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The Proliferation Risks of Plutonium Mines

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A number of observers have recently pointed to the risk that spent fuel repositories could eventually become relatively low-cost sources of fissile material for nuclear weapons—that is, "plutonium mines." However, the range of conditions under which repository mining will look attractive compared to other means of acquiring plutonium is extremely narrow.

At a minimum, mining significant quantities of plutonium will take several months and will be readily detectable if reasonable safeguards are applied at the repository sites. In any case, if spent fuel is not put into a repository, and is instead left in retrievable storage and eventually reprocessed, with the plutonium and other actinides in the spent fuel separated and transmuted, that course will itself generate significant risks of plutonium diversion or theft.

INTRODUCTION

Mined geologic repositories are the planned destinations of a large fraction of the world's commercial spent nuclear fuel and at least some of the plutonium recovered from retired nuclear warheads. The public debate on this issue has largely focused on the environmental ramifications of geologic disposal. However, there are nuclear non-proliferation issues involved as well. A number of observers have recently called attention to the risk that repositories could eventually become "plutonium mines": relatively low-cost sources of fissile material for nuclear weapons.[1] The International Atomic Energy Agency (IAEA) acknowledges this possibility, and is expected to require that safeguards be maintained on spent fuel repositories in perpetuity.

However, some analysts believe that repositories cannot be reliably safeguarded in the long term, and argue that direct geologic disposal of plutonium-containing materials is unwise. Instead, they advocate keeping these materials in monitored retrievable storage, while pursuing development of speculative technological approaches capable of completely eliminating plutonium stockpiles through nuclear fission.[2]

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An analysis of the risks of plutonium mining suggests that long-term safeguards on repositories can be at least as effective and reliable as those that will be necessary in any case for other nuclear facilities. In contrast, schemes to eliminate plutonium are associated with greater proliferation risks and would require much more extensive and costly safeguards.

Although the possibility that a repository may be mined one day for plutonium cannot be entirely precluded, this is not a reason for abandoning direct disposal altogether. Current (and steadily growing) world stockpiles of plutonium will pose proliferation risks long into the future, whether they remain in above-ground storage or are buried underground. However, these risks can be minimized by following the latter course. Whether the residual risk is low enough so that it can be justified by the benefits of continued production of nuclear power is a question that society needs to address.

THE COST OF PLUTONIUM MINING

Spent power reactor fuel is highly radioactive and contains a significant concentration (approximately one percent by weight) of long-lived, weapons-usable plutonium isotopes. The presence of gamma-emitting fission products in spent fuel, such as cesium-137, necessitates that spent fuel must be isolated from humans by thick shielding and can be handled only by remote control. This property of spent fuel is known as "self-protection."

A number of nations, including the U.S., Canada and Sweden, plan to directly dispose of spent fuel in mined geologic repositories. Others, such as France and the United Kingdom, reprocess their spent fuel, chemically separating plutonium from uranium and fission products. Purified plutonium, which can be directly handled, is much more vulnerable to diversion and theft than the original spent fuel, and more stringent safeguards and security measures are required to protect it.

In a repository, spent fuel will be maintained in a retrievable state for about a century after emplacement. After this period, access tunnels and ventilation shafts will be backfilled and sealed, and support facilities will be dismantled. After closure, recovery of the emplaced material, although still possible, would be more difficult, time-consuming and expensive.

The concern that repositories will become "plutonium mines" over time stems principally from two factors. First, the time and effort necessary to recover spent fuel from a repository, although significant, may compare favorably with other ways that a nation may acquire spent fuel, the "ore" from which plutonium can be extracted. Second, as a result of the relatively short

(30-year) half-life of cesium-137, the spent fuel radiation barrier will decay to a low level within a few centuries after discharge from a reactor, so that older spent fuel can be handled and reprocessed with lower risk of injury.

Approaches for retrieving spent fuel from a sealed repository were discussed in a study done for the International Fuel Cycle Evaluation (INFCE) in 1979.[3] In general, these would entail on-site assembly of equipment, construction of new surface support and handling facilities, drilling of new access tunnels and use of appropriate techniques to safely excavate the spent fuel and return it to the surface. The actual cost of the effort would depend on the desired plutonium production rate and specific details of the repository design. In this article, a baseline annual production of 100 kg of plutonium, enough for ten to twenty nuclear weapons, is assumed.

