Science & Global Security, Volume 6, pp. 1–29
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Long-Term Safeguards for Plutonium in Geologic Repositories

Per F. Peterson[a]

The level and duration of safeguards for geologic repositories will depend on the relative difficulty of reclaiming fissile material, compared to utilizing alternate sources. Old spent fuel, aged over 300 years, merits particular attention because of its relatively high plutonium concentrations and low radiation levels. Several parameters must be predicted to provide input for current nuclear fuel cycle policy decisions, including future maximum tunneling advance rates, noise generation, and cost; difficulty and cost of plutonium separation; and the utility of separated repository-grade plutonium for nuclear explosives. Mining of old spent fuel repositories will provide a new class of proliferation risks for future generations: with smaller capital and manpower investments, the potential plutonium production rates exceed significantly the rates possible with dedicated reactors and reprocessing.

INTRODUCTION

Repositories for high-level waste will contain substantial quantities of plutonium, either in relatively concentrated forms (i.e. spent fuel and vitrified weapons plutonium) or more dilute forms (vitrified reprocessing waste and transuranic waste). The International Atomic Energy Agency (IAEA) safeguards department has determined that safeguards must be continued indefinitely for repositories containing spent fuel. Conditioned reprocessing waste (i.e. vitrified in glass) presents a lower risk because of its dilute form, but with the current lack of consensus on future risks the IAEA will also require safeguards on repositories containing these materials.[1] Swahn[2] finds that plutonium recovered from an old repository could be readily utilized for nuclear explosives.

For old spent fuel (>300 years) radioactivity levels drop sufficiently to allow considerable direct-contact handling, simplifying chemical separation of plutonium. A much longer time, over 200,000 years, is required for the pluto-

a Department of Nuclear Engineering, University of California, Berkeley.

Table 1: Planned repositories.[3]

country	disposal technology	power reactors in operation	1994 net electrical generation (MWe)
Canada	spent fuel	22	15,422
Finland	spent fuel	4	2,310
Germany	spent fuel & reprocess	21	22,703
Spain	spent fuel & reprocess	9	7,085
Sweden	spent fuel	12	10,002
Taiwan	spent fuel	6	4,884
United States	spent fuel	109	99,510
Argentina	reprocess	2	935
Belgium	reprocess	7	5,527
China	reprocess	2	1,800
France	reprocess	56	57,623
Japan	reprocess	47	36,946
Russia	reprocess	25	19,799
Switzerland	reprocess	5	2,985
United Kingdom	reprocess	34	11,540
18 Other Countries	?	83	36,849

nium in the waste to decay to low concentrations similar to those in reprocessing wastes.[4] Future spent fuel repositories may be located in several countries. As many as 25 countries may construct repositories for spent fuel. Eight countries currently plan to reprocess all spent fuel and dispose of reprocessing wastes only (see table 1).

Investigations of the performance of geologic repositories have focused primarily on the potential for releases of radioactive materials by natural mechanisms or accidental human intrusion.[5] Methods for monitoring geologic repositories for unauthorized diversion of plutonium have also been proposed and are likely to be relatively inexpensive and simple. Proposed safeguard methods include the analysis of periodically obtained satellite images and periodic inspection of the above-ground site by international inspectors,[6] and the use of remotely operated seismic stations to detect drilling or tunneling operations in the vicinity of the repository.[7] Booby traps or other devices to prevent access or make access difficult may be considered, although such devices will most likely be rejected, because they also prevent legitimate

access to the repository. A sub-seabed geologic repository, constructed from a man-made or natural island, has been proposed, where the island would be removed following repository closure, which would eliminate most accidental and intentional intrusion scenarios.[8] Yet to be decided for conventional repository designs are the types of mining, industrial, and other activities that must be restricted at repository sites, how far from the sites the activities must be restricted, and what institutional and economic systems can be put in place to maintain adequate safeguards at multiple repository sites over time periods exceeding a hundred millennia.

The IAEA can formally terminate safeguards on geologic repositories if the IAEA determines that the fissile material in the repository "has been consumed or diluted in such a way that it is no longer usable for any nuclear activities or that it has become practically irrecoverable."[9] Ultimately some plutonium will be disposed of, most likely in geologic repositories, either in large quantities in spent fuel or in smaller, more dilute quantities in reprocessing wastes. Thus the appropriate technical questions in assessing the long-term security risks from geologic repositories are these:

- how easily (cost and manpower) could fissile materials be obtained by mining a repository, compared to alternative production methods;
- how easily might access to a repository be gained;
- what would the duration of overt activities be before production could begin;
- once production starts, how rapidly could fissile material be produced;
- and what is the probability that functional nuclear explosives could be produced from the fissile material?

The answers to these questions must be compared to the answers for alternative methods of procuring fissile material, the most important alternatives being:

- diversion of material from an existing civilian nuclear power program;
- production using dedicated reactors and reprocessing facilities;
- and production using isotopic enrichment of uranium.

The answers to the above questions, and the implications for security, will also depend on the type of group attempting to produce fissile material: the nation that owns the repository; another nation, using military force; or a subnational group.

For a nation that owns a repository, the most important questions are the duration of overt activities before production could begin and the rate at which fissile material could then be produced. The answers to these questions determine whether effective international sanctions or military intervention could be applied before significant numbers of nuclear weapons were fabricated and deployed.

National boundaries may shift over the next few hundred millennia in areas containing repositories. During such unstable periods fissile materials in repositories may be vulnerable to the second type of group, nations using military force. Likewise, with instability subnational groups may have easier access to repository sites, though relatively modest police capabilities should be sufficient to prevent subnational group access to repositories under normal circumstances. All groups would have much simpler access if advances in tunneling technology reduce noise levels significantly and make surface activities easier to conceal. On the other hand, future advances in enrichment technology may make mining repositories relatively less attractive as a source of fissile material for nuclear explosives.

This paper explores the current state of technology in several areas relevant to safeguards for geologic repositories. First it considers the tunneling and reprocessing technology that could be employed to obtain access to repository plutonium, comparing the cost and difficulty to that for a dedicated reactor. The properties of old spent fuel and repository-grade plutonium, and the utility of repository-grade plutonium for weapons purposes have been studied in detail by Swahn,[10] and are summarized here.

COMPARISON TO DEDICATED REACTORS

The proliferation risks from old spent-fuel repositories must be viewed in the context of alternative methods of obtaining fissile materials. Clearly, old repositories in nuclear-weapons states would present different proliferation risks from repositories in non-nuclear-weapons states. Likewise, diversion from an old spent fuel repository would be less attractive for a nation already reprocessing fuel for a domestic nuclear power program. However, any commitment to nuclear fission power, stretching over the hundreds of millennia that plutonium remains available in a repository, would likely recycle any buried spent fuel. Therefore, the long-term primary proliferation risks from spent-fuel repositories will come primarily from non-nuclear-weapon states without long-term commitments to nuclear fission power. For such states the appropriate technology to compare with mining is dedicated production in reactors or enrichment facilities.

The smallest practical production reactor would produce roughly 30 MW thermal energy, producing approximately 8 kg of plutonium per year. This plutonium mass can be compared to the 6-kg nominal mass of plutonium required to fabricate a single nuclear explosive. The capital costs for mining facilities (2500 tonnes per year of high-grade uranite to 500,000 t/yr of low-grade phosphate ore), milling and conversion facilities (100 t/yr of U_3O_8), a fuel fabrication facility (84 t/yr uranium metal), and a Brookhaven-type graphite moderated reactor (670 tonnes reactor-grade graphite, 300,000 cu ft/min air blowers requiring 6,300 kW of electricity), with research, development, testing and engineering costs (RTD&E) (10 percent - 15 percent of capital costs) and start-up costs (20 percent - 25 percent of capital costs) would be between $81 and $207 million (1992$) if the state building it did not try to keep it secret. The reactor construction would require eight engineers and a crew of 100 technicians working for 3 to 5 years.[11]

The capital cost for a larger 400 MWt reactor, capable of producing 100 kg of plutonium per year, would range from $400 to $1000 million (1992$), and require 50 to 75 engineers and roughly 150 to 200 technicians working for 5 to 7 years. Including mining, milling, conversion and fabrication costs, scaled from the smaller reactor, the total capital costs would range from $1.0 to $2.2 billion (1992$).[12]

To equal the plutonium production of a 30-MWt dedicated reactor, a mining operation at an old spent-fuel repository would require a single small (i.e. 2-m diameter) tunnel or shaft intersecting a single waste package, with a retrieval rate of 1 tonne of old spent fuel per year, requiring that two PWR spent-fuel assemblies be recovered each year. However, with access via a small tunnel or shaft, the excavation of backfill material between neighboring canisters could then occur. For multipurpose canisters (MPC) containing 21 PWR spent fuel assemblies, uncovering and opening one MPC in situ every two months would allow plutonium production at a rate equaling that of a large 2150-MWt production reactor. Because the incremental costs of excavation of limited quantities of backfill between canisters would be relatively small compared to the original cost of an access tunnel, the recovery cost for mined plutonium would be relatively insensitive to the production rate, up to rates comparable to large production reactors.

