

Sources of Nuclear Material

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A nation planning the development of nuclear weapons has several options for obtaining fissile material. Diversion from commercial nuclear power facilities has received the greatest attention recently: nuclear material could be obtained through the evasion of safeguards or the use of unsafeguarded facilities, possibly following abrogation of safeguarding agreements. The other routes are the construction of dedicated facilities, such as a small plutonium production reactor or a weapons-grade enrichment plant, and purchase or theft of weapons material or complete weapons. Each of these routes is subject to constraints and each country will weigh the options differently depending on its own resources, capabilities, political situation, and intentions.

DIVERSION FROM COMMERCIAL POWER SYSTEMS

Although none of the nations that have nuclear weapons have obtained them by this means, it is possible that a nation could extract the fissile material needed for nuclear weapons from its commercial nuclear power systems. This section will examine existing reactors and several under development, along with their complete fuel cycles. With this background, the relative difficulty of diversion from each system can be understood and compared. In the past, resistance to diversion has not been a parameter in the design of nuclear power systems. As diversion is increasingly seen as a problem, research is beginning on reducing the vulnerability of existing systems. Some preliminary conceptual work has also been done on reactor systems that are inherently resistant to diversion,

The Fuel Cycle

The flow of nuclear material in a commercial power program—from the mine, through

the reactor, to disposal or reuse—is called the nuclear fuel cycle. The nuclear materials of interest for either an explosive or a powerplant are those that release extra neutrons and energy when they fission, or split apart. Such fissile isotopes are not abundant in nature, although some are produced as a byproduct of power production: neutrons striking certain nuclei will convert them, after a short decay chain, to fissile isotopes.

Two general fuel cycles exist, each based on a different element. In the uranium cycle, the isotope U^{238} does not fission easily but does breed a fissile isotope of plutonium, Pu^{239} . A fissile isotope U^{235} is also present in natural uranium. In the thorium cycle, the thorium isotope Th^{232} breeds the fissile isotope, U^{233} . Within each of these fuel cycles, quantities and concentrations of various isotopes, and the procedures for processing them, vary with the particular reactor type.

The two types of nuclear power reactors available on the world market today both use

the uranium fuel cycle. These are light water reactors (LWRS) developed by the United States and Canadian heavy water reactors (CANDU). Others which have been largely developed and could be deployed in the near future are the high-temperature gas reactor (HTGR), and the advanced gas-cooled reactor (AGR). Most development effort in several advanced countries is focused on the liquid metal fast breeder reactor (LMFBR), but commercialization is not expected for at least 10 years. Development of another breeder reactor, the light water breeder reactor (LWBR) is proceeding at a slower pace.

All these reactors, plus a few others that could become important, are described in detail (along with their fuel cycles) in volume II, appendix V. Because they are of immediate interest, the fuel cycles and diversion potential of LWRS and CANDUS will be summarized in this section. The LMFBR, LWBR, and thorium cycle in general will also be examined briefly in this chapter. Research plans on alternate fuel cycles are briefly summarized. Conceptual studies on inherently nonproliferating reactors are described at the end of this section. Safeguards to prevent and/or detect diversion are discussed under "Safeguards" in chapter VIII.

Light Water Reactors

Technical Description

The common types of light water reactors differ in the coolant they use—either boiling water (as in BWRS) or pressurized water (as in PWRs). They present identical problems for proliferation prevention, and will be considered together here. Key characteristics of these reactors and their fuel cycles are given in figure VII-1.

The first stage in the LWR fuel cycle is the mining of ore, which contains about 1,500 parts-per-million uranium. The milling operation then concentrates the uranium by straightforward chemical processes into yellowcake (U^3O_8). By far the largest percentage of natural uranium (99.3 percent) consists of the isotope U^{238} . Only 0.7 percent is U^{235} , the isotope that will fission in a LWR.

Because LWRS are designed to operate with a U^{235} concentration of about 3 percent, natural uranium must be enriched. In preparation for enrichment, yellowcake is converted in a special plant to uranium hexafluoride (UF_6), which is a gas at a sufficiently low temperature to permit easy handling.

Although several enrichment techniques are known, the only full-scale plants built to date use the principle of gaseous diffusion. The separation achieved in one stage of a diffusion plant is small, so a series of stages, called a cascade is required to raise the U^{235} concentration to the desired level of enrichment. A gaseous diffusion plant must be very large to be economical. Commercial plants are built to serve at least 50 large (i.e., 1000 MW(e)) reactors. Each plant costs several billion dollars and consumes a large amount of electrical power (about 3 percent to 5 percent of the energy produced by its enriched product). Another enrichment technique—gas centrifuge—can achieve a greater separation factor between the isotopes in each stage. It appears to be economical on a smaller scale and requires much less electrical power. This technique has 'not yet progressed beyond the pilot plant stage, but several new commercial plants of this type are in the planning stage.

Other enrichment methods are much further from commercialization. Such new technologies should be watched as they develop, since they may become inexpensive and simple enough to be attractive to many countries.

After enrichment, UF_6 is converted to uranium dioxide (UO_2) and fabricated into fuel assemblies. The fuel assemblies are shipped and loaded into the reactor, where they remain for several years. One third of the fuel assemblies are replaced each year in a pressurized water reactor (PWR), and one fourth in a boiling water reactor (BWR). Refueling involves shutting down the reactor, allowing it to cool, removing the reactor head, and transferring the spent fuel underwater to a storage pool. The entire process takes 4 to 6 weeks.

At present, spent fuel is simply stored at the powerplant or in spent-fuel pools at other locations. The intention of the industry is to

Figure VII-1
Power Reactor Characteristics (For Units \geq 500 MWe)**

	BWR	PWR	AGR	HWR (CANDU)	HTGR USA	FB (US)		FB (UK)	
						CORE	BLANKET	CORE	BLANKETS
Thermal efficiency (%)	34	33	41	29	39	40	40	41.3	41.3
Average spec. power in fuel (kW/kg heavy metal)	26	39	13.5	24	76	19.8	155	138	5
Initial core: Irradiation level (MWd/kg heavy metal)	17	22.6		6	54.5	15.5	80	—	—
Fresh fuel enr. (% U 235)	2.03	2.26	1.6	Nat.	93.15	1.8			
Spent fuel enr. (% U 235)	0.86	0.74	0.9	50	0.8				
Inventory: kg nat. U/MWe	434	365	620	143	326	520	152	13.22	48 ²
kg SW/MWe	221	209	285	349	245				
(0.25 tails assay) kg Pu(E)/MWe							1.8	2.8*	
Pu(E) produced ⁴ (g/MWe yr)	296	300	120	581	180	70		214	
Replacement loadings: Irradiation level (MWd/kg heavy metal)	27.5	32.6	17.5	7.5	95	22	0	66	2
Fresh fuel enr. (% U 235)	2.73	3.20	2.3	Nat.	93.15	2.2			
Spent fuel enr. (% U 235)	0.84	0.90	0.87	0.2	30	0.63			
Net consumption:									
kg nat. U/MWe-yr ¹	165	173	165	168	90	182	1.9 ²		
kg SW/MWe-yr	125	137	119	—	96	120			
(0.25 tails assay)									
Pu(E) produced ⁴ (g/MWe yr)	248	260	187	502	(U 233) 250	170		214	
Operating time to reach equilibrium (yr)	4	3	4	1	5	3	3-7 ³	3	3-7

¹MWe-yr = 8760 MWh. Figures are based on instantaneous credit for spent fuel.

²Depleted uranium.

³Depends on position.

⁴Allows for reprocessing losses and, where appropriate, for the decay of Pu²⁴¹.

NOTE: All plutonium figures are expressed in equivalent grams Pu²³⁹, i.e. in Pu(E) for use in FBRs, applying the following "worth factor": 239 x .00; 240 x 0.18; 241 x .53; 242 x 0.08; [1 g Pu(E) corresponds to 0.85 g Pu (fissile)].

^{*}Out-of-pile 1 kg/MWe

^{**}Uranium Resources, Production and Demand. OECD Nuclear Energy Agency and the International Atomic Energy Agency, December 1975.

reprocess spent fuel to recover unfissioned U^{235} and plutonium that was generated from U^{238} . Plutonium can directly replace U^{235} as fissile material in fuel, thus reducing demand for uranium ore and the need for enrichment. If it is found undesirable for economic, political, or safety reasons to reprocess spent fuel, the cycle can terminate at this point. If this is the case, long-term storage facilities or a permanent disposal method for the spent fuel rods must be planned.

If reprocessing does occur, spent-fuel elements are sent to the reprocessing plant in large, heavy shipping casks designed to provide both shielding against intense radiation and cooling to remove decay heat. At the reprocessing plant, the fuel elements are chopped up and the contents dissolved in acid. Solvent extraction is then used to separate plutonium and uranium from the fission products, which are stored for eventual disposal. The plutonium and uranium emerge in separate streams. The uranium is converted to UF_6 for reenrichment, and the plutonium to plutonium dioxide (PuO_2) either for stockpiling or recycling. All operations in the reprocessing plant must be performed by remote control, because of the intense radioactivity of spent fuel and the toxic nature of plutonium.

If the plutonium is to be recycled, the PuO_2 is shipped to a mixed-oxide fuel fabrication plant, where it is combined with UO_2 so that the final mixture will contain the desired fraction of fissile isotopes. A mixed-oxide fuel fabrication plant is more expensive than a uranium fuel fabrication plant, because remote handling is required for plutonium.

Diversion From the LWR Fuel Cycle

Material convertible to weapons grade could be diverted at any point of the LWR cycle, but the difficulty of conversion, and hence the attractiveness of the diverted material varies markedly from point to point. This section will provide an estimate of the amount of material that must be diverted at each stage of the LWR fuel cycle in order to produce one nuclear explosive, give a summary of the operations that must be performed upon the

material to convert it to a form that can be directly used in a nuclear weapon (process details are given in volume II, appendix V), and assess the feasibility of (a) a nation and (b) a non-national group performing these operations.

The safeguards that a diverter or thief would have to evade or surmount are described under "Safeguards" in chapter VIII, and are only briefly mentioned in this section. The resources required to construct a nuclear weapon once weapons material has been obtained are discussed in chapter VI.

Yellowcake (i.e., U^{238}) from a uranium mill, after a few chemical steps, could be enriched to weapons-grade uranium or partially transformed to Pu^{239} in *national* dedicated facilities, as described in the "Dedicated Facilities" section of this chapter and in volume II, appendix VI.

Approximately 6.5 metric tons of yellowcake would have to be fed to an enrichment plant to yield 30 kilograms of 90 percent U^{235} (enough for one or two explosives). Approximately 75 metric tons of yellowcake would be required to supply enough natural uranium to fuel a dedicated production reactor that would produce 10 kilograms of Pu^{239} per year (enough for one or two explosives). In the latter case, it would not be necessary to refuel the dedicated production reactor more than once every 10 years or so. However, the nation probably would prefer to refuel every year or two in order to obtain weapons material quickly and steadily.

The capital cost of a reactor and reprocessing plant that could produce one or two explosive's worth of plutonium per year, starting with yellowcake, is in the tens of millions of dollars. This effort is within the capabilities of many (perhaps close to 50) nations, but is entirely impractical for a non-state adversary. The cost of a small enrichment facility is more complex to assess; it is discussed under "Dedicated Facilities" in chapter VII. It is also entirely impractical for a non-state adversary.

International Atomic Energy Agency (IAEA) and Euratom safeguards exist for yellowcake (in fact, Euratom safeguards start with uranium ore), but a country in the

market for yellowcake to supply a dedicated facility would probably have little difficulty in clandestinely purchasing a sufficient amount. Moreover, many countries have considerable resources of uranium ore, and in these countries a dedicated mine and mill could be used to supply a dedicated facility. (See chapter X.)

An enrichment plant presents a more attractive target to the diverter. Although the design output of commercial enrichment plants is only 3 percent to 4 percent U^{235} , and completely impossible (not merely impractical) to use directly in a nuclear fission explosive, much of the work to raise the enrichment to weapons grade has been accomplished. For 30 kg of 90 percent LWs, nearly 8000 kg of natural uranium hexafluoride feed and 6900 separative work units (SWU) are required, but if 3 percent U^{235} is the feed, only about 1500 kg of uranium hexafluoride and about 2500 SWU are required.

Several options are possible for a nation which elects to divert from its own commercial enrichment plant. The components of the entire plant could be reassembled so that the product would be highly enriched uranium. The change is not difficult for a centrifuge plant, but is complicated and time consuming for a diffusion plant. Nevertheless, the Chinese appear to have followed this route in converting a U.S.S.R. supplied diffusion plant. This change is too drastic to be done covertly if the plant were safeguarded.

If the nation had a large, safeguarded enrichment plant, it might choose to convert one section of the plant to a high-enrichment cascade. Again, this would be difficult to do in a diffusion plant and relatively easy in a centrifuge plant.

An alternate option would be to divert part of the low-enriched uranium product and feed it into a separate, small enrichment plant to boost it to highly enriched uranium. The additional small plant could be either inside the large plant or at another site. Only about 400 centrifuges of European design would be required to produce 30 kg of 90 percent U^{235} per year from 3 percent LWs feed. For comparison, an enrichment plant of near-competitive commercial size to supply ten, 1000 MW(e), LWRs with low-enriched uranium

would have a capacity of 1,300,000 SWU per year and contain approximately 200,000 centrifuges of European design. Enrichment plant safeguards are discussed under "Safeguards" in chapter VIII, but it should be noted here that the scenarios sketched in this paragraph are not implausible as long as inspectors are limited to monitoring the perimeter of the facility and unmonitored input and output paths are permitted.

As already discussed, enrichment is not an option for the non-state adversary. However, low-enriched uranium could be an attractive target for embezzlers if a criminal black market in low-enriched uranium developed. The black market could conceivably supply low-enriched uranium merely as a fuel for power reactors (see chapter V "Non-State Adversaries and volume 11, appendix 111 for a discussion of a case of low-enriched uranium smuggling), or more ominously, as feed for a dedicated national enrichment plant designed to produce weapons material.

From the output of the enrichment plant to the loading of the reactor the only target in the LWR fuel cycle (without plutonium recycle) is the low-enriched uranium itself, which must, as discussed above, be boosted to highly enriched uranium in a dedicated enrichment plant to be useable in nuclear weapons.

Because of the long time required for refueling a LWR, national diversion of irradiated fuel could not take place without considerable economic and power penalties, except at a normal discharge and loading operation, or from the spent-fuel storage pool.