The INFCE study identified two repository mining strategies. The first is an attempt to locate a few spent fuel packages by drilling small-diameter shafts into the repository. The second, which INFCE judged to be more credible, if somewhat more expensive, is a reconstruction of the original underground repository. Indeed, for a nation seeking plutonium for a large weapons program, the latter approach appears preferable for establishing a sustained production source.

Reconstruction of the repository would entail a substantial mining effort, comparable to that of the initial construction. Today, large underground mining operations typically require capital investments of hundreds of millions of dollars[4] and development times of 2–5 years before production can begin. For instance, the investment cost for developing a geologic repository in Sweden capable of accepting about 280 tonnes of spent fuel (containing about 2.8 tonnes of plutonium) annually was estimated to be about $1 billion.[5] For a plutonium throughput of 100 kg per year, this scales to a cost of over $100 million.

Recently it has been suggested that due to advances in the technology of tunnel boring machines (TBMs), the first scenario described by INFCE is more plausible today, and a substantial quantity of plutonium could be recovered from a repository in under a few months, for a cost of less than $10 million, simply by drilling a small-diameter tunnel.[6] For example, for the current design of the proposed U.S. repository at Yucca Mountain, Nevada, recovery of a single disposal package would net about 10 tonnes of spent fuel, containing 100 kg of plutonium.

However, this estimate does not account for the fact that the driller would, in all likelihood, have to dig several tunnels to intercept a spent fuel package, as the INFCE study pointed out. For instance, at Yucca Mountain, about 10,000 packages would be distributed in a single layer over an area of 500 hectares.[7] For this configuration, the probability of intercepting a package with a 3.6-meter diameter tunnel perpendicular to the repository plane is only 2 percent. It would not be feasible to search the repository level using a TBM, so that if a package were not intercepted by the original tunnel, the driller would have little choice but to start over. Thus, on average 50 tunnels would have to be drilled to locate a single package.

For a typical tunneling cost of $5,000 per meter, a single 1-kilometer long, 3.6-m diameter tunnel would cost $5 million; fifty such tunnels would cost $250 million. At an average advance rate of 30 m per day, each tunnel would take at least a month to complete; since tunnelling operations usually involve a "learning curve" of 5–10 weeks to reach the average rate, and require two to twelve weeks for preparation, an estimate of three to six months is more realistic. If the tunnels were drilled in series, it could take several years before the first canister were located. Drilling of tunnels in parallel could accelerate the process, but would require simultaneous acquisition and use of many TBMs, substantially increasing the cost, personnel requirements and observability of the operation. Thus even with state-of-the art TBMs, this approach would not be decisively more attractive than redevelopment of the mine.

THE MATERIAL PRODUCTION STANDARD

Whether a proliferating nation would choose to mine a repository depends on how the undertaking compares to other available ways to acquire plutonium or highly enriched uranium. A benchmark for evaluating the proliferation resistance of repository designs is the "material production standard": *plans for long-term management of nuclear wastes with fissile content should be designed so that a proliferant group would find it essentially as difficult to recover the fissile material as to obtain it from the least accessible alternative source (e.g. new production).*[8] If attention is given to this issue, it should not be difficult to design repositories that meet this standard with reasonable assurance.

The material production standard is a conservative one, because it is likely that in the future there will be easier ways to obtain fissile material than new production. In countries with operating nuclear reactors, there will always be a ready supply of spent fuel available, either in interim storage or in reactor cores. Mining a closed repository would be much less attractive than appropriating spent fuel from the existing fuel cycle. For countries operating reprocessing plants or possessing stockpiles of separated plutonium, the choice would be even more apparent.

If nuclear power and nuclear weapons were eventually phased out, different considerations would apply. In a "nuclear-free world," mining a repository could be an attractive route to obtaining spent fuel, since the only alternative would be producing new material from scratch. This route, which involves mining uranium, processing it into fuel, and constructing and operating plutonium production reactors, is certainly expensive and time-consuming.

According to an estimate by the U.S. Office of Technology Assessment, a program capable of producing spent fuel containing 100 kg of plutonium per year, based on a 400 megawatt-thermal reactor, would require a capital investment between $350 million and $800 million, and a construction time of 5–7 years.[9] However, through a crash effort, the lead time to develop a plutonium production capacity of 100 kg per year could be reduced to as little as two years, as was the case in the Manhattan Project,[10] but at greater cost ($2 billion in 1992 dollars).

