- Three Arab guerrillas stormed a residential building in Qiryat Shemona, killing 18 persons and wounding 16. The guerillas were said to belong to the PFLP-GC.

APPENDIX III-B

NUCLEAR NON-STATE ADVERSARY ACTIONS (NUCLEAR TERRORISM), WITH SPECIAL REFERENCE TO THE RAND CORPORATION DRAFT OF JANUARY 6, 1977*

L. Douglas DeNike, Ph.D.

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*The RAND draft of January 6, 1977 was an incomplete first draft which was subsequently revised, expanded, and edited to become Appendix III-A of this report.

This review evalutively analyzes the major issues involved in potential nuclear non-state adversary actions in relation to the Rand Corporation draft on this topic of January 6, 1977 (l).

The reviewer concludes that malevolent nuclear actions not authorized by national governments could pose quite extraordinary risks to the United States and to world order. The present report begins with clarification of matters pertaining to the definition and probability of acts of nuclear terror. It proceeds to answer reassurances contained in the Rand draft regarding the likelihood of such acts. The reviewer’s perspective on the topic follows. The latter half of this paper is devoted to specific observations on the contents of the Rand draft which are not dealt with in the earlier main text.

Most Nuclear Maleficence is Not Difficult Technically

The term “nuclear terrorism” tends, somewhat misleadingly, to connote a James-Bond sequence involving. theft of fissile material, atomic-bomb construction by subverted experts, and ultimate detonation of the device. However, many possibilities categorized as non-state nuclear adversary actions are more simple technically. The defining characteristic of a non-state action is the absence of official governmental orders. For example, a government could “leak” a nuclear explosive to a terrorist group, or military authorities could make unauthorized sales of nuclear weapons, especially under conditions of poor inventory control, such as prevail during and after wars. Moreover, nuclear weapons could be stolen and used, especially if national proliferation puts nuclear weapons in the hand of national governments who do not have the resources to guard their weapons adequately.

Also included are simple dispersals of radionuclides for purposes of territory denial and socioeconomic disruption. The most-discussed, but not the most convenient, example of the latter is the induced meltdown of a power reactor's fuel core. Hence, many kinds of nuclear terrorism do not appear to require prohibitively great resources or skills.

Probability of Successful Attempts

A meaningful answer to the question, "How likely is an event of this kind?" must be based on specification of additional particulars, such as: "By what means? " "In what country?" Involving whose nationals?" "In peacetime or wartime?" "Over what time interval?" All analysts in this field are obliged to work with unquantifiable guesses--with surmises that are not so much demonstrable as they are not convincingly refutable. This reviewer guesses that the probability is over 50%, worldwide, of a contaminative incident requiring the indefinite evacuation of one square mile or more, or nuclear explosive damage in excess of $100 million, over the span of the next five years. This probability may be expected to ascend with the proliferation of nuclear power, with the continued emphasis on such topics in the imaginative media, with media publicity given to the first major incidents if they occur, and with intensification of the global population-resources crisis (which help to create the disparate and desperate conditions by which terrorists justify their means and gain support and refuge).

Examining Rand's Guarded Optimism

Rand and this reviewer agree that a crude explosive device probably can be designed and built by some non-state adversary groups. (See also Volume I, Chapter VI). Rand adduces several arguments suggesting that these admitted opportunities might not be exploited. But dismayingly, rather good replies can be made to each:

(A) (It may not be in the interest of terrorists to induce mass casualties) This is undoubtedly true for most terrorists, most of the time. It cannot be shown true for all terrorists all of the time. Rand's Brian Jenkins has said that terrorism is perpetrated for an audience; "... terrorism is theater" (2). As Michael Flood points out in his comprehensive review of recorded malevolent acts involving the nuclear power industry (3), "... nuclear terror makes gripping theater." The more people dead, the more people watching on the news media.

Moreover, nuclear atrocities need not be equated with mass slaughter. Consider, for example, the detonation of a nuclear device at any one of a number of important sites at 3 A.M. on a Sunday morning when few people would be about. This might be calculated to damage or destroy a symbol of "capitalist imperialism" and yet to kill very few.[1] Again, to force prolonged evacuation and/or decontamination of an urban area would certainly be atrocious, yet given timely warning few casualties might be involved. Yet such an event could cause profound disruption nationwide, and considerable turmoil worldwide. The Atomic Energy Commission, it its 1974 GESMO draft environmental impact statement on plutonium recycle, calculated that the release of two kilograms

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[1] If U.S. retaliatory circuitry were programmed to respond reflexively and massively to such an event on the assumption of a Soviet attack, exceedingly many deaths could ensue. This exemplifies the possibility that terrorists might grossly underestimate the total effects of their destructive acts, or that, in the confusion of the moment, authorities might grossly overestimate the threat to the nation.

of particulate plutonium oxide at ground level would induce cancer in all inhabitants 1000 feet downwind, and in 1% of inhabitants even 40 miles downwind (4).[2]

(B) (Other, non-nuclear channels are available by which terrorists can pursue their objectives) The daily newspapers attest to the vigor with which terrorists are pursuing non-nuclear options. This behavior in itself justifies no reassurance that nuclear means will not be utilized in the future. That would require empirical analysis of terrorists' motivations and their awareness of nuclear security vulnerabilities, both of which could change in an inauspicious way as time goes on. Obviously, conventional weapons and explosives are more readily available to extremists than are fissile materials and other radioisotopes. However, such persons who were favorably situated to learn how to acquire and handle the latter materials might go the nuclear route. Access to a loose-mouthed, disgruntled, bribe-or-blackmail-vulnerable nuclear employee might tip the balance.

(C) (Terrorists might alienate their constituencies by nuclear violence or extortion) The constituency of onlookers might be enraged, but simultaneously impelled to yield in recognition of the adversaries' irresistible nuclear capability. The goal of terrorism is not necessarily to win friends, but rather to influence (possibly bitterly resentful) people that they have no choice but to accede to the terrorists' demands.

(D) (Nuclear terrorist could not handle excessively large money payoffs, nor maintain a credible threat long enough to significantly

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[2] Since evacuative dispersals (the "Seveso effect") may also be caused by non-nuclear substances such as dioxin and polybrominated biphenyls, nations in the future may be forced to choose between national defense and the health of persons working in key facilities contaminated by enemy action. This will not be an unconstrained choice. If the health hazard is manifest in obvious illness, or cannot be concealed from those in the affected zone, there may be little choice but to evacuate.

influence the policy of a national government) If such extortionists could initially establish the credibility of their nuclear devices which could possibly be transportable, they might elude capture for an extended period, as did Patricia Hearst.[3] Malefactors who convincingly claimed to be maintaining two such devices with a failsafe means of communication might threaten that the capture of one device would automatically detonate the other. The perpetrators might be expected to provide shielding which would lessen the effectiveness of searchers' neutron detectors. Unless physical descriptions of the terrorists were available, once they had hidden their devices in an area unlikely to be searched they would be relatively safe even from the outrage of an entire citizenry. As for the unwieldy weight to nuclear blackmailers of "a billion dollars in small bills," they might settle for a lesser sum, or installment payments by parachute, or credits to the treasuries of poor foreign states. If there were reason to believe the gang was not all holed up together, even an atomic bomb exploded by the victim government over their suspected backwoods hideaway would not be expected to neutralize them. And of course, attempts by authorities to capture the retrievers of extortion payments could be forestalled by advance threats to employ nuclear violence.

(E) (Terrorists sophisticated enough to utilize nuclear means, unlike common criminals, may possess a certain revolutionary humanitarianism making them loath to actually do so) The political changes sought by terrorists and guerrillas are known to require considerable bloodshed. A basically humane terrorist leader might wish to cut this short with a bloody but decisive nuclear strike. A "noble" justification can be

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[3] The "Weather Underground" group has eluded the FBI for seven years.

imagined for almost any unspeakable act, especially in the minds of warped individuals susceptible to rationalizations for butchery. All major governments have approved deeds of violence later considered to be unnecessary atrocities. Thus it should not be too surprising if extremist groups do also.

(F) (Terrorists have not signalled their willingness to go big-time by exploding gasoline tank trucks, oil tankers, chemical factories, major dams, or munitions sites; or by making nerve gas or poisoning water supplies). Attacks on intrinsically sabotageable fixed sites may be relatively unappealing since such targets may not be located in places optimal for producing disruptive effects. Or the targets may lack appropriate political symbolism, or endanger large numbers of innocent persons. Nuclear power plants would probably be an exception, since to many they symbolize an oppressive technocracy, and because the disruptive effects of electricity loss or radioactivity release would be felt over a wide area, without killing too many.

As for deadly bacteria and nerve gas, there have been reports that both have been prepared for terrorist use but that the plots were thwarted. In January 1972, Chicago police reportedly narrowly averted a scheme to introduce typhoid germs into the city water supply (5). In March 1976, gang members in Austria were reportedly arrested in possession of a quantity of poison DFP gas (6).

The foregoing discussion reveals no reason to dismiss or minimize the possibility of nuclear interventions by extremists. In assessing the extent of the danger, we might bear in mind not only some humans' tendency to borrow trouble, but many humans' tendency to be optimistic in confronting the unknown. Among professional analysts, there is an understandable tendency to “look reasonable, ” to avoid recommending expensive precautions unless the need for them is very salient, and to say to decisionmakers what one imagines they want to hear. The motive not to make waves in an organization, or not to make a fool of oneself, has led to more than one tragedy when clear signs of danger were overlooked. For example, on December 2, 1975, a radiobiologist on the train platform at Assen, Netherlands noticed seven youths bearing abnormally large gift packages. “ ...his immediate reaction was alarm,” which he stifled, and three innocent hostages were killed in the infamous Dutch Train Incident (7).

There is a strong tendency in human psychology to look on the bright side, and to ignore the evil not yet recorded as hypothetical if not purely speculative. Yet a simple mental exercise will demonstrate what many of us accept in principle, that the outlandish and unbelievable happen every week. Let the most seemingly preposterous news event of the current year be mentally framed as a prediction, and the prediction imagined as issuing from the mouth of some prognosticator of the previous year. Who would have dared to predict the actual course of the Watergate investigations? Who would be listened to if he speculated that a man “who wanted to tell the world his views on the dangers of tobacco” would hold “a man hostage for more that two hours at the top of the tallest building in Los Angeles” (8)? Who would forecast that Croatian nationalists would “hijack” the front pages of several major newspapers to publicize their obscure cause (9)? The reviewer hopes that the nation shall if possible avoid the dangers of unjustified optimism or unvoiced misgivings -- which later might be called the <u>stiff upper brain syndrome</u>.

A Perspective on the Topic

This reviewer defines a counterconspiratorial public-safety policy as one which seeks actively to anticipate possible disruptive malevolent events and to prevent, respond to, and recover from them. Such a policy may have undesirable consequences if the scenarios imagined or the precautions taken become self-fulfilling prophecies by firing the imaginations of evildoers. Counterconspiratorial policies are also expensive and run against the grain of free societies' thinking; even law-enforcement agencies do not relish such contingency planning.

However, a tacit reliance on minimum precautions and crossed fingers also bears risks. Such confidence seems to assume that rapidly proliferating new knowledge in nuclear physics, toxicology, and molecular biology will be much less appealing to public enemies than it is to the television writers who continuously suggest new malevolent schemes to a large and diverse audience. It further assumes that the first instances of a new terror technology (e.g., plutonium dispersal) will neither inspire imitators in such numbers as to overstrain the response capacity of government, nor will those first instances in themselves disrupt that response capability by attacking key administrative nerve centers.

The present and largely unarticulated public-safety philosophy of the United States and other democracies should be viewed as having wishful and frangible features. Up to the present time, the costs of unpreparedness have been sustainable. Next year, they may no longer be. One may reserve the term "ultrafrangible" for policies and programs the first clear sign of whose inadequacy is their total failure. The Teton Dam exemplifies an expensive and elaborately planned structure which proved to be ultrafrangible.

We have no proof that the American-Soviet mutual-assured-destruction nuclear deterrence system is not ultrafrangible. The same may hold for low budget, low-profile preparedness against nuclear terrorism.

A quest for inordinate coercive/destructive power almost defines potential nuclear terrorism. Small groups or possibly even individuals could assume powers vastly disproportional to those they customarily possess. Governments are still unaccustomed to the idea of gigantic forces being manipulated by small numbers of desperados. This, in conjunction with the aforementioned tendencies to minimize unrealized threat possibilities, leads to a lack of adequate contingency and response planning.

Even if planners have substantial motivation to provide against non-governmental acts of nuclear violence and coersion, they may not find their way clear to do so. As they start to compile vulnerabilities and modes of possible attack, they may find themselves writing an encyclopedia for atomic terror, which might have to be kept at an unusefully high level of security classification.

The concept of “Catalytic war” refers to the initiation of armed hostilities between countries X and Y by a deceptive destructive act perpetrated by Z. At some future time, the leaders of a third country might perceive it in their interest to foment war between the United States and the Soviet Union. If an important fraction of an urban area in the U.S. were to disappear beneath a mushroom cloud one day, the U.S.S.R. would quickly become aware of what had happened. The U.S.S.R. might assume that the U.S. would have no choice but to presume U.S.S.R. origin or instigation for the event. That assumption could lead directly to the Soviets’ launching a pre-emptive nuclear attack on the U.S. in order to lessen the blow from the U.S. retaliation for the original act. So pitilessly might history record our joint failure to recognize the fragility of bipolar deterrence theory based on “rational “ adversaries. The many weaknesses of deterrence have been elegantly spelled out by David Krieger (10) and Louis R. Beres (11).

Planners considering such an eventuality confront a dilemma. There may be no time to safely conduct an investigation, unless there are excellent grounds for reaching a quick understanding with the Soviets. But what can be said publicly in advance? If the U.S. should announce that it <u>will</u> retaliate against the U.S.S.R. without pausing to ascertain the bomb’s origin, we tempt would-be initiators of catalytic war. If, on the other hand, the U.S. makes it clear that it will <u>not</u> attack the Soviet Union until N bombs have gone off in American cities, it virtually invites anyone to detonate <u>N-1</u> devices of mysterious origin “for free”. Even if classified rather than open plans were drawn up to cope with this impasse, there would be constant dread that these plans might unawares leak to potential adversaries, conferring an enormous strategic advantage to them.

Hence, there is a possibility that <u>single</u> acts of nuclear terror could set in motion much larger and far-reaching responses and counter-responses. Recognition of this state of affairs is dulled in part by the bias toward optimism that stems from the very fact of our still being alive as individuals. All persons who are not now dead have experienced an uncanny amount of good luck. Those who got bad shakes of the dice are no longer with us.

The foregoing discussion provides the basis for an emergent principle in international relations, to wit, the absolute intolerability of translational nuclear terrorism. We see that the origin of such atrocities possibly could not be determined with sufficient promptness and reliability. Thus the line is blurred between such acts initiated covertly by foreign governments, and identical acts committed by fanatics without government sanction. Any barbarous deed could be assigned by a foreign state for commission by a trusted radical team, and the connection disavowed if the extremists were captured or identified. This kind of hand-washing would be intolerable to victim states. They would demand scrupulous adherence to the idea that nation-states have an absolute duty to prevent the incipient nuclear terroristic behavior of their own nationals from being exported beyond their own borders. Presumably, nations would wish to quell it within their borders as well.

If national governments come to be held accountable for nuclear blackmail or violence in another state traceable to their own citizens, it is plausible to expect attempts to diminish personal and civil liberties worldwide. Governments and citizens may then become locked in the familiar circle of repression and resistance.

Acts of nuclear aggression, because they can anonymously inflict massive losses on national governments have a potential altogether different from the maximum to be expected from today’s violent political episodes. It is a fundamental error to view atomic terrorism as merely a more serious type of deed of the kind to which we have grudgingly become accustomed . The threat of nongovernmental nuclear force, like governmental nuclear force, places unprecedented demands upon the assumptions underpinning present world order.

Attaining Closure on Sustainable Nuclear Policy:

Capitalization on Events Conducive to Internationalization of Energy

Many countries lack adequate fossil fuel reserves, and are presently incapable of substituting non-nuclear energy options. Such states may be expected to build nuclear electricity generating stations if they can afford them. Indeed, some countries may be willing to pay a premium price in order to acquire either the prestige or the weapons options (or both) implicit in such facilities. Thus at least until some dramatic occurrence, we may expect nuclear electricity units to be erected in such countries.

For the immediate future, United States policy could be based on the assumption that a global phaseout of either nuclear weapons or fission power is temporarily infeasible. However, breakthroughs in alternative energy sources, or achievement of suitable international agreements to share fossil fuels, or perhaps a nuclear tragedy will sooner or later enable the inception of denuclearization.

Countries obviously intent on joining the nuclear weapons club will need additional positive and negative inducements. The United States could take the lead in fostering new frameworks of regional security, that would damp down or eliminate A-bomb rivalries. Coordinately, we might be able to export some of our 200-year supply of coal as well as our rapidly accumulating expertise in energy efficiency and non-mineral (sustainable) power options.

If a threat or an actual commission of an act of nuclear violence occurred, the federal government could capitalize on the event to jawbone for gaining freedom from reliance on nuclear weapons and fission-generated electricity. At the same time, we can take two steps dramatizing our plight and furthering movement toward a post nuclear world energy order,

The first is to bring American nuclear exports to a close. A current unexamined premise is that U.S. withdrawal from the role of reactor vendor overseas would deprive this country of any leverage against the proliferative activities of other nations. American leverage against such proliferation inheres in our total national ability to aid, protect, substitute other energy sources, and administer sanctions. It does not depend on our participation in any given trade activity. A policeman who doesn't drink may still arrest a drunken driver. Nor will the salubrious effect of positive example by the United States be lost on other nuclear trading states.

The second interim goal is to upgrade the International Atomic Energy Agency inspectorate to a true international police force with power to arrest. This possibility will seem much less visionary following the first major event of nuclear maleficence. While it will take time and effort to emplace, and logically should be accompanied by an international judicial body to try offenders, its achievement will someday be seen as logical, natural, and inevitable."

A start toward realization of these objectives has already been made . Alternative energy sources are undergoing intensive development, and energy conservation is about to have a significant impact. Diplomacy is cheaper than either bombs or wars, so the taxpayers should welcome regional alliances which reduce the need for both. The U.S. is already exporting coking coal, and soon may be exporting Alaskan oil. Both the outgoing and the incoming federal administrations have given intensive thought to the nuclear-export question. That leaves only the upgrading of IAEA, which may have to await a conspicuous failure in the latter as presently organized. As Abba Eban said, people will do the sensible thing once all other alternatives have been tried.

Reviewer Comments
on Rand First Draft

Specific Observations on the Rand Corporation First Draft of January 6, 1977

> This first draft was provided by Rand's Brian M. Jenkins. Direct quotation has not been used here, in anticipation of further revision. However, material which follows the conjunction "that" is usually a direct quotation from the draft. While these comments necessarily focus upon differences, reviewer concurs with the bulk of the first draft.

Introduction: A distinctly misleading impression is given by failing to mention the variety of malevolent events later taken up in Section VI. A reader not familiar with the literature documenting multifarious illegal acts connected with the nuclear industry could readily conclude from this introduction that all is well.

Introduction (page 2): Rand sees disgruntled employees as capable of low-level sabotage. A seriously disgruntled or demented employee could cause damage, as witness the $10 million Indian Point arson incident and the $50 million accidental fire in the cable spreading room at Browns Ferry (12).

Section 11 (page 6): There is an unfortunate tranquilizing tone in the statement that people have come to accept the presence of nuclear weapons and have grown accustomed to living with the possibility of nuclear war, and that one nation more or less with nuclear weapons does not seem to make that much difference. India's entry into the nuclear club made a substantial difference, inasmuch as it concretely illustrated the tie between imported nuclear technology and indigenous weapons development.

Section 11 (page 7): The language of this section tends to suggest that nuclear terrorism is a bogeyman invented by nuclear critics. Yet elsewhere in the draft Rand concedes there is reason for doubt and fear.

Section 11 (page 8): Draft avers that there is no convincing evidence that violence on television or in the movies causes people to be violent. This statement is in conflict with studies on media-induced imitative aggression conducted by Professor Albert Bandura and others (13).

Section II (page 9): Reviewer concurs that some loss of confidence in political and economic institutions has occurred. The lagging performance of the criminal-justice system in particular may embolden potential nuclear thieves or saboteurs.

Section 111 (page 15): Rand notes that a hijacking or hostage incident may be in the news for days, even weeks. Contamination and disruption following a nuclear atrocity could be expected to yield a continuing flow of publicity attractive to potential perpetrators. Note the intense coverage given to the extended evacuation of several hundred acres of Seveso, Italy by dioxin dispersal (roughly analogous to urban release radionuclides or the fallout from a fission bomb). In less than a month, the Los Angeles Times carried nine stories on the event and its aftermath (July 26, 27, & 31; August 3, 6, 7, 13, 14, & 21, 1976).

Section 111 (page 15): Rand states here that terrorist violence is trivial compared to the world volume of violent deaths. In its immediate context this statement is misleadingly reassuring. More realistic measures of the impact of terrorism would be the cost to authorities of guarding against and fighting terrorism, the costs of ransoming kidnap victims, rehabilitating people and buildings affected by bombings, etc. Rand acknowledges elsewhere in the draft that body counts are not the measure, and that terrorism will continue to require a major diversion of resources into internal security functions, (e.g., p. 16).

Section IV; The most serious motivation for nuclear sabotage by a non-state adversary may perhaps be found among fifth-columnists or self-styled guerrillas, sympathetic to the aims of a hostile foreign government but still acting on their own initiative.

Section IV (page 17): It is distinctly bold to state that there is no discernible trend toward nuclear action. If we assume that the same mind-sets that yield nuclear hoaxes, small-scale bombings at European reactor sites, and thefts of isotopes could also predispose to major actions, then the great increase of such events in the 1970's is cause for substantial concern. Rand documents the increase in U.S. incidents in Figure VI-1 (p.38), then dismisses it as probably due to better reporting.

Section IV (p.23): Another significant statement by Rand is that at present, we can do no more than speculate about the types of demands non-state adversaries can, cannot, are most likely to make. Rand's appropriate statement here does not prevent unconservative speculation elsewhere in the draft that several types of threats are unlikely. This is a topic on which policy analysis is considerably less expensive than policy failure. Thus it would seem best to err on the side of inclusiveness -- to entertain all categories of possible threat until there is greater than speculative reason to exclude some of them from consideration.

Section IV (p. 23): The closing statement contradicts the principle which reviewer applauded in the immediately preceding comment. Now Rand's viewpoint seems to be that if terrorists have in the past used non-nuclear means to obtain a given type of goal, other terrorist will not use nuclear means to obtain a similar-level goal in the future. If terrorists were that successful at getting what they wanted by non-nuclear means, they would have long ago traded in their submachineguns for thrones. obviously they are still motivated to find more effective means of coercion and media coverage.

Section IV (p.24); Whether nuclear extortionists could semi-permanently alter national policy depends on their ability to elude capture, which in turn depends on their transportation, shielding from detection> etc. See reviewer's main text under point D. While they could not "persuade" a government to liquidate itself, they could directly liquidate its key leadership or effectively exile it from its capital city. In so doing, they would probably be precipitating chaos and/or military rule, but they might be willing to accept either condition on an interim basis, until they had gathered enough strength to pursue takeover.

Section IV (P. 24): Here Rand seems to be addressing an absent audience of potential terrorists of the "lunatic fringe", telling them that their goals cannot be met by demands Rand considers irrational. A large percentage of violent and extortive behavior seems irrational to one or another observer, but not to those who engage in it. Nor do we automatically call the bluff of every hostage-taker who looks like a mental case.

Section IV (p. 25): Rand states that because of the publicity factor, any terrorist believed to have a nuclear device is automatically a successful terrorist. The reviewer tends to concur, and points out how this short-circuits most counter-arguments as to whether the terrorists might not have the motivation to actually use the device.

Section V (p. 33): Reviewer is listed as the only observer espousing the view that crackdowns on organized crime following nuclear theft operations might be deterred with a nuclear threat. Yet on page 30, Willrich and Taylor (15) are quoted as saying, “A criminal organization might use the threat of nuclear violence against an urban population to deter police action directed against its nuclear theft operations.” Willrich and Taylor argue, as does Rand, that a criminal gang would probably not survive a showdown with the government. However gangs as well as nations have been known to engage in unsuccessful brinkmanship leading to their downfall. Moreover, national governments might initially not feel impelled to challenge in an all--out way small-scale nuclear thefts conducted by criminals, if it appeared that the stolen fissile material was being sent abroad.

Section V (p. 33); Here Rand seems to be addressing the Mafia, as on page 24 it addresses the lunatic fringe. It is expounded unequivocally that any involvement in nuclear action will inevitably result in a war that organized crime will not survive. The Mafia, knowing the ease of hiding and transporting stolen goods, and the authorities’ reluctance to conduct a “war”, might not agree.

Section VI (p. 37): Rand cites the Vermont Yankee incident as involvint the only casualty recorded. If foreign events are included, the takeover of the nuclear station under construction at Atucha, Argentina (March 25, 1973) warrants mention. In that event the guerillas wounded two policemen as they excaped (14).

Section VI (p.39): Reviewer concurs that the India-Nepal uranium smuggling scheme reveals the potentiality for an international black-market for nuclear material. Thus, stolen nuclear material could be smuggled into this country, possibly by organized criminals (see section V). It is debatable whether the first large theft of weapons material will adequately admonish other nations to buckle down, since its occurrence may well be kept tightly secret. A large ransom could be paid without the taxpayers knowing it.

Section IX (page 67); Rand states that is is a breathtaking inferential leap from non-nuclear to potential nuclear actions, implying that analysis of sophisticated non-nuclear crimes may not be fruitful. Reviewer disagrees. What is indeed breathtaking is the amount of resources, planning, and personnel involved in some nonnuclear crimes.

Section VII (page 54): Reviewer agrees it is not difficult for terrorists to assure that the general public is alerted to their nuclear threat. They could take over a broadcasting station, drop leaflets from a high building, mail warnings to randomly selected addresses, etc. Official attempts to discredit the threat could be overcome to some extent by release of radionuclides at important locations, with warnings issued to evacuate and decontaminate.

Section VII (p. 55): The assumption in this table that hoaxes have low coercive power manifestly depends on the authorities' ability to quickly, accurately, and credibly identify them as hoaxes. Bank robberies and at least two aircraft hijackings have been successfully carried out with simulated explosives, the most recent example of the latter being the Croatian nationalists incident (21).

Section VII (p.59): Here it is stated that major problems of prolonged large-scale evacuation have not been worked out While this discussion refers specifically to urban areas threatened by a nuclear explosive, the same lengthy set of problems would be encountered consequent to the accidental or induced meltdown of a nuclear power reactor.

Section VIII: The dilemma of a "no ransom" posture arises in connection with nuclear-blackmail The Wall Street Journal notes that this country has consistently adopted a hard line with terrorists, refusing to bargain with them or to meet demands. "There would be no end in sight if we started paying ransom every time a United States official was kidnapped -- it would be an open invitation to the U.S. Treasury," says L. Douglas Heck of the State Department's Office for Combating Terrorism (22). For example, in the French "sewer gang" robbery of the equivalent of $8-$10 million from a Riviera bank vault, the operation involved 18 months of planning and the recruitment of about 20 specialists (16). The mastermind's share of the loot reportedly went to "an international group of extreme right-wing militants identified as 'LaCatena'." A study for the NRC by International Research and Technology Corporation describes the particulars of ten very impressively designed criminal incursions (17).

Section VII (p. 48): The assumption that necrologic or bacteriologic agents may be more available to the general public than nuclear material may be due for revision. In the summer of 1976, the NRC gave approval for the wide-scale use of plutonium-238 cardiac pacemakers, anticipating a U.S. market of 10,000 units (18, 19).

Section VII (p. 51): Rand should be encouraged to explore in greater depth the implications of threats against capital cities in nuclear hoaxers' demands. Reviewer suspects that the real nuclear terrorists of tomorrow will present demands not unlike the nuclear hoaxers' threats of today.

Section VII: Dispersal of radioactive particulate is noted to be a less-popular threat option among nuclear hoaxers, who can claim possession of a hydrogen bomb just as cheaply. However, the socioeconomic disorder which could be inflicted by radiologic weapons is cause for very grave concern. The costs of evacuation, decontamination, and reoccupancy, especially if the interiors of buildings are compromised, "could run to many millions of dollars per gram of plutonium used" (20). Consider also that an inadequately designed plutonium implosion bomb, whose high-explosive component detonates but produces no nuclear yield, is still a plutonium dispersal device.
However, Willrich and Taylor warn, "If a government has made payoffs as a result of credible hoaxes, but not recovered any devices, it may establish a policy of no more payoffs. This could create a situation of extreme danger. The next credible bomb threat might be the real thing, and a nuclear catastrophe would be the probable result" (23).

Section IX: Rand's statement that no methodology has been developed to predict the occurrence of an event that has not occurred is not strictly true. Probability theory and pooled-opinion forecasting such as the Delphi method can be brought to bear on the likelihood of nuclear terrorism of various kinds. Reviewer is not aware that this has been done by anyone not potentially biased by an occupational or ideological commitment to fission power.

Section X (p. 76): Reviewer applauds the excellent reasoning here ragarding the unrealism of relying on rapid outside law enforcement agencies for response from offsite in the event of an attack on a nuclear facility.

Section XI: The potential for curtailment of civil liberties and democratic traditions inherent in nuclear-coercion countermeasures is discussed in two detailed reviews on these topics. These are Russell W. Ayres, “Policing Plutonium: The Civil Liberties Fallout, “Harvard Civil Rights-Civil Liberties Law Review, Vol. 10, 1975, pp. 369-443; and Michael Flood & Robin Grove-White, Nuclear Prospects: A Comment on the Individual, the State and Nuclear Power, 64 pp.; Friends of the Earth (England) in association with the Council for the Protection of Rural England and the National Council for Civil Liberties, 1976. (See also Appendix III-C of this report). Rand’s discussion here is by comparison but touching the tip of a very large iceberg. Recall reviewer’s expectation earlier in this review of attempts to strikingly diminish personal and civil liberties worldwide.

Rand discusses post-employment surveillance of former nuclear employees (p.85). Consider also that the U.S. has thousands of nuclear warheads (24), yet continues to add to the stockpile. Perhaps this is not unrelated to the disquieting question, “Can you safely lay off persons who know how to make bombs?”

References

1. Rand Corporation non-state adversary draft of January 6, 1977

2. B. M. Jenkins, "Will Terrorists Go Nuclear?" California Seminar on Arms Control and Foreign Policy Discussion Paper No. 64, October, 1975, p. 13.

3. M. Flood, "Nuclear Sabotage". Bulletin of the Atomic Scientists, October, 1976, p. 30.

4. U.S. Atomic Energy Commission draft Generic Environmental Statement on Mixed Oxide Fuel, WASH-1327, August 1974, Vol. 4, p. V-48.

5. L. Ponte, "Tomorrow the Terrorists May Hijack New York City," Gallery, February 1973, p. 53.

6. "Austrian Police Nab Poison-Gas Producers," Ottawa Citizen, March 2, 1976.

7. W. Mathewson, "The Terrorists: Bitterness Surrounding Dutch Train Hijacking Lingers a Year Later, Wall Street Journal, January 6, 1977, p.1

8. T. Paegel, "Gunman Holds Hostage Atop Skyscraper," Los Angeles Times, December 7, 1976, p.1.

9. "Text of Demands, Letter," Los Angeles Times, September 11, 1976, p.1.

10. D. Krieger, "The Dangers of Deterrence," The Progressive, October 1974, pp. 34-36.

11. L. R. Beres, "Nuclear Quills," Bulletin of the Atomic Scientists (letter), December 1976, pp. 4-5.

12. D. D. Comey, "The Incident at Browns Ferry," Not Man Apart, mid–September, 1975, Insert.

13. A. Bandura, Social Learning Theory, Prentice-Hall, 1977.

14. S. Burnham (Ed.), The Threat to Licensed Nuclear Facilities, MITRE Corporation, McLean, Virginia, September 1975, p. 47.

15. M. Willrich & T. B. Taylor, Nuclear Theft: Risks and Safeguards, Ballinger, 1974, p. 112.

16. "Chief of 'Sewer Gang' Confesses," Los Angeles Times, October 30, 1976, p.1.

17. Estimates of Security Personnel Required to Protect Nuclear Fuel Cycle Components Against Theft of Special Nuclear Materials and Sabotage, International Research and Technology Corporation, Arlington, Virginia, August 21, 1975. Appendix B.

18. “PU Pacemakers Okay,” *Nuclear News,* September 1976, p. 69.

19. U.S. Nuclear Regulatory Commission, *Final Generic Environmental Statement on the Routine Use of Plutonium-Powered Cardiac Pacemakers,* NUREG-0060, July 1976, p. 3-1.

20. Willrich & Taylor, op. *cit*., p. 108.

21. “Hijackers Returned to N.Y. to Face Charges,” *Los Angeles Times,* September 13, 197, p.1.

22. J.A. Tannenbaum, “The Terrorists: For World’s Alienated, Violence Often Reaps Political Recognition,” *Wall Street Journal,* January 4, 1977, p.1.

23. Willrich and Taylor, op. *cit*., p. 110.

24. “30,000 U.S. Nuclear Weapons,” *The Defense Monitor,* Vol. 4, No. 2, February 1975, p. 1.

APPENDIX III-C

CIVIL LIBERTIES IMPLICATIONS OF U.S. DOMESTIC SAFEGUARDS

Alan F. Westin

APPENDIX III - C CIVIL LIBERTIES IMPLICATIONS OF U.S. DOMESTIC SAFEGUARDS

Introduction: The Civil Liberties Context of Nuclear Power

Civil liberties issues have recently moved to a prominant position in the public consideration of nuclear power development. This growth of concern over the impact of nuclear power on civil liberties would probably have occured even without consideration of plutonium reprocessing. As incidents of non-nuclear terrorism have mounted world-wide, and as assaults have been made on nuclear facilities in several countries by various radical groups, there has been an increased program to safeguard such facilities from actions such as sabotage and deliberate release of radioactive materials. Such increased security measures raise some issues of civil liberties impact. But it has been plutonium recycle or other nuclear technologies (such as high temperature gas-cooled reactors) using material that could, if diverted, be made into nuclear explosives-- that has set off the current debates.

Plutonium reprocessing offers the greatest opportunity for potential non-state adversaries--terrorist groups, profit-oriented criminal organizations, deranged persons, or disaffected employees of nuclear facilities--to obtain special nuclear material. Therefore, this paper devotes its major attention to the civil liberties issues likely to be raised by safeguards measures necessary to prevent the theft of plutonium and to effect its recovery if it were stolen.

To analyze the potential impact of plutonium recycle on civil liberties, this presentation will be divided into five parts:

A. A General Perspective on Civil Liberties Issues.

B. Projections of the Size of the Plutonium Recycle Industry.

C. An Analysis of Likely Safeguard Measures and Their Civil Liberties

Consequences.

D. A Presentation of Three Positions Widely Held in U.S. Society as to the Civil Liberties Risks of Plutonium Recycle.

E. Observations and Comments on the Three Positions.

A. A General Perspective on Civil Liberties Issues

U.S. society has always had a fundamental commitment to civil liberties. It was part of the heritage from England, a rallying cry of the American Revolution, and the foundation for enacting the Bill of Rights and other constitutional guarantees. It has been a vital part of continuing efforts to expand and perfect democratic institutions under changing social and economic conditions. U.S. society today takes it as an article of faith that the enjoyment of liberty is vital to individual happiness and self-realization, to the conduct of socially valuable activities of private groups and associations, to the keeping of governmental power within proper bounds, and to the ethical and moral basis for public order, both at home and as the U.S. acts abroad. In both legal and social perspectives, American society recognizes that civil liberties must be exercised within the framework of an ordered society. Some civil liberties will therefore receive very broad, near-absolute status, such as the right of religious belief and exercise. Other civil liberties involving greater impact on the rights of others, on public health and safety, or on national security, have to be defined and applied in the context of balancing conflicting social interests or even conflicting civil liberties claims. But when such balancing of interests is done, whether by legislatures, executive agencies, or courts, Americans like to think that the claims of liberty carry special weight , so that serious limitations upon them must be shown to be clearly necessary, and to have been kept to the minimum required in a given circumstance.

It is in this broad context that debates have begun over the effects on civil liberties of measures to safeguard a future plutonium industry from assault or diversion.

Since the term civil liberties can be viewed in many different ways, it is helpful to this inquiry to note that protection of individual and group rights in American law and social values can be organized under three headings: liberty, equality, and fair procedure.

In a capsule, liberty refers to rights of expression and privacy. More concretely; this involves the guarantees of free speech, press, assembly, association, religious and non-religious exercise, and privacy that are embodied in the First Amendment to the Federal constitution and its state counterparts. Rights of liberty involve primarily volitional acts of individuals, things they have chosen to say, do, or be as part of their exercise of freedom.

Equality rights, usually expressed as rights to equal protection of the laws, deal with characteristics of people that are largely involuntary, such as race, nationality, sex, religious inheritance, and age. Growing out of the post-Civil War Amendments to the Federal constitution, their recent interpretation by the Supreme Court, and a growing armory ’of protective state and Federal laws and regulations, the equality principle forbids governmental and private discriminations that make invidious distinctions about individuals on the basis of characteristics that society has decided are not appropriate for those treatments. What is or is not an appropriate distinction is a judgment that varies over time, reflecting social values.

The guarantees of fair procedure, often called procedural due process, encompass two major dimensions of importance here. The first is that investigations, searches and seizures, arrests, interrogations and other police functions must be conducted in accordance with constitutional limitations, as judicially interpreted. Principally, this involves the procedural-rights guarantees of the Fourth through Eighth Amendments: the security of persons, houses, papers, and effects against unreasonable search and seizure; the privelege against self-incrimination; the right to counsel; and similar protections of individuals against arbitrary or coercive police practices.

The second aspect involves formal proceedings where sanctions are sought to be imposed on an individual or might lead to imposing penalties (such as criminal trials, government personnel security hearings, and legislative hearings). Here, the civil liberties requirement is that basic fairness be provided in the proceedings, a concept that has come to mean several key elements:

1. advance communication to the individual of behavioral rules that must be followed to avoid legal penalties.
2. if charges are made against the person, a fair hearing for adjudication of those charges (with rights to have a specification of the charges, to be represented by counsel, to hear witnesses and conduct cross-examination, etc.)
3. an appeal to a higher authority, for review of the initial hearing.

The amount of rigorous due process that individuals can demand varies with the context, but in virtually every setting of American organizational life, private as well as governmental) public expectations are that procedural fairness will be afforded.

Applied to the nuclear safeguards problem, it is the areas of liberty and fair procedure that would be most directly involved.

As briefly noted already, guarantees of civil liberties while they properly occupy a fundamental place in the U.S. ideological and legal system, are always matters of definition in context and must be weighed against competing values. The words used by the Framers of the eighteenth century Bill of Rights always need interpretation to apply them to new economic, social, and technological settings. Rights not mentioned in the constitution, such as freedom of association and privacy, have been read into the constitutional-rights code as these have come to be seen as necessary adjuncts to the protection of First Amendment rights. Sometimes, one civil liberties claim collides with another, as with free speech and privacy, or free press and fair trial, and courts must decide which right is to prevail in a given situation. Finally, judges must often weigh assertions of civil liberties against the protection of other fundamental social values in organized society-- such as public health, national security, public safety, to decide which value will be considered paramount in a given situation.

Thus, in each era there has been a struggle by governmental authorities, interest groups, dissenters, and other actors in the political and legal processes to define what exercises of liberty are vital to a democratic society at that time. There is also a struggle over whose characterization of the alleged threats to order, safety, health, or morals should prevail in defining limits on rights. Decisions about many civil liberties matters therefore inescapably involve judgments about social values, institutional philosophies, and the meaning of contemporary national and international events.

What follows from the” above points is that issues of civil liberties risks, options, and trade-offs should be seen as presenting elected officials and the American public with <u>policy choices</u> that must initially be worked out in the regulatory and legislative processes. These choices should be informed by an awareness of constitutional principles and their judicial interpretation but, of necessity, decisions here will be less circumscribed by clear law or predictable judicial responses than in most other governmental programs affecting civil liberties. For reasons that will be detailed later in this report, courts cannot be expected to play an immediate role in the judgment about the compatibility of adequate plutonium safeguards and preservation of a free society. This makes the quality of public debates and legislative/ regulatory decisions of exceptional importance.

Furthermore, even though courts may rule, sometimes reluctantly, that certain governmental or private actions do not violate the constitution, this does not mean that such measures are also wise policies for a democratic society. Courts only say what is the minimum that the constitution requires. This leaves entirely open for public debate and legislative judgment what further protections represent the best social policy to adopt.

B. Projections of the Size of the Plutonium Recycle Industry

When the consideration of civil liberties and a plutonium industry entered what might be called its first phase, in 1974-76, both critics and supporters of plutonium recycle based their arguments on projections that envisaged a very large plutonium industry by the year 2000, and especially by 2020.

In 1976, the chairman of the Nuclear Regulatory Commission (NRC) said that 205 nuclear reactors burning recycled plutonium could be completed in the United States by 1985, if licensing went forward at that time. l-/ By the year 2000, there were expected to be 2,000 nuclear reactors worldwide, producing and burning 2 million pounds of plutonium a year. ~/ The plutonium recycle industry was expected in these projections to reach maturity about the year 2020. Projections for that date assumed there would be some 60 fabricating plants and 2,000 reactors in the United States, with 100,000 shipments per year of special nuclear materials between fabricating plants, reprocessing plants, and storage sites. ~/ Workers and guards in the nuclear plants and those needed to transport and store plutonium were projected to constitute a plutonium work force of over 1 million persons in 2020.

These projections have been scaled downward sharply in the past year, reflecting a variety of factors. The following Table, drawn from the Final Generic Environmental Statement on the Use of Mixed Oxide Fuel (GESMO), indicates the current projections of components for a Light Water Reactor industry using uranium and plutonium recycle.

According to the GESMO assumptions, by the year 2000 there would be 507 light water reactors and 30 plants for fuel conversion, enrichment, fabrication, and reprocessing. The 1976 GESMO estimated that these facilities in the year 2000 would employ 27,000 people in the fuel cycle and 55,000

Table 1

THE PROJECTED LWR INDUSTRY, 1980-2000* WITH U AND Pu RECYCLE

LWR Industry Components	Number of Facilities		
	1980	1990	2000
LWR'S*	71	269	507
Mines**	416	1,856	4,125
Mills	21	56	77
UF6 Conversion Plants	2	4	5
Uranium Enrichment Plants	3	3	5
U02 Fuel Fabrication Plants	6	6	7
Reprocessing Plants	1	3	5
MOX Plants	1	3	8
Federal Repositories for Storage	0	2	2
Plutonium Shipments in metric tons**	5 tons	273 tons	1,170 tons
Commercial Burial Grounds	6	6	11

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* From Table S-10 of Final GESMO NUREG-0002, Vol. 1 Summary.

** From Page XI-35 of Final GESMO NUREG-0002.

people in the nuclear electrical production industry. Of these people, a maximum of 20,000 would be in positions that would require employee screening as currently used for security clearances, but perhaps only 13,000 would require such screening if the definition of sensitive positions was made on a restrictive basis.

As for the size of the employment force needed to transport special nuclear material between fabricating plant and reprocessing plant, and the safeguards problems such transportation would raise, this has become a matter of uncertainty rather than firm projection. If the decision were made to co-locate fabricating plants and reprocessing plants, this would eliminate the need for shipment off-site of pure plutonium. Coprecipitation of plutonium oxide and uranium oxide at the reprocessing plant would also eliminate transportation of pure plutonium.

Similar kinds of technological possibilities different than those currently being discussed are under consideration for dealing with storage of radioactive waste, including some that might reduce greatly the problem of safeguarding storage sites.

The basic point to draw from the 1976-77 revisions of earlier projections for a plutonium industry is that the size and distribution of such an industry is now seen as being much smaller than when the civil liberties impacts were first examined, and with several major technological aspects as yet uncertain or open to choice, rather than being technologically determined. How much this affects the essential civil liberties problems, and the main competing positions on these issues, will be discussed later.

C. An Analysis of Likely Safeguards Measures and Their Civil Liberties Consequences

1. Current Safeguards Measures for Nuclear Powerplants

There are Federal laws that forbid the unauthorized possession of special nuclear material, or efforts to obtain it illegally.[4] providing security against diversion, theft, or sabotage of special nuclear materials during production, transportation and storage has been part of military nuclear operations for three decades, and civilian reactor programs since 1957.[5] Although the standards and procedures of safeguards programs have undergone significant changes in these decades, and particular threats have also shifted, the basic elements of nuclear safeguards programs have remained fairly constant. These involve techniques to safeguard sites from internal or external threats such as the following:[6]

1. Personnel security: (Applies chiefly to the military programs): Investigation of persons applying for jobs handling nuclear material to assure their reliability and loyalty and monitoring their continued stability after employment.
2. Intrusion control: Protecting physical sites and transportation facilities from assault, theft or sabotage using a combination of guards, detection and alarm systems, and outside response forces.
3. Physical access controls: Limiting worker and visitor entry to persons with clearances and need-to-know-purposes, and setting special access controls for certain extra-sensitive locations within nuclear facilities.
4. Physical inspections and surveillance: Searching of persons and objects entering the facility to prevent the introduction of improper materials or removal of protected materials, and on-the-job physical surveillance techniques.
5. Materials accountability: Employing devices to measure, on a regular basis, the amount of nuclear materials present in operations or shipment, and to detect losses or unexplained shortages.

6. Preventive intelligence: Collecting intelligence about terrorist organizations, radical protest groups, criminal elements, and other potential assailants, to gain knowledge with which to forestall or be prepared for diversion attempts.

Current safeguards techniques also include security for transportation of special nuclear-material in special vehicles and under guard forces. Finally, there are diversion response plans for tracing, locating, and recovering nuclear materials that may be stolen surreptitiously or seized by force, or for responding to blackmail demands by successful diverters.

Protection of private power reactors proceeded in the 1950's and 60's from the awareness that most plants were using low-enriched nuclear materials that could not be used to make nuclear explosives. For those plants producing and storing plutonium, highly enriched uranium, and uranium 233, the growing awareness in the 1970's of threats from domestic or foreign terrorist groups, and several incidents or threats to nuclear plants, led to a major expansion of safeguards in 1974-76. However, the effectiveness of these measures has been criticized, and official safeguard requirements have recently been increased.7/

Much the same picture is involved in safeguarding worldwide nuclear power activities today. When the United States exports nuclear materials that could be diverted to produce explosives, it imposes physical security requirements on the recipient countries and has indicated that it uses team-inspections to assure that these are adequate.8/ In addition, the International Atomic Energy Agency (IAEA) has a safeguards program based on deterence of diversion and early detection of diversion attempts, with this program accepted by IAEA member States.9/ The adequacy of both the U.S. and IAEA programs has also been criticized at recent Congressional hearings, and concerns have been expressed whether effective safeguards could be maintained in the expanded worldwide plutonium industry projected for the future.10/

2. Safeguards Measures for a Plutonium Industry

Both experience with the existing nuclear power industry and other high-security industries and Government activities indicate that the measures that would be designed to safeguard plutonium would not be unique. We use many of them today in safeguarding sensitive security areas (e.g., nuclear weapons sites, gold depositories, intelligence facilities): in safeguarding the transportation of dangerous or valuable objects (e.g., bank currency shipments, nerve gas, Secret Service protection of high Federal officials); and in locating dangerous objects or persons by search techniques (e.g., airport scanning for weapons, public health inspections or quarantines when epidemics threaten, customs searches for drugs or contraband).

Some commentators conclude, therefore, that plutonium safeguards differ primarily in degree rather than kind from a variety of high-security situations that we now have, and with which we have dealt without major harm to civil liberties. Others point to the extremely high level of harm that would be done to society if a nuclear diversion and explosion were successful (e.g., in numbers of deaths and long-term radiation effects) and to the immense public fears that even a blackmail threat would generate; they conclude that these risks are so great that a plutonium safeguards program would be different in kind, not merely degree; it would have to be far more intense, permanent, and subject more people inside plants and outside the industry to preventive and responsive intelligence than anything we have experienced previously.

Trying to particularize and, if possible, narrow this disagreement requires that we go more deeply into what safeguards would be necessary in a plutonium industry, especially in terms of the possible availability of measures--technological or administrative--that might lessen the scope of intrusiveness into citizen’s rights.

Several points of agreement in the safeguards debate are important to note as a baseline for discussion:

a. There is general agreement that if plutonium recycle is initiated, there would be a genuine need for high-security measures. In other words, this would not be an instance in which responsible critics would allege that there was no need for such measures, such as when critics denied the presence of any real security risk to justify passage of the Alien and Sedition Laws in the 1790’s or the Palmer round-ups of aliens in the 1920’s, or the Joseph McCarthy investigations of the 1950’s.

b. There is general agreement also that there is no way to remove all possibilities of diversion by more humane, just, or effective social policies, and thereby obviate the need for high-security measures. In the debates over broad police powers of arrest, search, and seizure, for example, it is argued by some that we should work on the underlying problems that cause high crime--such as unemployment, racial discrimination, punishment of victimless crimes--rather than allow police to use intrusive or harsh techniques. In the case of potential threats against plutonium plants, there is general agreement that we have no real prospects in the foreseeable future of adopting national or international policies that would remove the causes of <u>all</u> political terrorism or of removing the causes of individual derangement or eliminating criminal organizations.

c. There is also general agreement that there is no complete technological solution available or foreseen that would make it unnecessary to have <u>some</u> safeguards measures that would affect civil liberties. Unlike the situation with machine scanners used in airport searches, which remove the necessity for hands-on searches of people and their property, safeguarding the physical sites and transportation routes in a plutonium industry, and especially recovering plutonium if it were diverted, would necessitate some measures that have potential for violating civil liberties. Just how many, and of what kind, represent the point at which informed debate begins.

One other important observation needs to be made. Our social values, political culture, and legal rules all combine to give us some common understanding about what is meant by “civil liberties,” and we are often able to turn to the courts to make authoritative rulings on what the Constitution requires. However, important as existing judicial decisions would be if and <u>when</u> plutonium safeguards measures were tested in the courts, or as policy guides to legislators and administrators setting up protections of civil liberties in a safeguards system, it would be a mistake to assume that the courts themselves would be quickly or easily available to correct any deficiencies in a program or protect individual rights. There are several reasons for this.

1. It is the nature of the American judicial process to require that claims of constitutional rights be determined in specific contexts, where the laws and regulations that have been established can be studied in detail, their application to real persons can be examined, and the surrounding ethos of an on-going program can be taken into account. Thus the U.S. Supreme Court does not issue advisory opinions on proposed or recently enacted laws; rather it requires real cases and controversies involving persons with proper standing to sue and genuine legal interests to assert. How the courts would assess the constitutionality of plutonium safeguards measures would thus depend heavily on how the programs were established, who ran them, what specific protections of individual rights were incorporated in them, how the programs were actually being administered, the circumstances under which a legal challenge to the program arose, and similar factors.

2. There are few decisions by the U.S. Supreme Court dealing directly with the constitutional aspects of personnel security, physical security, and preventive intelligence in the kind of clearly sensitive, high-security settings that plutonium safeguard programs present. There are a handful of decisions that approach the boundaries of this problem, such as rulings on standards and procedures in defense plant personnel clearance programs or in waterfront-security programs; presidential authority for warrantless wiretapping in domestic-security investigations; decisions dealing with physical searches in airports.[11/] Beyond these lie dozens of cases discussing principles of liberty and fair procedure in related but less high-sensitive settings; these cases provide judicial statements that can be analyzed for their

possible application as guides in the plutonium-safeguards context.[12/] But the primary fact is that existing judicial precedents offer only suggestive concepts to apply to the legal evaluation of plutonium safeguards measures,

3. Finally, American courts have a long history of deferring to the elected branches of government, particularly the executive branchs when genuine national-security or public-safety interests are seen to be involved. This would be especially true as far as government's response to a diversion. If it were learned that plutonium had been stolen and was somewhere in the vicinity of a nuclear plant, or if a credible nuclear blackmail threat were made by a political or criminal organization, the dangers of such a situation would closely resemble a state of national emergency in which, traditionally, courts give the widest immediate deference to what executive officials feel it necessary to do to protect the public. Later, usually after a war or national emergency has ended, courts may try to adjudicate the rights and wrongs of a government policy, and perhaps award compensation to injured persons. But the ancient maxim--during wars, the laws are silent--reflects realistically what courts actually do when genuine national or local crises arise.

This does not mean that constitutional guarantees would not apply to a plutonium industry or that court rulings provide no help in considering civil liberties risks and options in the nuclear safeguards area. What it does suggest is that <u>existing</u> decisional law offers only broad (and sometimes cryptic) concepts from which to work in considering the high-security milleu of nuclear power activities.

With these initial observations made, let us turn to a closer examination of potential safeguards measures and their civil liberties consequences.*

The safeguarding of any highly dangerous or valuable material can be posed in terms of four basic procedures. These are:

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*The following few pages depend heavily on J.N. O'Brien, "Nuclear Safeguards and Civil Liberties: A Regulatory Scheme," Working Title--Dissertation in progress, Social Science Department, Syracuse University.

0 Employee Screening--These measures are designed to prevent employment in the industry of individuals who might be likely to use their position to steal or harm the materials to be protected.

o Access Controls--These are methods of physically preventing protected material from unauthorized removal.

o Threat Analysis--This covers activities aimed at obtaining advance knowledge of attempts to steal or harm protected material.

o Recovery--In the event that a quantity of protected material is missing, these are measures to locate and recover the material.

The specific measures that could reemployed in each of these areas are quite varied.

Those measures which may be used in employee screening are:

o Compulsory disclosure questionnaires, which would force an applicant to supply detailed information about her or himself.

o National agency checks, conducted to gather, and evaluate all the information as to suitability that the Government maintains on applicants or employees.

o Full Field Investigations, in which the character and associations of an applicant or employee are investigated by interviewing friends and associates and asking detailed questions regarding the applicant's background and lifestyle.

o Polygraph testing, where an employee or applicant may be asked a series of questions and the employee's physical responses are evaluated, in an effort to expose any contemplated theft or other threatening activity.

o Personality and psychological testing, which is used to identify employees or applicants who may be considered unstable enough to be compromised by outsiders or to undertake themselves a theft of protected material.

Measures which have been employed to maintain control over access to various types of valuable or hazardous material are:

- Mechanical Detection, which entails a hands-off body search for various types of contraband (e.g., the magnetometer used in airports for detection of weapons).
- Inspection of hand carried items into and out of areas containing protected material, which is employed to assure that no weapons, explosives, or contraband enter or leave the area authorized as proper for the material.
- Identification checks, to maximize assurance that only those persons who have been screened are allowed access to the material.
- On-the-job surveillance, audible or visual, directed at maintaining employee security when employees are handling protected materials.
- Pat-down body searches (frisks), used to assure that an individual leaving or entering an area containing protected material is not carrying contraband.
- Strip searches and body cavity searches, which are employed as a means of absolute assurance that no small quantities of valuable material are being transported out of the authorized areas.
- Emergency responses to alarm warnings or material balance accounting insufficiencies, which may include detention, arrest, search, and interrogation of employees and visitors within the facility at the time of the emergency.

Those measures employed to give advance warning of a threat of theft or harm to protected materials by groups in the society at large are:

- Overt intelligence techniques, which include name check, telephone record checks, credit checks, and other techniques used in investigating ordinary crime, applied to individuals or groups suspected by investigators of being potential assailants of plutonium facilities.
- Covert intelligence techniques, which may include electronic surveillance, unauthorized or surreptitious entries, informants and agents in various organizations, and mail openings.

- Creation of a special unit in an existing law enforcement agency or a separate special intelligence force.

In the event that plutonium is diverted, a recovery operation could conceivably include:

- Perimeter searches aimed at cutting off routes by which protected material in a known area might be transported away. This search may be accomplished through mechanical detection, lessening the scope and degree of intrusion of the search.
- Area searches conducted on large areas, possibly of residential character. These searches may be conducted, partially at least, by mechanical detectors sc as to limit, to some degree, the scope and intrusion of the search.
- Evacuation of areas in which a credible threat has been made to detonate a clandestine explosive device.
- Restriction of population movement in the event of a crisis triggering a massive civilian retreat away from a threatened area.
- Press censorship may be employed to minimize the effects terrorist activity seeks: public attention and alarm. Censorship may be contemplated on a voluntary basis or by law.
- Harsh and unusual investigative techniques which may include measures ranging from a general round-up of those individuals suspected of being privy to information regarding the whereabouts of the missing material, to interrogation by torture of individuals who are believed to possess substantial information of the materials' whereabouts.

Some of those activities are mutually exclusive, in that the employment of one may eliminate the need for the other. In those instances, the least onerous alternative may represent a measure with little civil liberties damage. This is particularly true with respect to activities designed to detect or locate nuclear material. For example, if a portal monitor (doorway with a radiologically sensitive alar@) is available which could with great certainty warn of unauthorized removal, then the need for a physical hands-on search would be eliminated.

These devices are available in some cases. The technology for detection of even small amounts of radioactive material has been developed and further advancements are likely. Freedom from unreasonable search and seizure is meant to prevent arbitrary and intrusive actions by Government officials. A method of mechanical detection is a reliable method of locating persons or places which should be searched, and a warning from a mechanical detection device represents the functional equivalent of probable cause. The result is that employees leaving a material-control access area in a plutonium reprocessing plant need not be searched any further, if they can pass through a portal monitor which is properly operating. Present nuclear safeguards have been directed at making the detection devices as fail safe as possible, and with high reliability. If a totally fail-safe portal monitor system could be developed, it would negate the need for hands-on body searches altogether.

The same type of situation exists in the event of a recovery operation. As a result of the weapons program, hand-held radiologically sensitive devices have been developed which, within a certain radius, can detect the presence of even well-shielded radioactive material. As the sensitivity and reliability of these devices increase, the intrusion necessary to assure that an area does not contain radioactive material decreases. In that sense, some technological solutions are available; current research may yield better solutions.

It is useful to note that different safeguards techniques present different levels of potential civil liberties harm. Some intrusions are not overly onerous when compared to intrusions already accepted by American society. An example already noted is the search conducted by mechanical hands-off devices. In airports, the increasing potential of skyjacking led to the need to assure that weapons were not being carried into the passenger compartment of commercial aircraft. The magnetometer, which can detect a metallic mass such as a small handgun, is used to scan all passengers boarding the aircraft. The judiciary has found this to be an acceptably minimal invasion of privacy, given the serious threat of a successful skyjacking.

A safeguard activity of medium risk is the possibility of escalation of domestic intelligence activities in the interest of nuclear safeguards. The status of domestic security operations is currently unsettled. The recent study completed by the Senate Select Committee, charged with investigating domestic security, found numerous instances of sweeping and unjustified intelligence activity and abuse of lawful intelligence objectives during the past two decades; an absence of guiding standards to govern such activities and inadequate techniques for supervisory control. Some commentators have suggested that domestic intelligence activity for nuclear security may escalate to the same unacceptable levels that prevailed during the past twenty years. This represents the possibility of collecting extensive information, via such techniques as electronic surveillance, surreptitious entry, infiltrators and informants, as well as the creation of extensive files and databanks on anti-nuclear and dissident groups, not just declared terrorists. Whether such a phenomenon would be likely to take place is not clearly predicable, but the danger of it happening is sufficient to constitute a middle-level risk to civil liberties.

Finally, there are areas of concern which involve very high levels of risk. These are mainly in those activities which would result from a successful diversion of plutonium. The type of recovery operations which would follow such a diversion represent serious intrusions on civil liberties, and the likelihood of judicial intervention would be small. For example, if an area search were thought by responsible officials to be necessary, it is doubtful that the courts would interfere even though a sweeping area search represents an activity which is unlawful under current search and seizure doctrines. Although mechanical devices are available which make it possible to scan a room in a dwelling and detect the presence of plutonium, even if shielded, this only reduces the scope of the search; house to house, room by room searches over wide areas would still be required.

Rather than go on further in this section about the risks, tradeoffs, and possibilities for civil liberties protection involved in specific safeguards measures, we will develop these discussions in the context of three main positions about plutonium and civil liberties that have developed during the debates of the past few years, since these positions frame the issues with valuable clarity.

D. A Presentation of Three Positions Widely Held in U.S. Society as to the Civil Liberties Risks of Plutonium Recycle

The positions described below have been constructed from an analysis of public statements made by civic groups and industry representatives, scientific and legal experts, executive-agency officials, members of Congress, and similar commentators. The sources for their statements have been books and articles, state and federal legislative hearings, conference papers and reports, and special consultant studies, all of which are set out in the Bibliography.

The approach was to identify what seemed to be the logical, alternative viewpoints that have been voiced in the recent debates. Then a single, coherent statement of each position’s assumptions, arguments, and conclusions was developed. Despite the obvious usefulness of this exercise for policy-makers, no such analytic presentation of these viewpoints has appeared previously in the literature.

A. Position One: A Plutonium Economy Would Require Such Extensive Safeguards and Curtailment of Civil Liberties That Its Creation Would Jeopardize Our Free Society

The general theme of Position One is that the measures adequate to assure the safeguarding of a large-scale plutonium industry would, inevitably, require such severe intrusions into the civil liberties of employees and citizens that the maintenance of a plutonium economy is incompatible with the U.S. system of constitutional rights. In a phrase, plutonium would bring on a nuclear police state.

Position One begins with the following key assumptions:

1. The presence of millions of pounds of plutonium in reprocessing plants and in transit--when ten to twenty pounds would be enough to make a nuclear

device and with prevailing conditions of domestic and international terrorism--poses a situation so perilous to public safety that only a far--reaching, fail-safe type of safeguards program would be sufficient to protect the public. Therefore, the only kind of safeguards program to envisage, for purposes of considering civil liberties impact, is a far-reaching, fail-safe kind" of response. Government could do no less.

2. Despite decisions of the courts during the past decade setting important constitutional limits on personnel security programs, police intelligence operations, government search and seizure, and similar activities, the immense potential consequences of a nuclear diversion from inside or an assault from outside would probably lead the courts to uphold sweeping preventive measures for a plutonium industry. The courts would be even more likely to decline to interfere if government were taking Draconian measures in response to a blackmail threat or nuclear incident. This release of intelligence agencies and security investigators from constitutional limits would not only be harmful in itself but also be likely to stimulate surveillance and dossier-building in non-nuclear fields.

3. Even if a safeguards program were originally setup with strong civil liberties protections, written into legislation or set out by executive order, public reaction to thoroughly predictable incidents of diversion and blackmail, and certainly to any successful explosion, would probably lead to the dropping of such limitations and the adoption of a maximum security program. Thus no safeguards program can be expected to stay limited as a plutonium economy continues for any length of time.

4. There are special dangers to civil liberties in the fact that a plutonium safeguards program would be jointly administered by private industry and the federal government. Giving industrial security forces and corporate

managements a role in collecting data and managing security programs about employees, suspected assailants, and community anti-nuclear groups would be a major step backward in the development of good employer-employee, employer-union, and employer-community relations in this country.

5* Given all of these likely consequences to basic liberties, and the fact that alternative energy sources such as coal or solar power require no such safeguards measures, government and private-industry proponents of plutonium recycle must prove to Congress and the public that no other energy sources or conservation programs can be developed to meet American energy needs, even at higher but not unbearable economic costs.

6. It is increasingly clear that opposition to the proliferation of nuclear weapons and nuclear power plants is becoming a broadly-based political movement in the United States, and many other Western nations. Its supporters run a gamut from left to conservative political views as well as including various environmental-protection positions. There are bound to be protest meetings, demonstrations, and possibly some direct-action tactics in the tradition of earlier ban-the-bomb, civil rights, and anti-war movements. Given this growing political movement, any choice of energy policy that creates highly visible targets for concern and protest in thousands of local communities and along hundreds of transportation routes will require harsh protective responses and produce serious confrontations. Not to see this conflict arising in the last decades of this century--and to try to avoid it if possible--would be to invite cleavages in our society.

Based on these key assumptions, advocates of Position One have warned that most of the intrusive kinds of safeguards will inevitably be used, that they cannot and will not be conducted in tolerable fashion, that we can expect no timely intervention by the courts, and, therefore, that plutonium economy would mean unacceptable levels of surveillance and government control over free expression for people who would work in plutonium plants, reside in nearby communities, or exercise First Amendment rights of protest against plutonium.

This leads advocates of Position One to two conclusions:

1. Whatever the other objections might be, on civil liberties grounds alone, Congress should reject plutonium recycle as an energy policy and prevent the licensing of plutonium reprocessing plants for commercial use.

2. The United States should not export plutonium technology. Partly, this is to diminish the threat of plutonium diversions that might be smuggled by terrorists into this country and thus create the need for extensive customs-search procedures. It is also urged in order to avoid having the United States export a technology that would inhibit the evolution of greater civil liberties in developing nations.

One special outlook of Position One is important to note. Its advocates look at the future of safeguards in light of two critical events since World War II: the painful struggle to reverse the cold-war anti-communist hysteria of the 1940's and early 1950's and the set of executive misconducts that are now called by the shorthand of "Watergate".

They argue that any judgment of how carefully and responsibly a safeguards policy would be conducted over the next 25-50 years, and beyond, has to be considered in light of the fact that during the past 30 years, we have passed through two disturbing examples of abuse of government power. With this record, it is asked, why should a society that realizes how fragile freedoms are in this chilly authoritarian world want to create such dangerous tools to guard over the next half century?

Furthermore, advocates of Position One note a series of recent events involving the nuclear power industry which they see as demonstrating that abuses of individual rights have already begun to arise. They cite the creation of dossiers on anti-nuclear critics by the Texas State Police[13] and infiltration of anti-nuclear groups by police in Baltimore;[14] the compulsory polygraphing of employees at the Kerr-McGee nuclear fuel plant in Oklahoma, with questioning about employee memberships in a union, having sexual relations with fellow employees, and similar questions;[15] the efforts of Virginia Electric and Power Company to secure a bill from the state legislature giving its security force police-arrest powers and access to confidential police records, to meet the company's nuclear-security needs;[16] and allegations that local power companies and the national atomic industry association maintain files on anti-nuclear individuals and groups.[17] These are cited as events which foretell the kind of anti-libertarian atmospheres that plutonium protection would foster.

As for the consequences of <u>not</u> proceeding with plutonium recycle, those adopting Position One reject completely the argument that failure to proceed with a plutonium economy could lead to a severe energy shortage, increased unemployment, and widespread economic disruption; all of which would also bring serious <u>civil liberties</u> consequences. If rationing were necessary to enforce energy conservation, this is seen as not even approaching the curtailment of freedoms involved in plutonium safeguards. As for the dangers to civil liberties in a possible depression, Position One argues that this would still only cause temporary hardships involving civil liberties problems, and ones within the historical experience of this Nation several times before. According to Position One, there would be no comparison with the long-term system-transforming effects on civil liberties of a plutonium economy.

David Comey expressed the essence of Position One in this way:[18]

> "The nuclear industry's favorite taunt to its critics is: 'Well, do you want to go back to candles?' That is hardly the choice we face, of course, but if it were, then I should rather read the Bill of Rights by candlelight than not have it to read at all."

B. Position Two: Safeguards Can be Adopted for a Plutonium Industry That Would be Both Effective Against Threats and Acceptable in Terms of Civil Liberties

Essentially, this position sees civil liberties problems as manageable ones and the predictions of an inevitable "nuclear police state" as unjustified hyperbole, In their view, safeguards measures must be strong but reasonable, with the necessity for what is adopted vigorously defended before Congress, the public, and the courts.

Position Two proceeds from the following primary assumptions:

1. Both military and commercial operators of nuclear facilities have been managing safeguards programs successfully for decades; adapting these to the new scope and requirements of a plutonium economy would therefore represent not a totally new venture but an expansion of present operations. What is done effectively in 60 plants can be accomplished in 500, just as what safeguards 200 shipments can also safeguard 20,000. The difference is one of degree, not of kind.

2. It is simply unacceptable for a large and strong society such as the United States to let potential threats from a few terrorists, criminals, or disturbed people deprive the American economy and the public of a badly needed energy supply in the next 50-100 years.

Nuclear power is economically competitive with other sources, capable of safe use, and environmentally sound, therefore the need to safeguard nuclear power facilities is no more reason for rejecting nuclear power than allowing potential threats to close down natural gas facilities, city water reservoirs, subway systems, or other facilities that might be attacked with great harm to the public.

3. Whether the size of a plutonium work force would be 50,000 or several million, it is thoroughly justified to set initial personnel clearances and continued-suitability standards for persons who choose to apply for or work in that industry. This deprives no one of rights to pursue gainful employment, even in the nuclear field, as there will be many other nuclear research and operating facilities beside the commercial plutonium industry. Since there is no draft of persons to work in the plutonium industry, nor need there be any harmful consequences to persons denied a job in this industry (in a properly run program), it is no more justified to attack plutonium-industry clearance procedures as an unacceptable ban on individual rights than to do this for persons given suitability clearances today for working in the CIA, in top-secret defense production jobs, or as military personnel holding sensitive jobs at missile sites. The same justification of voluntary choice with advance knowledge applies to measures such as identification checks, screening parcels and people, administering polygraph examinations periodically, monitoring work stations by TV-camera, and conducting strip-searches if a diversion of materials has been detected.

4. The intrusions into personal liberties of workers, community residents, and diversion suspects that would take place should a diversion be detected or a nuclear blackmail threat be made--awesome as those situations are--are really no different than if nerve gas or highly-dangerous bacteriological agent were stolen from a civilian or military site, or a credible threat to use such substances were delivered to authorities. In all such cases, Preliminary investigation by professionals would establish the cred-

ibility of the danger, negotiations would be weighed, and a response pursued that would be appropriate to the situation. Harsh as it is to contemplate, there is simply no way a democratic society can <u>eliminate</u> the possibility of such episodes, even by abandoning plutonium recycle. The answer is neither surrendering to terrorists in advance nor installing a police state, but a concerted policy of prevention, deterrent, moral suasion, and particular response to specific incidents.

5. As for intelligence-gathering about potential diverters, there is a strong need for obtaining intelligence about terrorist organizations and other groups whose conduct indicates that they might use violence against nuclear facilities. However, this would not be done by any special nuclear intelligence force but by the FBI, operating under clear controls by the White House and with Congressional supervision. Legislation and regulations would spell out carefully the limits under which such intelligence programs would operate, both as to the range of groups on which data would be collected and the methods used to do so.

Based on these assumptions, Position Two reaches the following conclusions:

1. The United States should proceed with a plutonium licensing program, after full public participation in a rule-making proceeding, development of a set of safeguards requirements, and formulation of civil liberties principles under which the" safeguards program would operate.

2. The United States should also proceed with sales of plutonium recycle facilities abroad, under a safeguards program that would meet both U.S. and IAEA standards.

These conclusions are supported by the Ad Hoc Subcommittee to Review the National Breeder Reactor Program report of 1976, which stated: "The suggestion that the imposition of appropriate safeguards measures for the nuclear fuel cycle threatens the civil liberties of the people of this or any other country does not appear to be warranted."lg

The mood of those championing this position was well expressed by Gerald K. Rhode, Vice President of Niagra Mohawk Power Corporation, at an Atomic Industrial Forum Conference on Nuclear Safeguards in April of 1976.20 Chairing a panel on "Safeguards Studies and Legislation," Rhode commented that, from "the user side of this business," he felt it essential that "every <u>credible</u> situation be guarded against and every <u>reasonable</u> precaution taken . . ." He also agreed that "civil liberties are definitely involved" in the plutonium decision, and that "public review and involvement" in reaching decisions on plutonium "is an absolute necessity." However, he said, "there is a point of absurdity beyond which the rational public should not be expected to go in imagining safeguards hazards," by which he meant both security threats and civil liberties threats. "I am reminded," he observed, "of a young soldier who was placed on guard duty a number of years ago in an open field on the Kansas plains."

Soon after taking his post, he was visited by the lieutenant of the guard, who came by to check the effectiveness of this particular post. When the soldier had snapped to attention, the lieutenant asked him:

"What would you do if you suddenly saw a battleship coming across this field?"

The soldier thought for a moment, then brightened and replied:

"Sir, I would torpedo him."

"And where would you get the torpedo, soldier?"

"The same place you got your battleship, sir!"

In the view of the supporters of Position Two, Position One represents an entirely unrealistic picture of how safeguards measures would be conducted. In their view, fully effective plutonium safeguards can be installed without imposing improper limitations on the rights of plutonium workers, community residents, or anti-nuclear critics.

As for the concern expressed by Position One, that the United States has passed through two disturbing examples of abuse of government power in the past 30 years, Position Two replies that the United States has come through these periods without lasting harm to civil liberties. This illustrates, according to Position Two, that the United States Constitution and social system have the strength and resiliency to cope with any civil liberties impacts a plutonium safeguards program might bring. Position Two also contends that the civil liberties impacts of major and prolonged energy shortages would be at least as far reaching as those of a program to safeguard plutonium recycle and breeders.

C. Position Three: An Acceptable Program of Nuclear Safeguards is Possible but Only if American Society is Willing to Run Some Permanent Risks of Diversion in Order to Keep Civil Liberties Risks at a Low Level

This position maintains that *if* a persuasive case for plutonium recycle is proven in terms of national energy needs, and if safety and environmental problems are met, then a safeguards program could be designed that would be acceptable in civil liberties terms **if** Congress and the American people are willing to live with some risks of diversion in the interest of limiting risks to freedom.

The assumptions that underlie this position can be summarized as follows:

1. To adopt a fail-safe or zero-risk approach to safeguards, or even to speak of holding threats to negligible proportions, is to insure that the civil liberties costs of such a program will be unbearably high. Once it is assumed that reducing threats to near zero is the objective, man-

agers of a safeguards program would be driven to adopt highly dangerous techniques of personnel security and preventive-intelligence.

2. Instead of this standard, Position Three urges adoption of a standard that would trade off some small risks of diversion against heavy risks to basic civil liberties.

3. This would mean deliberately rejecting some widely proposed techniques of personnel screening, employee monitoring, intelligence gathering on anti-nuclear groups, not merely because many of these techniques are of doubtful real value but because their civil liberties costs are too high. In balancing slightly greater risks of diversion against very heavy risks to basic freedoms, the decision would have to be made to protect freedoms.

4. For plutonium recycle to go forward, such a set of fully-articulated tradeoffs would have to be set out as the philosophy of a safeguards program, tested before the public in a variety of hearings and proceedings, be fully accepted by the commercial firms and government regulatory agencies most directly concerned, be written explicitly into legislation and implementing regulations, be subjected to firm annual reporting duties and legislative reviews, and have procedures created for both administrative appeals and judicial review. Only if the accepted risks and tradeoffs were developed and institutionalized in this way should plutonium recycle be allowed to go forward.

5. It would be especially important to a proper safeguards program that the Nuclear Regulatory Commission not simply turn over to the discretion of the FBI the conduct of preventive intelligence for plutonium security,

or leave the decision-making responsibility in a recovery effort or diversion response to ad hoc developments among federal, state, and local officials. These activities, because they are among the most important for civil liberties, should be defined and supervised by the NRC, possibly with a Congressional oversight role.

6. Holding to this line would involve reaffirming the bargain year after year and decade after decade, especially in the face of predictable low-level incidents (see Appendix III-A) and possible serious incidents. This would mean that the American public would have to hold the line of moderation, refusing to let itself be stampeded by demagogues and forcing sufficient public supervision to prevent the program being subverted by secret-government.

Based on these assumptions, Position Three draws the following policy conclusions:

1. Congress should go forward with a full-dress review of the need to have plutonium recycle and breeders to meet America's future energy needs, and of whether this process can be made environmentally and physically safe. If the answer to these inquiries is yes, then Congress should receive from the NRC a fully-worked out plan for safeguards, which then would be publicly reviewed and implemented in the manner described earlier (paragraph 4).

2. There is no automatic judgment in Position Three as to plutonium export policies by the United States, nor has this been addressed in the literature thus far produced in support of a civil-liberties-acceptable domestic safeguards program. Certainly the risk of plutonium being diverted in another country and brought into the United States is a serious one, and it does not appear feasible to apply border control search measures to prevent this, even if the authorities knew that a diversion had taken

place and an effort to smuggle it into the U.S. would be made. Still, most advocates of this position would probably assume that other democratic nations could and would adopt the same freedom-respecting programs as we would, and that developing nations should be given the chance to have the energy technology they wish.

To see how this third position would go about fashioning a safeguards program, it is worth quoting in some detail from a report to the Nuclear Regulatory Commission by attorneys Timothy Dyk, Daniel Marcus, and William Kolasky, Jr. As their basic standard, they urged the Commission to adopt a “least restrictive alternative” test for each component of a safeguards program. 21

> We think it vital that such a “least restrictive alternative” approach be the keystone of the NRC’s approach to the selection and shaping of safeguards measures. In approaching a particular safeguards problem, the Commission should evaluate the impact on civil liberties of each of the ways of solving that problem. The factors to be considered in evaluating the impact of various safeguards measures on civil liberties should include the following: (1) the extent of the intrusion on personal liberties; (2) the frequency and pervasiveness of the intrusion on civil liberties (Will it be part of a daily routine or will it only occasionally be employed? Will its effects be temporary and limited or long-lasting?); (3) the number and types of individuals affected (employees in nuclear plants; members of suspected terrorist organizations or dissident groups; “innocent” members of the public); (4) the likelihood that a particular safeguards measure will actually be employed; and (5) the likelihood that the same or similar invasions of civil liberties will take place even if the safeguards measure under consideration is not employed.
>
> Where resolution of a safeguards problem involves a significant impact on civil liberties, the NRC should choose the method that has the least impact, even if that method is more costly or less efficient. To take a simplified example: physical body searches and mechanical detection techniques (such as those commonly employed in airports) both have an impact on civil liberties, in terms of invading privacy, restricting freedom of movement, and raising questions of reasonable search. But the physical body search clearly has a much more severe impact on individual privacy, and few would dispute that the mechanical

detection procedure is preferable even if more costly. On the other hand, if mechanical detection methods are far less effective than body searches, a substantial question would be presented as to whether they are a reasonable alternative safeguards measure.

By the same token, as to each alternate safeguards measure the question should be asked: how can any necessary intrusion on a civil liberties interest be minimized or mitigated, and"how can abuses be guarded against? There are a number of familiar procedural protections and checks and balances that-can be incorporated into various safeguards measures in advance: issuance of a warrant based on a probable cause showing before a home is searched or a phone tapped; providing a right to counsel during interrogation; conducting a hearing before denying or revoking a security clearance. Incorporation of such protections will not eliminate the intrusion on individual privacy or other personal rights and interests. But it can restrict the intrusion and give some assurance that governmental (or government-sanctioned) power will not be abused.

The same type of "least restrictive" alternative analysis should be applied across various areas of the safeguards system--physical security of facilities; personnel reliability; surveillance of potential thieves and saboteurs; and reaction and recovery plans. In fashioning a total safeguards program which will inevitably interfere with civil liberties in a number of areas, consideration should be given to whether the adoption of measures in one area with a certain cost in terms of civil liberties will obviate the need for adoption of more onerous or objectionable means in other areas. For example, should it prove feasible to require licensees to adopt "real time" inventory procedures that would make it possible to know at the end of each work shift whether any SNM was unaccounted for, it might be possible to dispense with routine searches of employees as they leave work. The more sophisticated inventory system would itself raise civil liberties problems--for example, detention of all employees on a shift pending resolution of accounting discrepancies and interrogation of employees about those discrepancies. But a decision-maker might conclude that the occasional intrusions on employee freedom resulting from such an accounting system were less restrictive and objectionable than a daily search procedure. On a broader scale, an extremely tight and effective facility security system might obviate the need for background investigations or psychological testing of employees. One might decide to tolerate greater intrusions on personal freedom at the working site if the far-ranging invasion of privacy and chilling impact on political freedom involved in a security clearance system could be largely or entirely avoided.

In sum, the NRC'S effort should be to design a safeguards system that, _in toto_, has the smallest impact on civil liberties

> consistent with the achievement of safeguards goals. Once that has been done, the Commission will be in a position to evaluate the benefit of authorizing new technologies such as plutonium recycling against that civil liberties cost (as well as other costs). Civil liberties, then, should enter into the NRC's decisionmaking both in designing particular safeguards measures and in reaching a decision on the basic issue of whether to proceed with the development of a new technology that will require the imposition of those safeguards. And in factoring civil liberties considerations into its deliberations, the Commission should be asking not only, What can we do?, but also, What should we do?

There are similar discussions of security-liberty tradeoffs in reports by Baron, Clune, and Wyle, with each insisting, as the essence of Position Three, that plutonium recycle should proceed only if some safeguards for high-security situations are willingly relinquished in the interest of preserving basic freedoms.*

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*T'hus far, the American Civil Liberties Union has not taken an official Position One stand on plutonium recycle. A recent ACLU report noted: "The Washington office has intervened in a Nuclear Regulatory Commission proceeding concerning the security measures that may be required to safeguard nuclear plants fueled by plutonium. The ACLU is arguing that recycling of plutonium should not be permitted without a full study and public airing of its impact on civil liberties, and contends that the practice should be barred if the requisite safeguards--such as stricter security clearance measures, expanded police powers to search for missing plutonium and surveillance of potential terrorists--would violate constitutional rights." ACLU Activity Report, October-December, 1976, page 1.

E. Observations and Comments on the Three Positions

At the outset, it is fair to note that the effort to isolate the key differences among the major discussants has produced some rigidity in the statement of premises and conclusions. Someone may share a premise or even several premises of one position yet not feel compelled to reach the same conclusion that the advocates cited as holding that position have reached.

For example, a person may believe that our experience in the civilian and military nuclear programs provides important insights without believing that it provides definitive answers to the civil liberties questions, a stated assumption of Position Two. Or a person may believe that the voluntary nature of employment in a plutonium industry justifies personnel clearances without concluding that it justifies more intrusive techniques, such as polygraph examinations.

Also the differences between Position One (which would forego plutonium recycle because of civil liberties concerns) and the other two positions (which would go forward with plutonium recycle with steps to solve civil liberties problems) are clearly more marked than the differences between Positions Two and Three. Both Positions Two and Three recognize some civil liberties risks, believe these risks should be minimized, are willing to accept some security risks, and believe in balancing the conflicting interests. As a result, an individuals viewpoint might include some aspects of both positions. Having recognized this, let us turn to a closer analysis of the assumptions and conclusions of the three viewpoints.

One problem with the plutonium dilemma is that each of the three positions outlined is partially right.

--Position One points correctly to the dangers of so much plutonium being handled in a world of terror and mishap; the pressure this could create from the public to use Draconian safeguards measures; and the remarkably optimistic assumptions as to unbroken national responsibility and moderation on which both Positions Two and Three rest their faith.

--Position Two reminds us that the year 2020 is not coming immediately; that a plutonium industry would develop slowly and could therefore be safeguarded step by step, modifying the technology, physical locations, plant design, shipment procedures, and many other elements as it went along; and that safeguards techniques could be installed in equally evolutionary and self-correcting fashion.

--Position Three is persuasive in suggesting that it has been a traditional feature of American pragmatism to resist either-or choices, and to seek ways to trade off one set of risks against another in a way that preserves important values of both liberty and order. By taking relatively minor risks of diversion, using all the mechanical and technological means available and going to hardened site, the necessity of using harshly intrusive employee security and potential-group surveillance could be avoided.

Though there are persuasive elements in each position, it is equally helpful to examine what are the weak points, or points of uncertainty, in the three main positions.

The extent to which the concerns expressed Position One are realistic is dependent to some degree on the specific details of the safeguards and security measures used by a plutonium industry. For example, the concerns about diversion during transportation of special nuclear material would be greatly reduced if collocation of fuel reprocessing and fuel fabrication facilities or coprocessing (without collocation) completely eliminated transportation of weapons material. Secondly, concerns about assaults by outsiders would diminish if facilities containing special nuclear material were convincingly designed to prevent removal of weapons material by a large, heavily armed band.

Such successful perimeter defenses for colocated facilities would probably reduce or eliminate the need for off-site security measures such as surveillance and dossier-building on members of the public. In effect, the industry’s attitude would be “We don’t care what plans outside groups are making; we can withstand anything they come up with.”

If the number of people in the plutonium industry who would be subjected to full field investigations of their backgrounds, and would be subjected from time to time to such measures as physical searches and surveillance were very limited in number (to a few thousand), the civil liberties infringements involved would not be significantly greater than presently exists in the defense industry or other sensitive private activities. It is not clear, however, what number of persons must be affected in order to reach a point of civil liberties concern; some people might regard 10,000 as an acceptable upper limit for such intensive security measures; others might accept higher numbers.

The assurances contained in Position Two would be disputed by many knowledgeable persons. It is not certain that the past and present safeguards system has been totally successful. The very large amounts of Material Unaccounted For leave open the possibility that diversions have already taken place over the past 20 years.

It is not clear that Position Two is correct in saying that an expanded plutonium industry merely represents a difference in degree, not in type. In cases where plutonium facility becomes a major employer (or the dominant employer) in a community, there is less freedom of choice for residents as to whether they laccede to the security restrictions or refuse to work at the facility. In small rural communities the company town syndrome may appear, making it difficult for employees to resist extensive security measures.

Position Three is not without its conceptual shortcomings as well. Past experience with security officers makes many persons dubious about the possibility of containing a security program to least restrictive security procedures. Security personnel are prone to seek tighter measures, regardless of civil liberties implications. They tend to gravitate toward easy or foolproof techniques that invariably involve infringement on civil liberties. Moreover, even with tight internal security and strong perimeter defenses, it is likely that security personnel would keep pushing for positive intelligence (e.g. surveillance, informers) about potential attackers or critics. The nature of security officers is to want to reduce all risks to negligible proportions, which contradicts the assumptions of Position Three.

It has been hypothesized by some proponents of Position Three that addition of ombudsmen or public advocates to the system would protect against unwarranted security intrusions. Such an ombudsman would act as a third party to restrain security or prosecutors when they sought judicial approval for search warrants, surveillance or surreptitious entry. Yet there is a danger that constant proximity to such processes may render the ombudsman too sensitive to the needs of the security forces so that she or he becomes part of a triumvirate (including the prosecutor and judge) that authorizes the infringements of civil liberties. Our experience with seeing regulators over-sensitized to the interests of the regulated should teach us that it is a basic phenomenon of human nature to become sympathetic to persons with whom one associates constantly.

It could also be said that Position Three assumes a greater degree of rationality than has yet been observed in the nuclear regulatory area or any other government agency. The procedural, legislative and administrative arrangements necessary may be beyond realistic implementation by Congress, agency officials, and management of industry.

Finally, Position Three may be ignoring the backlash effect that would occur if a successful diversion resulted in a major threat or actual casualties. It is not clear that the original limited safeguards system contemplated by Position Three would survive the pressures of an outraged public determined to prevent any further incidents. Indeed, it could be argued that to the extent one limits the original problem, one is increasing the risk of an incident, and this will ensure that such a backlash will eventually occur. On the other hand, a maximum safeguards program such as is contemplated by Position Two may preclude any incidents from occuring, but result in the same degree of infringement of civil liberties as would occur if an incident took place as a result of a limited program under Position Three.