Light water reactor fuel (without plutonium recycle) of typical burnup contains about 0.8 percent plutonium, of which about 25 percent is Pu^{240} plus Pu^{242} . With plutonium recycle, high burnup LWR fuel would contain about 1 to 2 percent plutonium of which about 35 percent would be Pu^{240} plus Pu^{242} (Detailed data is given in volume II, appendix v.)

A high Pu^{249} plus Pu^{242} content is widely—but incorrectly—believed to render plutonium unsuitable for militarily effective weapons. A high content of these isotopes is a complication; given a free choice, a weapons designer

would prefer plutonium with a low Pu²⁴⁰ content, but it should be realized that effective nuclear explosives can be made with plutonium of the Pu²⁴⁰ content described above. This point is discussed in greater detail in chapter VI.

With a plutonium content of 0.8 percent, approximately 1.4 metric tons of spent fuel in the form of uranium dioxide (UO₂) must be reprocessed (at 100 percent recovery) to obtain 10 kg of plutonium. In a PWR, this is contained in three fuel assemblies. Stated another way, 1 year's fuel discharge from a PWR consists of about 31 metric tons of UO₂ containing about 240 kg of plutonium.

As discussed in the "Dedicated Facilities" section of this chapter and in appendix VI, volume II, it is well within the capability of many developing countries to construct their own reprocessing plant to extract plutonium from spent fuel for use in weapons. However, it appears probable that the IAEA will develop the capability to safeguard LWRs and LWR storage pools so that it will be very unlikely that a diversion could take place undetected. Thus, national diversion from a safeguarded LWR or LWR storage pool would probably be overt.

If the operator arranges a series of plausible reactor problems leading to extensive downtime for the year preceding the diversion, low burnup fuel with a low Pu²⁴⁰ content will result. For example, at 5000 MW days/metric ton burnup, the plutonium content of the last reload would be about 70 kg, of which only 10 percent would be Pu²⁴⁰.

Theft of spent fuel by non-state adversaries is just barely credible. The theft itself and subsequent transportation of the highly radioactive fuel (which would have to be cooled and shielded in transit) would require a number of armed and highly organized adversaries, some of whom would have to be willing to accept considerable, possibly lethal, radiation exposure. Reprocessing of spent fuel by non-state adversaries is also just barely credible, even if the group were very well financed and possessed practical chemical engineering experience. A crude but technically feasible solvent extraction or ion-exchange system can be imagined, but it would require several

months of process time for extracting 10 kg of plutonium. During that time the group would be immobile and vulnerable to an intense search.

From the point of view of both the national diverter and the non-state adversary, a large commercial reprocessing plant is an attractive target. Appendix V of volume II discusses the diversion points in a model reprocessing plant. Plutonium nitrate stolen from the nitrate blending area would require only a simple precipitation to be converted into weapons material; plutonium dioxide from the conversion area could be used directly in a nuclear explosive. A national diverter would probably take the further step in either case of conversion to plutonium metal. The safeguarding of a reprocessing plant is discussed under "Safeguards" in chapter VIII, but the point will be noted here that materials accountancy, by itself, has neither the sensitivity nor the promptness to assure timely detection of covert diversion from a large reprocessing plant, either by a nation or by non-state adversary. Other safeguard measures are therefore employed, such as portal monitors which can detect gram amounts of plutonium. (See chapter VIII.)

A model mixed-oxide fuel fabrication plant is diagramed in appendix V of volume II. The output of the model plant consists of fuel rods with a mixture of uranium dioxide and up to 3.5 percent plutonium dioxide. To obtain 10 kg of plutonium, about 300 kg of mixed oxide would have to be diverted or stolen. The logistical problem of removing so much material is a significant deterrent, but the biggest obstacle to the non-state adversary is chemically separating plutonium from uranium. Although conceptually simple, involving dissolution followed by ion exchange, the task would need someone with practical chemical engineering experience and would require perhaps several weeks to several months, depending on the details of the adversary's separation facility. For the national diverter, the chemical separation problem would be minor and could probably be accomplished in one to a few days.

In the portion of the fuel cycle between the output of the reprocessing plant, and the

Figure VII-2.

Summary of the Diversion Points in the LWR Fuel Cycle

FACILITY	MATERIAL	IS THE MATERIAL USEFUL TO THE NATIONAL DIVERTER?	IS THE MATERIAL USEFUL TO THE NON-STATE ADVERSARY?
Mine Mill Conversion Facility	Natural uranium (0.7 percent U^{235} as ore (0.2 percent uranium) U_3O_8 UF_6	YES, but only as feed for a dedicated facility (plutonium production reactor or enrichment plant)	NO (but criminals might engage in black market in these materials)
Enrichment Plant Uranium Fuel Fabri- cation Plant Transportation to Reactor Temporary Storage at Reactor	low enriched uranium (3 percent U^{235} as UF_6 UO_2 UO_2 in fuel assemblies	YES, but only as feed for a dedicated enrichment plant Nation would eventually have to replace fuel	NO (Criminals might engage in black market in these materials)
Reactor Spent Fuel Storage	Pu —about 0.8 percent in highly radioactive spent fuel	YES; dedicated reprocessing facility required	NO except Yes for large, very well financed, technically compe- tent group with a secure base of operations and a few members willing to risk radiation injury
Reprocessing Plant* Transport to fuel fabrication plant Input area to fuel fabrication plant	Pure $Pu(NO_3)_4$ or pure PuO_2	YES; Nation would probably convert material to metallic plutonium	YES; If $Pu(NO_3)_4$, simple conver- sion to PuO_2 equmd. It PuO_2 , material directly usable in explosive
Plutonium Fuel Fabrication Plant	PuO_2 (3 percent to 7 percent) mixed with over 90 percent UO_2	YES, Chemical separation of Pu from mixture only a minor obstacle. Logistics of diverting 100 to 300 kg of material for one explosive troublesome.	Yes, BUT chemical separation a time consuming operation. Logistics of stealing or diverting 100 to 300 kg of material for one explosive cause problems.
Transport to Reactor Temporary Storage at Reactor	About 1 percent Pu as PuO_2 mixed with UO_2 in fuel assemblies	YES, as above. (Nation would eventually have to replace fuel)	Yes, BUT chemical separation a time consuming operation. Logistics of stealing complete fuel assemblies present signifi- cant obstacle.

*With coprecipitation, however, diversion potential at these plants would be similar to diversion potential at plutonium fuel fabrication plant. It is considerably less for the non-state adversary and somewhat less for the national diverter

SOURCE OTA

mixed-oxide blending area of the mixed-oxide fuel fabrication plant, plutonium would exist in the form of plutonium dioxide. This material is directly useable in the fabrication of nuclear weapons, although a nation would probably convert it to plutonium metal. This portion of the fuel cycle, which includes stockpiled plutonium, presents the most concentrated target for diversion. Although one can conceive of very stringent safeguards against covert diversion even in this exposed portion of the cycle, safeguards, by their nature, cannot prevent a nation from seizing a plutonium stockpile attached to its own reprocessing plant. As discussed in chapter VI, a modest national weapons development program can attain a high degree of confidence in the performance of its weapon without nuclear testing. Once the political decision is taken to seize the stockpile, the nation can have a reliable explosive in a matter of days to weeks, even using reactor-grade plutonium.

Summary of Diversion Points in the LVVR Fuel Cycle.—The preceding discussion has described the diversion points in the LWR fuel cycle, specified how much material would have to be stolen or diverted at each point to yield material for one or two explosives, and has evaluated the difficulty of chemical and physical processing necessary to convert the diverted material into weapons material. Figure VII-2 briefly and qualitatively summarizes this discussion.

The Canadian Deuterium Reactor (CANDU)

Technical Description

The Canadian Deuterium Reactor (CANDU) is able to operate with natural uranium because heavy water absorbs fewer neutrons than does ordinary water, leaving more to carry on the chain reaction. This eliminates the need for the entire enrichment process, including UF_6 conversion. The mining and milling processes are the same as for LWRS, but reactor operation is substantially different. The CANDU is designed for on-load refueling. Instead of shutting down and opening the reactor to change a batch of fuel, a refueling

machine opens both ends of one of the many tubes throughout the reactor. These tubes contain several short fuel rods. A fresh rod is inserted in one end and a spent rod removed at the other. The tube is then resealed and repressurized with cooling water.

There are no plans at present to reprocess CANDU spent fuel. More plutonium is produced than in an LWR of the same power level, but it is more dilute because of the greater amount of U^{238} . The fraction of U^{235} in the spent fuel is very low (actually less than in the tails from present enrichment plants), and reprocessing would be less likely to be economical than for the LWR cycle. The spent fuel is now being stored indefinitely, pending development of a final waste disposal method.

Diversion From the CANDU Fuel Cycle

The CANDU fuel cycle presents considerably different opportunities for diversion than does the LWR cycle. Separated fissile material is not exposed anywhere in the CANDU fuel cycle, in contrast to the LWR cycle with plutonium recycle. The enrichment and reprocessing facilities are totally absent. The only diversion points in the CANDU fuel cycle are the reactor itself and the spent fuel storage pool.

As in the case of the LWR, non-state theft of spent fuel from the storage pool followed by reprocessing is just barely credible.

As discussed for the LWR, reprocessing for weapons purposes, spent fuel that has been diverted from a reactor or spent-fuel storage pool is within the capabilities of many nations. The quantity of fuel that must be diverted from a CANDU to yield 10 kg of 1%, and the quality of the Pu obtained under various conditions, is discussed below.

CANDU fuel of normal burnup (about 7500 MW days/metric ton) has a plutonium content of about 0.4 percent of which about 25 percent is Pu^{240} . As described in appendix V of volume II, CANDU is refueled continuously and some fuel bundles could be pushed through more rapidly for lower burnup and lower Pu^{240} content. At a burnup of 2500 MW days/metric ton (one-third normal) the

plutonium content is about 0.2 percent, of which only 10 percent is Pu²⁴⁰. To obtain 10 kg of plutonium at least 5700 kg of low burn-up uranium-oxide fuel would have to be diverted, or about 260 fuel bundles. For normal burnup fuel about 2800 kg, or 130 bundles, would have to be diverted. For comparison, in the CANDU-600 model, about 12 fuel bundles are normally pushed through the reactor per day.

In contrast to the LWR, production of low pu²⁴⁰ plutonium in the CANDU does not involve a significant loss of power output.

Safeguard systems for a CANDU reactor and storage pool can probably be designed and implemented so that repeated covert diversions of fuel assemblies cannot take place undetected during either normal or accelerated refueling. Diversion from the CANDU is therefore also likely to be overt,

Liquid Metal Fast Breeder Reactor (LMFBR)

Technical Description

The LMFBR is expected by the industry in every nuclear supplier nation except Canada to be the successor to the LWR reactor since it would essentially eliminate uranium resources as a constraint. The reactor is somewhat analogous to a PWR, except that it uses liquid sodium at low pressure as a coolant and has no moderator. The fuel is mixed plutonium (10 percent to 20 percent) and U²³⁸ oxide. Radial and axial blankets of U²³⁸ surround the core to capture escaping neutrons and breed plutonium. The LMFBR is expected to produce as much as 15 percent more fuel each year than it consumes. This excess (about 250 kg per year) can be used to fuel other reactors or diverted to a weapons program with no impact on the fuel cycle. Refueling is similar to LWRS, with about one-half the core and one-third the blanket replaced each year. No enrichment is required, except possibly for the initial core, because the plutonium that is bred can be used in subsequent cycles. Reprocessing, however, is central to the LMFBR cycle. The bred plutonium cannot be recovered without reprocessing, and the whole point of the LMFBR is that it can breed enough

plutonium to refuel itself and to start up new reactors.

Diversion From the LMFBR Cycle

The diversion points in the LMFBR cycle can perhaps be best explained by comparing them to those of LWR cycle with plutonium recycle.

The mining and milling stages can be virtually eliminated, because the depleted uranium contained in the tails from present enrichment plants can be used. Enrichment is superfluous, except possibly for the initial core.

As in the case of LWR recycle, the reprocessing plant, fuel fabrication plant, and fresh-fuel storage area at the reactor, including the transportation links between them, are the points most vulnerable to diversion.

Diversion from the reactor itself is not credible and the material in the spent-fuel storage pool, in transit to the reprocessing plant, and in the input stages of the reprocessing plant is highly unattractive to the diverter because of its fierce radioactivity. However, as in the case of the LWR, handling and reprocessing diverted spent fuel in a small reprocessing plant dedicated to the task is within the capability of many nations.

The input to the fuel fabrication plant would consist of depleted or natural uranium dioxide and pure plutonium dioxide from the output of the LMFBR reprocessing plant, with possibly an additional contribution from a LWR reprocessing plant or stockpile. The uranium dioxide and plutonium dioxide will be mixed at the fabrication plant and compressed into fuel pellets. The ratio of plutonium to uranium in the fresh fuel varies with the exact design proposed, but would be in the range of 1:10 to 1:5. At 1:5, the material would be of only marginal usefulness in a nuclear explosive; at 1:10 the material could not be used directly in a practical nuclear explosive. However, only 55 to 110 kg of fuel would have to be stolen to obtain 10 kg of plutonium. Fresh fuel for the LMFBR would be a factor of 2- to 6-times more concentrated in plutonium than fresh fuel in the LWR cycle with plutonium recycle, depending on the details of both schemes.

Details on LMFBR reprocessing are not firm as yet. In general, diversion opportunities at an LMFBR reprocessing plant would be similar to those at an LWR reprocessing plant, heightened by the fact that the throughput of plutonium per metric ton of fuel input would be greater by a factor of approximately 10.

In general, approximately 5 times as much plutonium would flow through the LMFBR cycle as through the LWR cycle, for the same amount of electricity generated. (LMFBR fuel gives about twice as much electricity per metric ton as does the LWR.)

In addition to the quantitative differences between the two cycles (there is *more* plutonium in the LMFBR cycle and it is *more concentrated*), there is also a potential qualitative difference. A significant amount of the plutonium produced in the blankets will contain less than 5 percent Pu²⁴⁰, i.e., it will be weapons-grade plutonium in a normal fuel cycle. (See chapter VI.) In the LWR cycle, plutonium of this quality is produced only by operating with frequent, very costly refueling.

Thorium Fuel Cycles

Power-reactor fuel cycles employing thorium have received much less attention than uranium fuel cycles. The thorium fuel cycle uses U²³³ as the fissile isotope and Th²³² as the fertile isotope. Several reactors have been proposed that might employ thorium. A high-temperature gas-cooled reactor (HTGR) is operating, and a demonstration light-water breeder reactor (LWBR) is presently being constructed.