Figure 1 illustrates the relative capital costs of plutonium production in dedicated production reactors, compared to construction of a small access tunnel into a repository, showing substantially lower cost. Tunnel boring machines (TBM) are currently the most economical technology for excavating tunnels over 1 km in length; however, this is due primarily to reduced labor requirements and reduced interest charges from shorter construction time requirements. A low-technology group may select drill and blast methods to reduce capital costs for equipment. A new TBM of a size about 4-m diameter would cost 5 to 6 million dollars (1992$). Two recent tunneling projects about

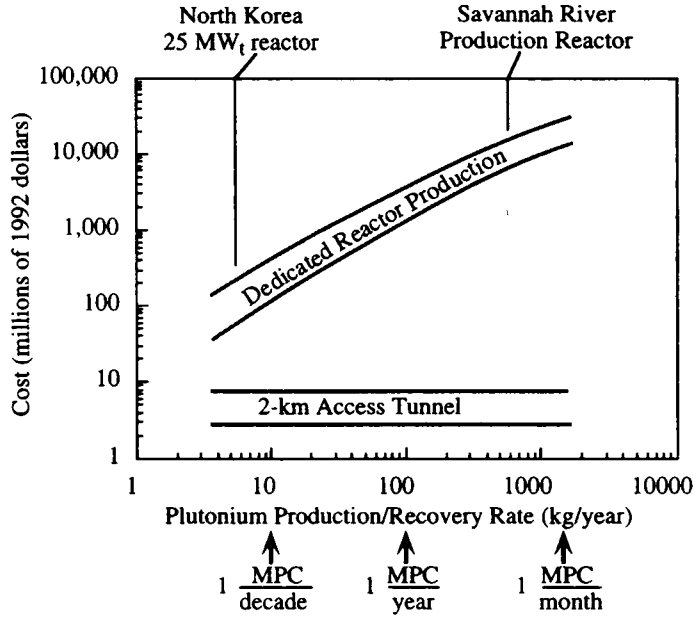

Figure 1: Cost comparison for producing irradiated fuel with dedicated mining, milling, conversion and reactor facilities, to recovery of irradiated fuel from an old spent fuel repository via a 2-m diameter, 2-km long access tunnel (1 MPC = 21 PWR spent fuel assemblies).

9-km long cost between $19 million (2.6-m diameter) and $45 million (3.6-m diameter) (1992$), including extensive civil and other additional work.[13] The cost difference scales closely with the excavated rock volume, $400 to $480 per cubic meter. Using these values, tunneling of the simplest, small, 2-m-diameter, 2-km-long access tunnel could cost $2.5 to $3.0 million (1992$). This cost range agrees well with historical costs for mine access tunnels, reported in mining journals, of $1,450 to $3,700 per meter (1992$), or $2.9 to $7.4 million for a 2-km-long mine access tunnel.[14]

The normal time required to deliver a new TBM is typically about 12 months, although delivery of a reconditioned TBM would require several months less. Drill-and-blast equipment can be obtained in a much shorter time. For example, a new drilling jumbo can be delivered in several months, at a cost about 11 to 13 percent of that of a new TBM.[15] The additional time period required for tunnel excavation, which can be compared with the 3 to 5 year period required for reactor construction, is discussed next.

TIME SCALES FOR TUNNELING

The two parameters of primary interest for setting safeguard and security requirements for repositories are the maximum anticipated tunneling advance rate and the maximum distance around a repository at which surface facilities for tunneling might be located. Noise levels generated by tunneling activities are also important if acoustic monitoring for safeguards is contemplated.

Currently the fastest tunneling advance rates are achieved with full-face TBM's, which drive numerous disk-shaped cutting tools mounted on a rotating cutterhead against the tunnel face to excavate the tunnel. Buckets on the rotating cutterhead collect the debris, or muck, and carry it to the top of the machine, where the muck drops on a conveyor belt to be carried to the back of the machine. Either a long conveyor belt or rail cars then remove muck to the tunnel entrance. Behind the rotating cutterhead the large pads are thrust hydraulically against the tunnel walls to provide reaction forces for both the thrust and torque of the machine.

Table 2 presents data for a selection of recent tunneling projects. Based on the current state of the art, average tunneling advance rates from 10 to 40 m/day are credible using a TBM. Initial TBM set up activities at the surface, which would include blasting of a starter tunnel of a few tens of meters depth, can be accomplished in 2 to 12 weeks. Conventional drill and blast methods could also be employed for the entire tunnel with significantly lower equipment costs, though advance rates would be reduced to under 5 m/day. Set-up and the initial tunneling could be concealed inside a modestly sized building, though muck disposal (excavated material from tunneling) would involve substantial material volumes and would be more difficult to conceal.

Tunnel lengths of 10 km are now routinely constructed from a single point of surface access. Substantially longer tunnels are credible. For the purpose of safeguards, a protected radius of 15 km around a repository would require tunnel boring for over one year at an average advance rate of 40 m/day, before the repository could be reached. It is important to note that the rapid increase in tunnel boring advance rates over the last decade may continue. Strong economic incentives exist to improve the technology for urban mass transit, other transit, and water and sewage transfer applications. Thus the 50 m/day advance rate may not be a conservative value for tunneling activities that would take place over 300 years from now, and the protected radius around repositories may increase in the future. Other advances in tunneling technology may make tunneling activities either faster or more difficult to detect.

Table 2: Selected tunneling projects.[16]

project	date	diameter (m)	rock	length (km)	daily shift length (hr/day)	average daily advance (m)	maximum daily advance (m)
Oahe Dam	1955	7.8	shale	—	—	15.2	42.8
IVAR (Norway)	1989	3.5	phyllites	8.1	18	24.1	96.6
Kelano Power Tunnel	1991	5.7	granite	6.1	14	28.9	80.5
SYAR (Utah)	1990	3.6	shale/sandstone	9.2	24	47.1	127.0

TBM performance is expressed in terms of utilization, penetration rate, and advance rate. Utilization refers to the fraction of time that the machine spends cutting, which is reduced by downtime for maintenance and repair of the TBM and muck removal systems, cutter replacement, additional work when adverse rock conditions are encountered, and shutdown time between work shifts. The penetration rate is the instantaneous penetration per unit time or per cutterhead revolution. The advance rate is the product of the utilization and penetration rate. Improvements in advance rates come from increased utilization by running longer work shifts and reducing maintenance requirements, and from improved penetration rates by improving cutters and cutter head designs, increasing power and torque, and active control of power and thrust.[17]

The maximum permissible downward TBM tunnel slope determines how close to a repository a TBM can begin tunneling and what the minimum tunneling distance is. TBMs are usually employed for tunnels with downward slopes less than 18°. The difficulties encountered with greater slopes are associated primarily with muck removal and can be remedied by replacing smooth conveyor belts with pleated conveyor belts, allowing downward tunnel slopes of up to about 30°. Other minor changes include modifications to sight glasses and fluid level sensors to adapt to the change in position of certain fluid levels on the slope and provision of a sump pump installed immediately behind the invert scraper to remove any water that may accumulate at the bottom of the slope.[18]

Manpower requirements for TBM operation are quite small. Typical crews for operating a TBM and muck removal equipment are six to eight. However, the 8.1-km-long, 3.5-m-diameter IVAR tunnel in Norway was recently completed using four-man crews in the tunnel, including the driver of the locomotive for muck removal.[19]

TBM sound levels are important if seismic monitoring is to be employed to detect tunneling activities. In general, TBM vibrations are one-half to two orders of magnitude lower than blasting vibrations. The magnitude and frequency characteristics of TBM vibrations have been characterized as being similar to those from moderate to heavy street traffic.[20] Because one of the growing applications for TBMs is tunneling for intracity rail transport, TBM noise levels are considered important, and effort will continue to reduce TBM noise generation. Some of the advanced tunneling technologies that may be developed, as discussed later, would be expected to have significantly lower and different noise characteristics from TBMs.