In trying to decide which one or combination of these views is more right and therefore should be used in policy-making, we should recognize that we do not have here a problem that can be put to the tests of either logic or empirical investigation. There is no way we could lay out a set of factual questions to be answered by research, or to design a pilot program from whose results clear guidelines for decision could be plotted. The reality is that each of these positions rests, fundamentally, on socio-political judgments as to how American government and public opinion have dealt in the past with threats to national security (real or assumed) ; how government and commercial security forces would be likely to carry out a safeguards program, even one that was highly respectful of civil liberties in its formal framework; how much privacy, dissent, protest, and cultural diversity our civil liberties traditions demand or our society should encourage; and how the American public would probably respond to diversions, blackmail threats, or a nuclear explosion, in terms of its shocked post-incident attitudes toward the scope of safeguards measures.

We also have no real guide to decision in the way that other industrialized democracies are dealing with the plutonium recycle issue. Inquiries made for this report in Canada disclosed that there has been no government inquiry or public debate as yet about the civil liberties aspects of nuclear power, though several environmental and civil liberties groups expect to raise this issue soon.[22]

In Britain the debate over plutonium and civil liberties is in almost exactly the same stage as in this country. Britain has been actively pursuing plutonium recycle during the past decade, with a government-sponsored program planned to move toward large-scale uses in the next 25-50 years very much like those projected by the AEC for the United States. However, a recent report of the Royal Commission on Environmental Pollution (the Flowers Committee) raised serious questions about the safety risks, environmental effects, and civil liberties dangers associated with nuclear power development.[23] on this last issue, the Flowers Report wrote:[24]

> The problems of safeguarding society against these hazards could become formidable in a “plutonium economy”. There are particular risks during transport of the element between nuclear installations, although techniques could be adopted to make access to the plutonium both dangerous and difficult. There is also, however, the risk of theft of plutonium by direct action at installations where it is stored or by people working in the industry. Of course, many measures are taken to prevent this but it cannot be entirely ruled out. In order to counteract these risks, some people foresee the need for the creation of special security organisations which, because of the vast potential consequences of plutonium loss, would need to exercise unprecedented thoroughness and vigilance to safeguard the material while significant quantities remained on the earth in accessible form...
>
> Many people are concerned about the implications for society of the security arrangements that might become necessary in plutonium economy. An effective security organization could not be merely passive, simply reacting to events. It would need to have an active role (as was recommended for the USA in the Rosenbaum report; that is, to infiltrate potentially dangerous organizations, monitor the activities of nuclear employees and members of the public and, generally, carry out clandestine operations,

> It would also need to have powers of search and powers to clear whole areas in an emergency. Such operations might need to be conducted on a scale greatly exceeding what would otherwise be required on grounds of national security in democratic countries. The fear is expressed that adequate security against nuclear threats will be obtained only at the price of gradual but inexorable infringements of personal freedom.
>
> We are sufficiently persuaded by the dangers of a plutonium economy that we regard this as a central issue in the debate over the future of nuclear power. We believe that we should not rely for something as basic as energy on a process that produces such hazardous substances as plutonium unless we are convinced that there is no reasonably certain economic alternative.

Last October, this position was taken up in greater detail in a booklet published by three organizations: Friends of the Earth, the National Council for the protection of Rural England, and the National Council for Civil Liberties. Titled Nuclear Prospects: A comment on the Individual, the State, and Nuclear Power, this booklet explored in detail all the civil liberties problems that safeguarding a British nuclear power program would entail. Given the wide powers of government secrecy, government controls over the press, and strong police emergency powers that British law and tradition support, the authors of the study conclude that the British nuclear power program presents grave threats to British freedom and is “bound to produce serious civil disorder”. However, these groups did not adopt a ban-recycle-now position (Position One in the American debate). Instead, they called on the government to address these issues in public proceedings:

> An over-riding characteristic of the recent nuclear debate has been the insistence of those committed to the nuclear option that the issues at stake are essentially technical. However, the matters discussed in this paper are not the province of experts. They are properly the concern of all of us.
>
> Any commitment to a new technology gives rise to social and political side effects. In our view this may prove truer of nuclear power than of most technologies. Moreover, the time to anticipate these side effects is now, before a full commitment to deploy the technology has been made. The scale of

> Britain’s contemplated commitment to nuclear power is so great that a decision to proceed could well be irreversible.
>
> Our survey makes no claim to being complete, nor does it pretend to answer the range of questions it raises. However, there is little in the public record to suggest that the Government, poised to vault us into a nuclear future has addressed itself to these questions in any but the most superficial way. We hope very much it will begin to do so now.

As these British commentaries (and others listed in the Bibliography, Section E) indicate precisely the same technical and socio-political issues are now being put to Parliament and the British public as Congress and the American public must decide. There is support in British government documents, parliamentary reports, commercial industry materials, and civic-group literature for each of the three positions competing on the American scene.

One other observation should be made, this one dealing with the capacity of the United States to police the adequacy of safeguards in other nations that might possess plutonium technology. Beyond the issue of whether we could have sufficient continuing powers of inspection to guarantee the internal measures against diversion or the physical security of facilities against attack, it seems doubtful that we could exercise many controls over the <u>civil liberties dimensions</u> of such foreign nuclear industries. Neither we nor the IAEA could reasonably expect such nations to allow monitoring of the way they conduct their employee screening and stability-monitoring programs, especially to let outsiders exercise any control over the criteria they used as to loyalty and disloyalty to the country or regime. Outside authorities could not reasonably expect to have supervisory authority over the way that nations’s intelligence agencies carried out surveillance of potential terrorist and radical groups, or political dissenters, within that country. Finally, if a diversion were suspected or established, any nation would insist upon entire freedom of action in determing how its security forces would respond. Thus it is clear that whatever supervision of physical security measures might be imposed and monitored bilaterally or by international agency, the civil liberties fallouts from a plutonium industry would be beyond such external influence.

The task that faces Congress in trying to control nuclear proliferation including the decision whether creation of U.S. plutonium industry at home or export of such technology abroad will increase the dangers of such proliferation, is an extraordinarily important choice. What this report has discussed is implications for civil liberties in what we decide, how we proceed, initially if we do license plutonium recycle, and how we police the boundaries and operations of a safeguards system throughout its course.

Ultimately, it would seem necessary for the U.S. to make its decision on a total package basis, not on the civil liberties considerations alone. To put this more clearly, Position One becomes harder to maintain <u>if</u> the case is made out that pursuing <u>some</u> plutonium recycle is essential for the energy needs and national independence of American society. Were that case made out in a public proceeding, there would still remain important issues of how large a plutonium industry needed to be, and how it might be located and used. These matters, as we have seen, would have important implications for safeguards and civil liberties impacts.

The single most important conclusion suggested by this review is that, if a plutonium industry as described in Table I were to be pursued in the near future, steady attention would need to be paid by Congress, the executive agencies, public-interest groups, and the courts to the way in which safeguards are defined, administered, monitored, and reviewed. Keeping such a plutonium safeguards program consistent with civil liberties would become one of the most important, continuing tasks of all those who cherish American freedom.

FOOTNOTES

Footnote citations are keyed to the Bibliography, which follows this section. Unless otherwise cited in full, reference numbers presented here with a # before them refer to the numbered items cited in full in the Bibliography.

1. Testimony of William Anders, Chairman, U.S. Nuclear Regulatory Commission, in House hearings, #56, Volume I, 66.
2. Statement of Senator Ribicoff, in Senate Hearings #4, page 763.
3. Atomic Energy Commission, Proposed Final Environmental Statement for the Liquid Metal Fast Breeder Reactor Program, WASH--1535, (December, 1974).
4. #51, pages 20-21.
5. For a discussion of these existing safeguards from a variety of perspectives, see the AIF Orlando Conference Report, #28.
6. Ibid.
7. See the testimony of witnesses Theodore Taylor, Eldon Greenberg, Herbert Brown, and Herbert Scoville, Jr., and the safeguards program discussions, in the 1976 Senate hearings, #4, and of witnesses Thomas B. Cochran, David F. Ford, Senator Mike Gravel, Ralph Nader, J.G. Spaeth, and Theodore Taylor, in the 1975 House hearing, #56.
8. Testimony of Alfred Starbird, Assistant Administrator for National Security, Energy Research and Development Agency, in 1976 Senate hearing, #4, at page 407.
9. Ibid, 408-411.
10. See note 7.
11. These are discussed in the items listed in Section C of the Bibliography.
12. Ibid.
13. Described in #78.
14. Ibid.

15* Ibid; Gravel, #69.

16. Described in #78.

17. Ibid.

18. Comey, #3.

19. McCormack, #25.

20. In #28.

21. Dyk, Marcus, and Kolasky, #68.

22. Communications to Alan F. Westin from Canadian Environmental Law Association, Canadian Civil Liberties Association, Probe, and Canadian Institute of International Affairs, January, 1977.

23. Flowers Committee, #80.

24. Ibid, at 81-82.

Bibliography

A. General Background on Nuclear Power and Proliferation.

1. Alexander, Tom. Our Costly Losing Battle Against Nuclear Proliferation. Fortune, v. 92, Dec. 1975: 143-146.

2. 2. Steven J. Commercial Nuclear Power and Nuclear Proliferation. (Ithaca, N.Y.) Cornell University Peace Studies Program, 1975. 66 p. (Occasional Paper No. 5). Brookhaven National Laboratory. IAEA costs and manpower rquirements under NPT. Prepared for the Office of Safeguards and Materials Management, U.S. Atomic Energy Commission, Upton, New York, 1970.

3. Comey, David Dinsmore, "The Perfect Trojan Horse," Bulletin of the Atomic Scientists, June, 1976.

4. 4. Committee on Government Operations, U.S. Senate, Hearings on the Export Reorganization Act of 1976, 94th Congress, 2nd Session, Jan. 19, 20, 29, 30 and March 9, 1976, especially testimony of Eldon V.C. Greenberg, National Resources Defense Council; Myron Kratzer, Acting Assisstant Secretary of State; Alfred D. Starbird, Acting Administrator for National Security, U.S. Energy Research and Development Administration; Dr. Fred C. Ikle, Director, U.S. Arms Control and Disarmament Agency; Victor Gilinsky, Commissioner, Nuclear Regulatory Commission; George Stathakis, Vice President, General E1ectric Co., Nuclear Energy Division; David Lillienthal, and Hans Bethe.

5. Commoner, Barry, The Poverty Of Power: Energy and the Economic Crisis (N.Y. : A.A. Knopf, 1976) , 82-120.

6. Dunn, Lewis A. and Kahn, Herman, Trends in Nuclear Proliferation (Hudson Institute, May 15, 1976) , Report Prepared for the U.S. Arms Control and Disarmament Agency.

7. 7. Energy Research and Development Administration, Final Environmental Statement: U.S. Nuclear Power Export Activities, April, 1976, especially Section 6, Safeguards and Physical Security and Section 7, Social and Other Impacts.

8. Epstein, William, The Proliferation of Nuclear Weapons, Scientific American, v. 232, April 1975: 18-33.

9. Feld, Bernard T., "The Menace of a Fission Power Economy." Science and Public Affairs, v. 30, April 1974: 32-34.

10. Ford, D.F. et al. The Nuclear Cycle: A Survey of the Public Health, Environmental and National Security Effects of Nuclear Power, Cambridge, Mass., 1974.

11. Ford Foundation Energy Policy Project, A Time to Choose (Cambridge: Ballenger Press, 1974.)

12. Geesaman, Donald P. and Abrahamson, Dean E., “The Dill- of Fission Power,” Bulletin of the Atomic Scientists, November, 1974.

13. Geyer, Alan. "The Nuclear Question Explodes;' Worldview, V. 8, Sept. 1975: 27-32.

14. Hans Bethe, et al. , "No Alternative to Nuclear Power," Bulletin of the Atomic Scientists, March, 1975.

15. Lindsey, George. "How Dangerous is Nuclear Proliferation," *Background* Paper for Canadian Seminar on Nuclear Proliferation, Trinity College, Toronto, February 7-9, 1975.

16. Mintz, Morton and Cohen, Jerry s., "Nuclear Power: 'The Faustian Bargain,'" Chapter 42, Power, Inc. : Public and Private Rulers and How to Make Them Accountable (N. Y. : Viking, 1976) .

17. Novick, Sheldon, The Electric War: The Fight Over Nuclear Power, (San Francisco: Sierra Club Books, 1976) .

18. "Nuclear Power Struggle Hits Critical Stage," Conservation Foundation Letter, March-April, 1976,

19. Redford, Robert W. Problems of Nuclear Proliferation, Canadian Institute of International Affairs, May, 1975.

20. Ross, Leonard, "How 'Atoms for Peace' Became Bombs for Sale," N.Y. Times Magazine, December 5, 1976.

21. Rowen, Henry S. and Jones, Gregory, Influencing the Nuclear Technology Choices of Other Countries: The Key Role of fuel Recycling in the U.S. (Los Angeles: Pan Heuristics, August 6, 1976).

22. Speth, J. Gustav, Tamplin, Arthur R., and Cochran, Thomas B., "Plutonium Recycle: The Fateful Step," Bulletin of the Atomic Scientists, November, 1974.

23. Stockholm International Peace Research Institute, Nuclear Proliferation Problems (Stockholm, 1974).

24. U.S. Congress, Senate. Committee on Banking, Housing, and Urban Affairs. Subcommittee on International Finance. Exports of Nuclear Materials and Technology. Hearings, 93d Congress, 2d Session. July 12 and 15, 1974. Washinqton, U.S. Gov't. Print. Off., 1974,

25. U.S. Congress. Joint Committee on Atomic Energy. Ad Hoc Subcommittee to Review the Liquid Metal Fast Breeder Reactor Program. Review of the National Breeder Reactor Program. 94th Congress, 2nd Session, January 30, 1976

26. Weinberg, Alvin, "Social Institutions and Nuclear Energy," Science, July 7, 1972.

27. Wohlstetter, Albert, et al., Moving Toward Life in a Nuclear Armed Crowd? (Los Angeles: Pan Heuristics, 1976).

28. Atomic Industrial Forum, Program Report: Conference on Nuclear Safeguards, Orlando, Florida, April 11-14, 1976 (AIF, Inc., 7101 Wisconsin Avenue, Washington, D.C., 20014) , especially Barton, John H., "The Societal lmpact of Safeguards" and conference discussions on this.

29. Atomic Industrial Forum, Technical Options for plutonium Safeguards, A Report of a Forum Study Group on Fuel Cycle safeguards (1975?).

30. Bennett, Carl A., William M. Murphey, and Theodore S. Sherr. "Societal Risk Approach to Safeguards Design and Evaluation." (Washington, U.S. ERDA) 1975, (ERDA-7) .

31. Brennan, C.D. et al. "The Threat to Licenses Nuclear Facilities." (Washington, The Mitre Corporation. 1975.) (MTR-7022)

32. Buchanan, J.R. , ed. "Safeguards Against the Theft or Diversion of Nuclear Materials" Nuclear Safety, v. 15, Sept.-Oct. 1974: 513-519.

33. Cohen, Bernard, "The Potentialities of Terrorism," Bulletin of the Atomic Scientists, June, 1976.

34. Comptroller General of the U.S., Role of the International Atomic Energy Agency in Safeguarding Nuclear Material, Report to the Committee on International Relations, House of Representatives, July 3, 1975.

35. Curray, Robert B. "Plutoniun Safeguards and Physical Security," Remarks before the Atomic Industrial Forum Topical Conference Kansas City, March 6, 1975.

36. De Nike, L. Douglas. "Radioactive Malevolence," Science and Public Affairs, Feb. 1974: 16-20; "Nuclear Terror," Sierra Club Bulletin, v. 60, November/December 1975: 9-13.

37. Dukart, Joseph M. "Atoms on the Move: Transporting Nuclear Material," Washington, U.S. Energy Research and Development Administration, 1975.

38. General Accounting Office, Improvements Needed in the Program for the Protection of Special Nuclear Material, November 7, 1973.

39. Gillette, Robert, "Nuclear Safety," Science, September 1, 8, 15, and 22, 1972; "Nuclear Safeguards: Holes in the Fences," Science, v. 182, Dec. 14, 1973: 1112-1114.

40. "Industry Inundated by Proposed New Safeguards Rules." Nuclear Industry, Feb. 1973: 45-47.

41. Ingram, Timothy H. "Nuclear Hijacking:" Now Within the Grasp of Any Bright Lunatic;' Washington Monthly, Jan. 1973: 20-28.

42. Inman, Guy. Research and Safeguards. Washington: U.S. Atomic Energy Commission 1968.

43. Jacobs, Paul. "What You Don't know May Hurt You: The Dangerous Business of Nuclear Exports," *Mother Jones,* v. 1, February/March 1976: 35-39.

44. Jenkins, Brian, "Will Terrorists Go Nuclear?" Santa Monica, California seminar on Arms Control and Foreign Policy, 1975. *(Discussion Paper NO. 64)* .

45. E.R. Johnson Associates, Inc. , *An Upper Estimate of Safeguards for Handling Plutonium,* Report prepared for Atomic Industrial Form, July 21, 1975.

46. Karber, P.A. et al. *Analysis of the Terrorist Threat to the Commercial Nuclear Industry*; Summary of Findings. Vienna, Virginia, BDM Corporation, 1975. 98 p. (Draft Working Paper B); *Analysis of the Terrorist Threat to the Commercial Nuclear lndustry*; supporting appendices. Vienna, Virginia BDM Corporation, 1975. Various pagings. (Draft Working Paper C).

47. Kinderman, E.M. *Plutonium: Home Made Bombs*? Presented at the Conference on Nuclear Public Information, organized by the Atomic Industrial Forum, March 5-8, 1972,

48. Krieger, David. "Terrorists and Nuclear Technology," *Bulletin of Atomic Scientists*, v. 31, June 1975: 28-34.

49. Kriegsman, William E. *Safeguards Objectives and Regulations in Perspective.* Remarks before the Atomic Industrial Forum Topial Conference. New Orleans, March 20, 1974.

50. Lapp, Ralph E. "The Ultimate Blackmail," *New York Times Magazine*, February 4, 1973: 13, 29-30, 33-34.

51. *Laws and Regulations Governing Nuclear Exports and Domestic and International Nuclear Safeguards*: *Message and Accompanying Papers from the President of the United States*, House Document No. 94-131, 94th Congress, 1st Session, May 6, 1975.

52. Leachman, Robert B. and Phillip Althoff, eds. *Preventing Nuclear Theft: Guidelines for Industry and Government.* New York, Praeger Publishers, 1972.

53. Meguire, Patrick G. and Kramer, Joel J., "Psychological Deterrents to Nuclear Theft: A Preliminary Literature Review and Bibliography," Prepared by Law Enforcement Standards Laboratory, National Bureau of Standards for Intelligence and Security Directorate, Defense Nuclear Agency, Washington D.C., March 1976.

54. Salisbury, David. "Quarantining Plutonium," ‘*Technology Review,* v. 78, January 1976: 4-5.

55. Stanley Foundation, Conference on Strategy for Peace, Discussion Group Report, *Nuclear Theft and Terrorism,* October 1975.

56. Subcommittee on Energy and the Environment, Committee on Interior and Insular Affairs, House Of Representatives, Oversight Hearings on Nuclear Energy, Part I, "Overview of the Major Issues," and Part Vl, "Safguards in the Domestic Nuclear Industry," 1975. In Part 1, see especially the testimony of William Anders Chairman, U.S. Nuclear Regulatory Commission, Daniel F. Ford, Union of Concerned Scientists; Senator Mike Gravel; Ralph Nader; Prof. Norman Rasmussen. n, M.I.T.; Rep. Frederick W. Richmond, N.Y. and Mason Willrich, Professor of Law, Univ. of Virginia. In Part VI, see especially the testimony of Rep. Hamilton Fish (N. Y.) ; the panel on nuclear threat (Bell, DeNilse, and Jenkins) ; the panel on Nuclear Regulatory Commission Safeguards (Chapman, Shapar, Builder, and Case) ; Arthur Tamplen and Tom Cochran, Natural Resources Defense Council; Frank Graham, Atomic Industrial Forum; Samuel Edlow, President, Edlow International Co. ; and Theodore B. Taylor, co-author, Nuclear Theft: Risks and Safeguards.

57. U.S. Atomic Energy Commission, Special Safeguards Study (Rosenbaum, et al.), April, 1974.

58. U.S. General Accounting Office. Protecting Special Nuclear Material in Transit: Improvement Made and Existing problem. Report to the Joint Committee on Atomic Energy, Congress of the United States, Washington, *1974.*

59. U.S. Nuclear Regulatory Cfission, Office of Nuclear Material Safety and Safeguards, Security Agency Study, August, 1976.

60. Willrich, Mason and Taylor, Theodore B., Nuclear Theft: Risks and Safeguards (Cambridge: Ballinger, 1974) .

C. Civil-Liberties-Oriented Analyses.

61. Ayres, Russell W., "Policing Plutonium: The Civil Liberties Fallout," Harvard Civil Rights-Civil Liberties Law Review, Vol. 10, No. 2, Spring, 1975.

62. Bartkus, Robert and Block, Gail, Rapporteurs' Report: Conference on the Impact of Intensified Nuclear Safeguards on Civil Liberties, Stamford Law School, October 17-18, 1975.

63. Barton, John H., Intensified Nuclear Safeguards and Civil Liberties, Paper prepared for the Nuclear Regulatory Commission, October 31, 1975.

64. Brookhaven National Laboratory, Technical Support Organization, Issues Related to Use of Guard Force to Protect Nuclear Materials and Facilities, July 8, 1974.

65. Bureau of National Affairs, Inc., Washington, D.C., Government Security and Loyalty: A Manual of Laws, Regulations, and Procedures (current edition) .

66. Clune, W.H. , Standards and Decision Rules for Evaluating Trade-offs Between Civil Liberties and Nuclear Materials Safeguards, Report to the Nuclear Regulatory Commission, October 31, 1975.

67. Cranston, Roger C. et al., Legal Implications of Guard Force Personnel: A Tentative Report prepared for the Brookhaven National Laboratory, June 26, 1974.

68. Dyk, Timothy B., Marcus, Daniel, and Kolasky, William J. Jr., Civil Liberties Implications of a Safeguards Program for Special Nuclear Material in the Private Nuclear Power Industry, a report to the Nuclear Regulatory Commission, October 31, 1975.

69. Gravel, Mike, "Plutonium Recycle: The Civil Liberties View," The Civil Liberties Review, April-May, 1976.

70. Green, Harold P., "Q Clearance:The Development of a Personnel Security Program," Bulletin of the Atomic Scientists, May, 1964, 9-15.

71. Orlansky, Jesse, "Security Investigations," in Wheeler, Stanton (cd.), On Record: Files and Dossiers in American Life, (N.Y.: Russell Sage Foundation, 1969), 275-315.

72. U.S. Atomic Energy Commission, Division of Security, Personnel Security Handbook (various editions, 1960's).

73. U.S. Nuclear Regulatory Commission, Final Generic Environment Statement on the Use of Recycle Plutonium in Mixed Oxide Fuel in Light Water Cooled Reactors, August, 1976.

74. Westin, Alan F., Privacy and Freedom (N.Y.: Atheneum, 1967).

75. Westin, Alan F. and Baker, Michael A., Data Banks in a Free Society (N.Y.: Quadrangle, 1972).

76. Wyle, Frederick S., Plutonium Recyclinq, Safeguards, and Civil Liberties, Report to the U.S. Nuclear Regulatory Commission, December, 1975.

D. Position Statements on Civil Liberties Issues by Interested Groups.

77. American Civil Liberties Union, Memorandum of Special Committee on Nuclear and Other Eneryy Programs Affectinq Civil Liberties, March 29, 1976.

78. Center for Science in the Public Interest, "Nuclear Power and Civil Liberties--Countdown to 1984?" People and Energy, September, 1976.

79. Industrial Union Department, AFL-CIO, "Nuclear Energy and America's Energy Needs," Viewpoint, Vol. 6, No. 3, 1976.

70. The Plutonium Economy: A Statement of Concern, Governing Board, National Council of churches, September, 1975.

E. British materials.

71. Atomic Energy Authority, Evidence to the Royal Commission on Environmental Pollution, 1974-75.

72. Barnaby, Frank, "Safguards - With or Without Strings," New Scientist, Feb. 25, 1971; "A Problem of Protection," New Scientist, May 29, 1975.

73. Bunejan, Tonv, The Political Police in Britain (London: Julian Friedmann, 1976).

74. Cox, Barry, Civil Liberties in Britain (London: Penguin, 1975).

75. "Democracy Versus the Breeder," (Comment), New Scientist, October 28, 1976.

76. Flood, Michael and Grove-White, Robin, Nuclear Prospects: A Comment on the Individual, the State, and Nuclear Power (Friends of the Earth Limited, Council for the Protection of Rural England, and National. Council for Civil Liberties, October, 1976).

77. Hill, John, "Tne Case for Saying Yes to Plutonium Recycle," The Observer, August 1, 1976.

78. Kenward, Michael, The Nuclear Backlash, New Scientist, v. 65, May 1, 1975: 263-264.

79. Report of the Committee of Inquiry on the Structure of the Electricity Supply Industry, January, 1976 (Plowden Report).

80. Royal Commission on Environmental Pollution, Sir Brian Flowers, Nuclear Power and the Environment, Sixth Report, September, 1976.

81. U.K. Department of Energy, Nuclear Activities in the U. K.: Commentary on Some Points of Public Interest, March, 1976.

82. Williams, David, Not in the Public Interest (London': Hutchinson, 1965).

Appendix IV: International Nuclear Industry

Stanford Research Institute

Appendix IV

International Nuclear Industry

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I INTRODUCTION

The objectives of this study are to present a comparative, analysis of various estimates (such as those by the IAEA and ERDA-52) of the probable rate of growth of the international nuclear industry, to select a likely growth for the midterm, and to discuss the factors that stimulate or constrain that growth. We also examine the importance of nuclear exports to the United States.

The approach to this task will be to consider the role of energy use in the economic development of the less developed countries (LDCs), and to investigate the relative benefits of an expanding nuclear industry to the LDCs and to those nations who are the primary vendors of nuclear equipment. Vendor nations include the U.S., France, Germany, Canada, and several others that manufacture and sell reactors and associated equipment on the world market. To streamline the discussion, we assume a familiarity with the principles of nuclear energy and the terminology of the industry, including the features of the nuclear fuel cycle: mining and milling, conversion and enrichment, fabrication, power generation, reprocessing, and waste disposal. Because of the time and budget constraints of this effort, the format of this report will be confined primarily to a review of the IAEA, ERDA, and other reports on this subject with a comparative analysis of their forecasts for tile growth of the international nuclear industry. We also assume familiarity with the above named reports and will only review those aspects of the reports pertaining directly to this discussion.

As the situation regarding many aspects of the nuclear industry is in flux, exact predictions of forward capacity are impossible to make. Therefore, the emphasis will be on establishing a reasonable expectation and its implications. The nuclear power industry is a complex of activities and facilities that requires several advanced technologies and substantial investment. It serves one customer, the electric power producer, who in turn requires capital intensive, high technology equipment, and deals in a product which must be produced instantly on demand with high reliability. These facts and the additional, and important consideration that the nuclear industry has grown from an exclusive military interest have made it unique among modern industries.

Some segments of the nuclear industry, such as reactor supply and fuel fabrication have reached industrial maturity and can offer equipment and services on a fully competitive basis. Other portions of the industry have still not entered the open market. Enrichment, for example, is exclusively under government management in the several countries concerned and reprocessing has not yet demonstrated commercial feasibility. Even for the mature segment (that dealing with power plant and nuclear steam supply) major technical advances, such as for the breeder reactor, are possible before the year 2000. If these are achieved, major revisions in other segments are inevitable.

Furthermore, health and safety problems of the industry and the controls implemented to deal with these have been evolved through experience and the impact of public debate. These controls have raised the costs of, and forecast .costs for, using nuclear energy. The debate has delayed government decisions that affect industrial development as in the case of plutonium recycling from reprocessing.

Finally, further debate and consideration of the prospects of terrorism and nuclear proliferation have led to government restrictions and controls which, in prospect, limit the normal commercial activities associated with industrial operations. In sum, the industry is maturing, albeit slowly but its future is not clear with its economics, technology, controls, and public acceptance all uncertain and subject to substantial change.

II THE ROLE OF ENERGY AND POWER IN ECONOMIC DEVELOPMENT

A. Forecasting of Use

Many correlations have been developed to relate economic activity, national development, and energy use.* Highly industrialized nations use more energy and generally have higher standards of living than less developed areas. Relationships between GNP/Capita and energy use/Capita have historically shown reasonable correlation. The driving forces behind the relationships are not well understood, however, and recent changes in energy prices, combined with a downturn in business activity and changes in attitudes toward energy use have called these relationships into question.

Forecasts of power growth within nations or groups of nations have often relied on extrapolations of historic trends, usually by an exponential function. For industrial nations during the period 1910 to 1970, this was adequate to forecast general trends for a few years into the future. While major wars caused deviations from the forecasts, the general trends were quickly resumed. Increased emphasis on use of machinery, concentration of activity in urban regions, greater economic advantage gained, central generating stations that could benefit from economies of scale, and the most efficient technologies all favored power growth. An average electric power growth of 8.1% per annum throughout the world was observed in the period 1950-70, for example. The LDC's

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* For example, see the Ford Foundation Policy Report, "A Time to Choose."

electric power growth was more rapid, 10.3% over the same period. These growths were higher than the annual growth for energy use as a whole of about 5% for the world and 6% for the LDCs.

In the period beginning in the 1960s, the energy growth rate first increased and then later decreased under the influence of increased oil prices and the recessions of the early 1970s. These rapid changes have caused many people to question the undoubtedly simplistic forecasting by extrapolation of historical growth, a process that does not fully consider effects of market saturation, changes in public attitudes (life styles) toward use of energy and power and the sensitivity of energy use to real changes in energy price on the demand for energy and power. Questions about availability of supply are also important. How much? At what price? Eventually the two forces should come to a dynamic equilibrium; however, different balance points and exchange prices can be expected to be different in different regions and countries of the world. Production costs will differ, transportation requirements (and costs) will have an influence, and national policy expressed in tariffs, embargos, and interest rates will all influence the. supply-demand-price relationship. Thus, full forecasts of power demand require evaluation and projection of at least the following:

- Resource-reserve relationships for major fuels, oil, coal, gas, and nuclear fuels in the important supply regions.
- Production cost relationships for these various regions.
- Transportation routes and costs between major supply and demand regions.

- Analysis and forecast for major demand regions (countries) of the composition and sensitivity of demand. This must include estimates of efficiency and capital cost associated with energy consumption, opportunities for conservation, and forecasts of public attitudes to energy use and environmental protection measures applied to energy activities.

From these, the general (regional) prices of fuels can be reduced, and rates of consumption estimated. To forecast individual demand into LDCs requires further analysis and projection, including:

- Development of demand-price sensitivities in individual or at least characteristic economies. (The behavior of industrialized nations should not be assumed for the LDCs.)
- Estimates of the regional or local efficiency and capital costs of energy use.
- Forecasts of the individual LDC development patterns. (Will the economy be agricultural, industrial, or service oriented? If industrial, will the development concentrate on energy intensive or non–energy intensive industry?)

To our' knowledge, there are no existing energy studies forecasting world supply-demand-price that consider regional characteristics and the dynamics of the energy market place, so that no one has established more than guesses about future regional or world price of fuels and the proportion that each will be used. Lacking that information, analysts assume various exponential growths related to industrial development and divide fuel use according to general estimates of price differentials. Analyses generally begin with some assumptions that energy prices will be less than, equal to, or greater than (by specified amounts) the current price of Mid-East oil and much general argument is offered to support the position taken by the individual setting forth the assumption.

In many applications, electricity competes with other energy forms. For example, in the case of residential space and hot water heating, the lower fuel costs of oil and gas systems often outweigh the economic advantage of electrical heating due to the less expensive equipment and maintenance costs. Many examples of competition can also be found in industrial applications. In some cases, electricity has a clear advantage because of its cleanliness or its essential nature (e.g. , electrolysis). In others, it is handicapped because of energy losses in transmissions. It has one substantial disadvantage. It cannot be stored on an industrial scale.

Electric power growth has come because of the essential convenience of electricity. It can be generated at large, economically-efficient stations, transported to point of use, and applied directly to the required task in almost any required quantity and manner. The central generating station also can be more easily operated to reduce environmental pollution.

Electricity use in the LDCs is generally characterized by lower capacity factors than found in the developed countries. The reasons for the lower capacity factors obtained for many of the LDCs are undoubtedly varied. However, those LDCs that lack a substantial industrial demand based on 7 day-a-week, 24 hour-a-day operations are likely to have greater fluctuations between peak and average demand, and therefore lower capacity factor, than that shown in industrialized nations. The industrial demand of developed countries increases the use of off-peak power and tends to smooth out a system's load curve.

Fission produced electricity generally comes from large units with high capital and low operating costs. It is most economic to operate these plants at the highest possible rating, therefore nuclear power stations are usually considered for base load application. Some details relating to costs are given in Chapter III. These special characteristics of nuclear power are important to the overall considerations of its application, especially in developing countries. This will be elaborated in the following section.

B. Characteristics of Nations Using Nuclear Power

At the present time, only a few of the less developed countries use nuclear power. Those expected to join in the future are expected to have certain essential characteristics now present in the major nations. First is the lack of cheaper energy sources properly located. Hydroelectric resources or cheap fossil fuel such as surface mined coal or excess natural gas generally produce cheaper electricity provided that supply and demand segments arc geographically related. A second characteristic is a sizable and preferably a rapidly growing power demand. Third, the sizable demand must be in a single, integrated power system. (Or if it is spread between two or more, then at least one must be large enough to support a nuclear station. We do not judge here whether the minimum plant size is 100 or 600 NW.) Finally, the power load curves should be such that the nuclear power plant can usually be operated (for economic reasons) at its full capacity.

Subsidiary to, but also determining, the capacity at load factors are such things as compactness of the demand area---a small area for the distribution system is desirable, and the presence of industrial operations that require constant or sustained power.

The larger nuclear plants also require substantial cooling water, and preferably sites that are free from natural disturbances, e.g., earthquakes and tornadoes. (These latter can be accommodated, but at high capital cost.)

Nations intending to install nuclear power must have, or be able to acquire, a labor force suited to the development. This force is not inordinately large, and nations having the required size and industrial development will very likely have or can train the necessary manpower for power plant operation. (A further discussion is provided by Appendix A.) Management of government interests in the nuclear operations and construction also make demands.

III REVIEW OF MAJOR ALTERNATIVE FORECASTS

Even though we are faced with the incomplete data and uncertain relationships mentioned earlier, it is still necessary to forecast. Nuclear power forecasts abound. They include some by the International Atomic Energy Agency (IAEA) alone, and in connection with the Organization for Economic Co-operation and Development, Nuclear Energy Agency (OECD-NEA). The IAEA/OECD-NEA forecast was amended by a study group of the International Energy Agency. This, still further modified, has been published by the U.S. Energy Research and Development Administration. The more recent estimates, made between late *1975* and fall 1976, predict total world nuclear installed capacity as ranging between 160-200 GW in 1980, 550-1000 GW in 1990 and 1410-2480 GW in the year 2000.

The OECD forecasts, published in late 1975, are shown in Table 111-1. These projections are based on individual OECD member country estimates which can be merely national policy statements or, as in the case with the U.S. forecast, be based, at least in part, upon analysis of energy - GNP relationships with certain assumed relative fuel costs and the like.

Two less recent forecasts of nuclear power growth in LDCs have been those made by the IAEA in its Market Surveys of 1973 and 1974. In the first of these, the growth of l4 developing nations was based upon previous detailed surveys of individual power networks and growth expectations.

Table III-1

IAEA/OECD-NEA NUCLEAR POWER GROWTH ESTIMATES* (GWe)

	1975	1976	1977	1978	1979	1980	1981	1982	1983	1984	1985	1986	1987	1988	1989	1990	1991	1992	[illegible]
Australia														0.5	0.5	1	1	1	6
Austria	-	-	0.7	0.7	0.7	0.7	0.7	2	2	2	3	3	4	4	5	6	7	8	14
Belgium	1.7	1.7	1.7	1.7	1.7	3.5	4.5	5.5	6.5	8.5	9.5	10.5	12.5	13.5	11.5	16.5	17.5	18.5	30
Canada	2.5	3.3	4	4.8	6.1	7.2	8.3	9.5	12.5	14.7	18.4	22	26	30	36	41	46	51	115
Denmark	-	-	-	-	-	-	-	0.9	0.9	1.8	1.8	2.7	2.7	3.6	3.6	4.9	4.9	6.2	11.4
Finland	-	-	0.4	0.4	1.5	1.5	1.5	1.5	2.7	2.7	3.9	3.9	3.9	3.9	4.9	4.9	5.9	5.9	13
France	2.3	5	5.9	7.7	13.2	20.4	27.2	33.8	40.8	47.8	56	62	69	76	83	90	97	104.0	170
Germany	3.2	7	9.1	10.6	14.1	19.1	24.6	28.6	32.6	39.6	44.6	51	57	64	70	77	82	87.0	131
Greece	-	-	-	-	-	-	-	-	-	0.6	0.6	0.6	1.2	1.2	1.2	1.2	1.5	1.8	4
Ireland	-	-	-	-	-	-	-	-	-	0.7	0.7	0.7	1.3	1.3	1.3	2	2	2	6
Italy	0.6	1.4	1.4	1.4	1.4	1.4	3.4	7.4	12.4	19.4	26.4	32	38	45	53	62	70	79	110
Japan	6.6	9	11	13	15	17	24	30	36	41	49	51	60	67	73	81	88	95	157
Luxembourg	-	-	-	-	-	-	-	-	-	1.2	1.2	1.2	1.2	1.2	1.2	1.2	1.2	1.2	1.2
Netherlands	0.5	0.5	0.5	0.5	0.5	0.5	1.5	1.5	2.5	2.5	3.6	3.5	4.5	5.5	6.5	7.5	7.5	8.5	16
New Zealand ...	-	-	-	-	-	-	-	-	-	-	-	-	-	1.2	1.2	1.2	1.2	1.2	3
Norway.........	-	-	-	-	-	-	-	-	-	-	-	-	0.9	0.9	0.9	1.8	1.8	1.8	4
Portugal	-	-	-	-	-	-	-	0.7	0.7	1.4	1.4	2.3	2.3	2.3	3.3	3.3	3.3	4.3	8
Spain	1.1	1.1	3	4.8	6.7	8.7	11.7	14.7	17.7	20.7	23.7	27	30	34	38	42	46	50	60
Sweden	3.2	3.2	4.7	5.6	6.5	7.4	8.3	8.3	9.3	10.3	11.3	12.3	13.3	14.3	15.3	16.3	17.3	17.3	24
Switzerland	1	1	1	1.9	2.9	3.8	4.8	5.8	6.9	6.9	8	8	8	8	8	8	8	8	12
Turkey	-	-	-	-	-	-	-	-	-	0.6	0.6	0.6	1.6	1.6	2.2	2.2	2.2	3.3	16
United Kingdom .	4.8	7.2	8.4	10.4	11.1	11.1	11.1	10.6	12.5	14.7	15.4	16.3	19	23	27	31	37	43	115
United States ...	40.1	47.5	54.6	61.8	68.2	82.2	102	126	152	179	205	234	266	301	341	385	432	461	680
OECD, High Estimate	68	88	106	125	150	185	234	287	348	416	484	518	622	703	791	890	981	1079	986
Low Estimate	68	86	101	118	139	171	215	264	324	376	437	491	553	620	692	774	847	926	885
African région[1].	-	-	-	-	-	-	0.5	1.4	1.4	2.3	3.1	3.9	3.9	5.4	5.4	6.9	7.7	8.9	29
American région[2]	0.3	0.3	0.9	0.9	2.8	3.6	4.4	7	8.6	12.2	14.4	18	22	26	31	35	41	47	147
Asian région[3] ...	0.7	0.9	2.3	2.9	4	5	8.3	12.1	15.8	21.7	28.2	35	44	51	61	72	81	94	224
TOTAL (High Estimate)	69	89	110	129	157	194	247	307	374	452	530	605	692	785	888	1 004	1 113	1 229	180
Low Estimate .	69	87	105	122	146	179	227	285	342	409	479	542	615	693	778	875	961	1 056	605

[1] Algeria, Egypt, Iraq, Kuwait, Morocco, Saudi Arabia, South Africa, Tunisia.

[2] Argentina, Brazil, Chile, Colombia, Cuba, Mexico, Jamaica, Peru, Uruguay, Venezuela.

[3] Bangladesh, Hongkong, India, Indonesia, Iran, Israel, Korea, Malaysia, Pakistan, Philippines, Singapore, Taiwan, Thailand.

* From "Uranium Resources, Production and Demand , Joint OECD/NEA-IAEA Report, Paris, December, 1975.

The second report was extended to consider projections for 41 additional countries. Another forecast, critical of the IAEA approach, was made recently by Richard J. Barber Associates. However, this too seems to use the Market Survey as a base.

Those forecasts made before late 1973 were largely out-dated by the sharp jump in oil prices and the rearrangement of thinking which followed the oil embargo. A similar situation occurred because of the rapid escalation of capital costs and spot purchase uranium fuel prices noted during the 1974-76 period. These cost increases produced a significant effect on the economics of nuclear systems in competition with fossil fired plants.

The general trend of these various forecasts has been toward progressively smaller nuclear capacity projections. Reduced energy demand, increases in nuclear fuel cycle and plant capital costs, and practical operating experience with lower than expected nuclear plant capacity factors are among the reasons for these increasingly conservative forecasts. In view of these considerations, and accounting for the potential development of a worldwide market in coal, and the potential increased use of hydropower and surplus gas, we believe that the most conservative of the major reports, the IEA estimate as modified by ERDA, is the most realistic.

The IAEA forecast approach used in the 1974 market survey formed the basis for much of the work and analysis which followed. The IAEA market surveys will therefore be discussed in detail in the following paragraphs.

A. IAEA Market Survey

Table III-2 lists the fourteen countries considered in the 1973 IAEA market survey. Each of these countries provided basic data and counterpart staff, and participated with IAEA teams in site surveys. Included in the individual country data was that on projected population and GNP growth. A relationship (based upon historical data for 111 countries in the period 1961-1968*) between GNP/capita and electric energy generation/capita was established. This relationship was then used to project annual electricity consumption to the year 2000 for each of the 14 countries in the Market Survey. In addition to these IAEA projections, some of the countries involved provided their own forecasts. For the 5 cases in which there were appreciable differences, they were included as high forecast cases above the more conservative IAEA projections.**

Table III-2

COUNTRIES INCLUDED IN THE 1973 IAEA MARKET SURVEY

Argentina
Bangladesh
Chile
Egypt
Greece
Jamaica
Korea
Mexico
Pakistan
Philippines
Singapore
Thailand
Turkey
Yugoslavia

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*This period saw a particularly rapid growth in electric power demand in countries such as South Korea.

**In each case the individual country forecast was higher than the IAEA.

The existing systems plus planned additions to about 1979 were used to construct the base system which was then expanded by the IAEA analysts to meet future demand using additions of economic base hydroelectric, base fossil, base nuclear, and intermediate and peaking fossil plants supplemented when possible by peaking load hydroelectric units. The expansion fitted new plants into the system to provide sufficient plant capacity to meet peak local and reserve criteria with each new plant added being chosen to obtain minimum present worth cost. Historical data from the individual countries about load patterns and “plausible” patterns of their future development were used by the agency and local officials to develop the load patterns. Capacity and reserve were chosen to reduce the generating systems’ loss of load probability to as close to 0.005* as possible, with a maximum of .01. It was felt that this range of values would be acceptable to developing countries, although they would be unacceptable to industrialized nations. The maximum size of units to be added to the country’s system varied between 5 and 20% of the peak load foreseen. It is important to note that the IAEA assumed nuclear power stations as small as 100 MW could be added to individual systems. The lowest capacity considered economic was 300 MW and only 9-10 units (from low and High forecasts respectively under reference market conditions) below 400 MW capacity, or a total of 3200-3500 MW, were assumed to be added by 1990.

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* Demand may exceed generating capacity for, at most, 0.5% of time during the year.

Capital, fuel and operating costs assumed were those of 1973 and earlier. In its capital cost estimates the IAEA used U.S.: data as developed by the Oak Ridge National Laboratory and the ORCOST program for their comparison. Capital costs for equipment were adjusted on a country by country basis considering the available international sources for equipment, country performance, transportation costs, etc. Materials costs were established for each country using construction and other cost indices. Labor costs and efficiencies were individually considered. In all cases the costs were estimated to increase at a uniform annual rate in all countries. Adjustments for varying plant size were made by standard scaling factors.

The reference case economic parameters used by the IAEA are set forth in Table III-3a and Table III-3b. The plant capital costs assumed here are based on data as of January 1, 1973, and therefore do not reflect the rapid increases noted in the mid 1970s.

Table III-3a

REFERENCE CASE ECONOMIC PARAMETERS, GENERAL

	Study Value[1]	Approximate Real Value
Discount Rate	8%	12%
Capital and O&M Cost Escalation	0%	4%
Fuel Oil and Gas Price Escalation	2%	6%
Depreciation	Linear	

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[1] General inflation rate was assumed constant at 4%/yr.

Table III-3b

REFERENCE CASE ECONOMIC PARAMETERS, CAPITAL COST

Plant Size, MW	Type	Capital Cost $/Kw[2] Max. Market Survey Nation	 Min. Market Survey Nation	 USA
300	Nucl	593	442	624
	Oil	268	206	315
600	Nuc[1]	439	322	460
	Oil	216	170	253
	Coal			287
1000	Nuc[1]	365	266	283
	Oil	189	146	223

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[1] PWR

[2] Based on data of 1 January 1973

Electric power production is a capital intensive operation. Rapid expansion of plant requires both the generation of excess revenue and borrowings. Current estimates place capital costs in the range of $1000/KW for large nuclear plants and $600 to $750/KW for coal plants, significantly higher than those found in Table III-3b.* At these costs, a modern, large station is a substantial additional investment for all but the largest of electric utility systems. Costs of $1000/KW are far from the $200/KW costs forecast for nuclear power stat-ions in the early 60’s and much has been said about the difficulties of capital formation to finance nuclear power growth.**

The higher capital investment may impact on developing nations with low gross national product. However, the developing countries may find is possible to raise the capital required, perhaps through favorable loans

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*More detailed discussion of capital costs and capital cost differentials will be found later in this chapter.

**From the viewpoint of the electrical utility systems (especially those in the U.S.) who have previously operated with declining real costs for new capital plant (because of technological innovation and economy of scale) and fuel costs and who now must both change their financial viewpoint and justify the change to consumer-conscious regulatory commissions, the change in cost is undoubted traumatic.

made by the exporting country, e. g., Federal Republic of Germany--Brazil, or international agency loans. For the former loans there is little alternative use possible, for the latter, the LDC must justify the application of funds to nuclear power in contrast to other industrial or agricultural development.

Heat rate data, important to evaluation of fuel costs, were furnished by Bechtel Corporation and represent low average of design data for many plants. This data was checked by other experts. Fossil fuel costs were estimated by the IAEA (R. Krymn). The price for oil in each country was based upon the price of crude in the Persian Gulf, then estimated at $1.80\bbl for Kuwait 31° API. Transport costs to country harbors were then estimated, e.g., $0.83/bbl to Rotterdam. Escalation of 6% was assumed for the crude oil price over the period considered. Costs of coal and lignite were established for each country having indigenous reserves. These were essentially each country's estimate of its production cost, a general escalation of cost of 4% was used. Fuel oil was priced at 95% of crude. In no case was tax on import duty added to the base cost of oil.

Nuclear fuel costs were estimated by IAEA from published data; the basic cost assumptions are shown in Table III-4. Interest was charged at 8% and payments were made at reasonable intervals as the fuel progressed from step to step in the processing and fabrication chain. Fuel costs resulting from the calculation for an equilibrium case are shown in Table III-5.

Table III-4

NUCLEAR FUEL CYCLE COSTS, IAEA MARKET SURVEY, 1973

	$	Unit	Loss %
Concentrate	7	lb/u308	
Conversion	2.60	Kg U	0.5
Enrichment	32	SWU	0.0
Fabrication--first core	110	Kg U	1.0
--equilibrium core	80		
Recovery Cost--first core	44	Kg U	1.3
--equilibrium core	40		
Plutonium Credit	10	g Pu fissile	

Other Data

Burn up 13,000 rising to 31,000 MW d/t

Enrichment 2.41 rising to 3.48% U235

Final fissile Pu 0.46 rising to 0.72%

Load Factor 80%

Table III-S

FUEL CYCLE COSTS, EQUILIBRIUM CASE

	U.S. mil/Kwh
Concentrate	0.681
Recovered U	-0.104
Recovered Pu	-0.228
Conversion, net	0.079
Enrichment, net	0.730
Fabrication	0.392
Recovery	0.131
	1.681

No transportation costs to individual countries were charged and general inflation of 4% per year was assumed.

In 1974 the IAEA issued a supplementary report which reflected the higher oil prices of that year and new nuclear cost figures while extending the report to 41 other countries, including 5 in Eastern Europe. The same general methodology was used but some modifications were noteworthy.

Detailed analyses of capacity additions were made for 2 countries to determine the fraction of total electric capacity additions that would be nuclear. These results were extended to the 12 other countries in the original Market Survey. Data on population, GNP and electricity consumption were collected for the 41 countries. These data were used as before to project electricity capacity to 2000. The load order analysis was changed to consider "practical" as well as economic solution factors in meeting each load. Break even load factors for nuclear plants compared to oil fired plants, using oil delivered at $\$6.00/10^6$ k cal($9/bbl) with updated capital costs for. both nuclear and oil fired plants were computed as they applied to each of the Market Survey countries. The break even plant capacity factors for small plants obtained ranged from 73.2% for a 100 MW unit at highest capital cost ($1052/KW), to 29.9% for a minimum cost 400 MW unit ($471/KW). For plant sizes larger then 400 MW, nuclear plants with even smaller capacity factors would remain economically competitive with oil. The results of the 1974 IAEA forecast are presented in Table 111-6.

The two IAEA market studies were completed before the total Impact of the oil price rise was felt and therefore neglected both the ultimate (current price) rise in oil and increase in nuclear fuel and capital costs. Other IAEA assumptions, namely high plant capacity factors, availability of small nuclear plants, and low inflation (discount) rates gave greater cost

Table III-6
1974 IAEA MARKET SURVEY, SCHEDULE OF NUCLEAR CAPACITY ADDITIONS FOR 1981-1990 (MW)

	1981	1982	1983	1984	1985	1986	1987	1988	1989		Total
Central and South America											
Mexico	600 800	800	2 x 800	2 x 1000	2 x 1000	2 x 1000	2 x 1200	2 x 1200	3 x 1200	1200 1500	20 900
Brazil	-	-	-	-	800	800	2 x 1000	2 x 1200	2 x 1200	2 x 1200	10 800
Argentina	-	600	-	600	800	800	800	1000	1000	1000	6600
Venezuela	600	600	600	600	-	600	600	-	800	-	4400
Columbia	-	-	-	500	-	-	600	-	-	600	1700
Peru	-	-	-	400	-	-	400	-	500	-	1300
Chile	-	-	-	300	300	300	400	-	400	-	1700
Cuba	250	250	-	300	300	-	300	300	400	-	2100
Jamaica	-	150	150	150	150	150	200	200	300	300	1750
Uruguay	-	150	-	200	200	-	250	250	-	-	1050
Costa Rica	-	-	-	-	-	-	150	-	150	-	300
Panama	-	-	-	-	-	-	-	-	150	-	150
Dominican Rep.	-	-	-	-	-	-	-	-	150	-	150
Ecuador	-	-	-	-	-	-	-	-	150	-	150
Bolivia	-	-	-	-	-	-	-	-	150	-	150
Guatemala	-	-	-	-	-	-	-	-	150	-	150
El Salvador	-	-	-	-	-	-	-	-	150	-	150
										Total	53 500
Europe Middle-East and Africa											
Spain	2 x 1000	1000	2 x 1000	1200	2 x 1200	2 x 1200	1500	2 x 1500	1500	2 x 1500	20 000
Yugoslavia	-	600	600	800	800	2 x 800	2 x 800	1000	1000	2 x 1000	10 000
Greece	500	-	500	500	500	600	600	600	600	600	5000
Turkey	600	-	-	600	-	600	800	800	2 x 800	-	5000
Egypt	-	-	600	-	600	600	600	2 x 600	600	800	5000
Israel	400	400	400	400	-	400	400	500	500	500	3900
Kuwait	150	150	-	200	200	-	200	200	250	-	1350

Table III-6 (cont.

Iraq	-	150	-	150	-	200	200	-	200	200	1100
Ghana	-	-	-	-	150	-	-	150	-	-	300
Morocco	-	-	-	-	-	-	200	-	200	-	400
Algeria	-	-	-	150	-	-	150	-	-	150	450
Nigeria	-	-	-	-	-	-	150	150	-	200	500
Lebanon	-	-	-	-	-	-	-	-	-	-	0
Cameroon	-	-	-	-	-	-	-	-	-	-	0
Syria	-	-	-	-	-	-	150	-	150	150	450
Albania	-	-	-	-	-	-	-	-	150	-	150
Uganda	-	-	-	-	-	-	-	-	150	-	150
Tunisia	-	-	-	-	-	-	-	-	150	-	150
Zambia	-	-	-	-	-	-	-	-	150	-	150
Saudi Arabia	-	-	-	-	-	-	-		150	-	150
										Total	54 200
Asia and Far East											
India	2 x 800	2 x 800	2 x 1000	2 x 1000	2 x 1000	2 x 1200	3 x 1200	3 x 1200	3 x 1200	4 x 1200	27 200
Iran	600	600	600	800	800	800	800	1000	2 x 1000	2 x 1000	10 000
Taiwan	600	600	600	600	600	2 x 600	800	800	800	800	7400
Korea	600	600	600	600	600	800	800	1000	2 x 1000	1000	8600
Pakistan	-	600	-	600	-	-	600	600	2 x 600	2 x 600	4800
Thailand	200	300	-	400	500	500	-	600	600	600	3700
Philippines (Luzon)	-	600	-	-	600	800	800	-	1000	1000	4800
Hong Kong	300	300	-	400	400	-	400	400	500	500	3200
Singapore	250	250	2 x 250	250	400	400	2 x 400	400	400	600	4250
Malaysia (Peninsular)	-	200	200	-	200	250	300	-	300	300	1750
Indonesia (Java)	-	-	200	200	200	-	200	300	300	300	1700
[illegible]	-	150	-	200	-	200	-	200	-	200	950
Bangladesh	200	200	250	250	400	400	500	600	600	600	4000
										Total	82 350

Table III-6 (cont.)

	1981	1982	1983	1984	1985	1986	1987	1988	1989	1990	Total
Centrally Planned Economies											
Poland	400	400	400	400	400	800	800	100	1200	1200	7000
Romania	400	·	400	400	400	400	609	600	1000	1000	5200
Czechoslovakia	400	400	600	600	600	800	1000	1000	1200	1200	7500
Bulgaria	400	400	400	400	600	600	600	600	800	800	5690
Hungary	400	·	400	400	400	400	400	600	600	600	4000
										Total	29800

advantage to nuclear plants than now seems justified. These factors were seemingly taken into account in the more recent OECD\IAEA review of December 1975 and further the reviews of early 1976.

B. Barber Study

A study by R. J. Barber Associates was published in 1975 which used different economic assumptions. These included higher capital costs, higher fuel cycles costs, a lower plant operating factor and a higher discount rate. Barber's capital costs, are based on the data given in WASH 1345. While Barber argues that the capital costs in the LDCs might well be 25% higher than in the U.S. , he does not use that factor. He lists minimum cost estimates and conservative cost estimates to be used by the LDC planner as

Plant Cost Estimates, 1000 MW Nuclear Station*
$/KW

	Minimum	Conservative
PWR	598	745
Coal	485	600
Oil (no $S0^2$ abatement)	372	460

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*1981 startup

Nuclear fuel costs were estimated at 4.39 mils/kWhr and 5.17 mills/kWhr for favorable and unfavorable assumptions about the various parameters. (Oxide feed was assumed at $20/lb $U_3 0_8$, enrichment at $75/SWU, and discount rate at 20 and 25% and capacity factors at 60 and 50% for the favorable and unfavorable cases respectively.)

Fossil fuel prices are discussed at length in the Barber report. A range of possible prices was presented. Generally it was assumed that oil could range from as low as $6.50 a barrel to more likely prices of $8-9/barrel.

Indigenous coal is offered as a viable alternative to oil and nuclear fueled plants. Several coal prices are quoted but fuel cycle prices of 6.12 mills/kWh assumed.

Most important to the comparisons made is Barber’s assumption that nations with high internal inflation will use higher discount factors. Barber assumes a “reasonable medium” discount rate of 20% and suggests that rates as high as 25-30% may be applicable in certain situations.

The Barber study also assumes that nuclear power plants smaller than 600 MW will not be available and eliminates them from consideration. While it mentions taxes and tariffs it makes no assumptions about them, apparently following the IAEA lead. An attempt to include these effects into the economic evaluation would be fruitless, for taxes and tariffs can be used by an LDC to encourage or discourage the use of nuclear (or other) power. Even though the Barber study disagrees with many aspects of the IAEA approach, and with the explicit data used, it still uses the IAEA Market Survey as the framework for its analysis. In addition, all other studies discussed seem tied to the IAEA data base and approach.

C. Other Studies

The IAEA market survey of 1974 formed the basis of an OECD\IAEA survey of 1975. This latter report took advantage of the passage of time by considering the escalation of construction costs during the 1974-75 period and the continued existence of the OPEC cartel. It is primarily, however, a digest of national plans of the participating countries as reported in the spring of 1975.

In the fall of 1975 and the spring of 1976, the International Energy Agency conducted another survey which projected further changes in nuclear plant construction and fuel cycle costs. This survey was subsequently revised by ERDA in a paper entitled “World Requirements and Supply of Uranium.”* Some of the results of various nuclear growth projections are summarized in Table III-7. SRI has regrouped this published data in certain cases in order to provide direct comparisons between the studies.

D. SRI Analysis

In assessing these studies, SRI has not attempted a new analysis of electric power demand or nuclear power share. It has examined the latest data presented on nuclear power costs and tested the stated assumptions for reasonableness. In general, SRI has used high capital and fuel cycle costs.

SRI has assumed that for the earlier periods of development, the developing nations will use tall stacks to dilute but not capture $S0_2$ emissions from coal-fired plants, resulting in capital costs in the $775/kW range. (It assumes the coal mined will have less than 270 sulfur.) SRI further assumes once through cooling, for nuclear and coal-fired power stations. These assumptions result in capital costs below the maximum assumed for U.S. built plants.

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* paper by E.J. Hanrahan, R.H. Williamson, and R. B. Presented at the Atomic Industrial Forum’s International Conference on Uranium, Geneva, September 1976.

Table III-7

COMPARISON OF PROJECTIONS FOR THE GROWTH OF NUCLEAR GENERATING CAPACITY (GWE)

Study and projected years

	IAEA (1974 study)			IAEA/OECD-NEA (1975 study)			ERDA (1976 study, modified IAEA data)			Barber (1975 study)
	1980	1990	2000	1980	1990	2000	1980	1990	2000	2000
World*				179- 194	875- 1004	2005- 2480	160- 1 1	620- 715	1410- 1650	
Non-U.S.*				97- 112	490- 619	1005- 1480	100	425	1030	
LDCs**	20	196	572	17+	159+	500+				
13 LDCs considered by Barber Report***	11	130	426							317

* Does not include Eastern Bloc countries.

** Includes 34 of the most important LDCs, but does not include any Eastern Bloc countries.

*** These 13 are projected by IAEA data (as modified by Barber Report) to generate over 90% of the nuclear power in the LDCs. They are Mexico, India, Brazil, Iran, Taiwan, Korea, Argentina, Pakistan, Singapore, Egypt, Philippines, Turkey, and Thailand.

\+ Includes South Africa (which is not considered among the 34 countries of the 1974 IAEA study).

++ This is a modification of IAEA data. The Barber Report still considers this modified estimate to be high.

SRI has estimated ranges of coal and oil prices as part of other project work. We find that several coal producing sections of the world such as Australia, S. Africa, and the Western U.S. could deliver coal to seacoast power plants in developing countries at prices ranging from low values of $17-24/ton. (Actual prices could be higher if the demand grows.) We believe that world oil supply estimates cited by Barber are optimistic and the prices for delivered oil on the low side. However, SRI's analyses also have indicated that supplies of oil will be adequate through the end of the century and that prices may moderate by 1980 when expressed on a constant dollar basis (see attached article by V. Eugene Harless in Appendix B).

Capital costs of nuclear power plants with once through cooling will lie in the $925/KW range for a 1985 starting plant.* We do not believe that the rapid changes in capital cost observed from 1970 to 1975 will necessarily continue. Much learning has taken place, retrofitting during construction should diminish, and labor efficiencies rise with the advent of standardized plants. Experience and better planning should also reduce the time required for plant construction. A reduction of 2-3 years seems possible with concomitant reduction in interest cost during construction. We believe that costs of $80/kg-SWU for enrichment, and $250-300 per kg of metal reprocessed are possible. This produces fuel cycle costs that are as high as 7 mils/kWh.*

Barber has suggested plant factors of 60 and 50% and perhaps lower. At least some of the unfavorable operating experience encountered with

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*V.S. Boyer, "The Economics of Nuclear Power." Speech presented at the Third Congressional Seminar on the Economic Viability of Nuclear Energy, January, 1976 current plants has been caused by retrofit and regulatory caution, especially in the U.S. Learning has been an expensive process in many aspects of reactor operation. Reactor suppliers and customers are both paying more attention to factors that improve plant on-line time (better maintenance scheduling and refueling procedures, for example). Recent data have shown that of all light water plants above 150 MW throughout the world, 75% had an annual capacity factor of greater than 50%, and 69% had a cumulative factor above 50%. U.S. experience shows an average annual capacity factor of 58% through the end of 1975. Three other countries with four or more reactors have achieved higher values: W. Germany (73%), France (70%) and the U.K. (66%). These data include plants such as Brown's Ferry 1 and 2 that were shut down for repair for approximately 8 months during the year, and other plants subject to extensive modification. On the other hand several plants have exceeded 80% capacity factor for a year or more. SRI has assumed a 60% capacity factor in its analysis. This may be considered conservative.

Given the previously stated assumptions by SRI concerning prices of nuclear and coal power generation systems and nuclear fuel cycle costs, break even coal costs can be developed for various plant sizes and fixed charge rates. Table III-8 shows these costs for plants of 600 MWe and 1100 MWe capacity installed in the mid-1980s.

Table III-8

MID-1980s BREAK EVEN COAL COSTS ($/TON)*

Fixed Charge Rate	Plant Size 600 MWe	Plant Size 1100 MWe
10%	28	23
15%	35	28
20%	42	32
25%	49	37

*Assumptions:
Nuclear plant capital costs--$925/KW (1100 MW), $1135/KW (600 M-w)
Coal-fixed capital costs--$690/KW (1100 MW), $775/KW (600 MW)
Capacity factor--60%
Nuclear fuel cycle cost--7.3 mils/kWhr at assumed capacity factor

As the above table indicates, moderate cost coal, hydropower and perhaps surplus gas could be competitive with nuclear power in the LDCs*. Although an independent country-by-country study might be desirable for confirming the competitive nature of nuclear power, the scope of this study precludes such an effort. We believe that the lowest estimate developed, that of the IEA as modified by ERDA, will be most representative of the future. This low estimate can be raised by many factors. Some of these are not of direct economic consequence. For example, incentives that seem to favor the spread of nuclear power include export pressures of nuclear suppliers, desire for alternate energy supply on the part of the installer, desire to prove modern attitudes and advance

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*The competitive picture changes when developed country economics is considered . In the first place we expect that requirements for $S0_2$ removal. instead of tall stack dispersal will add extra operations and capital costs and could decrease plant efficiency markedly. Partially counterbalancing this will be the added cost. of natural draft cooling towers added to the nuclear plant. Other factors may also he important.

industrial training, particularly on the part of less developed countries, and interest in nuclear weapon capability.

In addition to making less developed countries dependent upon developed countries, the extraordinary support requirements of nuclear plants creates pressure among the developed countries to export nuclear products. The support structure is expensive and unique, if domestic power requirements are not adequate to fill the order work of the various support facility, then the owner-operators and perhaps the country in which the plant is operated falls under pressure to export nuclear power elsewhere, to the LDCs for example.

We have not attempted a detailed analysis of the manufacturing capacity, engineering abilities and other support services related to nuclear power development. However, it is likely that the U.S. and several European countries have excess capacities “for reactor production and in nuclear support services. The temporary, if not permanent change in the rate of growth of electricity consumption, deferments in construction because of that change and higher capital costs, delays, postponements or cancellations of nuclear power prospects because of public opposition and related regulatory and judicial rulings has upset the growth of nuclear power stations. Therefore, existing and planned support installations in some segments of the industry are without adequate developed country markets.

The rapid changes in nuclear power plant planning--first, a rapid increase following the oil embargo and' large step increase in oil price and second, a rapid slowdown or cancellation phase following delays in authorization and rapid capital cost increases--have interacted throughout all segments of the industry --including the fuel cycle as well as the manufacturing and engineering support segments. Pressures also exist in these segments to stabilize activity and encourage moderate growth. Thus exporting countries may decide to offer trade incentives, including favorable loans, an action which reduces the effective discount rate.

Additional incentives for the development of nuclear power are the desire for diversification of energy supplies and the relative ease with which uranium and plutonium fuel supplies can be transported and stockpiled. All of the front-end fuel cycle materials can be shipped economically by air with the exception of the original ore. Thus shipping delays are not crucial. It is usual for a nuclear power station to have several weeks, or more likely, months of fuel supply in new fuel elements on hand so that temporarily interruptions due to embargo, strike etc. , are not so disruptive. Fossil fuels do not have these advantages, which can be important to LDCs with transport, harbor clogging, and similar problems.

It is obvious from their optimistic forecasts that many LDCs plan to have nuclear power play an important role in their development. In many regions this energy source represents the most economical means of generating electricity and also allows for a diversification of energy resources and a greater degree of energy self-sufficiency.

Without the nuclear option, those countries that do not possess sufficient indigenous hydrocarbon supplies or hydropower resources would have to rely on imported fossil fuels. This implies a strategic dependence on others for a continuous supply of energy. The possible consequences of such dependence were felt by most LDCs during the 1973 oil embargo and in the price jump that followed.

In oil importing LDCs, a high oil price makes a strong impact on agriculture and industry. There are very few non-essential uses of energy in LDCs. High oil prices mean higher costs for the fuel and fertilizer required for domestic food production and for the boiler fuel used in electric power generation and industrial heat processes.

South Korea, for example, paid $300 million for oil imported during 1973 but during 1974 this figure increases to $1.2 billion. The effect on the Korean economy was widespread; the price increases greatly hurt Korea’s balance of payments, sparked further inflation and hindered industrial production.

The price of fuel is only a small part of the cost of electricity from nuclear power generation. The economics of nuclear plants are therefore less affected by fluctuations in the price of fuel than fossil plants.

Nuclear power is seen by most LDCs as a means of reducing high priced oil imports and dependence on foreign-supplied fossil fuels. However, it is very likely that these nations are currently too optimistic about the amount of relief from fossil fuel dependence that even ambitious nuclear programs might provide. Nuclear energy can only be used practically for base-load power generation and it is not likely that more than a small fraction of total end use energy consumption will be in the form of electricity for many years to come. (In Asia and Africa electricity presently accounts for less than 5 percent of total end use consumption, in Latin America this figure is about 10%; in OECD Europe and North America electricity presently supplies 15% of end use energy).

IV THE MOVEMENT OF NUCLEAR MATERIALS AND EQUIPMENT

With the assumption of moderate nuclear power growth generally, and in the developing countries especially, we examine the likely flows of nuclear materials. We describe country location of important facilities and speculate on growth patterns.

A. Uranium Supply*

Data on world wide uranium resources as well as projected uranium demand to the year 2000 have been compiled and published in a joint OECD/NEA - IAEA Report entitled, “Uranium Resources, Production and Demand” December 1975. These estimates (with updated U.S. and Canadian figures) are shown in Table IV-la for two categories of confidence and two levels of extraction costs. An updated and expanded version of this report is scheduled for reissue in May 1978. A relatively recent world wide resource estimate for uranium at $30/lb. U_3O_8 which reflects data published subsequent to December 1975 has been prepared by John H. Patterson, Division of Uranium Resources and Enrichment, ERDA, and was presented at the American Nuclear Society Executive Conference on Uranium Supply in January 1977. The data assembled by Patterson is reproduced in Table IV-lb and is annotated with several recent additions. The two resource categories used by OECD/NEA-IAEA, "Reasonably Assured Resources" and "Estimated Additional Resources" have been retained by Patterson rather than the four resource categories normally used in domestic ERDA resource estimates.

In the OECD/NEA-IAEA report (op. cit.) the term "Reasonably Assured Resources" refers

> 1? to uranium which occurs in known ore deposits of such grade; quantity and configuration that it could be recovered within the given production cost range, with currently proven mining and processing technology. Estimates of tonnage and grade are based on specific sample data and measurements of the deposits and on knowledge of ore-body habit. Reasonably Assured Resources in the cost category below $15/lb are considered as Reserves for the purpose of the present report.
>
> The term Estimated Additional Resources refers to uranium surmised to occur in unexplored extensions of known deposits or in undiscovered deposits in known uranium districts, and which is expected to be discoverable and could be produced in the given cost range. The tonnage and grade of Estimated Additional Resources are based-primarily on knowledge of the characteristics of deposits within the same districts."

From Table IV-1 it can be seen that the estimated total resources for both resource categories each contain approximately 2.4 million short tons Of U_3O_8 at $30/lb. Of U_3O_8. About 80% of the reasonably assured uranium is

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*This section prepared by Lorin R. Stieff.

Table IV-la

World Uranium Estimates

ESTIMATED ADDITIONAL RESOURCES

(1,000 tonnes U)

(Data available 1st January 1976

Cost range	*< 15\$/lbU_3O_8*	*15–30\$/lbU_3O_8*
Algeria	–	–
Argentina	15	24
Australia	80	–
Brazil	8·8	–
Canada (*a*)	303	302(*b*)
Central African Republic	8	–
Denmark	–	10
Finland	–	–
France	25	15
Gabon	5	5
Germany	1	3
India	0·8	22·5
Italy	–	1
Japan	–	–
Korea	–	–
Mexico	–	–
Niger	20	10
Portugal	–	–
South Africa*(e)*	6	68
Spain(*d*)	8·8	98
Sweden	–	–
Turkey	0·4	–
United Kingdom	–	4
United States(*c*)	500	312
Yugoslavia	–	15·2
Zaire	1·7	–
Total (rounded)	980	890

(8) Categories are by reference to price.
(b) Estimates in this price range are preliminary, restricted only to principal deposits, and thus very conservative.
(c) Does not include 54,000 tonnes U as a byproduct from phosphates or 15,000 tonnes U as a by-product from copper production which might be recovered in the period to the year 2000.
(d) includes some 80,800 tonnes U reasonably assured resources in ignites in the cost range \$15-30/lb U_3O_8 for which the availability is uncertaln.
(e) The 350,000 tonnes U total uranium resource for South Africa as given in Part II has also been Supplied apportioned as a best estimate to the various resource categories although reservations have been expressed concerning the accuracy of split figures.

(a) Categories are by reference to price.
(b) Estimates in this price range are preliminary, restricted only to principal deposits, and thus very conservative.
(c) The following additional potential resources of greater uncertainty are indicated by the US.
Possible resources <30\$/lb: 978.10^3tU
Speculative resources <30\$/lb: 454.10^3tU
(d) Includes some 63,800 tonnes U estimated additional resources in lignites in the cost range \$15-30/lb U^3O^8 for which the availability is uncertain.
(a) The 350,000 tonnes total uranium resource for South Africa as given in Part II has also been supplied apportioned as a best estimate to the various resource categories although reservations have been expressed concerning the accuracy-of the split figures.

URANIUM INVENTORIES (tonnes U)

Australia 1750 (government); Canada 5580 (government); Japan S (producers); Mexico 40 (government); Portugal 350 (government); Sweden 200 (users); United States 55000 (government), 3300 (producers), 15000 (users) and West Germany 1370 (government). Information on stockpiles in other countries is presently not available.

Table IV-lb

WORLD URANIUM RESOURCES BY CONTINENT – $30/LB U_3O_8 @)

(EXCLUDES EASTERN BLOCK COUNTRIES)
THOUSAND TONS U_3O_8

	REASONABLY ASSURED	ESTIMATED ADDITIONAL
NORTH AMERICA	880	1.860
Us.	640	1,060
CANADA	225	787
MEXi CO	8	0
DENMARK (GREENLAND)	8	13
AFRICA	500	160
SOUTH &SW AFRICA	359	96
NIGER	65	39
ALGERIA	36	0
GABON	26	13
C.A.R.	10	10
ZAIRE	2	2
EUROPE	520	140
SWEDEN	390	0
FRANCE	72	52
SPAIN	30	56
YUGOSLAVIA	9	20
PORTUGAL	9	0
FINLAND	3	0
GERMANY	1	5
ITALY	2	1
U.K.	2	5
AUSTRALIA	430	100
ASIA	60	30
INDIA	38	30
JAPAN	10	0
KOREA	3	0
TURKEY	4	1
SOUTH AMERICA	40	60
ARGENTINA	27	51
BRAZIL	14	11
TOTAL (ROUNDED)	2,400	2,400

NOTES

Table IV-lb

a) “Foreign Uranium Sources - Status and Developments”, John A. Patterson, American Nuclear Society, Executive Conference on Uranium Supply, Moneterey, California, January 26, 1977.

b) Most recent ERDA estimates.

c) New discoveries should result in significant increases in this estimate.

d) This estimate reflects the uranium contained in the black shales of Sweden. It is unlikely that this uranium will be available at $30/lb U_3O_8.

e) Company Data.

f) Government Estimate.

confined to six countries, the United States, Canada, Australia, South and South West Africa, France and Niger. The large, reasonably assured supply of very low-grade uranium associated with the Swedish black shales probably should not be included in the table because the uranium from this source will not be available at $30/lb. U_3O_8, and because the substantial environmental consequences associated with extraction from this source have not been resolved.

The total of approximately 2.4 million short tons of U_3O_8 in the category of Estimated Additional Resources is dominated by only two countries, the United States and Canada. These two countries possess approximately 1.85 million short tons or roughly 75% of these resources. It is unlikely that these figures reflect the true world distribution of the Estimated Additional Uranium Resources. Rather, this large subtotal reflects the substantial exploration and resource appraisal efforts that have been made by both the United States and Canada. It seems reasonable to believe that the categories of Reasonably Assured and Estimated Additional resources will increase as comparable exploration and appraisal efforts are made in other parts of the world.

Thus the short term and probably even the mid-term supply of uranium appears adequate. Nevertheless, it is necessary to add that prudence dictates a much more conservative view of the tonnages of uranium that will actually be mined, milled and available. This prudence stems from the fact that serious errors in judgement on the long-term availability of uranium will have profound economic and political impacts particularly on the major industrial nations; that certain major decisions directly dependent on reliable long-term uranium resource estimates must be made now or in the near future, such as national commitments to nuclear power and the decision on breeder reactor development; and that it is difficult, if not impossible, at this stage to assign limits of error to the estimates of “Reasonably Assured Resources” much less the “Estimated Additional Resources”. Further, even though the quantities of ore in discovered reserves may be adequate through a certain date, the time required in developing them may necessitate the discovery and development of new deposits.

The uncertainty surrounding these appraisals is due, in part, to some of the following factors:

- Insufficient geologic information on the occurance, distribution, theories of origin and controls of ore deposition required to make the necessary extrapolations involved in the quantitative estimates of additional resources.

  Inadequate statistical methodology applicable to the special problems associated with uranium resource appraisal.

- Limitations in the availability of the relatively large amounts of risk capital required for the exploration and development of uranium mines and mills.
- Shortages in the supply of trained miners, skilled mill workers and qualified professional staffs.
- Uncertainties, even in the four major suppliers of uranium, concerning national attitudes towards nuclear energy and non-proliferation, national policies governing the development of uranium resources and the sale of uranium, and the stability of the political institutions essential to the orderly development of a major natural resource and the confidence that long-term contracts will be fulfilled.

Patterson (op. cit.) estimates that the current annual world requirement for U_30_8 of approximately 25,000 short tons is expected to increase to almost 200,000 short tons annually by the year 2000. The implied rate of growth for both the mining and milling segments of the industry is formidable and can be achieved only with considerable encouragement. The OECD/NEA-IAEA report is not so optimistic. It states (op. cit.):

> "In general, however, only ‘Reasonably Assured Resources’ can be considered for specific planning and forecasting in the short and medium term and even the availability of much of these resources is constrained. If it were assumed that the present ‘Estimated Additional Resource’ could be confirmed and developed, the total of the two categories would still be inadequate to meet the long term uranium requirement which has been estimated at up to four million tonnes by the year 2000, possibly reaching 10 million tonnes of uranium by the year 2025."

These projections have been reduced, but the urgency of the uranium resource problem is still generally recognized. The concerted action by industry as well as governments required to forestall serious problems in the late 80’s and 90’s is still in the formative stage.

B. Conversion

Conversion is now concentrated in the four countries which operate large-scale enrichment facilities--the U.S., UK, France and the USSR.

The capital costs of this process are not high, approximately $50 millions for a plant that will fuel 82 reactors at equilibrium. See Table IV-2. The technology requirements are not large. Production of florine, arid its associated electric power requirement, is the primary technical task. A 10,000 tonne/y plant requires about 300 workers and about 65 x 10^6 kWh/y of electricity (or an assured capacity of 7 NW).

Countries supplying substantial volumes of uranium ore may wish to convert concentrate to UF_6 to take advantage of the value that can be added. In addition, the modest capital cost and technology requirements will not present a problem. Therefore, conversion can be expected to spread to countries without present capacity for it, such as Australia.

Table IV-2

CAPITAL COST* OF NUCLEAR FUEL CYCLE FACILITIES NECESSARY TO SUPPORT A 1100 MWe LIGHT WATER REACTOR UNDER EQUILIBRIUM CONDITIONS AND NUMBER OF REACTORS SUPPORTED BY A LARGE COMMERCIAL FACILITY

Fuel Cycle Facility	Capital Cost of Facility per 1100 MWe Reactor (in millions of dollars)	Number of 1100 MWe Reactors Supported by Facility
Mining (surface)	2.33	6
Mining (underground)	2.84	3
Milling	10.47	7
Conversion	0.61	82
Enrichment	26.98	101
Fuel Fabrication (no Pu recycle)	1.75	27
Fuel Fabrication (with Pu recycle)	6.12	7
Reactor Plant	460.0	
Fuel Reprocessing	3.65	69

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*lnstant construction mid-1974 costs.

C. Enrichment

Enrichment, now concentrated in the U.S., the USSR, France, and the UK may be spread more widely, especially through the centrifuge and nozzle diffusion techniques. At the present, world enrichment capacity is 25-28 x 10^6 kg SWU per annum, primarily in the U.S. and USSR. All of this is not needed today and some “reproduction” is being undertaken so that future capacity additions can be delayed. New capacity is now being added by URENCO plants in Holland and the UK, and Eurodif (Coredif) expects to be in production about 1980 with a plant which will realize 10.8 x 10^6 SWU.

These additions plus U.S. uprating of its government owned diffusion plants (an additional 10.5 x 10^6 SWU) will bring the total capacity by 1985 to over 50 x 10^6 kg SWU (it could rise as high as 70 x 10^6 kg SWU). Table IV-3 lists existing and planned commercial plants and significant pilot plant operations.

Equilibrium operation nuclear electric plants using enriched uranium are stated to require from 119 to 137 kg SWU/y per MW of capacity at 65% capacity factor. If we assume all future plants use enriched uranium--an obvious oversimplification that emphasizes the need for separative work capacity--and an average equilibrium consumption of 120kg SWU/MW (60% plant factor), we find that the current capacity and postulated additions to 1985 will supply the enrichment necessary for the continuous running of about 385,000 MW. (In this and succeeding calculations we consider that nuclear power is produced only by LWRs. The contribution of HWR and other converters is estimated to be less than 5 percent before the mid 1990s. Breeder reactors should have little effect before that time.)

Enrichment plants operating before ’85 will generally be in the nations that now produce enriched uranium. The FRG (recently announced in public press) will make additions before then. It must be noted that the French organized and operated COREDIF and EURODIF organizations have additional partners, notably Iran and Spain, but also including Belguim and Italy, who will contribute financial and other support. After 1985, other nations plan to provide enrichment services. Brazil and the Union of South Africa will be using varieties of the jet nozzle process if current plans are carried forward. Japan has announced its intent to use the centrifuge process. Iran may build its own plant, etc.

Table IV-3*

STATUS OF PROCESSES FOR ENRICHMENT**

Owner	Location	Capacity 10S SWU	Schedule Operation
Gaseous diffusion process			
Operating plants			
ERDA	Oak Ridge, Tenn.	4.73	
	Paducah, Ky.	7.31	
	Portsmouth, Ohio	5“19	
Total, US		17.23	
USSR	Siberia	7-10'	
CEA	Pierrelatte, Franca	0.4-0.6	
UKAEA	Capenhurst, England	04-06	
China	Lanchow, China	?	
Under construction			
Improvement and uprating of ERDA plants - adds		10-5	1975—1 985
Eurordif (CEA. Iran, Belgium. Italy, Spain)	Tricastin, France	108	1978—1981
Under construction			
ERDA	Portsmouth Ohio	8-75	1985
Coredif (Eurodif, CEA Iran)	Tricastin, France	9—1 O	1985
Canadif (CEA Ouebec, Canada)	James Bay, Quebec	?	?
Gas centrifuge process			
Operating plants			
Urenco-Centec (UK, Holland, Germany)	Capenhurst England Almelo, Holland	0-4 to 2-0	1977—1982
Under coonstruction			
Urenco--Centec	Capenhurst England Almelo, Holland	Adds 8	1985
Exxon Nuclear Co.	USA	1“o to 3.0	1982—1986
Centar Associates	USA	0.3 to 3.0	1932—1988
Garrett Nuclear Corp.	Texas	0.3 to 3.0	1982—1989
	Japan	2	1998
Separation nozzle process			
Karlsruhe Nuclear Center	Steag A.G.	0.002	Shut down in 1972
Nuc!ebras	Brazil	2	1989
South African process			
UCOR	Valindaba, S.A.	0.006 5	Pilot unit ready being considered
Laser-based processes			
		Working material	
Avco-Exxon	Everett. Mass.	U metal vapor	
Lawrence Rad. Lab.	Livermore. Calif.	U metal vapor	
Los Alamos Sci. Lab.	Los Alamos	UFa Vapor	

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* From Nuclear Engineering International, November 1976.

* * **Presented by Manson Conference, June 1976.

\+ Believed that 3M SWU available for export.

The capital investment required for enrichment is small compared to that required for nuclear-electric power plants; it has been estimated capital costs will range from $200 to $370 per SWU\y. A representative capital cost of $310 per SWU converts to an expenditure of about $27 millions required to supply a single 1.100 MW nuclear power plant. See Table IV-2. (Compare this cost with the approximately one-half billion dollar cost for the nuclear power station.)

The diffusion process has a generally reported cost of 200-300 $\SWU only in large size. The unit cost rises rapidly with decreasing size. The economics of centrifuge and nozzle processes are much less sensitive to size and can be installed in smaller units. The centrifuge uses much less power (about 1/10 that of the diffusion), while the nozzle processes use somewhat more power than the diffusion process. Large diffusion plants require approximately 2,000 kWh\SWU. URENCO and others expect that their centrifugation plants (as small as 0.3 - 1 x 10^6 SWU\yr) will be competitive with large diffusion plants in the range of 9 x 10^6 SWU/yr. Thus, once centrifuge enrichment becomes a proven commercial process, it is likely that plants could be built to economically serve a nation with a nuclear electric capacity as small as 3,800 MW.

Even though some developing countries could afford the capital investment and match their enrichment needs with an economic centrifuge plant, other factors may discourage that choice. Centrifugation requires an equipment supply industry that must produce exceptionally precise and high quality, high speed, rotating machinery

More skilled operating manpower will be necessary for a centrifuge plant than for a diffusion plant. This is due largely to the maintenance requirements imposed by the large number of precision centrifuges. We nave estimated, from ERDA data, that 1,000 workers are required to operate a 9 x 10^6 SWU/y diffusion plant. It is likely that the centrifuge plant will require two to three times as many workers per unit output, for example from 250 to 300 workers for a 10^6 SWU plant.

Thus we do not expect the number of nations producing enriched uranium for a commercial electric utility market to increase greatly in number. Instead of just the U.S., UK, France and the USSR capable of serving world needs, we might foresee the following:

Australia	much discussion, but expected opposition from environmentalists and unions would make enrichment unlikely in the near term
Brazil	(already has announced plans for 1989 production)
Federal Republic of Germany	announced plans for a 10^6 SWU/y plant
Iran	(will have completely independent industry and direct knowledge, through COREDIF, of diffusion process)
Japan	(announced plans for 1988 production - centrifuge)
South Africa	(announced plans for larger pilot plant; nozzle)

Several factors could limit growth. A very important one is the potential for change in reactor type. A switch to heavy water moderated reactors or to plutonium-uranium breeding reactor systems would eliminate the need for expansion of enrichment services, and a gradual decrease in loading for the plants already' built as they pass from service. Thus investment in enrichment has a high speculative element, as indicated by the unwillingness of U.S. companies to invest in this sector of the nuclear industry without government protection.

A smaller practical increment in investment is offered by the centrifuge* and nozzle processes but these are still not fully demonstrated on large scale and thus have some risk. Also, as pointed out above, the greater mechanical complexity of the system and the specialized mechanical industry needed *to* support it could be difficult for a developing country to supply.

It is possible that others of the more wealthy, highly industrialized nations will supply enrichment services. They have shown no particular interest thus far in such activities. On the other hand, political decisions pending in the Netherlands have tended to slow plant development and may remove that country as a producer.

D. Fuel Fabrication

In the fuel fabrication segment of the industry the capital investment required is not as large and the economics of scale less important when compared with other fuel cycle activities. Substantial skill is required in welding (automatic) processes and quality inspection and and control. However, a nominal 600 tonne/y plant, sufficient in size to supply about 30,000 MW of nuclear generation capacity, requires a direct work force of only about 500 workers. The capital investment for such a plant is small, as shown in Table IV-2.

Currently commercial scale production facilities for oxide fuels are operating in 9 industrialized countries. See Table IV-4. Of the total capacity, nearly 80% is in two countries--the U.S. and Japan--and the U.S. has three/quarters of that fraction. Other producing countries

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* Centrifugation is a unit process, therefore plant capital costs vary nearly linearly with size.

Table IV-4*

LWR FUEL FABRICATION CAPACITY (Tonnes Heavy Metal/yr)

Countries	1974	1975	Planned 1978	Projected 1980	Projected 1985
Belgium	200	200	400-600	400-800	600-1,200
Denmark					200-400
France		200	220	500	>1,100
Germany	270	670	1,000	1,400	2,000
Italy	300	300	300	600	(600)
Japan	910	(910)	(910)	(910)	(910)
Netherlands	30	30	30	120	200
Spain			300	400	800
Sweden	250	250	400	400	(450)
UK	100	100	100	(loo)	(loo)
USA	3,050	2,750	3,350	8,200	8.200
Total	5,110	5,410	7,110	13,230	15,560

( ) Minimum figures.