Thorium fuel cycles that have been studied include:

- . High-Temperature Gas Reactor (HTGR);
- . Light-Water Breeder Reactor (LWBR);
- . Light Water Reactor (LWR);
- Heavy Water Reactor (HWR);
- . Molten Salt Breeder Reactor (MSBR); and
- . Thorium and mixed thorium/uranium fuel cycles in fast breeder reactors (FBR).

The limited availability of uranium is often cited as a major reason for considering the thorium cycle. However, although it is assumed that thorium is 3- to 5-times more plentiful than uranium throughout the world,

the actual quantity of thorium, and the likely concentration of the ores, are in fact uncertain.

In *thermal reactors* the thorium fuel cycle may permit (1) a more efficient use of resources, possibly including the operation of a breeder, which is impossible with the uranium/plutonium cycle. (U²³³ produces, on the average, 2.28 neutrons per thermal neutron capture, versus 2.11 for Pu²³⁹. This provides just enough extra margin so that breeding may be possible.); (2) more economic power generation than that from LWRS (uranium cycle) if uranium costs continue to increase (provided thorium costs are low); and (3) a delay in the need for fast breeder reactors (FBR) and a lower eventual demand for them because the demand for uranium would not be as great with thorium fuel cycles supplying some power.

In fast breeder reactors a thorium or mixed-fuel cycle may permit (1) a larger margin of safety in the control of the reactor; and (2) production of a fuel which could be employed for both fast and thermal reactors. (Thermal thorium-based reactors have a breeding ratio near one, so they produce little, if any, excess fuel.)

The thorium fuel cycle has both dangers and inherent safeguards from the proliferation point of view. The fuel that it breeds, U²³³ is an excellent weapons material, with a critical mass approximately one-third that of U²³⁵. It is comparable in weapons-material quality to Pu²³⁹. However, some protection against diversion is offered by the unavoidable production of U²³² when U²³³ is produced. U²³² is the first in a chain of radioactive decays which eventually yields thallium-208, which emits a penetrating 2.6-MeV gamma ray. The fabricated fuel and fuel materials are radioactive and present a definite health hazard a few days after separation. After several years, the radiation dose from kilogram quantities of U²³³ becomes high enough to rapidly deliver a lethal dose to anyone in direct contact.

Anyone diverting U²³³ fuel would have to overcome radiation hazards to obtain and transport the material, and to fabricate a weapon. The radiation also results in two indirect safeguards advantages. First, access to the material is limited by the requirement for

remote handling behind radiation shielding. With little likelihood of any hands-on operations, access to the material for diversion purposes is much more difficult. Secondly, the penetrating 2.6-MeV gamma ray enables portal monitors to detect extremely small (milligram) quantities of U^{233} .

However, the radioactivity of U^{233} fuel is primarily a safeguard with respect to non-national adversaries. A national diverter could easily provide the radiation shielding necessary to handle the material. Indeed the country would have to provide the shielding to utilize the thorium fuel cycle in its power reactors,

The radiation hazards of U^{232} unfortunately create problems for safeguard inspectors as well as potential diverters. The necessity for remote handling may limit the accuracy of safeguard measurements.

A key feature of the thorium fuel cycle relative to proliferation control is the fact that U^{233} can be denatured. That is, it can be mixed with the abundant U^{238} in concentrations of about 12 percent or less in order to make it unuseable in a practical nuclear explosive. By contrast, Pu^{239} cannot be denatured, as there are no plutonium isotopes that could be mixed with Pu^{239} that would preclude its use as a nuclear weapons material. (See chapter VI "Nuclear Fission Explosive Weapons".)

The number of gas centrifuges necessary to enrich U^{233} that has been mixed with U^{238} is significantly less than that required to enrich a mixture of U^{235} and U^{238} to the same degree. As a practical matter, however, the enrichment of denatured U^{233} would be difficult due to the significant radiation danger involved. Contact maintenance would be very hazardous. The costs and technology required for remote maintenance on a gas-centrifuge enrichment facility would be high.

The characteristics of reactors that might use thorium fuel cycles are not well defined because most have only been studied on paper. High-temperature gas reactors are the most advanced of all these concepts, with a small commercial plant (the 330 MW(e) Fort St. Vrain plant) in operation. However, as discussed in the following section, HTGRs expose

highly enriched uranium throughout their fuel cycle. An LWBR demonstration plant is now being completed. A very small MSBR has been operated successfully. The others are still design concepts. High capital costs associated with HWRS, due to the use of pressure tubes, large cores, and heavy water, and with LWBRs (including the costly prebreeder), may be a significant disadvantage.

Conclusions on the Thorium Cycle

Thorium cycles look attractive from a non-proliferation point of view, and they are especially resistant to diversion by non-state adversaries. Selected thorium cycles should be further studied to better define their economic, technical, and safeguards promise (e.g., see section on "Alternate Fuel Cycles and Nonproliferating Reactors" below).

High-Temperature, Gas-Cooled Reactor (HTGR)

A small (330 MW(e)) commercial HTGR is now operating near Fort St. Vrain, Colo. West Germany is constructing a 300 MW(e) plant based on a variation of this concept. Both are cooled by helium and moderated by graphite.

The outstanding feature of the HTGR from a proliferation standpoint is its use of highly enriched (93 percent U^{235}) uranium fuel particles. These fissile particles of uranium carbide, with a hard coating of carbon and silicon carbide, are mixed with fertile particles of thorium dioxide in the fuel elements. This fresh fuel would be attractive to a diverter. Separating the uranium from the manufactured fuel should be possible, even for a sub-national group, although their process would probably be clumsy and inefficient.

The HTGR must be shut down for refueling. Recycling is required to recover the bred U^{233} and the remaining U^{235} . As discussed in volume II, appendix V, the relative economic merits of various HTGR reprocessing and recycling programs have not been fully evaluated, but they may favor a one-time recycle.

Developers of the HTGR are studying alternate designs that would use lower enriched fuel.

Light-Water Breeder Reactor (LWBR)

Technical Description

The light-water breeder reactor (LWBR) relies extensively upon 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 maybe implemented by placing a different reactor core and control system in present PWR reactor plants. 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 U^{233} . Because the breeding (conversion) ratio is near one, prebreeders are required to produce enough U^{233} for the first few breeder cores.

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 hydrogen, so a water-to-metal ratio of about one-tenth that of the standard PWR has been proposed. Safety problems are exacerbated by this difference.

To avoid parasitic neutron capture in control rods, control is achieved by axial movement of the fuel modules in relation to each other. Fertile blankets increase the size of the core but capture neutrons that would otherwise be lost to the system.

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 taken off and a portion of the fuel removed.

Diversion From the LWBR Fuel Cycle

For the prebreeder, the first point at which the diversion potential differs from the LWR cycle is at the enrichment plant. Prebreeder fuel will contain 10 percent to 13 percent U^{235} . Although this enrichment is too low to be

used directly in a nuclear explosive, it provides excellent feed for a dedicated enrichment plant. About 440 kg of 10 percent U^{235} hexafluoride feed would be required to produce 30 kg of 90 percent U^{235} , and about 180 centrifuges of European design could produce this quantity of highly enriched uranium per year from 10 percent feed.

Fuel modules for the prebreeder will contain uranium dioxide rods and thorium dioxide rods. No chemical separation of the fresh fuel would have to be done to acquire 10 percent LWs.

A total fuel discharge from a 1000 MW(e) prebreeder would contain about 100 kg of plutonium concentrated to about 1 percent in the uranium dioxide rods, about 300 kg of U^{233} concentrated to about 1 percent in the thorium-dioxide rods, and about 800 kg of U^{235} at an enrichment of nearly 8 percent. No isotopic separation would be required to obtain pure plutonium or pure U^{233} . Only chemical reprocessing would be needed to acquire material that could be directly used in nuclear weapons. As for the LWR, this task is within the capability of many nations, but impossible for all but very technically competent and well financed non-state groups.

The above numbers should be regarded with caution. Detailed data have not been published for a commercial-sized plant.

Two separate reprocessing plants might be used to reprocess LWBR prebreeder fuel. The diversion potential for the facility reprocessing the uranium-dioxide rods would be very similar to that for the LWR facility. In the case of the thorium- U^{233} reprocessing plant, a major difference would be the intense and penetrating gamma radiation from U^{232} (as discussed in the previous section), rendering diversion more difficult.

Fuel going back into the prebreeder could either be reenriched uranium dioxide plus thorium dioxide, or, more likely, mixed plutonium dioxide plus thorium dioxide, plus uranium dioxide. In the second case the diversion potential for fuel fabrication and mixed-oxide fuel assemblies would be similar to that for the LWR.

The uranium fuel for the breeder is presently seen as being 90 percent U^{233} and 10 percent U^{235} . A reactor load for a 1000-MW(e) core would contain 2,000 kg of this 100 percent fissile fuel and 93,000 kg of thorium. The fuel would consist of mixed uranium dioxide and thorium dioxide pellets. The mixed pellets would contain about 5 percent uranium dioxide and 95 percent thorium dioxide. Fresh fuel could therefore not be *directly* used in nuclear explosive weapons, but only chemical separation would be required. This chemical separation would be a time-consuming process for the non-state adversary.

Pure fissile uranium would be available at the reprocessing plant.

The LWBR differs from the LMFBR in an important point. The LMFBR produces a distinct surplus of plutonium over what is required to refuel itself. The LWBR, with a breeding ratio of close to one, produces only enough to refuel itself. Thus, fissile material diverted by a nation from the LWBR cycle would have to be replaced from prebreeder output or stockpiles. The most likely penalty a country with an expanding LWBR economy would have to pay for diverting from its breeder cycle is a slowdown of expansion. For a country with a static LWBR system and no prebreeding, replacing the diverted fissile material would present a serious problem.

Comparison of Reactors

The discussion of diversion from the different reactor fuel-cycle systems has shown large differences in the levels and locations of vulnerability. The vast number of variables, variants, and unknowns make an attempt at quantifying these differences premature. Figure VII-3 presents a qualitative evaluation of opportunities presented by the systems discussed above and in volume 11, appendix V. The ranking is on the basis of the usefulness of the fissile material as follows:

- A—No significant diversion potential.
- B—Highly dilute AND substantially radioactive material. Diversion is barely credible for the non-state adversary.

C—Concentrated material, but contains sufficient radioactive isotopes to require heavily shielded processing.

Highly diluted material, so that large quantities must be diverted.

Not impossible for non-state adversary to steal and convert to weapons material, but difficulty provides a substantial deterrent.

D—As F, but substantial chemical and/or mechanical processing needed. Possible for non-state adversary to convert to weapons material.

or

As F, except material required for continued operation of fuel cycle.

F—Material in concentrated form suitable for straightforward conversion to weapons, with modest radioactivity. Easy for non-state adversary to use as, or convert to, weapons material.

The relative value of the opportunities for diversion as summarized in figure VII-3 depends on the intentions and capabilities of the diverters. Four general categories of proliferators can be envisioned.

Nations Desiring a Major Nuclear Weapons Force

A major nuclear force might be required by an industrialized or emerging country intent on becoming a world or regional power. A large and reliable supply of high-quality fissile material would be needed. Covert diversion from safeguarded facilities would probably be precluded by these criteria and by the incompatibility of this method with the goal of international prestige. Some non-weapons states (such as Germany and Japan) are capable of building their own facilities with the dual purpose of power and fissile material production. India is developing this capability, but few others will if economic power is a requirement (discussed in chapter X). Nations party

to the Non-Proliferation Treaty (NPT) or subject to safeguards on imported reactors would have to abrogate safeguard agreements after the necessary facilities were in place.

System characteristics that would be especially important for this category of proliferator are:

- . a high-production rate of high-quality fissile material;
- . immunity to international embargos and sanctions; and
- . minimum impact on the fuel cycle.

The specific paths which this type of proliferator could follow to obtain the strategic nuclear materials are at present:

- (1) *Enrichment*: A plant with more capacity than needed for domestic LWRS could be built. The excess could be rationalized as being for export if it were necessary to keep the intentions secret during construction. In fact, no LWRS are needed in countries (such as South Africa and Australia) that could become major uranium exporters and prefer to supply enrichment services also. The amount of highly enriched uranium that could be produced without impacting on the fuel cycle would depend on the excess enrichment capacity. A large supply of uranium, either domestic or from a secure source, would be needed to keep reactors and weapon programs supplied. The cost would primarily be the loss of enrichment revenues from the previously exported low-enriched uranium. This would amount to approximately \$20,000 per kg highly enriched uranium.
- (2) *Reprocessed LWR Fuel*: An entire LWR fuel cycle would probably be required to resist nuclear embargos. The output of one reactor operated to optimize the quality of the plutonium would be sufficient for 30 to 40 weapons per year. The frequent shutdown would result in the loss of one-half to one-third of the power output, which is a high penalty, but after several years a substantial arsenal would be available and the reactor

could be returned to normal operation. The plutonium lost to the fuel cycle would have to be replaced by enriched uranium, but the cost would not be high if the uranium is recycled.

- (3) *Reprocessed CANDU Fuel*: A reprocessing plant would have to be built, but this could be done covertly prior to the safeguards abrogation. If plutonium output is maximized, about 40 to 60 weapons could be derived from each 600 MW(e) reactor. Feed would have to be increased considerably, since uranium recycle would be less attractive than for the LWR. Full-power production could be maintained. Even if the feed is not increased, 20 to 30 weapons could be produced annually. Access to heavy water would have to be maintained in either case. About 10 metric tons are required per year for normal operation, more if refueling is accelerated. A small, unsophisticated plant might produce heavy water at about double the normal cost of about \$130 per kg. This cost increase could add \$1,300,000 or more per year for the quantity required for the operation of the reactor.

Comparison.—The third route is clearly preferred if heavy water is not a problem. The plutonium production rate is high, and vulnerability to international restrictions almost nonexistent. The total cost of the full CANDU cycle should be less, though the reactor is 10 percent more expensive, because a heavy water separation plant is cheaper than an enrichment plant.