Drilling and blasting has been used since before 1850 for hard-rock tunneling, and provides a low-technology alternative for access inside a repository. The drill-and-blast technique involves three sequential processes, as

opposed to the continuous operation of a TBM. First, miners drill a pattern of holes in the tunnel face and load the holes with explosives. Next the miners blast the round, then wait until blasting gases ventilate. Third, the miners muck the round, removing the blasted rock and, if needed, add rock support. Major advances in drill and blast technology have increased advance rates. These advances have included the replacement of gunpowder with nitroglycerin-based explosives, compressed air rock drilling machines (c 1860), tungsten carbide drill bits (c 1950), and the hydraulic rock drilling jumbos capable of rapidly drilling multiple holes (c 1980). Drill-and-blast methods typically would achieve advance rates of 2.5 m/day to 5.0 m/day.[21]

For the first thousand to several thousand years, miners entering a repository will encounter elevated temperatures due to decay heat from spent fuel. At Yucca Mountain, the repository would be above the water table, and a "hot-repository" design has been proposed that would reach temperatures as high as 120°C to prevent moisture contact with waste canisters. Other countries' repositories, with much smaller spent fuel inventories and total heat loads, have been proposed at depths below the water table, requiring that the repository temperature remain below 100°C to prevent damage to clay backfill material. In either case, for worker productivity, cooling would be required to maintain tunnel wet-bulb temperatures below 35°C. Cooling of a single, small-diameter access tunnel would not present a large impediment, however.

The tunnel heat load will be given by $\dot{q} = hA(T_r - T_a)$, where the heat load $\dot{q}$ is the product of the effective heat transfer coefficient h, the surface area A, and the temperature difference between the rock surface T_r and the air in the mine, T_a. With 10-cm-thick insulation, the heat load for a 2-m-diameter tunnel with 120°C rock and 35°C air is under 200 W/m. For a tunnel extending through 500 m of heated rock to reach a repository, this is a heat load of 0.1 MW, which can be handled with forced ventilation by outside air through a high-velocity supply duct running the length of the tunnel (i.e. with an outside air temperature of 25°C, a 9 m^3/s air flow is required to maintain the tunnel air temperature below 35°C).

In general, rapid tunneling is most feasible in "competent," unbroken rock. In particular, conditions such as excessive faulting can slow tunnel advance rates due to the looseness of the material and the difficulty in supporting and removing material from the tunnel face. These difficulties have been observed during initial TBM tunneling at the Yucca Mountain site. Unforeseen adverse geologic conditions are the principal impediment to tunneling. Because potential repositories will likely be well characterized and information on the geological conditions will likely be available publicly (and more likely will be available to the national group which originally constructed the repository), groups mining a repository will be better prepared than many tunneling projects to minimize and mitigate delays from adverse rock conditions.

The DOE is currently characterizing Yucca Mountain in southern Nevada to serve as a potential repository for US spent fuel and high level waste. If constructed, the repository will reside 200 m beneath Yucca Mountain, with access via a gently sloping tunnel entering from the side of the mountain. The shortest distance for mining of the repository would be to tunnel from the side of the mountain, requiring a tunnel length of 1 kilometer. The time required to access spent fuel in a repository in Yucca Mountain, at average advance rates of 10 to 40 m/day, would then be between 6 and 26 weeks including surface set up time, assuming that difficulties with incompetent rock could be mitigated sufficiently. Due to the high degree of faulting at Yucca Mountain, excavation of the first exploratory tunnel at Yucca Mountain required 36 weeks for the first kilometer (4 m/day), and 16 weeks for the second kilometer (9 m/day). Average advance rates reached 16 m/day in the third kilometer, due to TBM modifications and improved rock conditions. With the experience gained, future access into Yucca Mountain via TBM would likely require between 6 and 12 months. However, due to the shallow depth of this proposed repository, access through a vertical shaft would be more rapid. Large vertical holes, 1.4 to 3.0 m in diameter, have been routinely drilled nearby for underground nuclear testing to depths greater than the proposed Yucca Mountain repository, in time periods between 6 and 8 weeks.[22]

A generic high-level waste repository would be located 500 to 1000 m below the surface in relatively flat terrain. For a tunnel with a 1:2 downward slope (27°) the required tunnel length would be 1120 m to 2240 m. From initial activities at the surface, the time required to construct a single small access tunnel would range from 6 to 44 weeks for advance rates from 10 to 40 m/day. The longer time estimate is likely more reasonable for tunnels this short, due to the learning curve any tunneling project must undergo.

When the access tunnel reaches the repository horizon, the rate at which spent fuel can be removed will depend on the physical condition and layout of the spent-fuel canisters, the nature of the back-fill material in the repository tunnels, and the repository temperature. Many engineered aspects of repositories which will affect plutonium recovery rates remain to be decided. For a water-saturated repository with chemically reducing conditions, like those proposed in granite, waste canisters are expected to survive for long periods with little corrosion or degradation. Under oxidizing conditions, as at Yucca Mountain, more extensive corrosion can be expected, although extensive engineering effort will be devoted to maximize canister lifetimes.

With old spent fuel the fission product gases, in particular 10.76-yr half-life Kr-85, will have decayed to negligible levels, minimizing radiological hazards in opening canisters in situ. A single 125-ton multi-purpose canister con-

tains approximately 100 kg of plutonium, so the plutonium recovery rate could potentially be high and will depend on the rate of excavation of back-fill material.

More advanced tunneling technologies may also be developed. Potential advanced technologies include the subterrenne, a tunnel boring machine that melts and displaces rock using an electrically heated, refractory metal head. This type of tunneling machine has been demonstrated at small scale, using a 5-cm-diameter device in laboratory and field trials, and using analytic and numerical models to study basic parameters of melting penetration.[23] The device performs well in variable ground conditions, stabilizing the tunnel walls with a glass lining. Debris can be removed in glass rod, glass pellet, and glass wool forms. Alternatively, in porous rock-like tuff, small-scale experiments demonstrated that the higher density of the melt material allowed the melt to be entirely consolidated in the glass tunnel wall lining, eliminating the need to remove debris. By eliminating mechanical chipping and abrading, noise levels associated with rock melting can be reduced below those of conventional TBMs.

Other advanced technologies include water-jet cutting for tunneling. Recent emphasis has focused on the use of water jets to assist in TBM chip removal.[24] Effort has also been placed into development of high-pressure water jets to provide high-velocity cutting. Water jet cutting could potentially both reduce noise levels and increase tunneling speed.

REPROCESSING REPOSITORY—GRADE PLUTONIUM

Reprocessing of old spent fuel to obtain repository-grade plutonium differs in two important respects from reprocessing of fresh spent fuel. First, the radioactivity of old spent fuel is much lower, which reduces shielding requirements, allows extensive direct contact handling and maintenance, and hinders remote detection of reprocessing activities. Second, recovery of uranium in the spent fuel will not be required, simplifying the chemical processes required for plutonium separation. The technology employed for chemically separating repository-grade plutonium will be important, because separation rather than mining will most likely determine the maximum plutonium production rate.

Several significant advantages accrue from the reduced radiation levels in old spent fuel compared to young spent fuel. The first is the potential for direct contact handling of the spent fuel itself, which will emit under 1 rad/hr. The duration of direct contact and the efforts to minimize doses will depend on the total doses the workers are willing or required to accept. Recent information

on atomic workers in the former Soviet Union indicates that some of their workers received doses of 100 rem/year over several years.[25] Workers willing to accept these doses could perform direct contact work on old spent fuel for periods approaching 100 hours per year. With modest automation this would permit a single worker to cut open many spent fuel canisters and manually transfer fuel assemblies, particularly if rudimentary precautions were taken to minimize doses to the worker.