*From "Uranium Resources, Production and Demand," Joint OECD/NEA-IAEA Report, Paris, Dec. 1975.

are increasing their production capacity more rapidly than the U.S. ; but it still will dominate the world with an estimated 60% of the world capacity in 1980 (excluding the USSR).

The announced capacities for LWR fuel fabrication in 1985 of over 15,000 tonnes metal would be sufficient to fuel 783,000 MW of capacity at the assumed 60% capacity factor. (If fueling of new plants is required as well, then the fuel fabrication plants can handle over 500,000 MW of existing plant.) Expansion beyond this projected capacity, necessary only after about 1988, can occur in several countries. Developing nations such as Iran with large nuclear power programs in prospect, could build fuel fabrication plants. Brazil has announced its intention to do so; others can if they wish. (But see Section IV-F.) Many of the fuel fabrication facilities are likely to incorporate provisions for plutonium recycle after this is demonstrated in the major nuclear countries.

E. @recessing

The recovery of the slightly enriched uranium and of the plutonium discharged from power reactors and their preparation for reuse is the final step in the fuel cycle. While the recovery step could improve the economics of nuclear power by reducing the requirements for uranium and for enrichment services, it is not essential for LWR systems and is not now used for HWR fuel cycles. It would be essential to the operation of breeder reactor *systems* when and if they become commercially viable. (SRI estimates there will be no noticeable direct impact of breeder systems on the nuclear fuel industry until 1995.*) At the present time, reprocessing of uranium metal fuel elements is available through government owned and/or controlled facilities in France and the UK. These countries have plants run by government controlled corporations (those with greater than 50% government ownership). In the U.S., similar facilities exist and are operated by industry in contract to the government in its plutonium producing operations. Facilities also exist in the USSR and presumably in China.

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* Even though the French and others have operated prototype breeders, the expected time periods required for construction and commercialization of a full-scale plant account for this estimate. Breeders could have a more immediate indirect impact on the fuel cycle, however. Anticipation of their future development may cause some stockpiling of retrieved plutonium in competition with its potential use in mixed-oxide fuels for LWRs.

No commercial scale facilities for the reprocessing of oxide fuel **are** in operation. The one commercial plant that did operate in the U.S. is shut down and has been effectively abandoned by its owner. Another plant with 1500 tons/y capacity at Barnwell, S.C., could be put into operation in 2-3 years after decisions regarding licensing and waste treatment are reached. Modified metal processing plants (with special additions to handle oxide fuel) may be available in 1977 in France and slightly later in the UK. Full scale processing plants specifically designed for oxide fuels are not expected until after 1980. The status of current and planned plants (excepting those of COMCOM) is shown in Table IV-5. Additional capacity (approximately 1000 te/a) may be available in Spain. by 1985-90.

These facilities are more capital intensive than many other of the fuel cycle plants. Thus costs may rise beyond those quoted in Table IV-2. In the U.S., the single commercial plant that was operated **and the one under construction have suffered from regulatory actions that required retrofit and/or redesign, and costs have escalated. Operation of a large plant may only be justified by nationally generated reactor fuel that amounts to 500 t/y or more, equivalent to about 25,000 MW of installed capacity. The plant would require an estimated 500 workers to operate.**

Because of the capital investment, not many LDCs would decide to build commercial plants. However, pilot size facilities **could be constructed and used to produce plutonium for weapons or other use.**

Again, Brazil has **announced its intent to engage in reprocessing.**

Table IV-5

SUMMARY OF REPROCESSING PROJECTS AROUND THE WORLD*

Location	Operator	Type of plant	Capacity t/y	Date operational	Status
U.S.A.					
West Valley N.Y.	NFS	Old,	300	1966 to 1912	530 is processed before shut down for expansion
		Expanded, oxide	750	early 1980s	Dependent on new construction permit
Midwest Morris, Ill.	GE	Oxide, advanced process	300	—	present form Currently providing fuel storage
Barnwell S.C.	AGNS	Commercial, oxide	1500	1977-78	Depending on GESMO decisions
—	Exxon	Commercial oxide	—	mid - 1980s	Looking for site
U.K.					
Windscale	BNFL	Nat. U metal	1500-2500	1964	Operating near full capacity Head end improvement programme in hand
		Oxide head end	300	1972 to 1973	Operated but shut down for investigation of incident and subsequent modification
		Refurbished oxide head end	400 •	1977-78	Will feed into nat. U separation plant depending on availability of capacity
		New commercial oxide plant	1000	1984	For expected domestic requirements part of United Reprocessor's plan
		New commercial oxide plant "overseas"	1000	1987	Awaiting decision on public acceptability of overseas contracts.
France					
La Hague	CEA	Nat. U metal	800	1966	Main plant for reprocessing EdF nat. U fuel but due to be changed over to oxide
		Oxide head end	150 to 800	1976	Phased build up feeding into existing separation plant
		New commercial oxide plant	1000	1985	Detailed design just starting
Marcoule	CEA	Nat. U metal fuel	900-1200 •	1958	Early military plant. Will take over commercial nat. U from La Hague
Germany					
Karlsruhe WAK	KEWA	Pilot scale oxide	40	1970	Operating with fuel of increasing burnup
—	PWK/KEWA	Commercial oxide plant	1500	1984	Design specification being prepared. Site to be selected
Japan					
Tokai Mura	PNC	Demonstration scale oxide	200	1976	Non-active commissioning
—	PNC	Commercial oxide plant	1000	late 1980s	Projected if site can be found
Belgium					
Mol	Eurochemic	Multi-purpose semi-commercial international plant	60	1966	Shut down. Future in doubt. Has been used for reprocessing development
Italy					
Saluggia Eurex I	CNEN	Pilot scale oxide	10	1969	Currently shut down for modification
India					
Trombay	IAEC	Pilot scale nat. U oxide	60	1965	

Note: Several other pilot and laboratory scale plants have and are being operated for development of reprocessing technology. Commercial reprocessing of research reactor fuel has also been undertaken in several plants around the world. Fast reactor oxide fuel has been reprocessed in pilot scale plants in France and the U.K. and a plant for mixed thorium uranium oxides was built in Italy but has not been operated.

*From Nuclear Engineering International.

Japan and Germany are definitely interested. Other nations, including Iran, Pakistan and South Korea, have discussed the possibility of importing the technology. Spain, perhaps Italy, and others would seem likely candidate countries for full scale reprocessing activities.

F. Fuel Cycle Summary

The major elements of the fuel cycle cost much less than the reactor they support (when each unit is made to an economical size) as was shown in Table IV-2, and countries which can finance reactors can finance the support elements. However, if the fuel cycle plants (at an economical size) are sufficiently large to load from 7 to 101 reactors**, their installation will require that most of the developing nations seek an export business.

Even with the optimistic assumption of the 1974 IAEA Market Study, none of the countries considered in that study would, by themselves, generate the fuel through-put necessary to justify in the year 1990 the large scale plants considered economic by the U.S. Smaller sized fuel cycle plants could perhaps be considered by Mexico, Brazil, Argentina, Spain, Yugoslavia, India, Iran, Korea, Poland, Romania and Czechoslovakia on the basis of their indigenous nuclear power programs. These are all countries that:

1. Have large nuclear power programs in progress or well advanced in planning, or

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* Germany Is a partner in United Uranium Processors with the UK and France

** The larger number refers to a 8.75 $\times 10^6$ kg-SWU\y diffusion enrichment plant. Centrifuge plants serving many fewer large reactors may prove economical.

2. 2. Were singled out as likely to have substantial growth by the IAEA analysis, and

3. Are, for the most part, not fully democratic, i.e. they are countries where government policies can be implemented without full consideration of public wish or direct business interest.

Fuel cycle activities, except for mining and milling, would not be a logical economic investment for the others unless they could attract extensive export trade.

G. Reactor Supply

The reactor supply business has been pursued in several industrialized countries. The U.S., Canada, the Federal Republic of Germany, France, Italy, Japan, Sweden, and the USSR have viable operating companies supplying nuclear reactors. See Table IV-6. These organizations purchase heavy and special equipment such as pressure vessels and nuclear-quality stainless-steel valves from a host of suppliers located in many of the other industrialized nations of the world! Many of the components of the now-coventional nuclear systems are larger than previously needed for other industries, and new plants suitable for handling extra large and heavy equipment have been built to fill the demand. Also exceptional quality is required for many components and new standards of manufacturing performance involving physical operations, inspection activity, and quality control are demanded. For several years general manufacturing capacity fell behind demand, but today, following a drop-off in the rapid growth of nuclear plant ordering, there is spare capacity in most if not all segments of the reactor supply industry. The existence of this spare capacity is one factor behind the several efforts to export nuclear

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* Some examples are Austria, Finland, Netherlands, Belgium, Spain, and Switzerland

Table IV-6

PRINCIPAL SUPPLIERS OF HWR AND LWR REACTORS

HWR	
Atomic Energy of Canada Ltd	Canada
Siemans	FRG
Canadian General Electric	Canada
LWR	
Kraftwerk Union AG	FRG
Framatron	France
Atomenergoexport	USSR
ASEA-Atom	Sweden
General Electric Co*	USA
Westinghouse Electric Co*	USA
Toshiba	Japan
Hitachi	Japan
Combustion Engineering	USA
Babcock and Wilcox	**USA**
Ansaldo Meccanico Nuclear SpA	Italy
Mitsubishi Heavy Industries	Japan

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*Also European based subsidiary or joint companies.

systems to **developing countries.**

It is **believed that for a reactor supplier to be fully competitive, it must** have a minimum of 4-6 orders per year. The reactor producers in the U.S. have relied on export business to fill their factories. Sales are hard for new suppliers. Proof of prior successful operation is an important factor for a reactor sale. Examination of the history of nuclear power development indicates that the purchaser ordinarily requires a high degree **of** confidence in the supplier (a not unreasonable demand). This is evidenced in several ways. For example, a long term supplier-user relationship was required in the U.S. Of those companies who entered the reactor supply business, full acceptance has been given only to companies who had long standing relationships with utilities. In the international market, government guarantees or favorable loans have undoubtedly influenced the selection of particular suppliers. The existence of a strong relationship between vendor and purchaser seems important here as well. This must be supplemented by aggressive marketing and seemingly a demonstrated ability to field and operate reactor systems. For example, India, Italy, Japan, Spain, and Switzerland bought their first reactor systems from recognized suppliers in Canada, the UK, and the USA after the suppliers had built and planned reactors in operation in their own countries. Now all of these countries have their own nuclear component suppliers, many of which operate under license, producing systems whose design was proven in Canada or the U.S.

If developing countries are to enter the market they must overcome fierce competition from experienced suppliers. The optimistic IAEA Survey does not indicate sufficient reactor business in any LDC in the period 1985-1990 to justify market entry, and any such entry based on export could only come at substantial cost. We recognize there can be exceptions. India is now attempting to build a reactor supply business matched to its modest reactor needs. Its department of atomic energy is engaged in the construction of 880 MW of HWRs now expected to be operational between 1978-82.

The possibility of India making significant entry into the reactor export business within the next ten to fifteen years is small. In doing so, India would enter into competition with the AECL and Canadian industry which have more experience and will probably have greater production capacity. No Indian-built reactors have as yet become operational, and as stated above, demonstrated success is an important consideration to LDC buyers. In addition, the funds that most vendor nations make available to LDCs as an aid to financing a nuclear project are not readily available for India to lend.

V THE VALUE OF U.S. NUCLEAR EXPORTS

Exportation of nuclear-related equipment, materials, and services has had a significant effect on the growth of the U.S. nuclear industry. The two largest American reactor manufacturers, Westinghouse and General Electric, have together installed almost 6,000 MW of operating nuclear capacity in foreign nations, and are supplying over 19,000 MW of capacity to foreign plants currently under construction. Sale of these nuclear steam supply systems (NSSS) accounts for the largest share of the revenue obtained from U.S. nuclear exports. Other major contributors include "balance-of-plant" (non-NSSS) equipment, engineering and construction services, and enrichment services provided by the U.S. government. The dollar values of these purchases greatly outweigh the revenues from the other nuclear exports.

A primary incentive for the export of nuclear-related commodities is the favorable cash flow that accompanies the sale of capital-intensive equipment. Additionally, exports can be used to increase NSSS production if domestic ordering falls. Reducing idle production capacity can be extremely important, since much of this capacity is unique to the nuclear industry and very costly.

Noneconomic factors can also provide some incentive for nuclear exports. For example, because of the continuing replacement parts requirements, technical aid, and fuel cycle services, some influence can be gained by the exporting nation. This argument has been raised in support of the continuation of U.S. nuclear exports. It is reasoned that the safeguards required on American exports and an American presence in the world nuclear scene will ensure our standards are met.

Nuclear Plant Exports

This country has historically led the world in nuclear technology. The light water reactor concept, which was pioneered by the United States, is now by far the most commonly used reactor system around the world. Until relatively recently, America was the only exporter of LWRs, but several other free-world nations have now developed LWR export capability (based largely on U.S. technology and license arrangements). The most important of these are Germany and France, which have already penetrated the world reactor market with major sales. These nations can be expected to increase their share of the market in the future. In addition, Japan, Sweden, and Italy may also be expected to become exporters over the coming years. The USSR currently exports LWR systems to the Eastern Bloc countries, but is not expected to capture a significant portion of the free world market.

Heavy water reactors, which employ natural uranium fuel, have been successfully marketed by Canada.* These systems typically require a higher initial capital investment than LWRs, due largely to the high cost of heavy water. However, the fuel cycle costs are lower because the uranium enrichment step is not required. In addition, the use of a natural uranium fueled reactor is desirable to many smaller nations because of the freedom it provides from dependence on those larger countries that possess enrichment facilities.

As noted previously, the United States has installed nearly 6,000 MW of nuclear capacity *in* foreign countries. Seven percent of this figure (two reactors for India with a combined output of 396 MW) was exported to LDCs; the remainder went to European nations and Japan. Total reactor shipments to LDCs have accounted for 1,254 MW of capacity, as shown in Table V-la. The four non-U.S. supplied reactors were HWRS, and comprised about 68 percent of nuclear capacity installed to the LDCs.

Table V-1b lists the exports to LDCs of reactor systems for plants presently under construction or on order. In order to show current trends, **these** orders are split into three categories: those which have expected commercial operation dates before the end of 1980, between 1980 and the end of 1985, and after 1985. In the first time category, the American-supplied capacity is approximately 4,700 MW or 72 percent of the total

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* One was also exported by Germany.

Table V-1a

OPERATING REACTORS IN THE LDCs

LDC	U.S. Supplied (MW)	Year of Commercial Operation	Non-U.S. Supplied (MW)	Year of Commercial Operation
Argentina			319 (German HWR)	1974
India	198	**1969**	207 (Canadian HWR)	1973
	198	**1969**	207 (Canadian HWR)	1976
Pakistan			125 (Canadian HWR)	1972
Total	396		858	Total 1,254*

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* American, 32 percent
Non-American, 68 percent

Table V-1b

REACTOR PLANTS UNDER CONSTRUCTION OR ON ORDER IN LDCs

Commercial Operation	U.S. Supplied (MW)	U.S. (percent)	Non-U.S. Supplied (MW)	Non-U.S. (percent)	Total
1977-1980	4,657	72%	1,800	28%	6,457
1980-1985	4,570	38	6,817	62	11,987
Beyond 1985	0	0	600	100	600

LDC market. The only foreign competition over this time period comes from Canada and Germany.

When reactors starting up in the LDCs during the next time period, the end of 1980 to the end of 1985, are considered, the situation is quite different. The U.S.-supplied nuclear capacity is approximately 4,600 MW, down only slightly from the preceding period. However, the American-supplied fraction of the overall LDC market drops to 38 percent. For this period, Canada and Germany have increased their share, and France has entered the export market with two large reactors. To date, only one order has been placed by an LDC for a reactor starting up beyond 1985. This is for a Canadian HWR that will be shipped to Argentina.

The apparent trend is toward a smaller American share of the LDC reactor market In fact, no new orders for LDCs have been placed with American vendors for the last two years. (Exceptions are two reactors that progressed from the letter of intent to the ordered stage during the period.)

The share of the LDC market that the United States captures in the future will depend upon many factors. Important among these will be the cost and also the reliability of American nuclear plants.

Reliability can have a major impact on the planning of an LDC, because a nuclear plant would typically represent a relatively large fraction of the LDC's total generating capacity. The on-line refueling capability of the CANADA reactor system is attractive in this regard.

Another important consideration will be the type of governmental restrictions that are placed on nuclear-related exports. It has been reported that. Iran had investigated the possibility of purchasing some American reactors but felt that the agreement required by the U.S. government was too demanding. American export policy also prohibited the transfer of enrichment and reprocessing technology to other nations. In fulfillment of a contract signed with Brazil, Germany will not only supply nuclear generating plants, but will also provide the know-how for the construction of a demonstration enrichment facility. Canadian reactors can be expected to remain a strong competitor with American LWRs for the LDC's market. The CANADA system has many characteristics that are desirable to the LDCs. As mentioned previously, employment of a natural uranium fuel allows freedom from dependence on those countries that will be exporters of enrichment services. This factor would be especially important if LDC planners view the currently proposed enrichment capacity around the world as being inadequate to meet the expected demand. The

1974 reversal of the AEC's policy of booking orders for enrichment services may have contributed to this view. In addition, recent occurrences such as the defeat of the nuclear fuel assurance bill and the continued erosion of private interest in enrichment could have only further reinforced the fear of enrichment shortages.

CANADA reactors are built in a smaller size than most LWRs presently being made. A typical CANADA plant is in the 600 MW range, whereas that of a new American LWR is about 900 MW. The lower capacity of CANADA units makes them more suitable for use in LDCs, which typically have low total system capacities. Compared with LWRs, CANADA reactors are more efficient in the production of plutonium, and are also able to produce a grade of plutonium more suitable for weapon production. In addition, the on-line refueling capabiility of these reactors would enable plutonium to be removed without shutting down. These would be important characteristics to a nation that wanted to acquire a nuclear weapons capability or give the appearance of developing this capability.

It now appears that several countries may invest heavily in CANADA systems in the future. Argentina has ordered a series of these reactors, and Korea, with two American LWR plants currently under construction, has chosen a CANADA for its third plant. Mexico has ordered two U.S.-built reactors for its first nuclear plants. However, the Mexican government has now requested a technical proposal for construction of a 600 MW CANADA,

and is reportedly leaning toward this type of technology. India plans to produce its own HWR based upon Canadian technology, and is purchasing heavy water from the USSR. The possibility of India making significant export sales within the next ten to fifteen years, however, is small (see Section IV G).

Three factors could work against the future spread of the CANADA system. These are Canada's potential lack of capital to help LDCs finance plants, the strong export safeguard measures adopted by the Canadian government, and potential limitations in the reactor production capability of Canada. It is believed that after meeting its own reactor needs in future years, Canada may have only about one reactor per year available for export. At the present time, however, the Canada vendors (along with reactor manufacturers in general) are facing the opposite problem of not enough orders.

Political factors can also be expected to affect reactor sales to the LDCs to a certain extent. For countries that have close American ties, there will be some influence to purchase U.S. equipment. As can be seen by the cases of Mexico and Korea, however, this influence is not a guarantee for reactor sales. Some LDCs have also developed a mistrust of larger countries, and the superpowers in particular. This feeling could influence them to place orders with smaller vendor nations such as Canada.

It is very difficult to predict the future of reactor sales, but trends can be evaluated and estimates made. As noted, the American share of the LDC reactor market has been dropping ,and it appears likely that this trend will continue. The data suggest that the United States can be expected to supply between 35 and 40 percent of the LDC plants starting up in the 1980 to 1985 period. A drop in this fraction, to the 25 to 30 percent range, would be a reasonable expectation for the latter half of the next decade. Using the estimates for nuclear growth considered to be the most representative of the future (see Chapter III), U.S. industry should receive orders for 5,500 to 7,500 MW of capacity starting up in the LDCs in the former period, and 8,000 to 10,000 MW in the latter period. These estimates would result in a total installation of 18,000 to 22,000 MW of American-supplied capacity in the LDCs during 1977 to 1990. The future revenue to the United States that will result from the sale of these power plants could be expected to range from $5 to $7 billion in 1976 dollars.

American industry has supplied approximately 5,500 MW of currently operating nuclear capacity to developed foreign nations. The largest share of these orders has gone to Japan, which accounts for almost half

of the total. Table V-2 lists American-supplied reactors for plants in this group of nations that are currently under construction or on order. Spain can be noted as the major buyer of American plants in this category, accounting for 60 percent of the 17,000 MW U.S. export market to developed countries.

Many of the same factors that were noted earlier as affecting export sales to LDCs will play a part in determining future sales to developed nations as well. In the case of developed countries, however, the possibility of the buyer becoming a reactor producer is much more likely. Japan has developed LWR production capability and currently has operating reactors built by its indigenous industry, and American reactor sales to Japan have suffered because of this. In addition, the remaining share of the Japanese market, which will be open to imports, may be less available for U.S. vendors, because Japan is reportedly investigating the possibility of importing reactors from Germany or Canada in the future. Spain is currently developing indigenous manufacturing capability for many reactor components and hopes by 1980 to be producing complete NSSS units.

The fraction of reactor installation in developed countries, which is open to the world market, can therefore be seen to be decreasing. Also, competition from other reactor exporters is becoming stiffer for

Table V-2

U.S. SUPPLIED REACTORS ON ORDER OR UNDER CONSTRUCTION IN DEVELOPED COUNTRIES

Japan		Spain		Sweden		Yugoslavia	
Capacity (MW)	Start-Up	Capacity (MW)	Start-Up	Capacity (MW)	Start-Up	Capacity (MW)	Start-Up
1,120	1977	883	1977	912	1977	632	1979
1,067	1977	900	1977	912	1979		
1,120	1978	900	1978				
		883	1978				
1,067	1979	882	1979				
		882	1979				
		935	1980				
		939	1981				
		939	1981				
		1,036	1981				
		970	1982				

these markets. These factors can be expected to result in a smaller American share of the reactor market in developed countries.

Table V-3 shows the American-supplied and total nuclear capacities that are currently under construction or on order in Western Europe for the periods from 1977 through 1980 and 1980 through 1985.[*] The American share of orders for plants starting up in the first time period accounts for 18 percent of Western European installations. In the second time period, this share has dropped to 9 percent. Considering this trend and the envisioned development of the Western European reactor production capability, an American share of approximately 5 percent would be likely in the period from 1985 to 1990.

Using the expected growth of nuclear capacity in Western Europe, American-supplied capacity in this region would range from 6,000 to 8,000 MW installed for plant start-up between 1980 through 1985 and 4,000 to 7,000 MW in the succeeding five years.’ These estimates result in a capacity of 19,000 to 24,000 MW to be installed between 1977 and 1990. The contribution from reactor exports to Japan would increase this range to 30,000 to 35,000 MW of orders for American vendors over the same time period. The revenue (in 1976 dollars) to the United States obtained in the period 1977 through 1990 because of these nuclear plant sales would be in the range

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[*] The countries within this grouping, plus Japan, are the only developed countries expected to make significant purchases of U.S. reactors.

Table V-3

AMERICAN SUPPLIED AND TOTAL NUCLEAR CAPACITIES UNDER CONSTRUCTION OR ON ORDER IN WESTERN EUROPE*

Commercial Operation	U.S. Supplied (MW)	U.S. (percent)	Non-U.S. Supplied (MW)	Non-U.S. (percent)	Total
1977-1980	8,700	18%	40,300	82%	49,000
1980-1985	3,900	9	38,200	91	42,100

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* Includes Yugoslavia.

of $5.5 to $7 billion. When this is combined with the revenue expected from reactor sales to LDCs over the same period, the total value of American reactor plant exports would be between $10 and $14 billion.

Exported reactor plants currently make up a moderate share of the nuclear capacity produced by American industry. For American-built plants starting up from 1977 through 1980, the exported fraction is 30 percent. For the entire period from 1977 through 1985, this fraction will be approximately 18 percent.* Once again, the long-range trends are difficult to predict. It can be expected, however, that although the relative importance of foreign reactor sales is decreasing, these sales will continue to represent a significant potential source of income to American manufacturers through 1930 and probably beyond.

Nuclear Fuel Cycle Exports

As noted earlier in this chapter, the sale of enrichment services is another large contributor to the revenues obtained from nuclear-related exports. American capacity is currently committed through 1985, and no orders have as yet been taken beyond that date. Roughly one-third of this capacity (about 70 million SWU) has been ordered by "foreign customers for delivery in the 1977 to 1985 period. Assuming an average charge of $80 per SWU, the revenue expected from this source will be about $6 billion.

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* Tile shares of American-built plants starting up in the LDCs in the 1977 to 1980 and 1980 to 1985 periods are 8 and 6 percent, respectively.

Because of the many uncertainties surrounding the development of new enrichment facilities in the United States and elsewhere, it is difficult to estimate the potential export value of this service above that which is already committed. New U.S. capacity will face competition from new centrifuge and diffusion enrichment plants under construction and planned for Europe. However, if the U.S. has spare capacity, some enrichment services will be exported.

The export of fuel fabrication services presents a smaller revenue to the United States than does the sale of power plants or enrichment services. This process does not require a large capital investment and is not highly technical; therefore, in the future, many countries can be expected to be marketing fuel fabrication services. This will produce strong competition for this market. In addition, the U.S. industry may be hampered by the uncertainty about long-term permission to export fuel services and by the existence of government-supported activities in other countries. The value of the export of fuel fabrication services can be expected to be on the order of $1.5 to $2 billion through 1985.

The future of spent fuel reprocessing in the United States is still very uncertain. Even if the decision is soon made to go ahead with reprocessing and plutonium recycle, it would be many years before a commercial industry had developed sufficiently to provide reprocessing services to foreign customers, The effect of an American embargo alone on the export of nuclear-related commodities would not be expected to have a major effect on the use of nuclear power around the world. Competing manufacturers such as Germany currently have spare reactor production capacity and could increase their exports. In addition, fuel cycle services (with the possible exception of enrichment in the short term) could be readily obtained on the open market.

It is not clear what influence an American embargo would have on the export policy of the other exporting nations. If it was to have a major effect, then the use of nuclear power in many of the LDCs could be significantly reduced.

VI CONCLUSIONS

In the current economic, political, and social climate many difficulties arise in trying to forecast the future need for energy. The continued influence of the OPEC cartel and rapid escalation of construction costs have unsettled traditional methods for calculating economic equilibrium. Formerly reliable assumptions relating energy demand and electricity share to macro-economic parameters have been questioned and new ones suggested.

In analyzing the role that nuclear power will play in the world, SRI has evaluated the latest data available and drawn from other on-going studies. For clarity, this task was divided into four segments:

1. The role of energy and power in economic development
2. Review of the major alternative forcasts
3. The movement of nuclear materials and equipment
4. The value of U.S. nuclear exports.

The following conclusions have been drawn with regard to these major topics.

1. The role of energy and power in economic development

   - The quantitative nature of the relationship between economic growth and energy use in developed countries has been reevaluated in many studies recently (for example, the Ford

Foundation Policy Report). However, it is certainly still true that if the LDCs are to continue to sustain any measure of economic growth, they will require increasing energy consumption.

- A full forecast of power demand for the LDCs would require a projection of the developmental pattern of each country (for example, agricultural, industrial, or service orientation), projections of regional fuel prices, demand-price sensitivities, generation plant capital costs and regional efficiency of energy use.
- Certain characteristics predispose a nation to the use of nuclear power. The more important of these are a lack of cheap and conveniently located alternative energy sources, and a sizable (and preferably rapidly growing) power demand in a single integrated system. Other factors favoring nuclear power are compactness of demand area and the presence of industrial operations with constant power requirements.

2. **Review of** the major alternative forecasts of installed nuclear capacity.

- Jumps in the price of oil (and other energy sources) following the 1973 embargo, coupled with rapid capital cost increases in the 1974-75 period, outdated many of the cost assumptions of the earlier forecasts (such as the IAEA market surveys).
- **Direct comparison among the various forecasts is difficult because they deal with different groups of countries and**

different time frame. However, it is apparent that the more recent the study, the lower the value estimated for nuclear capacity growth. The major factors contributing to this are:

A decreased expectation for the growth of energy demand around the world due to decreases in projections of population and GNP growth, recent much higher average prices for energy, increased emphasis on conservation and improvements in the efficiency of energy use.

Increasing experience concerning the rising costs and difficulties encountered in the construction and operation of nuclear power plants.

Public opposition to nuclear power around the world has become increasingly effective.

- It seems now that nuclear fuel cycle costs and nuclear plant capital costs may range as high as 7 mils/kW hr and $925/kW respectively, for a plant beginning operation in the mid-1980s. These cost estimates are higher than those in the other studies reviewed in Chapter III.

- In general, the forecasts reviewed did not adequately consider the available alternatives to the use of nuclear power. For example, increasing use of indigenous coal and development of a world-wide trade in steam coal are likely. SRI believes that tanker-type shipment of coal could" be achieved to supply seaside power stations in the LDCs with coal at prices as low as $17-$24/ton. For these special locations, coal would be an obvious and economical choice.

- Competition to nuclear development could also come from hydropower and the use of natural gas that is currently a wasted by-product of much oil production.
- Partially offsetting some of the above factors are certain non-economic incentives that could be influential in expanding nuclear development. These might include export pressures by nuclear suppliers, the desire for developing diversified sources of energy, the prestige accompanying use of a modern technology, and possible interest in developing nuclear weapons capability, or the appearance thereof.
- Our own estimate of nuclear power growth is quite consistent with that of the International Energy Agency as modified by ERDA, the most conservative of the forecasts reviewed in this report.

3. The movement of nuclear materials and equipment. The primary conclusions for this topic can best be summarized by first considering each segment of the nuclear fuel cycle:

- Uranium Supply - Uranium ore supplies at foreward production costs of less than $30/lb are expected to be adequate for the study period of this report. Canada, Australia, South Africa, Gabon, and Niger will be the initial exporters; other nations will undoubtedly become suppliers at later dates.

- Enrichment - Large-scale enrichment facilities, all based upon the gaseous diffusion process, now exist in only four nations. (The extent of capacity in one other country, the Peoples' Republic of China, is unknown.) Alternate processes (notably centrifugation) promise to allow economical plants at smaller sizes, and such plants are currently under construction in Europe. However, a large increase in the number of nations providing commercial enrichment services is not expected, due largely to the technical complexity and capital costs involved.

- Fuel Fabrication - Commercial scale facilities for the fabrication of oxide fuels are currently operational in six countries. This technique does not require high technology or large capital expenditure, therefore it could potentially spread to those less developed countries planning large nuclear capacities such as Iran (Brazil has already announced its intention to fabricate fuel). On economic grounds alone, many facilities are likely to incorporate plutonium recycle if feasibility is demonstrated in the major nuclear countries.

- Reprocessing - No commercial scale facilities for the reprocessing of oxide fuels are currently operational, but several industrialized nations are expected to provide this service by the mid 1980s. Due to the capital investment and technical requirements of a full-scale reprocessing plant, not many LDCs could be expected to build such facilities. However, pilot size plants could be constructed and used to produce plutonium for weapons or other use.

Brazil has announced its intent to develop a pilot reprocessing plant, and several other LDCs have also discussed the importation of reprocessing technology. However, current indications are that all of the important industrialized nuclear countries are committed to an embargo on future export of reprocessing technology.*

- **It** is important to note that the large fuel cycle operations considered economic in the U.S. are too large to be supported by the nuclear capacity of any developing country, at least until. after 1990. This is true even if the most optimistic **forecast, that of the IAEA Market** Survey, is used. If an export market could be established, smaller but reasonably competitive plants especially for enrichment and fuel fabrication could be considered by 11 countries. These are Mexico, Brazil, Argentina, Spain, Yugoslavia, India, Iran, Korea, Poland, Romania, and Czechoslovakia. (Other activities including fuel reprocessing for plutonium recovery could be established if sufficient government support or incentives were offered.

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*Nuclear Engineering International, January 1977.

- **Large scale** commercial use of breeder reactors is not expected before the year 1995. Breeders would therefore not have a significant direct impact on the nuclear fuel cycle before the end of this century. However, anticipation of future breeder development may cause some stockpiling of retrieved plutonium in competition with its potential use in mixed-oxide fuels for LWRs.

4. The value of U.S. nuclear exports

- The commercial importance to the U.S. of exporting nuclear materials and services resides largely in the sale of reactors, associated nuclear generating plant equipment, and enrichment services. The dollar values of these purchases greatly outweigh the revenues expected from the export of other nuclear services and materials.

- In the past, the U.S. has captured a very large fraction of the reactor export market. However, with increasing competition from other vendor nations, the American share is expected to fall. For the case of exports to the LDCs, the fraction of U.S.-supplied nuclear capacity beginning commercial operation from the start of 1977 through the end of 1980 will be greater than 70%. In the succeeding five year period, 1980 through 1985, the American share is down to 38%.

- The major factors contributing to this downward trend are uncertainties in the future availability of enriched uranium from the U.S., governmental regulation of nuclear export sales, and reluctance of LDCs to become even more dependent on U.S. industry.

- Total foreign nuclear capacity currently committed to startup between 1977 and 1985, that is being supplied by American reactor vendors is in the 25,000 to 27,000 MW range. (Approximately 9,000 MW of this figure is scheduled for export to developing countries.) The future revenue to the U.S. accruing from these plant sales can be expected to reach $0-s billion.

- Additional new orders for plants coming on line by 1985 will likely push total exports to the 34,000-38,000 MW range, of which 10,000-12,000 MW would be to developing countries.

- **By** 1990, American-installed nuclear capacity in the developing countries could be expected to range from 18,000 to 22,000 MW. The revenues accrued from these sales would be on the order of $5 to 7 billion.

- The withdrawal of American reactors from the world market could have some political influence on the use of nuclear power in some of the developing nations. However, because of the many competing vendor nations that can be expected to have excess production capacity, an American export embargo alone would not significantly hinder the ability of LDCs to obtain reactor systems. It is not obvious to what extent an American embargo would influence other vendor nations to limit their exports of nuclear materials. This influence could be important, however.

- Enrichment services supplied by the U.S. government also have a major impact on the value of nuclear exports. About 70 million SWU is currently committed to foreign customers through 1985. Assuming an average charge of $80/SWU, the revenue obtained from this source will be near $6 billion. Beyond 1985, it is uncertain how much U.S. enrichment capacity will be available to provide for export.

Appendix A. Nuclear Power Plant Manpower Requirements

The operation of nuclear power plants, per se, requires the skills and abilities common to other large thermal stations. More careful training is usually given to nuclear plant operators but they are recruited from the general body of utility plant workers. It has been estimated that 95 skilled workers are required for normal operation of a nuclear power station of 1,100 MW capacity and 65 and 80 and required for oil and coal fired stations of 800 MW size respectively.

Maintenance of nuclear stations can require larger numbers of skilled workers with ability to work carefully under conditions of stress and in unusual environments. The radiation fields that can be encountered can limit the working time of an individual worker. These same fields may also require remote operations and thus reduce worker productivity. The presence of radioactive materials can require the use of protective clothing, masks, etc. These tend to reduce worker efficiency and can impair work quality as well. Many more workers of a given skill (e.g., welder) may be required for maintenance of nuclear power plants.

While large utility systems in industrialized nations usually have the required reserve of manpower for maintenance, it is not clear that developing countries can easily have the reserve manpower that may be necessary for nuclear power station maintenance. Importation of such manpower is possible, but it's use could decrease the apparent cost advantage of nuclear power.

Construction of nuclear power stations requires large numbers of skilled workers, many of whom must be certified or otherwise specially qualified. This labor is generally available in industrialized nations but scarce in developing countries.* Even in the USA there is evidence that proper construction labor is sometimes in short supply. The combined pressures of the World Trade Center construction in NYC, the rapid construction of an automobile plant in Ohio and the first wave of nuclear power plant construction in the late 1960s created labor shortages, a competition for labor through overtime authorization, and an inflated construction cost for all projects. Similar effects have been noted during the construction of the Alaskan pipeline. Relevant to this problem of labor scarcity is the experience of Babcock and Wilcox who attempted to establish a plant at Madison, Indiana, a labor surplus area, for the construction of LWR pressure vessels. B. and W. recruited and trained previously unskilled labor for the plant operations. As the labor force became trained in specialty welding and other related skills, it was rapidly depleted by recruitment from other employers and moved to other areas at higher wages. This could happen to the native construction labor force in a less developed country.

In addition to the large numbers of construction laborers required, a large staff with diverse skills is essential for nuclear plant construction. The erection of a nuclear power plant requires trained engineering staff for quality control, general engineering, design and other functions. The number of engineering man-hours has risen to about 2 million over the past several years as experience has shown the need. This particular labor requirement will not impact on all developing countries equally as some will purchase plant supply services from developed countries. Only a few, e.g., India, will do the engineering support work themselves.

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* **This statement is generally true** although even projects in industrialized countries must provide specialist training to many workers.

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APPENDIX B

Energy in a Changing World

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During the last, few years, crude oil prices have increased to levels that most of the world's people would have considered unbelievable in 1970. Pronouncements have asserted that crude oil supplies would not be adequate to meet aggregate demand by 1990 or even earlier. SRI'S Energy Center is frequently asked what the availability and prices of primary energy resources will be in the future and how energy will affect future economic developments and political decisions. Single and multiclient studies covering future energy developments for various countries and for the world have been prepared. Work is in progress on a multiclient effort entitled "World Energy Study- 1950 to 2000," which will provide further insights into these questions. A few observations from these projects are given below.

- Future petroleum prices may moderate when expressed in constant dollars, but they are unlikely to return to 1970 levels.
- Petroleum supplies probably will be adequate for the remainder of the 20th century.
- Demand for petroleum is expected to increase at lower rates than earlier forecasts had indicated because of conservation measures and substitution of other energy Sources.
- Investment and operating costs for energy production, processing and distribution, which in many cases had increased more rapidly than inflation during the early 1970s, are anticipated to increase at substantially lower rates during the next few years because of active competition among suppliers of the various energy sources.

World supplies of crude oils were abundant and low in cost after World War II up to the early 1970s. This materially contributed to the rapid postwar industrial recovery of the developed

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countries and the concomitant long period of general prosperity. Although coal consumption increased moderately, the majority of the growing demand for energy was satisfied by the increased use of natural gas and oil.

However. storm clouds were gathering that would raise energy costs. modify energy usc patterns, and even affect future economic growth rates of the developed and developing countrics. The cumulative effects of several events w'erc anticlpated by very few people, and even these individuals did not perceive their full impact.

The 1960 reduction of 10 cents per barrel in posted crude oil prices for the Middle East was one of the important factors leading to the formation of the Organization of Petroleum Exporting Countries (OPEC). During the early 1960s, OPEC was primarily concerned with increasing the volumes of crude oil marketed. The Six-Day War in 1967 resulted in the closing of the Suez Canal, which necessitated the increased use of large tankers to transport crude oil around Africa for delivery to Europe and the United States. Several events occurred in 1970 including Syria's cutting of the tapline in May and its refusal to allow the line to be repaired; Libya imposed restrictions on crude oil production rates: the 1967 Clean Air Act in the United States was amended leading to increased oil imports to replace some high-sulfur coal use; the Environmental Protection Agency was created in the United States; oil tanker shipping costs increased; and Libya forced the oil companies to increase posted prices. which led to posted price increases in other OPEC countries.

During 1971. the Tehran and Tripoli Agreements provided for additional increases in posted prices, crude quality adjustments. and increased tax payments. The U.S. dollar was devalued late in 1971, and OPEC raised the principle of participation: the Geneva Agreement of January 1972 provided for protection of crude export values against further depreciation of the dollar.

Several Middle Eastern countries signed participation agreements early in 1973, as well as a supplement to the Geneva Agreement. Rapid economic growth with substantial increases in energy consumption rates was occurring in the consuming countries, and concern was growing over rising inflation rates. This set the stage for the Arab oil embargo in October during the Middle East hostilities. By the end of 1973, Saudi Arabian light crude oil had an f.o.b. price of about $9.50 per barrel, an increase of more than $8.00 per barrel over the mid-1 970 price.

An oil price increase of this magnitude was sufficient to precipitate a worldwide recession during 1974 in nearly all non-OPEC countries. This cot]tributed to the positive benefit of moderating inflation rates. Economic recoveries were generally favorable in tile developed countries in 1975 accompanied by declining inllation rates, indicating that the developed countries had been able to adapt to higher energy prices.

What will happen during the remainder of the 20th century? Speeches have been given, articles written, and studies prepared covering nearly every possibility that might occur. A few of the more prevalent positions are repeated below. Since 1970 there have been recurring concerns that capital limitations will restrict future economic growth in developing and developed countries. Some believe that Inflation rates cannot be kept under control. which may lead to further recessions. There have been frequent pronouncements that the world will incur shortages of petroleum and uranium during this period, leading to reduced economic activity; also, there are those advocating the need for crash programs to develop nearly every possible substitute energy source, regardless of its economic viability. Some even believe that conditions will stabilize in a few years, resulting in economic and energy growth rates again becoming similar to those occurring in the 1960s.

Although all projections are subject to error because of the many variable factors, everyone (individuals, corporations. and governments) must provide for the future based on an assessment of what is likely to happen. SRI'S analyses lead to the conclusion that major events of the last five years will cause repercussions for many years. Petroleum prices, whether [hey increase or moderate on a constant dollar basis. are not likely to return again to 1970 levels. Economic activity. as measured by gross national product. is expected to increase at lowcr rates than prevailed in the 1960s. Population growth rates should slowly moderate.

The higher petroleum prices, lower rates of economic activity, and moderating population growth rates are anticipatcd to affect the demands for energy and the prirmary energy mixes. As an example of the magnitude of anticipated energy consumption in 1990. a fairly representative 1972 projection anticipatcd 116.3 million barrels per day of free world demand for oil and 214.0 million barrels per day of oil equivalent for total free world energy demand. SRI has estimated 1990 free world demands of 68.2 and 156.7 million barrels per day of oil equivalent. respectively (reduced forecasts of about 41 and 27 percent). The use of oil is reduced more than total energy because of conservation measures and the substitution of other energy resources. However. SRI'S Energy Center believes that adequate oil supplies will be available through the remainder of this century. Conversely, coal, natural gas, and,. uranium uses will be accelerated because of high oil prices and consumer desires to diversify supply sources, especially from non-OPEC countries.

Lower expected consumption of total energy and particularly the lower requirements for oil would have wide economic and political repercussions. Tanker requirements for transporting crude oil and petroleum products would be reduced. Additional pipelines would be required to transport natural gas. Exploration programs for uranium would be expanded as would the requirements for coal mining machinery and coal transportation facilities. Reduced economic activity and total energy consumption rates would adversely affect industry in general by lowering overall productivity.

Although only a few examples have been given. SRI has prepared studies to quantify these effects in assisting clients to develop their future long-range plans_

Appendix V: TECHNICAL DESCRIPTION OF FUEL CYCLE FACILITIES AND EVALUATION OF DIVERSION POTENTIAL

Appendix V

TECHNICAL DESCRIPTION OF FUEL CYCLE FACILITIES
AND EVALUATION OF DIVERSION POTENTIAL

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APPENDIX V

TECHNICAL DESCRIPTION OF FUEL CYCLE FACILITIES AND DIVERSION POTENTIAL

1. INTRODUCTION

Considerable concern has been expressed over the possibility that nations could extract from their nuclear power systems the fissile material essential for nuclear weapons. There is, in fact, no intrinsic reason why they could not do so, although no nation which has nuclear weapons has effected them by these means. It is the intent of this section to examine the existing and potential reactors and their associated fuel cycles. With this background, the possibility of diversion from each system can be understood and compared. In the past, proliferation potential has not been considered as a parameter in the design of nuclear power systems. If diversion is increasingly perceived as a problem, however, it may be found desirable to favor those systems which are least vulnerable.

2. THE NUCLEAR FUEL CYCLE

2.1 INTRODUCTION

Nuclear energy is derived from the conversion of mass to energy by splitting or joining nuclei. A fission reaction occurs when a heavy nucleus is struck by a neutron and shatters into two or more intermediate weight nuclei and additional neutrons with slightly less total mass than the original nucleus. This mass defect is converted to energy - in the form of radiation and particle motion. The only naturally occurring nucleus that readily fissions (i.e. is fissile) when struck by a neutron is ^{235}U (the isotope of uranium containing 92 protons and 143 neutrons for an atomic mass of 235). All others usually either deflect or absorb neutrons. There are other notable fissile isotopes, all manmade. These are ^{233}U and all isotopes of plutonium.

A chain reaction occurs when neutrons emitted from fissioning nuclei cause other nuclei to fission. This can happen only under certain conditions. **There** must be sufficient fissile material present, arranged in an appropriate geometry. A moderator may have to be present to slow the high energy (fast) neutrons emerging from the fissioning nuclei so that they may be more readily captured by other fissile nuclei. There cannot be too many other nuclei present which absorb neutrons. To produce useful power some means of control to keep the chain reaction at a constant rate must be included **and the heat generated must be removed by a coolant.**

Uranium is naturally found as a mixture of two isotopes: the fissile ^{235}U (0.71%) and ^{238}U (99.29%). Natural uranium can be made to go critical (i.e., sustain a chain reaction) only under very limited conditions

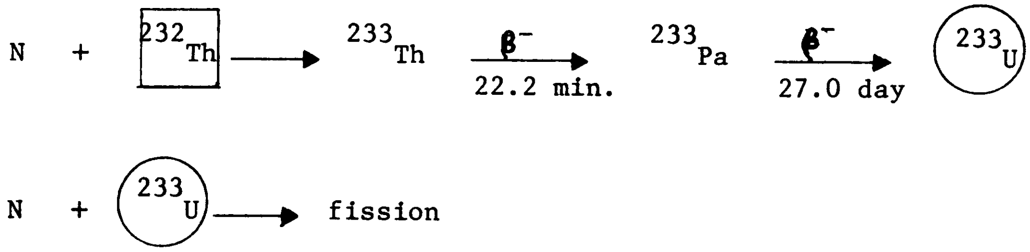
because the ratio of fissile to non-fissile material is low. Hence for use as a nuclear fuel uranium is usually enriched in the fraction of ^{235}U to perhaps 3%. The criteria for the choice of coolant, moderator and structural materials then become less stringent since fewer neutrons are abosorbed by ^{238}U.

When a nucleus absorbs a neutron without fissioning, it is converted into another isotope of the same element. This may be itself a fissile nucleus of it may indirectly result in one by a short term decay process. In this way the uranium isotope ^{238}U is transformed into ^{239}U which after emission of an electron (beta particle) becomes ^{239}Np. This in turn decays by a beta emmission to become ^{239}Pu. In a similar way, the thorium isotope ^{232}Th are said to be fertile. Reactors can be fueled with any of the fissile isotopes and supplied with fertile material to breed more fuel.

The fuelelements of nearly **all** power reactors contain both ^{238}U and ${}_{U}235$. In normal operation, some of the ^{238}U is converted to ^{239}Pu, some of which is fissioned. If the plutonium in the spend fuel is less than the ^{235}U in the fresh fuel, the reactor is called a converter or breeder. A sustainer reactor would be one which produces the same amount of fissile material as it consumes. Some reactors, known as breeders, produce more fuel from fertile isotopes than they use in operation.

Reactors operate on one of two major fuel cycles. The one used in most reactors today is the uranium-plutonium cycle where the initial fissile material is ^{235}U and plutonium is generated from the fertile ^{238}U. The other cycle is thorium-uranium where ^{233}U is fissile and ^{232}Th is fertile. The major nuclear reactions for these cycles are shown in Figure 1.

A neutron emitted by a fissioning atom has a high velocity and is referred to as a fast or high energy neutron. As it strikes nuclei in its path, it loses energy and slows down. It is then referred to as a slow or thermal neutron.



(b) Thorium - Uranium

Figure 1. Uranium and Thorium Fuel Cycles. (Nuclides in the circles are "fissile," that is, they readily undergo fission in nuclear reactors. Nuclides enclosed in square boxes are fertile. They undergo very little fission themselves, at least in thermal-neutron reactors, but are converted by neutron capture into fissile nuclides.)

The efficiency of breeding of fertile material is dependent upon the neutron energy spectrum. In general, thorium is bred more efficiently by thermal, or low energy neutrons while ^{238}U is bred more efficiently with fast or high energy neutrons. Present fast breeder reactors are generally based on the U-Pu fuel cycle although there is interest in a Thorium fast breeder. Thermal breeders must be based on the Th-U fuel cycle. The reactor neutron energy spectrum is mainly determined by the type of coolant and/or moderator.

As illustrated by the above discussion, there are many characteristics which define a nuclear reactor. Figure 2 illustrates a fission power reactor characterization tree. Since the reactor is the dominant part of the fuel cycle, the fuel cycle itself is generally characterized by the reactor. Typically, the fuel cycle is expected to contain those elements depicted in Fig. 3. At present, fuel is not being reprocessed, and the cycle ends with spent fuel storage. The component which are most vulnerable to diversions are uranium enrichment, spent fuel processing and the transportation of their products. Each of the major elements will be discussed. The reactor concept will be identified

2.2 MINING

Uranium is the principal fuel required for present nuclear reactors. It has been estimated that uranium constitutes 2-4 ppm of the earth’s crust. Most of it, however, is such low grade (less than 0.001% U_3O_8) that its extraction may not be economical. Presently, commercially

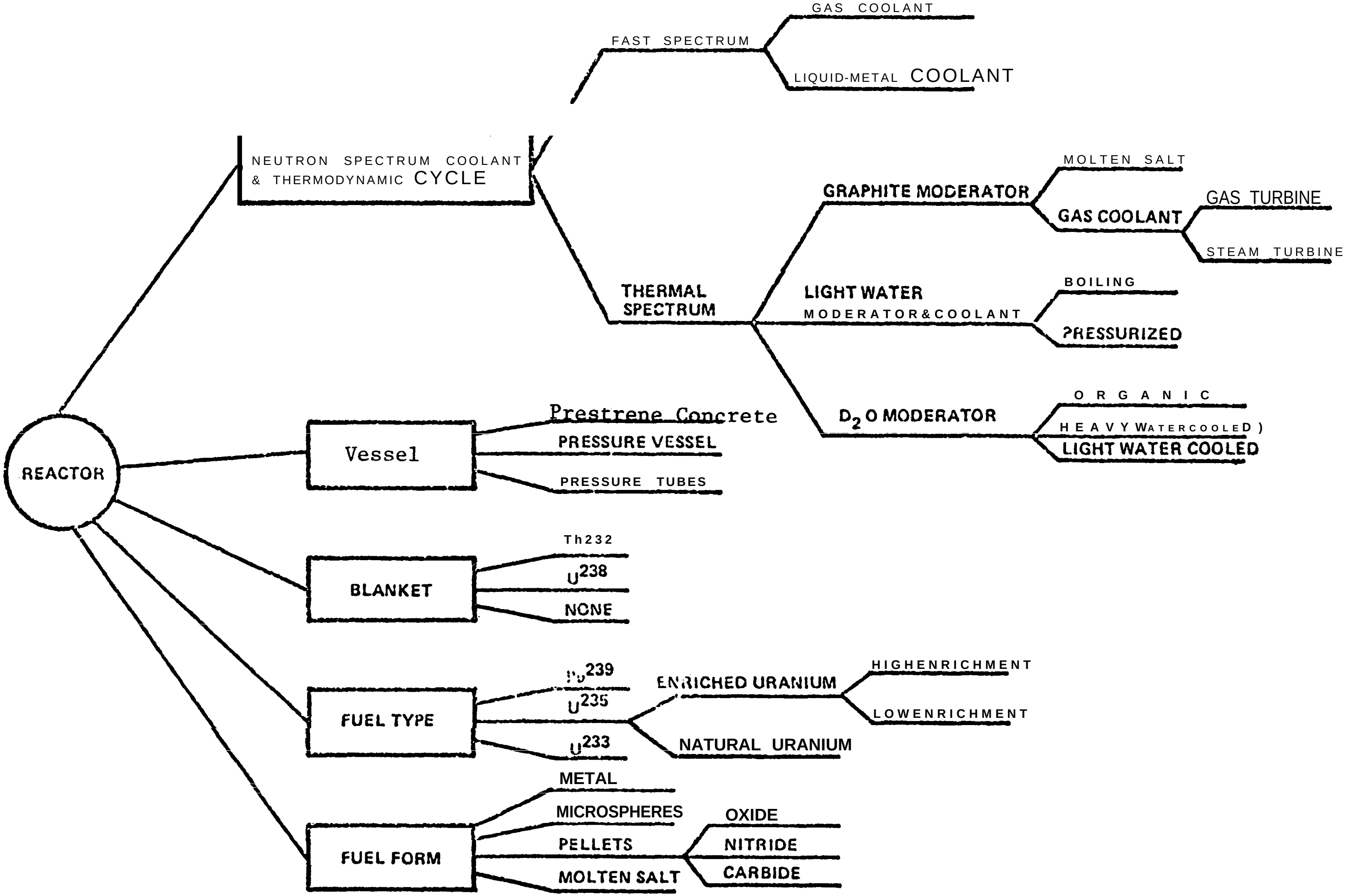


Fig. 2 . Fission Power Reactor Classification

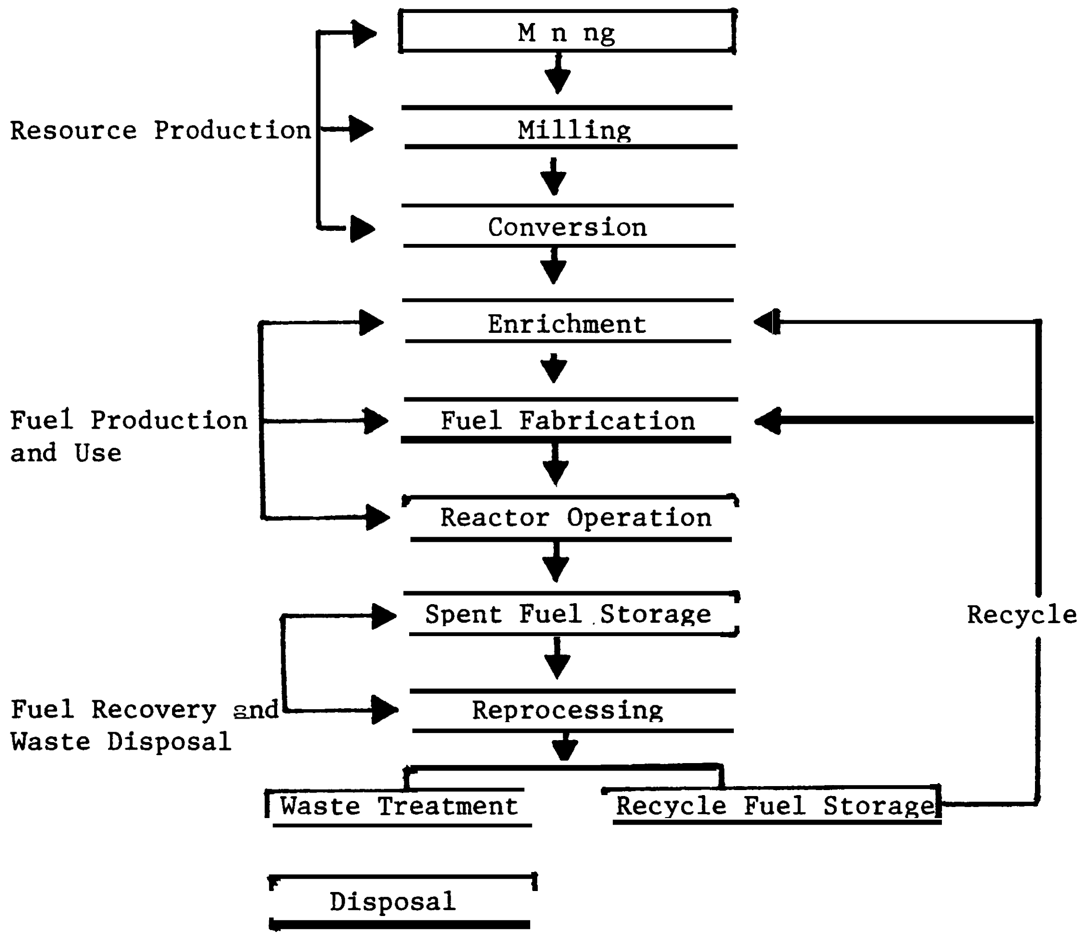


Fig. 3 The Generalized Fuel Cycle

attractive ores must contain at least 0.05% U_3O_8. Deposits mined currently contain between 0.1 to 0.5%. In some cases however, uranium ore is a byproduct of the recovery processes of other minerals such as gold or phosphates. About 12,000 metric tonnes (MT) of U_3O_8 are produced annually in the U.S. Proven reserves in this country are 500,000 MT. The total recoverable resource is probably several times this. World resources are discussed in Appendix VIII, but it should be noted that most nations have at least some low grade ores. A typical reactor requires about 150 MT of U_3O_8 per year.

Thorium is generally estimated to be three to five times more abundant than uranium and is found in veins, sedimentary rocks and sands. Most of the thorium currently produced in the U.S. (see Fig. 7) is a byproduct of rare earth extraction. The annual production is about 150 MT. There appears to be more than 100,000 MT of ThO_2 at $10/pound in the U.S.; world supplies are five to ten times this amount.

A typical uranium or thorium mine may process about 1,000 MT ore/day. This would yield about 1,000 MT U_3O_8 or 1,500 MT of ThO_2 per year. The ratio of overburden to ore ranges from 1 to 10. The capital cost for the mine would range from $10 to $20 million, with an operating cost of $1 million (about $0.50/lb for operations). Required equipment is similar to that required for other mining operations. Mines are either open pit or underground depending on depth. Underground mines are more expensive to develop but are more secure from surveillance than pit mines if clandestine operation is required. The usual hazards of underground mines are augmented by the presence of radioactive radon gas, which can in the long term cause cancer in the miners.

2.3 MILLING

In the milling operation uranium is recovered from the ore and purified in preparation for subsequent fuel fabrication operations or conversion for enrichment processing. The product of the milling operation is a uranium salt called yellowcake, which contains between 70% and 90% U_3O_8 The established milling industry in the U.S. has a capacity to produce about 20,000 tons U_3O_8 annually in 16 mills. Individual production capacity ranges from 400 tons of ore per day to 7,000 tons of ore per day.

The unit operations at a mill include crushing, grinding, leaching, solids separation, extraction and yellowcake precipitation. The specific methods vary with the composition of the ore mined. A general flow sheet for a uranium mill using the acid leach-solvent process is shown in Fig. 4.

Major plant features include an ore storage and blending area; a crushing building; a mill building containing grinding equipment, leaching tanks, precipitation tanks, drying and packaging equipment; a solvent extraction building; a tailings retention system; a sewage treatment system, and several auxiliary buildings needed for offices and maintenance. A typical mill could process 1,000 MT ore per day, requiring a capital investment of about $10 million with operating costs of about $10 per ton of ore (about $1.00/lb U_3O_8). The land required for the mill is about 300 acres. The equipment is similar to that in other ore milling industries.

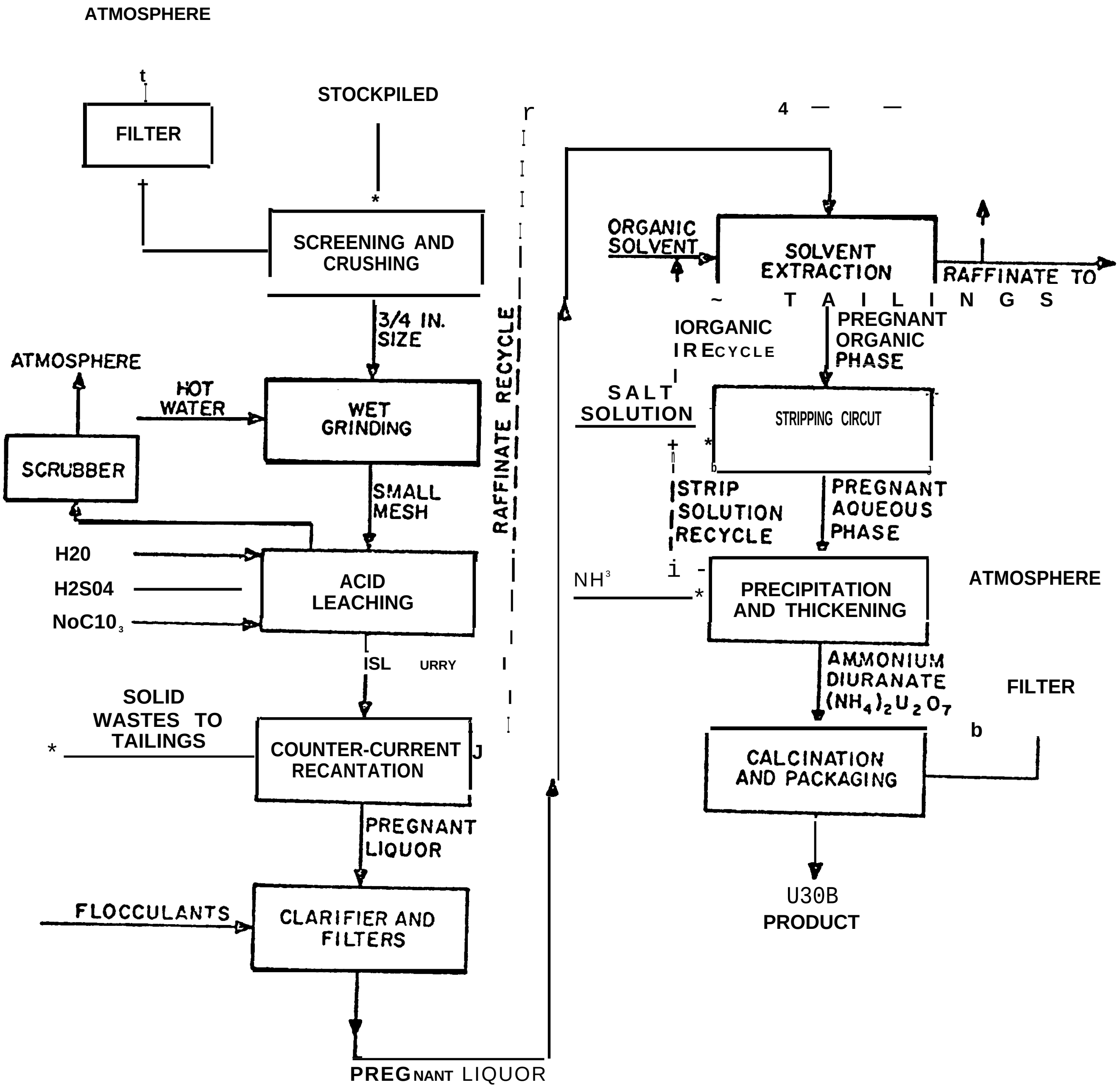


Figure 4. Generalized Flow Sheet for Uranium Milling

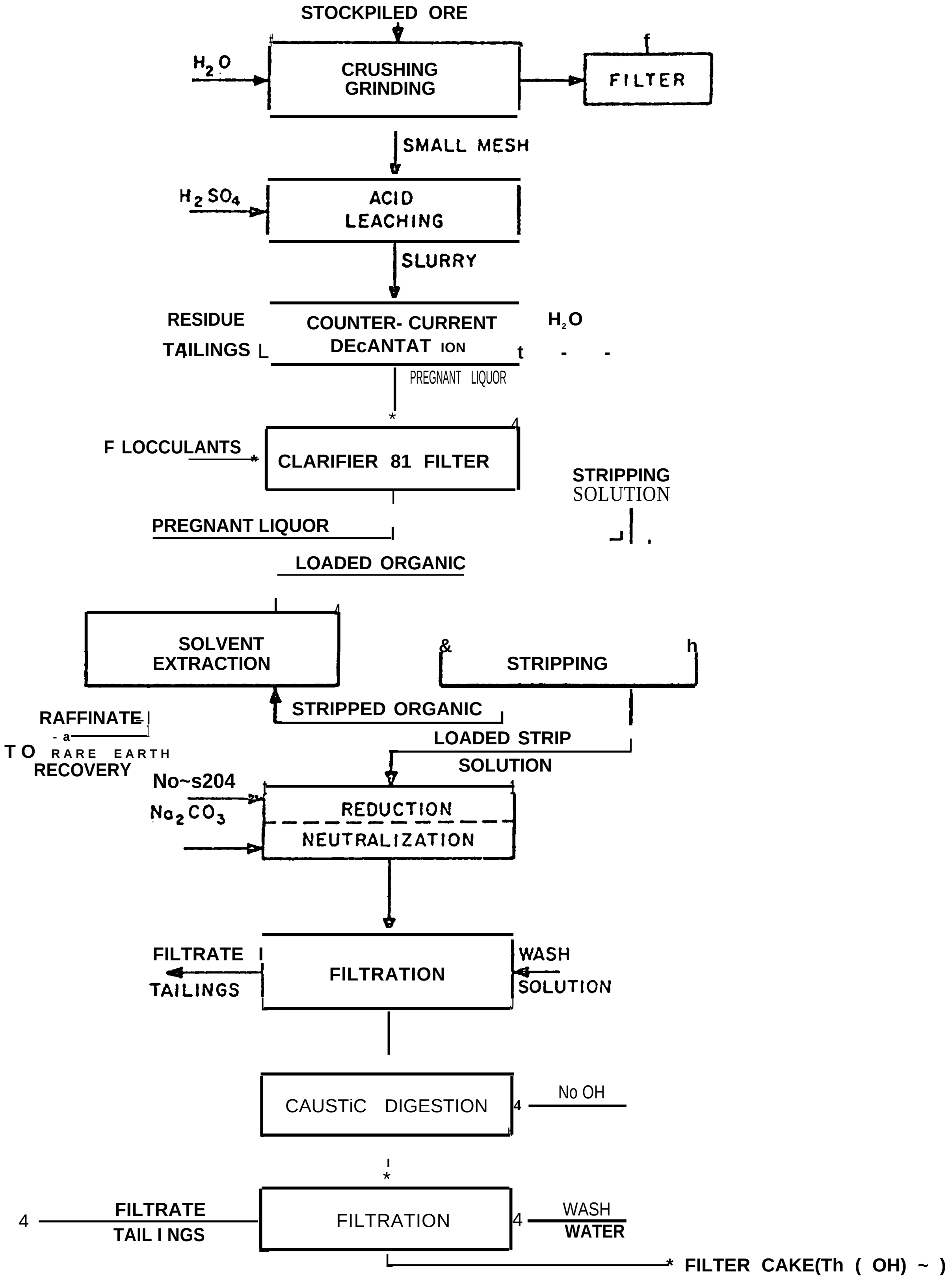


Figure 5. Thorium Milling Flow Sheet

Recovering thorium from its ore requires milling and refining. The milling process extracts the ore and upgrades it to predetermined specifications. The techniques for current production of thorium from monazite sand are proprietary. The thorium mill may employ an acid leach-solvent extraction process, as depicted in Fig. 5. The major steps in this milling operation include crushing, leaching, decanting, solvent extraction and precipitation to from a crude mill product.

The second part of the thorium recovery process is to refine this mill product into material suitable for nuclear reactor fuel. One requirement is that the uranium content must be less than 10 parts per million because of isotopic dilution of the U-233 formed in the reactor.

The large neutron cross section of the lanthanides requires that their concentration be reduced to 1-5 ppm. The most economical method of purification is considered to be the counter--current solvent extraction process. A flow diagram of the refinement is given in Fig. 6.

The capital and operating costs for thorium processing are likely to be similar to those for uranium.

2.4 CONVERSION

For those reactors requiring enriched uranium, i.e. concentration of U-235 greater than .71%, the U_3O_8 must be converted to uranium hexafluoride (UF_6), the only compound of uranium which is gaseous at a temperature low enough for easy handling. In a conversion plant, the yellowcake is purified and converted to approximately 99.9% Pure U^F6 and

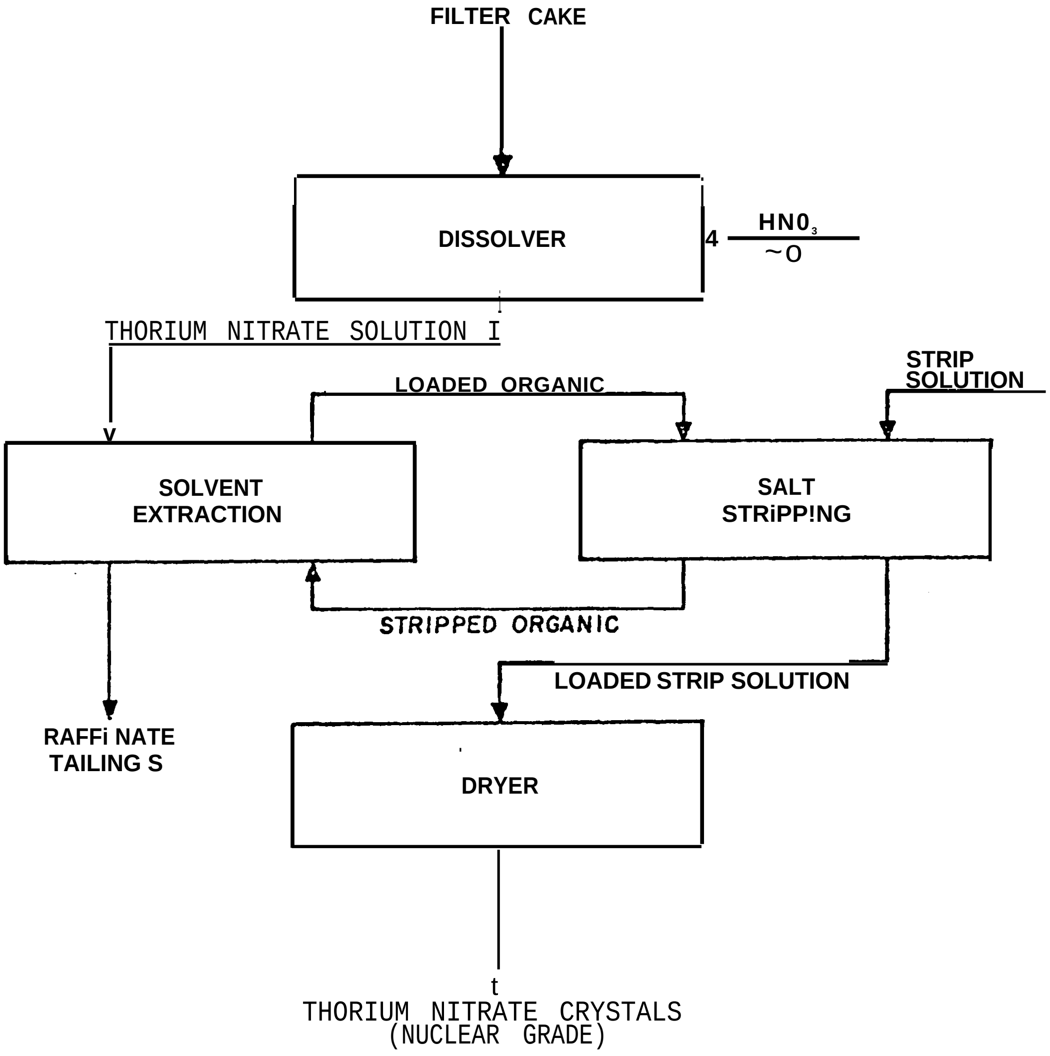


Figure 6. Thorium Refining

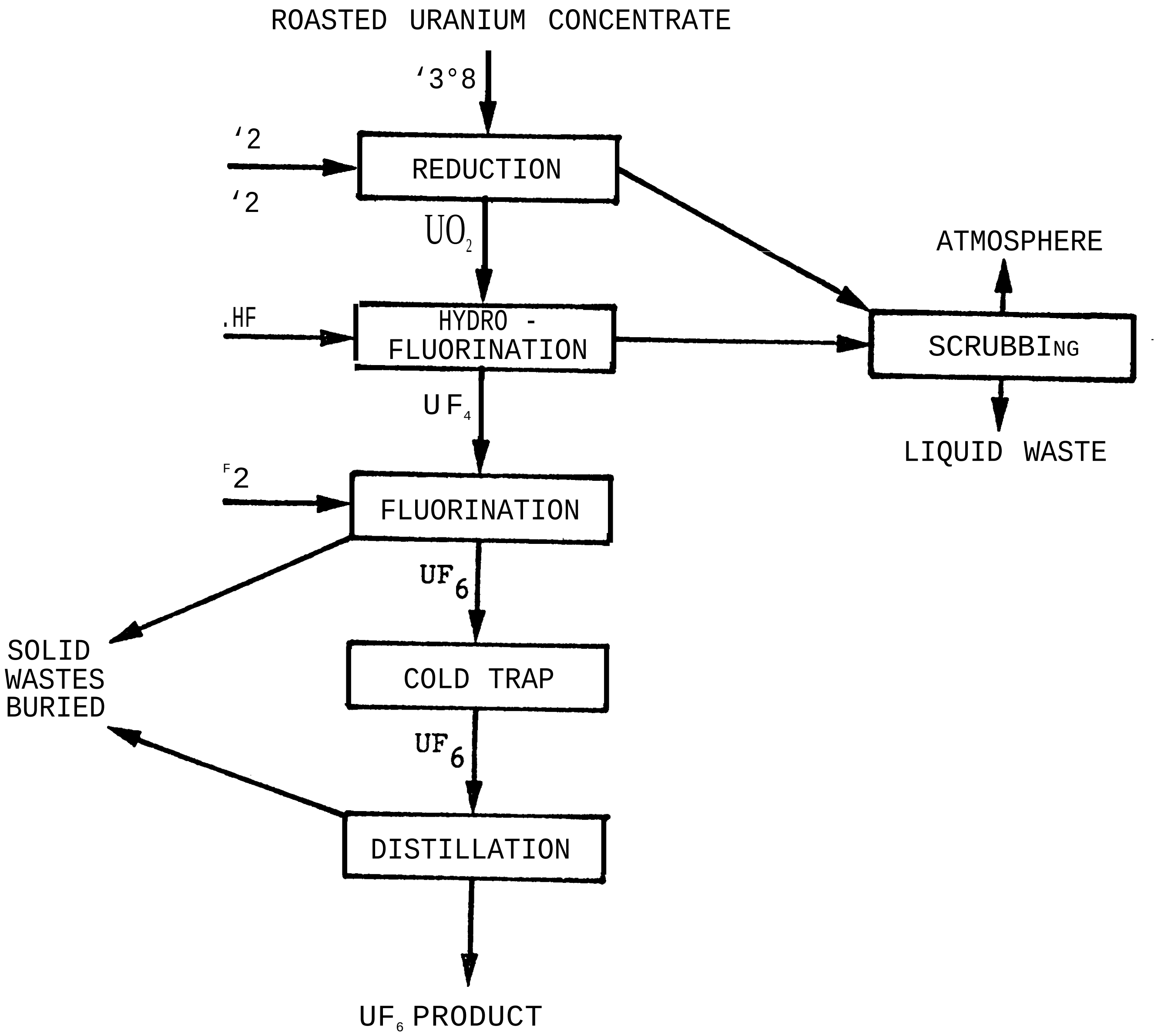


Figure 7. UF6 Production-Dry Hydrofluor Process, Simplified Block Flow Diagram

is shipped in special cylinders to the enrichment facilities.

Conversion plants in the U.S. use both a dry (hydrofluor) and a wet process. Total production capacity is about 20,000 MT of uranium per year as UF_6, with the hydrofluor process accounting for about 75% of this total. A simplified flow diagram of the hydrofluor process is shown in Fig.

A typical plant would have a capacity to convert 5,000 MT of uranium to UF_6 per year. This plant capacity requires approximately 1,000 acres and a capital cost of about $35 million. Operating costs for a plant of this type run about $1.25 per pound of uranium. Typical chemical process equipment is required.

If uranium is recycled from the reprocessing plant, it must be converted to UF_6 for reenrichment. The reconversion is performed in a plant specifically dedicated to that task; it converts $UO_2\ (NO_3)_2\ 6H_2O$ to UF_6* A typical plant might have a capacity of 1200 MT/year, with capital costs of about $50 million and operating costs of about $1.00 per pound of uranium.

There is no counterpart process for thorium because it contains no fissile isotope to be enriched.

2.5 ENRICHMENT

In none of the fuel cycle steps considered so far is the uranium in a form suitable for use in weapons; the concentration of the fissile isotope U-235 is far too low. The next step for most uranium reactor types except heavy water reactors is to enrich the uranium. Light water reactors (LWR) require 2-4% U-235 (still not suitable for weapons), but some power and research reactors use “fully enriched” uraniums which contains 93% U-235. Because of its potential for producing the highly enriched uranium required for nuclear weapons, the enrichment plant is of great concern in preventing proliferation. Even if a plant is built to produce low-enriched fuel for LWR's, it could be restructured, possibly even clandestinely, to produce weapons-grade uranium.

For all enrichment techniques, a key parameter is the separative work unit (SW), which is a measure of the work to obtain a certain degree of separation. It is defined in reference to a kilogram of uranium. An enrichment plant will use 1 kg of SWU in processing 2.35 kg of natural uranium feed (0.71% U-235) to provide 1 kg of product enriched to 1.4% 235U (twice the natural enrichment) and 1.35 kg of waste (called "tails") with a concentration of 0.2% ^{235}U. This is illustrated in Figure 8. The SWU required to enrich uranium depends in a complex way on the concentrations of 235U in the feed, product and trails. In general, a higher tails assay requires fewer SW'S and more feed. If resource utilization were not important a given quantity of enriched uranium could be obtained with less work by raising the tails assay.

The quantity of natural uranium feed and the separative work required for a product enriched to a specified level with 0.2% or 0.5% Tails assay is shown in Figure 9. For example, with 0.2% Tails, 4.3 SWU and 5.5 kg of Feed are required for 1 kg of 3% product. For one kilogram of 90% ^{235}U, 227 SWU and 176 kg of feed are required. Less than twice as much separative work is required to produce weapons grade material as is needed to enrich uranium to 3% from a given amount of feed.

Enrichment plants are designed for a specific SWU capacity. Other factors can be adjusted fairly easily however. Increasing the tails assay and the feed permit one to raise either the output or the enrichment level. The Chinese may have produced their first uranium bomb by converting a U.S.S.R. supplied low enrichment plant. The use of partially enriched uranium as feed would also increase the output of the plant. A given amount of separative work can, of course, be achieved by a small plant over a long period of time or by a large plant working for a short period

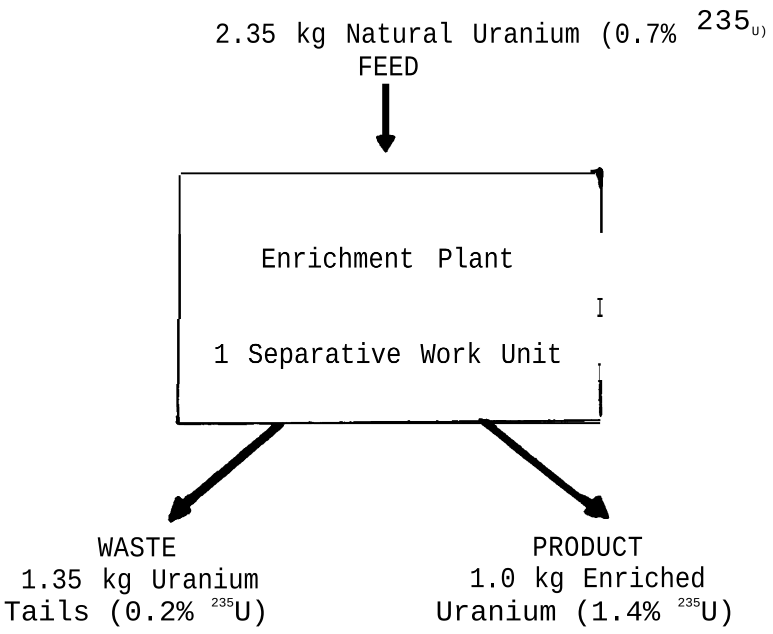


Fig. 8 Example of One Separative Work Unit

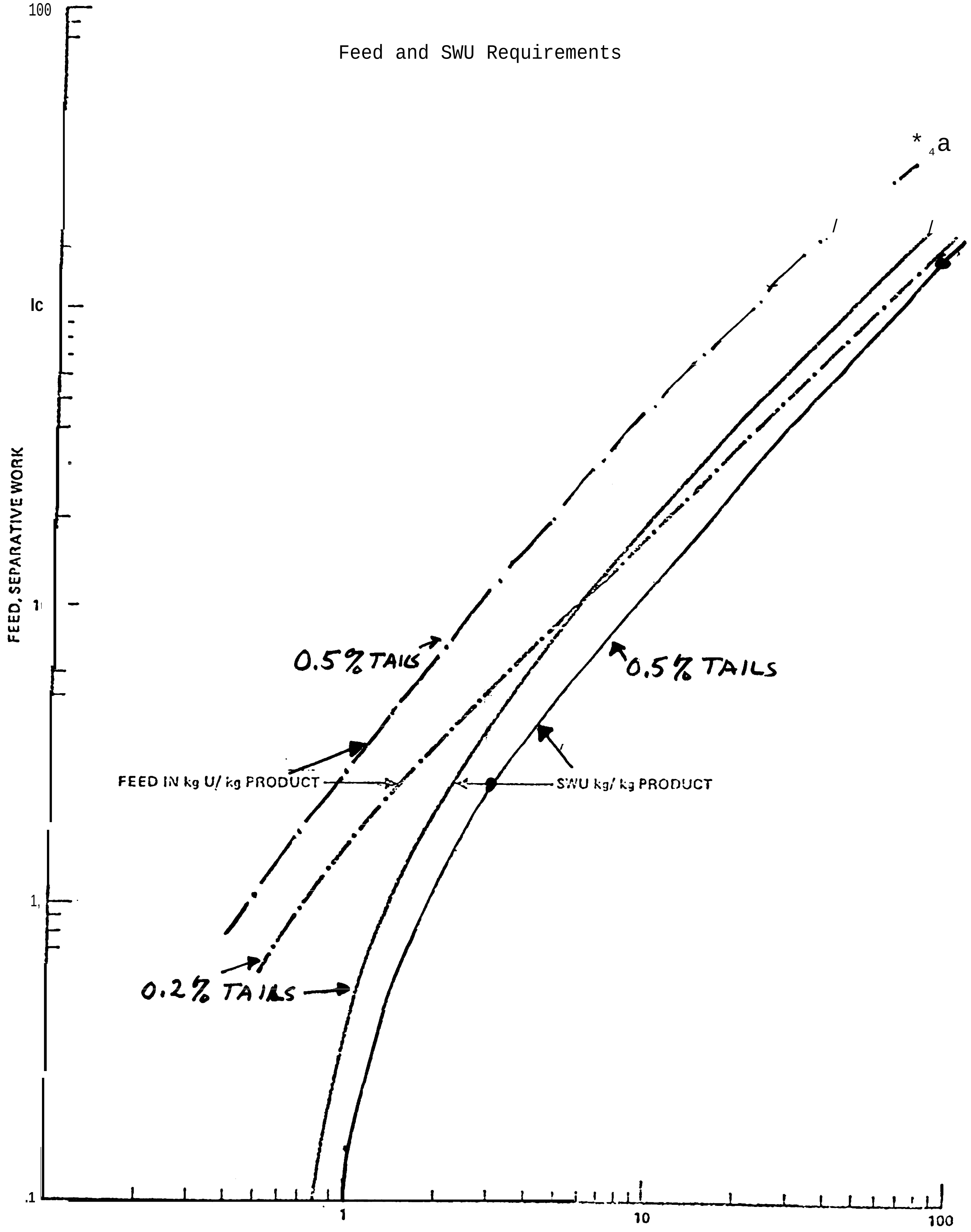


Fig. 9. % ^{235}U in Product

of time. **It is for this reason that plant capability is expressed in separative work per unit time.**

Although many processes have been investigated for potential applications to uranium enrichment, only relatively few are now considered to be serious candidates for practical applications. Thermal diffusion and electromagnetic separation were developed to the pilot plant stage during World War 11 and were found to be very inefficient. Techniques for laser isotope separation and plasma centrifuges are now under development but more work must be done before feasibility can be properly assessed. Isotopic enrichment by ion exchange processes is another candidate for possible future development.

All large scale enrichment facilities currently operating utilize gaseous diffusion. Recently the gas centrifuge has been attracting more attention because of its potentially smaller size and lower power consumption. Several pilot plants have been built, and larger facilities are planned by several nations, including the U.S. (See Table 2.) The jet nozzle is another technology under development but is attractive only where electrical power is abundant and inexpensive. The characteristics of various enrichment techniques will be discussed below.

2.5.1 Gaseous Diffusion

The gaseous diffusion process depends upon the separation effect that arises from the phenomenon of molecular effusion (i.e., the flow of gas through small openings). In a mixture of two gases, the molecules of the lighter gas have a higher velocity at a given temperature and therefore will strike the walls of the vessel more frequently, relative to its concentration. If the walls of the container (the barrier) are porous with openings large enough to permit the passage of individual molecules, but sufficiently small so that bulk flow of the gas as a whole is prevented (i.e., with opening diameters approaching the mean free path dimension of the gas), then the lighter molecules will pass through the barrier more readily than heavier ones. and this gas will be enriched with respect to the lighter component of the mixture. In this method, the degree of separation is determined by their relative velocities which depends upon the square root of the ratio of the masses of the isotopes. For UF_6 the maximum separation per stage, that is, the ratio of final to initial concentrations of U-235, is 1.00429. If one-half the input flow passes through the barrier and one-half is recycled to a lower stage, the theoretical separation factor is 1.0030. In practice, the properties of the barrier are not ideal. Back-diffusion through the barrier and some bulk flow through pores reduce the separation.

UF_6 is introduced as a gas and made to flow along the inside of a porous barrier tube containing thousands of submicroscopic openings per square inch. Through molecular effusion, the diffused stream is slightly enriched with respect to ^{235}U, the lighter uranium isotope, and the stream that has not been diffused is depleted. The enriched UF_6 in the outer cylinder is removed for input to the next stage. The process is illustrated in Figure 10.

Because the separation factor (ratio of final to initial ^{235}U content) is . highest at low throughput, it is necessary to use many parallel, connected units, each with the same composition of feed **material. This group of units is called a stage. Because the separation factor in a single stage (1.003) is very small, it is necessary to utilize many stages in series. A series of stages is called a cascade. The large**

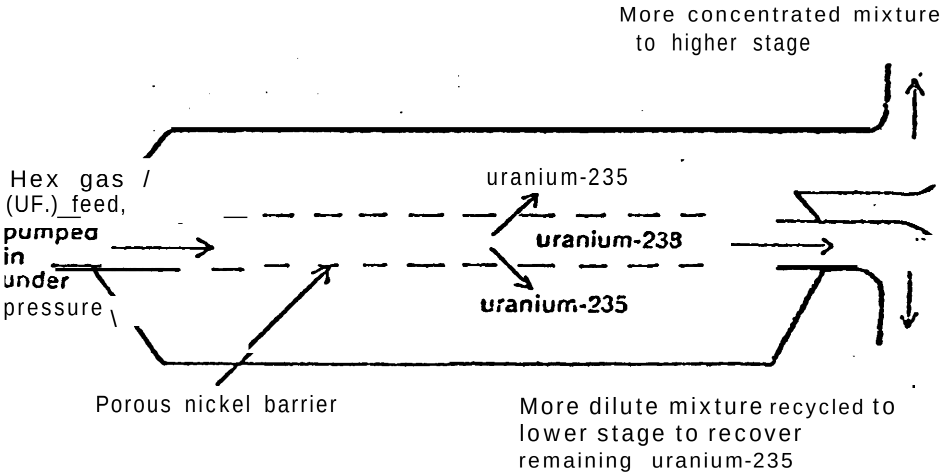


Figure 10. Gas Diffusion Barrier

number of stages makes the minimum economical size of a gaseous diffusion plant quite large. A large amount of electric power is also required to pump the UF_6 through the barrier in each stage. A cascade is shown in Figure 11.