Future Developments.—The near-term future reactors (HTGR and AGR) do not present markedly different opportunities. The HTGR uses high-enriched fuel, which means that if a nation has a full fuel-cycle capability it also has another direct route to weapons material. The fresh fuel itself would not be of interest, as then the reactor would have to shut down. The HTGR breeds more fuel than the LWR, and recycle is a virtual requirement. The HTGR has somewhat more potential for diversion than the LWR, but probably less

Figure VII-3.
Reactor Diversion Report Card

	Fabrication and Transport of Fresh Fuel	Reactor, including Fuel Storage at the Reactor	Spent Fuel Transport and Storage	Reprocessing	Reprocessed Fuel-Fabrication (including transport)	Stockpile of Excess SNM
LWR No Re-processing	A	B	B	(A)*	(A)*	(A)*
LWR, Reprocessing, No Pu Recycle	A	B	B	F	A	F
LWR, pu Recycle	c	C (Onsite Fresh MOX) B (Spent Fuel)	B	F	F (if fuel not blended at Repro. Plant) C (if fuel blended at Repro. Plant)	(A)*
LWR, Denatured U-Th	A	A	B	D	A	(A)*
HWR (CANDU), No Reprocessing	A	B	B	(A)*	(A)*	(A)*
Uranium gas cooled Reactors (AGR)	A	B	B	F	A	F
HTGR	D	D (Fresh Fuel) C (Spent Fuel)	c	F	c	(A)*
LMFBR and GCFR	D	D (Fresh Fuel) C (Spent Fuel)	c	F	F	F
LWBR	D	B	B	D (National diverter) F (Non-state diverter)	D (National diverter) F (Non-state diverter)	(A)*
MSBR	A	A	(A)*	F	(A)*	F

See figure VII-2 for a summary discussion of diversion points in the LWR fuel cycle
 *Nonexistent

SOURCE: OTA

than the CANDU. The AGR appears less appropriate for proliferation than the LWR. Fresh fuel has a lower enrichment and the spent fuel contain relatively little plutonium. Recycle is not expected, even if the fuel is reprocessed.

Some of the more distant reactors present more difficult problems. The LMFBR and the similar gas cooled fast reactor (GCFR) will both produce copious quantities of high-grade plutonium, and both are relatively easy to make independent of international interference since the cycles are self-supporting except for a supply of depleted uranium. The fuel-cycle impact of diversion is negligible because of the excess of plutonium.

The LWBR is not attractive to this type of proliferator since the entire production of U^{233} is required to continue operation. The prebreeder cycle could be supported, but most of the fissile material produced is U^{233} which is diluted in U^{238} . This cycle would probably be considerably more expensive than the PWR cycle for weapons-material production. The molten salt breeder reactor would be only marginally better in that the breeding ratio is slightly higher, thus producing an excess of U^{233} which would be adequate for producing 4-8 weapons per year.

A qualitative ranking of the resistance to proliferation for all these systems is shown in figure VII-4.

Nations Desiring a Small, Not Necessarily Sophisticated, Nuclear Capability

In this case, covert diversion is a possibility but may not be a necessity. If the facilities are not safeguarded, the important characteristics would be as follows:

- Immunity to international embargos and sanctions—this type of nation is less likely to have full-fuel cycle facilities.
- Minimum impact on the fuel cycle—a substantial power loss would be harder to absorb.
- Initial cost—nuclear reactors are already very expensive, These nations may not be

able to afford a more sophisticated one even if it is more vulnerable to diversion.

- Ease of conversion to weapons material—the lesser sophistication of this type of nation makes major processing difficult.
- Production rate and quality of fissile material—this is less important than for the previous case. Little material is needed and the yield of the weapon is much less important than the fact of its existence.

If the facilities are safeguarded, a different set of factors apply.

- High rate of material flow—to make diversion less noticeable.
- Many vulnerable points to make safeguarding difficult.
- Minimum impact on fuel cycle.
- Initial cost.
- Ease of conversion.

The enrichment option of the previous case will be plausible only if techniques other than diffusion become viable. Diffusion is simply too big and expensive for this type of nation. Covert diversion of low-enriched uranium could be improbable since the country might not have the capability of building a small dedicated weapons-grade enrichment plant, even using low-enriched uranium as the feed. Therefore, part of the plant itself would probably have to be modified to yield high-enriched uranium.

The LWR reprocessing route is particularly good for the covert diverter because of the large number of vulnerable points. The impact on the fuel cycle need not be large, because the diverted plutonium can be replaced by slightly more enriched uranium or slightly less power output. It would not be necessary to possess an enrichment plant. If there is no commercial reprocessing, however, spent fuel would have to be diverted to a small dedicated reprocessing plant. It would be difficult to evade safeguards for long, so this path is improbable. The overt diverter would need a

Figure VII.4.

Reactor Systems Resistance to Proliferation

(Note that a high rank means the system is least susceptible to diversion.)

Reactor system	Availability	1 Force	Small Force (unsafeguarded facilities)	Small Force (safeguarded facilities)	Option	Non-Sate Adversaries
Light Water Reactor (enrichment)	Present	5	6	7	1	1
Light Water Reactor (spent fuel)	Present	4	3	1	4	4
Light Water Reactor (reprocessing & recycle)	Present	6	5	8	5	6
CANDU	Present	8	7	2	2	2
High Temperature Gas Reactor	Near Term	7	4	6	6	7
Advanced Gas Reactor	Near Term	3	2	3	3	3
Liquid Metal Fast Breeder Reactor	R&D (advanced)	9	9*	9	9	9
Gas Cooled Fast Reactor	R&D	10	10*	10	10	10
Light Water Breeder Reactor	R&D	1	1	4	7	8
Molten Salt Breeder Reactor	R&D (presently inactive)	2	8*	5	8	5

*May not be an Option for cost or technological reasons

SOURCE: OTA

complete fuel cycle—including enrichment—in order to thwart embargos. This might be so expensive as to be impractical.

The CANDU would be excellent for the overt diverter who would simply process the normal spent fuel. The covert diverter would have to smuggle out his own spent fuel. This is not an impossible task, as up to 10 years of spent fuel could be in the pool in the form of thousands of bundles. Accounting for all of them will be a formidable, but not impossible, task.

Comparison.—The overt diverter will prefer the CANDU, again assuming access to heavy water. An LWR with Pu recycle would be better suited to the covert diverter because of the greater number of vulnerable points. The static nature of the source (spent-fuel rods) in the CANDU or LWR without reprocessing tends to make eventual detection of covert diversion quite probable.

Future Developments.—The AGR presents essentially the same opportunity as the LWR. Reprocessing is less important than for the LWR, and could be eliminated. If there is reprocessing but not recycle the overt diverter would have a substantial stockpile at his disposal, just as there would be for the same LWR cycle. The AGR's lower enriched uranium would be slightly easier to procure than that for the LWR in case of embargos, and there would be essentially no impact on the power production since the recovered plutonium is not being used. The HTGR with its high-enriched fresh fuel and required reprocessing presents more opportunities for both overt and covert diverters. The fuel-cycle facilities, however, are expensive and technologically demanding and might never be available for export. This could eliminate overt diversion.

The R & D reactors could again enhance or limit opportunities. The overt diverter would prefer the LMFBR and GCFR for the same reasons as would the major nation, but may not be able to afford them. The LWBR would be quite inappropriate. The MSBR might produce sufficient strategic nuclear materials, but its intricate technology would be difficult to manage. The MSBR concept, however, may be

readily adaptable to small sizes, which would make it more attractive. The covert diverter would also prefer fast breeders, possibly by a wide margin. Thermal breeders provide few opportunities.

Nations Desiring the Option of Rapid Development of Nuclear Weapons in the Future Should That Appear Necessary

The important factors are:

- . rapid access to strategic nuclear materials
- . high production rate of fissile material
- cost

The enrichment option is not particularly interesting because the process is too slow, except possibly for centrifuge designed for fast conversion to high enrichment.

The LWR reprocessing route is very vulnerable, in that a significant stockpile of plutonium can be legitimately maintained. This provides immediate access, and considerably more can be supplied from the batches of spent fuel waiting to be reprocessed. Spent fuel with no commercial reprocessing would require a small reprocessing plant to be built ahead of time and held in readiness. Even then, there would be no stockpile for immediate seizure,

The CANDU would be less appropriate for this proliferate unless an appropriate reprocessing plant already exists for other reactors.

The HTGR could be useful because fresh fuel could be quickly processed even if no other fuel-cycle facilities were available. This would mean loss of the reactor as it could not be refueled, but national emergencies might be seen to override this factor. The fast breeders would provide substantial strategic nuclear materials both in the fresh fuel and in reprocessing plant stockpiles.

The LWBR would provide useful high-enriched fresh fuel as in the HTGR and easily processed spent fuel if needed. The entire core inventory could be made available quickly and would provide a great many weapons. The MSBR contains 2300 kg U^{233} at all times

(enough for as many as 460 bombs). This material could be processed immediately because its low-fission product inventory eliminates the need for long-term cooling. The small normal excess of U^{233} could also be stockpiled, and would provide immediate access to about eight weapons for every year's stockpiling.

Non-State Adversaries

The prime requirements are:

- . many vulnerable points
- . high rate of material flow
- . ease of conversion

The only present generation system that offers a significant opportunity is the LWR with reprocessing. Plutonium recycle allows the reprocessing plant, plutonium shipments, mixed-oxide plant, and possibly even the fresh fuel to be targets for attack or diversion,

The AGR is as resistant as the LWR if no reprocessing takes place. The HTGR fresh fuel is a possibility, but considerable work must be done to separate the high-enriched uranium from the thorium. If the high-enriched uranium can be attacked before it is mixed with thorium, the weapon preparation would be easier.

The LWBR can be attacked at the fuel fabrication plant or at the reprocessing plant. The U^{233} is more easily separated from the thorium here than in the HTGR. The MSBR is almost invisible to the non-state adversary. All operations are performed at the plant site, and only a small amount of U^{233} need be exposed. This could easily be denatured in U^{233} before shipping.

Figure VII-4 ranks these systems in order of vulnerability to each of the diverters.

Research Reactors

There are many research reactors operating throughout the world, Appendix V in volume 11 lists the research reactors outside the United States with a power rating of 1 MW(t) or more. Examination of that list shows that

there are 18 countries which possess either (a) natural uranium or low-enriched uranium-fueled reactors that will have accumulated 10 kg or more of Pu^{239} by 1984, or (b) reactors fueled with 80 percent to 100 percent U^{235} with a power rating of 5 MW(t) or more (i.e., an annual fueling requirement of 5 or more kg of 80 percent to 100 percent U^{235}), or (c) both of the above.

Examination of a list prepared by ERDA shows that, through December 31, 1976, the United States exported a total of 1,115 kg of plutonium to 38 countries. Eight countries have received more than 5 kg of plutonium from the United States (see list in volume II, appendix V). From January 1, 1968, through December 31, 1976, the United States exported nearly 10,000 kg of uranium enriched to 20 percent or more in U^{235} to 21 countries. Eight countries have received substantial amounts of highly enriched uranium.

The exported plutonium is used largely in critical assemblies, that is, experimental facilities run at zero power. This plutonium is essentially uncontaminated by fission products, and is of very high quality for use in weapons.

Thus, substantial diversion or theft potential exists outside the commercial power industry. India's nuclear explosive was made with plutonium produced in one of the research reactors mentioned above.

Alternate Fuel Cycles and Nonproliferating Reactors

Present commercial and near-commercial fuel cycles have been conceived and developed with essentially no thought given to their implications for proliferation or to the difficulties of safeguarding them. Other possibilities exist, however, that are less vulnerable to diversion.

Alternate Fuel Cycles

ERDA has recently set up a study in the Office of Nuclear Energy Assessments, Division of Nuclear Research and Applications, to

investigate and evaluate alternative fuel cycles. The criteria for evaluation of the alternate cycles are: (a) proliferation risk potential, (b) safeguard potential, (c) technical feasibility, (d) economics and resource utilization, (e) commercial feasibility, and (f) introduction date. In evaluating proliferation risk potential, emphasis will be placed on diversion or theft of nuclear material for the purpose of making an explosive weapon. Both domestic and foreign applications will be considered.

The schedule calls for a final report in October 1978, with a developed set of proliferation criteria and an assessment of selected alternate fuel cycles. ERDA is requesting supplemental funds of \$4 million from Congress for FY 77, and has budgeted the program at \$7 million for FY 78.

The program is currently in the phase of collecting proposals for alternate fuel cycles and issuing some contracts for promising proposals already collected. Some work previously contracted by ERDA has been assembled under the aegis of this project. A screening for the most promising alternates is set for July 1977.

For the results of this program to be most useful, the alternates that are selected for further study ought to be balanced between relatively short-term payoff on technical modifications of existing cycles and radically new approaches. The differences between national capabilities and non-national capabilities should be kept in mind. An alternate such as coprocessing, for example, might put a substantial obstacle in the way of a non-national group but provide much less of a deterrent to national proliferation.

A good deal of emphasis is apparently being given to an effort to develop a quantitative methodology for evaluating proliferation potential. The first phase of this criteria effort is due to be completed in June 1977. Such an effort can be extremely useful in forcing the people involved to think through the problems in detail. However, a set of numerical criteria purporting to quantitatively evaluate proliferation risk should be regarded with skepticism.

The areas that the program is currently looking at can be grouped in the following categories:

- (1) Reexamination of the LWR and the LWR fuel cycle
- (2) Introduction of the CANDU into the United States
- (3) Thorium fuel cycles
- (4) The fast-breeder fuel cycle

In the first category, reexamination of the LWR fuel cycle, a variety of concepts are being considered, most of which are aimed at increasing the energy obtainable from LWR fuel without going to plutonium recycle.

Several possibilities exist for modifying the design of the LWR so that spent fuel will have a lower fissile content, approaching that of the CANDU, thus reducing resource-utilization pressures for plutonium recycle. Preliminary estimates indicate that a modified LWR could extract an additional 20 percent of power out of a given amount of uranium, as compared to an additional 30 percent with plutonium recycle and present LWR design. Possible changes include opening up the lattice and decreasing periods between refueling; increasing the initial uranium enrichment; decreasing neutron absorption in the coolant, moderator, and control rods by either geometry changes or material changes, including use of heavy water; or the use of uranium-metal fuel. (Some of the above design changes are incompatible with others.) Many such design variations have been considered in the past, when nonproliferation was not a consideration, and rejected because of technical or economic reasons.

An updated assessment of the use of metal fuel has recently been completed at ORNL. The study indicates that uranium enrichment could be reduced by up to one half (i.e. 1.5 percent instead of 3 percent), and that the fissile content of the spent fuel would indeed be very low. Metallurgical problems have in the past precluded this option; however, recent development work is reported to look extremely promising.