Reduced radiation levels also eliminate the need for massive shielding of reprocessing equipment for operation and maintenance. Reprocessing equipment could be housed in standard industrial buildings, reducing costs and making it substantially easier to keep reprocessing activities covert. The absence of significant quantities of 10.76-yr half-life Kr-85 would further complicate efforts to detect covert reprocessing. Releases of Kr-85 from reprocessing plants have, in the past, provided considerable information on production of separated plutonium.[26]

Due to very low burnup, spent fuel from dedicated production reactors can have much lower radiation levels than fresh commercial spent fuel, though still greater than old (>300 yr) commercial spent fuel. The cost and schedule estimates available for stripped-down reprocessing facilities for dedicated production reactors therefore provide useful estimates for the cost of similar reprocessing capabilities for old spent fuel. The lower radiation levels reduce the capital cost of a reprocessing facility considerably, to $16 to $50 million (1992$), including RTD&E and start-up, for a PUREX plant capable of processing 85 tonne per year of low-activity spent fuel.[27] For the low burn-up fuel from a dedicated reactor, such a plant would recover approximately 10 kg of plutonium per year. However, the much higher burn-up of commercial spent fuel would greatly increase the plutonium recovered by the same plant, to over 700 kg per year.

The low radioactivity of old spent fuel increases the probability that a group would remove old spent fuel not to separate the plutonium, but rather to sell directly to another group. Several countries have demonstrated the willingness to spend large sums of money to acquire fissile materials for covert weapons programs. It would not be unreasonable to expect that a market for illicit old spent fuel assemblies could exist in the future.[28]

CHARACTERISTICS OF OLD SPENT FUEL AND REPOSITORY—GRADE PLUTONIUM

The gamma dose rate from a typical 15-year old spent fuel assembly is 2000 rad/hr at 1 meter from the center of the assembly.[29] This gamma radiation level makes substantial shielding and remote handling necessary. Radiation levels drop substantially, however, as spent fuel ages. Table 3 lists the primary

Table 3: Spent fuel long-lived (>10 year) gamma emitters (>0.1 MeV for >0.1 percent of decays).[30]

isotope	atoms per fission at 150 days[a]	half life (yr)	decay mode	characteristic γ radiation (MeV)
Kr-85	2.48×10^{-3}	10.7	β	0.51 (0.4%)
Sn126	4.71×10^{-4}	1×10^{5}	β	1.21 (4%), 0.70 (32%), ...[b]
Cs-137	6.02×10^{-2}	30.2	β	0.66 (94.6%)[c]
Eu-154	1.39×10^{-3}	8.5	β	1.27 (33%), 1.00 (13%), ...
Cm-243	1.6×10^{-6}	28.5	α	0.27–0.23 (84%), ...
Cm-245	4.6×10^{-5}	8,500	α	0.17 (47%), 1.13 (46%), ...
Am-241	1.1×10^{-3}	432	α	0.10 (3%), 0.060 (80%), ...
Am-243	2.1×10^{-3}	7,370	α	0.33–0.22 (68%), ...[d]
Np-237	1.7×10^{-2}	2.14×10^{6}	α	0.41–0.30 (63%), ...[e]
U-235	1.8×10^{-1}	7.1×10^{8}	α	0.21–0.14 (75%)

a. Atoms per fission product pair, remaining at 150 days after discharge from once-through cycle in a 1,000 MWe uranium-fueled PWR.
b. Daughter Sb-126m (19 m half life) emits important gammas.
c. Daughter Ba-137m (2.55 m half life) emits gamma.
d. Daughter Np-239 (2.35 day half life) emits important gammas.
e. Daughter Pa-233 (27 day half life) emits important gammas.

isotopes which contribute to the gamma dose rate for older spent fuel. For young (15 years to 400 years) spent fuel the dose comes primarily from the decay of the fission product Cs-137, whose 2.55 minute half-life daughter Ba-137m emits a hard 0.662 MeV gamma photon. Because Cs-137 decays with a 30-year half life, for the first several hundred years the gamma dose rate from a spent fuel assembly decreases by 50 percent every 30 years, as shown in figure 2. Eventually the activity of Am-241 exceeds that of Cs-137, emitting 0.059 MeV gamma photons. More importantly, after approximately 400 years the activity of the 7950 year half life actinide Am-243 exceeds that of Cs-137, with the 2.35 day half-life daughter Np-239 emitting a 0.23 MeV gamma photon. However, at this point the total gamma activity has dropped by almost four orders of magnitude from the activity of the 15 year old spent fuel. At this age the gamma dose rate from spent fuel is under 1 rad/hr at one meter.

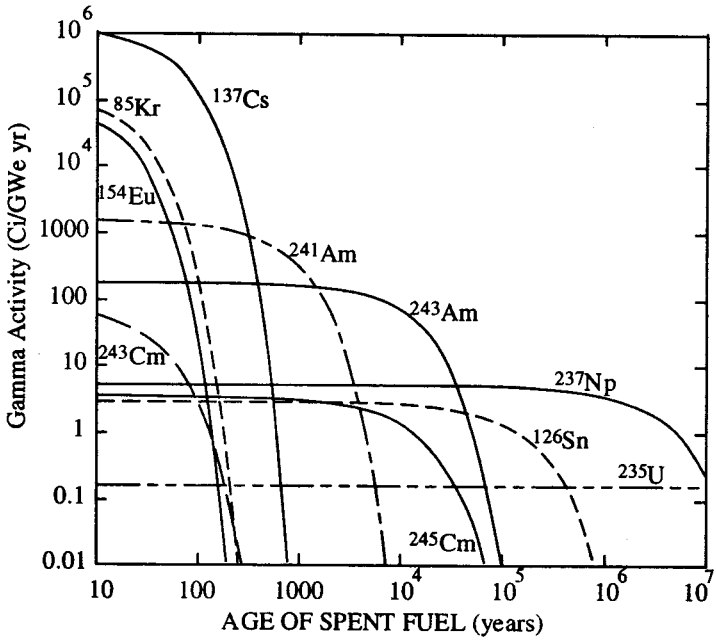

Figure 2: Long-term gamma activity for pressurized water reactor spent fuel.

The isotopic composition of plutonium mined from a repository will differ substantially from the composition generated expressly for weapons use.[31] Weapons-grade plutonium is generated by neutron capture in U-238 during a relatively short residence in a nuclear reactor, giving the approximate isotopic composition shown in table 4. Spent fuel from power reactors typically has much higher burn up, so that neutron capture generates significant quantities of the higher plutonium isotopes, while (n,2n) reactions create small but important amounts of Pu-238. The recovery of plutonium by reprocessing and recycle of plutonium in light water reactors as mixed oxide fuel (MOX) further increases the fractions of higher plutonium isotopes for MOX-grade plutonium.

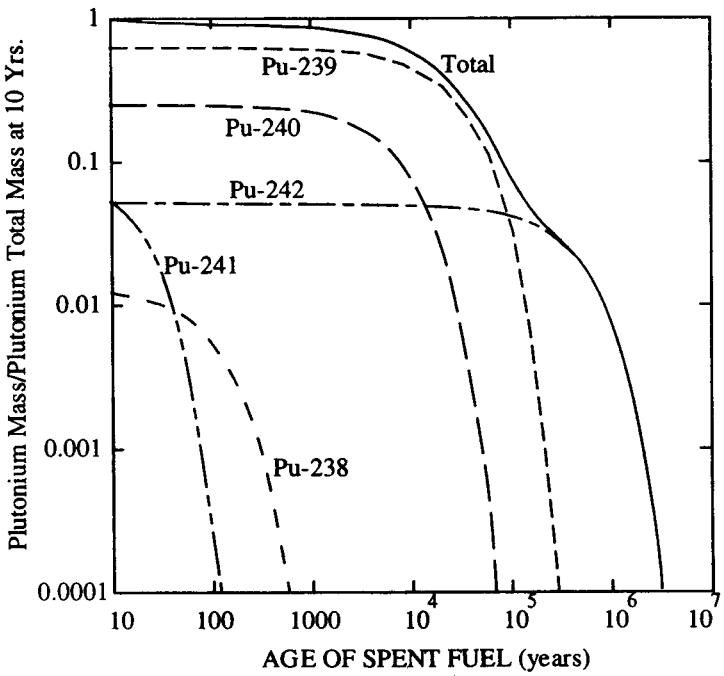

Figure 3: Ratio of quantity of each plutonium isotope to the total initial quantity of plutonium for pressurized water reactor spent fuel (see table 2).