The effort necessary to produce highly enriched uranium (HEU), another weapons-usable material, should also be considered. One estimate for a centrifuge facility capable of producing 300 kg of HEU per year (approximately equivalent to 100 kg of plutonium for weapons purposes) is between $100 and $500 million. While these costs appear similar to those of plutonium production, HEU production costs are more sensitive to technological advancement and can be expected to significantly decrease in the future.

Once a proliferant group obtained spent fuel, either by repository mining or by new production, it would need a chemical separations plant to extract and refine the plutonium. The cost of this facility would depend on its throughput and the degree of radiation protection it provides.

Because of its relatively low self-protection, spent fuel that has aged for several hundred years does not have to be isolated behind heavy shielding and could be processed in a contact-handled ("glovebox") facility, rather than in a remotely operated plant. It has been suggested that this would provide a strong incentive to mine old spent fuel from a repository rather than produce new spent fuel.

However, this advantage is not decisive. If weak radiation protection standards were applied, the cost of building a rudimentary plant to separate 100 kg of plutonium annually from 150-day-old production reactor fuel could be as low as $50 to $150 million, only a fraction of the cost of acquiring the spent fuel. Estimates of the lead time necessary to construct a small separations plant range from six months to four years.

Moreover, even after cesium-137 has decayed away, workers engaged in the mining and processing of old spent fuel will still require protection from the significant radiological hazards of the longer-lived radionuclides that remain, such as penetrating neutron radiation, internal exposure to alpha-particles and the potential for criticality accidents.

In a nuclear-free world, whether repository mining or new production is employed, establishing a plutonium production capacity of 100 kg per year is likely to require a capital investment on the order of a few hundred million dollars, and a development time of at least two years, assuming current technological capabilities. Future technological developments may facilitate either or both routes.

For higher production rates, comparable to those achieved during the height of the Cold War (several tonnes of plutonium annually), repository mining might provide a more efficient route than construction of the requisite number of production reactors. This imbalance could be corrected by modifying certain repository design parameters, such as waste package spacing or repository depth, to increase the cost of spent fuel recovery. However, these changes would also tend to make disposal more expensive, and it is unclear whether the corresponding risk reduction would be worth the cost.

THE ROLE OF LONG-TERM SAFEGUARDS

According to IAEA guidelines, safeguards on fissile material cannot be terminated unless the IAEA determines that the material is no longer usable for any nuclear activities or has become "practicably irrecoverable." In 1988, an IAEA Advisory Group found that spent fuel does not qualify as being "practicably irrecoverable" at any point, even after closure of a repository, and recommended that the IAEA should not terminate safeguards on spent fuel.[11] The IAEA is expected to require that safeguards must be maintained indefinitely on spent fuel repositories, a determination that appears warranted. Mining a repository would not be a quick or quiet operation, but it could be done. However, safeguards to effectively deter mining need not involve expensive and intrusive inspections, but could focus on containment and surveillance (C/S) procedures, including remote monitoring by satellites.

A requirement that repositories be safeguarded in perpetuity may seem unrealistic and unusually burdensome to future generations, but it is a reasonable demand. If nuclear power continues to operate, repositories will be but one of many types of facilities that will have to be safeguarded. If nuclear power fades away, in addition to safeguarding repositories, the international community will also have to verify that there is no clandestine production of weapons-usable material. Indeed, the task of monitoring a number of known repository sites would be far more straightforward than the task of verifying the absence of clandestine activities, which could take place at virtually any location.

Geologic disposal of spent fuel will actually reduce the future safeguards burden. The vulnerability of spent fuel to diversion or theft by sub-national groups will increase as the radiation barrier decreases. If spent fuel is maintained in retrievable storage for an indefinite period, safeguards and security measures at the storage facility will have to be tightened over time. On the other hand, emplacement of aging spent fuel in a sealed repository would provide a geologic barrier to compensate for the diminishing radiation barrier.

With respect to current safeguards practice, these two barriers are essentially equivalent. The IAEA, in setting its goals for timely detection of diversion of fissile material, assumes that plutonium in irradiated fuel can be converted to finished nuclear weapons components in 1–3 months; for plutonium in unirradiated mixtures (aged spent fuel would fall into this category) the corresponding period is assumed to be 1–3 weeks.[12] Even under the most optimistic assumptions about TBM performance, it is highly unlikely that a divertor could remove aged spent fuel from a sealed repository and convert it to finished components in less than a month. Therefore, the IAEA timely detection goal for safeguarding irradiated fuel should equally well apply to safeguarding a sealed repository.