The adoption of a throwaway cycle (i.e., no reprocessing) would make the LWR cycle a

less-attractive target for diversion by nations and a much less-attractive target for theft by non-state adversaries. The central international issues would revolve around the disposal of the spent fuel, including questions of transportation safety, disposal sites, long-term storage security, and disposal costs. Pressures to recycle might recur if uranium prices rose high enough.

Other LWR schemes under consideration (but apparently not funded as yet) include several reprocessing variants. In one concept, only uranium would be recycled; plutonium would be either (a) partially decontaminated and stored as highly radioactive plutonium nitrate solution, or (b) purified and stored. Variant (a) would provide some deterrent for the non-state adversary, but neither variant addresses the question of national proliferation. Indeed, variant (b) involves stockpiling plutonium. Plutonium stockpiles are the most vulnerable target for the national diverter and require massive security against the non-state adversary. Coprocessing is also on the list of alternates, and also apparently as yet unfunded. This concept would recycle LWR spent fuel without separation of uranium and plutonium. Instead of pure PuO_2 at the end of the reprocessing/conversion stream, there would be approximately 1 percent PuO_2 in 99 percent UO_2 . The economics are unclear. Fuel fabrication costs would increase because more fuel would contain toxic plutonium. Reprocessing costs would decrease. Claims have been made for increased fuel utilization.

Coprocessing would present a substantial obstacle to the non-state *diverter*. Plutonium would never appear in highly purified form in the fuel cycle. One thousand kg of mixed-oxide material would have to be stolen to obtain 10 kg of plutonium. The separation of PuO_2 in such a dilute form would present a very time-consuming task to the non-state adversary.

Coprocessing, however, presents a much less-significant hurdle to the *overt national diverter*. A nation could keep a small PuO_2 - UO_2 separation plant "on ice" until it made the decision to go for a nuclear explosive; it would then appropriate the mixed-oxide material, and separate it in a matter of days.

The implications of coprocessing for the *covert national diverter* are less clear. In the case discussed above, the equipment for separating uranium and plutonium would be absent, forcing the nation to divert 1000 kg of mixed-oxide material for every contained 10 kg of Pu. This presents serious logistical problems, which, however, possibly could be surmountable, even in a safeguarded plant. In a variant of the above process, where uranium and plutonium are only partially separated (to give about 5 percent PuO_2 and 95 percent UO_2 , as the final product) covert national production of tens of kilograms of pure PuO_2 , undetected by the materials accountancy system, is credible given a commercial-sized plant. Whether or not this material could then be removed from the plant without detection would depend on the efficiency of containment and surveillance safeguards. (See chapter VIII.)

ERDA is at present, actively looking at some of the problems of collocating reprocessing plants, fuel fabrication plants, and possibly plutonium-burning reactors. Generic studies of environmental effects and institutional problems are underway, as are technical studies of a possible nuclear energy center at Hanford. Confining plutonium in fresh fuel to a small number of fixed sites has the potential for reducing the risk of non-state theft. The results of these studies will also be applicable to multinational fuel-cycle centers. (See "International Control of Proliferation", chapter VIII.)

Another LWR option being investigated by ERDA is the tandem fuel cycle. In this scheme, discharged LWR fuel is inserted into a heavy water reactor (HWR) to achieve an additional 33 percent burnup. After discharge from the HWR, the fuel would be stored indefinitely. There are severe technical, economic, and licensability questions to be resolved, as discussed in appendix V of volume 11.

Other concepts to extend the use of spent fuel without recycle include bombarding spent fuel with neutrons from:

- . a target bombarded by protons from a high-energy accelerator (the accelerator breeder idea);

- . controlled thermonuclear fusion (the spent fuel would be inserted into a blanket in the fusion reactor);
- . laser or ion beams on fusion targets; and
- . an LMFBR

Using fusion neutrons to produce fissile material (either plutonium or U^{233}) could be economical before self-sustained fusion was achieved. The accelerator-breeder and fusion/fission devices may well have an important role to play in extending resources of fissile materials and possibly in cleaning up nuclear waste. Both devices might have applicability in the international thorium cycle discussed below.

However, such neutron irradiation schemes can clearly be regarded as antiproliferation measures only at an international center. A nation with a device designed to irradiate spent fuel could as easily irradiate clean uranium or thorium. A nation would ship highly radioactive spent fuel to an international irradiation center, where the plutonium or U^{233} content of the spent fuel would be increased by a factor of 2 or more. The spent fuel might then have to be refabricated. Finally, the still radioactive spent fuel, with enhanced plutonium or U^{233} content, is shipped back to the nation for reinsertion into the reactor. After one or more such round trips, the spent fuel is shipped back for disposal. Both this concept and the accelerator breeder are discussed in appendix V of volume II. Many of the metallurgical problems discussed for the tandem fuel cycle would exist for these options. Neutron irradiation of spent fuel appears to be a somewhat contrived antiproliferation measure.

The ERDA studies on introducing the CANDU into the United States appear to be focusing on economics, licensability in the United States and U.S. commercial feasibility. No current U.S. reactor vendors manufacture CANDU_s, and presently there is little U.S. utility interest. The proliferation potential of CANDU_s and LWRs was compared in the preceding section, where it was concluded that safeguarding against the national diverter was a harder problem for the CANDU than the LWR without recycle. Thus, purely from a

nonproliferation point of view, LWR redesign appears more attractive.

Through another program, ERDA is investigating the problems of commercializing the HTGR. Because the HTGR contains exposed 93 percent U^{235} in its fuel cycle, it has serious proliferation implications. However, the alternate program is investigating the use of less than 20 percent U^{235} in the HTGR cycle. The detailed assessment is underway but not yet completed. Earlier studies indicated that a low-enriched uranium cycle, possibly as low as 6 percent U^{235} , would be technically feasible but at a distinct economic disadvantage to the 93 percent U^{235} cycle. The low U^{235} HTGR would have better fuel utilization than the LWR. Major redesign of the HTGR might yield more favorable results.

The program is apparently planning an extensive investigation into thorium fuel cycles, including work on the recently proposed international thorium cycle. In this system, *national reactors* would operate on a fresh fuel mix of something like 1 part U^{233} , 6 parts U^{238} , and 10 to 60 parts thorium. As discussed in chapter IV, a U^{233}/U^{238} ratio of 1:7 represents a lower limit of concentration, below which the mixture cannot be used in a practical fission explosive. Preliminary calculations suggest that spent fuel from such a reactor would contain only one-fifth to one-tenth as much plutonium as spent fuel from present reactors, for the same amount of power output. Spent fuel would be sent to *international fuel support centers* which would reprocess the spent fuel, extracting the plutonium for burning onsite, possibly in fast breeders with thorium as the fertile element. The U^{233} produced in the fast breeders would be denatured with U^{238} at the center, fabricated into fresh fuel, and shipped to the national reactors. Thus either enrichment (for fresh fuel) or reprocessing (for spent fuel) would be necessary to extract weapons material from fuel in national hands. Both routes are possible for the national diverter, but both require the construction of a dedicated facility.

The national diverter, if discovered, is very vulnerable to fuel-supply cutoff in the international thorium cycle. The international thorium cycle offers a very high degree of protection against the non-state diverter.

A partial list of questions to ask about the denatured thorium cycle includes:

1. What is the concept for starting up thorium cycle reactors? Can startup fuel material be generated without paying the economic penalty that appears to be required for the LWBR?
2. How does the rate of growth of nuclear power affect the attractiveness of the cycle?
3. The thorium concept requires reprocessing, whereas an optimized throw-away LWR U-Pu fuel cycle does not. What are the relative safeguard, economic, and uranium utilization differences for each of these concepts?
4. How much redesign of LWR_s (and HWR_s) is necessary to achieve an optimum thorium fuel-management program?
5. What are problems and costs of production development of the thorium reprocessing (Thorex) process?
6. What is the increased safety/radiation risk of a thorium fuel cycle during
 - a) normal operation?
 - b) abnormal situation (e.g., sabotage attempt) ?
7. How much development and exploration is required for a large-scale supply of reactor-grade thorium?

The project is also studying coprocessing of fast-reactor fuel for either the U/Pu or the Th/U²³³ cycles. The emphasis would be on metallic fuels for breeding in the core, rather than in the blanket. As pointed out before, coprocessing is a tactic of limited usefulness against national proliferation.

Nonproliferating Reactors

One of the most intriguing concepts that ERDA is studying is being funded at \$250,000 for FY 77 by the Division of International Security Affairs. This is the concept of nonproliferating reactors.

Through strict design requirements, this approach attempts to eliminate the diversion paths present in current and projected power-reactor systems and their associated fuel cycles. Several key design criteria are: (a) the

system shall contain only a small amount of fissile material at any given time; (b) there shall be no access to the fuel during the lifetime of the reactor; (c) any diversion of fuel will cause the reactor to shut down; (d) the reactor shall be refueled by the addition of fertile (i.e., non-fissile) material only; (e) the reactor shall not operate as a breeder, but as a sustainer, producing just enough fissile material to keep itself running (i.e., the breeding ratio should be essentially one); (f) reprocessing shall be done onsite inside a biological shield.

In addition, the reactor is required to produce economical power and be designed so that accidents have minimum consequences of site,

This last requirement suggests that it might be possible to site the reactors fairly close to load centers and use the waste heat locally, thereby markedly increasing overall efficiency. Finally, although the optimum power level for such reactors is not known, preliminary studies suggest that the reactors may be economical on a small scale, i.e., 50 to 250 MW(e).

Preliminary conceptual studies have been done on three reactor systems.

- . Gas core reactor (\$100,000)
- . Suspended particle bed reactor (\$40,000)
- . Modified molten salt reactor (\$100,000 assigned; \$20,000 spent)

Conceptual and design studies on a gas core reactor have been carried out for a number of years at Los Alamos Scientific Laboratory (LASL) under NASA funding. Some experimental work has been done for NASA with a zero power assembly. An experimental flowing gas system has started up at LASL recently, and has attained criticality.

The gas core reactor designed for the nonproliferating reactor study is a conservative variant of the 6000°K plasma reactor being designed for NASA use around the year 2000. This particular nonproliferating gas-core design has the following features: U²³³F₆ gaseous fuel; beryllium moderator and graphite neutron reflector; molten thorium-salt breeding blanket; relatively low-operating temperature of approximately 1200 °K; power

level of 200 MW(t); entire plant-fissile inventory of 100 kg of U^{233} (i.e., this includes the material being reprocessed). Diversion of 4 kg of U^{233} will shut the reactor down, as would adding more thorium in an attempt to increase the breeding ratio.

Preliminary calculations indicate that if the operating temperature of a nonproliferating gas-core design is raised to the 4000°K range (i.e., the magneto-hydrodynamic range), the total inventory of U^{233} may decrease to a few tens of kilograms. Moreover, the quantity of U^{233} that could be diverted without shutting down the reactor would probably also decrease markedly. This sensitivity of fissile inventory to operating temperature should be explored more thoroughly.

Another aspect of the gas core design that merits further investigation is the possibility of using denatured U^{233} fuel.

The suspended particle bed reactor features extremely small coated-fuel particles and a gas-cooled, heavy water moderated, fluidized-bed design. Such high burnup is attained that reprocessing is of no benefit. The reactor is refueled online with fertile material only, but has a high fissile inventory of 3000 kg of U^{233} for a 300 MW(e) system.

The molten salt reactor concepts are based on the use of a circulating fluid fuel with online continuous fuel reprocessing.

A detailed 300 MW(e) molten salt breeder reactor design previously prepared for another purpose was examined to determine the feasibility of redesign for nonproliferation requirements. Potential diversion paths were

identified and changes suggested which were qualitative in nature (there was insufficient time to actually redesign the reactor).

The modified molten salt reactor as a nonproliferation reactor has many features which make it attractive. However, it appears that the system would have difficulty meeting the requirement for a breeding ratio of approximately one. It is not known how significant the deviation from one would be. The system inventory is high, on the order of 500 to 1000 kg of U^{233} , which at this time would be judged excessive. Finally, it is not clear that diversion of a significant quantity of U^{233} would cause the reactor to shut down.

For all the nonproliferating reactor designs, enough U^{233} to start the reactor up would have to be supplied from an external source, probably a thorium cycle fast breeder. One thorium cycle breeder could provide enough start-up U^{233} for many nonproliferating reactors. Start-up U^{233} would have to be produced, reprocessed and shipped under guard. In this sense, nonproliferating reactors would not *totally eliminate* diversion possibilities, but the concept does hold forth the promise of enormously limiting diversion and proliferation paths.

Conclusion on Nonproliferating Reactors.— This small program is the first attempt to design reactors specifically with nonproliferation and nondiversion in mind. As such, it deserves continued funding at an expanded scale, a wide hearing, a thorough assessment, and an open-minded comparison with other alternatives.

DEDICATED FACILITIES

All nations now possessing nuclear weapons obtained fissile material from facilities specifically *dedicated* to its production or separation. Therefore, a nation need not undertake a nuclear power program in order to have a nuclear weapons program. In fact, a nation determined to acquire nuclear weapons may be able to do so with lower capital costs, in a shorter period of time, and with less

scrutiny from other nations by building facilities specifically dedicated to the production of fissile material by *itself* (or with gray market aid).¹

¹See "purchase and Theft" section, this chapter and appendix VII of volume 11 for a discussion of black and gray markets.

Such a nation would have two basic options:

- (1) Construct a plutonium-production reactor plus a reprocessing plant to separate the plutonium from the spent fuel;
- (2) Construct an enrichment plant to produce highly-enriched uranium from natural uranium.

Variants on the above two options are possible. For example, a nation might feed a dedicated reprocessing plant with spent fuel obtained from an unsafeguarded power or research reactor. This is the route India took, removing fuel from the unsafeguarded Canadian-supplied Cirrus research reactor. Alternatively, a nation might divert low-enriched uranium from a safeguarded facility or buy low-enriched uranium in a black or gray market and boost it to highly enriched uranium in a dedicated enrichment plant. No case of the diversion or purchase-plus-boosting route is known to have occurred.

A major motivation for nations to build dedicated facilities is to have a reliable, possibly secret, and/or legal source of fissile material. As safeguards are improved and extended over all imported nuclear facilities, and as greater restraints are placed on the sale of enrichment and reprocessing plants, more nations may be inclined to develop their own facilities.

The construction of any facility dedicated to the production of weapons material, which of course is not safeguarded, would constitute a violation of the NPT by parties to that treaty. The NPT nation must accept IAEA safeguards on all its peaceful nuclear materials, in all its peaceful nuclear facilities, and must require IAEA safeguards on its nuclear exports to all non-nuclear weapons states. However, nothing in the NPT prohibits the transfer of nuclear material or technology to nonparties to the NPT, even though such nations may have some unsafeguarded facilities. At the present time, the non-NPT nation, even while receiving safeguarded imports from NPT parties, may still indigenously build or obtain unsafeguarded nuclear facilities from another nonparty to the NPT.