The need to use uranium hexafluoride as a working gas has a large impact on the design of the plant. This substance is a gas at a pressure of one atmosphere at 60°C. It reacts strongly with most materials. The system must be kept absolutely air tight so that it does not decompose to form particulate uranium dioxy-difluoride which will block the pores. Since corrosion rates must be low to insure a long life only a limited number of metals such as nickel or aluminum which form stable fluoride layers or fully fluorinated plastics can be used for the construction of the barrier in an element of a gaseous diffusion plant.

Table 1 gives the characteristics of the three operating gaseous diffusion plants in the U.S. A new enrichment facility (now expected to be a centrifuge plant) is projected to have a 9 million SWU/year capacity, operating at .3% tails and if based on gaseous diffusion, would require 2,500 MW of electricity. Capital costs would be on the order $3 billion, or $333/sw (about the same for gaseous diffusion or centrifuge). This could produce 1800 Tonnes of uranium enriched to 3% per year, enough to provide fuel for fifty 1000 megawatt power reactors.

2.5.2 Centrifuge

A centrifuge is a means for applying a high artificial gravitational field to separate fluids of different weights which would otherwise remain mixed because of the thermal motions of the molecules. A cylinder filled with uranium hexafluoride turns about its axis at high speed. The centrifugal field establishes a radial pressure gradient which results in an enrichment of the lighter isotope at the center and the heavier isotope at the wall.

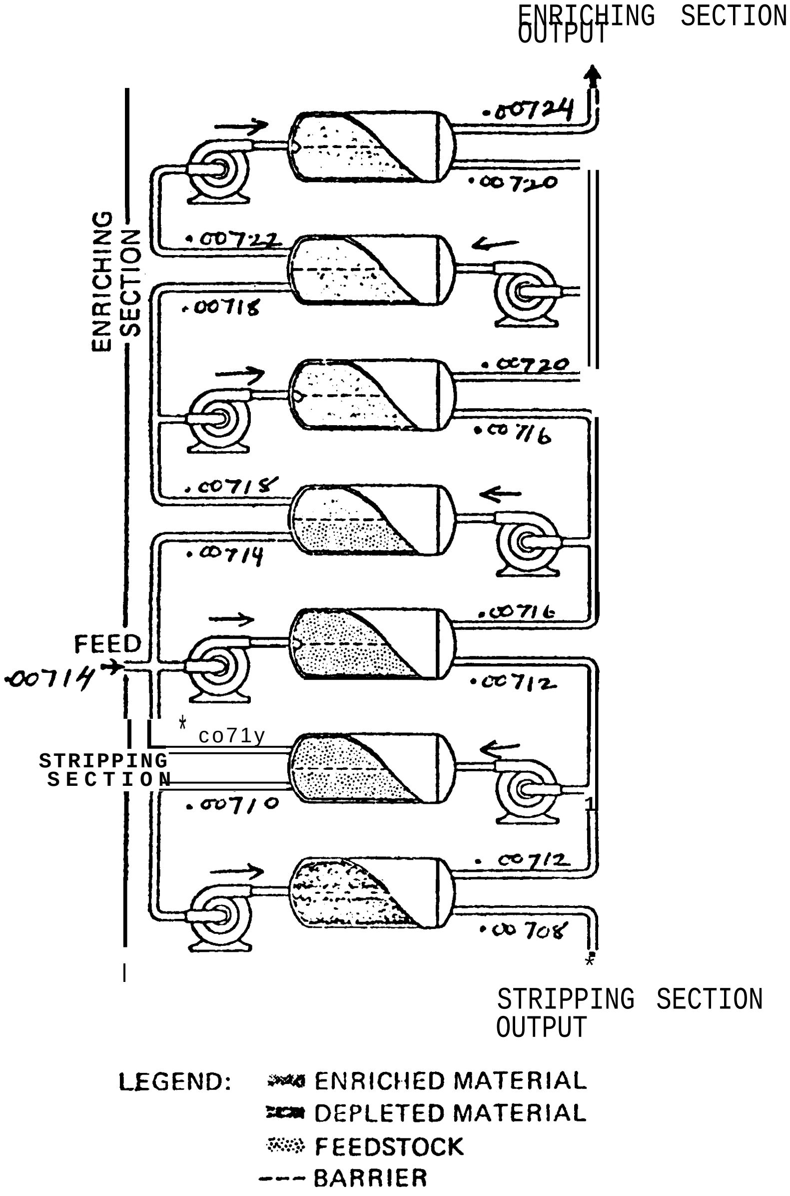


Figure 11. Cascade

Table 1. Characteristics of existing U.S. enrichment plants

Location	Oak Ridge	Paducah	Portsmouth
Completion Dates	Aug. 1945 - June 1954	Jan. 1953 - Dec. 1954	Nov. 1955 - Feb. 1956
Separative barrier stages	5,104	1,812	4,080
Feed Range (^{235}U)	0.3-1.1	0.3-0.711	0.3-1.1
Enrichment Range (^{235}U)	0.7-4	0.7-1.1	0.74-97.65
Capacity, 1970 (million SWU)	4.730	7.310	5.190
Disturbed area (acres)	640	345	515
Ground coverage (acres)	105	74	93
Electrical Power (MW(e))	1,600	2,550	1,900
Recirculating Water System (gpd)	400,000,000	500,000,000	450,000,000

A schematic diagram of a gas centrifuge suitable for use in an enrichment facility is given in Fig. 12. The rotor might be 40 to 300 cm long with a radius of 6 to 22 cm. A distinguishing feature of this counter-current gas centrifuge is the toroidal internal circulation of gas in the axial direction -- an upward flow in the center of the rotor and downward along the walls. As the gas moves up the rotor core, the ^{238}U diffuses outward in the centrifugal field. The gas arrives at the rotor top as a stream enriched in ^{235}U. Similarly, the peripheral downflow stream arrives at the rotor bottom enriched in ^{238}U.

A counter current flow may be induced either by establishing a small temperature-difference between the ends or by introducing a frictional mechanism (such as the scoops used to withdraw the product end waste). Due to the recirculation of gas within the tube, the separation achieved is greater than that expected for a single element.

An attractive feature of the centrifugal process is that the degree of separation depends upon the difference of masses of the isotopes rather than on their ratio as with gaseous diffusion. For a heavy element such as uranium, the ratio is close to unity. Thus a much larger separation factor per stage is possible with the centrifuge method. The major challenge has been to produce high speed centrifuges suitable for large-scale operations, because the separation factor for a centrifuge varies with the fourth power of the peripheral speed of the rotor. A major research problem has been to find materials for rotors that can withstand such high rates of rotation. Maximum rotor speeds vary from **300** m/see for aluminum alloy or high–strength steel, to a potential of 700 m/see for a carbon fiber/resin rotor. Separation factors of greater than 1.1 per stage are feasible.

speeds vary from 300 m/see for aluminum alloy or high-strength steel, to a potential of 700 m/see for a carbon fiber/resin rotor. Separation factors of greater than 1.1 per stage are feasible.

If the speed is doubled the theoretically predicted separating power will increase by sixteen times. A twenty percent increase in speed, will result in a doubling of its performance.

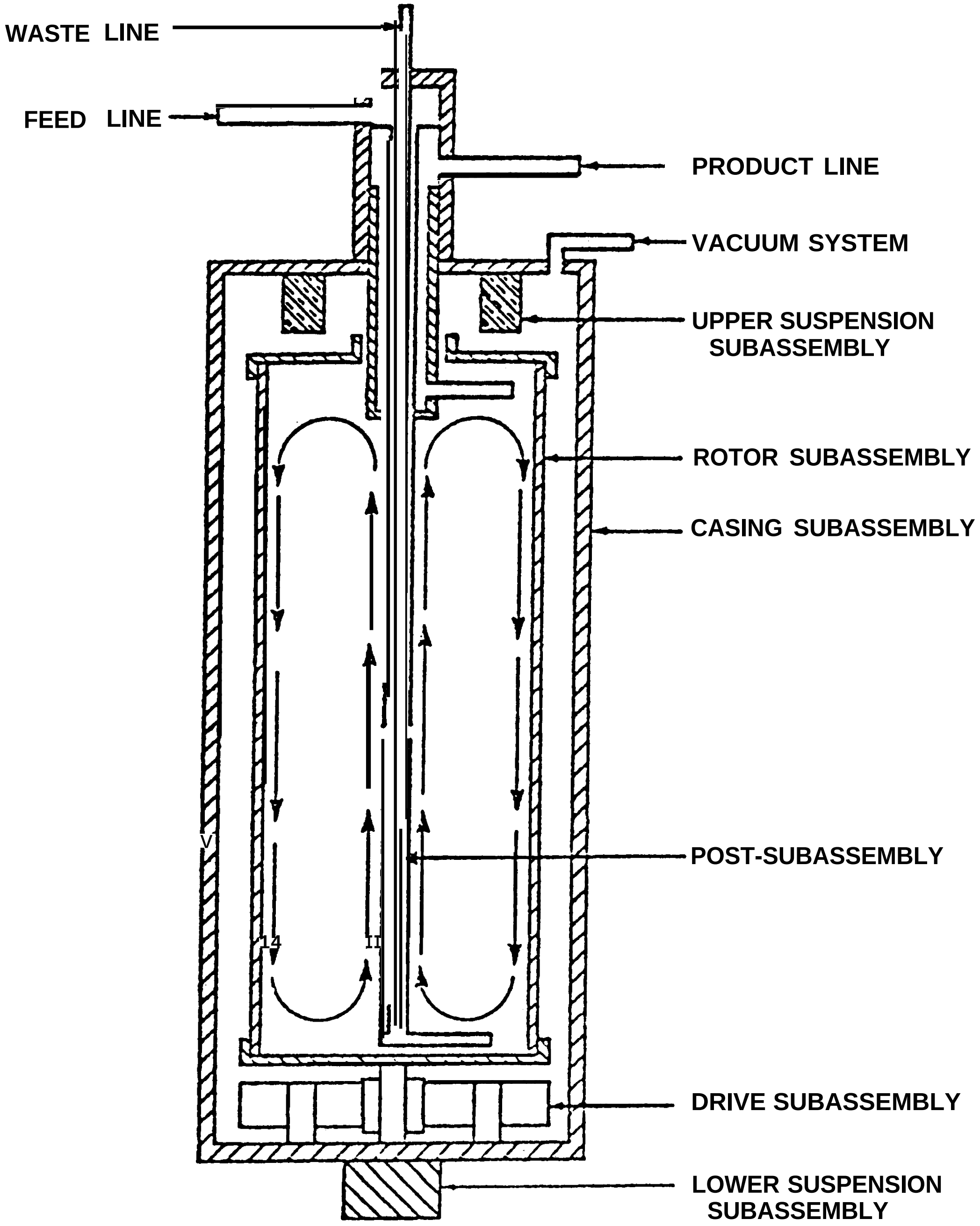


Figure 12. Schematic of Gas Centrifuge

The separation achieved also depends on the length to diameter ratio of the rotor. Long rotors can be expected to give increased performance. However, design of the unit may have to make provision for it to pass through “critical speeds” (corresponding to renounces of the tube) before it reaches operating speed.

A second difficulty is the fact that each centrifuge can handle only a small feed even though the separation per stage is high. An individual centrifuge can produce 2 to 5 kg of SWU per year. This means that 100,00 machines would be needed for a 300.000 SWU/year plant. Table 2 gives the number of machines per stage for a plant of this size. The estimated fractional cost of the plant is .3 for the machines, .35 for the plant, .10 for machine replacements, 15 for power consumption and .10 for operation and maintenance. An Anglo-German-Dutch enrichment group, Urenco, has successfully demonstrated the first cascades of two small centrifuge plants each with a planned capacity of about 200,000 kg. Separative work (SWU) per year at Capenhurst, England and Almelo, Holland. No full size production plants have yet been build. However, both the United States and Urenco have announced plans to build them.

The major advantages of centrifuge plants over diffusion plants are that they are expected to cost less to build per SWU, can be much smaller without losing economies of scale and have power requirements which appear to be about one-fifteenth as great. Difficulties can result from the thousands of complex mechanical units operating at very high rpm. Machine failure rates of less than 2% per year have been achieved, however, and it is believed that a plant can operate economically with failure rates as high as 2.5% per year.

2.5.3 Other Enrichment Processes

There are several other techniques which have been used in the past, demonstrated technically or show promise. An aerodynamic process, known as the jet or Becker nozzle process, has been under active development for the

Table 2. Centrifuge machines for 300,000 SWU/year enrichment plant to produce 2.8% enriched uranium with .2% tails

	Centrifuges per Stage	
	2,160	Product
	4,850	
	8,190	
	12,360	
Feed	17,570	
	15,990	
	14,020	
	11,580	
	8,540	
	4,740	Tails

past decade. It utilizes the pressure gradient developed in a curved expanding supersonic jet of a mixture of uranium hexafluoride and hydrogen to achieve a separation of the uranium isotopes. As the expanding jet traverses the curved path the heavier components tend to diffuse preferentially toward the curved outer wall. A knife edge placed relatively near the outer wall divides the jet stream into two fractions, the inner one enriched in ^{235}U and the outer one enriched in ^{238}U. The two streams are then pumped off separately. The placement of the knife edge in the jet stream is critical with respect to separation performance. The diameter of the curved deflecting wall is on the order of 0.1 mm and the spacing between the knife edge and the outer wall may be about 10$_{\text{P}}$m, with a tolerance of ±1$_{\text{P}}$ m. The process is illustrated in Fig. 13.

Because of the higher separation factor a jet nozzle plant will require about one-third the number of stages in a gaseous diffusion facility which will provide the same degree of enrichment. At the present time, the specific energy consumption estimated for the separation nozzle process is larger than that for gaseous diffusion. However, significant progress has been made. The specific energy consumption projected for the process has been reduced in recent years and may be further reduced to the present level of the gaseous diffusion process within the next few years.

A manufacturing process has been developed by a German firm for the mass production of the separation nozzle slits with the required tolerances, thereby leading to reduced capital costs. The development group at Karlsruhe is confident that the process technology will be advanced to the point where its unit cost for separative work will be equal to or less than that for gaseous diffusion by 1977. A joint development program has been arranged with Brazil, which is scheduled to lead to a full scale plant. This plant will take advantage of the otherwise unuseable cheap hydroelectricity in a remote region of the Amazon. South Africa has developed a similar process-and is now constructing a production plant,

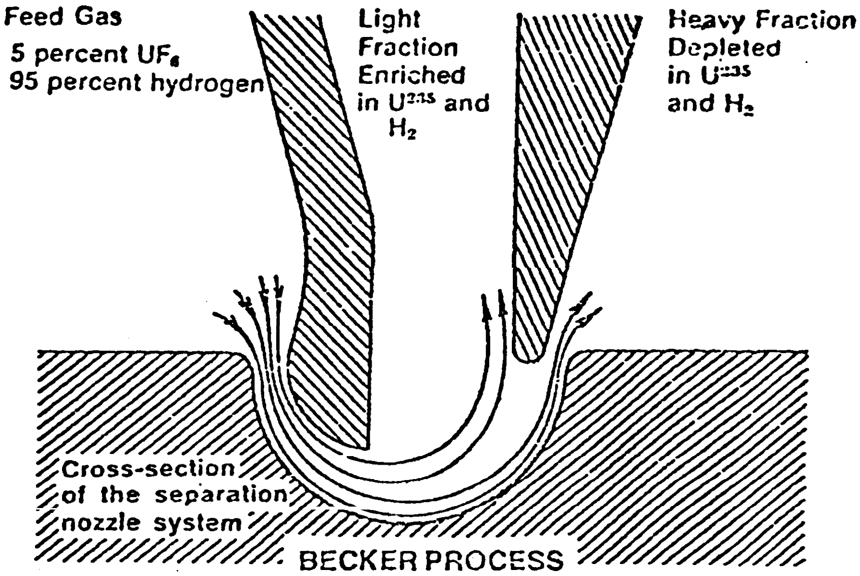


Figure 13. Becker Nozzle

The calutron process is one of the older separation methods. A compound of uranium is vaporized in an electrically heated container. The vapor passes through slots into an arc chamber where it is ionized by an electron beam. The ionized uranium is accelerated by electrodes in another slot. The high velocity stream then enters a vacuum tank where it is forced into a 180° curve by a large electromagnet. The ^{235}U and ^{238}U follow slightly different paths because of the different centrifugal forces and are collected separately in properly spaced graphite receivers. The graphite reacts with the uranium ions to form uranium carbide (UC). The receivers are processed chemically to obtain the separated isotopes. The calutron, although considered the best of the electromagnetic processes, was not economically competitive with the gaseous diffusion process for large-scale enrichment of ^{235}U. A pilot plant was built during World War II and found to be very inefficient, although it was adequate to produce much of the enriched uranium used in the Hiroshima bomb.

During the past thirty years there have been many advances in technology which are relevant to the development of electromagnetic separation of uranium on a large scale. These include magnets, pumps, controls and apparatus for carrying out the related chemical operations.

A significant contribution may be the techniques and hardware which have been developed for ion propulsion of spacecraft. It would be necessary, of course, to modify the systems to provide very intense focused beams of singly charged uranium ions instead of broad diffuse beams of lighter elements such as cesium. Some progress has been made in the development of electrohydrodynamic sources in which ions are extracted directly from the surface of a liquid metal. A reduced accelerating potential would permit the use of lower intensity magnetic fields of limited size.

If the many scientific and engineering problems can be solved, it seems possible that an electromagnetic isotope separator based on this technology can efficiently produce enriched uranium. Because individual units are small and are able to effect a rather high degree of separation of isotopes this process may be suitable for the production weapons grade uranium.

Within the past several years, two additional concepts for isotope separation have shown considerable promise, the plasma centrifuge and laser isotope separation (LIS). The former is similar to the gas centrifuge. As the name implies, the feed material is converted to a plasma, and centrifugal action is achieved electromagnetically. Theoretically, much greater rotational speeds can be achieved in the plasma centrifuge than in the gas centrifuge because no rotating parts are involved. Another advantage is that solids may be used as feed materials to the plasma. This concept is in the early stage of its development and no published experimental evaluation of its feasibility is available.

The feasibility of LIS, on the other hand, has been demonstrated on a microscale and it has been stated that a pilot plant could be built within five years. This process differs completely in principle from the physical separation mechanisms of the other methods. In this case, separation depends upon the ability to activate, in a specific manner, one of the isotopic species to be separated. A beam of uranium atoms (another LIS process uses uranium hexafluoride molecules) is generated in an oven, collimated and then directed through an evacuated region. In this region, two photon beams are applied; one laser beam selectively excites one of the uranium isotopes, while the other laser beam ionizes the previously excited uranium isotope. The ionized isotope is then removed from the atomic beam by an electric or magnetic field and collected on a plate. The process is still in the laboratory stage, where only minor quantities of uranium have been enriched. The ultimate industrial feasibility and economic practicality of this technology has not yet been fully defined and demonstrated. Laseer separation plants of commercial size would require individul lasers with at least 1 to 10 kw average power, a level significantly beyond the present state of the aret. One advantage that lasers have over most other enrichment methods is that extremely high levels of enrichment can be achieved in a single pass. Separation factors of nearly 100 may be feasible. Numerous material problems must be solved before this method can be applied on a large scale basis.

Some of the other processes which have been or are being studied are phase equilibrium processes -- such as gas-liquid chemical exchange; exchange chromatography or ion-exchange; diffusion processes -- such as thermal diffusion or sweep diffuson; aerodynamic Processes'- such as Fenn-shock process; molecular flow processes, and nuclear spin processes. None now appear likely to become economically competitive with either the gaseous diffusion or gas centrifuge processes in the near future.

2.5.4 Uranium Recycle

The Uranium spent fuel from an LWR contains about 0.9% ^{235}U. If it is to be recycled, it must be reenriched or blended with more uranium of much higher enrichment. This recycled uranium will contain traces of various radioactive fission products, actinides and many uranium isotopes. Facilities for the reenrichment of recycled uranium may require special traps such as cobaltous fluoride to remove these contaminants. Other uranium isotopes, such as ^{232}U and ^{236}U will "contaminate" both the product and the tails. "The ^{232}U may present a radiation hazard. Both ^{232}U and 236U will reduce the worth of the enriched material because they absorb neutrons in the reactor. It is expected that an enrichment facility will be dedicated to the reenrichment of recycled uranium if reprocessing is carried out.

2.6 FUEL FABRICATION

Depending upon the specific reactor type, the fabrication of many types of fuel elements is required. Light water reactors use slightly enriched uranium; gas cooled reactors require the fabrication of highly enriched fuel, while breeder reactors require cores containing depleted uranium or thorium as fertile material and ^{235}U and plutonium fuels.

2.6.1 Light Water Reactor Fuel

In the U.S. , the existing LWR fuel fabrication industry* consists of nine commercial plants, each of which performs part or all of the fuel fabrication operation. These facilities and their locations are listed in Table 3. Three of the facilities produce complete light water reactor fuel assemblies using enriched uranium hexafluoride (UF_6) as the feed material, while two other plants start with uranium dioxide (UO_2) powder or UO_2 pellets to produce fuel assemblies. The four remaining facilities produce only UO_2 powder or pellets from enriched UF_6 as feed for fuel assembly plants. Current capacity of the industry is about 3000 metric tons of uranium as fuel assemblies per year.

The dominant process used by the commercial facilities for production of UO_2 fuel for an LWR reactor is basically a three-phase operation:

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*Final Environmental Statement, LWBR Program, ERDA 1541, June 1976

Table 3 LWR Fuel Fabrication Plants

Licensee	Plant Location	Plant Feed Material	Plant Product
Babcock & Wilcox	Lynchburg, Va.	UO_2 Pellets	Fuel Assemblies
Combustion Engineering	Hematite, Mo.	UF_6	UO_2 Powder or Pellets
Combustion Engineering	Windsor, Corm.	UO_2 Powder	Fuel Assemblies
General Electric	Wilmington, N.C.	UF_6	Fuel Assemblies
Exxon Nuclear	Richland,	UF_6	Fuel Assemblies
Kerr-McGee	Crescent, Okla.	UF_6	UO_2 Powder or Pellets
Nuclear Fuel Services	Erwin, Term.	UF_6	UO_2 Powder or Pellets
B&W Nuclear Materials Division (Formerly NUMEC)	Apollo, S.D.	UF_6	Fuel Assemblies
Westinghouse	Columbia, S.C.	UF_6	Fuel Assemblies

1. Chemical conversion of feed material to powder,
2. Mechanical processing of materials into solid fuel pellets, and
3. Scrap recovery and recycle.

2.6.1.1 Chemical Conversion

Enriched UF_6 is the feed material used in the fabrication of LWR fuels. The enriched UF_6 gas is converted to $U0_2$ powder before being formed into pellets. The principal method employed to convert UF_6 to $U0_2$ is the wet process which involves the use of ammonia to form an intermediate ammonium diuranate (ADU slurry) compound prior to processing to $U0_2$ powder. The ammonium diuranate process shown schematically in Figure 14 involves :

1. Volatilizing and hydrolysis of the enriched UF_6 to form uranyl fluoride solution,
2. Precipitating ammonium diuranate by the addition of ammonia,
3. Dewatering the ammonium diuranate by centrifuging or filtering, and
4. Drying and reducing the ammonium diuranate to $U0_2$ powder in a hydrogen atmosphere.

There are two alternative processes used to convert uranium for fuel fabrication. These are the pyrohydrolysis and the Perclene methods.

In the pyrohydrolysis process, a continuous flow of gaseous UF_6 enters into a fluid bed conversion unit where the UF_6 combines with steam to form solid particles of uranyl fluoride. The uranyl fluoride particles then overflow the reaction bed and are collected in hoppers. In a batch-type process, the uranyl fluoride powder is placed in a second fluid bed reactor where it is reduced to UO_2 by the action of a fluidizing gas consisting of hydrogen and steam. The off-

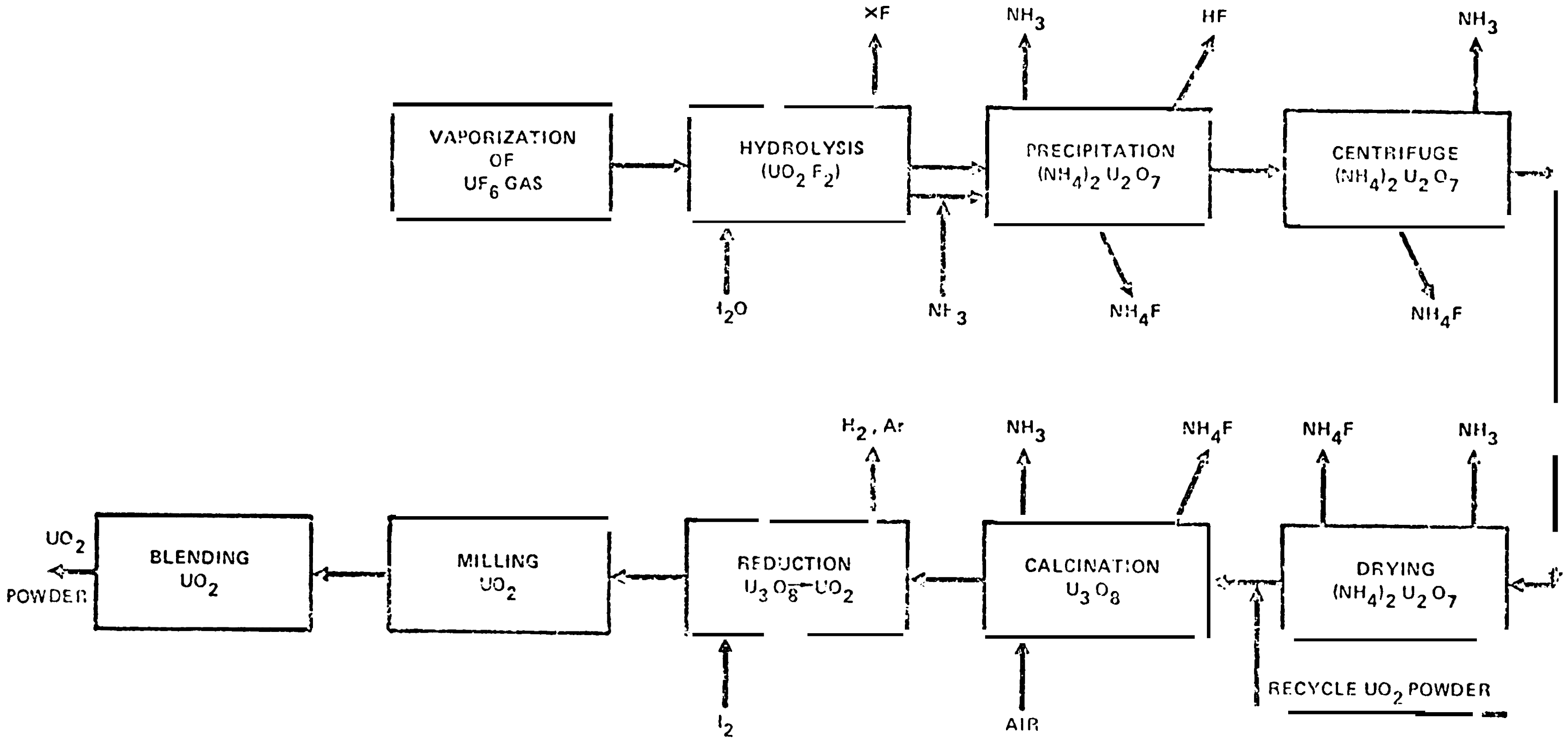

Fig. 14. Schematic Flow Sheet of Uranium Dioxide Conversion Process

gases, consisting of hydrogen fluoride, hydrogen, uranyl fluoride and UO_2 particles pass through a centrifugal collector and a metallic filter to remove uranium-bearing particles which are then returned to the fluidized beds.

The perclene process involves the reaction of UF_6 with perchlore.ethylene to form tetrachlorodifluorethylene and insoluble uranium tetrafluoride (UF_4) . The UF_4 is removed by filtration and pyrohydrolyzed into $U0_2$. This process requires the recovery and recycle of perchloroethylene and the recovery and disposal of contaminated tetrachlorodifluoroethylene gas, in addition to recovery, neutralization and solidification of hydrogen fluoride.

2.6.1.2 Mechanical Processing

In the mechanical processing of the uranium oxide powders to a specific “fuel form, the principal process steps are shown in Figure 15.

The steps utilized in forming fuel elements from the oxide powders are similar for all heavy metals. These steps are:

1. Powder Prepress - In the powder prepress or slugging operation, the powder is prepressed into short wafers to increase the bulk density of the material and to reduce the amount of entrapped air in the powder.

2. Powder Granulation - The short wafers are conveyed to the granulator where the material is granulated and screened through approximately a 14-mesh screen. The granulation process yields a standard agglomerate size of material for feed to the pellet press, which is important in obtaining a uniform die cavity fill. The amount of oxide granules in each die fill affects the pellet length and density parameters.

3. Pellet Pressing - The granulated powder is automatically fed into the die cavity at the pellet press where pellets of uniform density and size are pressed. A die lubricant, approximately 0.2 weight percent sterotex, is applied to the surface of the die walls and punches during pellet pressing. The sterotex is vaporized from the pellets during the sintering step and is expelled with the furnace off-gas.

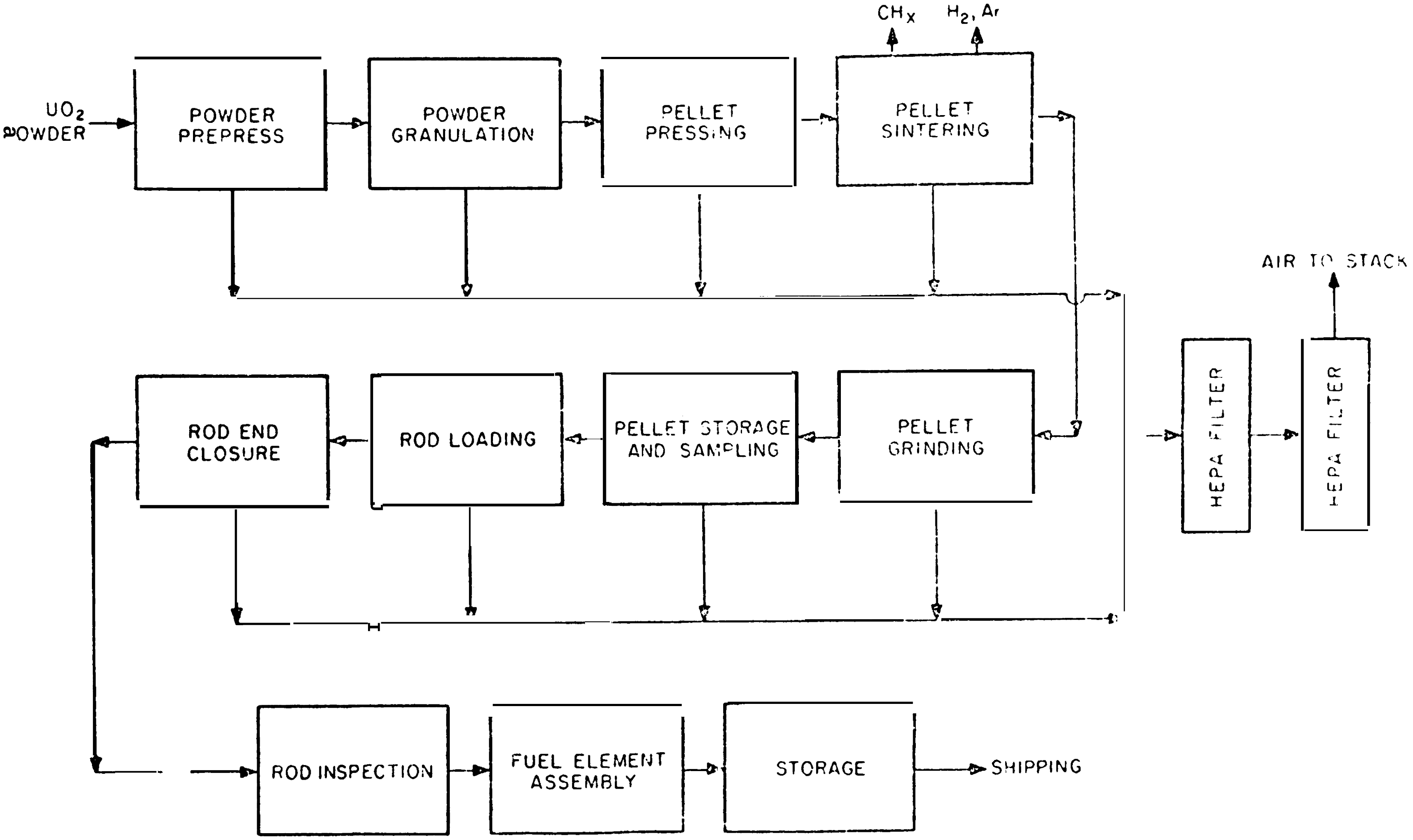

Fig. 5. Schematic Flow Sheet of Uranium Dioxide Fuel Fabrication Process

4. Pellet Sintering - The pellets are transferred from the penet pressing operation to the sintering furnace complex in molybdenum trays. The pellets are then sintered to the required density at a temperature of approximately 1700 C for approximately 12 hours in a hydrogen atmosphere. The exit flow of hydrogen from the furnace sintering atmosphere is diluted (with argon) to less than the explosive concentration prior to passage through the HEPA filter system and discharge at the stack.

5. Pellet Grinding - The sintered pellets are checked for correct density and dimensions and then transferred to the centerless grinder. The sintered pellets are dry-ground to a specified diameter.

6. Pellet Storage and Sampling - The dioxide pellets are statistically sampled, analyzed, and inspected to assure that pellet specifications have been met prior to further Processing.

7. Rod Loading - The fuel rod loading operation includes the receipt of sintered pellets, tubes with welded bottom plugs, springs, and top plugs. Dioxide pellets released by quality control are mechanically pushed into the empty tubes. Each fuel rod contains a pellet column length and weight which has been recorded and is in compliance with the specification requirements. A spring is then inserted into each rod and a top end plug is pressed into place.

8. Rod End Closure - The end plug welding is performed in a welding chamber with an inert helium gas atmosphere. The welding chamber is pressurized with helium gas and the rod is seal welded.

9. Rod Inspection - Each fuel rod is subjected to various inspections, including helium leak test, rod assay, visual, dimensional) fluroscopic~ cleanliness, and X-ray.

10. Fuel Element Assembly - After final inspection and quality control release, the fuel rods are stored in critically safe arrays prior to mechanical assembly into modules of reactor core.

11. Storage - The fuel assembly modules are inspected and held in storage in critically safe arrays until shipment.

2.6.1.3 Scrap Recovery and Recycle

Chipped or broken pellets and pellets that do not meet density or dimensional standards are recycled as oxide powder. Some of the material, however, is not suitable for dry scrap recovery and must be recycled through a solvent extraction process.

2.6.2 Highly Enriched Fuels

Many research reactors and High Temperature Gas-cooled Reactors (HTGR) require highly enriched uranium fuel. Research reactor fuel may be of the MTR. plate type, the HFIR plate type, or TRIGA rods. The fabrication process of the uranium oxide fuels is similar to that discussed in 2.6.1. HTGR and TRIGA fuels are unique and have custom fuel manufacturing facilities In handling highly enriched fuels, particular attention must be given to fuel geometry so that all operations are Performed within geometries that do not allow the accumulation of critical masses of material.

The HTGR fuel elements consist of a graphite block which serves as the reactor moderator. Each block is 79.3 cm high with a hexagonal cross section that is 35.9 cm across the flats. The graphite block is drilled lengthwise with two sets of holes: one allows the passage of the helium coolant, while the second accommodates the fuel rods. Fuel rods are formed by molding selected blends of fuel particles with a graphitic pitch; each fuel rod is 5.1 cm in length and has a diameter of 1.58 cm. Fuel particles are the basic material for the rods and elements, and have a core of either uranium dicarbide (highly enriched in ^{235}U or recycle ^{233}U or ThO_2 (thorim oxide). Particle diameters are 500 to 800 um.

TRIGA fuel elements are fabricated from an alloy of enriched uranium and zirconium. The alloy is produced by simultaneous vacuum arc melting of small pieces of uranium and zirconium into an ingot about 5 Cm in diameter and 50 cm long. This ingot is jacketed to prevent oxidation during further processing, forged and rolled into a thin strip. The jacket is removed from the strip, the surface cleaned by pickling and the strip is chopped into small pieces. These pieces are remelted and cast again into an ingot. The double melt technique is necessary to provide the required uranium-zirconium alloy homogeneity.

The remelt ingot is pickled and machined to approximate size. The ingot is then heated to about 900°C in a heat-treating furnace with a hydrogen atmosphere to form zirconium hydride. The hydrided ingots are machined to final size and inserted into either zircalloy or stainless steel tubes with one end cap already welded in place. The partial fuel rod assembly is swagged (to improve the mechanical contact between the cladding and the fuel), the assembly is evacuated and the second end cap welded.

2.6.3 Breeder Fuels and Blankets

The fabrication of depleted uranium oxide elements for breeder blankets follows essentially the same steps as discussed in 2.6.1.* Thorium fuels are required for thermal breeder blankets.

Processes similar to those used for uranium dioxide fabrication are used to produce $Th0_2$. For powder conversion, the feed material most commonly in use is in the form of nitrate crystals. The oxalate process used in the conversion of throium nitrate crystals to $Th0_2$ powder, shown in Figure 16 involves:

1. Dissolution of thorium nitrate crystals,

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*Environmental Statement - LMFBR Program, WASH 1535, December 1974.

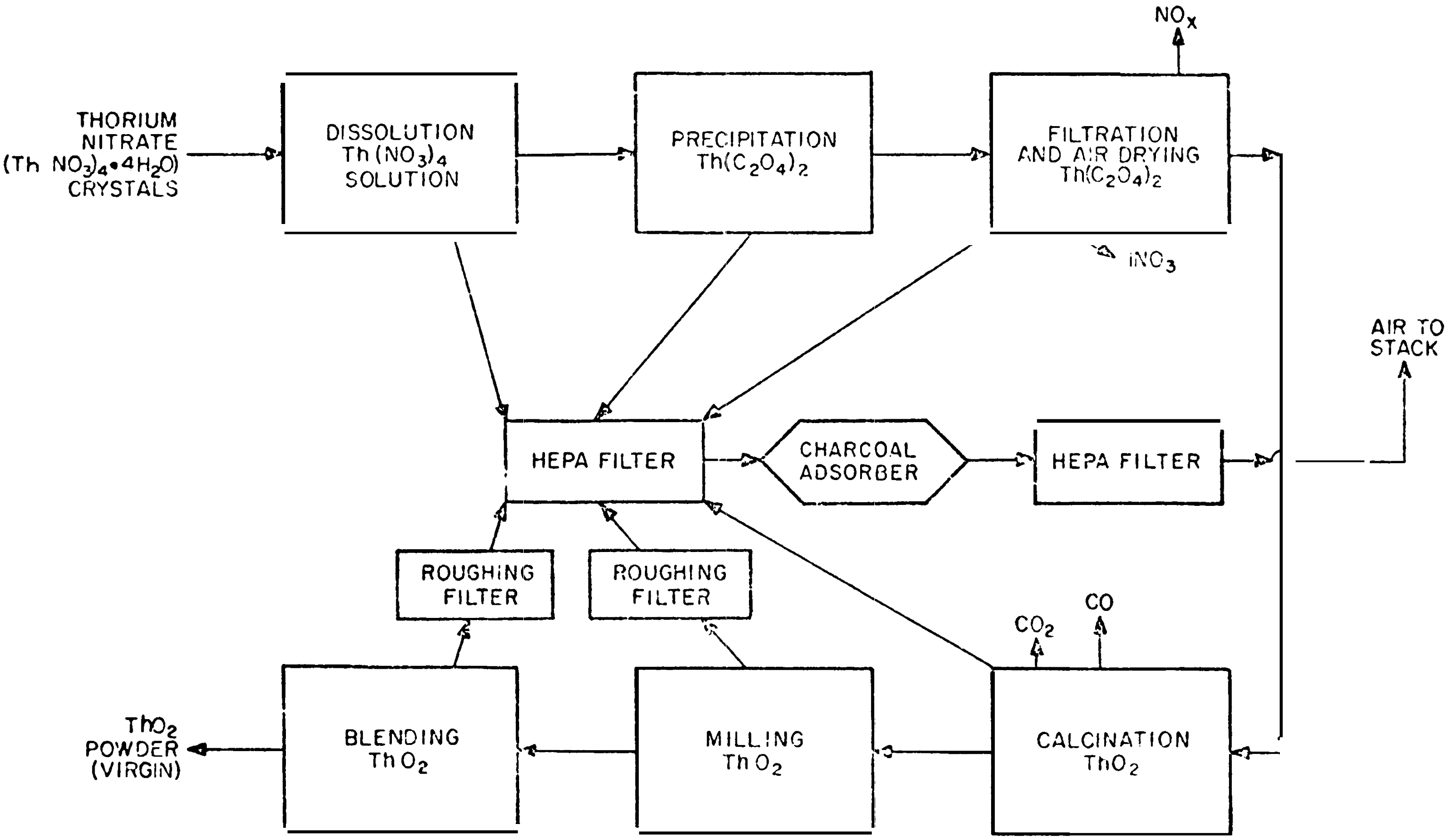


Figure 16. Schematic Flow Sheet of ThO_2 - Conversion Process

2. Precipitation of thorium with the addition of oxalic acid,

3. Filtration of the thorium-oxalate slurry,

4. Drying of the moist filter cake, and

5. Calcination of thorium-oxalate to ThO_2 powder.

The mechanical processing of ThO_2 powder to a specific form is identical to that used in the fabrication of UO_2 fuels. The recovery of scrap is similar, with somewhat different chemicals used when solvent extraction is needed.

The fabrication of ^{233}U fuel from a thorium blanket requires special consideration due to the ^{232}U contamination. Only a few hundred parts per million of ^{232}U is a sufficient quantity to prevent contact fabrication and handling techniques. Thus, a ^{233}U fabrication facility must be designed for remote operation and maintenance. The processes are the same as those shown in Figure 17.

Plutonium fuel is normally fabricated as an oxide mixed with uranium. Because of the toxicity, all operations are performed in multiple enclosures to prevent releases to the atmosphere. Thus, glove boxes enclose all processes and, if recycled plutonium is fabricated, the glove boxes must be shielded. plutonium dioxide (PuO_2) powder is mechanically blended and milled with the UO_2 powder in the desired ratios. The mixed oxide powder is then pelletized and the remainder of the process is the same as shown in Figure 15 (See section 4.3 for plutonium metal production.)

Some applications may involve metal or carbide fuels. For these fuels the fabrication techniques will be different from those previously discussed, with the differences depending upon the specific applications. The fabrication of uranium metal can be by conventional means, including casting, rolling, extrusion, forging, swaging, drawing, and machining. Hot-rolling of the alpha phase is a useful method for forming the metal. Because of the ease with which uranium oxidizes, especially at higher temperatures, it must be protected from air during fabrication either by means of a fused salt or by an inert gas atmosphere. The metal can be machined moderately easily if suitable lubricants and coolants are present to prevent oxidation. Uranium parts can be joined by welding or brazing. Fusion welding is achieved by using a Heliarc torch in an inert atmosphere.

2.7 FUEL STORAGE

It is necessary to store several types of fuel -- fresh fuel that is waiting to be loaded into the reactor, spent- fuel which has been irradiated and reprocessed fuel.

2.7.1 Fresh Fuel

Fresh fuel may be in many different forms, depending upon the type of reactor in which it is to be utilized. This fuel may be stored at the fuel fabrication facility) at the reactor facility, or in both locations. The length of storage time depends on schedules and operating history of the reactor but would probably be at least 30 days at each location. For power reactors, the fuel elements are generally very large (a LWR fuel element may be 4 meters long and weigh 300 to 700 kg) . Fuel elements for research reactors may be less than a meter long and weigh less than 50 kg.

2.7.2 Spent Fuel

Irradiated (spent) fuel is removed from the reactor and stored on site to allow the fission products to decay. This storage time varies considerably and in the near future will depend on the availability of reprocessing facilities or high level waste repositories. Due to the radioactivity and heat generated, the spent fuel must be handled remotely and shipped in shielded casks or stored in shielded facilities. Storage may occur. at the reactor site, at the reprocessing plant or both. Light water reactors replace about one-third of their fuel each year and must be shut down for up to 30 days to perform refueling. Some reactors, such as the CANDU; can be refueled on line, while other reactors, such as the Molten Salt Breeder, have continuous refueling.

The specific characteristics of spent fuel depend upon the integrated exposure (burnup) frequently quoted in megawatt days/metric ton (MWD/MT). The isotopic content depends on the neutron energy spectrum and the burnup. See the discussion on reactor types for specific information (Section 3) .

2.7.3 Reprocessed Fuel

Reprocessed fuel elements may yield plutonium, ^{233}U and ^{235}U with enrichments which depend upon the initial loadings. This “raw fuel” is different from the enriched UF_6 leaving an enrichment plant, in that it may be stored as a liquid or as a solid (oxide). Storage requirements are dominated by the necessity to prevent the arrangement of material in a critical geometry, the heat dissipation rate, and the physical security requirements. This fuel may be stored at the reprocessing facility or the fuel fabrication facility for periods up to months, depending upon the overall fuel cycle used.

2.8 REPROCESSING

A spent fuel reprocessing plant is a complex of facilities designed to recover fissionable material and to process radioactive wastes. Reprocessing of spent reactor fuel has had numerous problems in the past. There are, however, several plants which have operated (see Table 4). The

TABLE 4

NUCLEAR FUEL REPROCESSING PLANTS

Country	Type of Fuel	Start of Operation	Feed Capacity (Tonne U/yr)	Pu Product/yr(a) at Capacity (kg)	Comments
Argentina(1)		1968(5)	200 kg/yr	--	
Belgium (Mol)(4)	Metal/LWR		80	516 (1077)(a)	167 tonnes U have been processed
Eurochemic	METR(b)	1966	40	--	Eurochemic is not expected to process any more fuel
France(4)					
Marcoule	Metal	1958	500	2150	French military and civilian reactors
La Hague	LWR	1975/78	400	2580	Will increase production gradually until 1978
Germany(4)					
WAK, Karlsruhe	LWR	Sept 1971	36	232(206	32 tonnes U have been processed
KEWA	LWR	1988/89	1400	9030	
India(1)					
Trombay	HWR	1967	100	230	
Tarapur	HWR & LWR	1979	150	968	Assume all LWR fuel
Italy(4)	MTR	1970	5	--	
Eurex 1	LWR	1975	10	64	
Japan(2)					
Tokai-Mura	LWR & Nat U	1978	200	290	Assume all LWR fuel
Spain(1)					
Moncia	MTR		100 kg/yr	—	
Taiwan(3)					Small pilot plant

TABLE 4 (Cent)

NUCLEAR FUEL REPROCESSING PLANTS

Country	Type of Fuel	Start of Operation	Feed Capacity (Tonne U/yr)	Pu Product/yr(a) at Capacity (kg)	Comments
United Kingdom(4)					
Windscale 1	Metal Nat U	1964	2500	10,750	
Windscale 2	LWR	1970(76)	400	2580 (645)	Shut down 1973 after processing 100 Te will restart 1976 at 200 Te/yr and 1977 400 Te/yr
		1982	400	2580	
Dounreay(1)	Highly Enriched U and Pu		1	----	

(a) For LWR fuel we use an average production rate between JWR and BWR fuel. We assume a mature fuel cycle which produces 6.45 kg of fissile plutonium per tonne of uranium reprocessed. Heavy Water Reactor (HWR) fuel is assumed to have an average recovery of 2.3 kg Pu/TeU. Metal Fueled Reactors (that are used for power production) are assumed to produce 4.3 kg of fissile Pu per tonne of unanium.

(b) MTR - Materials Test Reactor uranium aluminum alloy fuel. Usually enriched to 20% or higher in ^{235}U, normally produces very little Pu.

(c) Assumes all 167 tonnes of uranium that have been processed were LWR fuel.

Reprocessing References

1. The Nuclear Industry, 1970, p 264.
2. Nuclear Engineering International, February 1955, page 82, World Digest.
3. Epstein, William, "The Proliferation of Nuclear Weapons", Scientific American, Vol. 232, Number 4, April 1975, p 18.
4. Schuller, Walter, "Reprocessing in Europe", ANS/CNA Joint Topical Meeting on Commercial Nuclear Fuel Technology Today, April 28-30, 1975, Toronto, Canada.
5. Science Vol. 184, No. 4144, p. 1315, June 28, 1974.

plant performs five major operations: (1) the receipt and storage of spent fuel assemblies, (2) the processing of the fuel assemblies to separate the fissionable materials from the other fuel assembly materials, (3) the conversion of the recovered uranium to UF_6 for return to an enrichment facility, (4) the conversion of the recovered plutonium to plutonium dioxide ($Pu0_2$), and (5) the processing of radioactive wastes into an appropriate form for transfer to a waste repository if uranium and plutonium are recycled, special design Considerations must be given to the added neutron fluences, heat loads and criticality issues.

A simplified block flow diagram of the Purex-type reprocessing plant is shown in Figure 17* The significant features of the process are described below:

1. Irradiated fuel elements are received at the reprocessing site in shielded casks via rail or truck. Fuel is removed from the shipping casks and stored under water until it is ready to be processed. The irradiated fuels are cooled for at least 150 days to assure the decay of short half-lived radionuclides.

2. Fuel awaiting processing is stored in the storage pool where fuel storage canisters limit fuel element placement to an array which is always safe from a criticality standpoint.

3. The uranium spent fuel rods are transferred to the Purex separations facility where they are chopped by a shear into short lengths (approximately 1 inch) to expose the core material and then charged directly to a dissolver. A semicontinuous dissolution of the oxide cores is performed to minimize, as well as control, the peaking of off-gas release.

4. A soluble nuclear poison is used in the nitric acid dissolvent to-assure nuclear safety in the dissolver.

'proposed Final Environmental Statement - LMFBR Program WASH-1535, December 1974.

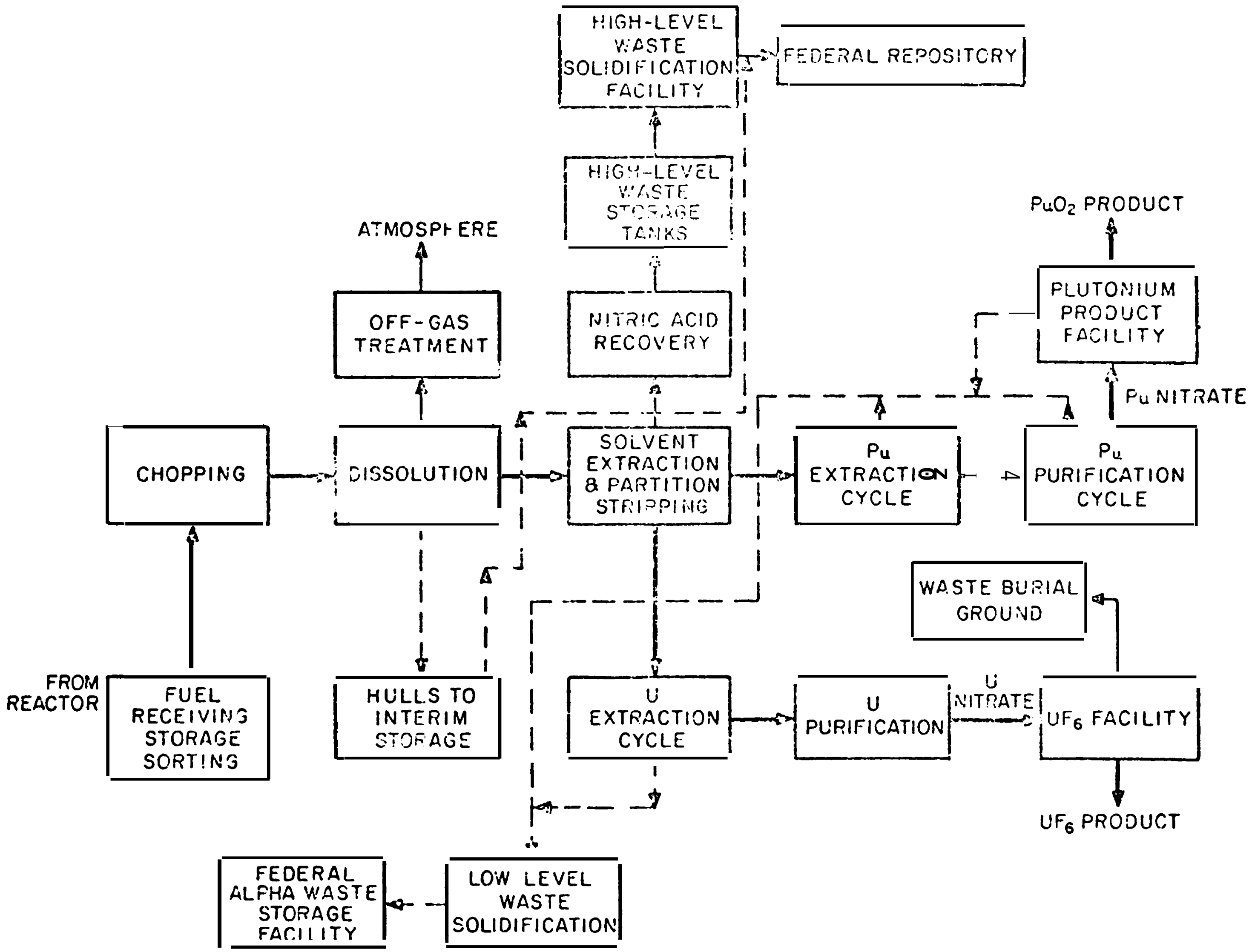


Figure 17. Simplified Flow Diagram of Purex Reprocessing Plan Complex.

5. Centrifugation is used to remove any suspended solids in the extraction feed.

6. A centrifugal contactor is used for the first cycle extraction where uranium and plutonium are separated from bulk fission products.

7. Pulsed columns are used for the partitioning (separation) of plutonium from uranium in the first cycle extraction.

8. Plutonium and uranium are processed simultaneously and separately in continuously operating solvent extraction columns. Uranium solutions are given a final silica gel filtration adsorption for removal of any residual zirconium. Final solutions of these plant products are concentrated prior to storage and/or further processing, such as UF_6 and PuO_2 generation.

9. Solvents used in fuel recycling operations are treated in two parallel solvent treatment systems before reuse.

10. All aqueous raffinates containing small quantities of fissile material (except solvent treatment wastes and the high activity waste stream) are passed through a recovery extraction system prior to concentration and storage. All potential fissile-containing organic raffinates are recycled through the partitioning column prior to routing to solvent treatment.

11. The combination of iodine and $^{14}C02$ scrubbers and inorganic adsorption beds give multiple assurance of effective iodine and $14C0_2$ cleanup of gas discharged to the atmosphere through the stack.

12. Tritium is released as water vapor from an evaporator through the stack. Nitric acid is recovered and reused.

13. The high-level wastes are chemically denitrated to a nitric acid concentration of 1-5 molar prior to interim liquid storage in cooled stainless steel tanks. High-level waste is transferred from the original tanks as the requirements for cooling decrease due to the decay of the heat-producing radionuclides. The storage of acidic high-level liquid wastes is an interim measure to

allow flexibility regarding their ultimate disposition. Multiple cooling systems for the tanks provide back-up cooling in case the primary cooling system fails.

A separate plant to convert the uranyl nitrate to UF_6 for return "to the enrichment cascade may be included within the facility. The capacity of the UF_6 facility would be compatible with the output of the Purex separations facility. Figure 18 contains a schematic flow diagram of the conversion process.

The solid waste (the spent fluorinator beds) contain the bulk of the radioisotopes entering the process, including the residual fission products and plutonium not removed in the separations facility. These are periodically replaced with fresh inert bed material. The spent material must be monitored for activity, packaged in suitable containers and transferred with other solidified high-level waste to a Federal repository.

The Purex separations plant also includes a plutonium product plant to convert recovered plutonium nitrate to plutonium oxide powder and to provide storage for the product. A chemical process, the oxalate process, may be used for this purpose. Figure 19 shows a block flow diagram for the principal steps involved in the oxalate process to produce plutonium oxide powder from the plutonium nitrate solution. An alternative process, Coprecipitation, involving the introduction of uranyl nitrate into the plutonium nitrate stream, results directly in a mixed oxide. Figure 20 contains a schematic for this process.

The processing of $Th0_2$ fuels containing uranium may utilize the Acid Thorex process (see Figure21).

Feed solution for these processes will be formed by reacting chopped thoria-based element material with a solution

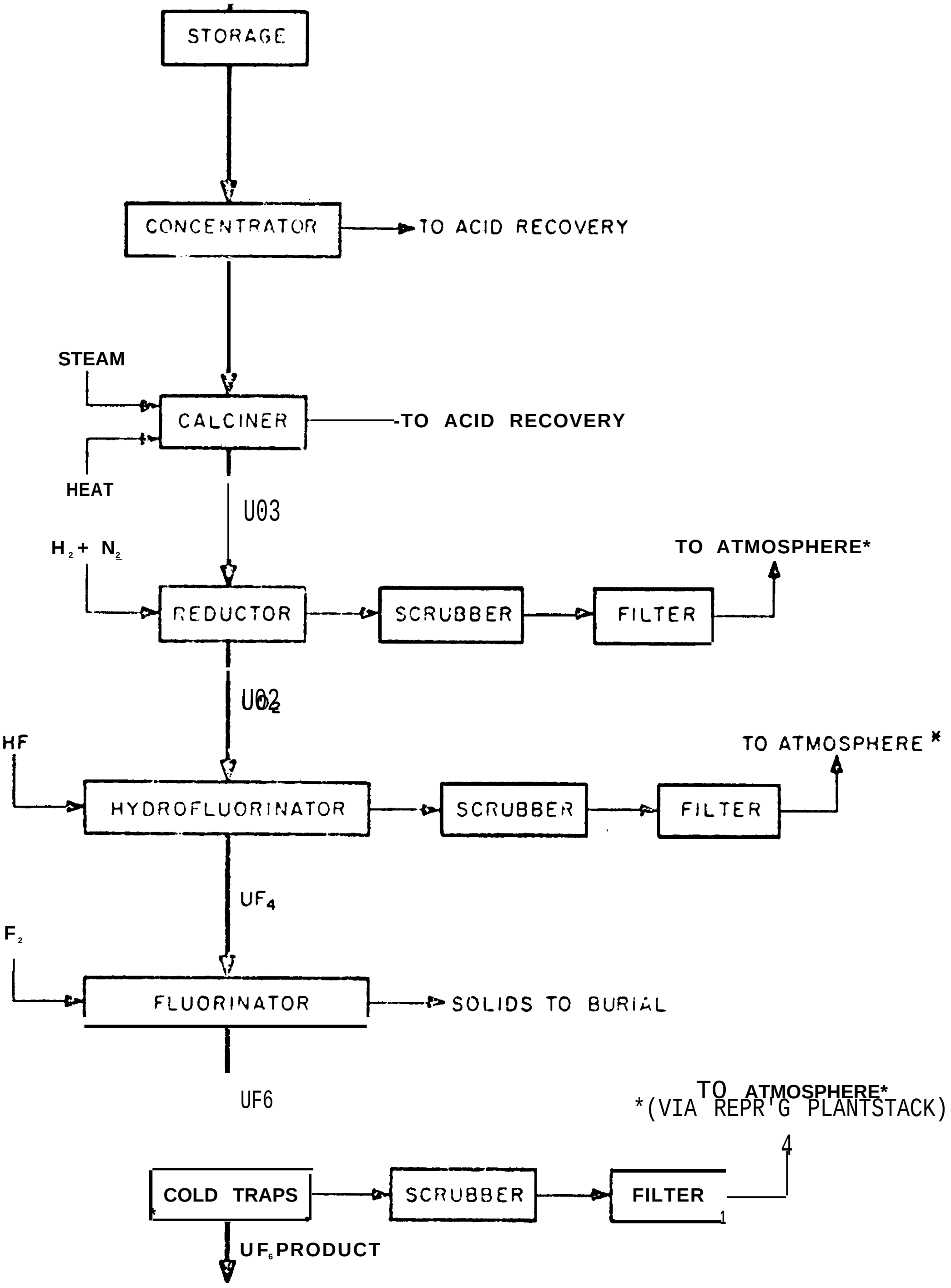


Figure 18. UF_6 Conversion Plant

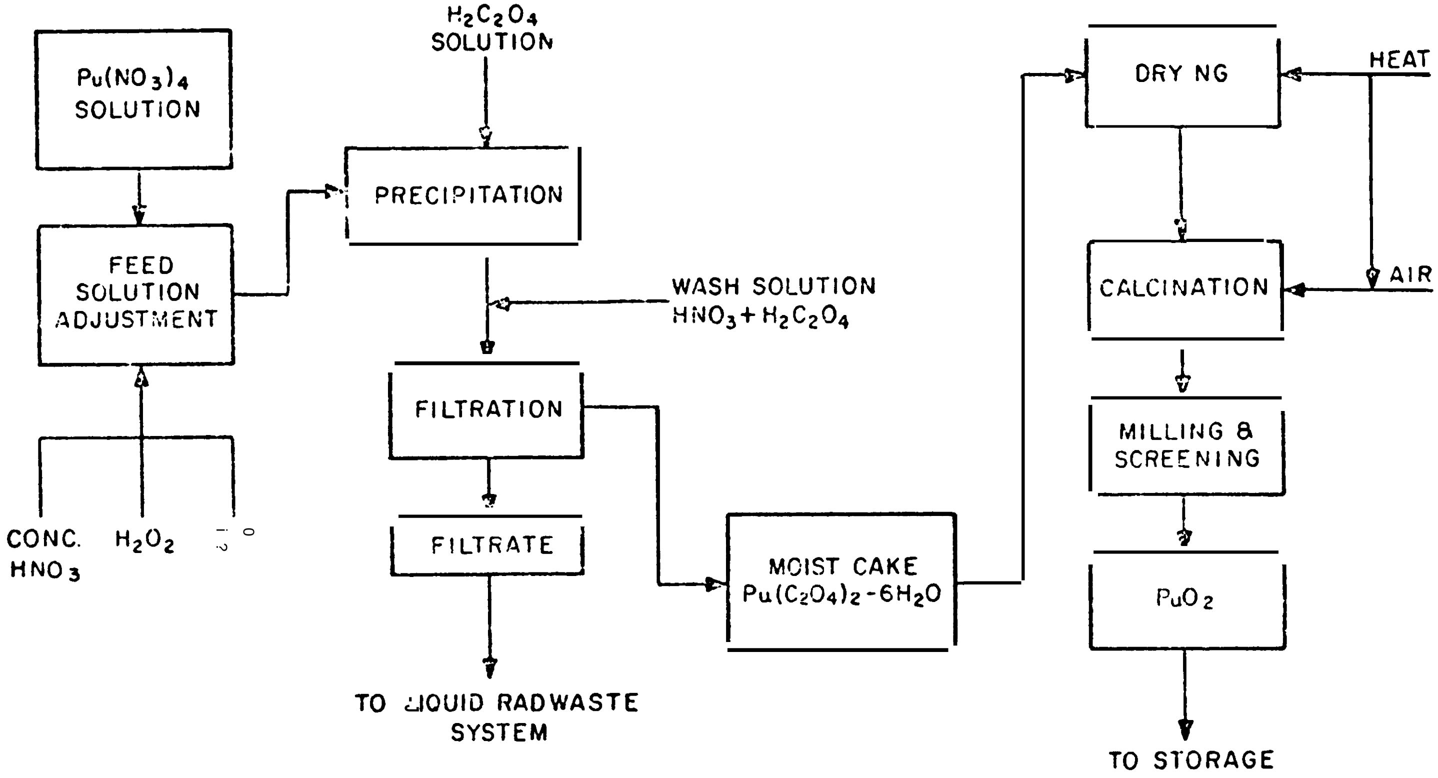
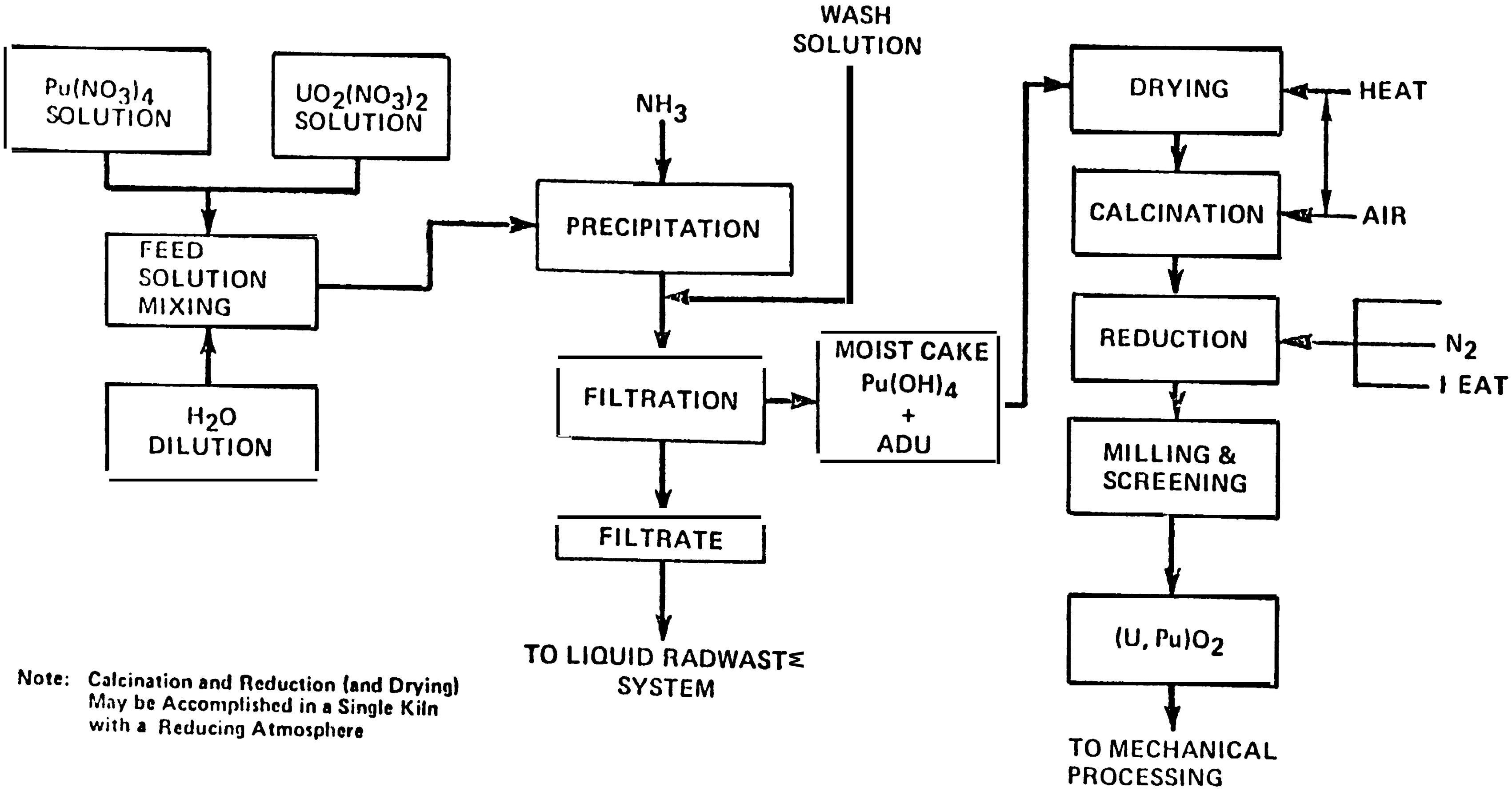


Figure 19. Oxalate Conversion Flow Sheet for PuO_2.



Note: Calcination and Reduction (and Drying) May be Accomplished in a Single Kiln with a Reducing Atmosphere

Figure 20. Coprecipitation Conversion Flowsheet for Fixed $(U,Pu)O_2$

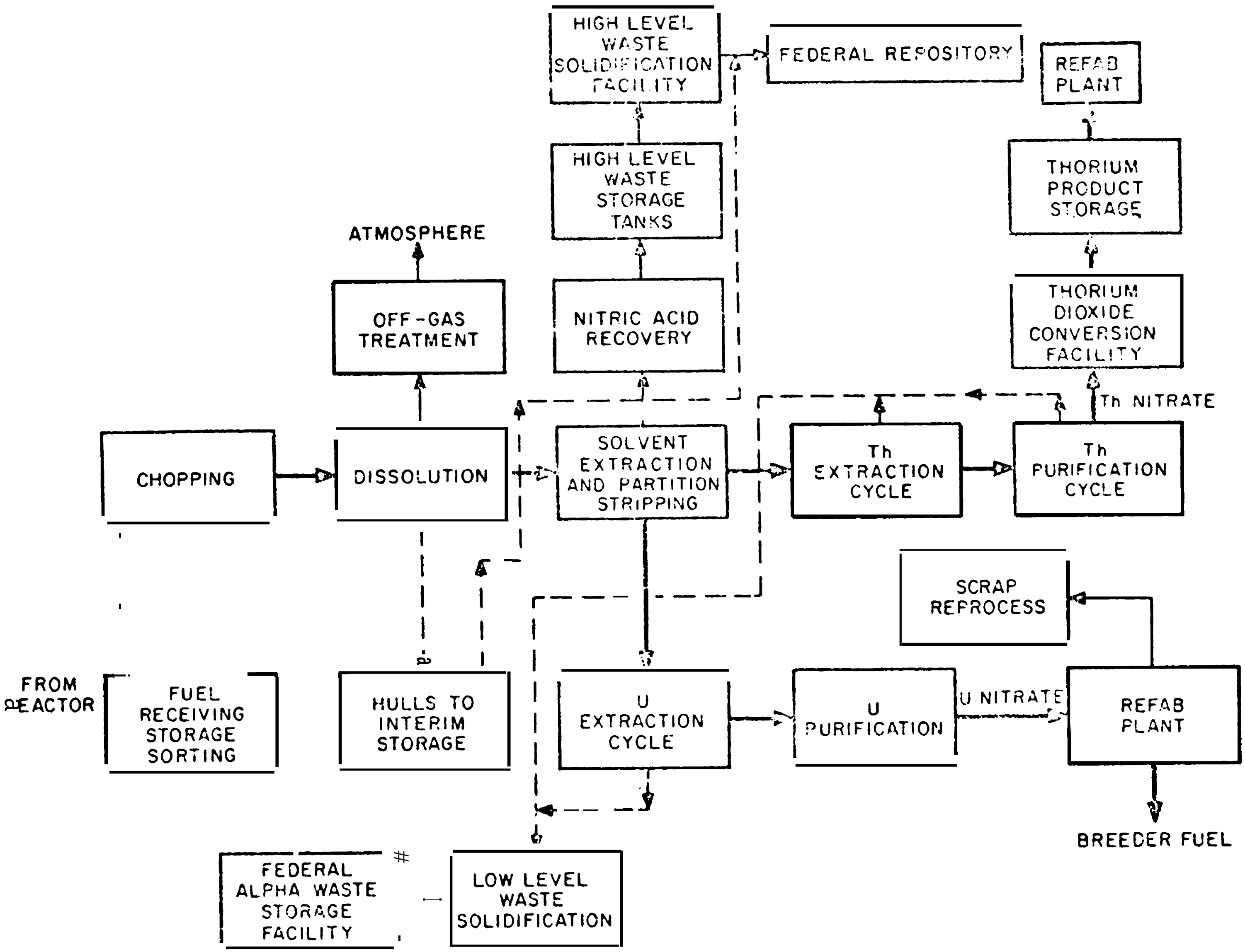


Figure 21. Simplified Block Flow Diagram of the Acid Thorex/Modified Acid Thorex Reprocessing Facility.

containing nitric acid, hydrofluoric acid, aluminum nitrate and a neutron absorbing material, such as boron or cadmium. The resultant solution can be chemically adjusted to solvent extraction flowsheet specifications and transferred into a feed tank for the first cycle solvent extraction.

The first extraction cycle serves to separate the uranium and thorium from the bulk of the fission products in the aqueous feed solution. A simplified block flow diagram of feed preparation and first cycle extraction is shown in Figure 22. In the extraction-scrub column, uranium and thorium will be extracted into the organic solvent and scrubbed with nitric acid to remove fission products.

In the stripping column, the organic solvent phase containing thorium and uranium will be stripped from the solvent using dilute nitric acid. In the solvent scrub column, the aqueous uranium-thorium solution will be contacted with kerosene, and concentrated, by evaporation, to about 1.5 molar thorium.

The uranium-thorium solution from the first extraction cycle will be fed into an extraction-scrub column where the thorium and uranium will be extracted into the solvent and transferred to the partitioning column. In the partitioning column, the thorium will be selectively stripped from the solvent with dilute nitric acid. The thorium solution will then contact fresh solvent to re-extract any remaining uranium. If the uranium content of the thorium solution is sufficiently low, it will be concentrated by evaporation and transferred to the ThO_2 conversion facility, where the nitrate solution will be precipitated using oxalic acid, air dried, and then calcined to the oxide prior to storage.

A typical reprocessing plant will process 1,500 MT/year of fuel, with capital costs for the reprocessing plant, waste solidification and PuO_2 conversion of $1.5 billion. The

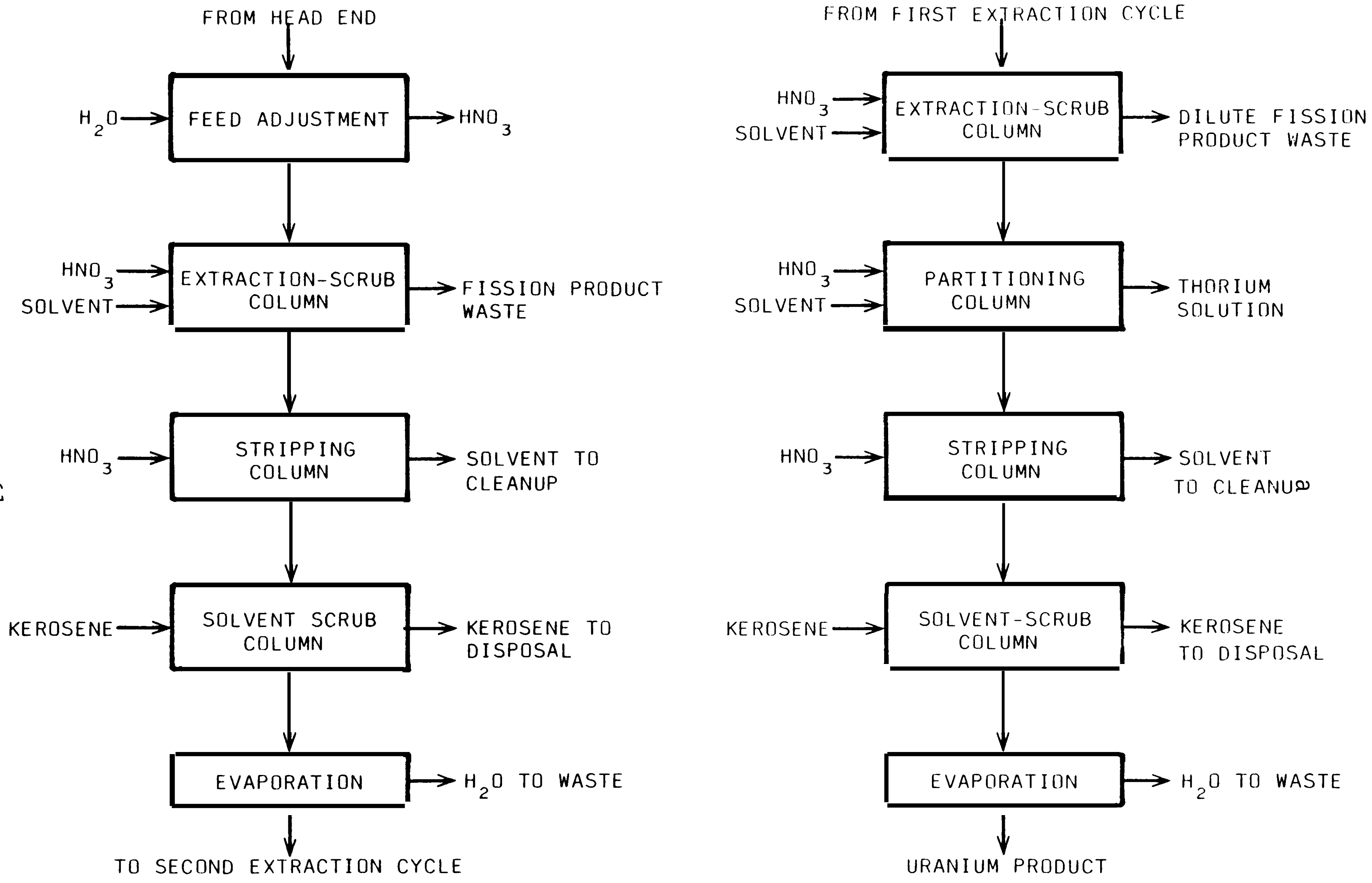


Figure 22. Block Flow Diagrams of Feed Preparation and First Cycle Extraction and Second Cycle Extraction-Acid Thorex Process

equipment required is typical of the chemical industry and the processes can be scaled down to very low throughput. Remote handling and maintenance are required.

Reprocessing of other fuels, such as the HTGR fuels, requires some unique processes* Figure 23 is a simplified block-flow diagram for HTGR fuel reprocessing. The spent fuel elements are mechanically crushed and then burned to remove the fuel element graphite and the pyrolytic carbon coatings from the fuel particles. Leaching permits separation of the fissile particles (those originally containing ^{235}U) and the fertile particles (those originally containing only thorium but now containing thorium and ^{233}U) because the fissile particles have a silicon carbide coating which remains intact during burning and leaching, while the all pyrolytic-carbon coatings on the fertile particles are burned away. Attainment of a perfect separation of the two particle fractions is not vital, but minimizing the loss of ^{233}U is important. The leach solution is treated by solvent extraction to remove fission products and to separate the bred ^{233}U from the thorium.

The silicon-carbide-coated fissile particles are mechanically crushed to expose the fuel and are burned to remove carbon and oxidize the fuel material; the ash is leached to separate the fuel and fission products from the coating hulls. The ^{235}U is then separated from the fission products by solvent extraction.

The acid thorex solvent extraction process is used to decontaminate and purify the ^{233}U and thorium and to separate the ^{233}U from the thorium:

Some fuels, such as those utilized in low power reactors, might consist of aluminum clad uranium metal. This type of fuel will be much easier to reprocess than the zirconium clad

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‘death, C. G., and Spaeth, M. E. “Reprocessing Development for HTGR Fuels”, Proceedings of Joint Topical Meeting on Commercial Nuclear Fuel Technology Today, ANS & CNA, April 1975.

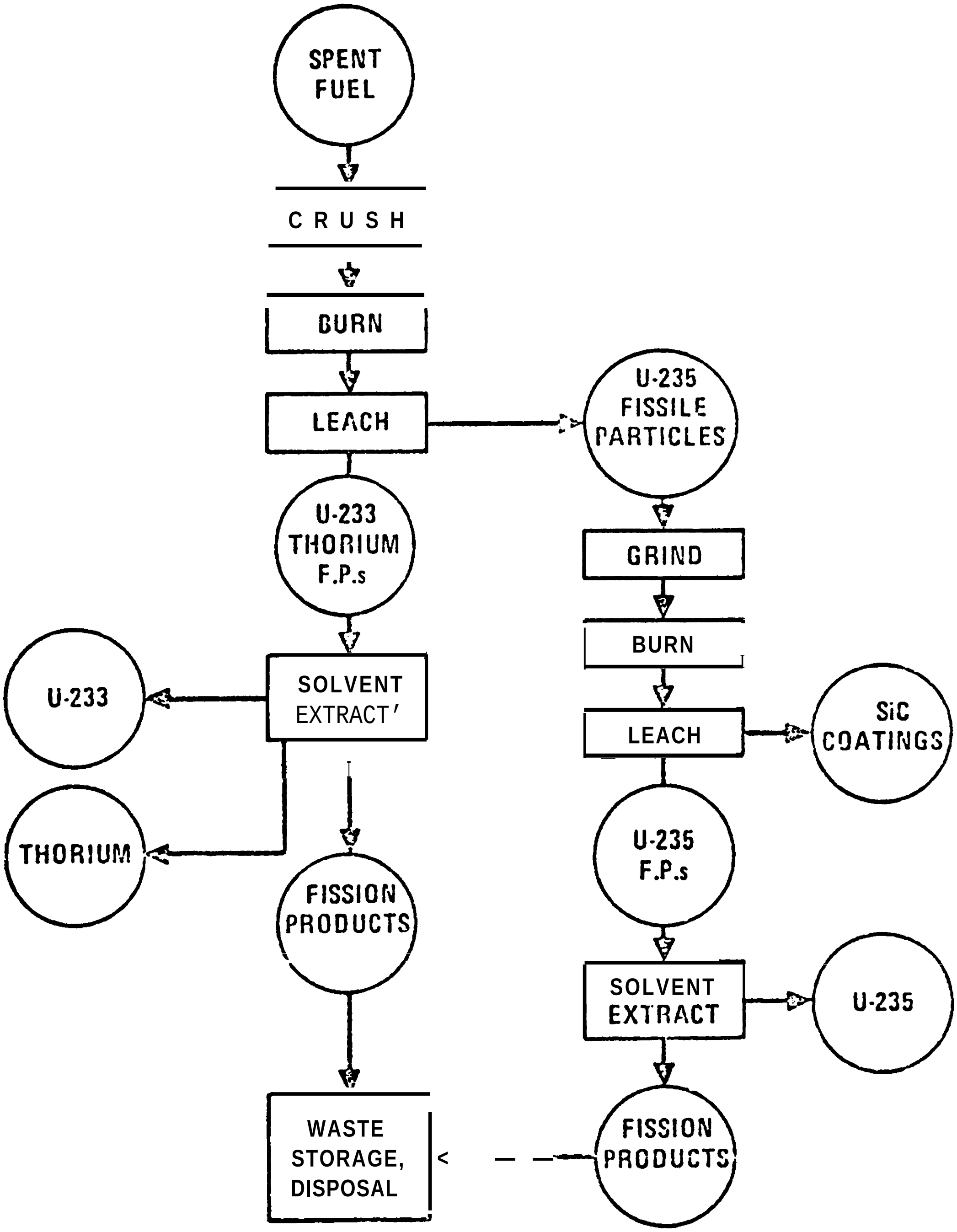

Figure 23. Block Flow Diagram for HTGR Reprocessing

oxide fuel of the light water reactors. Sodium hydroxide can be used to dissolve the clad and the uranium metal can be easily dissolved with nitric acid. Typically, the burnup will be lower for the aluminum clad fuel, so that the fission product activity will be less than that of power reactor fuels.

2.9 WASTE STORAGE

Radioactive wastes are generated at every step in the fuel cycle. The high level wastes containing fission products and the actinide wastes cause the greatest concern, however. For the most part, these wastes are contained in the spent fuel elements. The properly packaged spent fuel can be considered waste or it can be reprocessed to recover the fissile and fertile materials. The reprocessing waste must be solidified and properly packaged. This solidified high and intermediate level waste may occupy a volume approximately half that of the spent fuel.

The characterization of nuclear waste has received much attention. Low level waste has been stored in shallow land burial sites, and some has been dumped into the ocean. High level wastes have been stored as liquids awaiting decisions on ultimate disposal. Programs currently underway will lead to the solidification of the liquid wastes for permanent disposal. Ultimately, most radioactive waste will be stored at a Federal repository.

Design for a Federal repository is just beginning. This repository will be capable of handling high level waste, actinides, low level wastes and spent fuel elements. Criteria for packaging these wastes and for repository design are still under development. Although several repositories will be built, the first ones will probably be located in deep stable geologic formations.

A single repository will be capable of annually receiving up to $360 m^3$ of high level waste, $2100\ m^3$ (15,000 fuel assemblies) of spent fuel and $6000\ m^3$ for transuranic waste. Capital investment for a repository will be $300 million, with operating costs of $10 million/year.

2.10 TRANSPORTATION

The fuel cycle facilities which support light water reactors are widespread, and a broad transportation network exists to tie them together. Most shipments of nuclear material occur in routine commerce, using conventional transport equipment; for some nuclear material, however, specially designed containers, packaging, and transport equipment is necessary. Typical shipments for each element of the fuel cycle are presented in this section for U.S. operations.

2.10.1 Mine

Uranium ore is mined and shipped in bulk by open truck to nearby mills. Ore shipments require no specialized containers since the low concentration of naturally occurring radionuclides poses no contamination threat. Approximately 30 MT of ore per vehicle can be transported. The nominal distance in the U.S., from the mine to the mill, is 5 miles, and the average shipment takes about 1/2 hour.

2.10.2 Mill

The uranium concentrates from the milled ore are shipped to the UF_6 conversion plant in 55-gallon steel drums. Approximately 15 MT of U_3O_8 is transported per truck and 38 MT per rail car. The nominal distance in the U.S., from the mill to the conversion plant is 1000 miles. The average shipment takes 5 days by truck and 10 days by rail.

2.10.3 Conversion Plant

Uranium ore concentrates are processed and converted to UF_6, which is packaged in 2.5-, 10-, or 14-ton capacity steel cylinders and shipped by truck or rail to an enrichment plant. Unenriched UF_6 is handled by typical bulk material techniques for industrial chemicals whose primary hazard stems from the chemical rather than the nuclear properties of the material. Most shipments are made by truck with one 14-ton,two 10-ton, or four 2.5-ton cylinders per vehicle. The nominal distance for the shipment is 500 miles and the average shipment time is about 10 hours.

2.10.4 Enrichment Plant

The low-enrichment UF_6 product is shipped to fuel fabrication plants in 30-inch-diameter cylinders which are placed inside protective structural packages designed to protect the enriched UF_6 from impact and fire. Commercial vehicles can accommodate up to five 2.5-ton units at one time. Such shipments are transported an average distance of 750 miles and take about 1-1/2 days. The transportation activity is the same for shipments to a fresh fuel fabrication plant or to a mixed-oxide (MOX) fuel fabrication plant.

2.10.5 Fresh Fuel Fabrication Plant

For shipment to nuclear power plants, unirradiated fuel assemblies are packaged in special containers designed to prevent occurrence of a self-sustaining nuclear reaction in the unlikely event that a sufficient number of assemblies become separated from their shipping package, are arranged in a particular geometric pattern, and flooded with water. A nominal truck shipment contains 32 BWR fuel assemblies or 12 PWR fuel assemblies per truck. The average distance for the shipment is about 1000 miles and takes about 3 days.