Plutonium potentially will be placed in geologic repositories in several forms, in relatively high concentrations in spent fuel or weapons plutonium vitrified in glass, and in relatively low concentrations in vitrified high-level reprocessing waste and other transuranic wastes. This paper focuses on the example of spent fuel, as the waste form from which large quantities of plutonium could most easily be recovered. During storage in a repository the isotopic composition of plutonium will change, because each isotope has a different half life. Figure 3 illustrates how the isotopic composition of typical pressurized water reactor spent fuel would change over time in a repository. For the purposes of this paper, "repository-grade" plutonium is defined as plutonium separated from "old" spent fuel, defined as fuel over 300 years old, with a typical plutonium isotopic composition given in table 4.

Table 4: Isotopic composition of various plutonium grades.[32]

grade	Pu-238	Pu-239	isotope Pu-240	Pu-241[a]	Pu-242
super-grade	—	.98	.02	—	—
weapons-grade	.00012	.938	.058	.0035	.00022
reactor-grade[b]	.013	.603	.243	.091	.050
MOX-grade[c]	.019	.404	.321	.178	.078
FBR Blanket[d]	—	.96	.04	—	—
repository-grade[e]	.0013	.676	.266	10^{-8}	.057

a. Pu-241 plus Am-241.
b. Plutonium from low-enriched uranium PWR spent fuel with 33 megawatt-days/kg burnup, stored 10 years before reprocessing.
c. Plutonium from 3.64 percent fissile plutonium mixed-oxide (MOX) spent fuel produced from reactor-grade plutonium, with 33 megawatt-days/kg burnup and 10 years storage before reprocessing.
d. Fast breeder reactor.
e. Plutonium from low-enriched uranium PWR spent fuel with 33 megawatt-days/kg burnup, stored 300 years before reprocessing.

A typical pressurized water reactor spent fuel assembly, consisting of a 17x17 array of 0.92 cm diameter, 3.85 m long fuel pins, contains 520 kg of fuel and 4.7 kg of plutonium. For direct disposal in a repository, several fuel assemblies would be placed inside a hermetically sealed canister, and disposed with an overpack in either horizontal or vertical orientation, potentially with a low permeability backfill material. A likely canister design would be the multipurpose canister (MPC) now under development by the Department of Energy, the larger 125 ton version containing 21 PWR fuel assemblies, or approximately 100 kg of plutonium.[33] Typical repositories will contain a few hundred to many thousand MPC's (approximately 100 MPC's per plant lifetime). The utility of the various plutonium (and uranium) isotopes depend on several parameters, including their cross sections for fast neutrons, spontaneous fission rates, and decay heat generation rates. Table 5 provides useful values for these properties. A spontaneous fission reaction of an even plutonium isotope releases about 3 neutrons, and likewise, reactions of plutonium alpha decay particles with light elements can generate neutrons. Spontaneous fission occurs at higher rates in reactor-grade plutonium, over six times the rate for weapons-grade plutonium. Figure 4 shows that spontaneous fission neutron generation rates per unit mass of total Pu decline only slightly before 20,000 years as Pu-240 decays, and then begin to increase substantially as Pu-239 decays and the remaining fraction of long-lived Pu-242 grows.

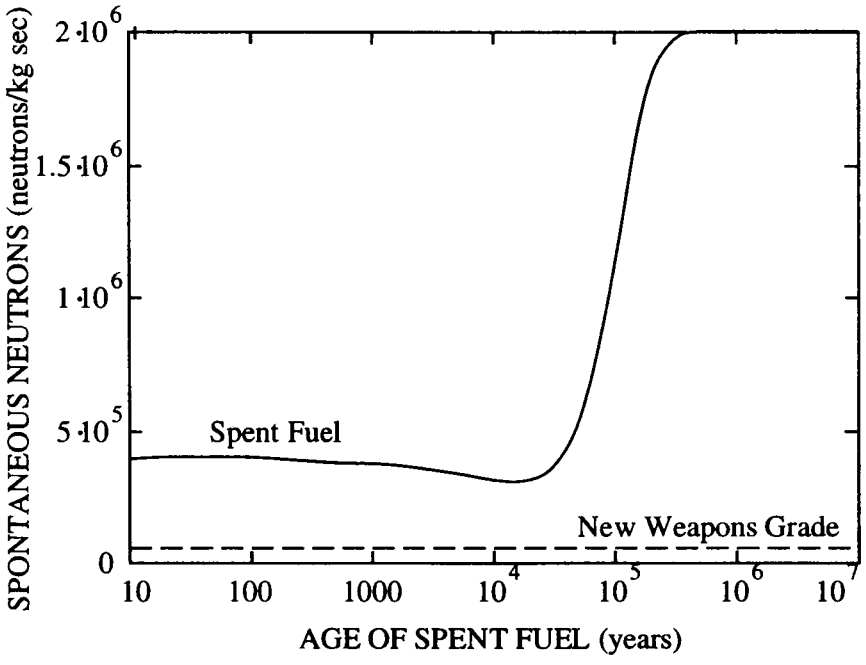

Figure 4: Spontaneous fission neutron rate from aged reactor-grade plutonium. Jump at 10^5 years occurs due to decay of Pu-239.

In plutonium separated from spent fuel, the radioactive decay of the plutonium isotopes, in particular Pu-238 (see table 5), creates an internal heat source. The accumulation of Am-241 from decay of Pu-241 gradually increases the internal heat generation, balanced by the decay of Pu-238 and the eventual decay of Am-241. For instance, the heat generation from spent fuel reprocessed at 10 years (with isotopic composition in table 4) is initially 10.5 W/kg, grows to 13.7 W/kg at 10 years, and peaks at 16.8 W/kg at 45 years. For weapons-grade plutonium the effect of Am-241 peaks at 64 years. Figure 5 shows that the heat generation is substantial for reactor-grade plutonium, but for plutonium separated after spent fuel ages the heat generation declines, eventually dropping below the value for new weapons-grade plutonium.

Table 5: Properties of selected isotopes.[34]

isotope	U-235	U-238	Pu-238	Pu-239	Pu-240	Pu-241	Pu-242	Am-241
half life (years)[a]	7.1×10^8	4.6×10^9	87.7	24,100	6,560	14.4	376,000	430
fission cross sections								
thermal (barns)	580	0	16	742	0	1,010	0	3
fast (2 MeV) (barns)	1.3	0.5	2.2	1.9	1.7	1.7	1.5	2.0
bare critical mass (kg)	52[b]	850[c]	10[d]	10[d]	40[d]	10[d]	100[d]	100[d]
spontaneous neutrons $(kg\ sec)^{-1}$	0.2	17	2.6×10^6	22	0.9×10^6	49×10^{-3}	1.7×10^6	1.2×10^3
decay heat $(W\ kg^{-1})$	5.8×10^{-5}	8.2×10^{-6}	560	1.9	6.8	4.2	0.1	114

a. By alpha-decay, except Pu-241, which is by beta-decay to Am-241.
b. Enriched to 94% U-235.
c. Enriched to 20% U-235.
d. Alpha phase, density = 19,600 kg/m^3.