In spite of the above fact, even countries not party to the NPT would usually have strong incentives to attempt to keep construction and operation of dedicated facilities secret, at least until they had built up a stockpile of weapons material. A nation that can suddenly demonstrate the capability to explode a nuclear device has a strengthened position. At the same time, a clandestine weapons program avoids the recriminations and international political pressures that the nation might encounter if it pursued the program openly.

Under some conditions, a nation might feel it had little to lose and perhaps some political prestige to gain by the open pursuit of a nuclear weapons option. This section will thus include consideration of dedicated facilities that would be difficult to keep secret.

Weapons Program Levels

The magnitude of the weapons program a nation decides to undertake is a crucial factor in determining what kind of dedicated facility it will choose to build.

A country interested in only a small weapons program would look first at option (a), the plutonium production reactor. As shown in appendix VI of volume II, the rate of plutonium production is proportional to the reactor-power level. For example, a reactor operating at 25 MW will produce between 9 and 10 kg of plutonium per year, enough for one or two explosives. As outlined below, such a reactor can be built and operated at nominal cost, in a relatively short time, with a small number of personnel, and there is at least a fair chance that its existence could be concealed for several years. This size will be referred to as a Level I reactor.

A more ambitious program, one which would yield between 10 and 20 explosives per year, would require a reactor operating at about 400 MW. This is referred to as a Level II reactor. Its construction would require a large investment in capital and involve a large number of engineers and construction workers. Because of the magnitude of the task,

there is little chance that the project could be kept secret, either during construction or in operation.

An alternative to a single Level II reactor might be the construction of several Level I reactors that together would yield the same plutonium output as the larger reactor. A nation with a limited technological base might find it easier to build several smaller reactors, each based on the experience gained with the first.

If a nation decided to build an enrichment plant to feed its nuclear weapons program, it would have to allow for 15 to 30 kg of highly enriched uranium for one explosive. The most likely choice of enrichment technique at present (as discussed below) is the gas centrifuge. Because construction of an enrichment dedicated facility would be more expensive and difficult than a Level I reactor it is unlikely to be considered by a nation that wants only one or two weapons per year. One exception might be a nation that has either developed or purchased a centrifuge enrichment plant for a commercial power program. In that case, the components for a dedicated enrichment plant might cost no more than add-ons to the existing plant. The cost for a small dedicated enrichment plant would then be low enough for a Level I weapons program. (See also chapter VII "Diversion From Commercial Power Systems" for a discussion of this route.) Another important exception in the future might result if other enrichment techniques are found that are cheaper and technologically simpler.

Assessment of the likelihood of a nation building any of these dedicated facilities, and of the probability that its efforts can be detected, requires an evaluation of the cost, time, and personnel required,

The numbers vary widely with the types of assumptions made. If one assumes that the dedicated facility will be essentially a scaled-down commercial facility, the cost, time, and personnel estimates are generally quite high. One might more realistically assume that a designer would make considerable simplifications if the facility were built specifically to

produce nuclear weapons material. In particular, such plants can be subject to less stringent safety and radiation-protection restrictions.

The estimates of cost, time, and personnel will also depend quite heavily on the particular nation building the facility. Important factors are the available natural resources, the technological and industrial base, the number of trained scientists and engineers, and the cost of labor.

Level I Plutonium Production Reactor²

The most likely choice for a Level I production reactor would be one fueled with natural uranium, moderated with graphite, and cooled by air. The uranium might either be mined and milled indigenously, since many nations have at least small uranium reserves (see appendix VI of volume II), or it might be purchased on a gray or black market if commercial purchases would raise suspicions. Graphite and heavy water are the only practical moderators to use with natural uranium. The heavy water is an improbable choice because it is expensive, available from only a few countries, and indicative of its purpose if imported in large quantities. Air is selected as a coolant rather than water because it simplifies the design, construction, and maintenance of the reactor and the fabrication of the fuel elements.

One graphite-moderated, air-cooled, natural-uranium reactor that has operated successfully is now fully described in open literature. It might well serve as a model reactor to guide the construction of a dedicated facility. This reactor is the Brookhaven graphite research reactor (BGRR), described in appendix VI of volume II. The BGRR is a 30 MW reactor which, when operated with natural uranium (from 1948 to 1957) for research purposes produced about 9 kg of

²Much of this section originally appeared in: John R. Lamarsh, "On the Construction of the Plutonium Producing Reactors by Smaller and/or Developing Nations," Prepared by CRS, April 30, 1976. See also appendix VI of volume II.

nearly pure Pu²³⁹ annually (enough for one or two weapons per year). The cost of the BGRR and its related equipment was \$16.7 million when built in 1948. It is not necessary to duplicate the BGRR in detail in order to attain the same rate of plutonium production. Simplifications in the BGRR design would permit the building of a plutonium-production reactor that would be cheap and reliable, and that would require the talents of only a small group of conventionally trained engineers.

The design of a simplified BGRR is discussed in detail in appendix VI of volume II with cost estimates for the various components. Costs are based on current U.S. prices, and as such they may have only the roughest applicability to another nation. Moreover, the costs in appendix VI refer to a bare-bones program, with primitive conversion and fuel-fabrication facilities and perhaps some sacrifice of safety and environmental controls. The overall reactor cost estimated with these assumptions is \$10 million. Other estimates have been made for a Level I reactor of the same basic type which are considerably higher.

A conservative estimate for the capital cost of a Level I reactor of modified BGRR design producing 9 kg of Pu²³⁹ per year, is, therefore, in the range of \$15 million to \$30 million.

The personnel requirements for the design and construction of the facility are modest, as all of the essential design parameters are in open literature. High-level research and development personnel are not required. Only a handful of experienced and competent professional engineers—possibly no more than 10—would suffice to design and oversee the construction of the facility.

The reactor could be ready for production approximately 3 years from the beginning of the project.

Level I Reprocessing Plant³

To fabricate nuclear explosives as quickly as possible, the fuel from a dedicated Level I production reactor would be removed after it had been in the reactor for approximately 1 year. The concentration of plutonium would then be about 9 kg in 75 tons of fuel, or about 120 grams per ton. The nation would have to build a reprocessing plant to separate the plutonium from the spent fuel.

A plutonium recovery plant must be designed and operated with care. The raw fuel, when first discharged from the reactor, is highly radioactive. Even if the fuel is allowed to cool for 120 days, during which time the activity decays by a factor of 100 or more, the total radioactivity is still about 45,000 curies per ton or 0.05 curies per gram of fuel. This means that the chemical processing of the fuel must be carried out remotely, in a shielded cell, at least up to the point where the fission products are removed.

It should be noted, however, that the radioactivity of the BGRR fuel is much lower than that of a typical power reactor. The activity of power-reactor fuel after a cooling-off period of 120 days runs between 2 and 3 million curies per ton, a factor of about 50 times higher than BGRR fuel. Considerably more precautions must therefore be taken in reprocessing power-reactor fuel than fuel from a BGRR.

Although the chemical steps required in the process are straight-forward and well-known, design and operation of the plant is complicated by the radioactivity of the spent fuel, the toxicity of plutonium, and the potential criticality of the plutonium fuel. These problems

³Much of this section originally appeared in: John R. Lamarsh, "On the Construction of the Plutonium Producing Reactors by Smaller and/or Developing Nations," Prepared by CRS, April 30, 1976. See also appendix VI of volume II.

require remote control, concrete shielding, and careful procedures, but do not constitute major obstacles,

Virtually all reprocessing plants built since the 1950's use the Purex solvent-extraction method. Both the chemical engineering techniques and the designs of actual reprocessing plants are well documented in open literature. For example, the plans for the Barnwell, S. C., reprocessing plant recently constructed by Allied General Nuclear Services (AGNS) have been widely distributed to the public and are available in the NRC Public Document Room. Because AGNS is such a large plant, with a through capacity of 5 tons of fuel per day (1,500 tons of fuel per year), considerable scaling down of this plant would be necessary for the purpose of reprocessing fuel from a Level I reactor.

Plans and specifications for a smaller plant are also available. In the late 1950's, the Phillips Petroleum Company undertook a feasibility study of a small reprocessing plant designed to handle spent fuel from Commonwealth Edison's Dresden-1 plant, then scheduled for operation in 1960. Phillips issued a report on this study in 1961, containing detailed drawings of every component of this plant. Although some chemical/nuclear engineers have expressed skepticism about the workability of the Phillips plant, because of its compact design and high level of automation, it nevertheless can be viewed as an excellent starting point for the design of a clandestine reprocessing facility in a small and/or developing nation.

A number of simplifications, described in appendix VI of volume II, are possible when the plant is designed for the sole purpose of recovering plutonium from BGRR fuel. Several of these simplifications result because the fuel has a lower burnup than fuel from a power reactor as discussed above, and, less shielding and fewer precautions are necessary when reprocessing the production-reactor fuel,

All of the equipment and supplies required to build and operate a plutonium recovery plant are generally available on the world markets. There is no single item that is so ex-

otic as to be obtainable from only a single source,

Estimating the cost of a reprocessing plant is difficult even for commercial operations. The discussion in appendix VI of volume 11 arrives at a figure of less than \$25 million, while estimates from other sources range from a few million, to \$10 million, to \$70 million. The highest cost estimates do not appear to take into account the simplifications possible with relaxation of safety and radiation protection standards and the use of lower burnup fuel. The lowest cost estimates correspond to extremely crude and imperfectly shielded (but technically feasible) solvent extraction or ion-exchange facilities, not suitable for a sustained program but which might be constructed to obtain material for a total of only a few explosives.

In view of this range of assumptions and costs, a reasonable estimate for the cost of a frugally designed reprocessing plant for BGRR fuel, based on the Purex solvent-extraction process, is less than \$25 million. If the plant were built to handle higher burnup fuel (for example, spent fuel diverted from a power reactor), the costs would be somewhat higher.

Thus the total capital costs of a Level I reactor and associated reprocessing plant are in the range of several tens of millions of dollars.

Many of the same technical personnel involved in the reactor project could be utilized for the plutonium recovery plant. Such a plan makes good sense because the recovery plant would necessarily be located adjacent to the reactor and would probably be built during the same time frame. The total engineering personnel for the two projects would be in the range of 10 to 20. Top-ranking research and development personnel are not required, as the staff largely follow and/or modify established designs. Nevertheless, the staff must contain competent engineers with applicable practical experience. A reactor and reprocessing plant cannot be built by reading books alone.

Many developing countries with a modest technical infrastructure would have the capability to build and operate the Level I

reactor and reprocessing plant described above, The construction of Level II reactors (producing 100 kg of plutonium/year), discussed below, would not be feasible for countries without a fairly high level of industrialization and a considerable nuclear base upon which to build.

Level II Plutonium Production Reactor

It is reasonable to assume that any dedicated plutonium production reactor would be fueled with natural uranium, because if facilities for enriching uranium were available it would be more logical to base a weapons program entirely on enriched uranium rather than reactor-produced plutonium.

In order to produce 100 kg of Pu²³⁹ per year (enough for 10 to 20 nuclear explosives), a reactor operating at about 400 MW is necessary (a reasonable allowance of 30 percent downtime is made).

Several different choices of moderator and coolant are possible. The moderator for a natural uranium-fueled reactor can be only heavy water or graphite. The coolant can be either ordinary or heavy water, or any one of a number of gases. As discussed in appendix VI of volume II, the most practical choice would probably be a graphite moderated, light-water cooled reactor.

Such a reactor would be similar to the first reactors built at Hanford, Wash., in the Manhattan Project. While a nominal 400 MW Level 11 reactor would operate at only about one-fifth the power of an early Hanford reactor, the nuclear designs of the two systems would be very similar. (The designs of the Hanford reactors have recently been declassified.)

One estimate of the total capital costs of a Level 11 reactor with associate reprocessing plant is in the range of \$175 million to \$350 million. Roughly 50 to 75 engineers would be needed in the design and construction phase of this Level II program, supported by roughly 150 to 200 skilled technicians. The length of time required from the start of the design to the first output of plutonium metal would be 5

to 7 years. As in the Level I reactor, the output would be nearly pure Pu²³⁹.

Level I and Level 11 Enrichment Plants

Several methods might be considered for enriching uranium. To date the most successful method is the gaseous diffusion process, which was developed by the Manhattan Project in World War II. This technique has remained essentially the only source of enriched uranium for military and civilian nuclear programs since that time, both in the United States and abroad. However, gaseous diffusion plants are inherently large structures that utilize a relatively sophisticated technology, much of which remains classified; they require an enormous investment of capital; and they consume large amounts of electric power. Finally, they cannot be concealed. The gaseous-diffusion route to nuclear explosives is not feasible for any but a handful of the largest and most developed countries, and will not be considered further in this report.

Another method for enriching uranium is the Becker nozzle process. Such an enrichment facility is being sold to Brazil by Germany, and a variation of it is being developed in the Union of South Africa. However, this method requires a large number of stages (see discussion of stages in appendix VI of volume II) and consumes 2-1/2 times as much electric power as gaseous diffusion and about 30 times as much as centrifuges (see below). Although the Becker method has fewer classified critical aspects, it does not appear to be a reasonable choice for any but an advanced nation.

Separation by means of high-speed centrifuges was explored during the Manhattan Project but later abandoned. This technique has reemerged in the last few years and has reached an advanced stage of development, both in this country and abroad. It appears likely that the centrifuge method of enrichment will prove to be cheaper than any other presently developed method of enriching uranium.

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 units (SWU) per year at Capenhurst, England, and Almelo, Holland. Urenco has plans to expand one or both plants to a total enrichment capacity of 2 million kg SWU by 1982. A small test facility is in operation at Oak Ridge, Term. One American firm has proposed building a major centrifuge uranium-enrichment plant to provide fuel for nuclear powerplants.

One advantage of the centrifuge method for a dedicated facility is that a small number of units or groups of centrifuges can be placed in operation as soon as they are built and tested. The separative operation need not wait upon the completion of a large facility. Production of weapons-grade uranium can begin at a small level and gradually be increased as additional centrifuges are installed.

The capacity of an enrichment plant necessary to produce 30 kg of highly enriched uranium (enough for one or two explosives) is shown in appendix VI of volume II to be between 6000 and 7000 kg SWU/year, depending on the tails assay. If each centrifuge has a capacity of 5 kg SWU/year this size plant would require 1200 centrifuges. An enrichment plant for a Level II weapons program would have to be about 10 times this size, with a capacity of 60,000 kg SWU/year.