2.10.6 Reactor

Irradiated fuel discharged from nuclear power reactors is stored onsite for several months before it is loaded into an irradiated-fuel shipping cask and transported to a fuel reprocessing plant. Casks are available for both truck and rail transport, and most can accept either BWR or PWR fuel assemblies. The cask must provide radiation shielding as well as a means to dissipate the large amount of heat (approximately 10 kw) produced by radioactive decay. The nominal distance from the reactor to the fuel reprocessing plant is assumed to be 1000 miles. The average transit time is assumed to be 5 days by truck and 10 days by rail.

2.10.7 Fuel Reprocessing Plant

Shipments from the fuel reprocessing plants will be of two types. Recovered fissionable materials will be shipped to the fuel fabrication or enrichment plant, and waste products will be shipped to a federal repository.

The plutonium shipped from the fuel reprocessing plant to the MOX fuel fabrication plant will be in the form of PuO_2 or uranium-plutonium dioxide. Present plutonium oxide packages contain a few kilograms of the oxide sealed in metal cans placed in an inner, gasketed steel container which is supported within an outer steel drum of 10 to 110 gallon capacity. The gasketed steel cylinder is supported within the steel drum by thermal and shock insulating material, such as cane fiberboard, vermiculite, or foamed phenolic plastic. Mass limits up to 4.5 kg plutonium per package are defined in present package designs primarily by heat dissipation requirements. Designs have been developed for plutonium product packages, or canisters, which can hold up to 18 kg of plutonium. Four of these cannisters can be packed into a primary pressure vessel, to provide additional containment. These pressure vessels must be transported in a special semi-trailer vehicle. This vehicle, termed an Integrated Container Vehicle (ICV), is a cylindrical steel secondary pressure vessel capable of carrying seven of the primary pressure vessels. With this system, the vehicle payload will be about 500 kg of plutonium oxide. The distance for this shipment may be 1000 miles, with a transit time of about 5 days.

The equipment for the shipment of reprocessing plant waste has not yet been developed. It is expected that the shipping containers will resemble the casks currently used for spent fuel transport. The cask will be designed to hold about 60 to 75 cubic feet of solidified waste. The containers for shipping low-level plutonium waste are expected to be 55-gallon steel drums packed in a secondary steel container, resulting in a total waste capacity of 1000 cubic feet. A similar package is expected for the contaminated cladding fuels, with a resulting container payload of about 125 cubic feet. If fuel is not reprocessed, and the waste is in the form of the fuel elements themselves, the spent fuel shipping casks may be used for transport. It is expected that shipments from the fuel reprocessing plant to the federal waste repository will be made by rail. Shipments are expected to take about 10 days, with a travel distance of 1500 miles.

2.10.8 Mixed-Oxide Fuel (MOX) Fabrication Plant

MOX fuel assemblies will be shipped to the reactor in packages similar to those used for shipping fresh fuel assemblies. These packages will be modified to provide neutron shielding. The transport capabilities and requirements are like those identified for fresh fuel elements. More detailed package designs will be developed as the need arises.

2.11 PROSPECTUS OF FUEL CYCLE COMPONENTS

A country may wish to establish commercial nuclear power fuel cycle components within its borders to support its own nuclear reactors and possibly to compete in the world market. An important question is what unit sizes make sense and what” design, construction, and production lead times are required before the facility begins to operate at design capacity.

Table 7 lists characteristics of some U.S. designed fuel cycle facilities along with the estimated capital cost in 1976 dollars. Of course, these cost estimates pertain to U.S. economics and industrial capabilities and may differ substantially with cost estimates for other specific countries. In addition, implicit in these estimates are U.S. environmental considerations on effluent control, and U.S. radiation safety requirements.

The fuel cycle components that are of primary interest in a proliferation assessment are the enrichment facility, the recycle fuel fabrication facility and the reprocessing facility. The parameters for the enrichment facility are for a gaseous diffusion plant, the present primary uranium enrichment method. A severe economic penalty must be paid for smaller sized diffusion plants. However, centrifuge enrichment plants can be scaled down more or less linearly with capacity. The total capital costs for a 9,000 MT SWU centrifuge plant are expected to be approximately equal to a simularly sized gaseous diffusion plant .*

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*Environmental Statement “Expansion of Us. Uranium Enrichment Capacity”, ERDA-1543, April 1976.

TABLE 5

CHARACTERISTICS OF FUEL CYCLE FACILITIES

Component	Unit Capacity/Yr	Design Construction Lead Time (yr)	Production Lead Time (yr)	Estimated Capital Cost (106 $)	Approximate LWR'S Supplied/Yr
Mining/Milling	1000 MTU_3O_8	3	2	20	5
Conversion	5000 MTu	3	1.5	35	29
Enrichment	9000 MT SWU	8	1	3,000	77
UO_2 Fuel Fabrication	900 MTU	3	0.5	70	31
Recycle Fuel Fabrication	200 MTHM	3	0.5	45	15
Reprocessing	1500 MTHM	8	2	1 ,500(‘)	51

(1) Includes Plutonium Nitrate conversion to oxide
UF6 conversion
Waste treatment

MT+ metric tonnes

MTU + metric tonnes uranium

SWU + separative work units

MTHM + metric tonnes heavy metal

Reprocessing plants also exhibit a non linearity in capital costs. A recent Savannah River Laboratory report* indicates that a 3000 MTU plant has a capital cost approximately 1.5 times the 1500 MTU plant. It appears the higher throughput plants are necessary to offset the required costs for remote operations-, high shielding, etc.

An interesting feature of Table 5 is the relatively long lead times required to bring a commercial enrichment plant or commercial reprocessing plant into production. These substantial lead time periods create pressures for accurate projections for the need of these facilities. On the other hand these time periods insure that commercial enrichment and reprocessing facilities will not proliferate the world in a short time period without an indication that they will be built.

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*"Light Water Reactor Fuel Recycle”" Savannah River Laboratory Quarterly Report DPST-LWR- 76-1-1 Jan-Mar 1976.

3. REACTORS

As noted in Section 2.1, there are many ways to characterize current reactor systems. With the growing concern over uranium ore supplies, enrichment facilities and plutonium recycle, there are numerous studies which consider combinations of fuel cycles, such as increased use of thorium-^{233}U, the use of lower enrichments for the HTGR, the use of mixed oxides, and other possible alternatives for fast breeders. This section presents the characteristics of generic reactor types and the current or near term fuel cycles. The many alternative fuel options are also considered in this section and in Section 4. In Section 3.8, future systems are considered from the standpoint of their ability to produce fissile material.

For each reactor type described, a detailed flow sheet depicting material flow throughout the fuel cycle is given. All power reactors are normalized to 1000 MWe with a 75% capacity factor assumed. To obtain material flows for another capacity factor , Z, and power level, Y, from the model plant data, X_M(1000, 75%), the following relation should be used:

$$x\ (Z,Y) = X_M(1000,75\%)^{Y} \quad \frac{Z}{75}$$

Material flows for research reactors are based on 10 MWth .

3.1 LIGHT WATER REACTORS*

The dominant nuclear power reactor in use today is the light water moderated and cooled reactor (LWR) . There are two basic types -- one, the PWR, in which the coolant is pressurized so that the water does not boil in the reactor, and the other, the BWR, in which the reactor coolant is used to drive a steam turbine directly. Both reactors utilize slightly enriched (2-4%) $U0_2$ fuel clad in zircalloy. The $U0_2$ pellets are inserted into the zircalloy tubing, with the small void regions filled with a gas such as helium. The enrichment, fuel management scheme, and burnup are dependent on whether the LWR is a BWR or a PWR. Both types of reactors must be shut down for refueling, which may take as long as 30 days.

3.1.1 Pressurized Water Reactors

PWR vessels are made of steel, are typically 20 meters high, and about 5 meters in diameter, and have walls that are about 20 cm thick. The hemispherical head is bolted into place, but must be removed for refueling. The coolant pressure is about 2250 psi and the outlet temperature is about 320°C. The fuel elements are typically 3.5 to 4 meters long and the core contains around 190 fuel assemblies. Each assembly contains approximately 250 rods and each rod contains about 250 pellets. The assemblies are approximately 20 cm square and 400 cm long. The fuel pellets are generally .8 cm in diameter and 1.3 cm long. The enrichment level of the UO_2, depends on the specific fuel management scheme, but will typically be 2 to 3%. Reload fuel may contain fuel enriched to 3.3% ^{235}U. There may be several core regions of uniform enrichments. Burnable neutron poisons are utilized to provide higher burnups and to balance power density.

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* "Comprehensive Standards: The Power Generation Case", EPA No. 68-01-0561, Teknekron Inc., Report March 1975.

Approximately one-third of the fuel elements are replaced each year. Frequently, the refueling schedule is dictated by other plant maintenance requirements and not necessarily by the estimated burnup. Burnup variations of 25% may exist within a single fuel element, and from fuel element to element. A typical burnup appears to be close to .8E x 10^4 MWD/MT, where E is the enrichment of the fuel. This value may be altered by the burnable poisons and by the fuel management scheme. Experience tends to indicate burnups of 20,000 to 25,000 MWD/MT. With this type of reactor, a fuel element suffering clad failure may be removed prior to achieving full burnup by removing the entire assembly.

When the fuel is removed from the reactor, it is stored on site for at least 150 days to permit partial decay of-the fission products. The spent fuel is stored in racks in a water pool at least 5 meters deep to provide the required shielding. When the fuel is shipped, it is transported through a canal and loaded into a shipping cask. A typical reactor facility can store about 3 core loadings in the spent fuel pool. Table 6 gives representative characteristics for a PWR.

3.1.2 Boiling Water Reactor

BWR vessels are about 20 meters high, 6.5 meters in diameter, with wall thicknesses of about 15 cm. The coolant is pressurized to about 1000 psi which permits boiling at around 240°C. The steam-water mixture leaves the core and flows through steam separators before leaving the reactor vessel. The hemispherical head is bolted to the pressure vessel, so both the head and the steam separators must be removed for refueling.

The fuel assemblies are about 450 cm long and are 13.8 cm square. There are over 730 assemblies which may contain either 49 or 64 fuel rods. Each fuel rod contains about 350 pellets. The enrichment varies by zone and can range from 1.5 to 2.3%. Reload fuel enrichment levels can be as high as 2.8%.

Approximately one-fourth of the fuel assemblies are replaced annually. A typical burnup is about 25,000 MWD/MT for equilibrium conditions and less for the initial loading. As with the PWR, refueling of the BWR may be dictated by other schedules and full burnup may not be achieved. Also, the burnup may vary by 25% within a fuel element and from element to element. Refueling will require about 30 days and the reactor head and steam separators must be removed and the core flooded. The spent fuel is stored on site for at least 150 days. Table 6 gives general characteristics for a BWR.

3.1.3 Material Flow in Light Water Reactors

The material flow (and particularly the discharge) depends upon the burnup level achieved in the fuel. As noted above, burnups of 33,000 MWD/MT are design goals. Table 7 contains the material flows for this burnup under the title PWR 1. Also included, under PWR 3, are data for a 23,000 MWD/MT equilibrium burnup. As experience is gained, the average burnup will probably be somewhere in between these two values.

One current fuel cycle issue is the recycle of plutonium. Table 7 also contains, under PWR 2, the material flows for a typical plutonium recycle case. It should be realized that there are many options and that this may or may not be typical. Figures 24-26 schematically illustrate the material flows for these equilibrium cycles.

Table 8 contains fuel cycle requirements for a BWR with and without plutonium recycle. This information is schematically shown in Figures 27 and 28.

It should be noted that the material flows assume uranium recycle. Depending on future decisions, uranium recycle may not occur and the uranium requirements would be made up for uranium ore.

3.2 HEAVY WATER REACTORS

3.2.1 Introduction

The use of heavy water, D_20, in reactors has been considered for many years. Presently, only Canada, the West Germans and, more recently, the British have actively pursued the concept for commercial power. Only the Canadians are marketing heavy water reactors at this time.

Heavy water is desirable as a reactor moderator ‘due to its satisfactory neutron slowing power and its very small neutron absorption cross section. These factors allow natural uranium to be used as a fuel. However, the need for large quantities of heavy water partially offsets the advantages of not needing enriched uranium. Heavy water costs are around $50 per pound with an enrichment of 99.8% D_2O. Even at the .2% light water impurity level, the light water absorbs as many neutrons as the heavy water. About one tonne of heavy water is needed per MWe of installed capacity.

The greatest advantage of heavy water moderated reactors is their ability to use natural uranium fuels or fuels of near natural enrichment with high neutron economy, long reactivity duration, and, therefore, high fuel utilization. Burnups in the neighborhood of 10,000 Mwd/T of natural uranium fuel are possible in heavy water reactors. Higher burnups have been achieved in other reactors, but only with enriched fuels. Natural uranium can also be used in graphite-moderated reactors, but the burnups there are comparatively low due to physics and metallurgical reasons. There is a great incentive, therefore, to develop heavy water reactors, particularly for those countries with no fuel-enriching facilities. The capture-to-fission reaction rates in heavy water reactors make it possible to more fully utilize the natural uranium.

The strength of the economic incentive to develop heavy water reactors depends upon the different methods used for estimations and projections. In Canada, for example, it is believed that natural uranium-heavy water moderated reactors can produce power at a lower cost than enriched-fuel reactors. Canada has, therefore, concentrated on developing this type of reactor. These Canadian-type reactors are now being built in such countries as India and Pakistan. In the United States, however, it is believed that cheaper power can be obtained from enriched-fuel, light-water reactors and that, even if heavy water is used, power would be cheaper if enriched fuels are used. The factors that influence this decision are the higher capital costs, the large, expensive heavy water inventory needed, and the availability of large enrichment facilities.

Heavy water reactors can use either metallic or oxide natural fuels. Metallic fuels are more desirable when parasitic neutron absorption is considered, while the oxide fuels are desirable from the standpoint of resistance to radiation damage. The oxide fuel consideration favors the use of UO_2 in power reactors where higher burnups are sought. Cladding materials of low neutron absorption must be used in all natural uranium reactors. Zircaloy, beryllium, and beryllium magnesium alloys are suitable for the higher-temperature natural uranium power reactors. Aluminum may be used in low-temperature reactors.

Heavy water moderated reactors require large moderator-to-fuel volume ratios. Such reactors, therefore, require large-diameter reactor cores. Because of this large diameter, large power reactors operating at high temperatures and pressures require larger, thicker, and costlier pressure vessels than ordinary-water reactors of comparable output. Both pressure vessel and pressure-tube designs have been used. The latter design allows the use of lower-pressure, less costly vessels but adds the expense of constructing a leaktight calandria vessel, free of differential expansion. It also results in the separation of the coolant and moderator. Operational problems associated with D_20 reactors are the loss, by leakage, of the expensive D_20 and the high activity associated with the decay of tritium formed in the reactor.

Presently, the dominant heavy water reactor concept is the CANDU-PHW (Canada Deuterium Uranium-Pressurized Heavy Water) reactor in which D_20 is utilized as both the moderator and the coolant. Reactors in the range of 500-750 MWe are currently operational. Reactors of 850 MWe capacity are under construction. HWR reactors cooled with light water or organic materials are also possible. A prototype station (Gentilly 1) , in which a light water coolant is allowed to boil in the pressure tubes, has been in operation since 1972. This reactor, CANDU-BLW (Canada Deuterium Uranium-Boiling-Light Water) , is very similar to the Steam Generating Heavy Water Reactor (SGHWR) now being developed in Great Britain as their next generation of power reactors. The organic cooled reactor concept (OCR) has the potential for achieving high temperatures. Table 9 summarizes several characteristics of the various heavy water reactor concepts.

3.2.2 CANDU-PHW*

Atomic Energy of Canada Limited (AECL) is presently the only commercial manufacturer of HWRs. A 600 MWe unit has been selected by AECL as its standard model. The so-called CANDU 600 units are being installed in Canada (at Gentilly and Lepreau) as well as in Korea and Argentina.

The uranium oxide fuel is supported in a suitable spatial arrangement in the heavy water-moderator which is contained in a vessel called a "calandria”" This spatial arrangement is provided by a system of tubes which pass through the calandria in a regular pattern (lattice) . Due to the moderating

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McIntyre, H. C., “Natural Uranium Heavy-Water Reactors”, Scientific American, Vol. 223, No. 4, October 1975.

characteristics of D_2O, the optimum lattice spacing of the fuel is relatively large compared to the lattice spacing in a light water reactor.

To permit removal of the nuclear heat, the fuel bundles are contained in pressure tubes which pass concentrically through the calandria tubes, but are separated from them by an insulating gas gap. The nuclear heat is removed by a coolant which is pumped through the pressure tubes. The heavy water coolant transports the heat, in a closed, high-pressure circuit, to heat-exchanger boilers where it generates steam to drive the turbine.

A principle feature of the CANDU reactor is the complete separation of the moderator system from the heat transport system. The moderator system is a cool (non-boiling) system maintained at substantially atmospheric pressure. The typical primary coolant system, on the other hand, operates at a reactor outlet temperature of approximately 300°C and a pressure of 100 kg/cm^2. The CANDU coolant is contained inside the 10 cm diameter pressure tubes as it passes through the calandria. This separation of systems reduces the severity of the design basis accident and some believe that the HWR is, therefore, safer than the LWR. The large heat sink, which exists in the form of the relatively cool heavy-water moderator in the calandria, minimizes the consequences of pressure-containing component failure within the reactor core.

The reactor is fueled with natural uranium in the form of compacted and sintered cylindrical pellets of uranium dioxide (UO_2). Approximately 30 of these UO_2 pellets, stacked end-to-end, are sealed in a zirconium alloy sheath to form a fuel element. Thirty-seven of these elements are welded to two end-plates to form the cylindrical bundle. The elements are separated by split spacers.

The reactor is refueled by two remotely controlled fueling machines, one at each end of the horizontally-tubed reactor. The fueling machines, working at opposite ends of the same fuel channel, insert new fuel and remove spent fuel while the reactor continues to operate. The spent fuel is transferred under water, through a canal and transfer lock to the spent fuel bay.

At the present time, it is not economically feasible to reprocess the spent fuel to recover the plutonium. Storage space adequate for accumulation of 10 reactor-years of spent fuel is a design requirement. It is not expected, however, that Canada will have a reprocessing capability within 10 years and must, therefore, provide either additional storage facilities at the reactor sites or a rational program of interim storage. Three concepts have been proposed for long term spent fuel storage; one wet storage concept and two dry storage concepts utilizing concrete canisters and convection vaults.

Several studies have analyzed the use of thorium and mixed oxide fuels in the HWR. The feasibility of the use of these fuels depends strongly upon the long term uranium prices and the feasibility of reprocessing. A conversion ratio of .9 is feasible if enriched uranium or bred fissile fuels are used.

3.2.3 Heavy-Water Moderated Boiling Light Water Reactor

The HW-BLW reactor is a conceptual 1000 MWe design developed jointly by AECL, and Sargent and Lundy. The design features a vertical pressure tube calandria-type reactor, cooled with boiling light water. The coolant enters the bottom of the reactor at about 1,000 psi and exits at the top as 30% quality steam. The steam, after separation, goes directly to the turbine. The fuel assemblies for this reactor consist of 19-rod, Zr-4 clad oxide pellets. Five assemblies, each 1.5 m long, are stacked in each of 688 pressure tubes. Burnups of about 8,000 Mwd/MT are possible.

3.2.4 Heavy Water Moderated-Organic Cooled Reactor

The fuel cycle for a 1000 MWe natural uranium carbide fuel HWOCR is based on a design developed at ORNL. There appears to be little current interest in this approach. The main asset of an organic cooled reactor is an increased plant efficiency, resulting from a higher temperature operation.

3.2.5 Material Flow in Heavy Water Reactors

Table 10 summarizes the material flow in the various heavy water reactors. It is noted that the ^{235}U content of the discharged fuel from the CANDU-PHW is .22%, which is less than the current tails assay from the enrichment plant. Figures 29-31 illustrate the fuel cycle material flows.

3.3 GAS-COOLED REACTORS

3.3.1 Introduction

The attractiveness of gas cooling lies in the fact that, in general, gases are safe, are relatively easy to handle, have low macroscopic neutron cross sections, and may be operated at high temperatures without pressurization. The main disadvantages are the lower heat-transfer and heat-transport characteristics of gases, which require large contact surfaces and flow passages within the reactor and heat exchangers, and their high pumping requirements (between 8 to 20 percent of plant’s gross power) .

To partially overcome the inherent disadvantages of gas coolants and, at the same time, to obtain attractive thermodynamic efficiencies, it is necessary to operate the fuel elements at high temperatures (commensurate with metallurgy) and to permit a high gas-temperature rise in the reactor by reducing the gas mass-flow rate and pressurizing the gas. Because the fuel operates at high temperatures, fuel-element and cladding-material choice and fabrication in gas-cooled reactors present major problems, and the trend seems to be toward using ceramic fuels in such reactors. Because gas-cooled reactors are inherently large, they are particularly suited to large-capacity power plants, but the reactor itself may impose structural and foundation problems. The size of the units can, of course, be reduced to a certain extent by increasing the fuel enrichment.

Significant gas-cooled reactor development and commercialization programs have been undertaken by Great Britain, France, West Germany, the United States, and the USSR. Historically, the British led the way with their natural uranium, carbon-dioxide cooled and graphite moderated reactors. Since the fuel was in the form of metallic uranium rods, canned within a magnesium alloy cladding, these plants became known as MAGNOX reactors. In an attempt to improve the steam conditions by raising the coolant temperatures, a second generation of gas-cooled reactors evolved in Great Britain. These advanced gas-cooled reactors (AGR) are characterized by their carbon dioxide coolant, graphite moderator, and stainless steel clad rods of slightly enriched uranium dioxide. Continued efforts in raising the coolant temperatures have resulted in a class of high temperature reactors. The two outstanding examples are General Atomic’s HTGR and the West German thorium high temperature reactor (THTR). Both are graphite moderated and helium cooled, and operate on the uranium-thorium fuel cycle. Presently, 300 MWe demonstration plants for both the HTGR and THTR are nearing commercial operation, and large commercial plants (in the neighborhood of 1000 MWe) have been designed.

The basic differences between the HTGR and THTR lie in the fuel design and refueling procedures. In the HTGR, microsphere of fuel are mixed with a graphite binder to form fuel rods which are subsequently inserted into prismatic blocks of graphite. Annual refueling is anticipated for the HTGR. On the other hand, the THTR is a pebble-bed concept, designed for continuous on-line refueling. A design for even higher coolant temperatures is referred to as the very high temperature reactor (VHTR). Finally, a gas-cooled fast breeder reactor (GCFR) has been proposed. The basic idea is to combine the helium coolant technology from the HTGR program with fuel development from the liquid metal fast breeder program and produce a GCFR with a minimum of additional research effort. In Table 11 the general characteristics of each type of gas-cooled reactor are given.

3.3.2 High Temperature Gas-Cooled Reactor[**]

The HTGR is a thermal reactor characterized by a helium coolant and a uranium-thorium fuel contained in graphite blocks which serve both as moderator and core structural material. The entire nuclear steam supply system, which includes the reactor core, steam generators, helium coolant circulators, control rod drives, and the auxiliary core cooling system, is housed in a pre-stressed concrete reactor vessel. The unique material requirements demand about 2 million cubic feet of helium and over 50 cubic meters of graphite per core for a 1160 MWe plant.

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[*] “Development Status and Operational Features of the High Temperature Gas-Cooled Reactor”, Electric Power Research Institute, April 1976, EPRI NP-142

The basic fuel element in the HTGR is a graphite block with a hexagonal cross-section. Each element is 35.6 cm across the flats and 78.7 cm long. The fuel is in the form of coated particles of uranium dicarbides and oxides as the fissile material and thorium oxide as the fertile material. These are bonded in a graphite matrix to form fuel rods which are located in vertical blind holes in the fuel elements. Vertical coolant holes are provided for helium flow through the fuel elements. The core is formed by stacking these graphite blocks into 493 columns, each eight blocks high. The core is divided into 73 fuel regions. Each region is composed of a central control fuel column surrounded by six columns of standard fuel elements, except at the core periphery, where reflector columns replace some of the fuel columns. Each group, called a refueling region, rests on a graphite support block and is located directly below a refueling penetration that houses a control rod drive assembly. The refueling regions are grouped into four segments for refueling purposes, and one segment is refueled each year.

The fuel cycle for HTGRs is based upon the 93% enriched ^{235}U-thorium fuel cycle, with recycle of bred ^{233}U. This fuel cycle can involve two different modes of operation over the lifetime of the plant. These are:

1. Non-recycle operation, in which fuel removed from the core is placed in storage awaiting processing and recycle. Core operation is sustained by the introduction of additional fresh fully enriched fuel.

2. Recycle operation in which the fuel removed from the core is reprocessed and the ^{233}U is fed back into the core along with sufficient ^{235}U.

The utilization of ^{233}U has advantages because, 1) ^{235}U yields about 10% fewer neutrons per absorption than ^{233}U,

2) the fission rate per atom of ^{235}U is much more temperature sensitive than ^{233}U and 3) significant amounts of ^{236}U are formed by radiative neutron capture in ^{235}U. Since ^{236}U is an undesirable neutron poison) the continued use of the uranium fissile material may be limited to one recycle.

Two types of fuel particles will be used. The recycled ^{235}U, as well as the highly enriched uranium feed, will be contained as UC_2 in the kernel of the fissile particle which has a special coating. The thorium will be contained as $Th0_2$ in the kernel of the fertile particle. The fuel particles are blended in suitable proportions and formed into fuel rods using a graphite matrix as binder material. The fuel rods are about 16 cm in diameter and 5 to 6 cm long. The fuel rods are loaded into a graphite block to make a completed fuel element. Each fuel block contains only one of the three types (initial or makeup, highly enriched uranium; recycle ^{233}U, and once irradiated ^{235}U) as well as the fertile thorium.

Refueling must be performed when the reactor is shut down, the PCRV* depressurized to slightly subatmospheric pressure, and the core inlet temperature reduced to about 120°c. The fuel elements and replaceable reflectors are installed or removed through penetrations located in the top head of the PCRV; these penetrations also serve as control rod drive supports. During refueling, the control rod drives are removed and the fuel handling equipment mounted directly over the penetration. Removed elements are placed in a transfer cask, which is shuttled to the fuel storage area. During a normal refueling year approximately 18 regions are visited and 1000 elements are replaced. The total shutdown time is believed to be about 20 days.

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*Pre-stressed concrete reactor vessel

3.3.3 Thorium High Temperature Reactor*

The pebble bed reactor is an alternative to the GA-HTGR as a viable high temperature gas-cooled reactor concept. Pebble bed reactors are characterized by a mixture of fuel and some or all of the moderator, which is fabricated into spherical “pebbles”. The pebbles are then randomly packed into a suitable vessel, or bed, to form the reactor core. Core cooling is provided by gas flowing through the space between the pebbles. Figure 32 schematically compares the THTR and the HTGR.

Development of pebble bed reactors has occurred principally in West Germany. The initial result of this effort is the 15 MWe helium cooled pebble bed reactor at Jülich. A 300-MWe THTR (thorium high temperature reactor) is currently under construction at Uentrop. Designs for 1000 MWe THTRs have also been initiated.

The Uentrop THTR primary system is integrated into a pre-stressed concrete reactor vessel. The core, i.e., the pebble bed, is enclosed in a round graphite structure which is 5.6 m in diameter and approximately 6 m high. The bed contains 674,200 fuel spheres, each 6 cm in diameter. Control rods enter from above the core. A bank of 42 rods may be inserted pneumatically directly into the core and a total of 36 control rods may be inserted vertically into the reflector surrounding the core. Average core power density is 6 MWt/m^3

The spherical fuel element of the THTR contains 200 gm of graphite and 33,000 uranium-thorium oxide kernels, coated with a layer of pyrolytic carbon which has a minimum thickness of 0.5 cm. Each kernel is 0.4 mm in diameter and is enclosed in two layers of pyrolytic carbon 0.18 mm thick. The metallic content of an element is 0.96 gm ^{235}U and 9.62 gm ^{232}Th. In order to equalize the radial power and helium

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[*] Oehme, H. , “Comparative HTGR Designs”, ANS Topical Meeting Gas Cooled Reactors: HTGR and GCFBR CONF-740501, May 1974.

outlet temperature, there will be two concentric core enrichment zones. Average fuel burn-ups of 110,000 MWd/MTM are anticipated.

A continuous refueling scheme has been adopted for the THTR. Fuel elements which are discharged from the bottom of the core are monitored for burn-up and either returned to the core or disposed to waste storage. A pneumatic tube mailing system is installed beneath the core to perform the refueling. An average throughput rate of 1.8 times per year is anticipated. Thus, an average of 5-8 passes through the reactor are made by each element during its 3 year life.

The design principles of the Uentrop THTR can only be conditionally applied to large pebble bed reactors of 1000 MWe rating. The increase in the number of fuel elements required for higher thermal power cannot be accommodated by the larger scaling of the core dimensions. Thermodynamic and physical considerations limit the core height. Thus, a relatively flat core with an enlarged diameter of over 10 m is envisioned. Additionally, for the 1000 MWe system, a new on-line refueling scheme is proposed. The fuel elements would pass through the reactor only once. This scheme is known as OTTO for Once-Through-Then-Out. The pebbles are inserted through the top of the core by gravity discharge through 24 tubes and withdrawn at the bottom through 3 discharge tubes. Since the pebbles are not recycled, the pneumatic fuel handling facility and the burn-up measurement system are excluded. The power distribution is shifted towards the cold upper region of the core, which reduces the maximum fuel temperature and increases the reactivity value of the shut-down and control rods in this core region.

Detailed fuel cycle information suitable for a 1000 MWe plant is not available.

3.3.4 Advanced Gas-Cooled Reactors*

The Advanced Gas-cooled Reactor (AGR) represents the second generation in Great Britain’s development of graphite-moderated and $C0_2$ cooled reactor plants. The objectives of the AGR program are to construct nuclear power stations that supply steam at conditions comparable with those in modern fossil-fueled power stations and with a degree of integrity which permits siting nearer population centers. Five commercial-sized AGR plants are in various stages of construction and operation.

These plants are very similar and each plant consists of 2 reactors. The reactors have a thermal output of nearly 1400 MWt, with reactor thermal efficiencies of 45.3% and plant net efficiencies of 41.6%. Coolant temperatures at the core inlet and outlet are approximately 300°C and 650°C, respectively. Steam conditions at turbine inlet are about 550°C at 170 kg/cm^2.

The reactor core is a 16-sided structure constructed from polygonal graphite blocks arranged in a square lattice. The blocks are interconnected by graphite keys to provide stability and to maintain the correct pitch. Large vertical bores through the blocks form the vertical fuel channels. Square interstitial graphite blocks are placed between the polygonal blocks and contain coolant channels and control rods.

To maximize the temperature of the coolant while maintaining fuel pin integrity, a stainless steel cladding is used. This cladding requires low enrichment fuel (~2% ^{235}U): The fuel elements consist of 36 pins containing hollow $U0_2$ pellets. The pins are arranged in three rings within a graphite sleeve. Eight such elements are linked together by a tie bar to a fuel unit extending to the top of the refueling standpipe and terminated with a pressure closure. Fuel

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* "Hinkle Point B, A Survey of Design and Construction," Nuclear Engineering International, Vol. 13; No. 147, August 1968.

and control rods are replaced on line. Burnups of 18,000 MWd/MT are anticipated. The fuel cycle does not generally require axial shuffling of fuel elements.

Refueling of the twin reactors is accomplished with a single refueling machine that runs on a moving gantry spanning both reactors. A central service block contains all the shielded cells required for the assembly and dismantling of fuel stringers, for the maintenance of control rods, and for storing complete fuel stringers as necessary. During a refueling operation, a stringer of spent fuel is removed from the core and allowed to decay 10 to 12 hours before being lowered into the Irradiated Fuel Dismantling Cell. After the fuel stringer is disassembled, the spent fuel elements are stored in a cooling pond. Provisions are available for sealing the fuel elements within a stainless steel bottle which has an inert atmosphere before discharge to the pond. It is anticipated that the spent fuel will be shipped by rail and road to Windscale for reprocessing.

3.3.5 Gas-Cooled Fast Reactor*

This concept requires that the neutron spectrum not be degraded by a moderator so that the resonance capture of neutrons in ^{238}U is maximized. Consequently, there is no graphite moderator and the reactor core is similar to the LMFBR.

The major characteristics of the current reference concepts of a gas cooled fast reactor (GCFR) are based on minimizing development work. This results in the selection of the steam cycle for power conversion and of bundle type fuel elements containing oxide ceramic fuel pellets in steel cans. Concepts have been proposed by General Atomic (GA), the Gas Breeder Reactor Association (GBRA) , and Kraftwerk Union (KWU) . The development of the HTGR and the AGR provides the required

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*“Development, Status and Operational Features of the High Temperature Gas-Cooled Reactor”, Electric Power Research Institute, April 1976, EPRI NP-142

background for designing a nuclear steam supply system entirely housed in a pod type prestressed concrete reactor vessel (PCRV) in all three cases. The major difference from the LMFBR fuel element design is the need to withstand a substantially higher coolant pressure in the GCFR for adequate heat transfer. The current concepts are based, therefore, on equalizing the pressure between the interior of the individual fuel pin and the ambient coolant. Also artificial roughening of the fuel cladding is proposed to improve heat transfer.

Considerable effort has been made to develop a 300 MWe demonstration plant. Preliminary analyses for a 1500 MWe commercial plant have been performed and are summarized in the following paragraphs.

The reactor core consists of 271 hexagonal, vented fuel elements, 2.5 m long and 21.36 cm across the flats. There are 27 similar control elements. The core is arranged into four enrichment zones and a radial blanket.

The fuel elements are made up of 331 individual, .696 cm diameter fuel rods, fabricated from 316 stainless steel cladding with a wall thickness of about .037 cm. In this respect, these rods are similar to LMFBR fuel rods except that these employ surface roughening to enhance the heat transfer by a factor of two and to reduce clad surface temperature. The roughness results in a factor of three increase in friction losses and, thus, increases the coolant pumping requirements.

Each fuel rod contains mixed (U,Pu) oxide annular fuel pellets in the form of a right circular cylinder. The pellets have a center hole to prevent center line melting. The U/Pu fraction is such that the initial average fissile loading is approximately 18 percent. Each fuel rod has a depleted UO_2 axial blanket below and above the stack of core pellets and an individual alumina thermal shield and 3-inch activated carbon fission-product trap. The radial blanket fuel rods are similar to the core rods except that they are larger, 1.98 cm o.d., are not roughened, and contain only pellets of depleted UO_2 without a center hole. Alternatively, the radial blankets may be loaded with ThO_2 for the Production of ^{233}U. Because of the larger size, only 61 rods are contained in the 126 blanket fuel elements.

Refueling is carried out with the reactor shut down and at atmospheric pressure, with either air or helium in the vessel. The fuel transfer machine is placed in the plenum space beneath the core by raising it through a port in the bottom of the vessel. This machine has a vertical receptacle tube which can be positioned under any core or blanket element. Spent fuel elements are removed from the core by lowering them into the receptacle tube by means of reach rods which extend through nozzles in the top of the pressure vessel. The elements are then transferred to a spent fuel removal port in the bottom of the vessel, through which they are discharged and moved to a storage pit. Cooling of the fuel is provided during all stages of the fuel transfer.

3.3.6 Material Flows in the Gas Cooled Reactors

The fuel cycle requirements for the HTGR and AGR are given in Table 12. They are depicted schematically in Figures 33′ and 34 for both the start-up and equilibrium cycle. Data for the pebble bed reactor were not available, but they are expected to be similar to the HTGR cycle.

There are several options in the GCFR fuel cycle which depend upon the use of thorium or uranium blankets and the use of high or low burnup plutonium in the core. Table 13 contains fuel cycle information for the uranium blanket. This information is shown schematically in Figures 35 and 36 Figure 37 shows similar results if a thorium blanket is used with low burnup plutonium.

3.4 LIQUID METAL FAST BREEDER REACTOR*

The liquid metal fast breeder reactor (LMFBR) is the most widely used breeder reactor concept under development throughout the world today. This concept utilizes a liquid metal coolant, no moderator and is based on the uranium-plutonium fuel cycle. Plutonium from LWR’S is needed to provide initial fuel loading but after startup the LMFBR generates all the plutonium needed for subsequent refueling. Depleted uranium (the enrichment plant tails) is used as the fertile material. (There are some 200,000 tons of depleted uranium stored in the U.S.) ^{238}U is fissionable by fast neutrons and about 20% of the fissions in the LMFBR are from the ^{238}U.

The central core contains the fissile material and provides the main source of energy. The core is surrounded by radial and axial blankets of depleted uranium. The coolant is generally liquid sodium and both loop and pot concepts have been used. The loop concept is similar to the PWR coolant system and the pot concept utilizes a large reservoir of sodium which contains the heat exchanger, primary pumps and the reactor. Some believe, since the loop concept is more susceptible to a loss-of-coolant accident, that the pot concept is inherently safer.

The decision to pursue a LMFBR program has been made by every nation having a nuclear development program, with the exception of Canada. Figure 38 shows the various LMFBR’s which have been built throughout the world along with the

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* ‘Proposed Final Environmental Impact Statement for LMFBR Program, WASH 1534, December 1974.

planned higher power reactors. Major difficulties center around the steam generator and material problems. The Clinch River Breeder Reactor Plant, a 380 MWe demonstration facility, is the lead fast reactor in the U.S.

The fissile loading of the core at the beginning of the life cycle is essentially all ^{239}Pu and ^{241}Pu. Depleted uranium, containing from .2 to .3% ^{235}U, is utilized as the fertile material. The core undergoes burnups of 70,000-100,000 MWD/MT and the blankets will undergo from 5,000 to 20,000 MWD/MT. The axial blankets are generally part of the core fuel element and will not be reprocessed separately.

The fuel is generally UO_2-PuO_2 clad in stainless steel. The core for a 1,000 MWe plant will be about 1 meter high and 2.0 to 3.0 meters in diameter and contain about 200 to 300 fuel assemblies. The radial blanket will contain another 100 to 150 assemblies, and may contain two or more radial zones. The number of pins per assembly may range from 200 to 300 for the core, and from 50 to 100 in the blanket. The plutonium loading in the core will probably vary from 10 to 20% Pu over several regions. The breeding ratio will be around 1.2 to 1.3.

Refueling will occur once a year, replacing about one-half of the core and one-third of the radial blanket. The spent fuel will be stored on site for more than 30 days before shipment to a reprocessing facility. The reactor must be shut down for refueling but the fuel elements are withdrawn through the top of the reactor vessel. The spent fuel will be stored in hot cells or in sodium-cooled decay tanks on site.

3.4.1 Material Flow in the Liquid Metal Fast Breeder Reactor

Table 14 depicts the material flow in the nuclear fuel cycle for a “typical” 1,000 MWe LMFBR. This material flow is shown schematically in Figure 39. It is assumed that the depleted uranium is recovered from the waste tails of the enrichment plant, so that no mining or milling is required.

3.5 LIGHT WATER BREEDER REACTORS*

The light water breeder reactor (LWBR) relies extensively upon the LWR technology and has the major purpose of producing as much fissile material as it uses. The present concepts are based on the pressurized water reactor (PWR) and may be implemented by placing a different reactor core and control system in present PWR reactor plants. The reactor concept is being studied in the U.S. and a demonstration operation in the Shippingport reactor is scheduled for the late 1970’s.

The LWBR is a thermal reactor which would convert thorium to ^{233}U. Because the breeding (conversion) ratio is near 1, prebreeders are required to produce enough ^{233}U for the first few breeder cores. The prebreeder cores have different neutron requirements. The basic core design utilizes the seed-blanket concept, in which each fuel module contains fissile regions (seeds) and a fertile blanket. A low water content in the core is required to minimize neutron capture in the hydrogen and a water-to-metal ratio of about 1/10 that of the standard PWR has been proposed.

To minimize parasitic neutron capture in control rods, various designs utilize either fissile or fertile materials as the control element. Fertile blankets increase the size of the core but utilize the leakage neutrons. For a given PWR reactor vessel, a LWBR core could produce only about 70% of the power of the PWR. A prebreeder would not result in a significant derating of power.

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*Final Environmental Statement LWBR Program, ERDA 1541, June 1976

Burnup of the core will be about 20,000-50,000 MWD/MT. It is expected that the reactor will be refueled in a manner similar to the LWRS. The reactor will be shut down for a period of up to 30 days, and the pressure vessel head removed to retrieve a portion of the fuel.

3.5.1 Prebreeder

The prebreeder will be obtained by placing a new core in an existing PWR. For example, the Westinghouse PWR core module could be replaced by one containing UO_2 and ThO_2, rods.[6] About 190 modules will fill the 360 cm high, 360 cm diameter core. Each module will contain 240 UO_2 rods .75 cm in diameter and 100 ThO_2 rods 1.7 cm in diameter. The UO_2 is enriched to 10-13% ^{235}U.

3.5.2 Breeder

A larger reactor vessel is necessary for a breeder core to prevent derating an existing PWR vessel. The core will be about 450 cm in diameter and have an active height of 320 cm, with a reflector region about 20 cm on both the top and bottom and contain about 74 fuel modules. The $^{233}UO_2$-ThO_2 seed region of the fuel module will contain about 620 rods, .91 cm in diameter, and the blanket region about 445 rods, 1.7 cm in diameter.

3.5.3 Material Flow in Light Water Breeder Reactors

The material flow for both a prebreeder and a breeder are shown schematically in Figures 40 and 41 . Table 15 provides more detailed information on the fuel cycles. Since detailed data have not been published for a commercial size plant, the data given should be applied with caution.

3.6 MOLTEN SALT BREEDER REACTOR*

The molten salt breeder reactor (MSBR) concept is based on the use of a liquid fuel which circulates between the reactor vessel and a heat exchanger. The fuel is a complex salt ($LiF-BeF_2-ThF_4-UF_4$) in the ratio of 71.7-16-12-.3 mol percent. This chemically toxic salt melts around 500°C and serves as the fuel for the reactor. The salt flows through channels in a graphite moderator in the 6.6 meter diameter, 6.0 meter high reactor vessel. The coolant flow is about 4 m^3/sec and leaves the core at about 700°C. The heat is transferred to another molten salt in a heat exchanger. A fraction of the fuel (about 3 liters/minute) may be continuously removed for chemical removal of fission products. The entire fuel inventory is processed about every 10 days. The thorium, uranium and plutonium are not separated.

The major disadvantages of this reactor concept are related to the containment and continuous processing of very radioactive, toxic, and corrosive materials. Maintenance of the system must be a dominant design goal. Most of the processes involved are not utilized elsewhere in the nuclear industry, so the development costs will be high.

3.6.1 Material Flow in the Molten Salt Breeder Reactor

As in other reactor concepts, there are several options available. These options include the use of batch or continuous reprocessing, (this affects the breeding ratio) , the use of plutonium as an initial salt, the replacement of the graphite, etc. Figure 42 schematically illustrates the fissile and fertile material flow. Table 16 provides additional characteristics of the reactor.

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*"The Use of Thorium in Nuclear Power Reactors," USAEC WASH-1097, June 1969.

3.7 RESEARCH AND MARINE REACTORS*

In this section research reactors and the low-power reactors designed for propulsion of merchant ships are discussed. There are many types of research reactors operating throught the world -- See Appendix B2. As with power reactors, it is possible to categorize them in various ways -- by type of fuel, type of moderator, power level, type of coolant, etc. Some general characteristics can be determined without regard to detailed features. For example, Fig. 43 indicates the annual natural uranium fuel requirements of an enrichment plant serving various types of 10 MWt reactors. As expected, regardless of fuel enrichment, between 1 MT and 10 MT of fuel are required. The SWU requirements are given in Fig. 44 and Fig. 45 shows the annual uranium fuel requirements for the reactors. It is noted that for fully enriched uranium, about 10 kg of uranium per year are required. (Marine reactors (non Navy) are also shown in these figures) . Figure 46 summarizes the plutonium production, per MWt per year, for 75% operation. The graphite reactors produce about .9 gm ^{239}Pu per day, per MWt. For high burnup cores, the plutonium production rate may be high due to the assumption, in our analysis, that none of the plutonium is fissioned. In the operation of research reactors it is usual practice to replace a portion of the core and to shuffle the remaining fuel elements in order to achieve a higher uranium burnup.

3.7.1 Heavy Water Moderated Research Reactors

These reactors are generally tank-type reactors, with the heavy water acting both as moderator and coolant. A tank-type reactor has a closed, pressurized primary coolant system which transfers reactor heat to a light water, secondary coolant system. Fuel enrichments may vary from natural uranium to fully enriched. The natural uranium fuel elements have relatively low

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*"Power and Research Reactors in Member States," 1974 Edition International Atomic Energy Agency, Vienna, 1974.

burnup (600-1500 MWD/Ton) and are usually aluminum clad uranium metal rods. Low enriched fuel elements include higher burnup aluminum clad uranium - molybdenum alloy rods and clad UO_2 fuel. Highly enriched fuel is generally dispersion type, of which the Material Test Reactor, fuel element is a typical example. Straight place elements are also in use. The MTR fuel element has aluminum clad plates, with an aluminum-uranium dispersion fuel. The MTR fuel element may contain between 10-19 curved or straight fuel plates, with a variety of fuel enrichments (generally 20-93%) and fuel loadings (8 to 19 gm ^{235}U per plate). Due to its flexibility, the MTR fuel element is widely used in heavy water and light water research reactors.

Dispersion fuel reactors characteristically have high burnup. Twenty percent enriched MTR-fuel heavy water reactors have demonstrated 15,000-26,000 MWD/MT, while 90-93% enriched heavy water reactors have reached burnups well above 200,000-250,000 MWD/MT. The National Bureau of Standards is currently operating with fuel burnups as high as 50-55% of fissionable material, which corresponds to a burnup greater than 400,000 MWD/MT. Figure 49 illustrates the material flow for a 10 MWt heavy water moderator research reactor.

3.7.2 Graphite Moderated Research Reactors

These reactors are generally air cooled, graphite pile. Light water coolant may be required for high power levels. Fuel is generally natural uranium slugs clad in aluminum. Some graphite reactors, such as the Brookhaven Graphite Reactor, have operated with fully enriched uranium fuel. The natural uranium fuel has a burnup in the range of 600-2000 MWD/MT. Fuel loadings are very high on the order of tens or hundreds of metric tons. Typically, the BR-1 reactor, operating at 4 MWt, required approximately 24,000 kg of natural uranium.

High plutonium production rates are achieved with natural uranium fuel. These reactors are easily fueled on line. Figure 47 illustrates the fuel cycle feed/discharge characteristics of graphite moderated reactors.

3.7.3 Light Water Moderated Research Reactors

These reactors may be pool-type (generally low power, < 5 MWt), tank-type or pressurized water type (generally higher power, > 5 MWt). This is a very simple type of reactor, without the multitude of supporting systems and secondary coolant loops typical of the higher power, tank-type reactors and PWRs.

The fuel is enriched (10-93%) uranium in dispersion type elements. Amont the types in widespread use are the MTR type, previously discussed, and the TRIGA-type. TRIGA elements are usually 20% or 70% enriched; however, 93% enriched elements are contemplated for use in the latest and largest TRIGA core designs. The fuel is a uranium-zirconium hydride matrix, clad with aluminum (on the elements with the lowest ^{235}U loading) or stainless steel. Uranium loadings vary from 37 to 53 grams of 20% enriched uranium, to 136 grams of 70% enriched uranium in each fuel element. A TRIGA core consists of 85-100 fuel elements. Burnable poison is incorporated in the 70% enriched fuel elements, which contain 1.6 W/o Erbium to compensate for the high uranium loading. See Figure 48 for a 10 MWt research reactor fuel cycle.

3.7.4 Critical Facilities

The assembly-machine type of critical facility provides the designer the opportunity to investigate subcritical and critical reactor configurations with a wide variety of lattice arrangements, fuel loadings and fuel types. The flexibility of a plutonium critical facility is well illustrated by the Zero Power Plutonium Reactor (ZPPR) which can accommodate fourteen fuel types, including plates of unclad uranium metal, clad Pu-A1 and clad U-Pu-Mo alloys and rods of clad (U-Pu)0_2 and U0_2. A wide range of enrichments of both Pu and U are utilized.

An example of a ZPPR core is a 6000 liter, 2-zone core, measuring approximately 120 cm in height, with an inner zone diameter of 180 cm and an outer zone diameter of 250 cm. The fuel is Pu-U-Mo, with an approximate critical mass of 2260 Kg, including 2083 Kg ^{239}Pu, 144 Kg ^{241}Pu and 33 Kg ^{235}U.

Critical facilities are generally characterized by very low power levels, on the order of hundreds of watts, to a few kilowatts. As a result, there is negligible fuel burnup or fission product generation. In addition, there is negligible plutonium buildup in uranium fueled cores and fuel loading is generally accomplished by manually loading clad plutonium or uranium fuel elements. Because of the flexibility required in performing critical experiments, several researchers will have access to the fuel.

3.7.5 Marine Reactors

To date, marine reactors (non-Navy) have been characterized by relatively low enrichment (4-6.5%), high burnup cores, using U0_2 type of fuel elements similar to those used in commercial LWRS. The more recent designs, typified by the B&W CNSG design, provide for extensive burnable poison zoning in order to achieve high fuel burnup. The average CNSG core burnup is approximately 36,000 MWD/MT. This is on the same order of magnitude as the current generation of commercial PWR power reactors.

Current marine reactors are PWRs with stainless-steel clad fuel. Their design may differ significantly from that of land based PWRs.

The marine reactor fuel cycle is generally designed to provide complete core replacement after a 3 to 4 year service life. Because of this, the spent fuel elements are characterized by high fission product inventory, high ^{235}U burnup and high plutonium buildup. Due to the long residence time in the core, there is substantial burnup and transmutation of ^{239}Pu. At the end-of-life, the 313 MWt B&W CNSG reactor contains a total plutonium loading of 103 Kg, including 85.5 Kg of fissile plutonium. Operating Marine reactors are considerably smaller than the current CNSG design. The U.S. Savannah reactor was rated at 70 MWt and the German Ship Otto Hahn operates with a 38 MWt reactor plant.

3.8 ADVANCED CONCEPTS

In this section, several specific topics are presented. These include the use of the tandem fuel cycle, fissile material production in fusion reactors and electric breeding.

3.8.1 Tandem Fuel Cycle

A variation on the basic light water reactor fuel cycle concept is a tandem fuel cycle. This fuel cycle is based on the use of nuclear fuel in LWR’s and, after mechanical refabrication, using it” as fuel first in LWR's and, after mechanical refab- fuel cycle option does not involve the chemical reprocessing of spent nuclear fuel from LWR’s. Most of the useful fissile material content of the LWR fuel is utilized without separating the uranium and plutonium from the radioactive fuel elements.

Because deuterium is a more efficient neutron moderator than light water, HWRs can utilize fuel with a lower fissile material content. Studies have indicated that PWR spent fuel could generate an additional 30% to 45% more electricity if the spent fuel is placed in a HWR. These analyses were based on a 33,000 MWD/MT PWR fuel burnup, and indicated that an additional 10,000 MWD/MTU burnup is achievable in a HWR. (Current experience with LWR fuel indicates a burnup of only about 25,000 MWD/MT, indicating that more than 10,000 MWD/MT may be possible with the HWR.) This additional energy is roughly equivalent to the energy which would result from the reprocessing of spent PWR fuel and the recycle of both recovered uranium and plutonium. Table 17 summarizes the changes in fuel composition during the tandem fuel cycle.

TABLE 17
FUEL COMPOSITION

	Fuel Charged (K/MT)	LWR Discharge (33 ,000 MWd/MT)	HWR Discharge (45 ,000 MWd/MT)
U-235	32 (,3 . 2% U-235)	7.2 (@.72% U-235)	2.8 (~O. 28%)
Pu Total	0	9.1	8.7
Pu 239 + 241	0	6.4	4.8

It is interesting to note that the final ^{235}U enrichment of HWR fuel is at or below the depleted uranium level from enrichment facilities and that the total plutonium contained by the HWR spent fuel is almost as great as that in the PWR spent fuel but with a reduction in the thermally fissile content. The significance of these observations are as follows:

- The utilization of uranium resources by the tandem fuel cycle is approximately equal to that of the light water reactor with recycle.

- Because of the depleted nature of the resultant uranium and the low fissile content of the plutonium, the spent HWR fuel is probably economically unsuited for reprocessing as a source of fissile material for the LWR fuel cycle.
- The spent HWR fuel represents a source of plutonium which could be useful in future LMFBR development. The spent HWR fuel could be stored as spent fuel which would discourage unauthorized use.

The commercialization of the tandem fuel cycle requires the resolution of several technical problems, detailed analysis of economic potentials, and formulation of a new set of regulations and regulatory procedures. All of these issues are inter-related and must be resolved.

The first technical step is the verification of the preliminary reactor calculations both by additional calculations and actual reactor demonstration. The major technical difficulty is the mechanical refabrication of LWR spent fuel so that it can be utilized by a HWR. The LWR fuel has a different configuration than current HWR fuel, and the LWR spent fuel has a high temperature history, variations in ^{235}U and fissile plutonium content, and brittle fused chunks of fuel.

There are several approaches to the conversion of LWR fuel for use in HWRS. Some are listed below:

1. Mechanical disassembly of the LWR fuel with a subsequent rejacketing and swaging into a HWR configuration.
2. Mechanical disassembly of the LWR fuel followed by grinding of the LWR fuel with subsequent reformation and fabrication in a suitable geometry.
3. Modification of HWR designs to utilize the LWR fuel with minor modifications. This entails recladding the fuel, as a minimum, and possible power derating to allow for nonuniformity of fissile content.

Problems associated with irregularities in fuels causing low thermal conductivity, non-uniform power generation and poor bonds between fuel and cladding must be addressed in any utilization” scheme.

The fuel from three or four 1,000 MWe LWRs would supply fuel for one 1,000 MWe HWR. Economic considerations include the capital cost of constructing a significant number of HWRs to accept the fuel from LWRs (HWRs are about 10-20% more expensive than LWRs) , and the capital cost of facilities required to refabricate LWR fuel to HWR as compared to the LWR fuel cycle capital costs. Finally, the operating costs of safeguards and security must be considered. These will most likely be less than for a LWR recycle. The regulatory problems of such a fuel cycle center around the licensability by NRC. The basic Canadian HWR is not currently licensed in the U.S. , although it is proven and used in several other countries. The problems of licensing, considering the fact that the fuel will have a unique and variable history, may increase the cost of reactor construction.

3.8.2 Fission-Fusion Systems

One of the major efforts now underway to develop long term energy sources is in the area of controlled fusion. At present, the major objective of the fusion program is the development of a commercial electric power reactor. The potential also exists for using controlled fusion to produce fissile material although this is currently being pursued at a low level in this country. Of the several possible reactions for a fusion reactor, the most promising is that of the two hydrogen isotopes, deuterium and tritium (the D-T reaction). This reaction produces a neutron and a helium nucleus, and releases 17.6 million electron volts of energy- The kinetic energy of the neutron accounts for about 75% of the energy releases by the reaction.

In a fusion device using this reaction, the neutrons would have two functions. First, they would provide a source of heat to generate steam and second, a fraction of the neutrons would be used to produce tritium, to fuel the reactor, by reacting with lithium. The latter occurs in an assembly, called a blanket, which surrounds the chamber in which the fusion reactions take place. The lithium moves through the blanket as a liquid metal. Only a small fraction of the lithium is converted to tritium by reactions with the neutrons and the remainder is heated upon absorbing the neutron's kinetic energy. This heated lithium is extracted from the blanket and passes through a heat exchanger where steam is produced.

As indicated, however, there are other ways to use the energy and neutrons produced by the fusion reaction. Because it is a source of fast neutrons, the possibility exists of producing fissile material to be used in a fission reactor. This could be accomplished by placing fertile material in the blanket which would absorb a fraction of the fusion neutrons.

There have been several studies of fissile material production in potential fusion reactors. Three candidate systems have emerged. The first produces only fissile material and no energy is extracted to produce electricity. The second is a hybrid system that produces both fissile material and electric energy from the fusion reaction. The third is also a hybrid system but the energy production results from fission reactions in the blanket and from the fusion reactions. In this case a portion of the neutrons from the fusion reactions are used to produce fissile material which is in a critical assembly, while the remaining are used to produce tritium and heat the lithium. The scientific conditions that must be achieved so that the system has energy gain are theoretically less stringent than needed for a fusion reactor by itself because of the potential energy yield of the fissile material. For a given sized device, however, the total energy yield would be less than if one could achieve conditions needed for a fusion power reactor so if the latter works, it should be less expensive. The conditions required for successful operations appear to be less stringent for fission-fusion systems, however, so they may become available sooner.

Of course, the fissile material produced in a hybrid system can also be used for weapons, Therefore, fusion-fission devices would be subject to problems of proliferation and safeguards considerably more severe than would be the case for a fusion system alone. It is possible that the latter could be modified after construction to produce fissile material but this would involve placing fertile material in the blanket after it was constructed. In all probability this would mean an entirely new blanket assembly since it is unlikely that the original could be modified. The requirements of the blanket assembly in terms of structure and neutron reactions with the lithium for a given reactor means that it would have to be redesigned if fertile material were also to be included in order for the fusion reactor to continue operation. Since the blanket assembly will be a large cost item for any potential reactor and since it will not be easily accessed, it is probable that there would be easier ways to obtain fertile material than to either modify an existing fusion reactor or build a hybrid system.

A fertile blanket may contain natural or depleted uranium or thorium. Due to the rapid buildup of fissile material, the blanket lifetime is limited by the power density resulting from the fissioning of the bred material. Calculations indicate that about <u>1.5 kg</u> of fissile material are produced, per metric ton of fertilemetal, per <u>100 days</u> in a blanket. A 600 MWe fusion reactor might utilize a blanket containing 100 tons of uranium, so nearly

500 kg of Pu could be produced per year. Due to the high energy neutrons and relatively low burnup, the plutonium would contain greater than 95% fissile isotopes.

Experiments to test the design analyses of fertile blankets are believed to be some of the goals of the Russian T-20 fusion test reactor. The blanket design is probably one of the least difficult portions of a fusion-fission system and a fertile blanket could be incorporated into a fusion reactor without a major development effort. Blanket refueling and heat removal are two major potential problems with this system.

3.8.3 Electric Breeders

When high energy protons strike a high Z target, such as Tangsten, many neutrons result. These neutrons could be used in a depleted uranium or thorium assembly to produce fissile material. Alternatively these neutrons could be directed into a reactor containing spent fuel and convert some of the remaining fertile material into fissile material. This concept may be viewed as a re-enrichment process and if metallurgical issues can be resolved, the fuel could reenter a fission reactor without reprocessing. Thus, an accelerator could be used to reenrich spent fuel, burn actinides in the spent fuel, or convert fertile to fissile material. For example, ^{233}U could be produced form thorium for a denatured LWR fuel cycle On the other had, the device could also be used to produce fissile material for weapons. Hence the technology presents the same proliferations dichotomy as advanced enrichment techniques.

This concept has been pursued more vigorously by the Canadians than by other countries. Technologies utilized in producing neutron beams in facilities such as the Los Alamos Meson Physics Facility can be used to investigate this concept in the U.S. An 800 MeV proton incident on depleted uranium will produce about 25 neutrons with an energy spectrum not much different from that due to fission. About 50 MeV of energy will be depposited in the uranium target, per proton, and this energy could be reconverted to electricity through a steam cycle turbine. A 30 milliamp proton beam produces about 100 kg of plutonium per year. The heat removal for the high power density targets and the improvements on the current maximum beam currents of about 1 ma are two major problems inherent to this concept.

In the United States there has been recent interest in electric breeding utilizing 500 MeV deuterons incident on lithium targets surrounded by uranium or thorium. For a 375 ma beam of 500 MeV deuterons about 1000 kg of plutoniun can be produced per year at a cost of approximately $100/gram.

TABLE 6

REPRESENTATIVE PWR AND BWR CHARACTERISTICS

Reactor Characterization	PWR	BWR 1
Date of Information	1974	1970
Representative Reactor		
Reactor Thermal Power (MWt)	3250	3293
Net Electrical Power (MWe)	1050	1053
Net Plant Efficiency (%)	32.3	32.3
Average Burnup (MWd/MTM)		
Initial	15,000	19,000
Equilibrium	25,000	25,000
Core Inventory (MTM)	80.12	148.50
Core Height (m)	3.65	3.66
Neutron Flux (n/cm^{L}/see)		
Peak Thermal	7.8x10^{13}	3x10^{13}
Average Thermal	2.6x10^{13}	7.8x10^{13}
Peak Fast	NA	NA
Average Fast	3x10^{14}	1x10^{14}
Fuel Description		
Number of Assemblies (core/blanket)	193/ --	764/ --
Dimensions of Assembly (hxd)m	4. 06x0. 215	4. 47x0. 138
Number of Rods per Assembly (core/blanket)	204/ --	49/--
Chemical Composition (core/blanket)	UO_2/--	uo_2/ --
Cladding Material/Thickness (cm)	Zr- 4/ 0.062	Zr-2/O. 08
Enrichment (%) (Initial/Equilibrium)	(2. 8/3. 3) U^{235}	(2. 25/2 .60) U^{235}
Control Material	Ag-In-Cd rods B in solution	B_4C $H_2$0 flow regulations
Control Rods/Assembly	20	1/4 cruciform rod 1/2 curtain rod
Refueling Interval	1 year	1 year
Fraction Reload per Cycle	1/3 core batch	1/4 core batch
Conversion Ratio (Initial/Equilibrium)	.5/ .6	0. 6/0.6

TABLE 7

FUEL CYCLE REQUIREMENTS (100 MWe, 75% LOAD FACTOR)*

REACTOR CHARACTERIZATIONS	PWR1-U Fueled		PWR2-Pu nat U Fuel		PWR3-U Fueled	
	Initial Load	Equilibrium Cycle	Initial Load	Equilibrium Cycle	Initial Load	Equilibrium Cycle
Mining (10^3 MT)	61,672	19,860	13,916	3,837	66,359	23,346
Material Removed						
Uranium 0.2% concentration	208.14	67.029	46.966	12.950	223.961	78.792
Thorium 0.2% concentration	0	0	0	0	0	0
Milling (MT U_3O_8)	466.355	150.184	105.230	29.015	501.083	176.538
(MT Th O2)	0	0	0	0	0	0
Conversion (=Enrichment Feed) (MT UF_6)	581.947	223,012	0	0	621.181	272.059
Enrichment						
SWU (MT)	301.52	125.15			322.36	163.31
Tails (MTU at 0.2%	316.45	125.011			339.55	146.61
Enriched Product (MTU)	77.07	25.78			83.86	37.35
Assay (% U-235	2.8	3.3			2.78	3.4
Feed nat U (MTM	393.50	126.722			423.41	148.96
Fuel Fabrication						
Input (MT)	77.07	25.78			83.86	37.35
Output (MT)	76.31	25.52			83.03	36.62
No. Assemblies/year	184	61			200	88
Composition	UO_2 enr.	UO_2 enr.			UO_2 enr.	UO_2 enr.
Weight of Assembly MTM	0.415	0.415			0.415	0.415
Used in Reactor	core	core			core	core
Reactor Load in Quantity (MTM) U/Pu/Th	76.31/0/0	25.52/0/0	87.912/2.598/0	24.24/1.281/0	83.03/0/0	36.62/0/0
Isotopics (%)						
U-233	0	0	0	0	0	0
U-234	0.03	°.0352	0	0	°.035	°.035
U-235	2.80	3.3	0.71	0.71	2.78	3.4
U-236	0	0	0	0	0	0
U-238	97.17	96.66	99.29	99.29	97.18	96.56
Pu-239	0	0	67.7	56.4	0	0
Pu-240	0	0	18.8	24.0	0	0
Pu-241	0	0	10.0	11.24	0	0
Pu-242	0	0	2.51	3.92	0	0

TABLE 7 (Cont)

FUEL CYCLE REQUIREMENTS (1000 MWe, 75% LOAD FACTOR *

REACTOR CHARACTERIZATIONS	PWR1-U Fueled		PWR2-Pu nat U Fuel		PWR3-U Fueled	
	Initial Load	Equilibrium Cycle	Initial Load	Equilibrium Cycle	Initial Load	Equilibrium Cycle
Reactor Discharge						
Quantity (MTM) U/Pu/Th		24 39/0.229/0		23.67/0.833/0		35.46/0.266/0
Isotopics						
U-233		0		0		0
U-234		0.012		0.007		0.019
U-235		0.83		0.327		1.44
U-236		0.44		0.079		0.30
U-238		98.72		99.59		98.24
Pu-239		58.4		38.68		67.7
Pu-240		24.0		27.53		18.8
Pu-241		11.2		18.08		10.0
Pu-242		3.92		11.53		2.51
Th		0		0		0
Fission Products (MTM)		0.891		0.891		0.891
Net Plant Thermal Efficiency (%)	32.5	32.5	32.5	32.5	32.5	32.5
Burnup (Avg. MWd/MTM)	14,040	33,000	14,040	33,000	14,700	23,000
Spent Fuel Storage						
Decay Heat (W/kg)		28		24		26
Days Holdup		150		150		150
Activity at Discharge From Pool (10^6 Curies F.P.)		113		116		79
Fuel Reprocessing						
Input (MT)		25.52		25.52		36.62
Recycle Uranium (MT)						
U-233		0		0		0
U-235		0.200		0.077		0.506
U-238		23.833		23.34		34.488
Plutonium Production (MT)						
Pu-239		0.133		0.356		0.178
Pu-241		0.026		0.166		0.026

TABLE 7 (Cont)

FUEL CYCLE REQUIREMENTS (1000 MWe, 75% LOAD FACTOR *

REACTOR CHARACTERIZATIONS	PWR1-U Fueled		PWR2-P nat U Fuel		PWR3-U Fueled	
	Initial Load	Equilibrium Cycle	Initial Load	Equilibrium Cycle	Initial Load	Equilibrium Cycle
Mixed Oxide Fuel Fabrication						
Input (MT) U/Pu		0	88.791/2.624	24.482/1.294		0
Output (MT)		0	90.51	25.52		0
No. Assemblies/year			201	57		
Composition		0	nat.UO_2+PuO_2(2.85%	nat.UO_2+PuO_2(5.02%)		0
Weight of Assembly (MTM)			0.450	0.450		
Used in Reactor			core	core		
Waste Disposal						
High Level Wastes						
(HLW+Cladding hulls)						
Volume (ft^3)		115		115		115
Activity (10^6 Curies)		18.5		15.8		18.5
Activity of Pu (10^3 Curies)		20.5		189.0		20.5
Canisters (a 3.5 ft^3)		33		33		33
Low Level Wastes						
Volume (ft^3)		8,600-16,000		18,600-46,000		8,600-16,000
55 Gallon Drums		640-1,660		2,040-5,860		640-1,660
Burial or Repository Space ft^3)		900-2,200		2,900-8,200		900-2,200

*Note: All reactors are assumed to have uranium recycled. This is not a necessary condition only an example of possible fuel schemes

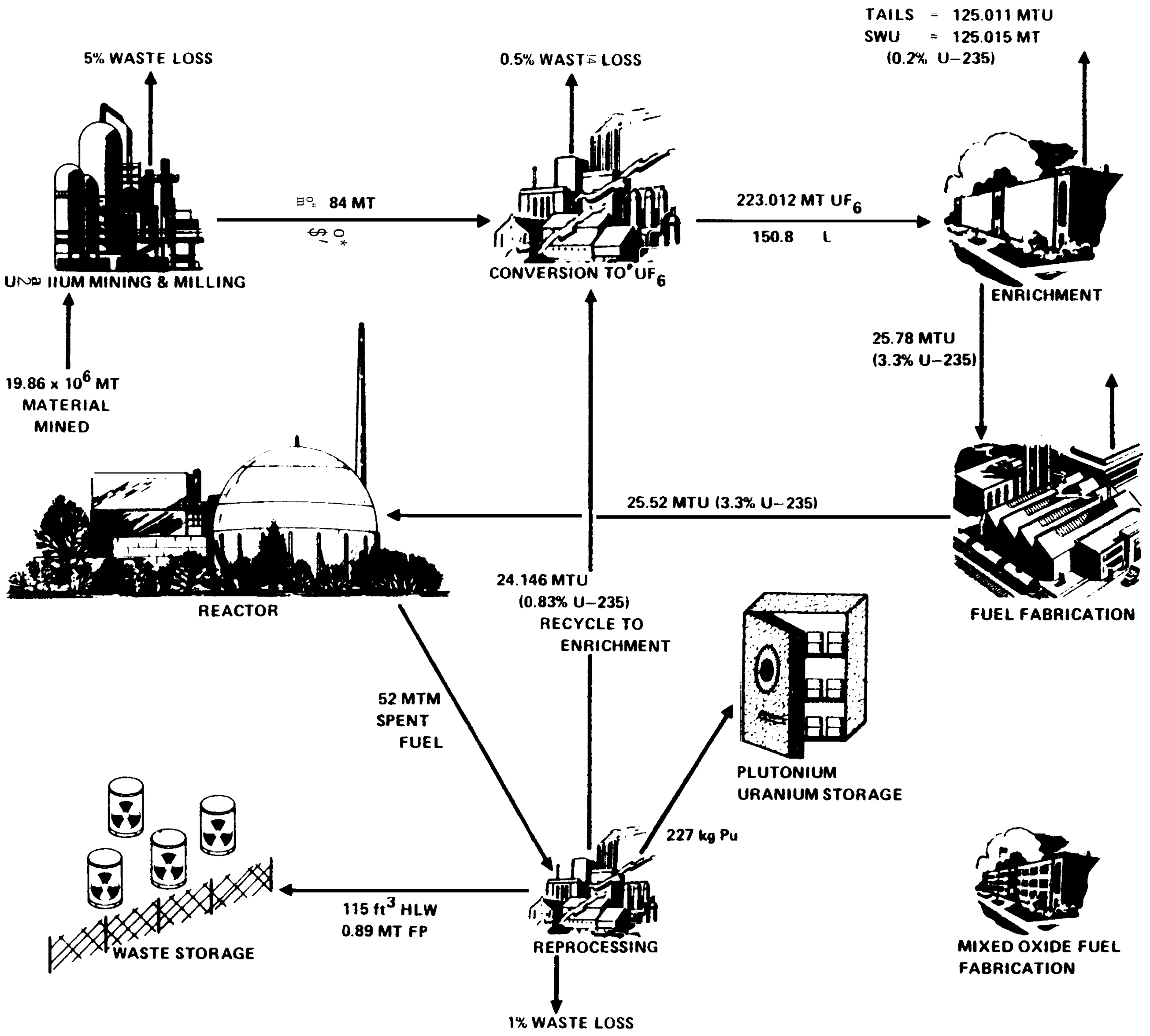


Fig. 24. PWR 1 Equilibrium Cycle (U Recycled)

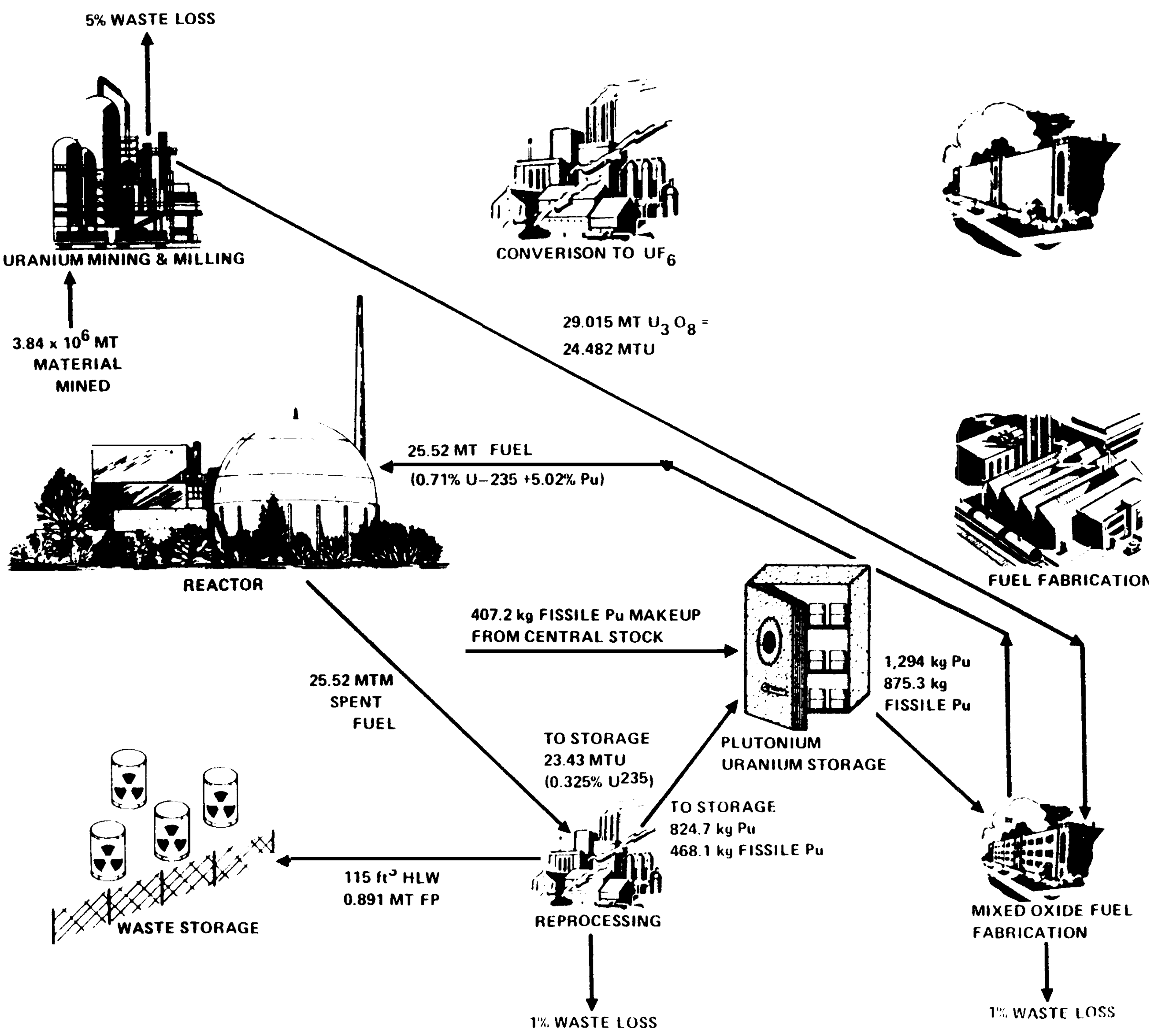


Fig. 25. PWR 2 Equilibrium Cycle (Pu Recycle)

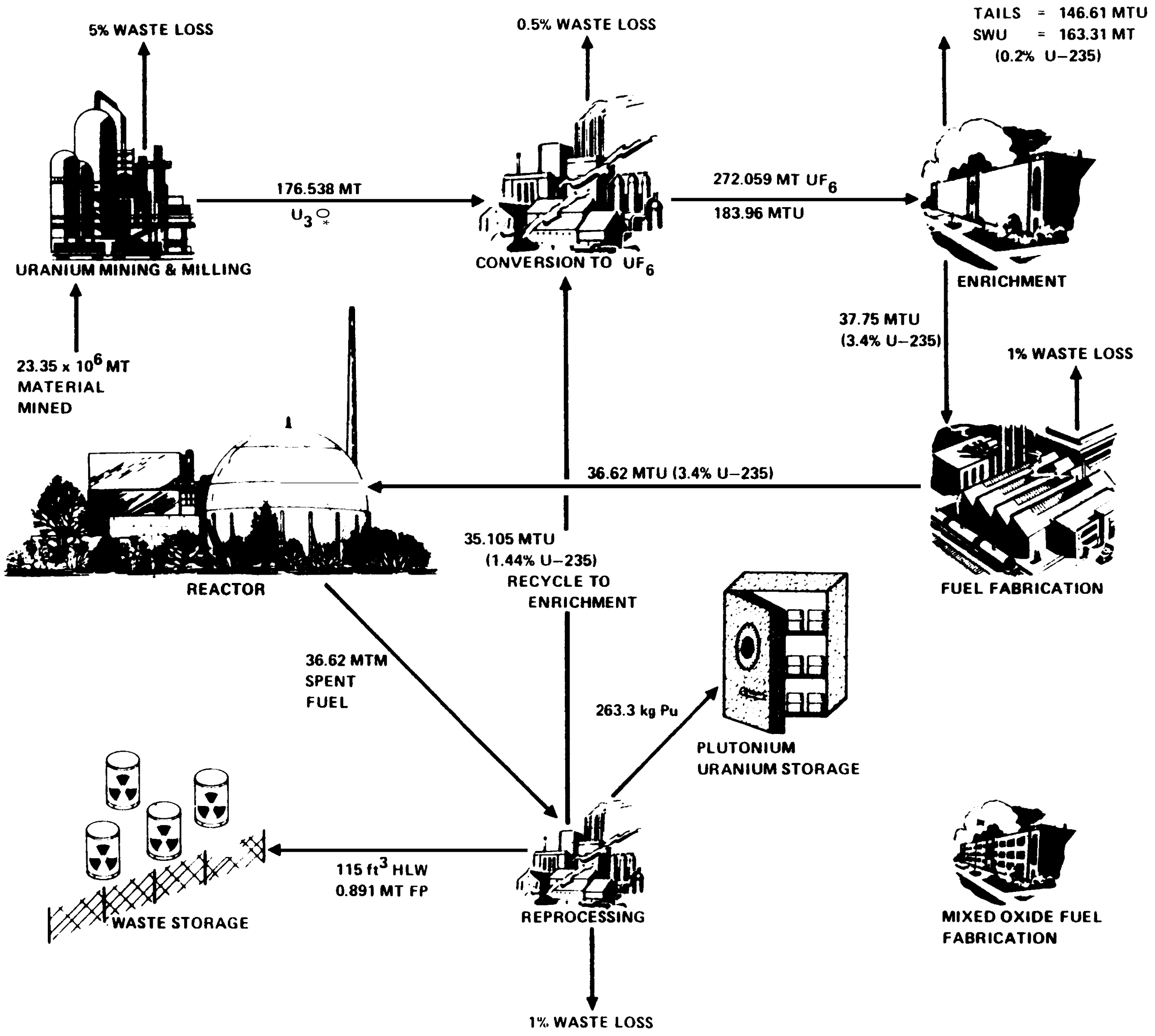


Fig. 26. PWR – Equilibrium Cycle Recycled)

TABLE U3

FUEL CYCLE REQUIREMENTS (1000 MWe 75% LOAD FACTOR)

REACTOR CHARACTERIZATIONS	BWR1-U Fueled		BWR2-60% U Fueled and 40% nat.U+Pu Fueled	
	Initial Load	Equilibrium Cycle	Initial Load	Equilibrium Cycle
Mining (10^3 MT)				
Material Removed	89,564	18,432	20,213	12,376
Uranium 0.2% concentration	302.277	67.208	68.232	41.770
Thorium 0.2% concentration	0	0	0	0
Milling (MT U_3O_8)	672.276	139.381	152.876	93.589
(MT Th O_2)	0	0	0	0
Conversion (=Enrichment Feed)	845.150	219.217	0	143.970
(MT UF_6)				
Enrichment				
SWU (MT)	307.03	109.84		70.29
Tails (MTU at 0.2%)	429.03	115.390		77.24
Enriched Product (MTU)	142.44	32.84		19.513
Assay (% U-235)	2.25	2.61		2.61
Feed nat U (MTM)	571.47	117.607		66.55
Fuel Fabrication				
Input (MT)	142.44	32.84		19.513
Output (MT)	141.03	32.2		19.32
No. Assemblies/year	725	166		102
Composition	UO_2 enr.	UO_2 enr.		UO_2 enr.
Weight of Assembly (MTM)	0.194	0.194		0.185
Used in Reactor	core	core		60% core
Reactor Load in				
Quantity (MTM) U/Pu/Th	141.03/0/0	32.3/0/0	127.704/3.437/0	31.615/0.585/0
Isotopics (%)				
U-233	0	0	0	0
U-234	0.03	0.235	0	0.147
U-235	2.25	2.61	0.71	1.873
U-236	0	0.065	0.	0.040
U-238	97.72	97.09	99.29	97.94
Pu-239	0	0	67.7	42.05
Pu-240	0	0	18.8	27.35
Pu-241	0	0	10.0	15.35
Pu-242	0	0	2.51	11.83

TABLE 8- (Cont)

FUEL CYCLE REQUIREMENTS (1000 MWe. 75% LOAD FACTOR)

REACTOR CHARACTERIZATIONS	BWR1-U Fueled		BWR2-60% U Fueled and 40% nat.U+Pu Fueled	
	Initial Load	Equilibrium Cycle	Initial Load	Equilibrium Cycle
Reactor Discharge				
Quantity (MTM) U/Pu/Th		[illegible].025/0.276/0		[illegible]606/0.574/0
Isotopics				
U-233		0		0
U-234		0.121		0.076
U-235		0.822		0.631
U-236		0.425		0.292
U-238		98.631		99.00
Pu-239		60.55		43.58
Pu-240		23.93		25.97
Pu-241		10.66		15.88
Pu-242		3.25		1.12
Th		0		0
Fission Products (MTM)		0.891		0.891
Net Plant Efficiency	32.5	32.5	32.5	32.5
Burnup (Avg. MWd/MTM)	19,250	26,160	19,250	26,160
Spent Fuel Storage				
Decay Heat (W/kg		16		17
Days Holdup		150		150
Activity at Discharge From Pool (10^6 Curies F.P.)		89		92
Fuel Reprocessing				
Input (MT)		32.2		32.2
Recycle Uranium (MT)				
U-233		0		0
U-235		0.252		0.191
U-238		30.295		29.997
Plutonium Production (MT)				
Pu-239		0.165		0.248
Pu-241		0.029		0.090

TABLE 8 (Cont)

FUEL CYCLE REQUIREMENTS (1000 MWe. 75% LOAD FACTOR)

REACTOR CHARACTERIZATIONS	BWR1-U Fueled		BWR2-60% U Fueled 40% nat.U+Pu Fueled	
	Initial Load	Equilibrium Cycle	Initial Load	Equilibrium Cycle
Mixed Oxide Fuel Fabrication				
Input (MT) U/Pu		0	128.996/3.472	12.418/0.591
Output (MT)		0	131/141	12.88
No. Assemblies/year		0	709	72
Composition		-	nat.UO_2+PuO_2 2.62%)	nat.UO_2+PuO_2(4.54%)
Weight of Assembly (MTM)			0.185	0.185
Used in Reactor			100% core	40% core
Waste Disposal				
High Level Wastes				
(HLW+Cladding hulls)				
Volume (ft^3)		115		115
Activity (10^6 Curies)		18.5		15.8
Activity of Pu (10^3 Curies)		20.5		189.0
Canisters (a 3.5 ft^3)		33		33
Low Level Wastes				
Volume (ft^3)		8,600-16,000		18,600-46,000
55 Gallon Drums		640-1,660		2,040-5,860
Burial or Repository Space ft^3)		900-2,200		2,900-8,200

TABLE 9
HEAVY WATER REACTORS

Reactor Characterization Date of Information Representative Reactor	HWR 1973 CANDU-600 Gentilly 2	HW-BLW 1972 CANDU-BLW Gentilly	SGHWR 1967 UKAEA Design	HWBLW 1967 WASH-1086	HWOCR 1968 NUC-WASH 1083
Reactor Thermal Power (MWt)	600				
Net Electrical Power (MWe)		250	625	965	1118
Net Plant Efficiency (%)	[illegible]	30.0	32.9	29.8	34.2
Average Burnup /MTM					
Initial	NA	NA	12700	NA	NA
Equilibrium	7500	7000	20700	8000	8000
Core Inventory (MTM)	85.82	65	100.1	[illegible]	[illegible]
Core Height (m)	5.94	5.00	4.68	7.62	5.42
Fuel Description					
Number of Assemblies (core/blanket)	4560/-- 12 assemblies/channel	308	532	3440 5 assemblies/channel	assemblies/channel
Dimension of Assembly (hxd)m	.495x.102	.50x.102	3.80x.13	1.52x.102	1.12x.094
Number of Rods per Assembly (core/blanket)	37/--	18/--	36/--	19/--	19/--
Chemical Composition (core/blanket)	UO_2/--	UO_2/--	UO_2/--	UO_2/--	UC/--
Cladding Material/ Thickness (cm)	Zr-4 .0419	Zr-4 .059	Zr-4 NA	Zr-4 .076	SAP .076
Enrichment (%) (Initial/Equilibrium)	Natural Uranium	Natural Uranium	(2.139 avg./2.105 avg.)	Natural Uranium	Natural Uranium
Control Material Control Rods/Assembly	21 SS adjuster rods 4 cadmium absorber rods 28 cadmium-SS rods gadolinium in solution	7 cadmium rods 16 booster rods flow regulation	boric acid	90 absorber rods 36 booster rods flow regulation	158 B_4C SS shutdown rods 32 B_4C SS rod clusters
Refueling Interval	Continuous	Continuous	1/2 year	Continuous	Continuous
Fraction Reload per Cycle	.96 core/yr at 82% C.F.	[illegible] core/yr at 80% C.F.	.086	0.5 core/year	.49 at 80% C.F.
Conversion Ratio (Initial/Equilibrium)	(NA/0.6)	(NA/ NA)	.56/NA)	NA/.78)	(NA/0.70)

TABLE 10

REACTOR CHARACTERIZATIONS

	CANDU-PHW		HW-BLW		HWOCR(nat UC)	
	Initial Load	Equilibrium Cycle	Initial Load	Equilibrium Cycle	Initial Load	Equilibrium Cycle
Mining (10^3 MT)						
Material Removed	22530	19430	39600	18260	33740	15700
Uranium 0.2% concentration	76.05	65.58	133.27	61.63	113.9	62.0
Thorium 0.2% concentration	0	0		0	0	0
Milling (MT U_3O_8)	170	147	300	138.1	255.1	118.7
($Th(NO_3)_4$	0	0	0	0	0	0
Conversion (=Enrichment Feed) (MT UF_6)	0	0	0	0	0	0
Enrichment						
SWU (MT)	0	0	0	0	0	0
Tails (MTU at ? %)	0	0	0	0	0	0
Enriched Product (MTU)	0	0	0	0	0	0
Assay (% U-235)	0	0	0	0	0	0
Feed nat U (MTM)	0	0	0	0	0	0
Fuel Fabrication						
Input (MT)	144.5 U	124.6 U	254.0U	117.1U	216.4U	100.7 U
Output (MT)	143.0 U	123.3 U	252.0U	115.9U	214.3U	99.68 U
No. Assemblies/year						
Composition	UO_2	UO_2	UO_2	UO_2	UC	UC
Weight of Assembly (MTM) Used in Reactor	.019	.019	.071	.071	.052	.052
Reactor Load in						
Quantity (U/Pu/Th) (MTM)	143.0/-/-	123.31/-/-	252.0/-/-	115.9/-/-	214.3/-/-	99.68/-/-
Isotopics (%)						
U-233	0	0	0	0	0	0
U-234	0	0	0	0	0	0
U-235	.711	.711	.711	.711	.711	.711
U-238	0	0	0	0	0	0
U-239	99.29	99.29	99.29	99.29	99.29	99.29
Pu-239	0	0	0	0	0	0
Pu-240	0	0	0	0	0	0
Pu-241	0	0	0	0	0	0
Pu-242	0	0	0	0	0	0