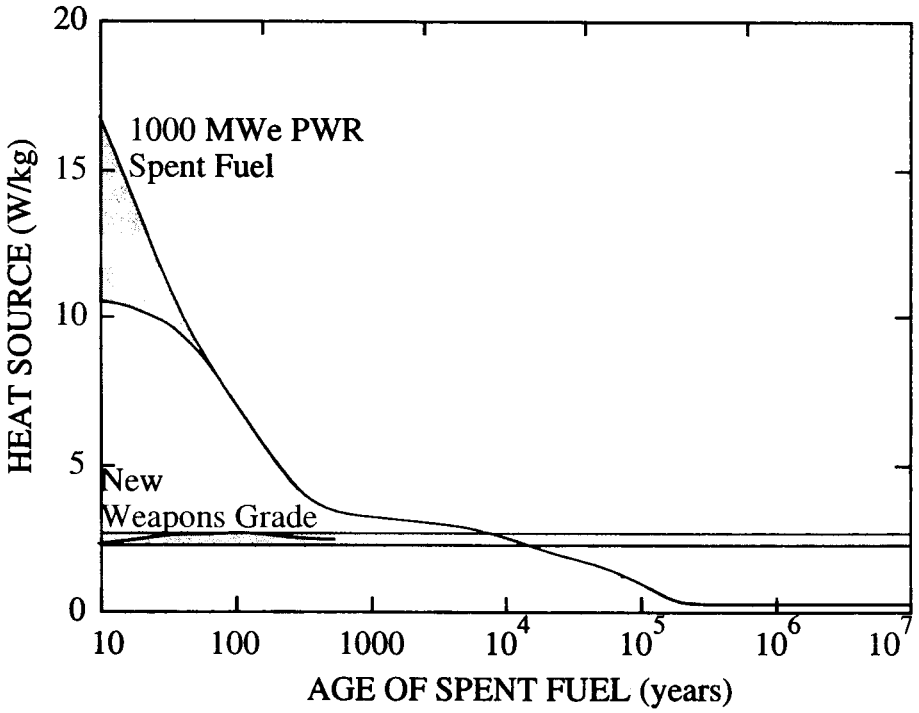

Figure 5: Heat generation rate from repository-grade plutonium.

UTILITY OF REPOSITORY—GRADE PLUTONIUM FOR NUCLEAR EXPLOSIVES

Swahn provides a detailed discussion of the utility of plutonium from old spent fuel for nuclear weapons.[35] The primary difficulties in nuclear weapon design introduced by the use of repository-, reactor- and MOX-grade plutonium arise from higher spontaneous neutron generation rates, higher heat generation rates, larger critical masses, and the increased gamma radiation from growing concentrations of Am-241 as Pu-241 decays. The problems of high heat generation rate and Am-241 gamma radiation disappear for repository-grade plutonium.

Fission weapons rely on the energy release accompanying a rapid multiplication of the neutron population which can occur after assembling a supercritical mass of fissile material. The rate that the neutron population increases is determined by the degree of supercriticality, given by the neutron multiplication factor k, the average number of neutrons released by a fission which go on to cause another fission, and Δt, the time between successive neutron generations. The multiplication factor k depends on several parameters, including the density of fissile material, the fissile material geometry, the presence of an external neutron reflecting material, n-2n and n-3n reactions, and the fission cross sections of the fissile isotopes.

The probability that a neutron will cause fission of an isotope is proportional to the fission cross section of the isotope, given in barns (1 barn = 10^{-24} cm^2) in table 5. The odd isotopes of uranium and plutonium have large fission cross sections for thermal neutrons, neutrons which have been slowed to thermal velocities by exchanging energy with moderating elements like hydrogen or carbon. However, for nuclear explosives the time required to slow down neutrons is too long to permit sufficiently rapid neutron multiplication to obtain a large energy release before the fissile material disassembles. Thus nuclear explosives are designed to assemble a sufficiently dense and large mass of fissile material to be supercritical with fast neutrons. The only isotope in table 5 with a fast neutron fission cross section too small to be useful in nuclear explosives is U-238. When enriched to 20 percent U-235, the bare sphere critical mass is 850 kg, which is considered too large to construct a nuclear explosive of practical weight.[36] All of the isotopes of plutonium have similar fission cross sections for fast neutrons, and the bare-sphere critical mass of any mixture of isotopes of plutonium is relatively small.

To employ plutonium in a nuclear explosive, chemical high explosive (HE) is typically used to rapidly implode a solid sphere or hollow spherical shell of plutonium from a subcritical to a supercritical geometry. The amount of plutonium required is less than the amount required to create a critical mass with a bare sphere, both because any materials surrounding the core can reflect neutrons back, and because higher than normal plutonium densities can be achieved. Compared to the 10-kg bare-sphere critical mass for plutonium-239 given in table 5, the fully-tamped critical mass is 4.4 kg. The Trinity device tested in 1945, often referred to as a crude design, reportedly used a 1.5 m diameter, 2300 kg sphere of high explosive.[37] Current warheads are considerably smaller than the Trinity device.

Neutrons generated by spontaneous fission or alpha reactions with light elements in the period of time τ after an imploding pit reaches a critical condition (k_c=1) but before the pit reaches the design maximum multiplication fac-

tor k_{max}, have some probability of initiating a chain reaction prematurely, before an intentional pulse of neutrons is released to initiate the chain reaction. Premature initiation reduces the yield of the nuclear explosive below the design value. The implosion reverses when sufficient energy has been released by fission to heat the core material to pressures greater than the pressures imparted by the HE driving the implosion. If a spontaneous fission occurs at the worst possible time during the implosion, just as the core reaches a critical configuration $k = 1$, the core continues to implode while the neutron population climbs. When the core pressure finally reverses the implosion, the multiplication factor k is significantly above unity. Subsequently considerable additional energy is released, and the neutron population continues to climb until the core expands to $k = 1$, then the neutron population drops as fission continues. Even with preinitiation, the energy liberated in the core material is substantially greater than would be liberated in a corresponding mass of HE.

Von Hippel and Lyman[38] provide scaling calculations which suggest that for a Trinity device design, using reactor-grade plutonium, premature initiation from spontaneous fission neutrons gives a 90 percent probability that the device yield will be less than 20 percent of design yield. However, for this relatively crude design this scaling indicates that the minimum yield is still 2.7 percent of the design yield, or about 0.5 kilotons. This "fizzle" yield is still substantial.

The probability of premature initiation decreases as the time Δt that the imploding mass spends between $k = 1$ and k_{max} is reduced. This time period depends on both the implosion velocity and the difference in outside radius Δr of the imploding pit between the $k = 1$ and k_{max} configurations. Higher implosion velocities increase the final compression of the core material, reducing Δr and further reducing Δt. Noting that critical mass scales with the inverse of density squared,[39] and that the maximum density scales very roughly with the square of implosion velocity, Δt scales with the inverse cube of velocity. Thus doubling the implosion velocity can reduce the time available for preinitiation by a factor of 8, or doubling the implosion velocity of a Trinity-type nuclear explosive would permit equally reliable yields with repository-grade plutonium (see figure 4).

The recent NAS study on weapons plutonium disposition, citing a classified study,[40] states explicitly that "with a more sophisticated design, weapons could be built with reactor-grade plutonium that would be *assured* of having higher [than fizzle] yields" (italics added). With the current knowledge that higher yields can be reliably obtained with reactor-grade plutonium, and that modern nuclear explosives are much more compact and light than the early

Trinity design, it is doubtful that any group attempting to use repository-grade plutonium would mimic the Trinity design, even though relatively detailed descriptions of the device are available.[41]

The radioactive decay of the plutonium isotopes creates an internal heat source substantially larger in reactor-grade plutonium than weapons-grade.[42] The concern with heat generation centers on the relatively low thermal conductivity of the HE surrounding the pit, so that steady-state heat removal requires a substantial temperature difference between the pit and the surrounding environment. Only 10 centimeters of HE around a reactor-grade plutonium pit could result in a long-term temperature of the core above 200°C, substantially above 100°C where HE begins to degrade and melt.[43] Technical means can be envisioned to mitigate the problem of heat removal, such as using high-conductivity metal like aluminum to create a heat bridge across the HE, [44] or installing the pit a short time before the explosive is used. For higher heat loads the heat removal system could make a nuclear explosive significantly less attractive for military applications. However, for repository-grade plutonium, heat generation rates are equal to or less than for weapons-grade plutonium, as shown in figure 5.

A final concern for handling plutonium centers on the shielding requirements for the 0.059 MeV gamma radiation emitted by Am-241. This gamma radiation builds up after plutonium is chemically separated, as 14.4-yr half-life Pu-241 decays, at substantially higher rates in reactor-grade plutonium due to higher initial Pu-241 concentrations. However, repository-grade plutonium has negligible concentrations of Pu-241 compared to weapons-grade plutonium (see table 4), so that contact gamma radiation from repository-grade plutonium would be less hazardous than for weapons-grade plutonium.

Though the major disadvantage of reactor-grade plutonium—large internal heat generation—disappears for repository-grade plutonium, it is important to note some of the potential liabilities to the use of repository-grade plutonium that arise from the substantial concentrations of even isotopes of plutonium. These liabilities could influence decisions to mine repository-grade plutonium versus producing new weapons-grade plutonium or uranium. An implosion design that provides a given implosion velocity and degree of compression will reach a lower maximum multiplication factor k_{max} with repository-grade plutonium than with an equal mass of weapons-grade plutonium due to the smaller neutron fission cross sections. Put another way, similar implosion designs will provide a somewhat lower yield using repository-grade plutonium than weapons-grade plutonium, even if preinitiation is avoided.