The costs of a Level I or Level II centrifuge plant can only be based on estimates made by those now planning commercial plants. Those figures are not only estimates themselves, but most are for plants considerably larger than a dedicated enrichment plant would be and costs do not scale linearly with size. Urenco, which plans a plant whose capacity is several million kg SWU/year, (i.e., hundreds of thousands of machines), has estimated its capital costs at \$165/SWU. A U.S. estimate of capital costs for a 3 million kg SWU/year plant is \$300/SWU. Another U.S. estimate for a smaller (300,000 SW U/year) plant is \$700/SWU. Finally, Japan expects the cost of a 50,000 kg SWU/year plant to be \$3,300 /SWU.

The only one of these estimates to correspond closely to the size of a Level II centrifuge plant is the Japanese estimate. On

this basis, one might put the cost per SWU at \$2,000-\$4,000 and the total plant capital cost at \$120-\$240 million. Because, as discussed earlier a Level I centrifuge-enrichment plant is likely to be built only as an "add-on" to an existing plant, its costs may run the same per SWU as those of a larger plant. Taking the range of U.S. estimates of capital costs of \$300 -\$700/SWU, this assumption leads to a cost estimate for a Level I add-on plant of between \$2 million and \$5 million.

The costs discussed above do not include those for research and development. Centrifuge separation is a difficult technology only recently developed by a few of the most advanced nations. The AEC classified centrifuge technology in 1960, and Urenco also maintains tight security. Although unclassified details of early centrifuge technology are available, considerable development work would be necessary before even a small operable enrichment plant could be built.

Comparison

The centrifuge enrichment route calls for quite different resources and capabilities than does plutonium production reactors. In the latter case not only are complete facility plans readily available, but nuclear reactor and chemical engineers are being trained openly around the world.

For these reasons it is improbable that centrifuge enrichment would be the route taken by a country with a limited industrial and scientific base interested in a Level I facility.

There do not appear to be major differences in personnel requirements between the two types of Level II facilities—plutonium production and centrifuge enrichment—although the centrifuge program might require somewhat more manpower. The centrifuge program might also take longer from inception to metallic-weapons material. The capital and operating costs appear comparable.

Thus, an industrialized country desirous of producing significantly more than one bomb per year might carefully weigh the centrifuge

enrichment plant against a large plutonium reactor.

Advanced Isotope Separation Techniques

Several enrichment processes are under development that may allow highly enriched uranium to be produced from natural uranium (or even depleted uranium) in a very small number of stages. Two of the processes, laser isotope separation (LIS) and the ion-cyclotron resonance process (the Dawson process), are under development on contract to ERDA. There are two variants of the LIS process. One, the atomic LIS process, is under development at Lawrence Livermore Laboratory (LLL). The other, the molecular process, is under development at Los Alamos Scientific Laboratory (LASL). The atomic process is also being developed by a private U.S. firm, Jersey Nuclear Avco Isotopes (JNAI), a subsidiary of Exxon Nuclear and Avco Corporation. Research applicable to LIS is also being conducted in a number of other countries, notably the U. S. S. R., France, and West Germany.

A third process, an advanced form of electromagnetic separation, is under conceptual investigation by a private U.S. firm, Phrasor Technology, Inc., and research may be underway in at least one other country. It is unclear how much actual laboratory research and development has been done.

The three processes, LIS, advanced electromagnetic, and Dawson, share several key features. All promise to extend uranium resources, because low-tails assay should be easily achievable. The present gaseous diffusion facilities produce tails of 0.2 percent to 0.3 percent U^{235} , and operation at lower tails assay would be very expensive.

The advanced processes project a tails assay of 0.05 percent U^{235} or less, and an economical extension of uranium resources of about 30 percent could therefore be achieved from lower tails assay. In addition, tails accumulated over the years from the gaseous-diffusion process could be run through an advanced process to extract residual U^{235} . ERDA

has estimated that by 1989, at an average of 0.25 percent U^{235} in accumulated tails, enough extractable U^{235} will be contained in the tails for the lifetime fueling of 40 to 50 reactors, each of 1000 MW(e).

The three processes also hold forth a promise of lower cost enrichment. The goal of the ERDA program is a 50 percent to 75 percent reduction in enrichment costs, but much greater cost reduction may also be possible. If these approaches are economical on the large scale, all would be also economical in small-scale plants, in marked contrast to centrifuge processes and especially to gaseous diffusion processes. The reason for this is that the advanced technologies will probably require very few stages (possibly only one) to go from natural uranium to low-enriched uranium for reactors. The gaseous-diffusion process requires over a thousand stages; the centrifuge process requires the order of ten stages, with many centrifuges per stage.

The LIS processes and the Dawson process are still in the research stage, with solutions to several difficult problems still to be demonstrated. The proprietors of the advanced electromagnetic process claim that they are ready to begin pilot plant development, but they have apparently done little laboratory development. (It should be noted that a version of the electromagnetic process, the calutron, was used during the Manhattan Project to separate U^{235} for the first uranium weapon. The calutron method is described in appendix VI of volume II.)

The EXXON LIS process, although closer to the pilot-plant stage than the corresponding ERDA process (perhaps partially because of its less ambitious cost-reduction goals) also has technical problems to solve.

All three processes have built on a high technology base. LIS development in the United States depends heavily on the electro-optical base developed by the Department of Defense. The electromagnetic process has apparently built upon ion propulsion research in the space program.

All three processes have the potential for exacerbating the nuclear proliferation

problem. This is true in general of all enrichment processes which could produce highly enriched uranium from natural uranium in a few steps, because such processes are highly economical on a small scale once research and development have been completed.

This report has looked more closely at laser isotope separation (LIS) than the other two processes, and has had access to classified material, including ERDA-prepared responses to a series of questions and a classified discussion meeting with representatives from LASL and LLL. In order to keep this document unclassified, much of the detailed material supplied by ERDA has been omitted. As a consequence, the detailed state-of-the-art and description and evaluation of remaining technical problems are not presented.

It appears unlikely, based on knowledge of U.S. technology, that LIS could contribute to nuclear proliferation before the 1990's. ERDA plans to reach a decision in 1979 on which of the approaches, atomic LIS, molecular LIS, or Dawson, to fund to the pilot-plant stage. Pilot-plant operation is scheduled for 1984. This schedule depends on the successful solution of a number of difficult technical problems.

Proliferation From Advanced Isotopic Separation Techniques

Like any other enrichment technology, LIS could theoretically contribute to proliferation in the following ways:

1. The indigenous development of a dedicated facility;
2. Misuse of a commercial facility;
 - (a) Replication for the purpose of producing weapons material,
 - (b) Covert diversion, and
 - (c) Seizure.

These routes are considered in turn below.

Once LIS is known to work on the pilot-plant scale, research and development can be expected to intensify in several technically advanced countries. Some of these countries would probably develop LIS 5 to 10 years after a U.S. demonstration. Countries with only a moderate technological base would take longer.

The above discussion presupposed that LIS technology remained tightly and effectively classified. Leaks of essential data or technical details would speed-up development of LIS by other countries by eliminating the need for some basic research. However, the design, construction, and operation of a workable LIS system (even one that was not commercially competitive) from source preparation to isotope extraction would still require a lengthy and expensive development and learning program.

For these reasons, indigenous development of an LIS dedicated facility to produce highly enriched uranium is unlikely to be a feasible route for nations with a low or moderate technological base.

A greater danger is that LIS technology will be marketed by one or several advanced countries. France and the U.S.S.R, in particular could well succeed in LIS technology at about the same time as the United States (again, it should be noted that the eventual success of LIS is not a certainty). As noted above, several other countries would probably be only 5 or 10 years behind. Because LIS is economical on a small scale, many countries with a small nuclear power program could make a good economic case for wanting an LIS enrichment plant.

The spread, through sale, of commercial LIS technology would teach many purchasing nations a technology that they probably could not have developed for themselves. Replication of the technology in a small facility to produce weapons material would not be easy, but would be possible for more nations than indigenous development. The sale of commercial LIS technology could also result in many nations possessing a declared and safeguarded facility that could be modified, covertly or overtly, to produce weapons material.

It would be the aim of safeguards to detect covert production of weapons material in a commercial LIS facility. It is not possible to assess a nonexistent safeguards system on a nonexistent plant containing a nonexistent process. However, several general statements can be made. The most important obstacle to effective safeguarding of a LIS plant against covert diversion could turn out to be the

obstacle that presently might hamper safeguarding of centrifuge enrichment facilities: the fact that inspectors do not have access to the area where the actual enrichment process is going on, but must rely on monitoring inputs and outputs at the perimeter of the facility, with some input and output routes exempt from monitoring (i. e., perimeter monitoring with undeclared paths. See chapters VIII "Safeguards" and VII "Diversion From Commercial Power Systems".) On the other hand, the intrinsic nature of the LIS process, with relatively small pieces of equipment and a low-process inventory, could make LIS plants easier to safeguard against covert diversion than present enrichment facilities. In addition, many LIS plants would be small, and small plants are intrinsically easier to safeguard than large plants because the uncertainties in materials accountancy are smaller in absolute terms of kg of enriched uranium. Therefore, LIS plants may not present uniquely difficult safeguarding problems.

A greater danger than covert diversion is overt diversion, which international safeguards, by their nature, cannot prevent. Some form of sanctions would be the only effective response to overt diversion. A nation with an enrichment facility is in a strong position to withstand international embargos aimed at LWR fuel, and LIS facilities could provide this immunity to countries that could not consider present enrichment technologies. (See chapters 111 and VIII for a discussion of sanctions.)

The difficulty of modifying a commercial LIS plant designed for 3 percent U^{235} reactor fuel to produce highly enriched U^{235} for weapons would depend on the engineering details of the process. (It should be noted that one need not go to 90 percent enrichment to have useful weapons material: anything above about 50 percent U^{235} would be useful.) There do not appear to be any basic physics reasons to preclude obtaining weapons-grade material in a few stages in either the atomic or molecular LIS processes. Jersey Nuclear Avco Isotopes (JNAI) has stated that their process appears to be unsuitable for the production of highly enriched uranium. Representatives of the Lawrence Livermore Laboratory (LLL) LIS

group have stated that they do not agree with the JNAI statement, if it is meant to apply to all possible atomic vapor processes, although, LLL continues, it could be true for the particular JNAI design. The concept of a "tamper-resistant" LIS process, atomic or molecular, is an attractive idea, but a good deal of technological analysis would be necessary to establish how tamper resistant any particular design was. Moreover, too much reliance should not be placed on tamper-resistant LIS designs. Even a very tamper-resistant design would not be an absolute fix; what it would do is drive the nation towards the route of replication with modifications (a research and development program might be necessary to accomplish this) rather than overt seizure.

Some observers have suggested a U.S. moratorium on LIS development, coupled with strenuous U.S. diplomatic effort to obtain agreement from other countries to suspend work on LIS. Others express great doubt that the United States could achieve international agreement to stop the development of LIS or other advanced enrichment technologies, in view of both the pressures in many countries for independent and inexpensive enrichment and the worldwide market for enrichment services expected to develop in the 1990's.

ERDA predicts the worldwide market for enrichment to reach about 130 million SWU per year in the year 2000, based on their projections of 1200 GW(e) for LWRS worldwide by the year 2000. These projections may prove to be too high, nevertheless present and planned U.S. and foreign enrichment stands now at about 60 million SWU per year, all of it the expensive diffusion or centrifuge processes (see figure X-18). The advanced enrichment technologies, promising much less expensive enrichment, are thus extremely attractive to countries wanting both to assure themselves of self-sufficiency at a low cost in meeting their own enrichment needs and to profit from the sale of enrichment services.

Some observers have argued that the United States should develop an advanced enrichment technology and guarantee to sell enrichment services for a low fee or at cost. If

this were done, they maintain, the profit incentive for other countries to develop such technologies would be removed, and the incentive for smaller countries to buy an advanced enrichment facility would be much reduced. Thus, these observers argue, U.S. development of these technologies would in fact slow down their spread.

It would be unrealistic to expect, if this happened, that no other countries would develop advanced enrichment technology. A few advanced countries, with large nuclear programs and an avowed interest in LIS or another advanced enrichment technology (notably France and the U.S.S.R.), would almost certainly prefer their own low-cost enrichment facilities, even at the cost of indigenous development, to reliance on U.S. guarantees.

The same argument of desire for independence could be used by countries seeking to purchase an advanced enrichment facility, even if guaranteed services were available from the United States and perhaps a few other suppliers. Whether the independence argument will be plausible, or will be perceived as only a mask for an unstated weapons objective, would depend strongly on how supplier-importer relationships develop over the next decade.

In summary, the sale of LIS and other advanced enrichment technologies presents a greater proliferation danger than indigenous development of the technologies. The present course of formulating suppliers' agreements to end the sale of enrichment facilities is therefore particularly crucial in the case of the advanced technologies. (Chapters III and VIII discuss methods to restrict the spread of enrichment and reprocessing.)

All enrichment technologies capable of producing highly enriched uranium from natural uranium in a few stages should be closely watched by the United States. At the time of the ERDA decision point in 1979, the competing ERDA technologies should be evaluated for proliferation potential, in addition to economical and technical promise. In particular, the ability to safeguard advanced enrichment facilities and the possibility of tamper-resistant processes should receive attention.

In evaluating the proliferation potential of advanced enrichment technologies, the effect that their uranium-conserving properties might have on the economics of the introduction of plutonium recycle and fast breeder reactors should also be considered.

Detection of Dedicated Facilities

This report has not had access to any classified intelligence information. Therefore, only a few general comments on the detection of dedicated facilities can be offered.

Once the political decision has been made, it would take up to 5 years to build a facility dedicated to the production of weapons material and to obtain the material for the first explosive. As discussed in chapter VIII "International Control of Proliferation," a nation would probably be at an advantage if its weapons program were not detected until after it had assembled its first explosive. Therefore, the question of the detection of dedicated facilities focuses on the probability of detection within a time span of approximately 5 years—between the time a nation begins serious internal discussion of the possibility to a short but significant time before it has the weapons material in hand.

The likelihood of detection of a dedicated facility in a particular country depends on several factors. For example, it will be relatively easy to detect a clandestine nuclear facility in a country which otherwise has a very limited nuclear program. It will be relatively easy to detect a clandestine nuclear facility in a country which appears to have cause to want a nuclear weapons capability, because intelligence analysts will be more alert for early indications of a move towards clandestine nuclear activity. It will also be relatively easy to detect a large Level 11 nuclear facility.