TABLE o (Cont)

REACTOR CHARACTERIZATIONS	CANDU-PHW		HW-BLW		HWOCR (nat UC)	
	Initial Load	Equilibrium Cycle	Initial Load	Equilibrium Cycle	Initial Load	Equilibrium Cycle
Reactor Discharge						
Quantity (U/Pu/Th)(MTM)		121.8/.41/--		114.5/.421.--		98.46/.367/--
Isotopics						
U-233						
U-234						
U-235		.22		.247		.208
U-236				.078		.0812
U-128		99.78		99.7		99.7
Pu-239		67.0		56.1		59.9
Pu-240		26.0		29.5		28.9
Pu-241		4.7		11.2		8.72
Pu-242		1.6		3.22		2.46
Th		0.0		0.0		0.0
Fission Products (MT)		973		.971		.842
Net Plant Efficiency (%)		29.6	29.8	29.8	34.2	.842
Burnup (Avg. MWd/MTM)		7500	NA	8000	8030	8030
Spent Fuel Storage		--	--	--	--	--
Decay Heat (W/kg)						
Days Holdup		indefinite		indefinite		indefinite
Activity at Discharge From Pool (10^6 Curies F.P.)		--		--		--
Fuel Reprocessing (Possible)						
Input (MT)		122.5		115.3		99.68
Recycle Uranium (MT)						
U-233		--		--		--
U-235		.268		.252		.205
U-238		121.5		113.0		97.27
Fissile Plutonium Production (MT)						
Pu-239		.280		.234		.220
Pu-241		.020		.047		.032

TABLE 10 (Cont)

REACTOR CHARACTERIZATIONS	CANDU-PHW		HW-BLW		HWOCR (nat UC)	
	Initial	Equilibrium	Initial	Equilibrium	Initial	Equilibrium
Mixed Oxide Fuel Fabrication						
Input (MT) U/Pu						
Output (MT)						
No. Assemblies/year	NO MIXED OXIDE FABRICATION					
Composition						
Weight of Assembly (MTM)						
Used in Reactor						
Waste Disposal						
High Level Wastes						
(HLW+Cladding hulls)						
Volume (ft^3)						
Activity (10^6 Curies)						
Activity of Pu (10^3 Curies)						
Canisters (a 3.5 ft^3)						
Low Level Wastes						
Volume (ft^3)						
55 Gallon Drums						
Burial or Repository Space (ft^3)						

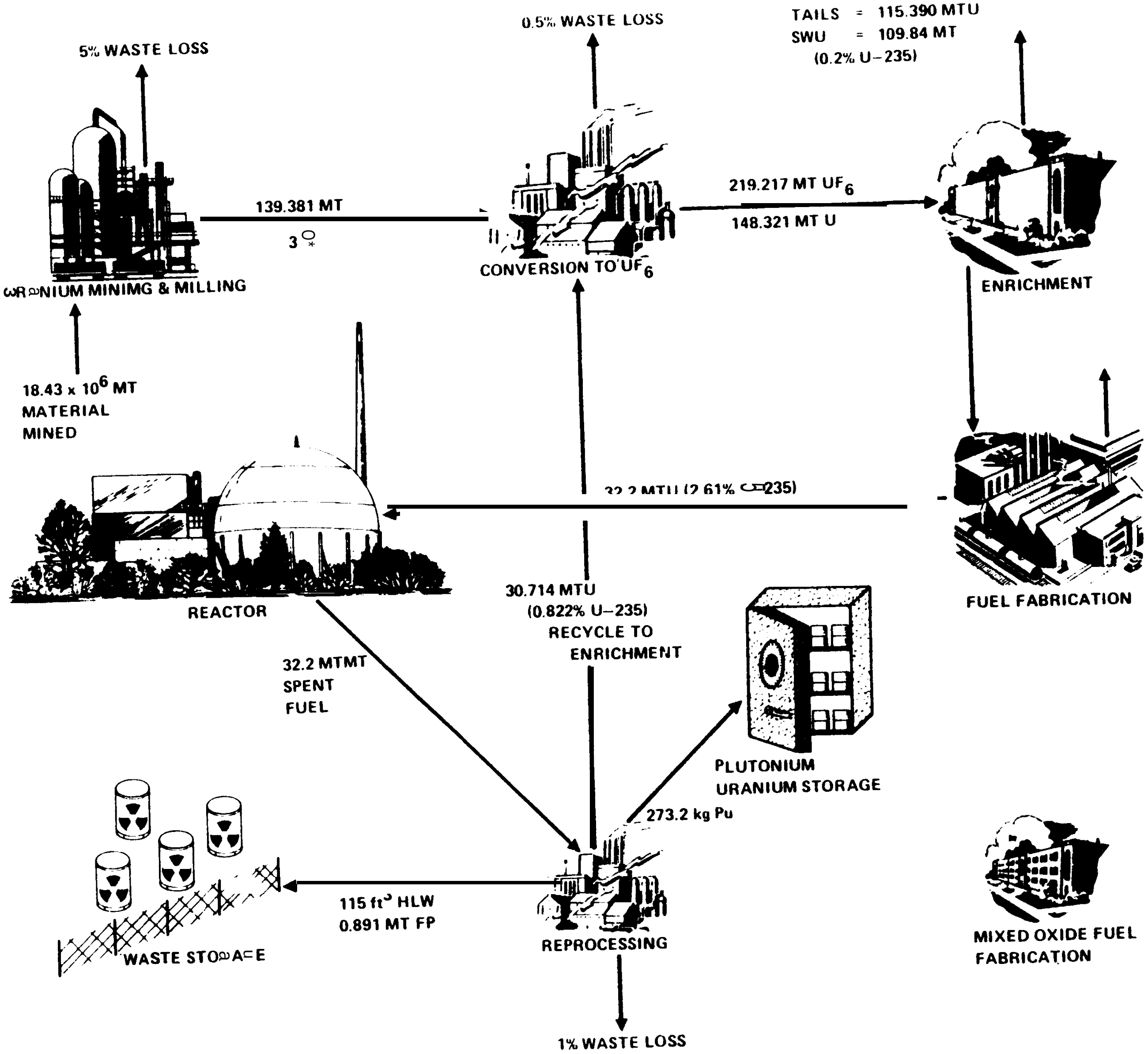


Fig. 27. BWR Equilibrium Cycle (U Recycled

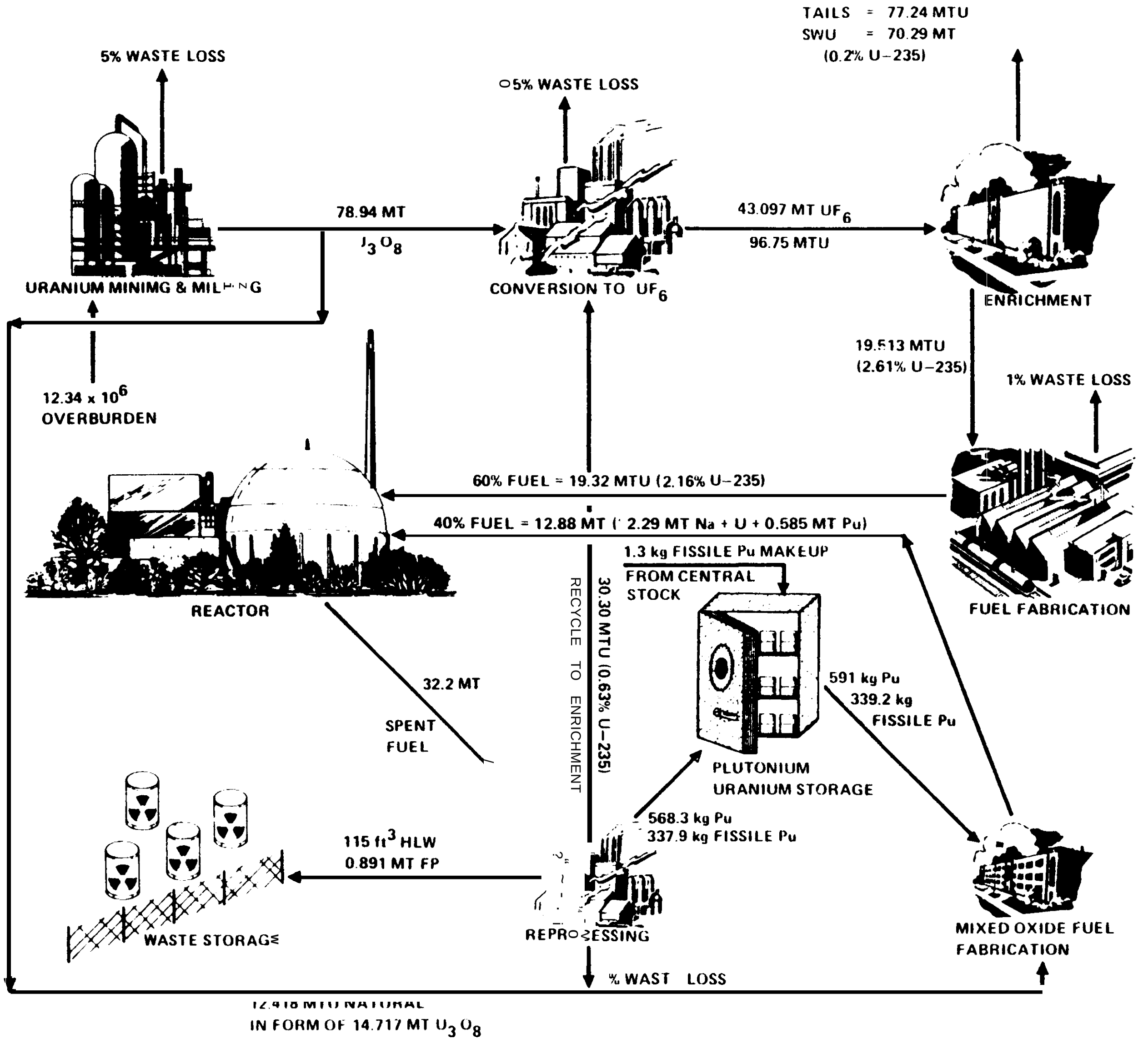


Fig. 28. BWR 2 Equilibrium Cycle (U and Pu Recycle

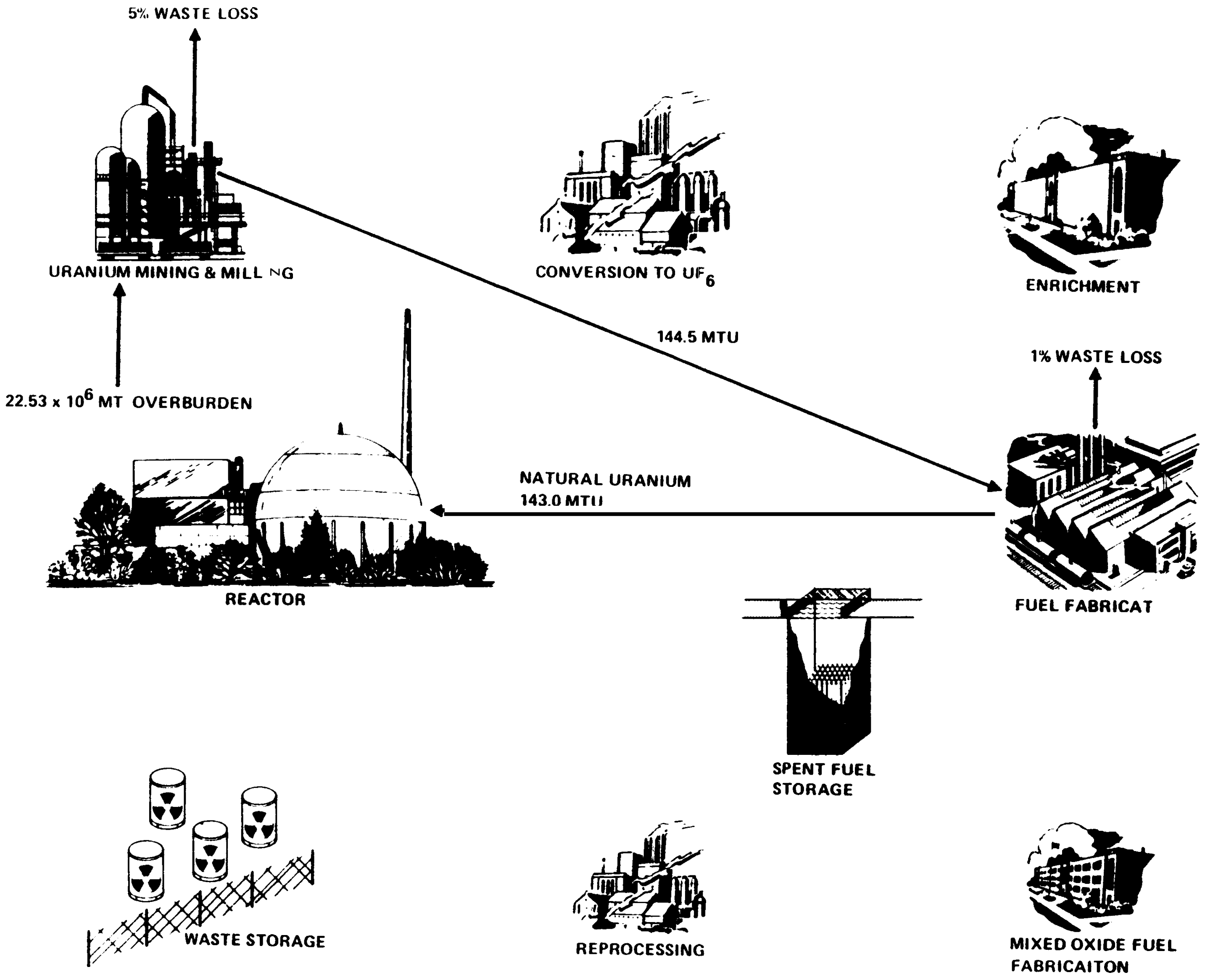


Fig. 29. CANDU-PHW Startup Loading

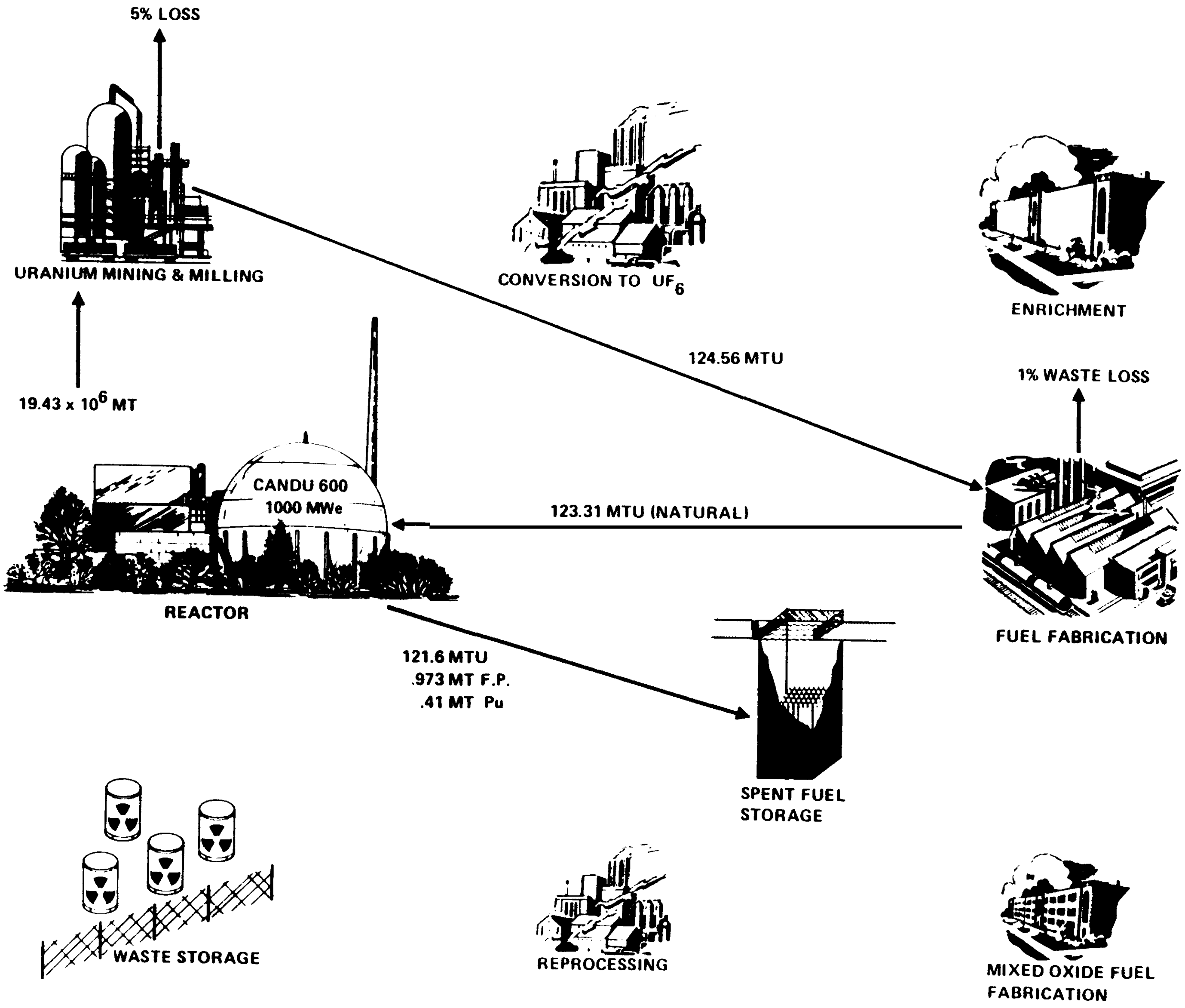


Fig.29. (Cont). CANDU-PHW Equilibrium Cycle

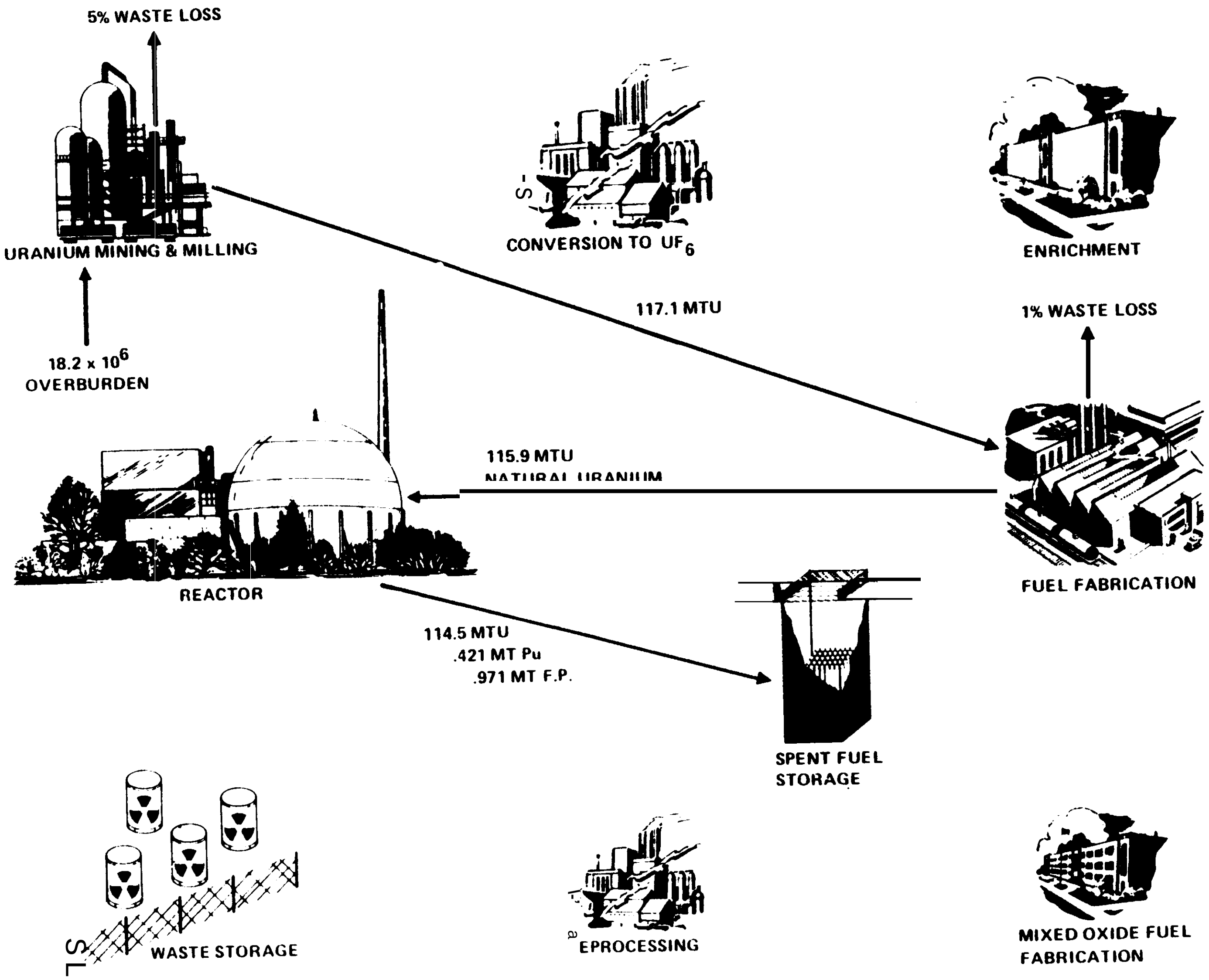


Fig. 30. HW-13LW Equilibrium

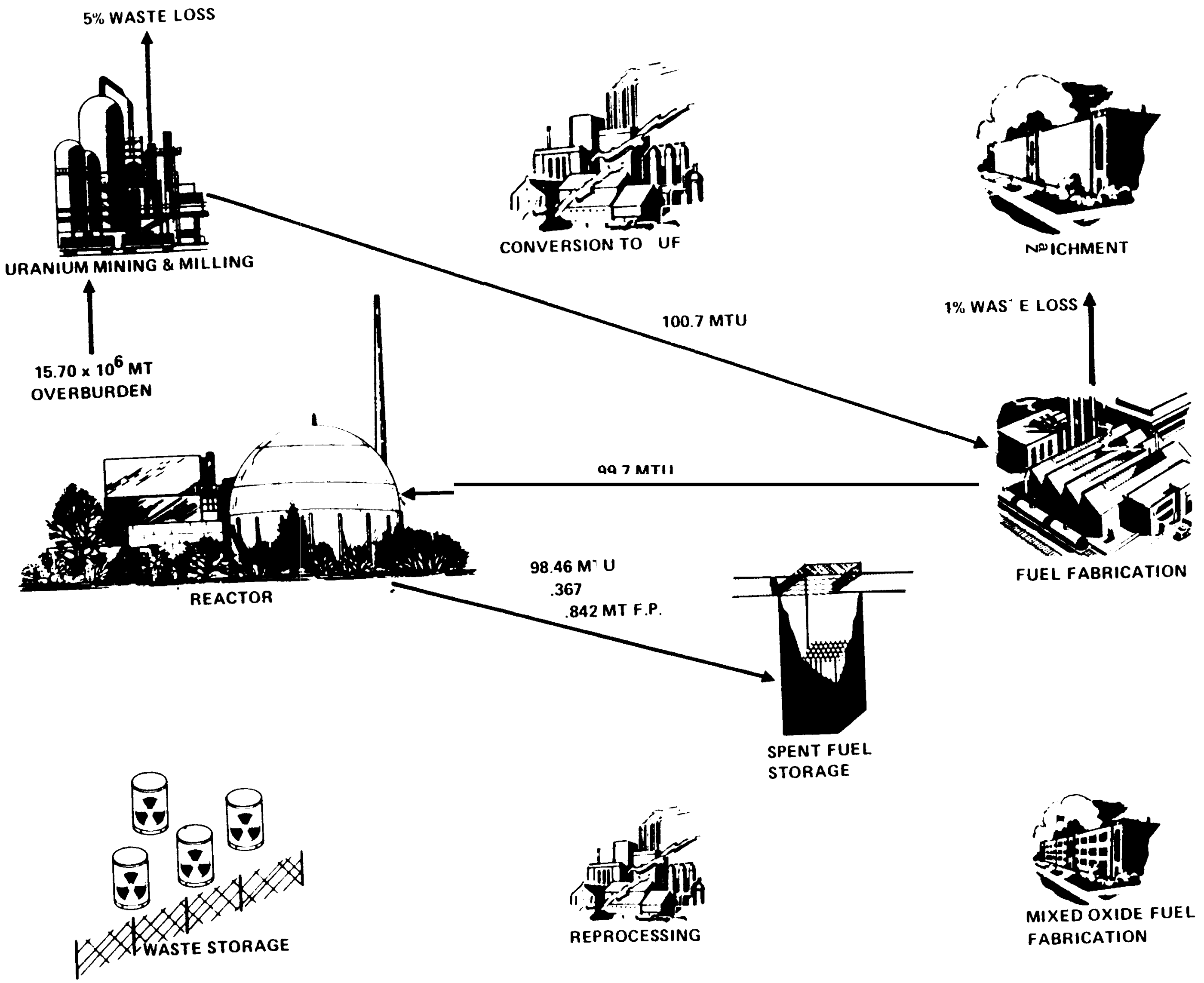
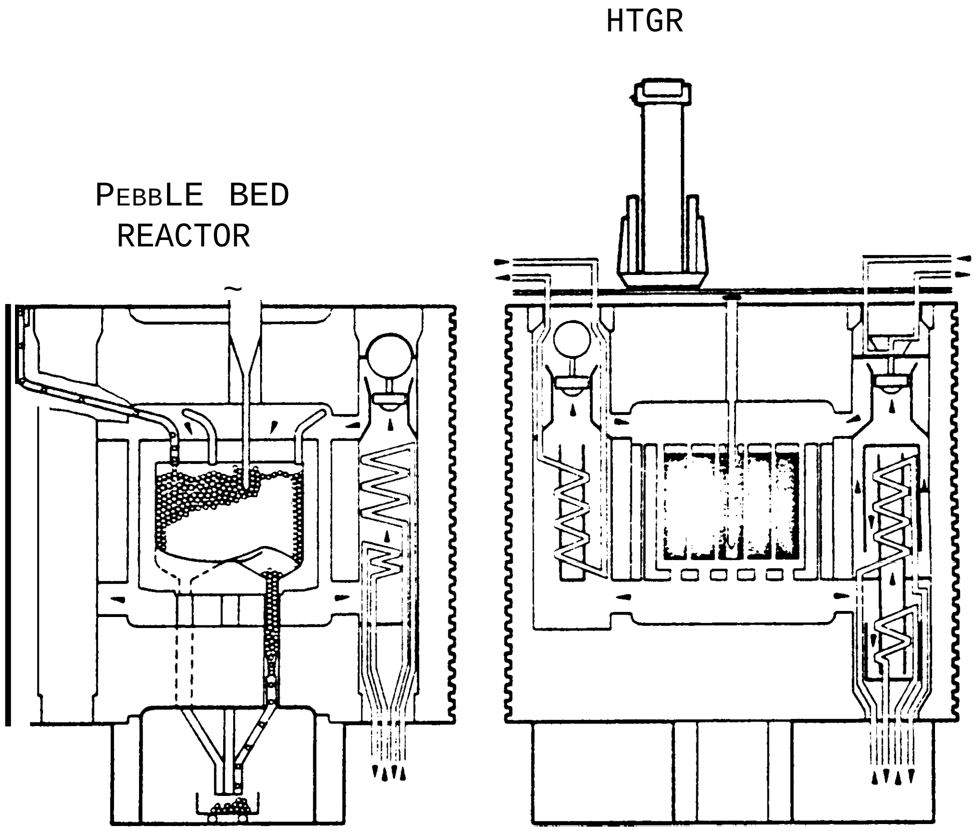


Fig. 31. HWOCR Equilibrium (Natural Uranium Carbide Fuel)

TABLE 11
GAS-COOLED REACTORS

Reactor Characterization **Date of Information** **Representative Reactor**	GCFR (34) 1976 GA 1500, MWe Design	HTGR (30) 1974 Fulton Station	AGR (21) 1976 Hinkley-Point B	THTR (38,39) 1972 THTR Uentrop
Reactor Thermal Power (MWt)	3997	3000	1493	750
Net Electrical Power (MWe)	1500	1160	621	300
Net Plant Efficiency (%)	37.5	38.6	41.6	40.0
Average Burnup (MWd/MTM)				
Initial	NA	NA	13,000	NA
Equilibrium	88,400/6200/2100	98,000	18,000	113,000
Core Inventory (MTM)	125.2	39.22	114	6.56
Core Height (m)	2.50	6.30	8.3	5.1
Neutron Flux (n/cm^2-sec)				
Peak Thermal	NA	NA	13×10^{13}	19×10^{13}
Average Thermal	NA	NA	8×10^{13}	13×10^{13}
Peak Fast	NA	NA	NA	NA
Average Fast	NA	NA	NA	NA
Fuel Description				
Number of Assemblies (core/blanket)	**271/126**	3944 **○ assemblies in each of 493 columns**	**2464 assemblies** **8 assemblies per channel**	**74,200**
Dimension of Assembly (hxd)m	**2.50x.214**	.79x.36	1.039x.238	**6 cm diam. spheres**
Number of Rods per Assembly (core/blanket)	331/61	102/--	36/--	NA
Chemical Composition (core/blanket)	$UO_2/PuO_2/UO_2$	$UC-UO_2-ThO_2$/--	UO_2/--	$UC-UO_2-ThO_2$/--
Cladding Material/ Thickness (cm)	SS 316 0.37 core .057 radial blanket	TRISO/BISO coating .17/.09	Stainless Steel .038	Pyrolytic Carbon .50
Enrichment (%) (Initial/Equilibrium)	15.4/ 5.4	93 U^{235}	(1.46,1.75/2.10,2.54)	93 U^{235}
Control Material	B_4C	B_4C	Boron	B_4C
Control Rods/Assembly	37	2 in each of 73 channels	N control channels	36 control rods 42 safety rods
Refueling Interval	Annually	[illegible]	Continuous	Continuous
Fraction Reload per Cycle	1/3 core 1/4 radial blanket	1/4 core	[illegible] 1½ channels/week	1.[illegible] cores/year
Conversion Ratio (Initial/Equilibrium)	(NA/1.44)	(NA/.67)	(0.6/0.5)	(NA/0.53)



PEBBLE BED REACTOR

HTGR

Fig. 32. Comparison of the main systematic differences of two typical designs with pebbles and prismatic fuel.

TABLE 12
FUEL CYCLE REQUIREMENTS (1000 MWe, 75% LOAD FACTOR

REACTOR CHARACTERIZATIONS	HTGR		AGR	
	Initial Load	Equilibrium Cycle	Initial Load	Equilibrium Cycle
Mining (10^3 MT)				
Material Removed	44,940	12,385	78,000	20,750
Uranium 0.2% concentration	136.4	37.813	263.3	70.04
Thorium [illegible] concentration	16.27	3.966		
Milling (MT U_3O_8)	303.4	84.71	590.0	156.9
$(Th(NO_3)_4$	63.38	15.52	0.0	0.0
Conversion (=Enrichment Feed) (MT UF_6	378.1	105.6	735.6	195.6
Enrichment				
SWU (MT)	332.1	92.72	247.3	89.5
Tails (MTU at 0.2%)	254.6	71.09	311.8	99.0
Enriched Product (MTU	1.408	.393	186.1	33.3
Assay (% U-235)	93.12	93.12	1.46/1.75	2.10/2.54
Feed nat U (MTM)	256.0	71.48	497.9	132.4
Fuel Fabrication				
Input (MT)	1.408U/30.62 Th	.393U/4.011 Th	186.1	33.3
Output (MT)	1.394U/30.31 Th	.389U/3.92 Th	184.2	33.0
No. Assemblies/year	3188	800	4000	720
Composition	ThO_2-UC	ThO_2-UC	UC_2	UO_2
Weight of Assembly (MTM) Used in Reactor	.010	.010	.075	.075
Reactor [illegible]				
Quantity (U/Pu/Th) MTM	1.394/--/30.31	.794/--/7.349	184.2/--/--	33.0/--/--
Isotopics (%)				
U-233	0	21.49	0.0	0.0
U-234	.74	5.19	0.0	0.0
U-235	93.12	62.63	1.46/1.75 (a)	2.10/2.54
U-236	.28	4.07	0.0	0.0
U-238	5.86	6.62	98.54/98.25 (a)	97.9/97.46
Pu-239	0	0	0.0	0.0
Pu-240	0	0	0.0	0.0
Pu-241	0	0	0.0	0.0
Pu-242	0	0	0.0	0.0

TABLE 2 Cont
FUEL CYCLE REQUIREMENTS (1000 MWe, 75% LOAD FACTOR)

REACTOR CHARACTERIZATIONS	HTGR		AGR	
	Initial Load	Equilibrium Cycle	Initial Load	Equilibrium Cycle
Reactor Discharge				
Quantity (U/Pu/Th MTM)		.498/-/6.901		32.15/ 16/-
Isotopics				
U-233		38.75		--
U-234		12.81		--
U-235		10.67		.59/.78
U-236		29.56		--
U-238		8.21		99.41/99.22
Pu-239		0		74.
Pu-240		0		17.
Pu-241		0		8.
Pu-242		0		0.4
Th		100		
Fission Products (MT)		.744		.690
Net Plant Efficiency (%)		38.7	41.6	41.6
Burnup (Avg. MWd/MTM)		87,000	13,000	20,000
Spent Fuel Storage				
Decay Heat (W/kg)		1290		10.6
Days Holdup		180		180
Activity at Discharge From Pool (10^6 Curies F.P.)		78.5		135
Fuel Reprocessing				
Input (MT)		3.58 U		33.0 (a)
Recycle Uranium (MT)				
U-233		.174		--
U-235		.048		.216
U-238		.018		31.93
Plutonium Production MT)				
Pu-239		0		.120
Pu-241		0		.013

TABLE 12 (Cont)

FUEL CYCLE REQUIREMENTS (1000 MWe. 75% LOAD FACTOR)

REACTOR CHARACTERIZATIONS	HTGR		AGR	
	Initial Load	Equilibrium Cycle	Initial Load	Equilibrium Cycle
Mixed Oxide Fuel Fabrication				
Input (MT) U/Pu		.387U/3.412 Pu		- -
Output (MT)		.386U/3.378 Pu		- -
No. Assemblies/year		NA		- -
Composition		ThO_2-UO_2		- -
Weight of Assembly (MTM)				
Used in Reactor		.010		--
Waste Disposal				
High Level Wastes				
(HLW+Cladding hulls)				
Volume (ft^3)		71.		218.7
Activity (10^6 Curies)		35		NA
Activity of Pu (10^3 Curies		.26		NA
Canisters (a 3.5 ft^3)		20.3		62.49
Low Level Wastes				
Volume (ft^3)		10,000-30,000		10,000-30,000
55 Gallon Drums		1,400-4,200		1,400-4,200
Burial or Repository Space (ft^3)		2,000-6,000		2,000-6,000

Notes: (a) No plutonium recycle is assumed in the AGR fuel cycle. However, quantities of recycle plutonium are presented to indicate the amounts present.

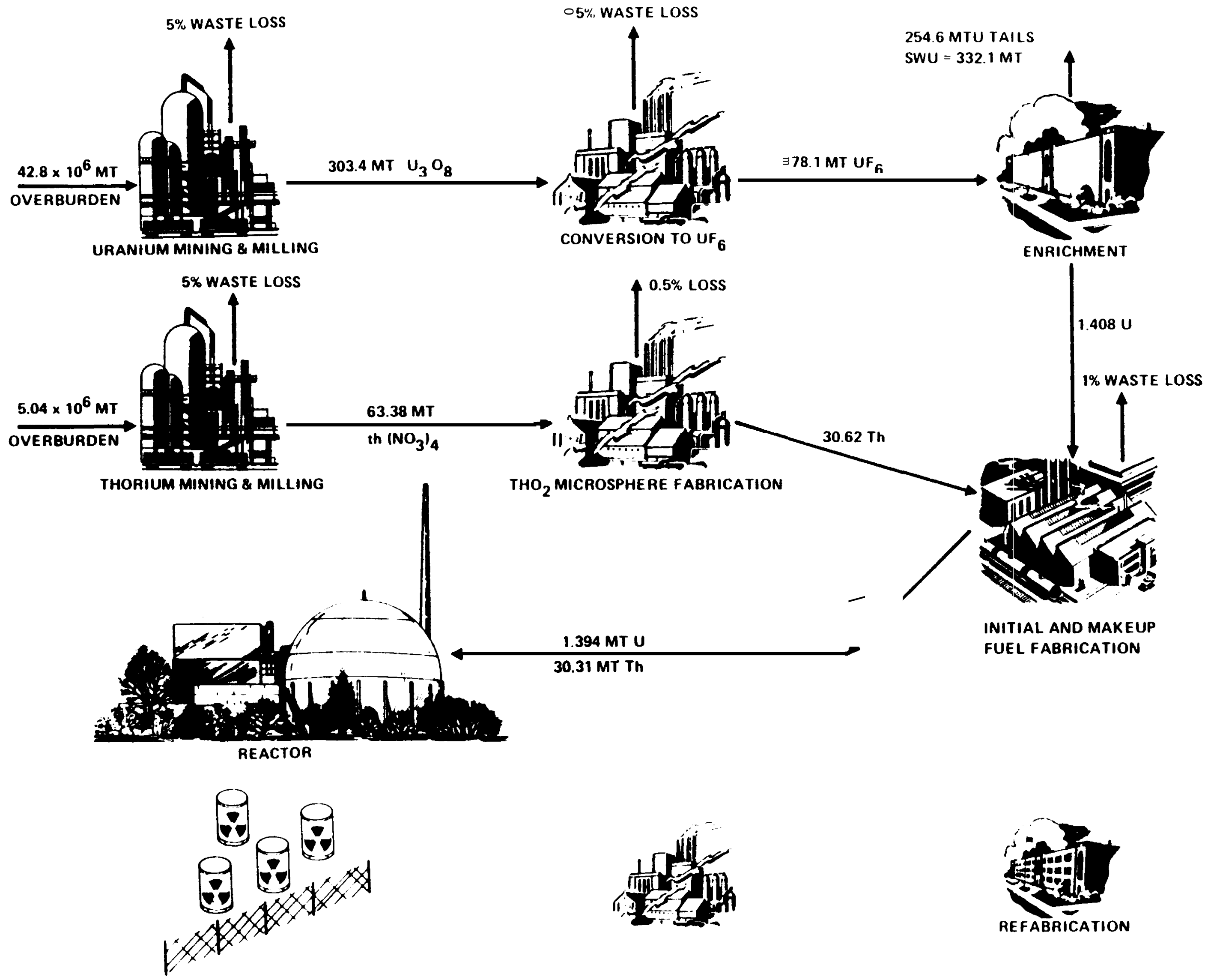


Fig. 33. HTGR Start-up

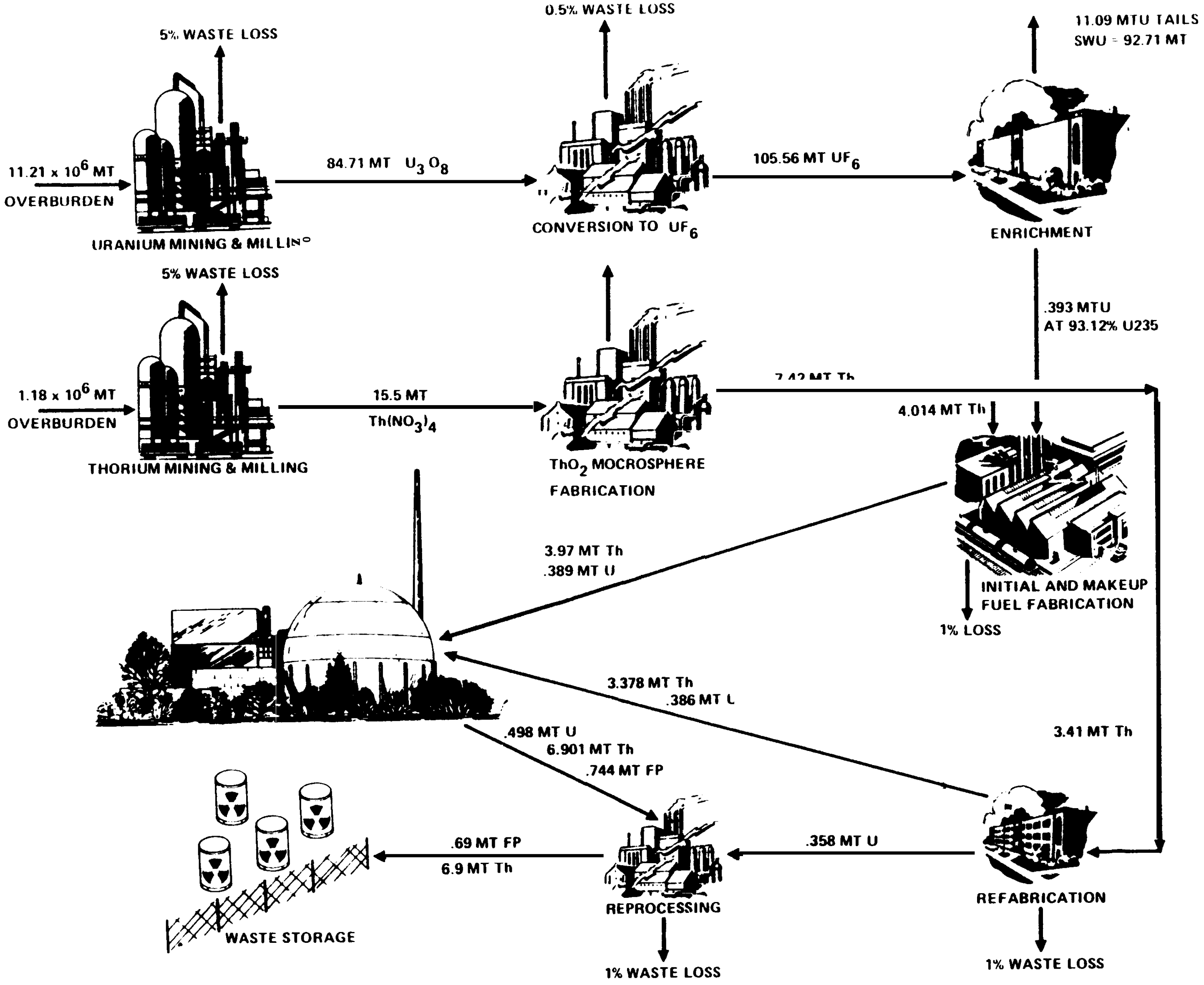


Fig. 33. (Cont). HTGR Ninth Year Conditions

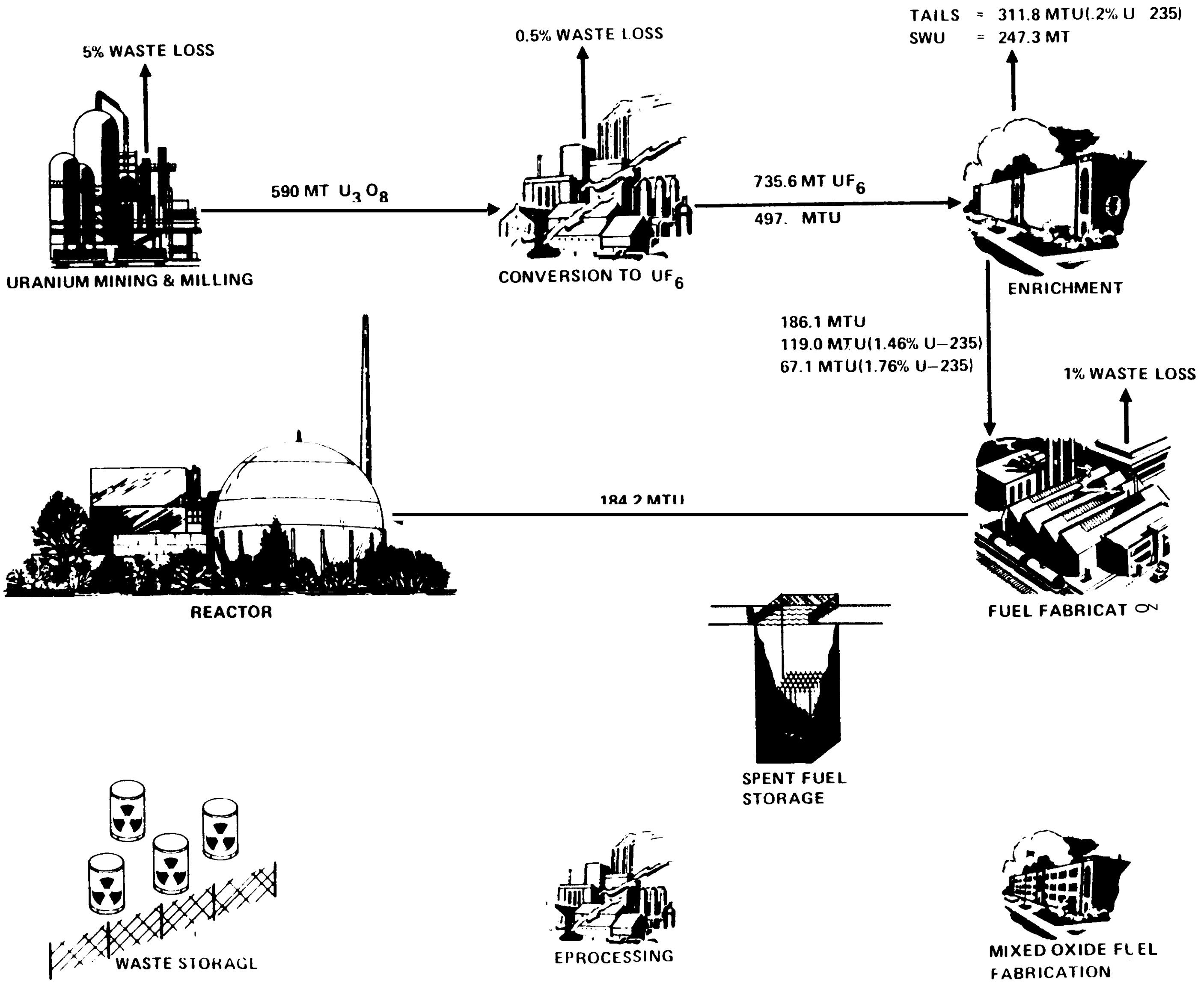


Fig. 34. AGR Initial Loading

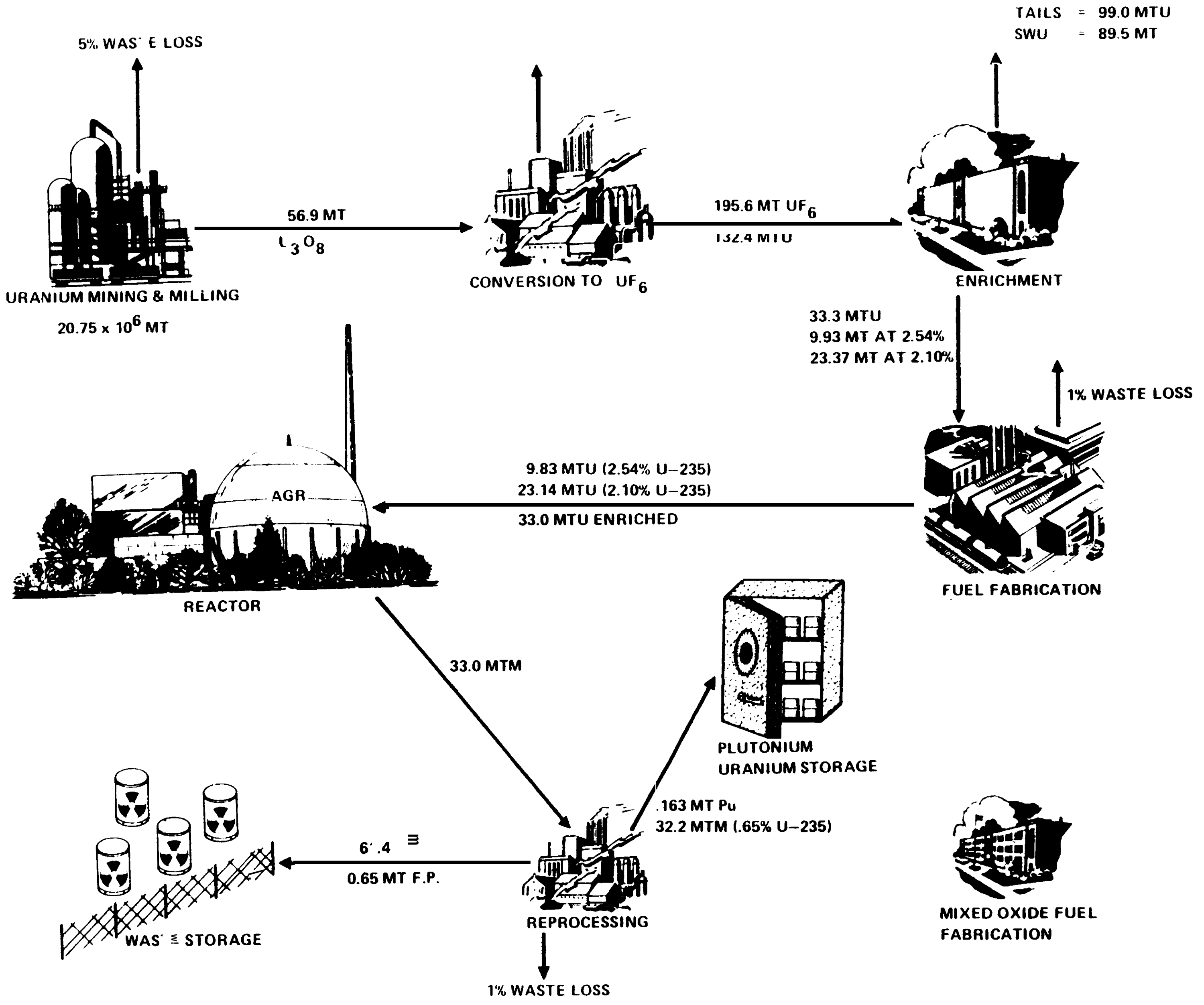


Fig. 34. (Cont) Equilibrium AGR Fuel Cycle (No Recycle is Assumed

TABLE 13.

REACTOR CHARACTERIZATIONS

	GCFR Uranium Blanket			
	High Burn-up Plutonium		Low Burn-up Plutonium	
	Initial Load	Equilibrium Cycle	Initial Load	Equilibrium Cycle
Mining (10^3 MT)				
Material Removed	0	0	0	0
Uranium 0.2% concentration	0	0	0	0
Thorium 0.2% concentration	0	0	0	0
Milling (MT U_3O_8)	0	0	0	0
(Th$(NO_3)_4$	0	0	0	0
Conversion (=Enrichment Feed) (MT UF_6)	0	0	0	0
Enrichment				
SWU (MT)	0	0	0	0
Tails (MTU at 0.2%)	0	0	0	0
Enriched Product (MTU)	0	0	0	0
Assay (% U-235)	0	0	0	0
Feed nat U (MTM)	0	00	00	00
Fuel Fabrication				
Input (MT)	54.86	13.71	35.96 U	8.87 U
Output (MT)	54.31	13.58	35.60 U	8.78 U
No. Assemblies/year	180	60	NA	NA
Composition	UO_2	UO_2	UO_2	UO_2
Weight of Assembly (MTM) Used in Reactor	.287	.292	NA	NA
Reactor Load in				
Quantity (U/Pu/Th) (MTM)	41.38/4.94/--	25.94/1.65/--	68.70/4.041/--	19.81/1.35/--
Isotopics (%)				
U-233	0.0	0.0	0.0	0.0
U-234	0.0	0.0	0.0	0.0
U-235	0.25	0.25	0.25	0.25
U-236	0.0	0.0	0.0	0.0
U-238	99.75	99.75	99.75	99.75
Pu-239	54.8	54.8	66.9	6.9
Pu-240	25.0	25.0	26.1	26.0
Pu-241	14.1	14.1	5.0	5.0
Pu-242	6.1	6.1	2.0	2.0
Th	0.0	0.0	0.0	0.0

TABLE 13. (continued)

REACTOR CHARACTERIZATIONS	GCFR Uranium Blanket			
	High Burn-up Plutonium		Low Burn-up Plutonium	
	Initial Load	Equilibrium Cycle	Initial Load	Equilibrium Cycle
Reactor Discharge				
Quantity (U/Pu/Th) (MTM)		24.86/1.96/--		18.69/1.69/--
Isotopics				
U-233		--		--
U-234		--		--
U-235		.19		.19
U-236		--		--
U-238		99.81		99.81
Pu-239		65.6		71.46
Pu-240		21.8		23.57
Pu-241		7.3		3.30
Pu-242		5.3		1.68
Th		0.0		
Fission Products (MT)		.77		.77
Net Plant Efficiency)	37.5	37.5	37.5	37.5
Burnup (Avg. MWd/MTM	NA	88,400 in core	NA	88,400 in core
Spent Fuel Storage				
Decay Heat (W/kg)		160		NA
Days Holdup		30		30
Activity at Discharge From Pool (10^6 Curies F.P.)		400		400
Fuel Reprocessing				
Input (MT)		27.59		21.16
Recycle Uranium (MT				
U-233		0.0		0.0
U-235		.048		034
U-238		24.56		18.47
Plutonium Production (MT)				
Pu-239		1.28		1.20
Pu-241		.143		055

TABLE 13. continued)

REACTOR CHARACTERIZATIONS	GFCR Uranium Blanket			
	High Burn-up Plutonium		Low Burn-up Plutonium	
	Initial Load	Equilibrium Cycle	Initial Load	Equilibrium Cycle
Mixed Oxide Fuel Fabrication				
Input MT U/Pu	37.44U/4.96Pu	12.49U/1.67Pu	37.45U/4.99Pu	11.14U/1.36Pu
Output (MT)	37.07U/ 4.91Pu	12.37U/1.65Pu	37.08U/4194Pu	11.03U/1.35Pu
No. Assemblies/year	181	46	NA	NA
Composition	UO_2-PuO_2	UO_2-PuO_2	UO_2-P[illegible]	UO_2-PuO_2
Weight of Assembly (MTM Used in Reactor	.235	.238	NA	NA
Waste Disposal				
High Level Wastes (HLW+Cladding hulls)				
Volume (ft^3)		215		215
Activity 10^6 Curies)		525		525
Activity of Pu (10^3 Curies)		~70		61
Canisters (a 3.5 ft^3)		62		62
Low Level Wastes				
Volume (ft^3)		10,000-30,000		10,000-30,000
55 Gallon Drums		1,400-4,200		1,400-4,200
Burial or Repository Space (ft^3)		2,000-6,000		2,000-6,000

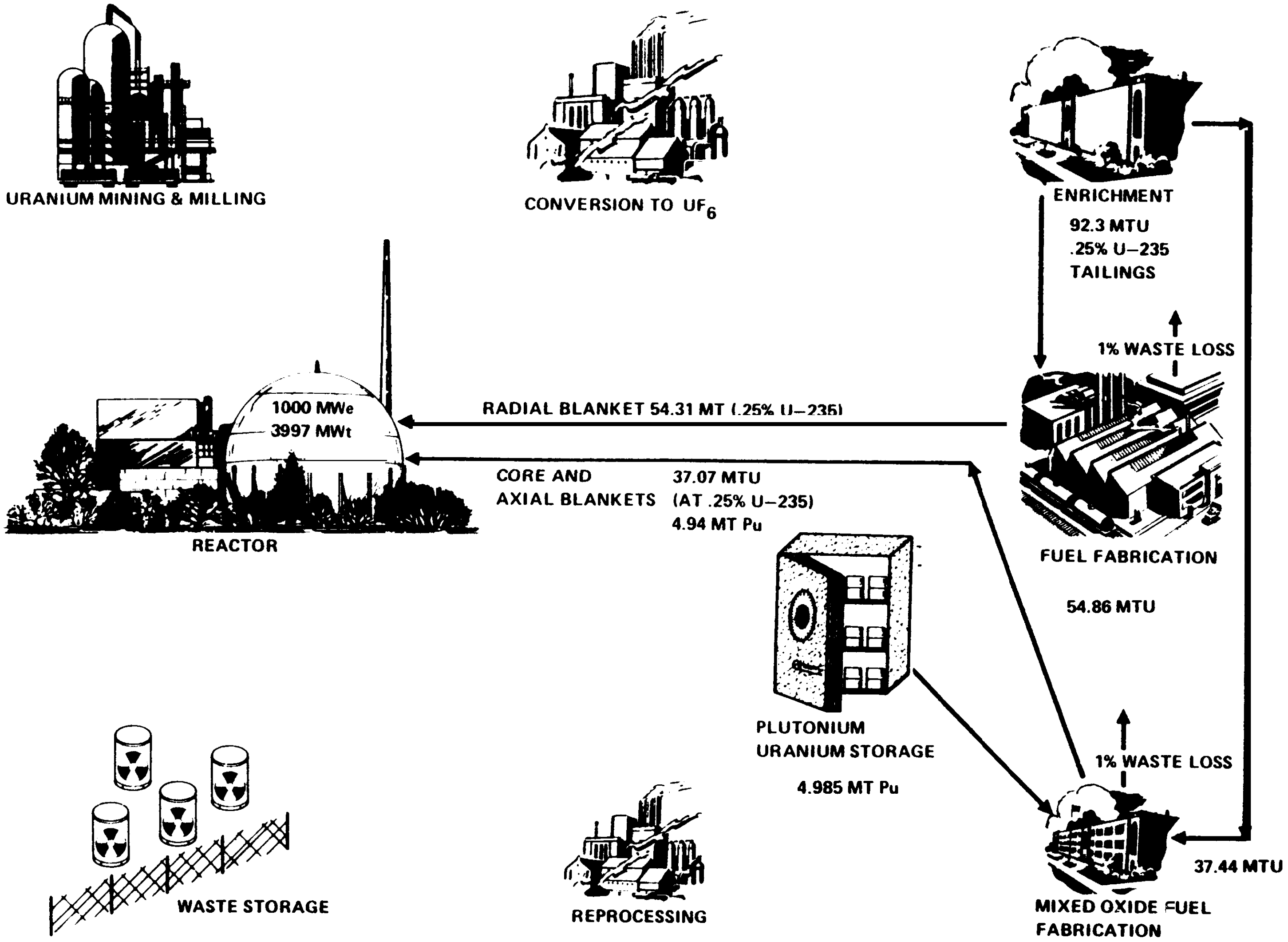


Fig. 35. GCFR Startup High Burn-up Pu)

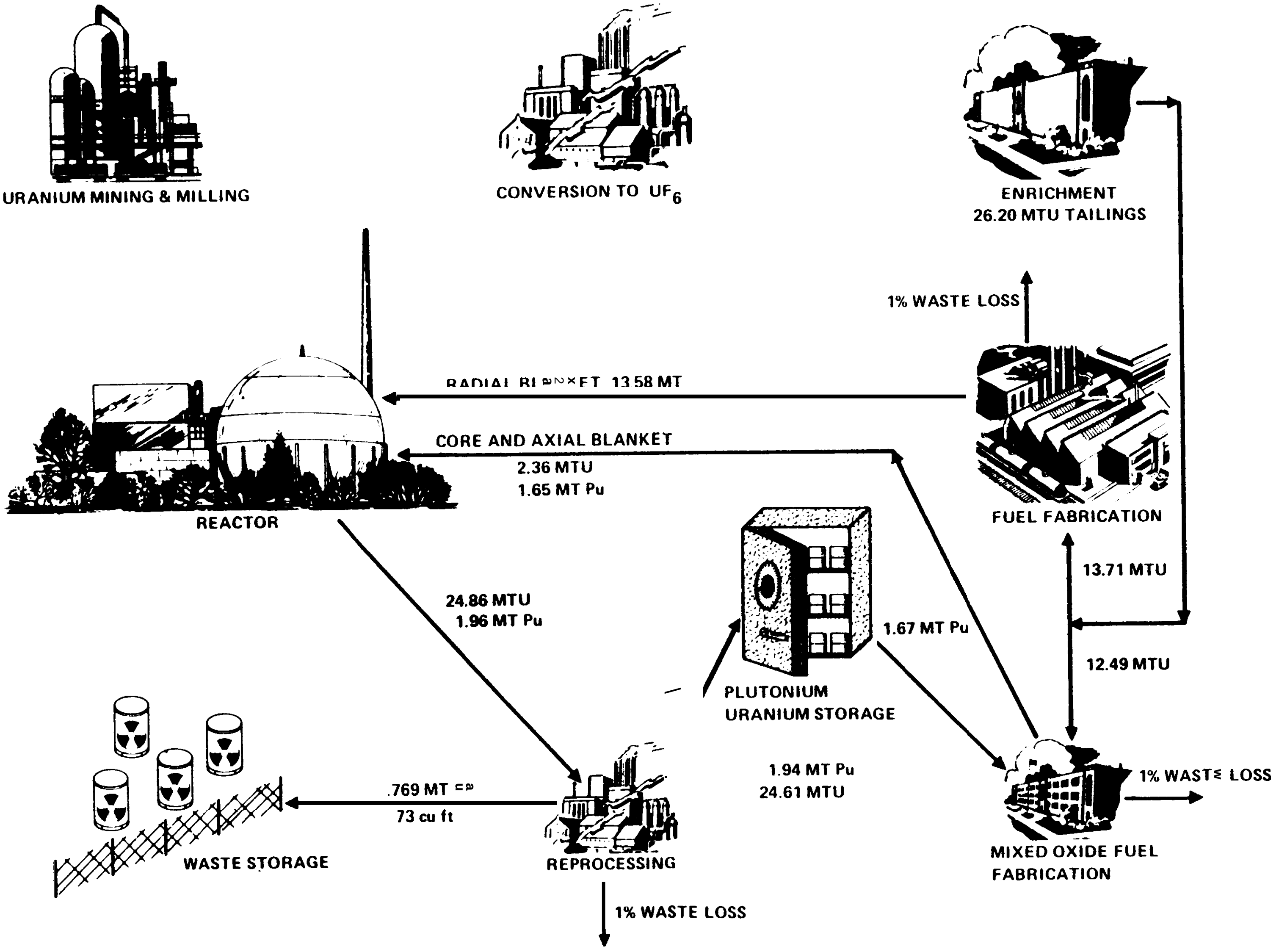


Fig. 35. (Cont). GCFR Equilibrium Cycle Uranium Blanket, High Burn-up Pu)

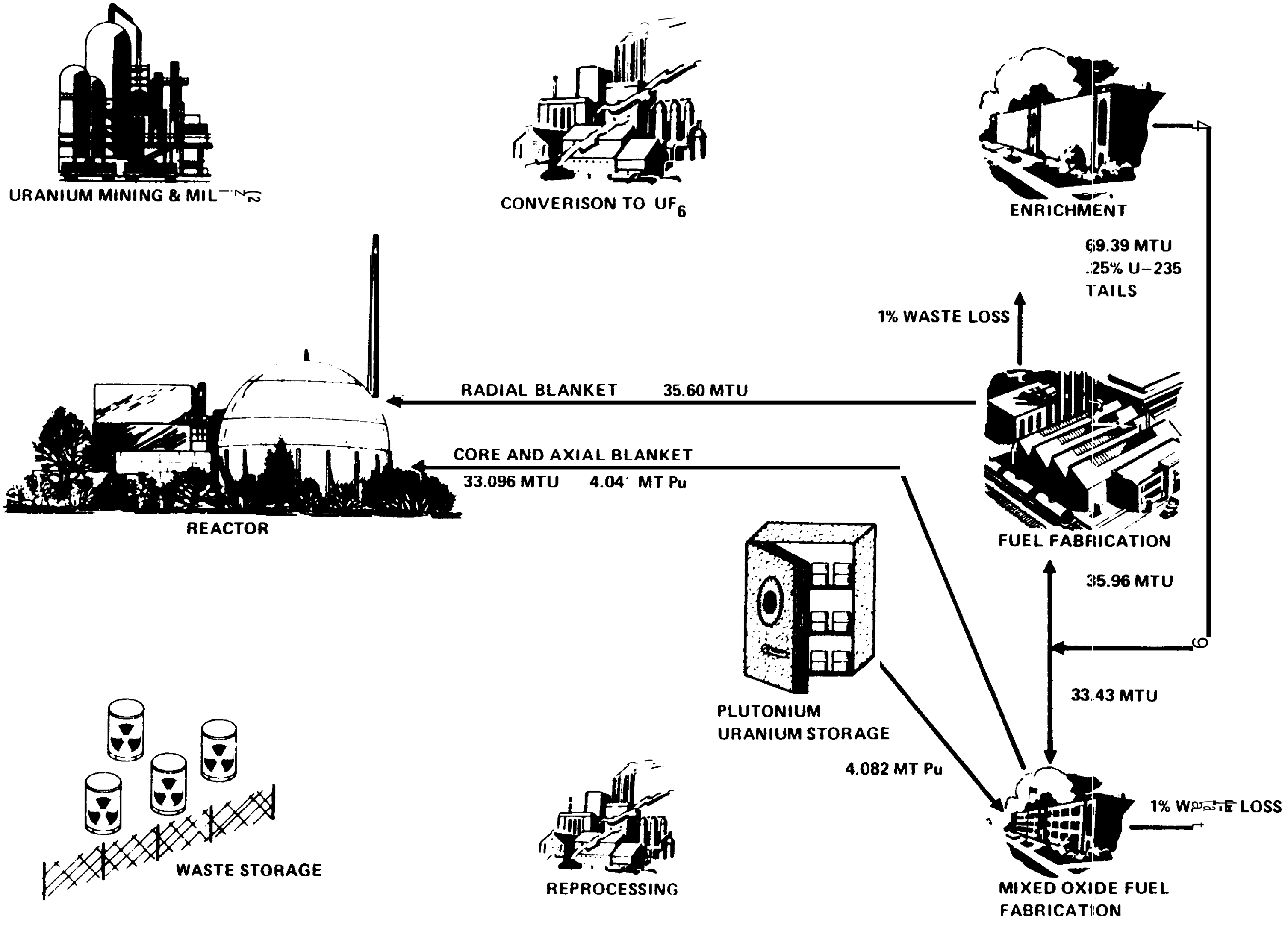


Fig. 36. GCFR Startup (Low Burn-up Pu, Uranium Blankets)

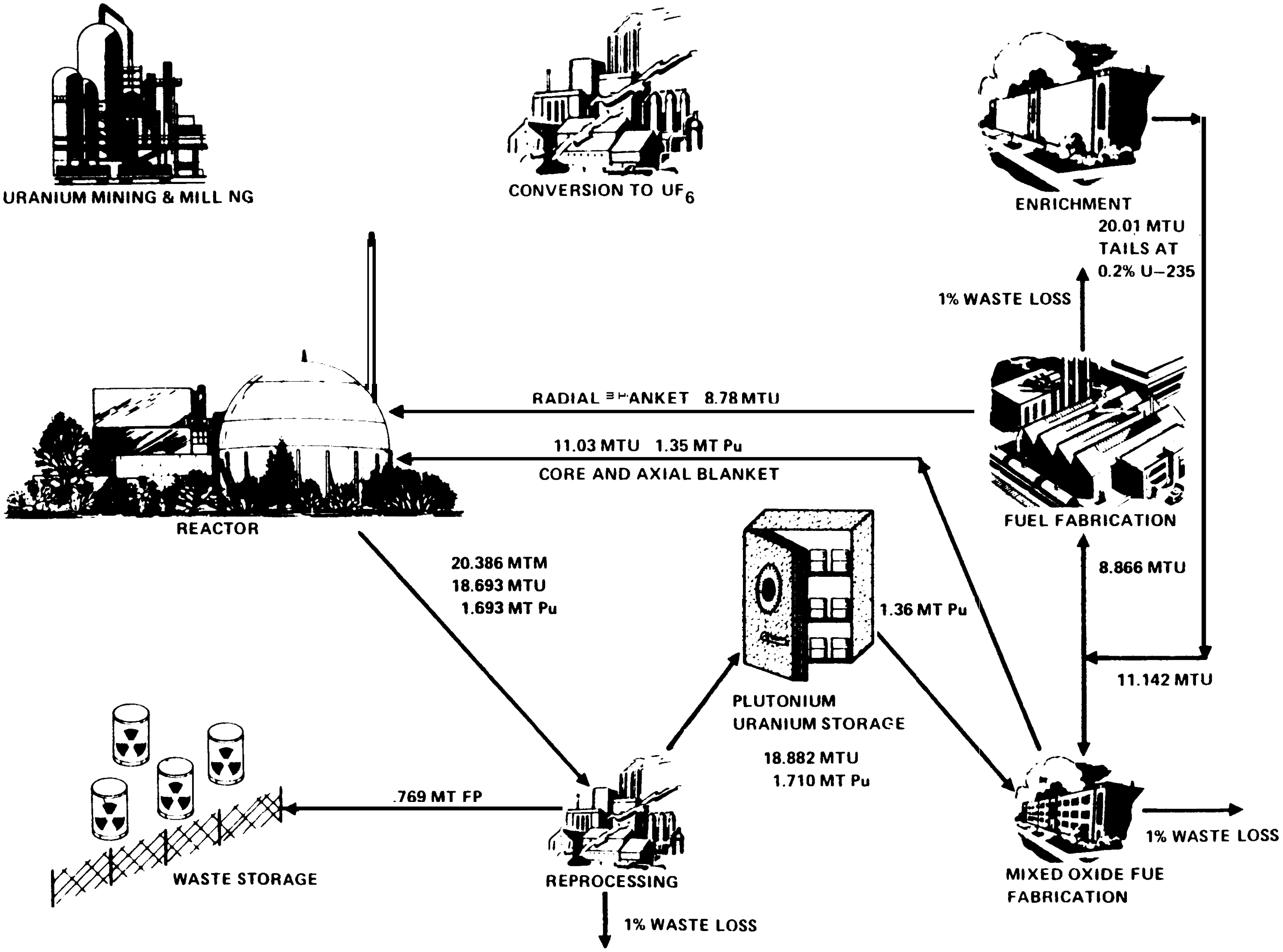


Fig. 36. (Cont). GCFR Equilibrium Cycle (Uranium Blanket. Low Burn-up Pu)

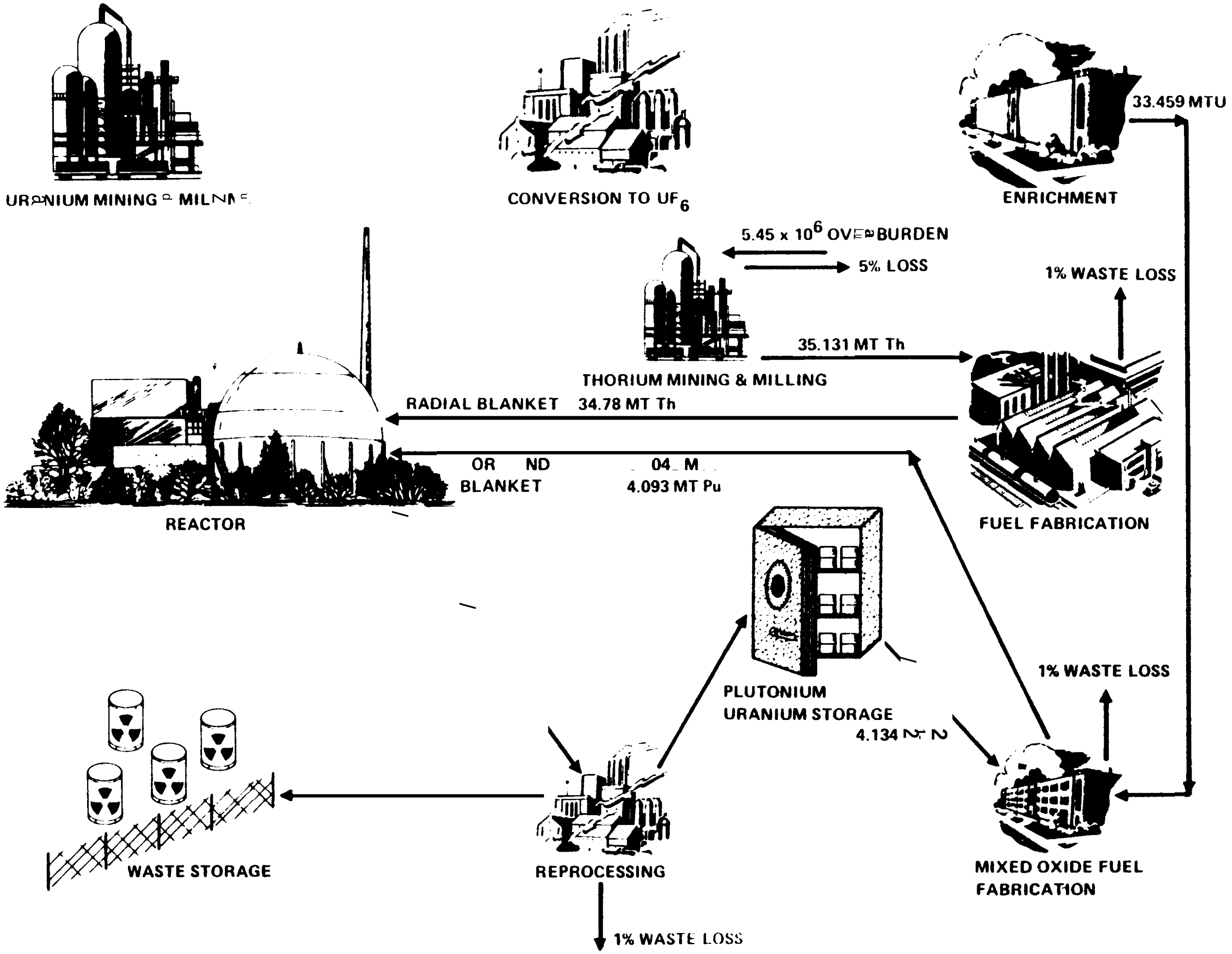


Fig. 37. GCFR Startup (Thorium Blanket Low Burnup Pu)

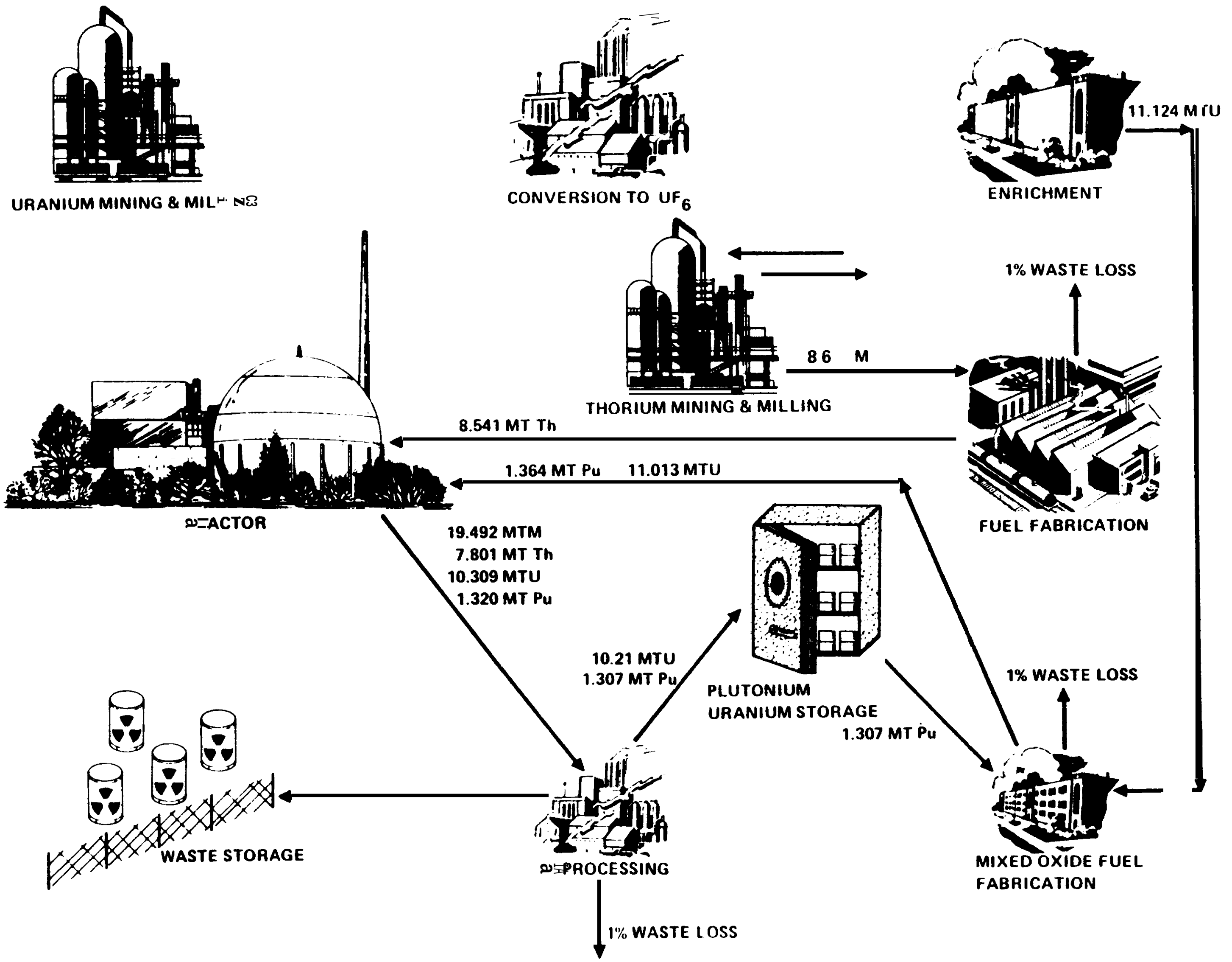


Fig. 37.(Cont). GCFR Equilibrium (Thorium Blanket Low Burnup Pu)

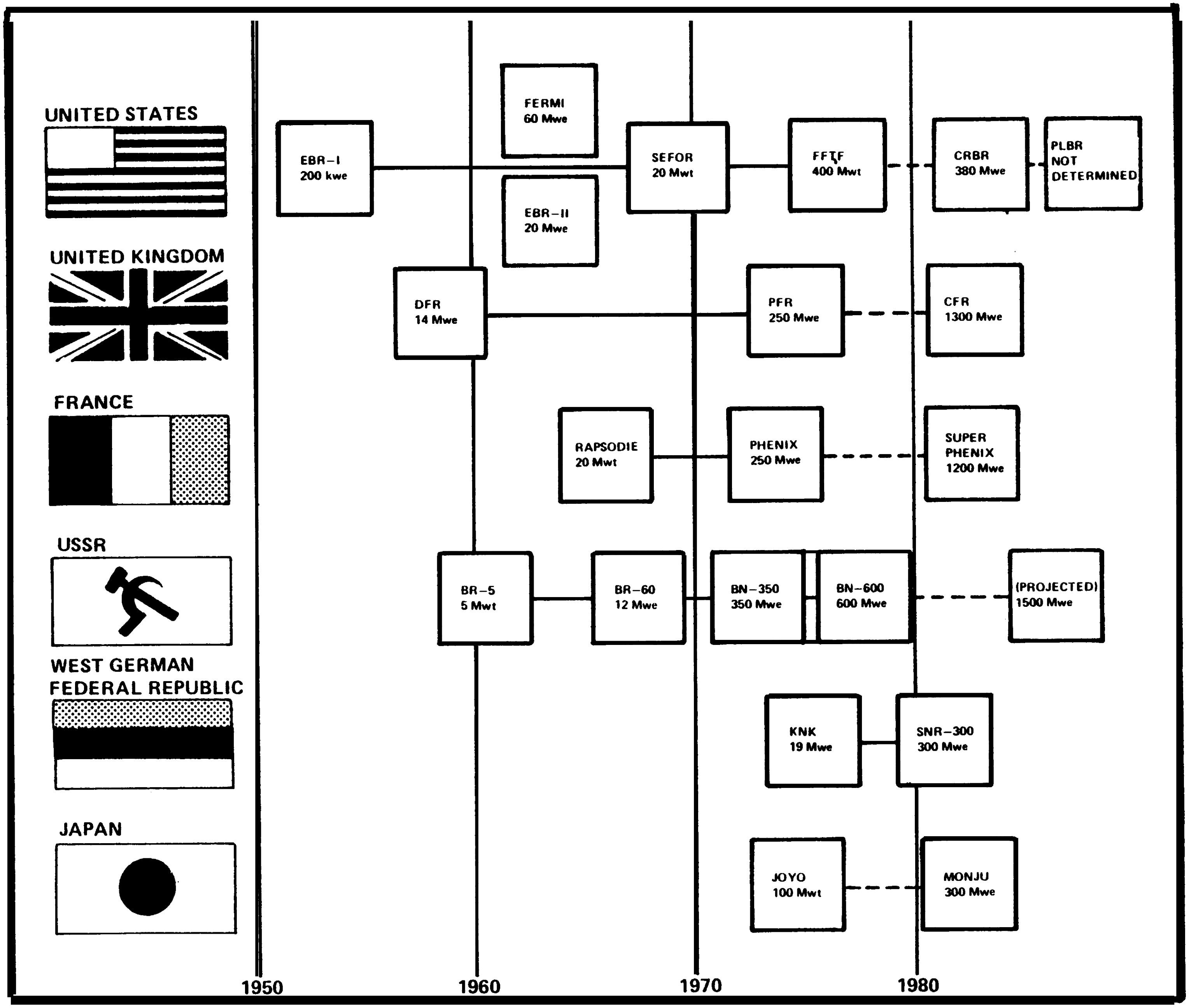


Fig. 38. International LMFBR Progress

TABLE 14

FUEL CYCLE REQUIREMENTS (1000 MWe, 75% LOAD FACTOR)

REACTOR CHARACTERIZATIONS	LMFBR1-AI Reference oxide	
	Initial Load	Equilibrium Cycle
Mining (10^3 MT)		
Material Removed		
Uranium 0.2% concentration		
Thorium 0.2% concentration		
Milling (MT U_3O_8)		
Conversion (MT (=Enrichment **Feed)** (MT UF_6)		
Enrichment		
SWU (MT)		
Tails (MTU at 0.2%)		
Enriched product (MTU)		
Assay (% U-235)		
Feed nat U (MTM)		
Fuel Fabrication		
Input (MT)	15.453	2.558
Output (MT)	15.3	2,533
No. Assemblies/year	138	23
Composition	depl.UO_2	depl.U02
Input U (MTM)	43.733	1.302
From Enrichment tails	(0.3%U235)	(0.3% U-235)
Weight of Assembly (MTM)	0.1109	0.1109
Used in Reactor	radial,bl.	radial bl.
Reactor load in		
Quantity (MTM) U\Pu\Th	43.3/4.3/0	16.25/1.528/0
Isotopes (%)		
u-233		0
u-234		0
u-235	0.3	0.063
u-236		0.051
u-238	99.7	99.896
Pu-239	71.5	71.5
Pu-240	25.2	25.18
Pu-241	2.4	2.40
Pu-242	0.9	0.902

TABLE 45 (Cont)

FUEL CYCLE REQUIREMENTS (1000 MWe, 75% LOAD FACTOR)

REACTOR CHARACTERIZATIONS	LMFBR1-AI reference oxide	
	Initial Load	Equilibrium Cycle
Mixed Oxide Fuel Fabrication		
Input (MT) U\Pu	28.28/4.343	13.728/1.545
output (MT)	32.3	15.120
No. Assemblies/year	274	128
Composition	depl.u0$_2$+PuO$_2$	depl.u0$_2$+Puc$_2$
Weight of Assembly (MTM)	0.′1179	0.1179
Used in Reactor	core & axial bl.	core & axial bl.
Waste Disposal		
High Level Wastes (HLW+Cladding hulls)		
Volume (ft3)		220
Activity (106 Curies)		24.3
Activity of Pu (103 Curies)		83
Canisters (a 3.5 ft^3)		63
Low Level Wastes		
volume (ft^3)		16,000-42,000
55 Gallon Drums		2,240-5,880
Burial or Repository Space (ft^3)		3,200-8,400

TABLE 14(cont)

FUEL CYCLE REQUIREMENTS (1000 MWe, 75% LOAD FACTOR)

REACTOR CHARACTERIZATIONS	LMFBR1-A1 reference oxide	
	Initial Load	Equilibrium Cycle
Reactor Discharge		
Quantity (MTM) U/Pu/Th		15.135/l.815/o
Isotopics		
U-233		o
u-234		0
U-235		0.042
U-236		0.056
U-238		99.902
Pu-239		71.7
Pu-240		25.1
Pu-241		2.38
Pu-242		0.76
Th		0
Fission Products (MTM)		0.690
Net Plant Thermal Efficiency (%)	41.8	41.8
Burnup in core (Avg. MWd/MTM)	40,000	67,600
Spent Fuel Storage		
Decay Heat (W/kg)		149
Days Holdup		30
Activity at Discharge From Pool (106 Curies F.P.)		301
Fuel Reprocessing		
Input (MT)		17.653
Recycle Uranium (MT)		
U-233		0
U-235		0.006
U-239		14.967
Plutonium Production (MT)		
Pu-239		1.2883
Pu-241		0.0429