A second disadvantage relates to testing requirements. It is generally agreed that fission weapons can be designed to have high reliability, though uncertain yield, without testing. Only testing of the HE implosion system is

required with appropriate x-ray diagnostics to confirm that the desired compression and geometry of the core material is achieved.[45] However, for national groups reconstituting a stock of thermonuclear (fission-fusion) weapons which had originally been designed to use weapons-grade plutonium to drive the secondary fusion reaction, testing of the fission triggers could be required if repository-grade plutonium were substituted in the design. Such testing would slow down the introduction of repository-grade plutonium-based thermonuclear weapons, although national groups could conceivably conceal the tests of the fission triggers.[46] A third disadvantage with repository-grade plutonium is the probability that the isotopic composition will likely be heterogeneous between batches, varying with the degree of burnup in the spent fuel assemblies processed.

CONCLUSIONS AND RECOMMENDATIONS

Using a single, small-diameter access tunnel or shaft, plutonium can potentially be recovered from old spent fuel from a geologic repository in less than one year from start of tunneling, at rates exceeding those of large production reactors. With current repository designs, production of 700 kg/year of plutonium would require a capital investments $2.5 to $7.4 million (1992$) for a single small-diameter access tunnel and $16 to $50 million for a reprocessing facility. In contrast, a uranium mine and small fuel production, reactor and reprocessing facilities capable of producing 8 kg of plutonium per year require 3 to 5 years to construct, with a capital investment over $100 million. To attain a production rate of 100 kg/year with a dedicated mine, fuel production, reactor and reprocessing, capital costs would rise over one billion dollars.

The institutional and technological methods for insuring safeguards for spent fuel repositories over very long time periods have not yet been fully developed, and ongoing study may eventually conclude that geologic repositories provide an inadequate barrier to rapid retrieval of spent fuel. Therefore current policies should not preclude the decision of a future generation to recover and reprocess old spent fuel to reduce long-term proliferation risks. Current policies should attempt to minimize future proliferation risks of spent fuel repositories, both by minimizing the number of spent fuel repositories and by searching for the most robust, long-term safeguard methods. The following specific policy recommendations can be made.

Minimize the number of spent-fuel repositories. If current policies are followed, world-wide as many as 25 spent fuel repositories may be built. Even the smallest possible repository, containing spent fuel from a single commercial power reactor, can contain over 10,000 kg of plutonium. Because the U.S. nuclear industry is so large, increasing the capacity of the United States' planned spent fuel repository by 100 percent would allow one repository to

accommodate all the spent fuel that will be generated by all existing plants in countries which do not currently plan to reprocess spent fuel.[47] A single, international repository would also help reduce the risks of diversion of spent fuel remaining above ground as reactors are decommissioned, particularly in smaller countries which have made little progress in plans for disposal of spent fuel.

Maintain retrievablilty. Oil and natural gas will likely become scarce in the next century. No alternatives have yet been demonstrated at the scale required to replace oil and natural gas, except coal and nuclear fuels. In the course of making energy-related decisions, a future generation may decide to retrieve and reprocess old spent fuel. Alternatively, a future generation may decide that the long-term security risks of spent fuel are too large, and may develop and implement technologies to eliminate plutonium. Spent fuel repositories should be designed to remain open, with the spent fuel retrievable in an economical manner, until permanent, sustainable replacements for oil, natural gas, and coal have been implemented at full scale.

Study Alternatives to Direct Disposal. Fuel cycle alternatives that would remove most of the plutonium from high-level waste streams deserve detailed study and demonstration.[48] Further study is needed to determine if adequate technological means are available to detect future tunneling technologies, to determine whether institutional controls can be designed to function continuously over hundreds of millennia, and if institutional controls fail, to quantify the risks and potential consequences of diversion of plutonium. The risks of future plutonium diversion should be compared to the current risks and costs of alternative disposal technologies which would separate and eliminate plutonium.

NOTES AND REFERENCES

1. G. Linsley, A. Fattah, "The Interface Between Nuclear Safeguards and Radioactive Waste Disposal: Emerging issues" *IAEA Bulletin,* **36** (1994) pp. 22, state further, "For spent fuel in repositories, the IAEA safeguards department's policy is to continue safeguarding after repository closure...The acceptance of a requirement for open-ended surveillance of spent fuel in repositories raises two issues: 1) a contradiction with one of the objectives of radioactive waste management, that is not to impose a burden on future generations; and 2) the troubling aspect of making economic provisions for an activity of unknown duration and, therefore, with a cost that cannot be estimated reliably."

2. J. Swahn, Technical Peace Research Group, Institute of Physical Resource Theory, Chalmers University of Technology, Goteberg, The Long-term Nuclear Explosives Predicament: The Final Disposal of Militarily Usable Fissile Material in Nuclear Waste from Nuclear Power and the Elimination of Nuclear Weapons (1992).

3. Abstracted from "World List of Nuclear Power Plants," *Nuclear News* (September 1994) pp. 57.

4. Plutonium-239 decays by alpha emission, yielding uranium-235. In most spent fuel, this U-235 is intimately mixed with U-238, and thus would require enrichment to be suitable for weapons use. The decay of Pu-239 disposed of in a vitrified waste form

without U-238 would leave U-235 with a 0.7-billion-year half life, which could be chemically separated and used in nuclear explosives.

5. An extensive body of literature treats natural release mechanisms. For future human activities, an OECD NEA Working Group states "Disruptive human actions can be divided into those in which the barrier system is intentionally disrupted and those in which it is inadvertently disrupted. Human actions leading to the release of radioactivity and committed intentionally, rather than inadvertently, can be considered the responsibility of the society that takes these actions. These intentional actions have not been considered quantitatively in past safety assessments, whereas actions in which the disposal system is inadvertently disrupted have received consideration in most programmes." D. R. Anderson, D. A. Galson, E. S. Patera, "Assessment of Future Human Actions at Radioactive Waste Disposal Sites: An International Perspective," Fifth International Conference on High Level Radioactive Waste Management (American Society of Civil Engineers, Las Vegas, Nevada, 1994), vol. **3**, pp. 1286.

6. Linsley and Fattah, *op. cit.*

7. National Academy of Sciences, *Management and Disposition of Excess Weapons Plutonium*. (National Academy Press, Washington, DC, 1994) p. 59, and P. Baumgartner, G. R. Simmons, "Safeguarding the Disposal of Canada's Used Nuclear Fuel," Fifth International Conference on High Level Radioactive Waste Management (American Society of Civil Engineers, Las Vegas, Nevada, 1994), vol. **3**, pp. 1782.

8. C. W. Forsberg, "An Ocean Island Geological Repository — A Second-Generation Option for Disposal of Spent Nuclear Fuel and High-Level Waste," *Nuclear Technology* **101** (1993), p. 40.

9. Linsley and Fattah, *op. cit.*

10. Swahn, *op. cit.*

11. U.S. Congress, Office of Technology Assessment, "Technologies Underlying Weapons of Mass Destruction," U.S. Government Printing Office, OTA-BP-ISC-115 (1993), p. 156.

12. U.S. Congress, 1993, *op. cit.*, p. 158.

13. Metropolitan Sanitary District of Greater Chicago, 9.1 km long, 2.6m diameter tunnel, 1983, cost $15,387,000 (1983$), included concrete lining and 18 drop and access shafts (D. P. O'Conner, "Economy Version of Small Diameter Rock Boring," C. D. Mann, M. N. Keleys, Eds., Rapid Excavation and Tunneling Conference (Society of Mining Engineers, New York, 1985), vol. 2, pp. 738). The SYAR project, a 9.2 km, 3.6 m diameter tunnel, 1990, cost $43,762,203 included concrete lining of tunnel, 970m gravel surfaced roadway, portal earthwork, restoration activities, and 12 miles of 46 kV power line, P. R. Busmann, D. J. Rogers, "Rapid Construction of the SYAR Tunnel Central Utah Project," Rapid Excavation and Tunneling Conference (Society for Mining, Metallurgy, and Exploration, Seattle, Washington, 1991), p. 473.