PLUTONIUM: BURN IT OR BURY IT?

Glenn Seaborg is typical of those who invoke the "plutonium mine" argument to justify extraction of plutonium from spent fuel. At a 1995 meeting of the American Nuclear Society (ANS) in San Francisco, he attacked "the widespread assumption that by leaving spent fuel intact, proliferation risks are avoided," arguing that "those who advocate the disposal of spent fuel...do not necessarily occupy the high ground in the non-proliferation debate."[13]

If one does not put spent fuel into a repository, then what? According to a report by an ANS panel chaired by Seaborg, "...over the long term,... the proliferation risk of plutonium can be wholly eliminated only through its consumption as a nuclear fuel."[14] Indeed, if one disregards exotic alternatives, such as shooting plutonium into the sun, the main alternative to geologic burial is an ambitious procedure known as "separations and transmutation" (S&T). S&T aims to eliminate long-lived radionuclides (including plutonium, higher actinides and some fission products) by extracting them from spent fuel and fissioning or transmuting them in a nuclear reactor or an accelerator-driven spallation source.[15]

Implementation of S&T would involve reprocessing and recycling on a truly grand scale. For example, consider what would be involved in treating the U.S. spent fuel inventory, which is now about 35,000 tonnes and is increasing by approximately 2,000 tonnes per year. Reprocessing this amount would require four plants each the size of the THORP reprocessing plant in Great Britain, assuming a 40-year plant lifetime.

Since there are about 10 kg of transuranics (plutonium, neptunium and higher actinides) per tonne of light-water reactor (LWR) spent fuel, the S&T system would have to process a backlog of 350 tonnes of transuranics, plus an additional 20 tonnes per year. Used as an actinide burner, a 1,400 megawatt-electric liquid metal fast neutron reactor with a conversion ratio of 0.62 could absorb about 30 tonnes of transuranics in its forty-year lifetime. Assuming that U.S. LWR capacity remains constant over 40 years, a S&T effort would require nearly 40 fast reactors. Because the transuranic inventories in the fast reactor spent fuel will still be substantial, this fuel also would have to be reprocessed and the recovered transuranics fed back into the process. Depending on how completely one wishes to destroy the transuranics, S&T could take from hundreds to thousands of years.

In addition to reprocessing plants and reactors, the S&T system would include an array of additional facilities for plutonium fuel fabrication, scrap recovery, waste processing and storage, as well as numerous transport links. This unprecedented scale of activity would be extremely difficult and expensive to safeguard. Even if technologies can be devised so that the plutonium nominally stays mixed with fission products throughout the entire fuel cycle, it would always be possible to re-configure the process to purify plutonium.

Therefore, safeguards would have to be maintained in perpetuity on a S&T system, just as they would on spent fuel repositories. Moreover, the burden would be much greater for S&T, with respect to both the number of facilities and the type of safeguards involved. Safeguards on bulk-handling facilities, such as reprocessing plants, are based on material accountancy methods that are intrinsically less reliable and more difficult to apply than the C/S procedures needed for repository safeguards. Even if the long-term risks of plutonium mining in a repository were significantly reduced through S&T, this advantage would be overwhelmed by the near- and medium-term proliferation and environmental risks of reprocessing and recycling.

CONCLUSIONS

On balance, the range of conditions under which repository mining will look attractive compared to other means of acquiring plutonium is extremely narrow.

In countries with working nuclear fuel cycles, mining a repository will be less attractive than more direct ways to obtain weapons-usable material. In a nuclear-free world, mining very large quantities of plutonium from a repository might be quicker and cheaper than the production route, although given uncertainties in technological development it is hard to make definitive comparisons. At a minimum, mining significant quantities of plutonium will take several months and will be readily detectable if reasonable safeguards are applied at the repository sites. In any case, if spent fuel is not put into a repository, and is instead left in retrievable storage and eventually processed in a S&T program, that course will itself generate significant risks of plutonium diversion or theft.

For these reasons, recent suggestions to scale back efforts to develop a geologic repository in the U.S. are regrettable, for they could delay for decades the movement of spent fuel out of retrievable storage in the U.S. and abroad. Geologic disposal may not be the ideal solution of the nuclear waste problem, but it is the least risky option available now for the backlog of spent fuel and plutonium the world has already produced.

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