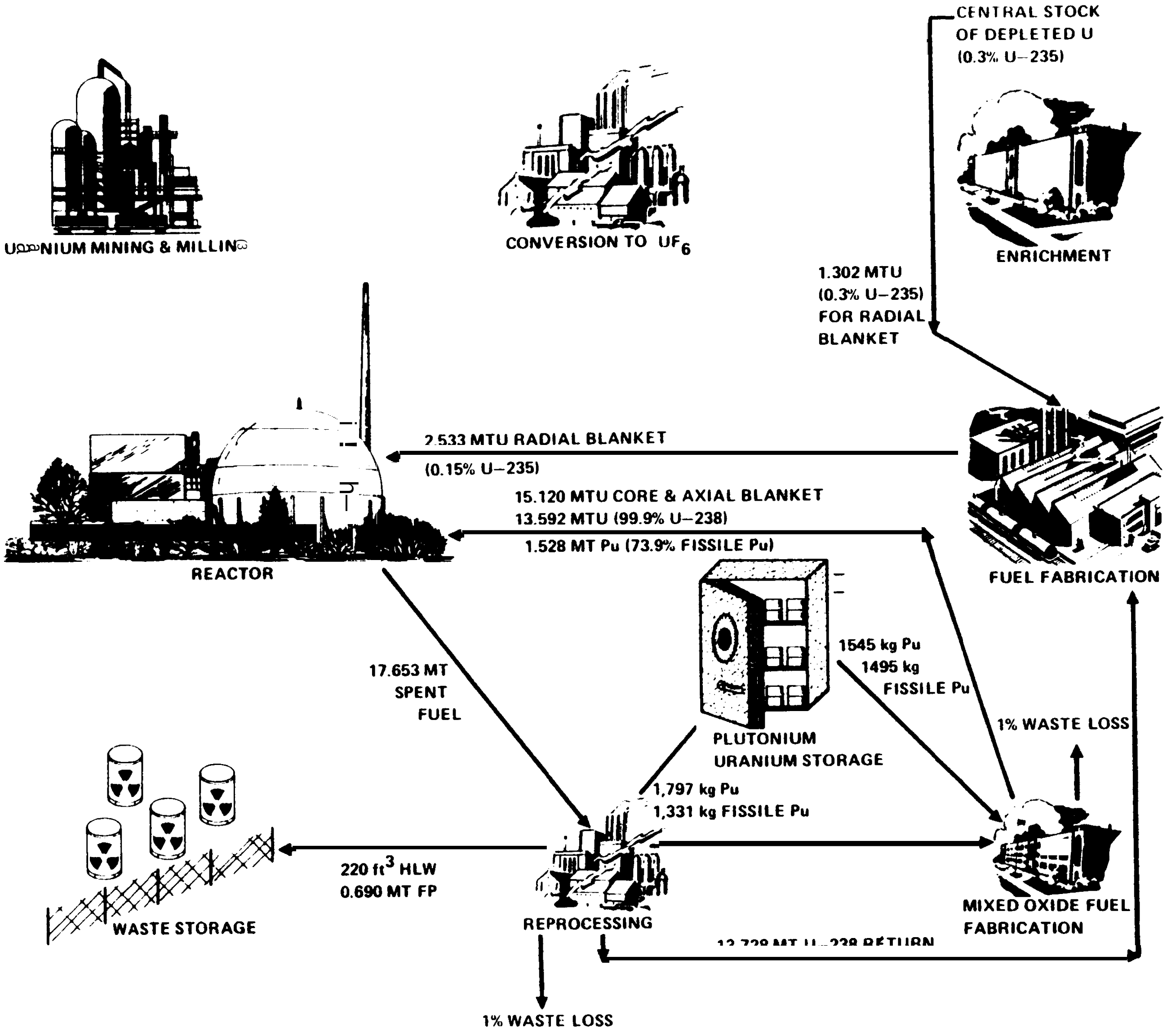


Fig. 39 . LMFBR I Equilibrium Cycle

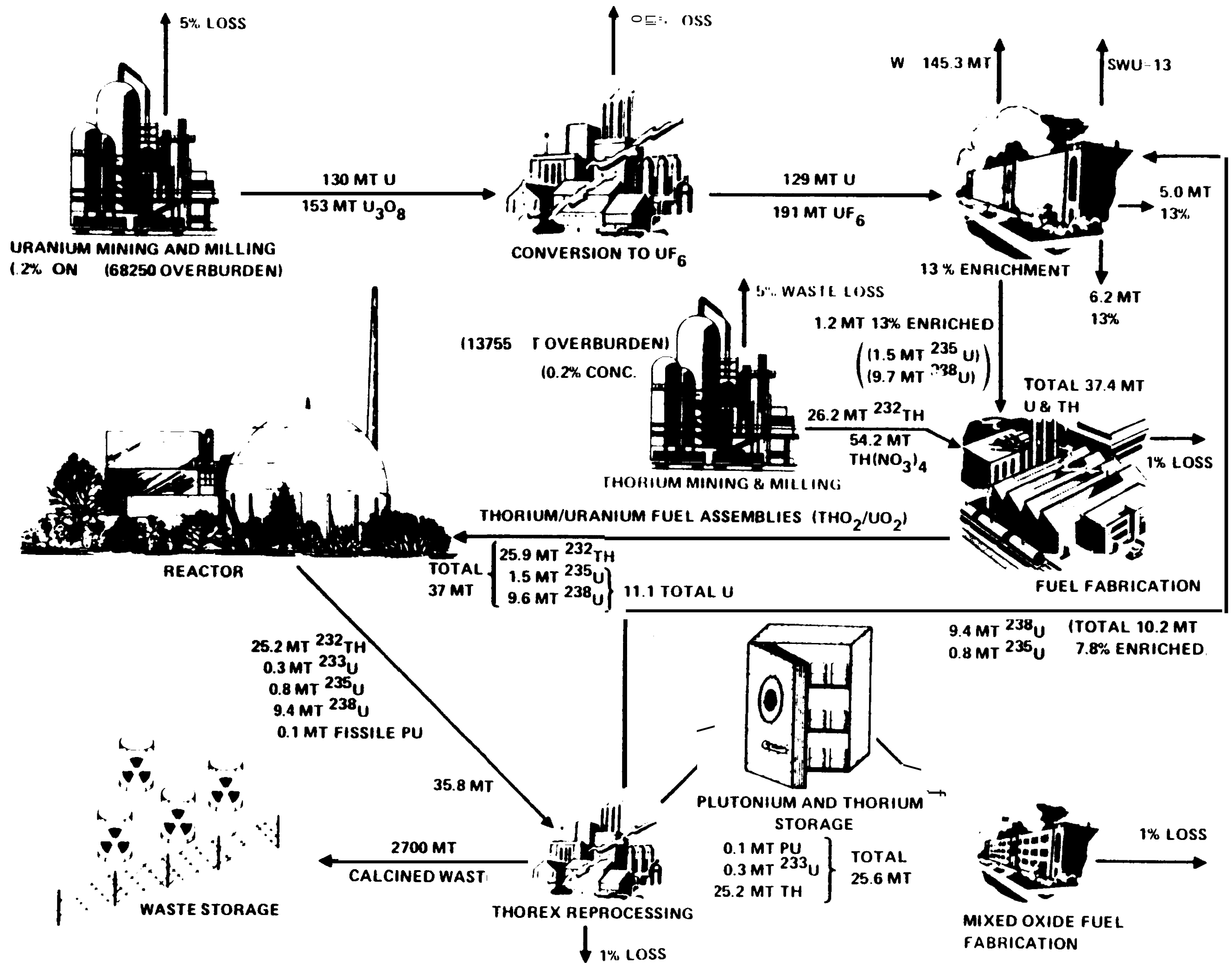


Fig. 40. Prebreeder Fuel Cycle

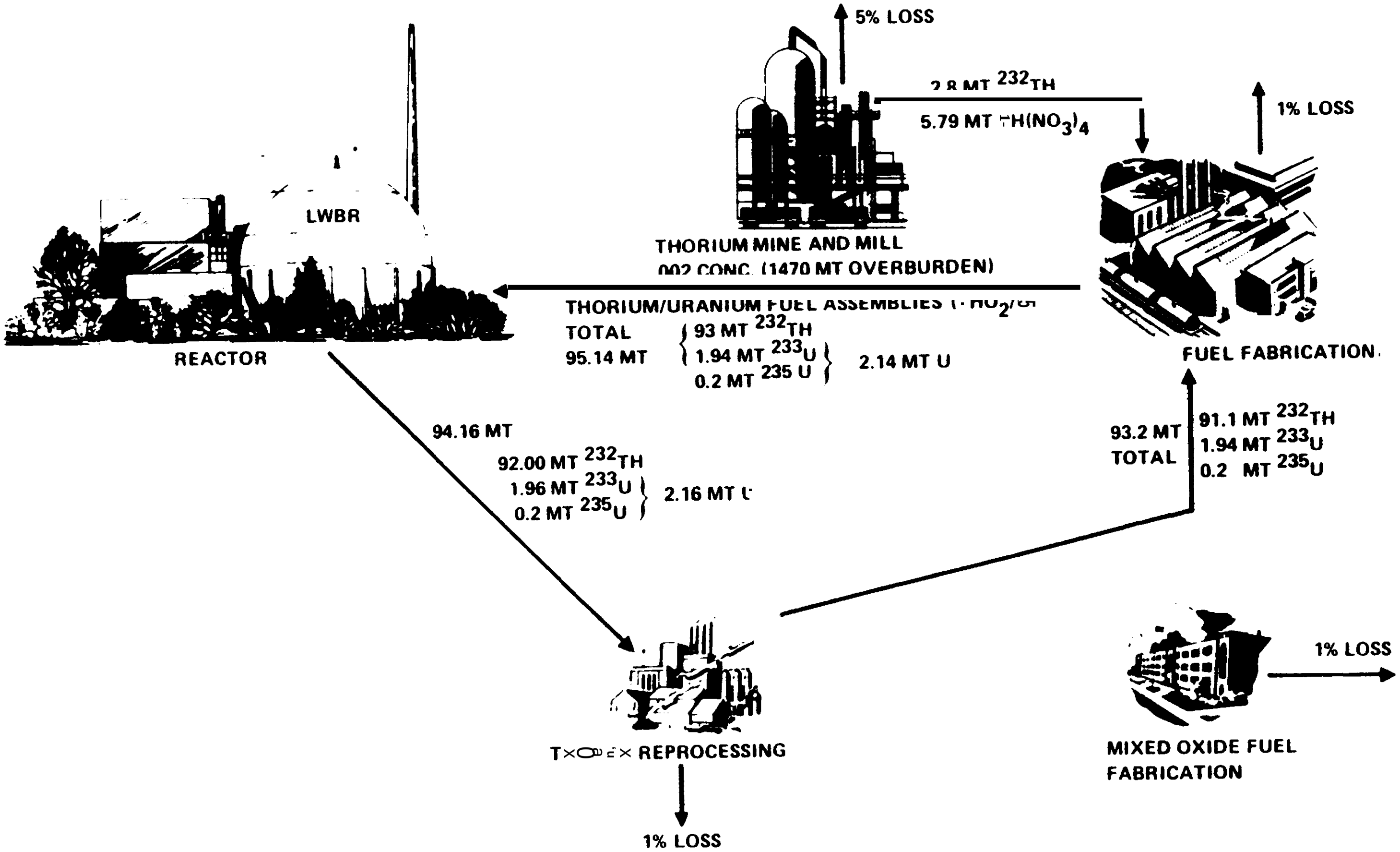


Fig. 41. Breeder Fue Cycle

TABLE 15

LWBR FUEL CYCLE REQUIREMENTS (1000 MWe, 75% LOAD FACTOR)

REACTOR CHARACTERIZATIONS	PREBREEDER	BREEDER
Mining (10^3 MT)		
Material Removed		
Uranium 0.2% concentration	76.5	
Thorium 0.2% concentration	27.1	
Milling (MT U_3O_8)	153	0.0
(Th $(NO_3)_4$	54.2	5.79
Conversion *=Enrichment Feed) (MT UF_6)	191	0.0
Enrichment		
SWU (MT)	158	N/A
Tails (MTU at 0.2%)	118	N/A
Enriched Product (MTU)	11.2	N/A
Assay (% U-235)	13%	N/A
Feed nat U (MTM)	129	N/A
Fuel Fabrication		
Input (MT)	37.4	96
Output (MT)	37.0	
No. Assemblies/year		
Composition	UO_2/ThO_2	
Weight of Assembly (MTM) Used in Reactor		
Reactor Load in		
Quantity (U/Pu/Th)(MTM)	11.1/--/25.9	2.14/--/93
Isotopics (%)		
U-233	0.0	90.7
U-234	0.0	0.0
U-235	13.0	9.3
U-236	0.0	0.0
U-238	87.0	0.0
Pu-239	0.0	0.0
Pu-240	0.0	0.0
Pu-241	0.0	0.0
Pu-242	0.0	0.0

TABLE 15 (Cont)

LWBR FUEL CYCLE REQUIREMENTS (1000 MWe, 75% LOAD FACTOR)

REACTOR CHARACTERIZATIONS

	PREBREEDER	BREEDER
Reactor Discharge	10.5/.11/25.2	2.2/--/92
Quantity (U/Pu/Th)(MTM)		
Isotopics %		
U-233	2.3	90.7
U-234	--	----
U-235	7.6	9.3
U-236	--	----
U-238	89.6	----
Pu-239	--	--
Pu-240	--	--
Pu-241	--	--
Pu-242	--	--
Fission Products (MT^n		
Net Plant Efficiency (%)	33.5	33.5
Burnup (Avg. MWD/MTM)	51,400	16,300
Spent Fuel Storage	--	--
Decay Heat (W/kg)	--	--
Days Holdup	--	--
Activity at Discharge	--	--
From Pool (10^6 Curies F.P.)		
Fuel Reprocessing		
Input (MT)		93.2
Recycle Uranium (MT)		
U-233		1.94
U-235		.2
U-238		--
Plutonium Production (MT)		
Pu-239		0.0
Pu-241		0.0
Thorium		

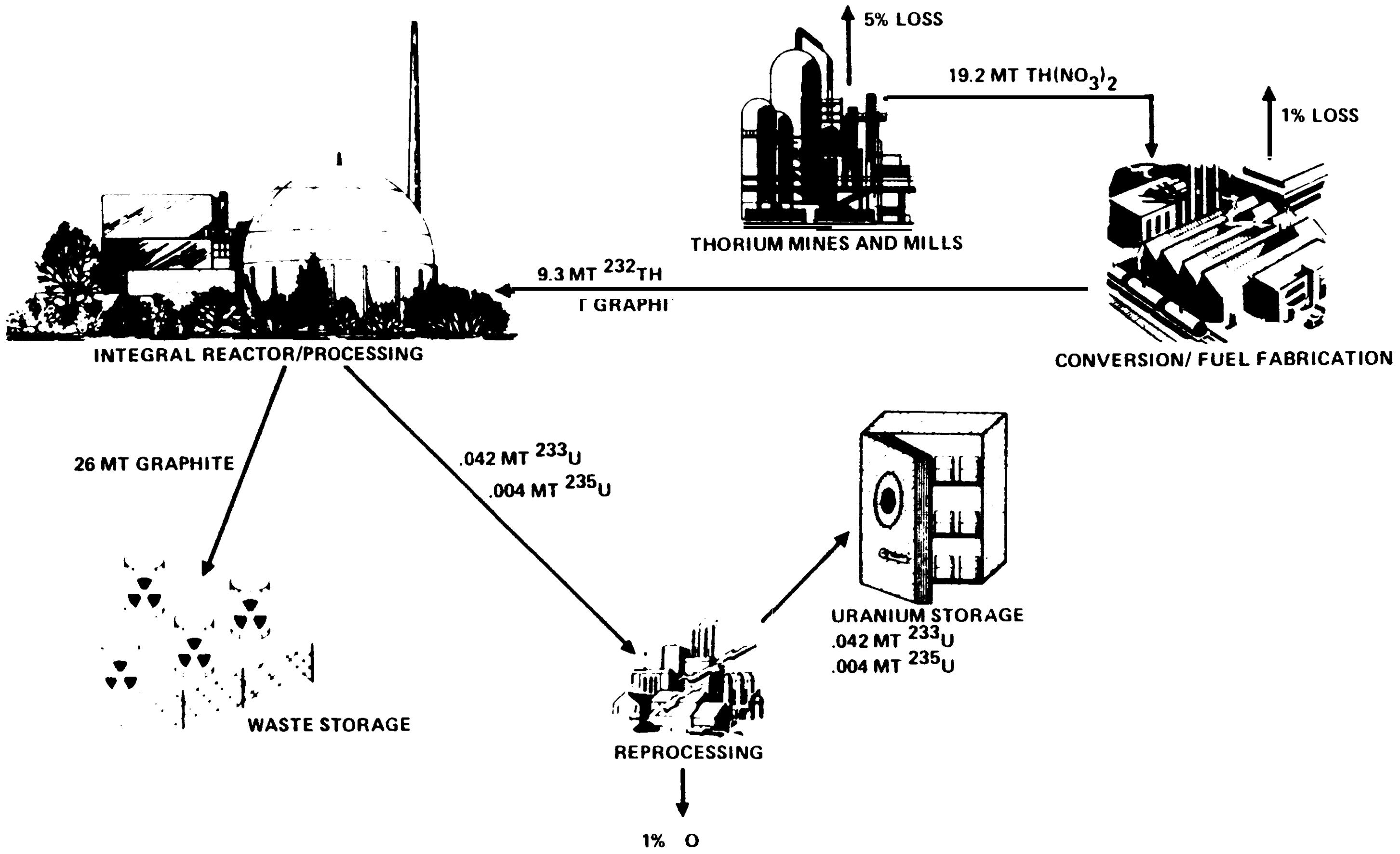


Fig. 42. Material Flow for the Molten Salt Breeder Reactor

Table 16

MSBR (1000 MWe 75% Capacity Factor)

	Start Up	Equilibrium
Mining (103 MT)		
Uranium 0.2% concentration	234	
Thorium 0.2% concentration	73	10.1
Milling (MT U_3O_8)	521	
(MT Th $(NO_3)_4$	281	19.2
Conversion (=Enrichment Feed) (MT UF6)	650	
Enrichment		
SWU (MT)	**570**	
Tails (MTU at 0.2%)	**436.9**	
Enriched Product (MTU)	**2.4**	
Assay	**93%**	
Feed nat U (MTM)	**439**	
Reactor Load in		
Quantity (U/Pu/Th) (MTM)	2.419/ - / 136	
Isotopics %		
u-233	0	
U-234	0	
U-235	93	
u-236	0	
U-238	7	
Reactor Inventory		
Quantity (U/Pu/Th) (MTM)		2. 3/-/ 136
Isotopics %		
U-233	0	68
U-234	0	17
U-235	93	7
U-236	0	8
U-238	7	
Net Plant Efficiency (%)	43	43
Reload in kg/yr		
Th-232	9281	9281
Graphite	26219	26219
Reload out kg/yr		
U-235	4.2	4.2
U-233	42.8	42.8

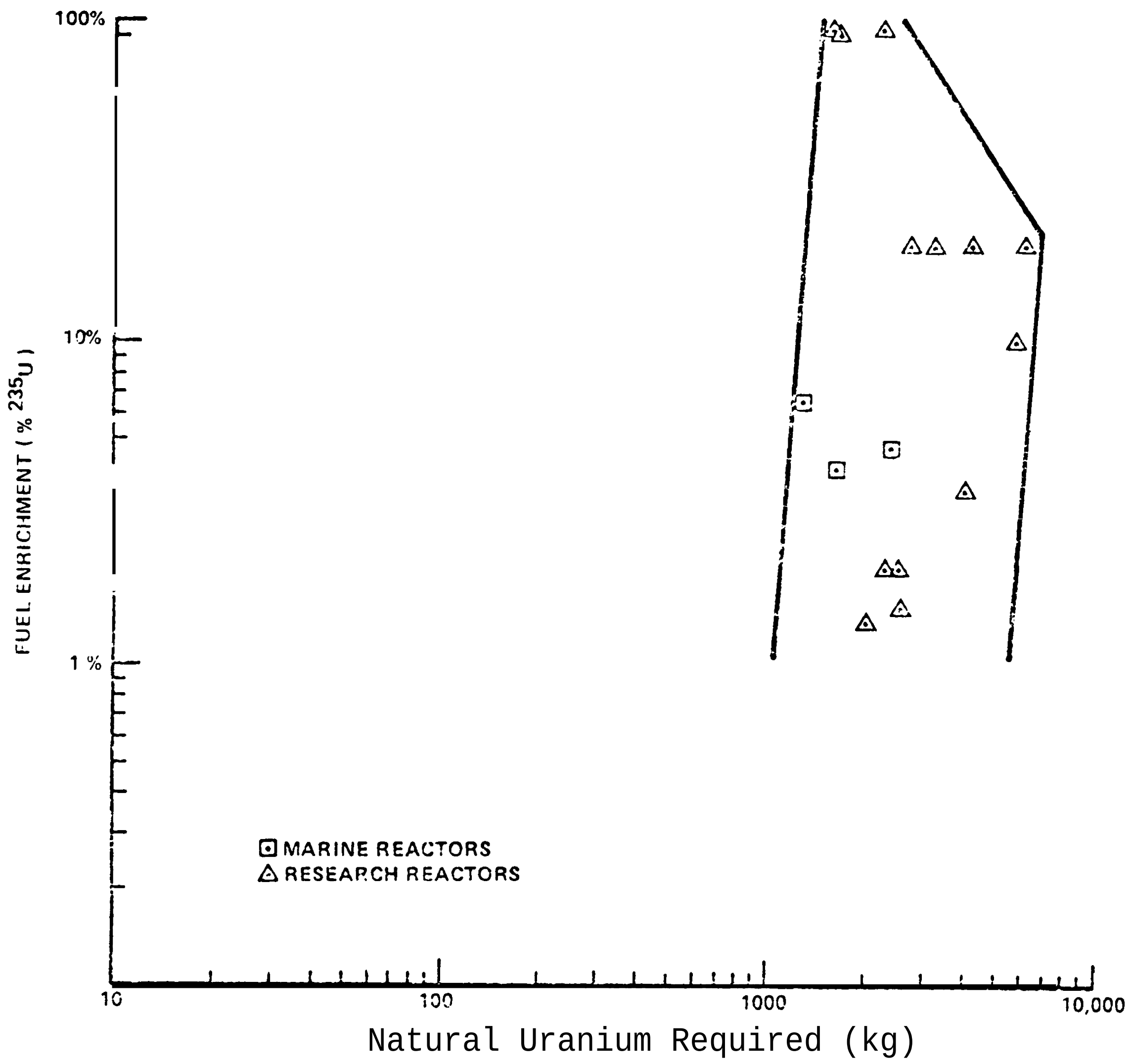


Fig. 43. Annual Natural Uranium Requirements to Enrichment Plant to Provide for 10 Mwt Reactor Annual Fuel Requirements

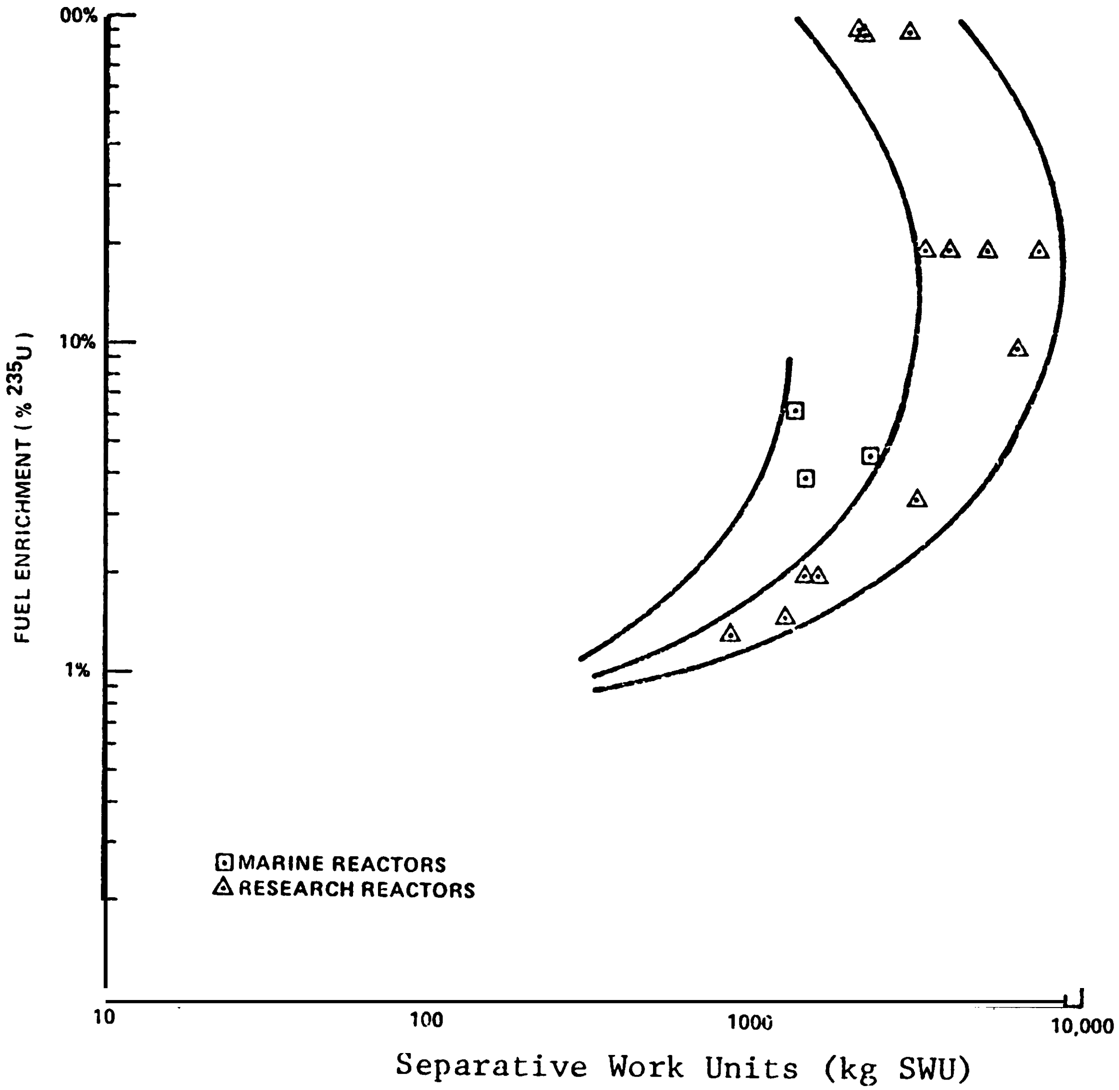


Fig. 44. Seprative Work Units Requirements to Provide for 10 Mwt Reactor Annual Fuel Requirements

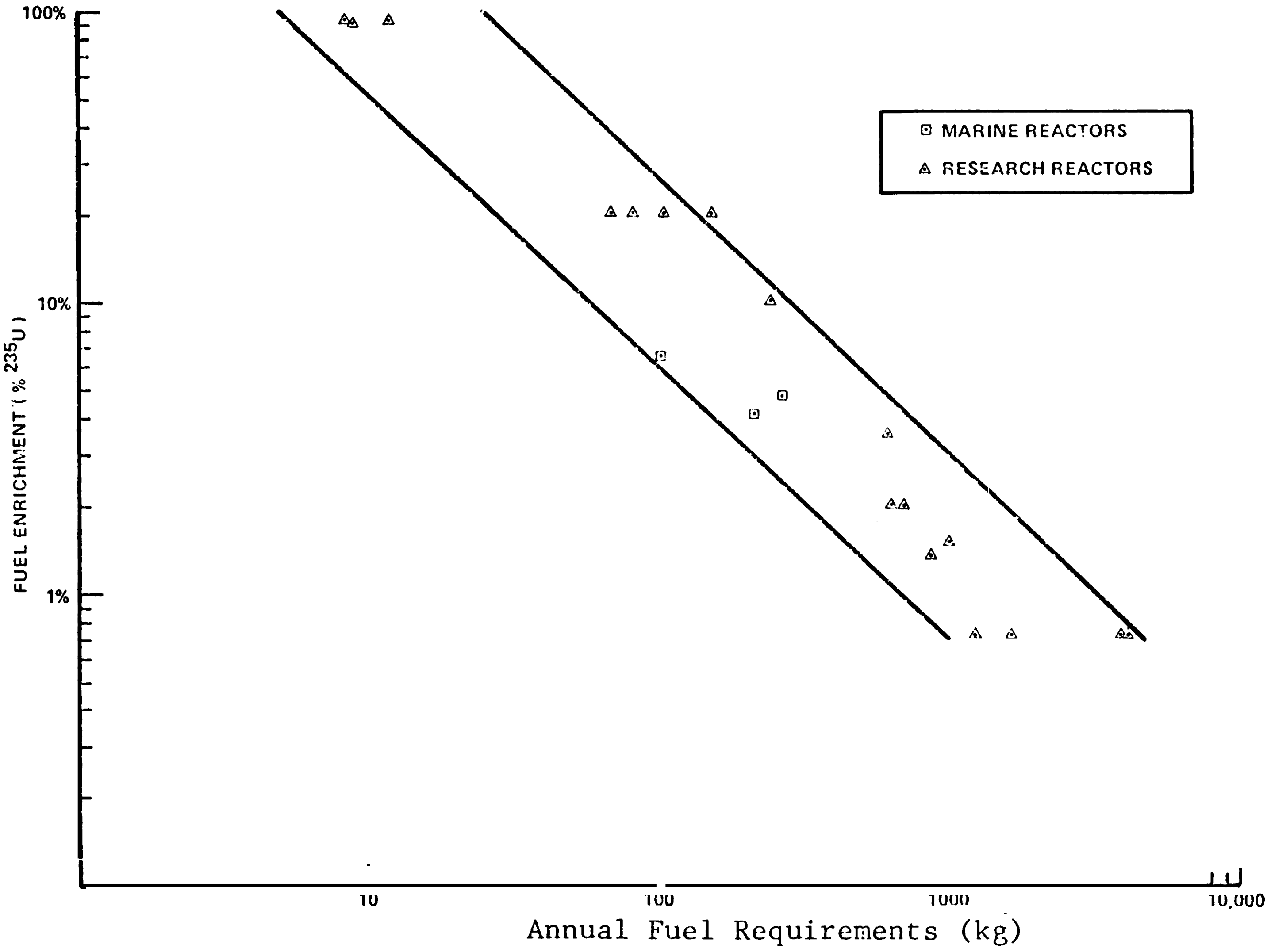


Fig. 45. Annual Uranium Fuel Requirements for a 10 Mwt Reactor

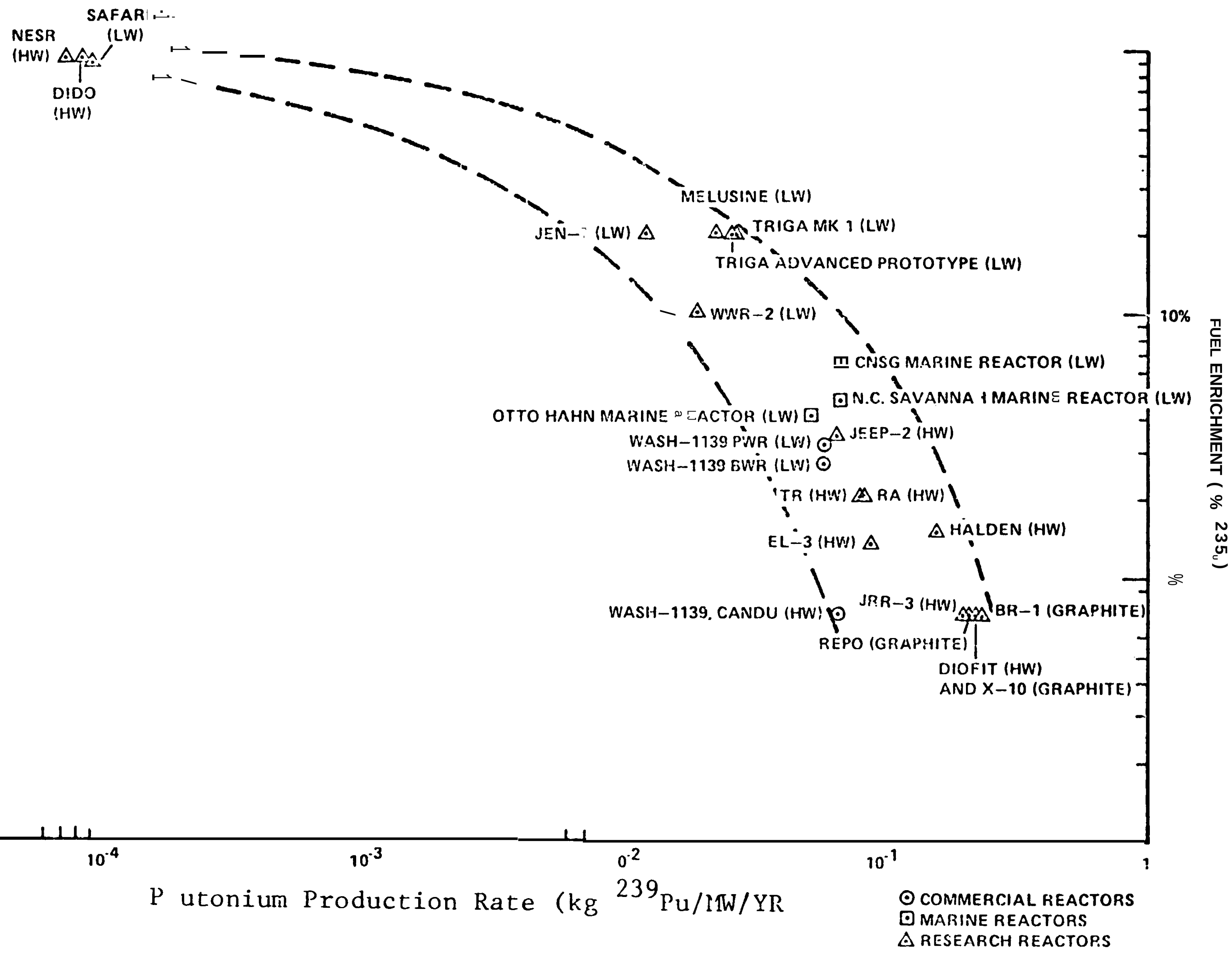
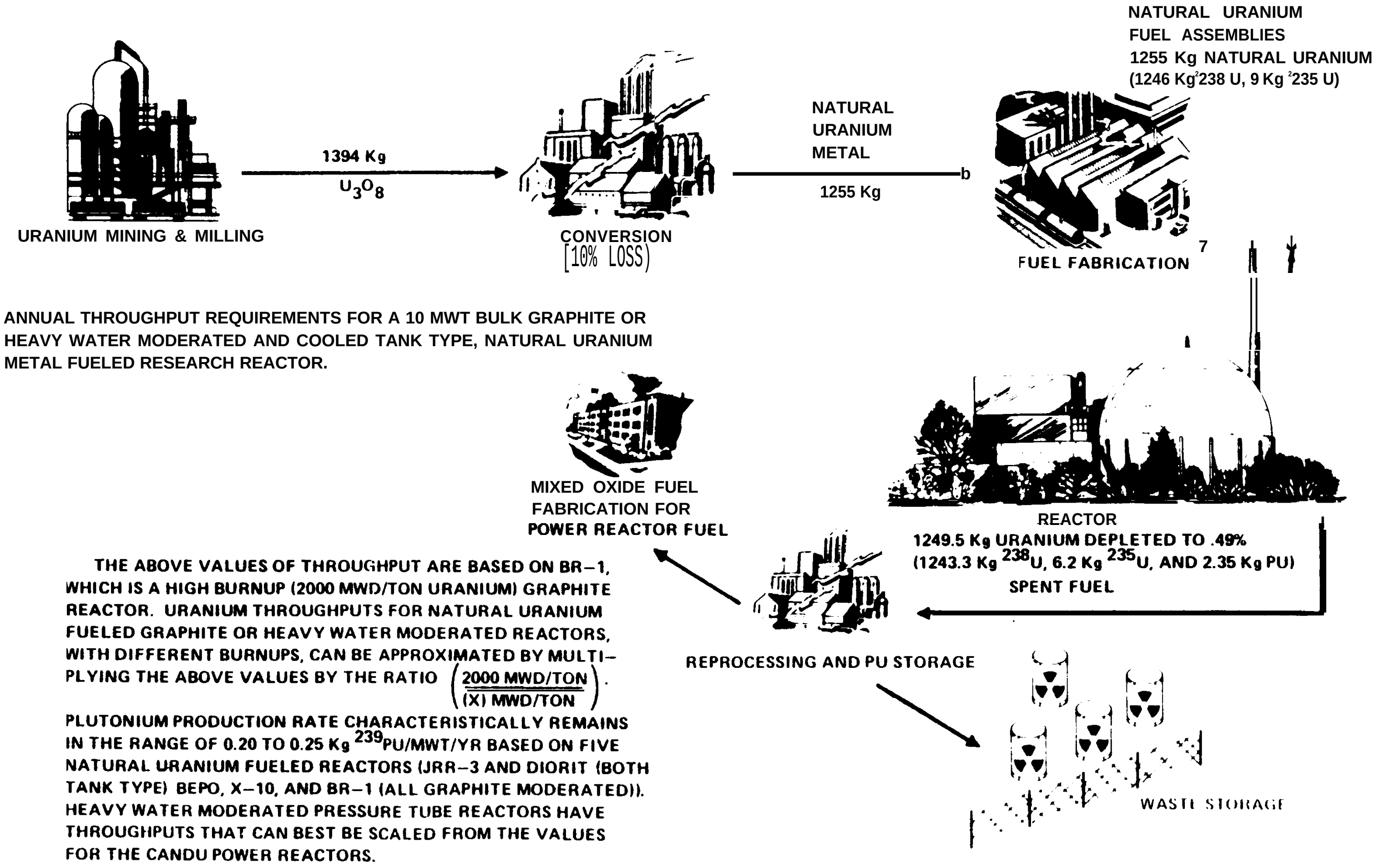


Fig. 46. Estimated Plutonium Production for Various Research and Power Reactors

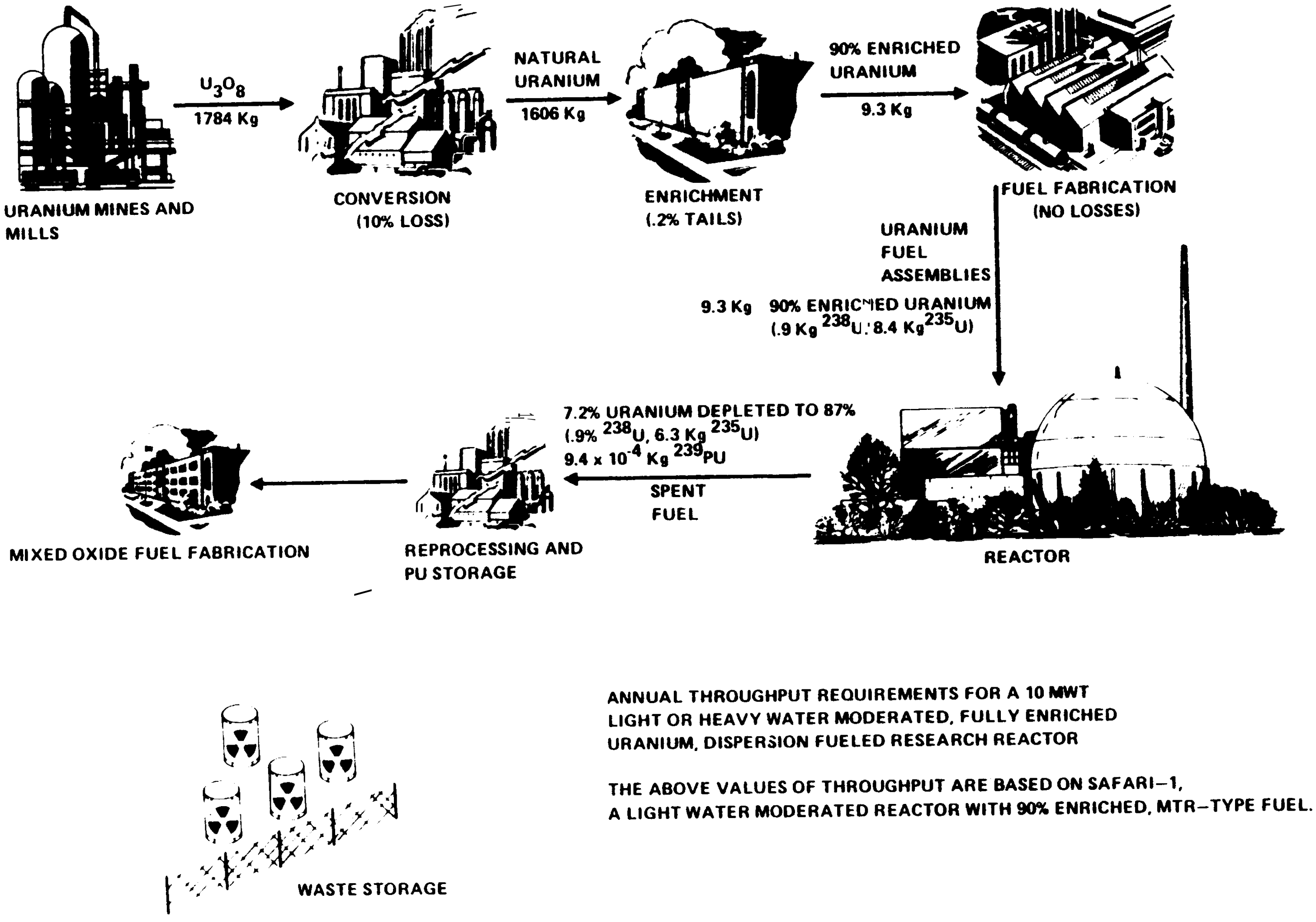


ANNUAL THROUGHPUT REQUIREMENTS FOR A 10 MWT BULK GRAPHITE OR HEAVY WATER MODERATED AND COOLED TANK TYPE, NATURAL URANIUM METAL FUELED RESEARCH REACTOR.

THE ABOVE VALUES OF THROUGHPUT ARE BASED ON BR–1, WHICH IS A HIGH BURNUP (2000 MWD/TON URANIUM) GRAPHITE REACTOR. URANIUM THROUGHPUTS FOR NATURAL URANIUM FUELED GRAPHITE OR HEAVY WATER MODERATED REACTORS, WITH DIFFERENT BURNUPS, CAN BE APPROXIMATED BY MULTIPLYING THE ABOVE VALUES BY THE RATIO $\left(\frac{2000\ \text{MWD/TON}}{(X)\ \text{MWD/TON}}\right)$.

PLUTONIUM PRODUCTION RATE CHARACTERISTICALLY REMAINS IN THE RANGE OF 0.20 TO 0.25 Kg ^{239}PU/MWT/YR BASED ON FIVE NATURAL URANIUM FUELED REACTORS (JRR–3 AND DIORIT (BOTH TANK TYPE) BEPO, X–10, AND BR–1 (ALL GRAPHITE MODERATED)). HEAVY WATER MODERATED PRESSURE TUBE REACTORS HAVE THROUGHPUTS THAT CAN BEST BE SCALED FROM THE VALUES FOR THE CANDU POWER REACTORS.

Fig. 47. Material Flow for Heavy Water Research Reactors



ANNUAL THROUGHPUT REQUIREMENTS FOR A 10 MWT LIGHT OR HEAVY WATER MODERATED, FULLY ENRICHED URANIUM, DISPERSION FUELED RESEARCH REACTOR

THE ABOVE VALUES OF THROUGHPUT ARE BASED ON SAFARI–1, A LIGHT WATER MODERATED REACTOR WITH 90% ENRICHED, MTR–TYPE FUEL.

Fig. 48. Material Flow for Light or Heavy Water, Fully Enriched Uranium, Dispersion Fueled Research Reactors.

4. DIVERSION POTENTIAL OF REACTOR FUEL CYCLE MATERIAL**

The proper perspective on nuclear weapon proliferation requires knowledge about nuclear weapon material requirements and their relation to reactor fuel cycle material. Since a detailed analysis of nuclear fission weapon parameters would require a classified report, the unclassified details reported below only define the order of magnitude of the weapon requirements. In any case, the exact amount, type, and geometrical configuration of material depends upon a specific design for a desired explosive yield

The isotopes of particular interest for the construction of nuclear explosives are ^{233}U, ^{235}U, and ^{239}Pu. (However, it should be noted that all Pu isotopes are fissile to fast neutrons.) Since each of these isotopes have different nuclear properties, differing amounts of these materials, in pure form, are required to sustain a critical reaction. Inside an infinitely thick, heavy metal-reflector, approximately 5 kilograms of ^{239}Pu or 233U, or 15 kilograms of ^{235}U are required for a critical mass (1,2)

None of the nuclear power reactor fuel cycles can be considered "ideal" sources for weapons material since they do not contain isotonically pure, metallic* fissile material at any

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1. H. C. Paxton, "Los Alamos Critical-Mass Data", Los Alamos Scientific Laboratory report LAMS-3067, April 1964.
2. W. R. Stratton, "Criticality Data and Factors Affecting Criticality of Single Homogeneous Units", Los Alamos Scientific Laboratory, July 1964.

* HTGR fuel comes relatively close, in that highly enriched uranium (93% 235U) is utilized.

** See Appendix A for discussion of diversion potential from critical fuel cycle facilities.

point in the fuel cycle. The fuel cycles do, however, contain fissile material in other chemical forms such as oxides, carbides, or nitrates, typically mixed with other isotopes from the same element.

The other isotopes (^{238}U, ^{240}Pu, ^{242}Pu) generally found in fuel cycle material act as impurities as far as weapons are concerned The inclusion of these isotopes does not preclude the use of the material for the construction of weapons. Material enriched with 20% or more ^{235}U and any isotopic form of plutonium found in a power reactor fuel cycle could be converted to an explosive without enriching the isotopic fissile content of the material. The larger the percentage of these isotopes, however, the less attractive the material becomes in terms of weapon parameters, such as explosive yield per gram, weapon size, spontaneous radiation from the nuclear material, and predictability.

The stable chemical forms of fissile material found in fuel cycles include the oxides, carbides and nitrate solutions. Theoretically, pure oxide and carbide fissile material could be used directly in a weapon core(3). As before, the oxygen and carbon act as "foreign" elements by changing the fissile material density and scattering properties of the material. The nitrate solutions could not be used directly in a weapon. All of these chemical" forms can be converted to metallic form, however, through standard chemical techniques found in open technical literature. On the national threat scale, the chemical form of the fissile material presents no particular difficulty. This may or may not be true for a terrorist or subnational threat.

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3. Mason Willrich and Theodore B. Taylor, "Nuclear Theft: Risks and Safeguards", Ballinger Publishing Co. , 1974.

4.1 EXPOSURE OF STRATEGIC SPECIAL NUCLEAR MATERIAL

An educational, but imprecise, technique for qualitatively classifying reactor fuel cycles is to look at the fuel cycle components for the various reactors having strategic special nuclear material (SSNM) exposed at some point in the process. (Exposed is defined to mean that the material exists in a pure chemical form separated from other compounds and SSNM indicates that no further isotopic enrichment is necessary to produce weapons grade material.) This taxonomic procedure is useful but does not necessarily rate the fuel cycles in terms of proliferation potential. A systematic consideration of the threat, plus specific scenarios on the fuel cycle components, require additional information for a fuel cycle proliferation rating. For example, in a country which contains only a reactor and no other fuel cycle components, the proliferation potential of-each of the fuel cycles is nearly the same. The only proliferation difference exists in the difficulty of separating fresh fuel SSNM versus the separation of SSNM in irradiated fuel.

In Table 18 the exposure of SSNM for the representative reactor fuel cycles is shown for the various fuel cycle components. A quick perusal of Table 18 indicates that no ideal reactor fuel cycle exists -- they all contain SSNM. In addition, SSNM is generally exposed in the facilities in the back end of the fuel cycle (i.e., reprocessing and recycle fuel fabrication).

Before discussing additional details relative to the exposure matrix table, the typical exposure modes for fuel cycle processes should be mentioned. In an enrichment plant, the SSNM may appear as the output of the plant -- it is the end

TABLE 18

STRATEGIC SPECIAL NUCLEAR MATERIAL EXPOSURE MATRIX

REACTOR TYPE*

FUEL CYCLE COMPONENT	LWR NO RECYCLE	LWR WITH RECYCLE	HWR	HTGR	LMFBR	LWBR	MSBR	RESEARCH REACTORS		
								MTR	TRIGA	D_2O
ENRICHMENT	3	3	–	1	– or 1	3	1	1	1	–
FUEL FABRICATION	3	3	3	1	1	3	–	1	1	3
REACTOR	2	2	2	2	2	2	2	2	2	2
REPROCESSING	–	1	–	1	1	1	–	–	–	–
RECYCLE FABRICATION	–	1	–	1	1	1	–	–	–	–
WASTE DISPOSAL	2	2	2	2	2	2	2	2	2	2

LEGEND

1 – STRATEGIC SPECIAL NUCLEAR MATERIAL (SSNM) EXPOSED DURING THE SPECIFIC FUEL CYCLE COMPONENT PROCESS

2 – SSNM EXISTS IN THE PROCESS BUT MUST BE SEPARATED FROM OTHER MATERIAL

3 – SSNM DOES NOT EXIST IN THE FUEL CYCLE PROCESS

– – THIS FUEL CYCLE COMPONENT IS NOT CONSIDERED TO BE A STANDARD COMPONENT OF THE REACTOR FUEL CYCLE

LWR – LIGHT WATER REACTORS
HWR – HEAVY WATER REACTORS
HTGR – HIGH TEMPERATURE GAS–COOLED REACTOR
LMFBR – LIQUID METAL COOLED FAST BREEDER REACTOR
LWBR – LIGHT WATER COOLED BREEDER REACTOR

MSBR – MOLTEN SALT BREEDER REACTOR
MTR – MATERIALS TEST REACTOR (URANIUM ALUMINUM ALLOY FUEL)
TRIGA – RESEARCH REACTOR MANUFACTURED BY GENERAL ATOMIC
D_2O – HEAVY WATER MODERATED REACTOR (NATURAL URANIUM FUEL)

*THE INITIAL AND EQUILIBRIUM CORE LOADINGS ARE CONSIDERED TOGETHER product of the process. The chemical form of the SSNM is uranium hexafluoride or after conversion, uranium oxide (UO_2). This material is input to the fuel fabrication facility, where it is processed into fuel elements which are, in turn, input to the reactor. After sufficient reactor operation, the irradiated fuel may be reprocessed; here the SSNM is exposed as the reprocessing plant product. The typical chemical form for the reprocessing plant product is a nitrate or after conversion, an oxide. This material may be then input to a recycle fuel fabrication plant and refabricated into reactor fuel and fed back to the reactor.

The light water reactor fuel cycle without recycle does not expose SSNM in its normal operation. This is the present mode of operation in the United States, with the irradiated fuel temporarily stored until a reprocessing or permanent disposal decision is made. The irradiated fuel contains significant amounts of plutonium. In the LWR fuel cycle with recycle, SSNM (plutonium) is exposed at the reprocessing and recycle fuel fabrication facilities. The rationale for recycle is more efficient utilization of the energy content in uranium fuel. The economic basis for recycle is unclear, since total recycle costs have not evolved into a predictable value. Uranium resources would be extended by recycle by about 30%. It must be noted however, that there are alternative methods of extending the uranium resources to about the same fractional increase. The use of more efficient converter reactors, such as the HTGR, the development of a high burnup, throwaway LWR fuel cycle, thorium fuel cycles, the tandem fuel cycle, or the development of laser enrichment (with a decreased tails enrichment) would all tend to extend the uranium resources. The economic value and practicality of these alternatives has yet to be proven.

An alternative reprocessing scheme is also available and technically proven. In this scheme the uranium and plutonium are never separated but are decontaminated from the reactor poisons (fission products) only. Some advantages of this scheme include the following:

- A simplified reprocessing flow chart, with fewer safety problems and improved efficiency.
- Improved recycle fuel because of the intrinsic homogeneity of the coprecipitated uranium and plutonium oxides.
- Improved safeguards because the uranium and plutonium would only contain approximately 1.5% fissile material. A diverter would have to divert approximately 1000 kg of coprecipitated material to separate out 5 kg of fissile plutonium for a nuclear weapon. The safeguard advantages are primarily against a subnational threat, since a national entity with large resources could, with relative ease, separate the plutonium from the uranium.

The major disadvantage of the coprecipitation reprocessing scheme is the recycle fabrication plant. Large amounts of mixed oxide fuel have to be handled (increasing plant size), and all waste and scrap streams are contaminated with plutonium. In addition, the mixed uranium-plutonium oxide has to be enriched to roughly 4% fissile content. These disadvantages incur economic penalties which tend to detract from the advantages.

Heavy water reactors, like the Canadian CANDU, have a rather simple fuel cycle, with no reprocessing and no exposure of SSNM. Even though the SSNM is not exposed during the “standard” CANDU fuel cycle, this reactor does have proliferation liabilities. Because of the on-line refueling capabilities of the pressurized tube design, fuel management can be optimized to produce weapons grade plutonium with no power production penalty. Of course, the fuel throughput must be increased accordingly; this, however, is a relatively minor economic penalty.

There are heavy water reactors which utilize a pressure vessel design and consequential, off-line refueling. A notable example of this is the German built reactor in Atucha, Argentina.

The high-temperature gas-cooled (HTGR) reactor promoted by the General Atomic Company in the U.S. is the **only** operational civilian power reactor concept that utilizes fully enriched uranium (93% ^{235}U) as fuel. The exposure of

SSNM in the front end of the HTGR fuel cycle requires careful safeguards considerations, particularly if this concept becomes popular on a world-wide scale. The manufactured HTGR fuel does have some intrinsic protection against a subnational threat, since recovery of the uranium is not a trivial task.

The backend of the HTGR fuel cycle has not been fully developed, not even to the incomplete extent of the LWR fuel cycle. Consequently, a substantial uncertainty exists as to the relative economic merit of various HTGR reprocessing and recycling programs. A recent report(6) indicates that the most economic schemes involve mixing recovered ^{235}U and ^{233}U for one recycle back through the reactor. After the one recycle, the remaining ^{235}U and ^{233}U is retired. The indications are that the HTGR recycle has a significant economic advantage over a throw-away fuel cycle. HTGR recycle may be limited to a one-time recycle because of the build-up of ^{236}U -- a reactor poison.

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6. N. D. Holder, V. H. Pierce, and M. P. Rothstein, “An Economic Analysis of U-235 Recycle in the HTGR”, General Atomic report GA-A13836, July 15, 1976.

HTGR recycle material has built-in protection against a subnational diversion, because of the in-breeding of ^{232}U -- an active precusor of a highly radioactive chain of daughter products. For example, 5 kg of ^{233}U, containing 1000 parts per million of ^{232}U, would have a radiation dose rate near 10 Rem per hour, one foot from the material, after a 20 day delay period following uranium separation. For longer delays, the radiation dose builds up to saturation level roughly 10 years after separation.

There are alternative HTGR fuel cycle concepts to the present fully enriched uranium-thorium fuel cycle. A 1968 General Atomic report[7] concluded that a low-enriched uranium fuel cycle, possibly as low as 6% ^{235}U, would have fuel cycle costs comparable to a throw-away thorium cycle. A more recent economic analysis tends to support this conclusion. The effect of utilizing a low-enriched fuel cycle would lower the conversion ratio substantially (it would now be roughly the same as LWRS), require more uranium fuel and introduce substantial quantities of plutonium into the fuel cycle. It would, however, remove the exposure of SSNM from the front end of the HTGR fuel cycle.

The liquid metal-cooled fast breeder reactor (LMFBR) has SSNM exposed throughout its fuel cycle. The enrichment facility is only needed in the fuel cycle, if the initial core load is made of enriched uranium and not plutonium. Since the LMFBR is a breeder reactor (it produces more fissile material than it consumes) the reprocessing and recycle fuel fabrication plants are required components of the fuel cycle. An important feature of an LMFBR is the amount of plutonium involved in the fuel cycle. An initial load in a 1000 MWe reactor would involve some 3 to 4 metric tons of plutonium. Annual reload requirements are roughly 1 ton of plutonium.

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[7] P. U. Fischer, S. Jaye, and H. B. Stewart, "Alternate Fuel Cycles for the HTGR," Gulf General Atomic report GA-9010, October 4, 1968.

The light water breeder reactor (LWBR) necessarily exposes SSNM in the backend of its fuel cycle. Since it operates on a thorium fuel cycle, the comments on the in-breeding of ^{232}U in the HTGR fuel are also relevant here. An interesting feature of the LWBR is that it is just barely self-sustaining. Removal of significant quantities of SSNM from the fuel cycle shut down the reactor for power production or require a corresponding importation of fresh fuel.

The molten salt breeder reactor (MSBR), with its unusual fuel cycle, does not expose SSNM during its operational cycle, except for the possible production of roughly 3% excess fuel per year. The initial core would most likely start up with 93% enriched uranium.

Research reactors are normally characterized by their small core fissile inventory, an uncertain operational schedule and lack of a commercial backend of the fuel cycle. These features are generally considered positive assets for safeguards purposes. On the other hand, research reactors are often sold on the basis of their flexible fuel management options and relative ease of refueling. This flexibility gives the operators many options.

MTR (Material Test Reactor) type fuel is often used to generically describe uranium-aluminum alloy fuel clad in aluminum. Fuel enrichments for research reactors using MTR type fuel vary from slightly enriched to fully enriched (93% ^{235}U), with typical enrichments at 20% and 93%. The MTP--type fuel plate is relatively easily processed to separate out the uranium. The chemistry involved is well known and available in open literature.

TRIGA fuel elements consist of uranium-zirconium alloy. The enrichment may be 20%, 70% or 93%. The reprocessing and recovery of uranium from these types of elements is much more difficult than for MTR fuel.

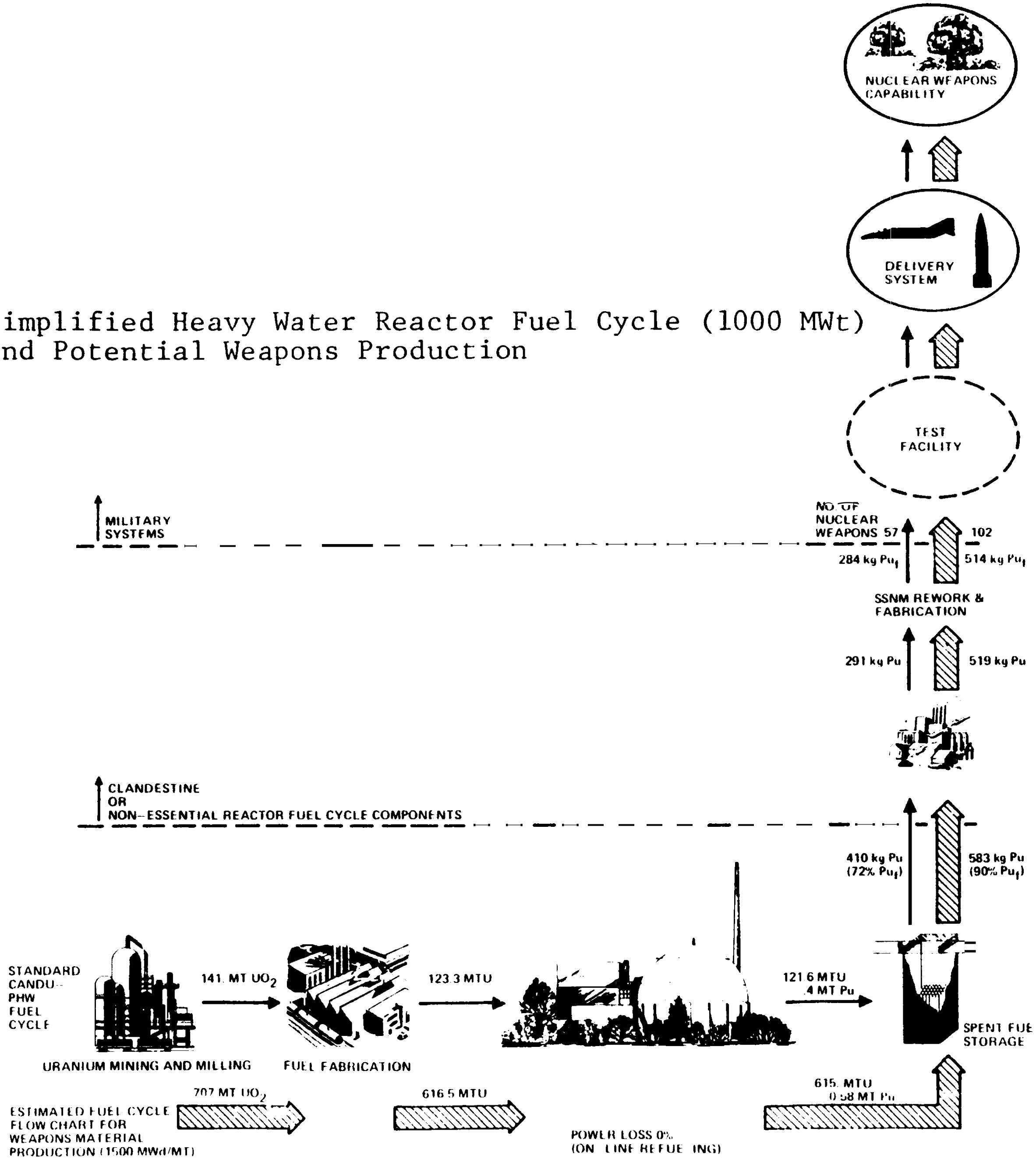
Heavy water moderated and cooled research reactors using natural or slightly enriched uranium fuel, appear to be the most easily safeguarded reactor. They are, however, capable of producing plutonium on a small scale, as India proved in May 1974.

4.2 DIVERSION PATHWAYS FOR SSNM

Assuming that a political/technical decision has been made to develop the most effective nuclear weapons possible by diverting material from a reactor fuel cycle, the most cost effective, least detectable and lowest impact pathway to acquiring the necessary SSNM must be determined. There is no simple, unique manner to make this determination. It depends upon the threat (large country, small country, sub-national group), the resources available, and the specific reactor fuel cycle under attack. In this section, we shall examine a few representative fuel cycles to illustrate the impact on the fuel cycle (power production, fuel throughputs, etc.) and the additional facilities required to produce nuclear weapons from fuel cycle material. Since fuel cycle plutonium is not optimum SSNM for nuclear weapons production, we shall also discuss fuel cycle tampering to produce fore favorable isotopic concentrations of SSNM.

At the bottom of Figure 49, the fuel cycle for a 1000 MWe CANDU-type heavy water reactor is depicted with annual equilibrium cycle fuel flows. The most obvious, straightforward method for achieving nuclear weapons capability without affecting the power production is to reprocess spent fuel containing approximately 0.4 tons of plutonium (72% fissile Pu) into roughly 57 nuclear weapons. This assumes a 1% Pu loss to reprocessing and SSNM rework and fabrication. Each of the weapons would contain 5 Kg of fissile Pu and nearly 2 Kg of ^{240}PU + ^{242}PU.

Fig. 49. Simplified Heavy Water Reactor Fuel Cycle (1000 MWt) and Potential Weapons Production



Plutonium with a higher percentage of ^{239}Pu could, in principle, be achieved in a CANDU fuel cycle without causing any power production losses. Instead of burning the fuel to 7500 MWd/MT, the fuel times faster, producing more total plutonium (.58 MT Pu) , with a more favorable fissile content (90%). This procedure would ultimately produce roughly 102 weapons per year for a 1000 megawatt reactor. The only tampering indication would be the increased fuel throughput. The key safeguards management point in the fuel cycle is the spent fuel. An account of all the spent fuel emanating from the reactor counters this method of clandestine weapons production.

A surveillance technique for fuel removal from a CANDU reactor has, in fact, been demonstrated.* The on-line refueling machine, of course, complicates the accounting of fuel bundles discharged from the reactor; however, the transfer channel can be monitored (for high activity gamma ray sources) to count the number of irradiation fuel bundles as they pass by on their way to the storage bay. The item count of the stored bundles in the bay correlated with the tamper proof continuous surveillance monitor could -_ assure an inspector that all irradiated CANDU fuel is accounted for. Monitoring of the spent fuel discharged from CANDU reactors is not presently required.

In Figure 50 a simplified 1000 MWe LWR fuel cycle with no recycle is depicted. This fuel cycle is representative of the majority of power reactors operating in the world today. Assuming 75% power production (i.e., 75% capacity factor) for the year, this equilibrium cycle pressurized water reactor produces approximately 230 Kg of plutonium each year. After

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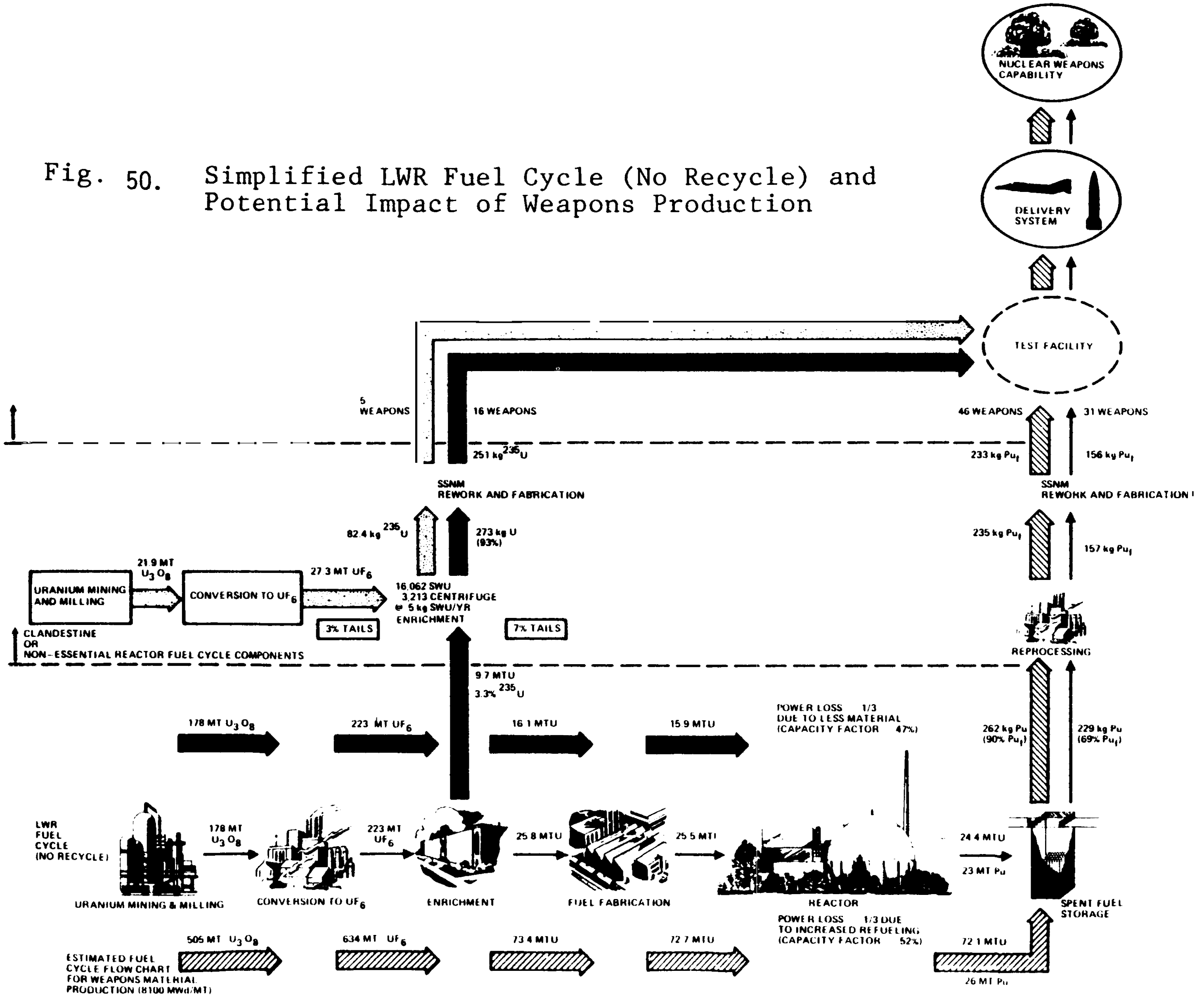
* D.B. Siden, J.G. Hodgkinson, J.W. Cornbell, H.D. Kosanke, "Testing of Techniques for the Surveillance of Spent Fuel flow and Reactor Power at Pickering Generating Station," International Atomic Energy Synposium on Safeguarding Nuclear Materials, 20-24 October 1975, Vienna, IAEA-SM-201/67.

Fig. 50. Simplified LWR Fuel Cycle (No Recycle) and Potential Impact of Weapons Production



accounting for losses, this amount of Pu could produce up to 31 nuclear weapons.

The isotopic concentration of the plutonium could be made more attractive for weapons (i.e., from 69% fissile Pu to 90% fissile Pu) by lowering the fuel burnup from 33,000 MWd/MT to 8100 MWd/MT. This, in effect, increases the fuel throughput in the fuel cycle. For LWRs, however, the refueling must be performed off-line. Consequently, a power production penalty must be paid for the additional refueling required by a lower burnup, higher fuel throughput. For the situation depicted in Figure 50 the power loss is almost 1/3 the yearly power production, assuming that four refueling with typical down times(8) are required. An additional indicator that an abnormal fuel cycle is in operation is the roughly 3 fold increase in fuel. If this material is being imported (i.e., the country has no enrichment capability), then the abnormal situation is discernible. The lower burnup fuel can produce more plutonium than the normal fuel cycle (even with less power production), with higher Pu isotopic concentration. The resultant weapons production increase is almost 50%.

There are, of course, other LWR fuel management schemes available to a reactor operator which produce weapons grade plutonium. The impact on power production, fuel requirements, and weapons production may differ in detail from those depicted above. The sense of the impacts is apparent, however. The critical safeguards management point for LWR plutonium production is accounting for the spent fuel emanating from the reactor (as in the case for the HWRs).

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8. A. Fattah, R. Skjoeldbrand, "Performance Analyses on Nuclear Power Plants from Operating Experience Data", IAEA-SM-195/36, Symposium on Reliability of Nuclear Power Plants, April 14-18, 1975.

LWR fuel assemblies have identifiable serial numbers that can be utilized by safeguards inspectors for accounting purposes. However, BWR assemblies can and occasionally are disassembled to remove fuel rods. This practice, potentially, could be subverted to produce optimum weapons material if a clandestine source of fuel rods is available. A detection counter to this hypothetical threat is the use of tamper proof seals on BWR and PWR fuel assemblies. These seals are presently under test and development.*

There is another credible weapons production possibility associated with the LWR fuel cycle. The diversion of a portion of the slightly enriched fuel to a clandestine centrifuge enrichment plant could facilitate the production of nuclear weapons. Assuming that a power production loss of roughly 1/3 is acceptable (to an overall capacity factor of 47%), then- almost 10 tons of the 3.3% enriched uranium could be diverted to the centrifuge plant. With a 0.7% tails enrichment, some 16 MT of separative work units (SWU) are required to produce 273 Kg of 93% enriched uranium. This corresponds to roughly 16 nuclear weapons. The number of centrifuges, at 5 Kg SWU/year capacity, required to further enrich the LWR fuel is over 3,000, These same centrifuges could be utilized to enrich natural uranium to weapons material at 93% enrichment. This type of clandestine operation could produce approximately five uranium weapons, less than 1/3 the number produced by the fuel cycle diversion method.

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* S.J. Crutzen, R. Haas, P.S. Jehenson, A. Lamourox, "Application of Tamper-Resistant Identification and Sealing Techniques for Safeguards," International Atomic Energy Agency symposium on Safeguarding Nuclear Materials, 20-24 October 1975, Vienna, IAEA

4.3 CONVERSION OF FUEL CYCLE MATERIAL TO WEAPONS MATERIAL

A country desiring an efficient, reliable nuclear weapons capability, particularly one that would be handled by sophisticated delivery systems, would have to convert the fuel cycle material into weapons material. This section summarizes the resources and physical facilities required to convert either plutonium nitrate or plutonium oxide to plutonium metal. The conversion of highly enriched uranium to weapons material is somewhat similar, except that less attention would have to be paid to the containment of the uranium within the process. The emphasis is on well-known and proven production processes as opposed to R&D or laboratory scale operations. Other processes do exist and may be more efficient. The required techniques and equipment are more complex, however.

Assumptions

1. The simplest operational facility will be scoped.
2. No seismic or tornado design requirements will be imposed on the design.
3. Minimum contamination containment systems will be provided (i.e. only one level of filtration of process cell air will be considered).
4. No scrap recycle or recovery will be provided. All scrap material will be treated as waste.
5. All solid waste will be disposed of by shallow land burial.
6. All liquid waste streams will be disposed of by cribbing (shallow land disposal).
7. All remote operations will be done in glove boxes.
8. Recovery rates as low as 85% of the original material as metal are acceptable.
9. All unit processes are batch type.
10. The two most important criticality control Parameters will be batch size and equipment design.

There are two separate process steps to be considered. The first is the conversion of plutonium nitrate to plutonium oxide; the second is the conversion of plutonium oxide to plutonium metal. It is possible to go directly from the oxide to the metal or to by-pass the oxide on the way to the metal, but these processes will not be considered because of the assumptions stated **above.**

There are two well-known, dependable processes for the conversion of plutonium nitrate to plutonium oxide. These processes are referred to as plutonium peroxide precipitation and plutonium oxalate precipitation. The flowsheet concepts are the same for both cases. The plutonium feed streams are first adjusted for plutonium and acid concentrations. Next, the precipitation agent, either oxalic acid or hydrogen peroxide, is added. This is followed by a digestion period, then filtration of the plutonium precipitate. The plutonium cake is then decomposed to plutonium dioxide by calcining the cake. Figure 51 outlines a typical plutonium oxalate precipitation flowsheet.

The conversion of the oxide to the metal is a two step process. The plutonium oxide is first converted to plutonium tetrafluoride by reacting the oxide with dry hydrogen fluoride. Secondly, the tetrafluoride is reduced to metal by the high temperature, high pressure reaction with metallic calcium.

plutonium metal can be prepared in the massive state by reducing any of the several plutonium halides with an appropriate alkali or alkaline earth metal. In practice, plutonium fluoride is used, principally because it is nonhygroscopic. Figure 51 shows a typical material balance for reduction of plutonium fluoride.

Operational Cycle

All unit operations are assumed to be batch type separations. This allows the design of the equipment to be simple and manually operated. Criticality control is also important in the design.

Based on a batch operation with approximately 5 Kg of plutonium being processed, the following operational time cycles might be expected:

1.	Feed adjustment, precipitation, and digestion	1.5 hours
2.	Filtration	0.75 hours
3.	Drying, calcination, and hydrofluorination	4.5 hours
4.	Reduction	5.0 hours
		11.75 hours

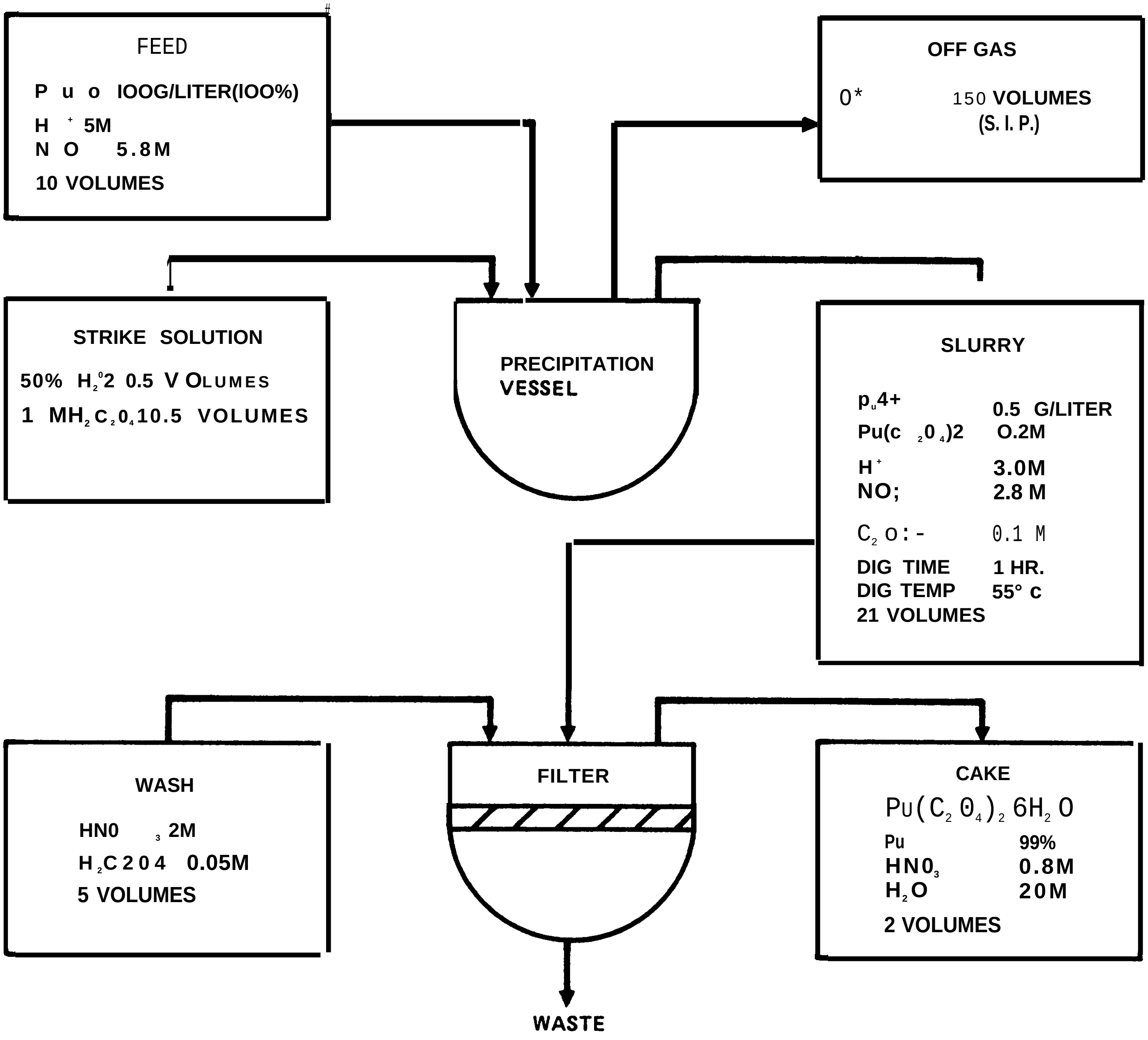

Fig. 51 Plutonium Oxalate Precipitation Flowsheet

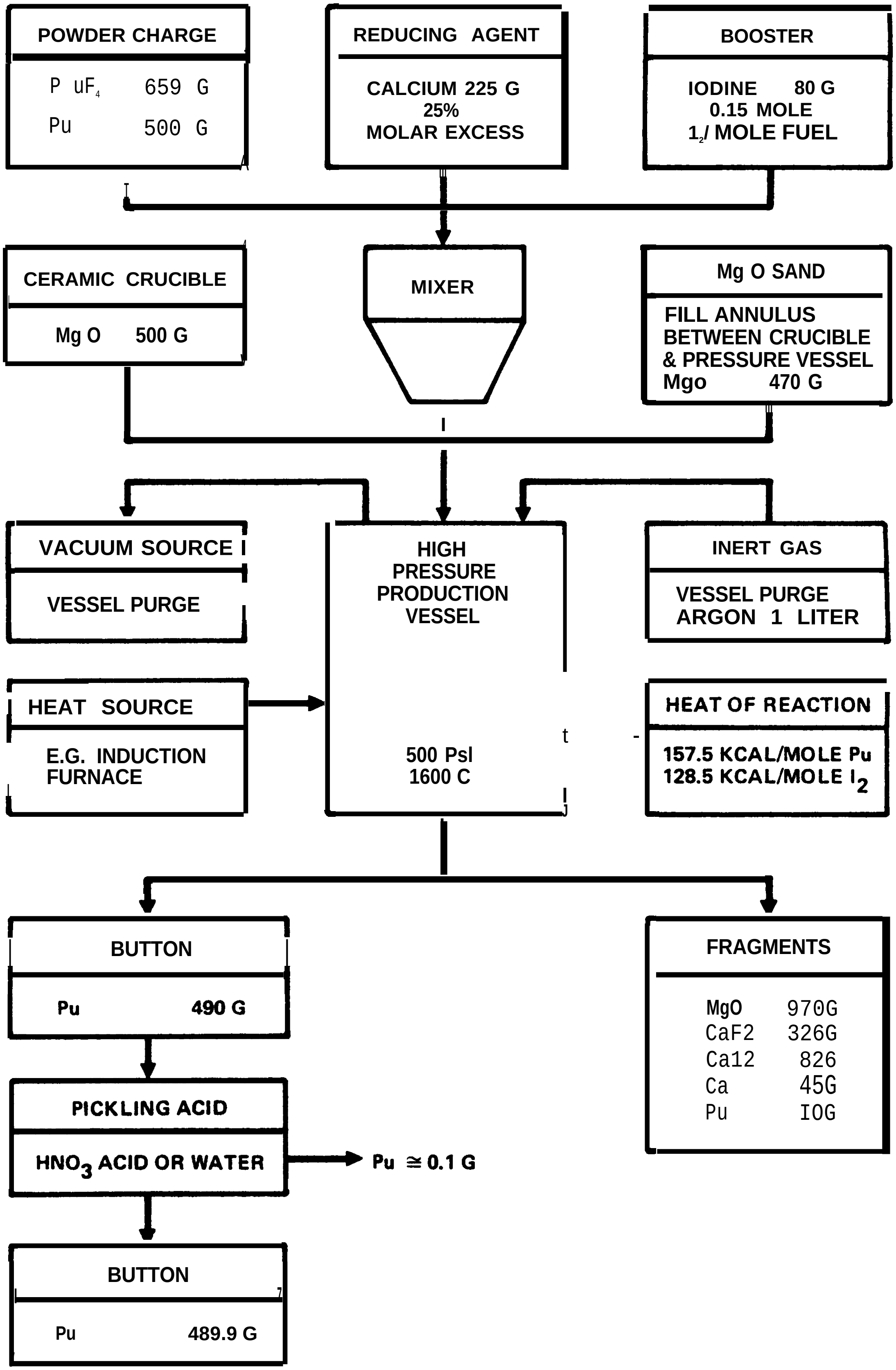

Fig. 52. Plutonium Fluoride Reduction Material Balance

The total cycle time for a one 5 Kg batch of plutonium metal is approximately 12 hours. But it is important to note that there are two independent operations which require a majority of the process time. These are the hydrofluorination step and the reduction step. This means that both operations could be conducted at the same time, allowing a 5 Kg batch of plutonium to be produced every six hours. This means a total of 20 Kg of plutonium metal per day, with a single process line using all of the equipment designed to handle 5 Kg batches of plutonium.

The selection of 5 Kg batch sizes is based on criticality considerations, in that it is reasonably easy to design critically safe equipment for 5 Kg batch sizes. Larger batch sizes present more of a problem.

For a single process line, it is conservatively estimated that all of the process and support areas could be contained within a 3,600 ft^2 building. The actual glove box process area would be no larger than 350 ft^2 with operational glove ports in the front and maintenance access through the back.

Cost Estimates

The following order-of-magnitude estimate is for a one process line operation.

Process Equipment	$ 750,000
Building	350,000
Piping and Instruments	150,000
Glovebox system	75,000
Building Ventilations	45,000
Personnel Support Systems	50,000
TOTAL	$ 1,420,000

These costs include all direct and indirect costs, such as design, engineering, construction and startup. The numbers are only representative of the simplest operating facilities.

There are three important time increments in any construction schedule. These time periods are:

- Scoping and design
- Procurement
- Construction

The controlling scheduling factor for the construction of a facility such as the one being discussed is procurement. The reason for this is that several major items of equipment must be fabricated to specific design and require somewhat unusual materials. The three longest lead items for procurement are the hydrofluorination vessel, the hydrofluorination furnace, and the reduction furnace. Following the detailed designs of these items, procurement would probably require 14 to 24 months fabrication.

It is important to note that detail design and construction of the building and operational support systems can be underway during the procurement phase. With good coordination between all phases of the project, operational startup could be between 24 to 36 months after the start of the project.

5. SUMMARY OF REACTOR CHARACTERISTICS

There are many characteristics pertinent to power reactors that are decisively important to countries that wish to purchase a reactor. The previous sections discussed in detail the general technical and quantitative aspects of the power reactor fuel cycles. This section will summarize some of these technical detail-s concentrating on the resource utilization and safeguards characteristics. Many of the other characteristics are often subjective by nature or specific to a particular situation and not amenable to a generalized technical discussion.

A partial list of reactor characteristics that might be considered by a country embarking upon a nuclear power program should include the following:

1. Remaining R&D problems and requirements
2. Resource requirements
3. costs
4. Fuel cycle independence
5. Design available in size desired
6. Environmental effects
7. Safeguard characteristics

Remaining R&D problems and requirements are listed first on the list, not necessarily because it is the number one consideration, but because it focuses attention on the power reactor fuel cycles that would be considered by a country that wishes to <u>purchase</u> a reactor. At the present time only the light water reactors and the CANDUS are available in essentially off-the-shelf designs.

The other reactor concepts require considerable R&D to achieve a commercial status. We will limit the remaining discussion to the reactors that might be commercialized within the next decade: PWR, PWR with recycle, BWR, BWR with recycle, CANDU-PHW, HTGR, AGR and LMFBR. (Over the next decade isotopic enrichment methods are likely to advance faster than the other reactor concepts -- consequently in 10 years, uranium enrichment may have the clear edge as a potential proliferation pathway.)

Table 19 summarizes the equilibrium fuel cycle material flow characteristics along with other pertinent characteristics. The material utilization is normalized to 1000 MWe and a 75% capacity factor. The requirements for a BWR recycle reactor is included in Table 19, however, it must be noted that there are many recycle fuel management plans that could be utilized, some of which differ significantly from that listed in Table 21.

The net fissile material utilized to produce 1000 MWe is substantially less for a heavy water reactor like the CANDU than for other reactor types (approximately 33% less than for a PWR). This efficient use of fissile material is a direct manifestation of the superior neutron economy of heavy water reactors. If the amount of fissile material remaining in the tails of the enrichment process is included this difference is even higher. On the other hand, the amount of energy necessary to supply the heavy water is not included. In addition, a more efficient utilization of fissile material could be achieved in the LWR's via the use of a tandem fuel cycle, recycle fuel cycle management plan, or an optimum throw-away fuel cycle. There is little room for improvement in a heavy water fuel cycle without substantial reactor design changes.

Table 9. SUMMARY OF REACTOR MATERIAL FLOW

	REACTOR TYPES						
	CANDU-PHW	HTGR	AGR	PWR	BWR	BWRRC	LMFBR
Milling (MT)*	125	72	133	[illegible]	[illegible]	79	--
SWU (MT)	--	93	89	128	114	70	--
Uranium Enrichment (%)	.71	93	2.1- 2.5	3.3	2.61	--	--
Fissile in (MT)	.88	.66	.76	.84	.85	.98	1.14
Fissile out (MT)	.56	.25	.35	.36	.45	.54	1.34
Total Fissile (MT) (including tails)	.32	.55	.61	.74	.65	.59	-.2
Burnup MWD/MT	7,500	87,000	20,000	33,000	26,160	26,160	67,600
Initial Fissile Inventory (MT)	1.02	2.96	2.14	3.17	4.5	3.59	
Net Plant Efficiency	29.6	38.7	41.6	32.5	32.5	32.5	41.8

*Includes recycle

costs are certainly an important point in considering a reactor purchase. However, the total capital cost often is determined by the financial arrangements, We note here that the total capital costs of LWRs are thought to be at least 10% less than for an equivalently sized CANDU.

Natural uranium reactors such as the CANDU offer fuel cycle independence to those countries not having enrichment facilities. In addition, they are generally available in smaller sizes (600 MWe is to be a standard export CANDU whereas most present LWR designs are over 1000 MWe) . The smaller size power station is often more compatible with a country's electric power grid. (Because of the necessary shutdowns for refueling and maintenance, no single power station should be more than approximately 15% of the total grid capacity.)

The environmental effects of the various reactors do differ. The lower efficiency reactors such as the CANDU promote more thermal pollution. Some reactors produce more of certain types of radioactive isotopes. However, none of these considerations are decisive in a proliferation potential discussion.

In Table 20 some of the reactor safeguards considerations relative to various threats are summarized. If a country manufactures fuel rods from raw materials then the LWR with recycle, the HTGR, and the LMFBR could be credibly threatened by any of the groups listed. If a country receives only fresh fuel assemblies then the threat diminishes somewhat for these fuel cycles. All of the irradiated fuel from the various reactors contain strategic special nuclear material. A credible threat can be directed against this material if the group can put together the necessary facility to separate this SSNM from the highly radioactive fission products.