14. W. C. Peters, *Exploration and Mining Geology*. (John Wiley and Sons, New York, 1987), p. 266.

15. P. N. Nelson, T. D. O'Rourke, R. F. Flanagan, F. H. Kulhawy, A. R. Ingraffea, US Department of Transportation, Tunnel Boring Machine Performance Study (1984), p. 2-1.

16. Oahe Dam: G. West. *Innovation and the Rise of the Tunneling Industry*. (Cambridge University Press, Cambridge, 1988) p. 254; Y. Jordal, S. Hartwig, "The IVAR Project: An Uncommon, Everyday TBM Tunnel," W.D. Wightman, D.C. McCarrys,

Eds., Rapid Excavation and Tunneling Conference (Society for Mining, Metallurgy, and Exploration, Seattle, Washington, 1991), p. 473; G.M. Davey, K. R. Dickson, I.M. Gowring, "Kelano Power Tunnel," *loc. cit.*, p. 487; Busmann and Rogers, *op. cit.*

17. Nelson et al., *op. cit.*, provide a detailed discussion of performance study on 6 TBM tunnels. H. A. Janzon, "Tunnel Boring Machine for Nuclear Waste Repository Research Project," Fifth International Conference on High Level Radioactive Waste Management (American Society of Civil Engineers, Las Vegas, Nevada, 1994), vol. 2, pp. 403 discusses optimizing TBM performance using automatic thrust control and variable frequency drives.

18. Janzon, *op. cit.*

19. Jordal and Hartwig, *op. cit.*

20. Nelson *et al.*, *op. cit.*, p. xxxi.

21. West, *op. cit.*, p. 31; Nelson *et al.*, *op. cit.*, p. 2-1.

22. United States Congress, Office of Technology Assessment, "The Containment of Underground Nuclear Explosions," U.S. Government Printing Office, OTA-ISC-414 (1989) pg. 18.

23. J. C. Rowley, in *Tunneling and Underground Transport,* F. P. Davidson, Ed. (Elsevier, New York, 1987) p. 157.

24. R. J. Robbins, in *Tunneling and Underground Transport,* F. P. Davidson, Ed. (Elsevier, New York, 1987) pp. 142.

25. D.A. Rossin, "Viewing Russian Radiation Exposure Data," *Nuclear News.* (September, 1993), p. 110.

26. N.A.S., *op. cit.*, p. 97.

27. U.S. Congress, 1993, *op. cit.*, p. 156.

28. "In particular, one significant component of the risk of theft is likely to be theft by parties who do not have the capability to process the material or fabricate it into weapons, for sale to those who do. Forms of plutonium that would be quite difficult for unsophisticated parties to remove, store, and transport — such as those emitting intense radioactivity — are likely to pose major obstacles to this form of theft, even if they would pose significantly smaller barriers to parties with the sophistication required to fashion a nuclear weapon." (N.A.S., *op. cit.*, p. 64.)

29. National Academy of Sciences, *Management and Disposition of Excess Weapons Plutonium.* (National Academy Press, Washington, DC, 1994) p. 150.

30. Abstracted from M. Benedict, T.H. Pigford, H.W. Levi, *Nuclear Chemical Engineering.* (McGraw-Hill, New York, 1981) p. 359, 370; C.M. Lederer, V.S. Shirley, Eds., *Table of Isotopes* (Wiley and Sons, New York, 1978).

31. Plutonium from dismantled weapons, disposed of by vitrification in glass, would maintain the isotopic composition and nuclear properties of weapons-grade plutonium.

32. Adapted from J. Carson Mark, "Explosive Properties of Reactor Grade Plutonium," *Science and Global Security* 4, (1993) p. 111.

33. The mass of fuel in a typical PWR is around 101,000 kg, with 193 fuel assemblies (N. E. Todreas, M. S. Kazimi, *Nuclear Systems I Thermal Hydraulic Fundamentals.* (Hemisphere, New York, 1990) p. 31). At 33,000 MWday/tonne burnup, the fuel con-

tains approximately $9.03x10^3$g/Mg plutonium (Benedict *et al.*, *op cit.*, pg. 388), giving 4.7 kg/assembly. The standard multipurpose canister now under consideration for rail transport weighs 125 tons with overpack and contains 21 PWR fuel assemblies, giving 100 kg/MPC.

34. Adapted from J. Carson Mark, *op. cit.*, A. De Volpi, *Proliferation, Plutonium and Policy/Institutional and Technological Impediments to Nuclear Weapons Propagation.* (Pergamon Press, New York, 1979); M. Benedict, T.H. Pigford, H.W. Levi, *Nuclear Chemical Engineering.* (McGraw-Hill, New York, 1981); and U.S. Congress, Office of Technology Assessment, *Nuclear Proliferation and Safeguards* (Library of Congress Catalog No. 77-600024, 1977). Mark's figure 2 provides detailed fission cross sections as a function of incident neutron energy.

35. Swahn, *op. cit.*

36. U.S. Congress, 1977, *op. cit.*, p. 143.

37. R. Rhodes, *The Making of the Atomic Bomb.* (Simon and Schuster, Inc., New York, 1986) p. 657.

38. Mark, *op. cit.*, p. 125.

39. T. Greenwood, G. W. Rathjens, J. Ruina, *Nuclear Power and Weapons Proliferation* (Adelphi Papers No. 130, The International Institute for Strategic Studies, London, 1977) p. 3.

40. N.A.S. *op. cit.*, p. 32 cite the classified report by W. G. Sutcliff, T. J. Trapp, Lawrence Livermore National Laboratory, Extraction and Utility of Reactor-Grade Plutonium for Weapons (S/RD), UCRL-LR-115542 (1994).

41. For instance, Rhoads *op. cit.* describes the fabrication and plating of the Trinity pit (p. 480), tamper geometry and installation (p. 658), HE with lower detonation velocities cast and machined to form lenses generate a spherical detonation wave using initiation at discrete points (p. 575), the use of high-speed x-ray diagnostics to study pit implosion rates and symmetry (p. 573), the use of a neutron initiator located at the center of the pit and activated by the arrival of the compression shock wave (p. 578), and gives a photograph of an early version of the bomb showing the HE configuration (figure 78).

42. Note that the difficulty of internal heat generation is further increased because a larger mass of reactor-grade plutonium is required due to the smaller fast neutron cross sections of Pu-240 and Pu-242. For example, a 4 kg weapons-grade plutonium pit (2.5W/kg) would generate around 10 W, while an 8 kg reactor-grade plutonium pit (10.5-16.8W/kg) would generate between 85 and 135 W.

43. For a 10 cm inside diameter, 30 cm outside diameter 0.4 W/m°C HE shell the temperature difference is 2.6 °C/W, or between 225 and 360 °C for reactor grade plutonium. Heat transfer to an ultimate heat sink would require additional temperature drop, for instance, natural convection to air from a 30 cm diameter sphere with an internal heat source of 85 W requires a temperature difference of 70°C.

44. Mark, *op. cit.*, p. 122.

45. U.S. Congress, 1977, *op. cit.*, p. 140; W. Van Cleave, in *Nuclear Proliferation: Phase II* R. M. Lawrence, J. Larus, Eds. (University Press of Kansas, Lawrence, Kansas, 1974) p. 53.

46. The Department of Energy declassified a large quantity of previously secret information on nuclear weapons in 1993, including data on 252 secret nuclear tests. "One point of concern is that the 18 unannounced tests that were made during the Reagan

and Bush Administrations do not seem to have registered on the sensitive seismological monitoring equipment then in place." *Programme for Promoting Nuclear Nonproliferation Newsbrief.* (Mountbatten Centre for International Studies, University of Southampton, 4th Quarter, 1993), p. 9.

47. This assumes roughly equivalent plant operating lives and capacity factors for the 99,255 MWe capacity in the 24 countries in table 1 which do not currently plan to reprocess spent fuel (excluding the U.S., with 99,510 MWe capacity). This also assumes that the current U.S. law which limits the capacity of the first repository is amended, and that the political difficulties in accepting foreign spent-fuel are overcome.

48. Current reprocessing facilities typically send 0.1 percent of the plutonium to the waste stream, typically to be vitrified in glass with the separated fission products.