One of the most important intelligence techniques, especially for the first indications of a dedicated facility, is political reporting. The very first indications of a dedicated facility are unlikely to come from technological techniques, such as satellite photography. Visible photography from satellite or aircraft

would become an important tool only after an active, coordinated surveillance program has begun.

A sustained effort, probably over a period of several years, coordinating many elements of the intelligence system—political reporting, visible photography, monitoring of the movement of materials and persons, sampling for chemical or isotopic indicators (such as Kr⁸⁵ for a reprocessing plant) would be necessary to build up familiarity with the target of surveillance and thus confidence in conclusions.

It appears unlikely that a Level II facility could long escape detection. Too many people would be involved in its design, construction, and operation. Level I facilities probably would present a detection problem in many countries, especially if the country were not considered one of the five or six most likely Nth countries. Intelligence agencies cannot continually monitor the whole world for dedicated facilities, and must allocate their resources according to priorities of problems and priorities of targets.

PURCHASE AND THEFT

A third potential route to the acquisition of nuclear weapons is the direct purchase or theft of either the fissile material or the weapons themselves. The commodities might be purchased through an illegal nuclear black market, bought or traded from a friendly nation in what is termed a gray market, or even stolen directly from some national nuclear-weapons arsenal. These paths bypass the need for the expensive and demanding technologies required by either the commercial power or dedicated facilities route. Thus, if this type of transaction emerges, the scope of proliferation could be extended to technologically limited nations and non-state adversaries (NSAS) who would otherwise have found the task difficult and risky. The pace of proliferation could be further accelerated by the relative ease of obtaining weapons, a general sense that the nonproliferation regime was crumbling, and a specific concern that one's enemies could be covertly arming. This section describes and evaluates the three elements to this route: black market; gray market; and theft. Appendix VII of volume II provides further detail.

Black Market

The term black market, as used here, means the illicit trade of goods where the commodity does not in general belong legitimately to the seller. The commodities traded in a nuclear black market could be fissile material,

weapons designs, or actual weapons. The most probable fissile material is plutonium derived from commercial power cycles, because it can be directly used for weapons fabrication. Only a very small fraction of the plutonium expected to be moving in a worldwide plutonium fuel cycle by the end of this century would have to be diverted to produce many bombs annually. Research-reactor and breeder-experiment fuel are other potential sources. A detailed design of an effective bomb would be an attractive commodity, especially for NSAS, because it would reduce the time and risk necessary to develop an effective weapon. The third black market commodity—weapons—might be stolen from military stockpiles, particularly if proliferation continues and security is lax in the new weapons states.

Participants in black markets can be categorized as buyers, suppliers, and intermediaries. Several potential participants can be identified in each category, and the type of transaction and motivation varies with the participants. Buyers might be nations or sub-national groups (terrorists, political or military factions, and criminals). The types of nations most likely to pursue a black market route are those technologically limited but internationally ambitious or those confronted with a sudden dire emergency which precludes the more conventional but time-consuming routes. Demand for illicit weapons or strategic nuclear materials could arise for

economic reasons. An approximate price for plutonium if freely traded could be about \$9000/lb. (\$20/gram).⁴Ten kg for one or two bombs would at that price be \$200,000, and a small arsenal of 20 bombs would cost less than \$4,000,000. The black market price would probably be several times higher, but even so the total cost could still be much less than that of the construction and operation of dedicated facilities. Subnational groups that consider terror to be a legitimate weapon could be drawn to nuclear weapons as described in chapter V, but might find procurement of the material otherwise too difficult. A military faction might want nuclear arms to facilitate a coup, or to hold in reserve for a national emergency if the civilian government has forsworn their development. Criminal groups, conceivably even individuals, might want to acquire arms for extortion.

Different commodities require different suppliers, Fissile material (plutonium) might be diverted by an employee at a nuclear facility such as a reprocessing plant. Motivation could be money, coercion, or ideology. Alternatively, strategic nuclear materials could be acquired by terrorists or criminal groups staging an armed attack, probably on shipments. Military weapons might also be procured by armed attack, but the tighter security would require even higher motivation on the part of the attackers. Corrupt military elements in a nuclear weapons state might steal their own bombs for profit, especially if security is casual. If intermediaries are involved they would most likely be criminal or international terrorist groups.

One constraint on a nuclear black market is the difficulty of initiating transactions. Most buyers and suppliers are unlikely partners. Contact and trust may be difficult to establish, except possibly between terrorist groups. Suppliers can generally find buyers more easily

⁴Based on previous expectations and discussions with industry representatives. Utilities presently assign zero value to their plutonium in the spent fuel, but if recycle is allowed, the value would depend on the cost of the enrichment which the plutonium replaces, the cost of reprocessing, and the additional cost of mixed-oxide fuel fabrication.

than vice versa, since potential buyers are relatively obvious. By contrast, a supplier might be the only employee out of 500 at a reprocessing plant with the motivation and the ability to divert plutonium. The supplier, however, runs the greater risk since he enters into the transaction with the illegally obtained commodity.

These transactions are more likely to occur if both the supply and demand are high. The supply of weapons designs and weapons themselves is likely to change only slowly (although access to them may increase faster). The potential supply of fissile material, however, could increase dramatically if large-scale reprocessing and plutonium recycle are initiated. If all the spent fuel from 1,000 LWRS (anticipated by 1995) is reprocessed, then diversion of one-tenth of 1 percent of the annually produced plutonium would be sufficient for about 50 bombs. This supply might be limited by effective safeguards and physical security, which can sharply reduce opportunities for illegal diversion, just as they reduce opportunities for national diversion. Material accounting, containment, and surveillance will reduce employee theft, while physical security should deter and repel armed attack. Physical security is especially important to protect weapons.

Given sufficient supply and demand, a sustained market could emerge from initial intermittent transactions. Thus, the market would be transferred from an amateur to a professional operation. The latter would be more dangerous because it would be continually seeking new suppliers and customers, and because the greater expertise of the operators would inhibit interference. A full-blown market could consist of many individual diversion activities and continuing networks, with criminal organizations providing necessary middleman services. A sustained black market requires a high demand, which would probably come only from less developed countries: more advanced countries would want more and better bombs than a black market could be expected to provide, and NSAS are unlikely to be able to afford more than a few. The major source of supply might be a number of reprocessing plant employees. If each smuggled out just one gram of

plutonium per day (an amount probably too small for either material accounting or portal monitors to detect) he should realize at least \$5,000 per year and maybe several times that. This source could be supplemented by attacks on shipments of plutonium, which could net several million dollars worth of material. A market of several hundred pounds of fissile material worth millions of dollars per year seems credible. Although small by comparison to the drug market, this is large enough to interest criminal groups and to have a major impact on proliferation.

Gray Market

A gray market falls between a black market and normal commercial transactions. The commodity belongs legitimately to the seller and the transaction is legal under the laws of the nations concerned but must be covert because it would be unacceptable if known publicly. The main reasons for secrecy of nuclear transactions would be to avoid alerting an enemy and to avert domestic or international reaction to furthering proliferation, especially if in violation of the NPT. The transaction could involve weapons, fissile material, or technical assistance.

The buyer in a nuclear gray market could only be a government, because purchase by any non-national group would be illegal. The supplier could be another government, a corporation, or an individual. Government-to-government transfer of nuclear arms could occur if a close and valued ally was on the verge of annihilation. Sale or barter of such weapons under more normal conditions is less likely. Fissile material is a more probable commodity, and technical assistance the most likely. The latter could consist of design information for either weapons or plutonium production facilities, or the critical components for either one. A supplier nation might enter into gray market transactions either at the demand of a nation that provides a vital resource (e.g., oil) or by the desire to gain political support (e.g., Pakistan and India both trying to gain favor with Arab nations). Alternatively, some nations may engage in a joint development program to reduce costs and shorten schedules.

Corporations with a large investment or substantial business expectations in another country could be subjected to considerable pressure to assist in a weapons program, particularly the plutonium production aspects. Revelations of corporate bribing of foreign officials gives a certain credence to this speculation, but the difference between a bribe and a contribution to proliferation will not be lost on corporation executives. The impact of exposure could also be much larger. Furthermore, the nations with the most leverage would be the ones needing the least assistance. Hence, this type of transaction seems less likely than governmental assistance. If it does emerge, however, the most likely suppliers would be reactor manufacturers, architect-engineers, and consulting companies. These are discussed in appendix IV of volume 11. Companies might be more susceptible to foreign overtures if their domestic nuclear activities are curtailed.

Individuals could contribute to a weapons development program by becoming scientific mercenaries. A sizable pool of scientific manpower conversant with plutonium reprocessing, materials handling, and related fuel-cycle technology already exists. Lack of demand for their skills at home might force a few to seek employment elsewhere, and bitterness over their loss of careers could overcome their scruples about contributing to proliferation. A constraint on this movement would be the desire of most nations to keep their weapons program secret. The nation may not wish to rely on the loyalty of foreigners in this situation, and may be unable to sequester them voluntarily for the long duration of the development program.

It is possible that some examples of gray marketing have already occurred. It was reported in 1975 that West Germany had been covertly involved in South Africa's uranium enrichment development programs. This cooperation was denied but some evidence indicates it may have existed. Nuclear mercenaries have a precedence in the migration of scientific manpower to the developed countries in the brain drain of the 1950's and 1960's.

⁵*The Observer* (London), Oct. 5, 1975.

Countermeasures to Black and Gray Market

An important step in combatting these transactions is to detect them. Intelligence-gathering operations can serve to identify participants, but the difficulty experienced with cracking the illegal drug market illustrates the problems that will be encountered in penetrating a nuclear black market. Isolated transactions would be even harder to detect unless the participants revealed themselves. If the buyer in either a gray market or black market is a government, then some aspects of its weapons fabrication may emit unique intelligence signals (as for other weapons development programs). This is discussed in the previous section, "Dedicated Facilities." Intelligence activities could also track migrating manpower, but the difficulty of separating the critical cases from the legitimate movements will be great and conflicts with civil liberties may arise. International safeguards should be capable of at least detecting when significant diversion has occurred. With that as a start, then intelligence can more easily track the material and determine the participants.

International safeguards have been directed at national diverters, but the same methods would be effective against black market diverters. Both intelligence and safeguards can be enhanced and reoriented towards this threat. Increased effectiveness in detection would be a potent deterrent to potential participants. The factor that would probably have the greatest impact in controlling a black market in fissile material would be to limit plutonium recycle. The supply that does exist can be made less accessible by enhanced physical security,

The willingness of participants to engage in these transactions depends not only on perceived rewards and risks of detection, but also on the consequences of detection. Possible responses might include sanctions against countries engaged in nuclear gray marketing, police work to capture black marketeers, and control of the activities of potential nuclear mercenaries and corporations abroad.

Theft of Nuclear Weapons

The most direct route to a nuclear weapon is the theft of someone else's. This report does not analyze weapons security in detail. Nevertheless, certain observations can be made. Fewer groups are capable of attacking a nuclear weapons stockpile or transport than could participate in a black market. Only highly motivated, well-organized, and well-armed attackers would have much chance of overcoming effective military security surrounding weapons.

U.S. nuclear weapons consist of bombs, missiles, artillery shells, depth charges, torpedoes, and demolition charges.⁶ All are protected against unauthorized use by internal mechanisms. None of these can prevent the weapons from being used simply as a source of high quality fissile material, but the delay would enhance the chances of recovery. Even without rebuilding the weapons, however, the thief would achieve full psychological value of possession.

U.S. weapons are kept in Europe, the Pacific Ocean area on naval vessels, and at home. Storage sites are usually on military installations. The protection provided is more stringent than that required for commercial fissile material, but the need for upgrading is recognized and being addressed by the Department of Defense. Weapons stored abroad might become less secure if the host government suddenly changed hands. Transport for logistical purposes is probably the most vulnerable link, but it is also infrequent.

It is difficult to defend against a determined, effective, comando type of attack. Groups of about 8 to 20 attackers using an imaginative plan and aided by one or more insiders would be especially difficult to resist without rapid reinforcement. On the other hand, it would also be difficult to mount this type of attack

⁶Joint Committee on Atomic Energy, Development, Use and Control of Nuclear Energy for the Common Defense and Security and for Peaceful Purposes, 1976.

without giving some warning to appropriately oriented intelligence activities. Massive attacks such as the Israeli raid on the Entebbe Airport are least likely to be successfully resisted, but neither can they be accomplished anonymously. Consequently, political and military responses, if activated, can be expected to ensure return or destruction of stolen weapons.

Other present nuclear weapons states appear to present about the same barriers to theft as the United States. New nuclear states, however, may be more vulnerable. Some potential Nth countries have experienced turbulent domestic politics, and factions could seize weapons for their own use or for sale on a black market. This threat could be exacerbated if some Nth countries are unconcerned about physical security, or feel it is secondary to the need for immediate operational readiness. Furthermore, such nations will probably not have the sophisticated protective mechanisms built into their weapons.

Conclusions

The emergence of a black market is presently constrained by the lack of supply of fissile material. Widespread plutonium recycle would remove this constraint. Some demand appears to exist, as already evidenced by Libya's attempts to buy a bomb.⁷This demand

⁷Steven J. Rosen, *Nuclear Proliferation and the Near-Nuclear Countries*, p. 178, Ballinger Publishing Co., Cambridge, Mass., 1975.

could increase if more nations feel intense security concerns or if they sense a continuing pattern of proliferation and feel they, too, should have a few nuclear weapons in reserve. The inherent lack of prestige of weapons attained by this route may deter some, but others might feel no compunctions. Thus, if supply is not limited, the outcome is likely to be at least intermittent black market transactions.

Gray market transactions appear at least as likely as those on the black market. The supply of some commodities already exists, the participants are more natural partners, and less risk would be involved. Gray market transactions would be individually negotiated, and so present less danger of spreading. The existence of either black or gray markets would be a serious blow to nonproliferation. They would themselves lower the barriers to weapons, and the feeling that nonproliferation efforts had failed would spur other nations to procure their own weapons.

Theft of weapons is the hardest to evaluate. Largely unpredictable conjunctions of motivation, ability, and opportunity would have to occur. Unless the attack is overwhelming, success will depend to some extent on luck. The military and psychological effectiveness of a stolen weapon would probably be substantially greater than that of a homemade one, particularly for non-state adversaries. Hence, physical security of weapons must be such that the risk of losing them is very low.