Table 20 REACTOR SAFEGUARDS CONSIDERATIONS

MATERIAL EXPOSURE

Reactor **Fuel** Material	LWR	LWR with Recycle	CANDU-PHW	HTGR	AGR	LMFBR
Fuel (Raw Materials)	0	3	0	3	0	3
Fuel Assemblies	0	2	0	2	0	2
Irradiated Fuel	1	1	1	1	1	1

0 **No Strategic Special** Nuclear Material (SSNM) involved
1 SSNM involved but must be separated in reprocessing plant
2 SSNM can be separated by standard chemical and mechanical processes (no high radiation)
3 SSNM **could be converted with little or no processing into a weapon**

MATERIAL EXPOSURE RATING VERSUS THREAT

	Rating 0	1	2	3
Subnational Group	▨	▨	**Credible Threat**	
Nation Desiring a Quick Response Capability	▨	▨	**Credible Threat**	
Small Nation	▨	**Credible Threat**		
Large Nation	▨	**Credible Threat**		

REACTORS VERSUS THREAT CREDIBILITY

	LWR	**LWR with Recycle**	**CANDU-PHW**	**HTGR**	**AGR**	**LMFBR**
Subnational Group		C		C		C
Nation Desiring a **Quick Response Capability**		C		C		C
Small Nation	U	C	C	C	U	C
Large Nation	C	C	C	C	C	C

C- **credible threat**
U - **credible** but unlikely

It seems obvious that exposure of SSNM in the power reactor fuel cycle either through the use of reprocessing and/or SSNM in fresh fuel assemblies makes the fuel cycle somewhat more vulnerable to a broader spectrum of threats. The decision as to the relative significance of this increased vulnerability might better be answered by other considerations such as:

1. Can effective safeguard measures be incorporated to counter this increased vulnerability?
2. How significant is this vulnerability relative to the use of dedicated facilities?

Extensive programs are being conducted in the United States by ERDA and NRC, and throughout the rest of the world to arrive at acceptable answers to these questions.

BIBLIOGRAPHY

WASH-1099, Reactor Fuel Cycle Costs for Nuclear Power Evaluation, USAEC, December 1971.

Directory of Nuclear Reactors, Vol. X, Power and Research Reactors, IAEA, Vienna, 1976.

Comprehensive Standards: The Power Generation Case, EPA No. 68-01-0561, Teknekron Inc. Report, March 1975.

Kiat Peon Aug: Quantities of Actimides in Nuclear Reactor Fuel Cycles Ph.D. Thesis, April 1975, LBL Berkeley.

WASH-1098, Potential Nuclear Power Growth Patterns, USAEC December 1970.

WASH-1139 (74), Nuclear Power Growth 1974-2000, USAEC February 1974.

Study of Advanced Fission Power Reactor Development for the United States, Final Report, I, II, III. Battelle, Columbus Laboratories, June 1976.

D.E.W. Leaver: Strategies for Plutonium Recycle in a System of Pressurized Water Reactor, Ph.D. Thesis Stanford University, Dept. of Mech. Engineering, Stanford, March 1976.

WASH-1348, Computer Program NUFUEL for Forecasting Nuclear Fuel Requirements and Related Quantities, USAEC October 1974.

WASH-1327, Generic Environmental Statement Mixed Oxide Fuel, USAEC, August 1974.

Directory of Nuclear Reactors, Vol. VII, Power Reactors IAEA, Vienna 1968.

The World’s Reactor No. 68, SNUPPS, Nucl. Eng. International, 20 November 1975.

Proposed Final Environmental Statement-LMFBR Program, USAEC Report No. WASH-1535, Vol. 1 to VI1, December 1974.

WASH-1400 (NUREG-7S 1014) Safety Design Rationale for Nuclear Power Plants, Appendix IX, Fig. IX-31-1; USNRC, October 1975.

R. Harris, J.M. Christenson: Post Shutdown Fission Product Decay Heating for Plutonium 239 fueled Fast Reactors, Nucl. Technology 25, 440 (1975).

Directory of Nuclear Reactors, Vol. IX, Power Reactors IAEA, Vienna 1971.

R.C. Smith, L.G. Faust, L.W. Brackenbush, Nucl. Technol. 18, 97 (1973).

E1-Wakil, M.M., Nuclear Energy Conversion, International Text-Book, Scranton, Pa. 1971.

"Development Status and Operational Features of the High Temperature Gas-Cooled Reactor", Electric Power Research Institute, April, 1976, EPRI NP-142.

Rippon, Simon, "The AGRs Make a Start", Nuclear Engineering International, April/May, 1976.

"Hinkley Point B, A Survey of Design and Construction", Nuclear Engineering, Vol. 13, No. 147, August 1968.

"World List of Nuclear Power Plants", Nuclear NEws, Vol. 19, No. 10, August 1976.

"Hinkley Point B Power Station" Directory of Nuclear Reactors, Vol. X, International Atomic Energy Agency, March 1976.

"Dungeness B Nuclear Power Station", Directory of Nuclear Reactors, Vol. X, International Atomic Energy Agency, March 1976.

"Hunterson B Generating Station", Directory of Nuclear Reactors, Vol. X, International Atomic Energy Agency, March 1976.

"Nuclear Power Growth 1974-2000", WASH-1139, USAEC February 1974.

Snyder, A.J., "Computer Program NUFUEL for Forecasting Nuclear Fuel Requirements and Related Quantities", WASH-1348, USAEC October 1974.

Rippon, Simon, "Reprocessing - What Went Wrong?" Nuclear Engineering International, February 1976.

Oehme, H., "Comparative HTGR Designs", in Gas Cooled Reactors: HTGR and GCFBR, ANS Topical Meeting, CONF-740501, May 1974.

Boyer, V.S., et al., "Fulton Station HTGR" Nuclear Engineering International, Vol. 19 No. 2, 19 August 1974, pp. 635-658.

Walker, R.E., and Johnston, T.A., "Fort Saint Vrain Nuclear Power Station", Nuclear Engineering International, December 1969.

Brooks, L.H., Lotts, A.L., and Wymer, R.G., Progress in the Thorium-Uranium 233 Reprocessing-Refabrication Technology, in CONF-740501.

Heath, C.A., and Spaeth, M.E., "Reprocessing Development for HTGR Fuels, in Proceedings of Joint Topical Meeting on Commercial Nuclear Fuel Technology Today, AND and CNA, April 1975.

Study of Advanced Fission Power Reactor Development for the United States, Vol. III, Battelle Columbus Laboratories, BCL-NSF-C9&6-2, June 1976, pp. C-69 through C-76.

"THTR, Prototype-Kerkraftwerk Uentrop", in Directory of Nuclear Reactor Vol. X, IAEA, March 1976, pp. 305-311.

Pigford, T.H., et al., "Fuel Cycle for 1000 MWe High Temperature Gas-Cooled Reactor", Teknekron Report No. EEED 105, March 1975.

Pigford, T.H., et al., "Fuel Cycles for Electric Generation", Teknekron Report No. EEED 101, January 1973, Pg. 194.

CANDU Nuclear Power Station, AECL, October 1973.

CANDU 500 Pickering Generating Station, AECL, 1969.

McIntyre, H.C., "Natural Uranium Heavy-Water Reactors", Scientific American Vol. 223, No. 4 October 1975.

Masters, Richard, "Co-operation and Concentration Pay Dividends in Canada", Nuclear Engineering international Vol. 2, No. 244, June 1976.

Taylor, M.L. and Therrien, M. "Gentilly-Commissioning and Early Operation" Nuclear Engineering International, Nov. 1972.

Pen, G.A., "Candu-BLW-250" in Heavy Water Power Reactors IAEA, Vienna, 1968.

Duret, M.G., "Plutonium Production and Recycle in Heavy-Water Reactors", in Heavy Water Power Reactors, IAEA Vienna, 1968.

An Evaluation of Heavy-Water Moderated Organic Cooled Reactors, USAEC, WASH-1083, March 1968.

An Evaluation of a Heavy Water Moderated Boiling-Light Water-Cooled Reactor USAEC, WASH-1086, Dec. 1969.

Lane, J.A., et al., "Comparative Evaluation of the Performance and Economics of Heavy-Water-Moderated Reactors, in Heavy Water Power Reactors, IAEA, Vienna 1968.

Barnes, R.W., and Mayman, S.A., "The Canadian Program for Management of Spent Fuel and High Level Wastes", in Proceedings of Joint Topical Meeting on Commercial Nuclear Fuel Technology, ANS and CNA, April 1975.

APPENDIX A

DIVERSION POTENTIAL OF CRITICAL FUEL CYCLE FACILITIES

Fuel cycle facilities that may contain strategic special nuclear material in a separated form are of particular interest to a safeguards and proliferation assessment. The exposure matrix (Table 18) lists the critical facilities for the various power reactor fuel cycles. Enrichment plants, reprocessing and possibly to a lesser extent recycle fuel fabrication plants merit special attention as explicitly implied in Table 20. The capability of an enrichment plant and reprocessing plant to generate separated strategic special nuclear material makes them particularly vulnerable to a diversion threat.

Reprocessing Plant

There have been a number of reasons expressed by various countries for acquiring a reprocessing plant. Included among these reasons are typically the following:

1) Going to light water recycle fuel to more economically operate LWRs, con-serve uranium resources, and to gain more control over their LWR fuel cycle.

2) Eventually expect to go to a breeder fuel cycle which must include reprocessing. The reprocessing plant is needed to gain the necessary experience.

3) Spent LWR fuel assemblies have to be reprocessed to generate an acceptable waste disposal form.

All of these responses have a base of validity; however, the firmness of these bases is uncertain at the present time. For example, the economic gain in using LWR recycle fuel is a rather sensitive function of uranium prices and the cost of reprocessing. Neither of these costs are firm at the moment and they have a rather large uncertainty for a time period eight years in the future (following the decision to build a plant) when a reprocessing plant might come on line. The conservation of resources argument is certainly true with a most likely uranium savings of 25%. However, as discussed in Section 4.1, there are alternative ways of achieving roughly the same gain in resources without resorting to the use of recycle LWR fuel. The other arguments (2 and 3) also have rather large associated uncertainties which preclude them from being definitive statements on a perceived positive requirement for a reprocessing plant.

For example, it is clear that any breeder fuel cycle requires reprocessing. However, it is not clear that breeder reprocessing will utilize the PUREX process that is standard for production metal fuels and the oxide fuels of LWRs. Consequently, experience in reprocessing LWR fuel may only apply in a limited way toward the reprocessing of LMFBR fuel because of the higher burnup, higher plutonium throughput, and possible fuel dissolution problems with LMFBR fuel.

The West Germans have repeatedly stated that reprocessing of spent LWR fuel gives them a flexibility in developing waste disposal forms that will be acceptable for disposal in their country. Until recently, U.S. policy has assumed a base case fuel cycle that includes reprocessing and waste treatment prior to disposal. The alternative of directly disposing spent fuel assemblies (after some treatment) has been assumed to be technically feasible. There has not been an extensive experimental program to demonstrate this, however.

An additional argument against a country developing an indigenous reprocessing capability is that analysis indicates* that large plants are by far the most economical. Large plants mean a capacity of 1500 to 3000 MT (roughly 15 to 30 MT of Pu) capacity per year, or fifty to one hundred 1000 MWe nuclear

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*"Light Water Reactor Fuel Recycle," Savannah River Laboratory Quarterly Report, DPST-LWR-76-1-1, January-March, 1976.

power reactors. Few countries outside the U.S. are expected to develop a nuclear power reeactor electric generating capacity of this magnitude. Moreover, there are design problems associated with large capacity reprocessing plants (particularly for those greater than 1500 MT capacity) that have not been completely resolved. These problems are primarily related to ensuring that a sufficient criticality safety factor is achievable under all credible circumstances.

Reprocessing plants have one obvious proliferation potential when viewed in the context of a national threat. If the host country abrogates the Non-Proliferation Treaty and refuses to allow IAEA inspection of the operating reprocessing plant, then the country can rather overtly proceed to generate weapon material from the stockpile of spent fuel. (The likely amount of Pu that could be separated from spent power reactor fuel is listed in Appendix B1 for the various countries. One result of an overt proliferation attempt might be the shutoff of the imported fresh LWR fuel from supplier countries.

An assessment of covert diversion of plutonium from a reprocessing plant by the host country or by a subnational group requires some consideration of the material form and flow through the reprocessing plant.

Figure Al* is a schematic illustration of the principal physical areas and average daily material flow through a model 1500 MT\year reprocessing plant. The principal areas are:

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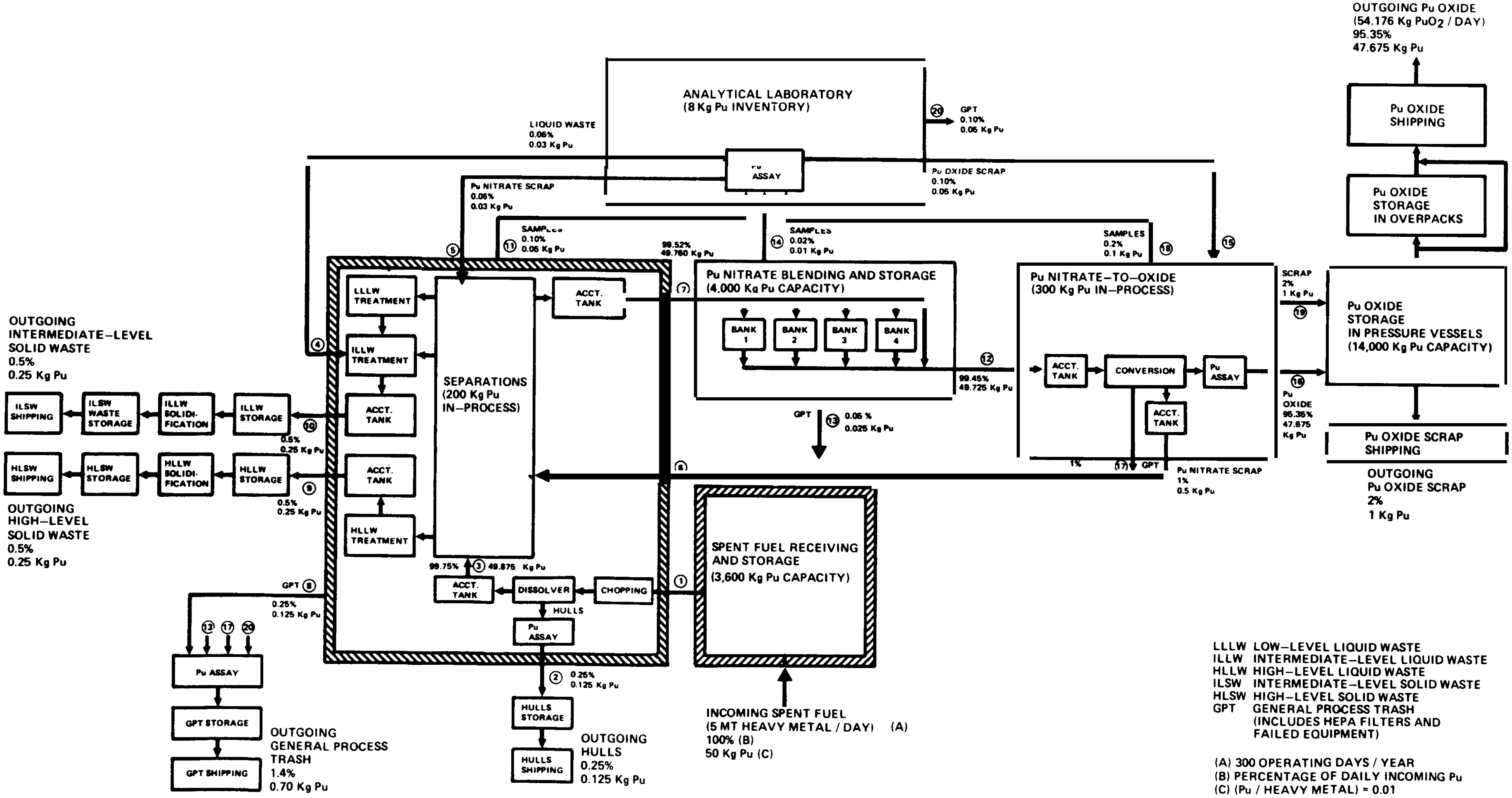
* G. Bray and H. Kendrick, ‘Spent Fuel Reprocessing Plant Characteristics Important to an Integrated Safeguards Design”. INMM 17 Annual Meeting, Seattle, Washington. January 22-24, 1976. PP. 485-494.

Figure A1. AVERAGE DAILY PLUTONIUM FLOW FOR MODEL 1500 MT HEAVY METAL / YEAR SPENT–FUEL REPROCESSING PLANT



- Spent fuel receiving and storage
- plutonium, uranium and fission product separation
- Plutonium nitrate blending and storage
- Plutonium nitrate-to-oxide conversion
- Plutonium oxide storage and shipping

The average daily plutonium flow between plant areas is shown in the figure. The daily plutonium flow is expressed in kg Pu/day and as a percentage of the average 50 kg Pu/day assumed coming into the plant. Plutonium assay stations and accountability tanks, which are required for material balance accounting are also shown in Figure Al. The data and physical arrangement shown is intended to be representative of present design criteria.

The cress-hatched enclosures of the spent fuel receiving and storage area and the separations area indicates the highly radioactive nature of these areas. Material in these areas is not attractive for diversion.

The plant processes manifest certain key characteristics which relate to the attractiveness of the material to potential diverters, and to the accessibility of the material. The attractiveness of the material can be expressed in terms of the form (chemical composition, physical form, packaging, etc.), concentration (grams plutonium per gram of material), and the presence or absence of hazardous levels of radioactivity. The accessibility of the material is related to its form, the type of processing or material-handling equipment used, the degree of automation of that equipment, and the quantity of plutonium available in a given location.

Key process characteristics have been determined for all areas of a model reprocessing plant, including both mainstream and sidestream material flows, and are shown in Figure A2

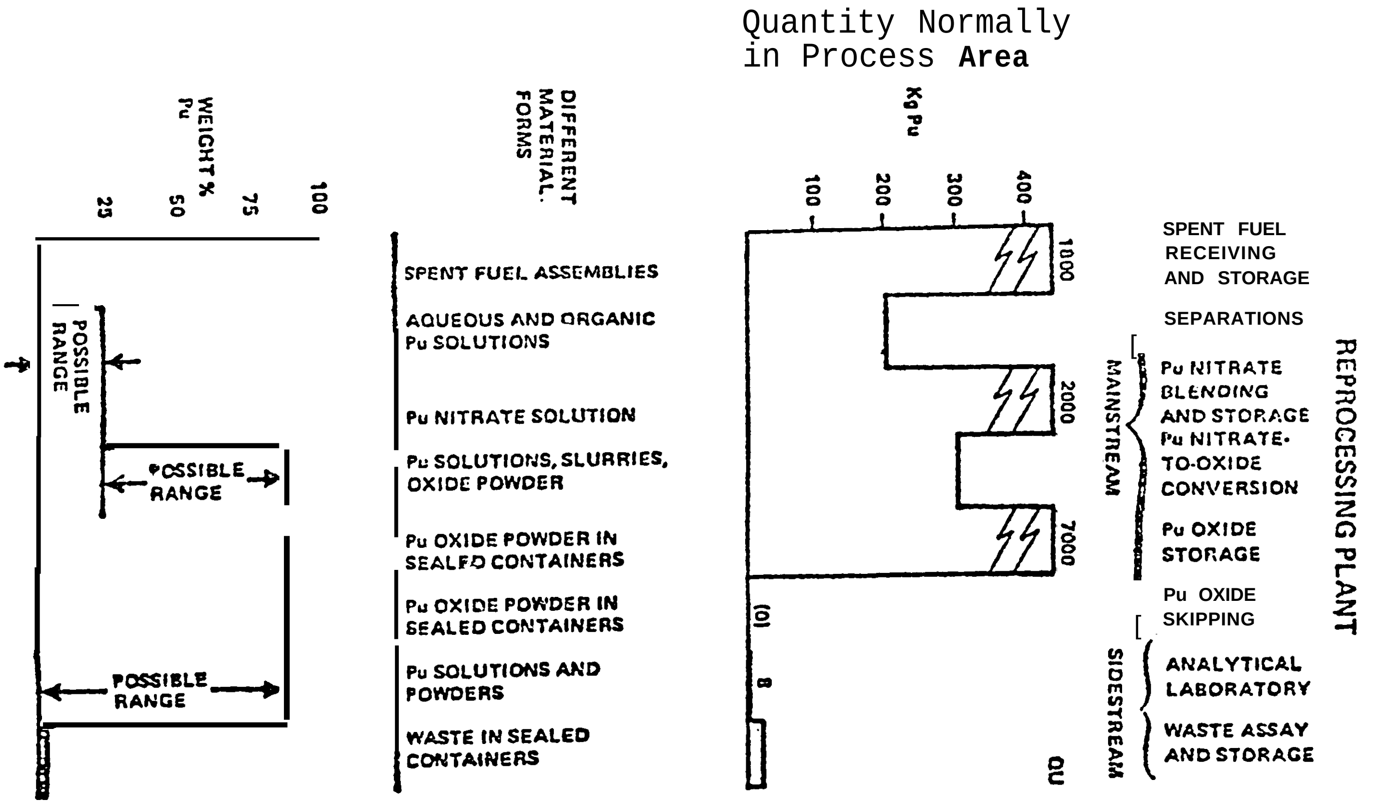


Figure 2A(a) - Reprocessing Plant Characteristics

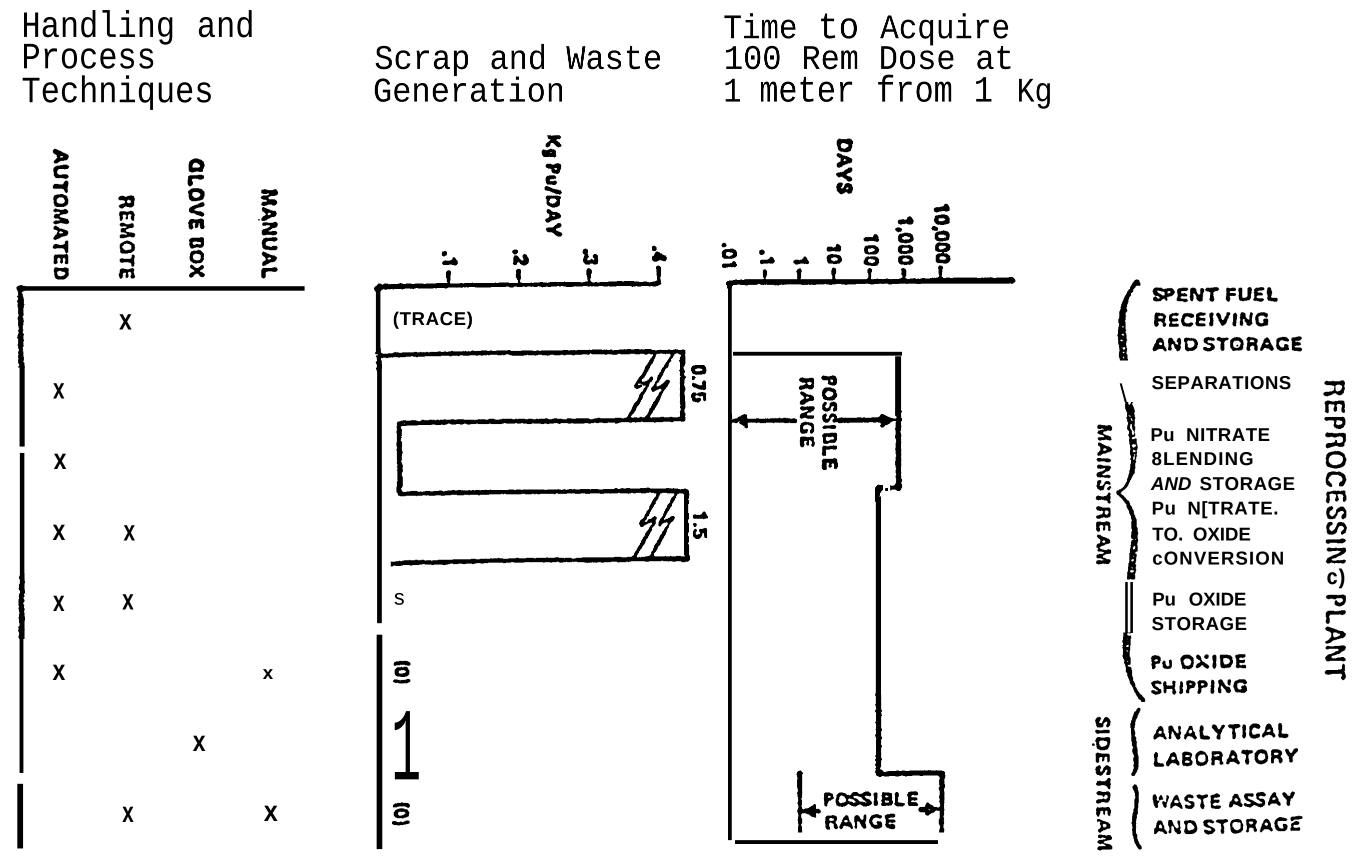


Figure 2A(b) - Reprocessing Plant Characteristics

These figures illustrate the important differences in process characteristics across the plant. The figures ‘on the left side of Figure A2 represent the maximum quantity of plutonium that normally might be present in the various plant areas, the chemical form of this material, and the possible range of plutonium concentration in this chemical form. Note that the high points on the figures represent the more attractive material from a diversion standpoint.

The three figures on the right side of Figure A2 are measures of the accessibility of the material in the various plant areas. The top figure on the right illustrates the time necessary to acquire a 100 REM dose at a one-meter distance from one kilogram of material. As before, the high points on the figure represent the more accessible material (i.e., less radioactive) . Scrap and waste (middle figure, right side of Figure A2) generally is considered to be more accessible material partly because it may indicate a process upset and often is more difficult to accurately measure. Even though the scrap may not meet the customer’s specifications, it may still consist of relatively concentrated Pu material that can be reclaimed and transformed to weapon material. In addition, scrap and waste represent outgoing material streams from the main process line. The lower righthand figure illustrates the handling and process technique. The accessibility to the Pu-containing material is rated from manual through automatic.

Considering all of the characteristics of the various areas delineated in Figure A2, the Pu nitrate blending and storage area, the Pu nitrate to oxide conversion area, and the analytical laboratory all would appear to be critical areas for material measurements and accounting. An indication of an accounting system detection capability for the conversion area of our model reprocessing plant that is operating with presently available measurement equipment and an accounting interval period of two months (U.S. NRC requirement) is that an individual or group has a 50 per cent chance of avoiding detection by the accounting system if they divert 13.2 kilograms of plutonium. For the analytic laboratory, the SO per cent probability of detection amount is 1 kg of Pu for the two-month accounting period. If these systems were upgraded to state-of-the art measurement instrumentation, approximately 8.7 kg of Pu from the conversion area, or 0.5 kg from the analytical laboratory, or 11.7 kg Pu from the nitrate blending and storage area could be diverted with a 50 per cent probability of detection by an accounting system. It is highly likely that these upgrade numbers represent the most optimistic detection capability since many of the assumed measurement capabilities are laboratory results that may degrade when introduced into a production facility. The larger numbers quoted above are achievable with proven measurement hardware and procedures.

Accounting procedures monitor nuclear material in the main process stream, the associated sidestreams and, of course, the sealed, item count material in storage. Undetected diversions from these areas are statistically possible for measurement and accounting systems as discussed above. However, the material must then be removed from the process line or storage area. Now a number of containment and surveillance procedures come into play that are designed to detect the removal of the nuclear material from its authorized location. Many of these surveillance procedures can utilize tamperproof hardware that can be left unattended by IAEA inspectors. A partial listing of these procedures include the following:

- portal monitors for nuclear material
- CCTV surveillance
- door or glove box access alarms
- motion detectors
- random personnel or package searches
- clothing changes
- randomly located radiation detectors

The applicability of specific procedures varies according to the particular area; however, it should be possible to design and implement a set of redundant protective measures to meet a specified subnational threat (for example, six adversaries with two being inside employees) to the material access areas. Consequently, an undetected diversion of nuclear material would have to overcome the containment and surveillance systems in addition to the measurement and accounting systems.

The reprocessing diversion potential as described above differs if an alternative reprocessing scheme is employed. For example, if a coreprocessing scheme (see Section 4.1) is used so that none or only some of the uranium is separated from the plutonium, then the model plant is changed along with measurement procedures. Most significantly, the amount of material a divertor would have to remove to obtain a strategic amount of special nuclear material is increased. In addition, the divertor would have to chemically separate the plutonium from the uranium. For subnational groups, the required chemical separation could be a significant obstacle to overcome.

An enrichment plant is the only other nuclear fuel cycle facility besides a reprocessing plant capable of generating separated strategic special nuclear material. A significant difference exists, however, in that a reprocessing plant normally handles an intrinsic strategic special nuclear material--plutonium; whereas an enrichment plant built to service a LWR fuel cycle would only generate slightly enriched uranium (approximately 3% ^{235}U). Consequently, the diversion/proliferation potential of an enrichment plant exists in its potential capability for generating highly-enriched uranium (typically 90% or greater ^{235}U).

Since most commercial enrichment plants will only be designed and operated to produce slightly enriched uranium, the proliferation threat to the facility is limited somewhat. It is not credible that a small group of adversaries (particularly outsiders) could subvert the normal plant operation to produce hiqhly-enriched uranium. A credible threat would have to include most of the plant management and many of the operating personnel. Thus, a diversion threat directed by the operating country is of most concern for an enrichment facility.

The remainder of this section on enrichment plants will be primarily directed toward centrifuge enrichment plants. There are two main reasons for focusing this discussion of the proliferation potential of enrichment plants on centrifuge techniques and facilities rather than the present dominant enrichment technique of gaseous diffusion:

1) Centrifuge plants can be initially constructed with a modest separative work capacity and then added to as the demand for enrichment services grows. Gaseous diffusion plants make economic sense only in very large capacity such as 9,000,000 kg SWU\year.

2) Gaseous diffusion plants require approximately 15 times more electric power per SWU than centrifuge plants.

(The Becker nozzle process which requires somewhat fewer stages but consumes more than twice as much electric power as gaseous diffusion is also not an attractive choice for production of weapons material.) These points are discussed in more detail in Section 2.5 and 2.11. The primary effect on the above is that small enrichment plants, particular those build with a limited amount of capital, will undoubtable be centrifuge plants. The advanced isotope separation processes such as laser enrichment techniques are not likely to be available for use before 1985.

Before concentrating on the centrifuge technique, it is of interest to note a few technical differences between gaseous diffusion and centrifuge enrichment that relate to their diversion potential.

- Enrichment Limits

  The amount of enrichment obtainable from a single barrier in a gaseous diffusion plant (GDP) is small and relatively fixed. Consequently, all barriers are connected in series, thus limiting the maximum enrichment that can be obtained with natural uranium feed. The amount of enrichment from a single centrifuge is much larger and variable as discussed below.

- Electric Power Usage

  The amount of separative work performed in a GDP is proportional to the power used to pump the UF6 through the plant. Thus, the power usage is a direct and external indicator of the SWU actually performed. The power used to drive the centrifuges is relatively small and a poor separative work indicator.

- process Inventory

  The process inventory of a GDP is orders of magnitude larger than that of a centrifuge enrichment plant. Since there is always a rather large uncertainty associated with the process inventory, this could create a rather large MUF in GDPs.

To facilitate a coherent discussion of centrifuge enrichment plants, we shall develop a reference centrifuge plant following Kouts.* The characteristic parameters listed are nominal values traceable to results reported in the literature; however, there may be significant differences between these reference values and those actually utilized in a specific centrifuge plant. For example, European centrifuge development (Urenco) is known to be concentrating on developing highly reliable (failure rate less than 2 per cent per year), low-capacity centrifuges, whereas American development efforts are reported to be directed toward higher separative work capacity machines with a reduced reliability. Hopefully, the reference characteristic numbers are somewhere in between these values.

Table A2 lists the design characteristics of the reference centrifuge enrichment plant. Note that this is a very small plant (when compared with U.S. diffusion plants) , representative of the initial enrichment plants expected to come on-line in Europe and Japan. A mature LWR industry would require much larger plants with at least an order of magnitude or more additional capacity.

Table A3 lists the design material flow through the individual cascades. Table A4 illustrates the cascade that produces 4% enriched ^{235}U. Note there are 29 stages with varying numbers of centrifuges in each stage. The other cascades that produce a lower enrichment product are similar in nature with fewer stages.

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* Herbert Kouts, "Reference Uranium Enrichment Plant," Technical Support Organization, Brookhaven National Laboratory, December 6, 1972.

TABLE A2

REFERENCE CENTRIFUGE PLANT

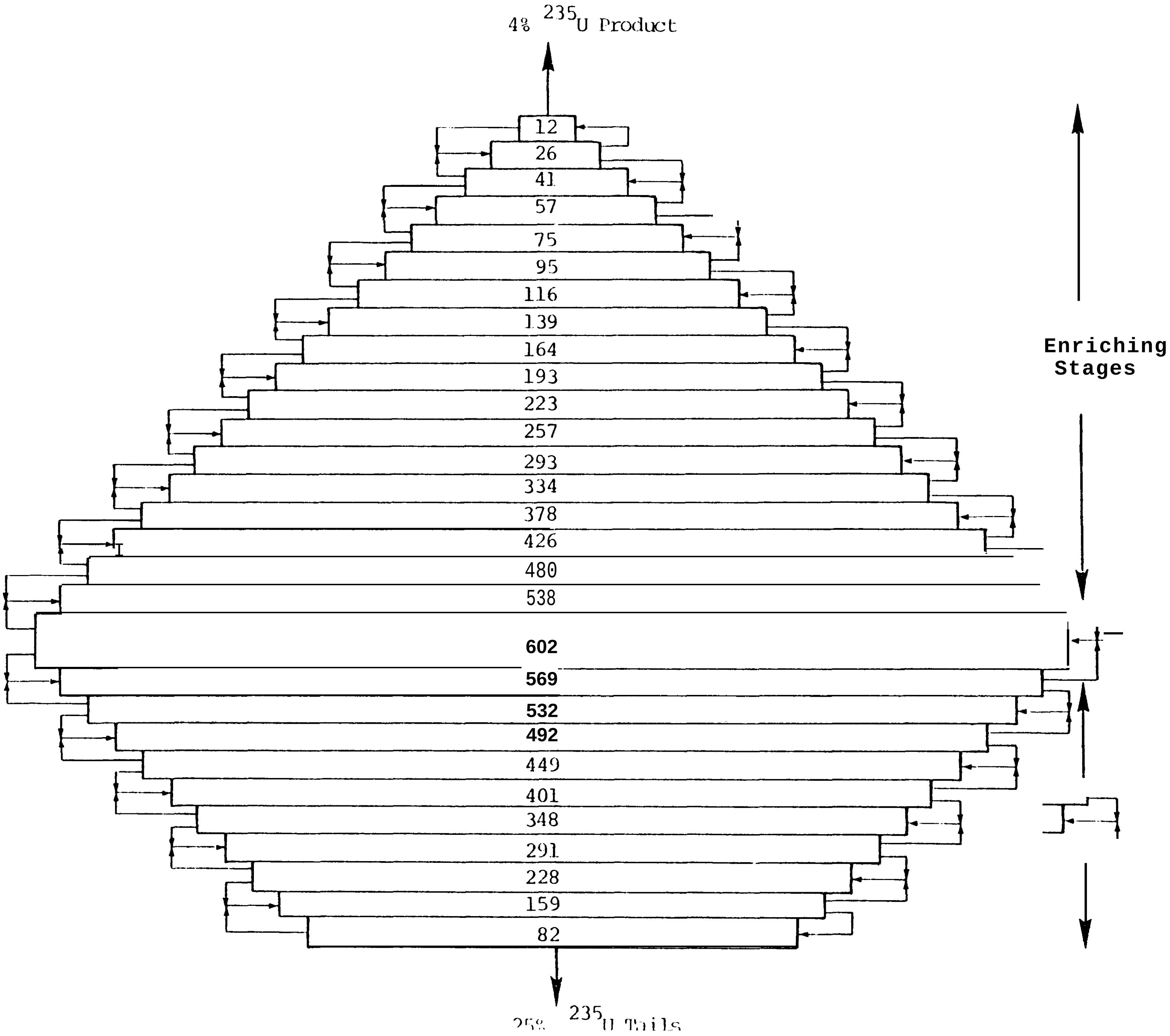
Total Separative Capacity MT SWU/Yr	200
Unit Separative CapacitY kg SWU/Yr	5
Number of Cascades	5
Number of Centrifuges Per Cascade	8,000
Total Feed Rate MTU/Yr (natural uranium)	325.2
Total Product MTU/yr (various enrichments)	60.8
Total Tails MTU/Yr at .25% ^{235}U	264.4
Centrifuge Floor Area ft^2	200,000
Centrifuge Building Area ft^2	320,000
Nuclear Power Industry Supported 1000 MW(e)	about 1.5

TABLE A3

MATERIAL FLOWS IN THE CASCADES

Product Enrichment (% U -235)	Feed (Tonnes U/Yr)	Product (Tonnes U/Yr)	Tails (Tonnes U/Yr)
2.0	79.4	20.9	58.5
2.5	68.7	14.1	54.6
3.0	62.6	10.5	52.1
3.5	58.7	8.4	50.3
4.0	55.8	6.9	48.9
TOTAL	325.2	60.8	264.4

TABLE A4
8000 CENTRIFUGE
(numbers represent centrifuge per stage)



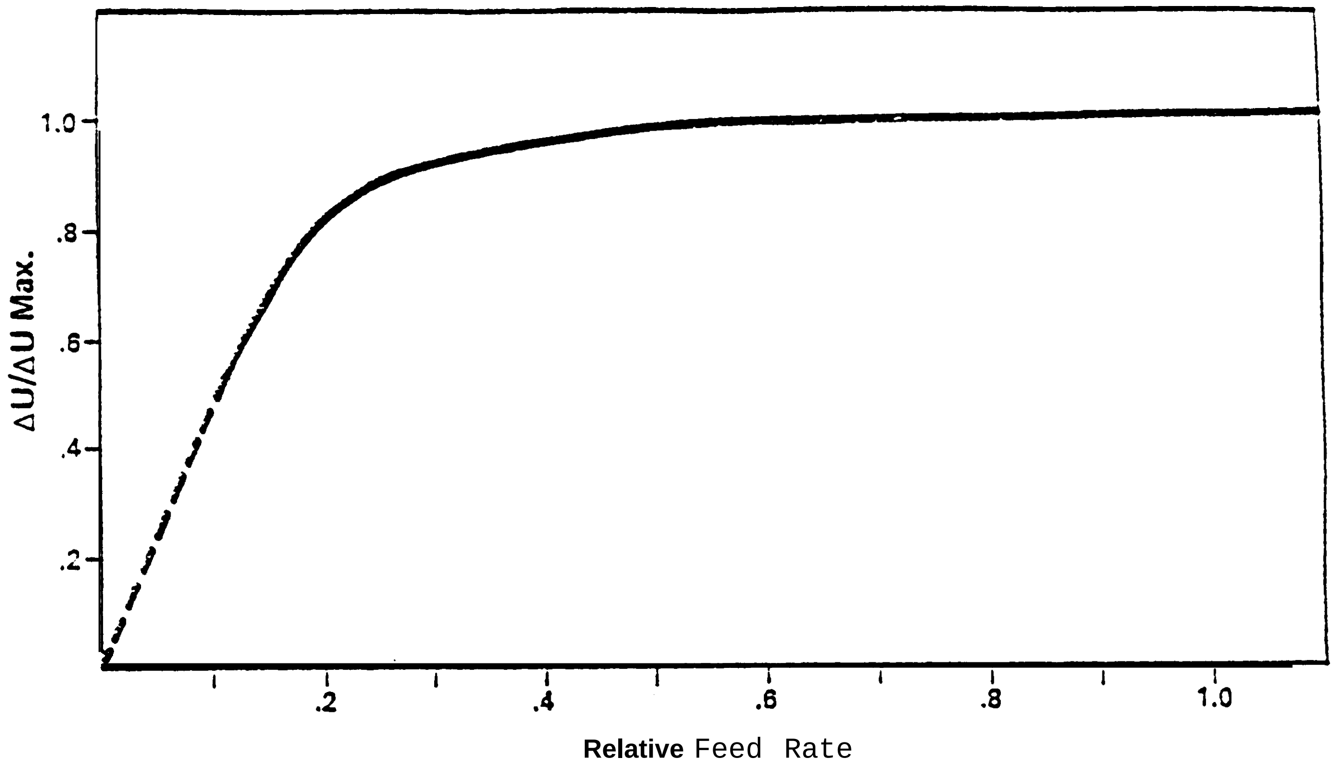
An important feature to note about the above example is that centrifuge enrichment plants are inherently versatile--much more so than gaseous diffusion plants.

This versatility that is inherent with the overall configuration of centrifuges in an enrichment plant also extends to the operation of individual centrifuges. Figure A3 illustrates the characteristic curies of enrichment for a gaseous centrifuge. The top figure shows the variation in separative work with feed rate and the bottom figure the variation in the enrichment factor with the feed rate. The implication of these curves are that changes in the plant operation can produce an enriched product that is higher than the design enrichment.

Measurements and material accounting in enrichment plants that produce slightly enriched uranium can be viewed from a different prospective than for reprocessing plants because the normal product material does not contain strategic special nuclear material. Nevertheless, material accounting can be important for some diversion scenarios and it is of interest to consider the various loss mechanisms as causes of inventory uncertainty. A comprehensive list of uranium loss mechanisms would have to include:

traps in vacuum system
centrifuge failure
centrifuge maintenance
accidental losses
wet air inleakage
reaction of UF_6 with impurities
intermetallic diffusion
surface absorption of UF_6
active chemisorption of UF_6

The importance and absolute gram value of each of these mechanisms is difficult to predict in the absence of experimental data from a production centrifuge plant. The total loss might be comparable with that of a GDP which is 0.5 per cent of the product (for 4 per cent enrichment) .



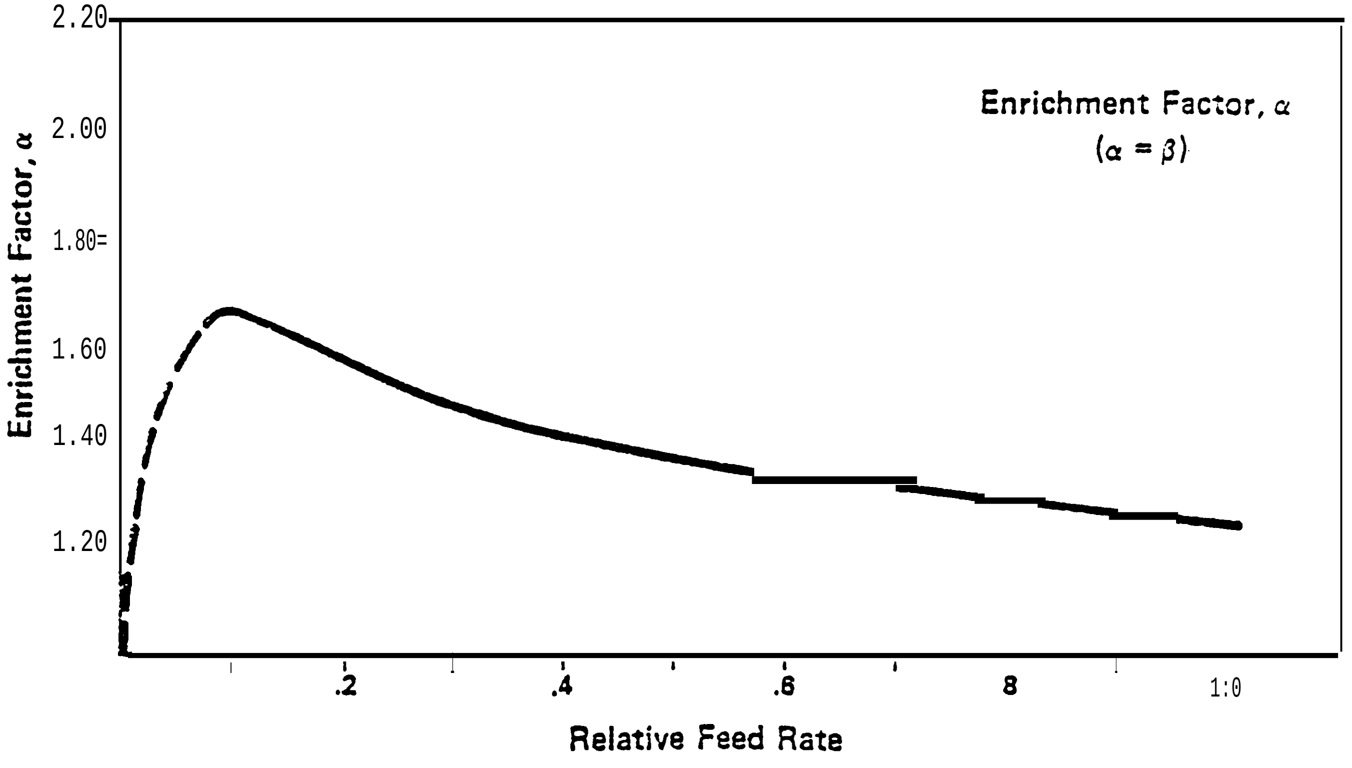


Figure A3. Assumed Centrifuge Characteristics

A quick consideration of material diverted within the material **measurement and accounting uncertainly indicates that this amount of** material is not very important for a plant the size of the reference plant. Assume a physical inventory every three months. The expected accuracy of material accounting (IAEA) should be .2 per cent of the throughput for this period. This corresponds to roughly 1 kilogram of highly-enriched uranium every three months if all this could be diverted and enriched to **90%** ^{235}U.

-Table A5 shows typical inventories inside the fenced area. We note that the major inventories are in the feed, product, and tails. These can be measured quite accurately .2% and thus contribute a rather small total uncertainty to the plant inventory.

To complete the reference plant model, a layout of the plant is shown in Figure A4. The cascade area (which at present is not accessible to IAEA inspection) also contains the sensitive areas associated with the plant such as the centrifuge maintenance, decontamination, and test areas as well as the control room. In the U.S. and possibly elsewhere an outside perimeter fence would surround the entire plant. The key measurement points (KMP) for flow, inventory, and surveillance are as indicated on the figure.

As stated above the prime diversion potential associated with these types of enrichment plants is related to an undeclared upgrading of material beyond the maximum enrichment designed into the plant. There are a number of ways that this could be accomplished:

1) Reconfiguration of unit cascades
2) Recycle of plant product
3) Off-design cascade operation
4) Internal cascade recycle

TABLE A5

TYPICAL IVENTORIES IN FENCED AREA

Location	kg u	kg U-235
Gas Phase in Centrifuges	40	0.4'
Traps	100	1.0
Deposition in Centrifuges	2000	20.0
Feed*	2300	16.4
Product**	3800	114.0
Tails***	3800	9.5
Waste Recovery	Nominal	

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* Assumes 1 half-full cylinder feeding all cascades from feed purification, 1 cylinder waiting.

** Assumes equivalent of half-full cylinder at each product withdrawal point.

***Assumes tails from separate cascades sequestered. Equivalent of half-full cylinder at each tails withdrawal point.

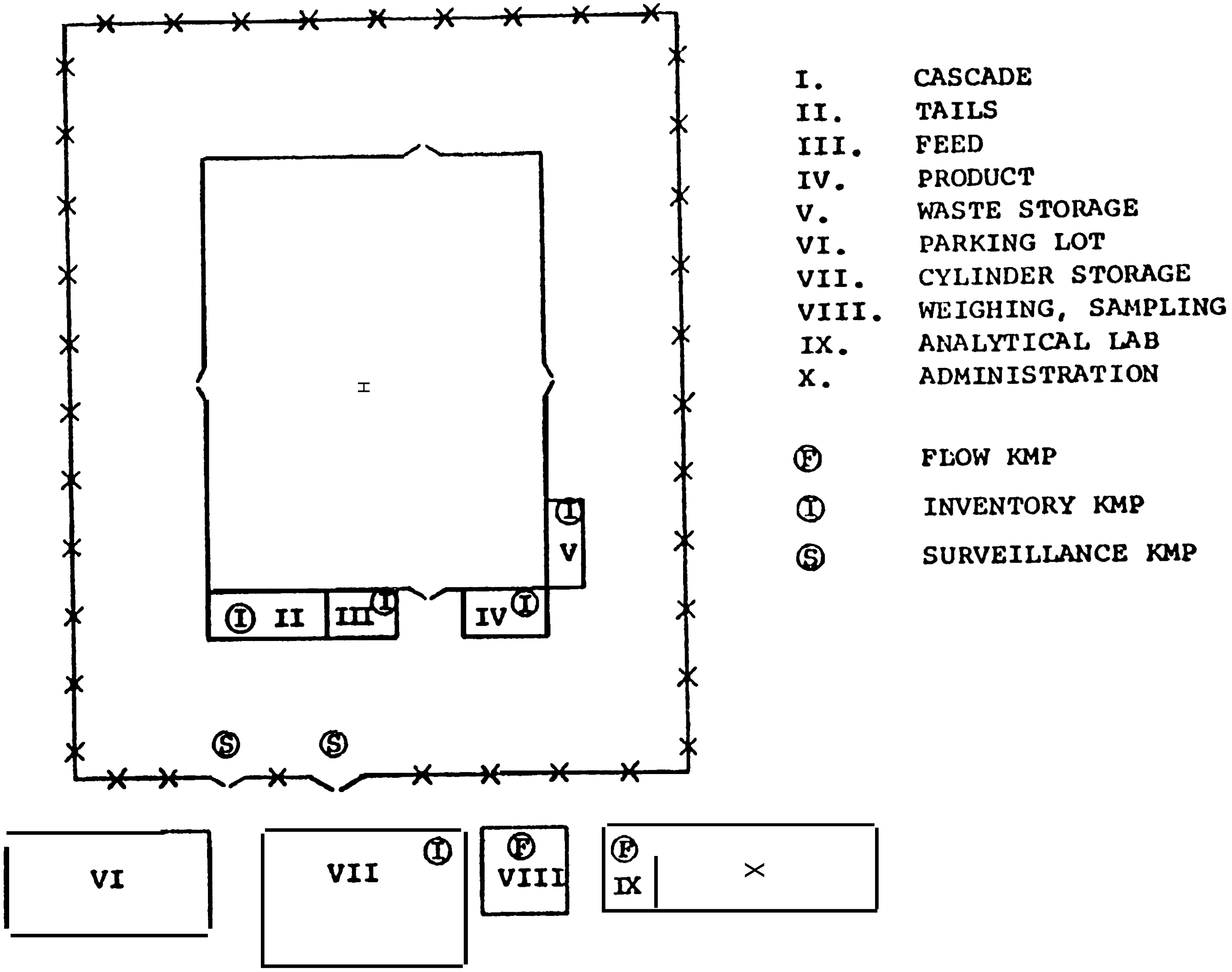

Figure A4

LAYOUT OF REFERENCE PLANT

The implications or details of each of these will be discussed in turn.

1) The centrifuges in one or several of the cascades could be reconfigured to take natural uranium feed to a 90 per cent enriched product. A cascade that would accomplish this might consist of 77 enriching stages and 10 stripping stages. Each stage could, of course, contain a minimum of one centrifuge. Consequently, this covert cascade could conceivably be constructed from one of the 8000-unit reference cascades.

2) If the 4 per cent product were fed into another covert cascade that had a natural enrichment tails, then 58 enriching staqes would be required with 18 **stripping stages.** Again, this cascade could be configured from one or a portion of one of the model cascades.

3) The feed rate, product rate, and reflux ratio (the relative amount of interstage circulation to product flow) could be varied to produce a more highly enriched product. The maximum enrichment obtainable requires a detailed analysis; however, it is not likely to exceed 20% 235U. Thus, this material would require further enriching to achieve a 90 per cent product. In addition, the off-design operation would lead to significant inefficiencies in the cascade operation.

4) Each cascade could be equipped with lines to recycle cascade product and tails into the feed stream. If only the product were fed back with a continuing tails withdrawal the product assay would rise. The maximum rise might be to roughly a 10 per cent enrichment requiring a further enrichment for weapons grade material.

TO accomplish these undeclared upgrading operations? a corresponding source of material would have to be developed. Techniques to accomplish this might (1) overstate the MUF; (2) **overstate** the inventory; (3) have a stored undeclared feed; and (4) have a steady undeclared feed and takeoff.

Inspection techniques that are presently proposed for enrichment plants include input-output monitoring of the cascade area (basically considers the cascade area to be black box with a detailed monitoring of all input and output of material) .

Figure A5 shows a schematic of all inputs and outputs from the cascade area of a centrifuge enrichment plant. At present new equipment is an undeclared path. This creates a problem since conceptually unaccounted feed material could be introduced via this feed stream.

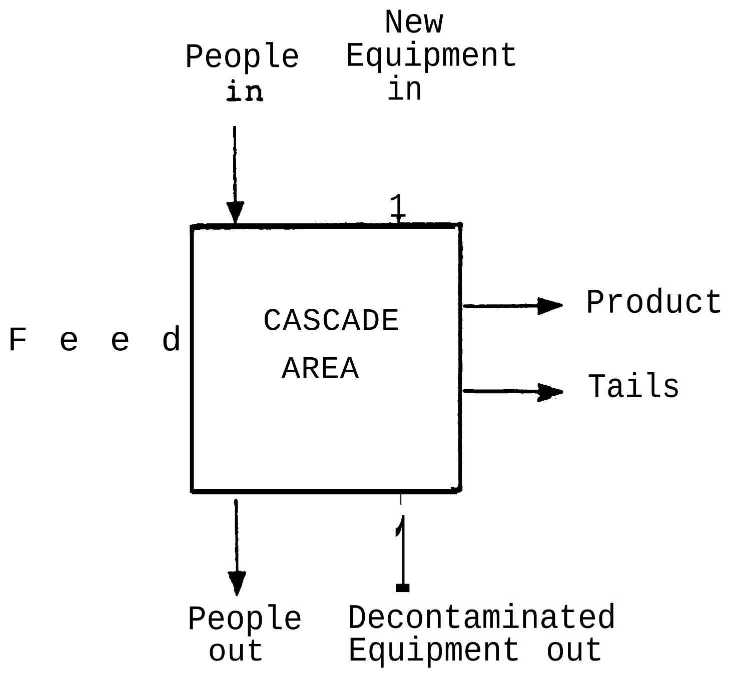

Figure A5

INPUT-OUTPUT INSPECTION STREAMS

For input-output to be effective, all streams need to be monitored. Physical inventory and surveillance methods need to complement the continuous input-output monitoring. Other complementary inspection techniques would include enrichment monitoring (particularly checking the tails enrichment) and the use of the minor isotope technique (311ST) to check the product and tails U-235/U-234 ratio. Table A6 shows how this would vary for the design product.

The effectiveness of these inspection techniques applied in an integrated way to a centrifuge enrichment plant has not been demonstrated as yet. One improvement that would make all of these inspection methods more credible would be to allow the inspectors access to the cascade area upon demand. Inspection accessibility to the cascade area would certainly not insure that the plumbing changes required for an undeclared cascade reconfiguration would be detected in the mass of necessary piping in the cascade area. However, it could act as a significant deterrent for any country wishing to conduct a covert operation. In addition, undeclared feed, product, or tails takeoff would also have a higher probability of detection.

TABLE A6

MINOR ISOTOPE CONTENT OF STREAMS

Product Enrichment (% U-235)	Product U-235/U-234 ratio	Tails U-235 U-234 ratio
2.0	114	231
2.5	112	235
3.0	111	239
3.5	110	243
4.0	109	245
AVERAGE :	112	238

APPENDIX B

WORLD POWER AND RESEARCH REACTORS

Table B-1

WORLD POWER REACTORS

LOCATION	TYPE	MW_e	REACTOR SUPPLIER	START DATE(1)	PU PROD Kg/Yr	Separable Fissile Pu Accumulated (Kg) Through				
						69	74	79	84	89
ARGENTINA										
Atucha 1	PHWR	319	SIEMENS	6/74	70	0	35	385	735	1,085
Cordoba	PHWR	600	AECL	1/82	132	0	0	0	396	1,056
Atucha 2	PHWR	600	AECL	1/84	132	0	0	0	132	792
					Total	0	35	385	1,263	2,933
AUSTRIA										
Tullnerfeld 1	BWR	692	KWU/AEB	10/76	118	0	0	374	964	1,554
Stein-St. Pantaleon 1	PWR(2)	1300	-	1/83	221	0	0	0	442	1,547
					Total	0	0	374	1,406	3,101
BELGIUM										
Doel 1	PWR	390	W-ACEC-COCKERILL	2/75	70	0	0	344	694	1,044
Doel 2	PWR	390	"	1/75	70	0	0	292	642	992
Doel 3	PWR	900	FRAMATOM-ACEC-COCKERILL	2/81	162	0	0	0	635	1,445
Tihange	PWR	870	"	9/75	157	0	0	680	1,464	2,250
CNW 1	PWR	1000	W-ACEC-COCKERILL	1/83	180	0	0	0	360	1,260
CNW 2	PWR	1000	"	5/82	180	0	0	0	480	1,380
Tihange	PWR	910	FRAMATOME-ACEC-COCKERILL	4/81	162	0	0	0	611	1,426
					Total	0	0	1,316	4,886	9,797
BRAZIL										
Angra 1	PWR	626	W	3/79	113	0	0	85	650	1,215
Angra 2		1245	KWU	1/85	216	0	0	0	0	1,080
Angra 3		1246	KWU	7/86	216	0	0	0	0	756
					Total	0	0	85	650	3,051
BULGARIA										
Kozloduy 1	PWR	440	AEE	1/75	79	0	0	395	790	1,185
Kozloduy 2	PWR	440	AEE	1/76	79	0	0	316	711	1,106
Kozloduy 3	PWR	440	AEE	1/81	79	0	0	0	395	790
Kozloduy 4	PWR	440	AEE	1/81	79	0	0	0	316	711
					Total	0	0	711	2,212	3,792

Table B-1 (Cont'd.)

WORLD POWER REACTORS

CANADA										
NDP	PHWR	25	AECL	6/62	6	45	75	105	135	165
Douglas Point	PHWR	206	"	9/68	45	60	285	510	735	960
Pickering 1	PHWR	514	"	8/71	113	0	386	951	1,516	2,081
Pickering 2	PHWR	514	"	1/72	113	0	339	904	1,469	2,034
Pickering 3	PHWR	514	"	7/72	113	0	283	848	1,413	1,978
Pickering 4	PHWR	514	"	7/73	113	0	170	735	1,300	1,865
Gentilly 1	BLWHWR	250	"	6/72	55	0	142	417	692	967
Bruce 1	PHWR	746	"	8/77	164	0	0	389	1,194	1,999
Bruce 2	PHWR	746	"	4/77	164	0	0	451	1,271	2,091
Bruce 3	PHWR	746	"	6/78	164	0	0	0	1,052	1,872
Bruce 4	PHWR	746	"	6/79	164	0	0	0	888	1,708
Bruce 5	PHWR	769	"	10/83	169	0	0	0	211	1,056
Bruce 6	PHWR	769	"	7/84	169	0	0	0	85	930
Bruce 7	PHWR	769	"	4/84	169	0	0	0	127	972
Bruce 8	PHWR	769	"	1/86	169	0	0	0	0	845
Gentilly 2	PHWR	600	"	1/81	132	0	0	0	528	1,188
New Brunswick	PHWR	600	"	10/80	132	0	0	0	561	1,221
Pickering 5	PHWR	516	"	4/81	114	0	0	0	428	998
Pickering 6	PHWR	516	"	1/82	114	0	0	0	342	912
Pickering 7	PHWR	516	"	1/82	114	0	0	0	257	827
Pickering 8	PHWR	516	"	7/83	114	0	0	0	171	741
					Total	105	1,660	5,310	14,375	27,410
CZECHOSLOVAKIA										
Bohunice 1A	GCHWR	112		1/72	25	0	75	200	325	450
Bohunice 2A	PWR	440	AEE	7/78	79	0	0	119	514	909
Bohunice 2B	PWR	440	"	7/79	79	0	0	0	435	830
Czechoslovakian 3	PWR	440	"	1/81	79	0	0	0	316	711
Czechoslovakian 4	PWR	440	"	1/82	79	0	0	0	237	632
					Total	0	75	319	1,827	3,532
DENMARK										
Unnamed	LWR	900	-	1/83	162	0	0	0	324	1,134
EGYPT										
First	PWR(2)	600	-	1/83	108	0	0	0	216	756

Table B-1 (Cont'd.)

WORLD POWER REACTORS

FINLAND										
Louiisa 1 (C)	PWR	420	AEE	1/77	76	0	0	228	608	988
Louiisa 2 (C)	PWR	420	AEE	2/79	76	0	0	70	450	830
TVO 1 (C)	BWR	660	AA	8/79	112	0	0	47	607	1,166
TVO 2 (C)	BWR	660	AA	8/81	112	0	0	0	383	943
					Total	0		345	2,048	3,927
GERMANY (Democratic Republic)										
Rheinsberg 1	PWR	80	AEE	5/66	14	51	91	161	231	301
Nord 1-1	PWR	440	"	1/74	79	0	79	476	869	1,264
Nord 1-2 (C)	PWR	440	"	1/76	79	0	0	316	711	1,106
Nord 2-1 (O)	PWR	440	"	7/78	79	0	0	119	514	909
Nord 2-2 (O)	PWR	440	"	7/79	79	0	0	40	435	830
Magdeburg 1	PWR	440	"	7/81	79	0	0	0	237	632
Magdeburg 2	PWR	440	"	7/81	79	0	0	0	237	632
	.				Total	1	170	1,112	3,234	5,674
GERMANY Federal Republic)										
Gundremmingen-Block A	BWR	237	GE	4/67	40	110	310	510	710	910
Lingen	BWR	256	AEG	6/68	44	70	290	510	730	950
Karlsruhe Mzfr	PHWR	52	SIEMENS	9/65	11	48	103	158	213	268
Obrigheim	PWR	328	SIEMENS	3/69	59	49	344	639	934	1,229
Stade	PWR	630	SIEMENS	5/72	113	0	301	866	1,431	1,996
Wurgassen	BWR	640	AEG	3/72	109	0	309	854	1,400	1,944
Biblis A	PWR	1150	SIEMENS	6/74	207	0	121	1,156	2,191	3,226
Biblis 2	PWR	1240	"	8/77	223	0	0	539	1,654	2,769
Brunsbuttel	BWR	771	AEG	8/76	131	0	0	448	1,103	1,758
Neckar GKN	PWR	805	KWU	4/77	145	0	0	495	1,220	1,945
Isar KKI	BWR	870	AEG/KWU	5/77	148	0	0	395	1,135	1,875
Phillippsburg 1	BWR	864	KWU	1/78	147	0	0	294	1,029	1,764
Phillippsburg 2	BWR	864	KWU	1/83	147	0	0	0	294	1,029
Thtr-Uentrop	THTR	300	HRB	7/78	66	0	0	99	429	759
Kalkar SNR-300	LMFBR	282	INTERATOM-NERA	3/82	40	0	0	0	113	313
KKN-Niederaichback	GCHWR	100	SIEMENS	1/76	22	0	0	88	198	308
Krummel	BWR	1260	AEG	3/79	214	0	0	178	1,248	2,318
Unterweser	PWR	1230	SIEMENS	1/77	221	0	0	663	1,768	2,873

Table B-1 (Cont'd.)

WORLD POWER REACTORS

Gundremmingen-Block B	BWR	1249	KWU	7/83	212	0	0	0	318	1,378
Gundremmingen-Block C	BWR	1249	"	7/82	212	0	0	0	530	1.590
Kernkraftuerk Sud.	PWR	1300	KWU	7/80	234	0	0	0	1,053	2,223
Kaerlich	PWR	1228	BBR	5/79	221	0	0	147	1,252	2,357
Grohnde	PWR	1294	KWU	2/32	233	0	0	0	214	1,378
KKG (Grafenrheinfeld)	PWR	1225	KWU	9/80	221	0	0	0	956	2,063
Neckar (GKN 2)	PWR	805	KWU	1/83	145	0	0	0	290	1,015
Brokdork	PWR	1300	KWU	1/85	239	0	0	0	0	1,195
Hamm Ventrop (KKH)	PWR	1300	KWU	1/83	239	0	0	0	478	1,673
Biblis 3	PWR	1228	KWU	1/83	239	0	0	0	478	1,673
					Total	277	1,778	8,039	23,369	44,779
HUNGARY										
Paks 1	PWR	440	AEE	1/81	79	0	0	0	316	711
Paks 2	PWR	440	AEE	1/82	79	0	0	0	237	632
Paks 3 (PAKS)	PWR	440	AEE	1/85	79	0	0	0	0	395
Paks 4 (PAKS)	PWR	440	AEE	1/85	79	0	0	0	0	395
					Total	0	0	0	553	2,133
INDIA										
Tarapur 1	BWR	220	GE	10/69	34	9	179	349	519	689
Tarapur 2	BWR	200	GE	10/69	34	9	179	349	519	689
Rajasthan 1	PHWR	200	AECL	1/74	40	0	44	264	484	704
Rajasthan 2	PHWR	200	AECL	3/77	44	0	0	125	345	565
Madras 1	PHWR	220	DAE	1/79	52	0	0	52	312	592
Madras 2	PHWR	220	DAE	1/81	52	0	0	0	208	468
Narora 1	PHWR	220	DAE	1/83	48	0	0	0	96	336
Narora 2	PHWR	220	DAE	1/84	48	0	0	0	48	283
					Total	18	402	1,139	2,531	4,326
IRAN										
Iran-1	PWR	1200	KWU	1/82	216	0.	0	0	648	1,728
Iran-2	PWR	1200	KWU	1/83	216	0	0	0	432	1,512
Iran-3	PWR	900	FRAMATOME	1/84	162	0	0	0	162	972
Iran-4	PWR	900	"	1/85	162	0	0	0	0	810
					Total	0	0	0	1,242	5,022
ISRAEL										
Unnamed	LWR	600	-	1/84	108	0	0	0	108	648

Table B-1 (Cont'd.)

WORLD POWER REACTORS

ITALY										
Latina	GCR	150	TNPG	1/64	20	120	220	320	420	520
Garigliano	BWR	150	GE	6/64	26	145	275	405	535	665
Trino Verceuese	PWR	247	W	1/65	44	220	440	660	880	1,100
Cirene	LWCHR	40	AMN	1/80	10	0	0	0	50	100
Enel 4	BWR	840	AMN-GETSCO	1/76	142	0	0	572	1,287	2,002
Enel 5	PWR	952	ELECTRONUC-ITAL	1/83	171	0	0	0	342	1,197
Enel 6	BWR	982	AMN	1/83	167	0	0	0	334	1,169
Enel 7	PWR	952	ELECTRONUC-ITAL	1/84	171	0	0	0	171	1,026
Enel 8	BWR	982	AMN	1/84	167	0	0	0	167	1,002
					Total	485	935	1,957	4,166	8,781
JAPAN										
Fukushima 1	BWR	460	GE/TOSHIBA	3/71	78	0	299	689	1,079	1,469
Fukushima 2	BWR	784	GE	7/74	133	0	67	732	1,397	2,062
Shimani	BWR	439	HITACHI	3/74	75	0	63	438	813	1,188
Mihama 1	PWR	320	W	11/70	58	0	242	532	822	1,112
Mihama 2	PWR	470	MHI	7/72	85	0	213	638	1,063	1,488
Tsuruga	BWR	340	GE	3/70	58	0	280	570	860	1,130
Tokai 1	GCR	159	GEC	7/66	21	74	179	284	389	494
Tokai 2	BWR	1067	GE	1/78	181	0	0	362	1,267	2,172
Takahama 1	PWR	781	W	11/74	141	0	242	729	1,434	2,139
Takahama 2	PWR	781	MHI	11/75	141	0	101	588	1,293	1,998
Genkai 1	PWR	559	MHI	3/82	101	0	0	430	934	1,439
Ohi 1	PWR	1122	W	6/78	202	0	0	320	1,330	2,340
Ohi 2	PWR	1122	W	7/79	202	0	0	101	1,111	2,121
Mihama 3	PWR	781	MHI	1/77	141	0	0	423	1,433	2,443
Fugen	LWCHR	200	HITACHI	7/77	48	0	0	120	360	600
Ikata	PWR	538	MHI	4/77	97	0	0	267	752	1,237
Hamaoka 1	BWR	516	TOSHIBA	3/76	88	0	0	337	777	1,129
Hamaoka 2	BWR	840	TOSHIBA	9/78	138	0	0	184	874	1,564
Fukushima 3	BWR	784	TOSHIBA	3/76	133	0	0	510	1,174	1,840
Fukushima 4	BWR	784	HITACHI	10/78	133	0	0	166	831	1,496
Fukushima 5	BWR	784	TOSHIBA	4/78	133	0	0	234	898	1,563
Fukushima 6	BWR	1100	GE	10/79	187	0	0	31	966	1,901
Monju	LMFBR	300	-	1/84	42	0	0	0	42	252
Onagawa	BWR	500	TOSHIBA	1/82	85	0	0	0	255	600
Genkai 2	PWR	1300	BBR	1/85	239	0	0	0	286	791
					Total	74	1,686	8,685	22,440	36,648

Table B-1 (Cont'd.)

WORLD POWER REACTORS

KOREA (South)										
Ko-Ri 1	PWR	564	W	11/77	102	0	0	221	731	1,241
Ko-Ri 2	PWR	600	W	1/85	108	0	0	0	0	540
Nae-Po 1	PHWR	600	AECL	1/84	132	0	0	0	132	792
Nae-Po 2	PHWR	600	AECL	1/85	132	0	0	0	0	660
Chang-Yung 1	-	800	-	1/86	176	0	0	0	-	-
Chang-Yung 2	-	800	-	1/87	176	0	0	0	0	-
					Total	0	0	221	863	3,233
LUXEMBOURG										
Remerschen	PWR	1300	BBR	1/85	239					
MEXICO										
Laguna Verde 1	BWR	654	GE	3/81	111	0	0	0	426	981
Laguna Verde 2	BWR	654	GE	3/82	111	0	0	0	315	870
					Total	0	0	0	741	1,351
NETHERLANDS										
Dodewaard	BWR	55	GE/GKN	3/69	9	8	53	98	143	188
Borssele	PWR	477	KWU	10/73	86	0	100	530	960	1,390
					Total	8	153	628	1,103	1,578
PAKISTAN										
Kanupp	PHWR	125	CGE	12/72	28	0	61	201	341	431
Chasma-Barrage	-	600	-	1/83	132	0	0	0	264	924
					Total	0	61	201	605	1,405
PHILLIPINES										
Bagac 1	PWR	626	W	1/84	113	0	0	0	113	678
Bagac 2	PWR	626	W	1/84	113	0	0	0	113	678
					Total	0	0	0	226	1,356
PORTUGAL										
Unnamed	LWR	600	-	1/83	108	0	0	0	216	756
Unnamed	LWR	600	-	1/85	108	0	0	0	0	540
					Total	0	0	0	216	1,296
POLAND										
Zarnowieckie	PWR	440	AEE	1/85	79	0	0	0	0	396

Cont'd.)

WORLD POWER REACTORS

RUMANIA										
Olt	PWR	440	AEE	1/82	79	0	0	0	237	632
SOUTH AFRICA										
Koeberg 1	LWR	922	FRAMATOM	1/83	166	0	0	0	332	1,162
Koeberg 2	LWR	922	FRAMATOM	1/84	166	0	0	0	166	996
					Total	0	0	0	493	2,158
SPAIN										
Santa Maria de Garona	BWR	440	GE	3/71	75	0	281	656	1,031	1,406
Vandellos	GCR	480	GC	7/72	62	0	155	465	775	1,085
Jose Cabrera	PWR	153	W	8/69	28	12	152	292	432	572
Asco 1	PWR	900	W	7/79	162	0	0	81	891	1,701
Asco 2	PWR	900	W	1/80	162	0	0	0	810	1,620
Almarez 1	PWR	900	W	7/77	162	0	0	405	1,215	2,025
Almarez 2	PWR	900	W	7/78	162	0	0	243	1,053	1,863
Confrentes	BWR	930	GE	1/81	158	0	0	0	632	1,422
Lemoniz 1	PWR	901	W	3/79	162	0	0	135	945	1,755
Lemoniz 2	PWR	901	W	4/80	162	0	0	0	770	1,580
Cabo Cope	BWR	930	GE	1/83	158	0	0	0	316	1,106
Valde Caballaros 1	BWR	937	GE	1/83	159	0	0	0	337	1,183
Valde Caballeros 2	BWR	937	GE	1/83	159	0	0	0	169	1,014
TRILLO 1	PWR	997	KWU	7/82	180	0	0	0	270	1,170
					Total	12	588	2,277	9,646	19,502
YUGOSLAVIA										
Krsko	PWR	615	W	7/79	111	0	0	55	610	1,165
SWEDEN										
Oskarshamn 1	BWR	440	ASEA-ATOM	2/72	75	0	212	587	962	1,337
Oskarshamn 2	BWR	580	"	1/75	99	0	0	495	930	1,485
Ringhals 1	BWR	760	"	2/75	129	0	0	634	1,273	1,924
Ringhals 2	PWR	809	W	2/75	146	0	0	661	1,411	2,141
Ringhals 3	PWR	900	W	1/78	162	0	0	324	1,134	1,944
Ringhals 4	PWR	900	W	1/80	162	0	0	610	1,620	2,430
Barsebeck 1	BWR	580	ASEA-ATOM	7/75	99	0	0	446	941	1,436
Barsebeck 2	BWR	580	"	7/77	99	0	0	248	743	1,238
Oskarshamn 3	BWR	1060	"	1/85	180	0	0	0	0	901

Table B-1 (Cont'd.)

WORLD POWER REACTORS

Forsmark 1	BWR	900	ASEA-ATOM	7/78	153	0	0	230	995	1,760
Forsmark 2	BWR	900	"	1/81	153	0	0	0	612	1,377
Forsmark 3	BWR	1000	"	1/84	180	0	0	0	170	1,020
					Total	0	212	4,455	10,791	18,993
SWITZERLAND										
Beznau 1	PWR	350	W	12/69	63	5	320	635	950	1,265
Beznau 2	PWR	350	W	3.72	63	0	178	493	808	1,123
Muhleberg	BWR	306	GETSCO	10/72	55	0	124	349	574	799
Geosgen	PWR	920	KWU	4/78	166	0	0	291	1,121	1,951
Graben	BWR	1140	GETSCO	1/81	194	0	0	0	970	1,940
Leibstadt	BWR	955	"	1/80	160	0	0	0	800	1,600
Kaiseraugst	BWR	932	"	1/81	157	0	0	0	471	1,256
Ruthi	-	900	"	-	153	0	0	0	-	-
					Total	5	622	1,768	5,694	9,934
TAIWAN										
Chin-Shan 1	BWR	604		1/78	103	0	0	206	721	1,236
Chin-Shan 2	BWR	604		1/80	103	0	0	0	515	1,030
Kuosheng 1	BWR	951	GE	4/81	162	0	0	0	540	1,350
Kuosheng 2	BWR	951	"	4/82	162	0	0	0	446	1,256
Nr. 5	PWR	907	"	4/84	163	0	0	0	122	937
Nr. 6	PWR	907		4/85	163	0	0	0	0	774
					Total	0	0	206	2,344	6,583
					TOTAL	1,035	8,397	39,588	120,444	237,526

Table B-2

RESEARCH REACTORS ≥ 1 MW(t)

Location	Type	MW_{th}	Operating Date	Fuel	^{239}Pu (2) Prod. kg/yr	^{239}Pu Accumulated (kg) Through				
						69	74	79	84	89
Argentina										
RA-3	Tank	8	5/67	Enr. U						
Australia										
HIRAR	Tank, D_2O	10	1/58	93% Enr U	.0009 (3)	.011	.016	.020	.025	.029
Austria										
ASTRA	Pool	12	9/60	90% Enr. U	.001 (8)	.01	.015	.02	.025	.03
Belgium										
BR-1	Graphite	4	5/50	Nat. U	.94	12.9	17.6	22.3	27.0	31.7
BR-2	Tank	100	7/61	90% Enr U	.01 (8)	.085	.14	.19	.24	.29
Brazil										
IEAR-1	Pool	5	9/57	20% Enr. U						
Bulgaria										
IRT-SOFIA	Pool	1	8/61	10% Enr. U						
Canada										
NRX	Tank, D_2O	33	7/47	Nat. U	2.18 (7)	49.1	60.0	70.9	81.8	92.7
NRU	Tank, D_2O	110	11/57	Nat. U	7.26 (7)	88.3	124.6	160.9	197.2	233.5
MNR	Pool	2	2/50	90% Enr. U	.0002 (8)	.002	.003	.004	.005	.006
WR-1	Tank, Organic, D_2O	60	11/65	2 4% Enr. U						
Chile										
CNEN	Pool	5	/73	Enr. U						
Czechoslovakia										
WWR-S	Tank	4	9/57	10% Enr. U	.077 (4)	.95	1.34	72	2.11	2.49
Denmark										
DR-2	Pool	5	12/53	90% Enr. U	.0005 (8)	.006	.008	011	.013	.016
DR-3	Tank, D_2O	10	1/60	93% Enr. U	.0009 (3)	.009	.014	018	.023	.027
Italy										
ISPRA-1	Tank, D_2O	5	3/59	20% Enr. U						
AVOGADRO RS-1	Pool	7	9/59	90% Enr. U	.0007 (8)	.007	.010	014	.017	.021
RC-1 (Triga)	Pool, U-ZrH	1	6/60	20% Enr. U	.026 (5)	.25	.38	51	.64	.77
GALILEO RTS-1	Pool	5	4/63	90% Enr. U	.0005 (8)	.0033	.0058	0083	.011	.013
ESSOR	Tank, Organic D_2O	40	3/67	Nat. & 90% Enr. U						
PEC (C)	Fast	130								

Table B-2 (Cont'd.)

RESEARCH REACTORS ≥ 1 MW(t)

Location	Type	MW_{th}	Operating Date	Fuel	^{239}Pu (2) Prod. kg/yr	^{239}Pu Accumulated (kg) Through				
						69	74	79	84	89
Japan										
JRR-2	Tank, D_2O	10	10/60	90% Enr. U	.001 (8)	.01	.015	.02	.025	.03
JRR-3	Tank, D_2O	10	9/62	Nat U	2.04	15.0	25.2	35.4	45.6	55.8
KUR	Tank	5	6/64	90% Enr. U	.0005 (8)	.003	.005	.008	.01	.013
JRR-4	Pool	25	1/65	90% Enr. U	.0025 (8)	.013	.025	.038	.05	.06
JMTR	Tank	50	3/68	90% Enr. U	.005 (8)	.008	.033	.058	.083	.11
JOYO (C)	Fast	50	75							
Mexico										
RCN (Triga)	Pool, U-ZrH	1	11/68	20% Enr. U	.026 (5)	.004	.13	.26	.39	.52
Netherlands										
HFR	Tank	45	11/61	90% Enr. U	.0045 (8)	.036	.059	.081	.10	.13
HOR	Pool	2	4/63	90% Enr. U	.0002 (8)	.0013	.0023	.0033	.0043	.0053
KSTR	Aqu. Homog.	1	4/74							
Norway										
Halden	Tank, D_2O	25	6/59	1.5% Enr. U	4.46	40.1	62.4	84.7	107.0	129.3
JEEP-2	Tank, D_2O	2	12/66	3.5% Enr. U	.13	.40	1.05	1.70	2.35	3.00
Pakistan										
PARR	Pool	5	12/65	90% Enr. U	.005 (8)	.002	.0045	.007	.0095	.012
Phillippines										
PRR-1	Pool	1	8/63	20% Enr. U						
Egypt										
WWR-C	Tank	2	7/61	10% Enr. U	.038 (4)	.32	.51	.70	.89	1.08
Germany, Fed. Republic										
FRM	Pool	4	5/68	20% Enr. U						
FRG-1	Pool	5	10/58	20% Enr. U						
FR-2	Tank, D_2O	44	7/66	Nat. U	10.3 (6)	36.1	87.6	139.1	190.6	242.1
FRJ-1	Pool	10	11/71	80% Enr. U						
FRJ-2	Tank, D_2O	23	12/67	93% Enr. U	.002 (3)	.004	.014	.024	.034	.044
FRG-2	Pool	15	2/68	90% Enr. U	.0015 (8)	.003	.010	.017	.025	.033
FMRB	Pool	1	10/67	90% Enr. U	.0001 (8)	.0002	.0007	.0012	.0017	.0022
FRN (Triga)	Pool, U-ZrH	1	8/72	20% Enr. U	.026 (5)	-	.063	.19	.32	.45
BER-2	Pool	5	12/73	Enr. U		-				
Greece										
Democritus (GRR)	Pool	5	7/61	20% Enr. U						
Hungary										
WWR-C	Tank	2	3/59	10% Enr. U	.038 (4)	.41	.60	.79	.98	1.17

Table B-2 (Cont'd.)

RESEARCH REACTORS >1 MW(t)

Location	Type	MW_{th}	Operating Date	Fuel	^{239}Pu Prod kg/yr (2)	^{239}Pu Accumulated (kg) Through 69	74	79	84	89
India										
APSARA	Pool	1	8/56	46% Enr. U						
CIRUS	Tank, D_2O	40	7/60	Nat. U	9.4 (6)	89.3	136.3	183	230.3	277.3
FBTR (C)	FBR	50	/75	Thorium	-	-				
Iran										
UTRR	Pool	5	11/67	20% Enr. U						
Iraq										
WWR-C	Tank	2	1/63	10% Enr. U	.038 (4)	.27	.46	.65	.84	1.03
Israel										
IRR-1	Pool	5	6/60	90% Enr. U	.0005 (8)	.005	.007	.010	.012	.015
IRR-2	Tank, D_2O	26	12/63	Nat U	6.11 (6)	37.2	67.8	98.3	128.9	159.4
Poland										
EVA (WWR-C-WARSAW)	Tank	10	1/53	10% Enr. U	.19 (4)	2.28	3.23	4.18	5.13	6.08
MARIA (C)	Pool	30	Unknown	Enr U						
Portugal										
RPI	Pool	1	4/61	Enr U						
Romania										
WWR-C	Tank	3	7/57	10% Enr. U	.06 (4)	.75	1.05	1.35	1.65	1.95
(Super Triga)	Tank, U-ZrH	14	77	Enr. U						
South Africa										
SAFARI-1	Tank	20	3/65	90% Enr. U	.002	.01	.02	.03	.04	.05
Spain										
JEN-4	Pool	3	10/58	20% Enr. U	.04	.45	.65	.85	1.05	1.25
Sweden										
R-2	Tank	50	5/60	90% Enr. U	.005 (8)	.048	.073	.098	.12	.15
R-2-0	Pool	1	6/61	90% Enr. U	.0001 (8)	.0008	.0013	.0018	.0023	.0028
Switzerland										
SAPHIR	Pool	5	4/57	20% Enr. U						
DIORIT	Tank, D_2O	20	8/60	Nat U	4.47	42.1	64.4	86.3	109.1	131.5
Taiwan										
TRR	LWCHWR	40	1/73	Nat U	2.64 (7)	-	5.3	18.5	31.7	44.9
Thailand										
TRR-1	Pool	1	10/62	90% Enr. U	.0001 (8)	.0007	.0012	.0017	.0022	.0027

Table B-2 (Cont'd.)

RESEARCH REACTORS >1 MW(t)

Location	Type	MW_{th}	Operating Date	Fuel	^{239}Pu Prod. kg/yr (2)	^{239}Pu Accumulated (kg) Through				
						69	74	79	84	89
Turkey TR-1	Pool	1	1/62	90% Enr. U	0001 (8)	.0008	.0013	.0018	.0023	.0028
Uruguay RUDI	Pool	1	73	Enr. U						
Venezuela RV-1	Pool	3	10/65	20% Enr. U						
Yugoslavia R-A	Tank, D_2O	10	12/59	1.5% Enr. U	82	8.27	12.37	16.47	20.57	24.67
Zaire TRICO (Triga)	Pool, U-ZrH	1	72	20% Enr. U	.026 (5)	-	.078	.14	.27	.40

UNITED STATES
ENERGY RESEARCH AND DEVELOPMENT ADMINISTRATION
WASHINGTON, D.C. 20545

March 2, 1977

Ms. Audrey Buyrn
Office of Technology Assessment
Congress of the U.S.
Washington, D.C. 20510

Dear Ms. Buyrn:

As requested in your telephone conversation of February 17, 1977, I am enclosing two schedules reflecting total United States exports, by country, of enriched uranium of 20 percent or greater U-235 since 1968 and of all plutonium since the beginning.

Data on uranium enriched to 20 percent and above prior to January 1, 1968, has not yet been computerized, and accordingly, we are unable to readily furnish you exports prior to 1968. This data is now being recovered from historical files and will be automated for recovery by October of this year.

If I can be of further assistance, please call.

Sincerely,

Thomas J. Haycock Jr.

Thomas J. Haycock, Jr.
Assistant Director for Information
Support
Division of Safeguards and Security

Enclosures:
As stated

Schedule **A**

Plutonium
Exported by the United States
From Beginning Through December 31, 1976

Country	**Grams**
Argentina	5
Australia	6,577
Austria	296
Belgium	16,349
Brazil	80
Canada	4,928
China **(Taiwan)**	683
Columbia	80
Denmark	81
Eurochemic	14
Finland	2
France	41,442
Germany	767,126
Greece	192
IAEA	44
India	82
Iran	112
Iraq	16
Ireland	16
Israel	605
Italy	129,097
Japan	111,227
Korea	8
Mexico	164
Netherlands	790
New Zealand	80
Norway	1,083
Pakistan	117
Philippines	32
South Africa	159
Spain	6
Sweden	9,143
Switzerland	1,502
Thailand	80
Turkey	368
United Kingdom	22,417
Uruguay	80
Venezuela	**10**
Total Exported	**1,115,093**

SCHEDULE B
ENRICHED URANIUM
EXPORTED BY THE UNITED STATES
FROM JANUARY 1, 1968 THROUGH DECEMBER 31, 1976
(Transfer of 500 grams or more - enriched to 20% or more)

COUNTRY	KILOGRAMS ELEMENT	KILOGRAMS ISOTOPE
Argentina	31	28
Austria	2	1
Belgium	23	13
Brazil	6	6
Canada	619	575
China (Taiwan)	5	5
Colombia	1	1
Finland	11	2
France	2,371	2,087
Germany	3,543	2,775
Greece	6	6
Israel	9	8
Italy	164	138
Japan	1,707	
Korea	7	3
Netherlands	2	2
Portugal	8	7
South Africa	25	23
Switzerland	2	2
United Kingdom	1,119	1,040
Yugoslavia	5	3
TOTAL EXPORTED	9,666	7,405

SCHEDULE B

ENRICHED URANIUM

EXPORTED BY THE UNITED STATES

FROM JANUARY 1, 1968 THROUGH DECEMBER,R 31, 1976

(Transfer of 500 grams or more - enriched to 20% or more)

COUNTRY	KILOGRAMS	
	ELEMENT	ISOTOPE
Argentina	31	28
Austria	2	1
Belgium	23	13
Brazil	6	6
Canada	619	575
China (Taiwan)	5	5
Colombia	1	1
Finland	11	2
France	2,371	2,087
Germany	3,543	2,775
Greece	6	6
Israel	9	8
Italy	164	138
Japan	1,707	
Korea	7	3
Netherlands	2	2
Portugal	8	7
South Africa	25	23
Switzerland	2	2
United Kingdom	1,119	1,040
Yugoslavia	5	3
TOTAL EXPORTED	9,666	7,405