VIEWPOINT: ALTERNATIVE APPROACHES TO RUSSIAN PLUTONIUM DISPOSITION

by Kory W. Budlong Sylvester

As a result of arms reduction treaties made possible by the decline and end of the Cold War, the United States and Russia have been dismantling thousands of nuclear weapons. While this is valuable from an arms control perspective, it has created large quantities of excess plutonium in both countries. This material, unless it is stored or disposed of securely, creates the possibility for theft by potential proliferants.

In a September 1998 Joint Statement of Principles, the US and Russian governments agreed to "remove by stages approximately 50 metric tons [MT] of plutonium from their nuclear weapons programs, and to convert this material so that it can never be used in nuclear weapons."[1] As part of its Fissile Material Disposition Program, the United States has decided to process its surplus plutonium into a form "as unattractive and inaccessible for retrieval and weapons use as the residual plutonium in the spent fuel from commercial reactors."[2] This disposition criterion has been termed the Spent Fuel Standard (SFS).

Russia has endorsed the idea of irradiating surplus plutonium to produce spent fuel because it is intent on extracting the energy value of the material.[3] However, it lacks the necessary infrastructure to do so. US funds have recently been made available to support Russian disposition activities,[4] but US support is likely to be limited and vulnerable to political opposition if it is seen as supporting the development of a plutonium fuel cycle.[5] Official US policy does not support the development of such a cycle because of the proliferation risks associated with the production and handling of large quantities of separated plutonium.[6]

As fabricating the excess plutonium into fuel in Russia would take decades even with assured financial backing, programmatic delays are likely to be significant. Under these conditions, alternate disposition options that could be implemented in a more timely fashion should be considered. This viewpoint proposes two alternative approaches to Russian plutonium disposition that satisfy Russian fuel-value concerns while effectively meeting nonproliferation objectives.

Producing a secure plutonium host form that does not preclude the use of as fuel is one alternative. Virtually all the security benefits attainable by material processing techniques can be obtained by immobilizing plutonium in large-unit-size/mass monoliths without a radiation barrier. Such a form could be readily verified and safeguarded, requiring industrial equipment for removal. Russia would be allowed to extract the plutonium at a future date for use as fuel if it saw fit. Eliminating contentious fuel-cycle investments may also clear the way for greater US financial support. Finally, if proven feasible, the encapsulation of remote tracking devices in the monoliths would further improve safeguarding capability.

The proposed plutonium storage form would not appear to meet the SFS because it would not expose a potential thief to high doses of radiation—a deterrent called a radiation barrier. However, the marginal benefit of a radiation barrier (primarily its ability to incapacitate a thief during a diversion attempt) is limited to a period of several decades following the removal of plutonium from a nuclear reactor. Because fabricating and irradiating a significant amount of Russian plutonium is likely to take decades, the ability to process plutonium more quickly may alone make the proposed approach a more effective one. If the proposed tracking devices prove effective, a safeguarding capability beyond what is provided by the SFS would be attained.

A second alternative would be to reduce the opportunity for theft by removing plutonium from Russia for processing in another country. To permit this, the United

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States would compensate Russia for the fuel value of its plutonium. A market-based method for pricing plutonium is proposed, wherein surplus plutonium is valued in terms of its ability to provide access to nuclear fuel at a fixed price at a future date. This position can be replicated in the uranium market and priced using derivative theory. Russian plutonium could then be purchased and burned in European reactors or disposed of in the United States. The European approach would greatly speed disposition because a large plutonium processing infrastructure is already in operation.

While considering final plutonium disposition decisions of the type described above, the United States and Russia should agree to process their surplus pits into non-weapon forms. A plutonium pit is the core element of a nuclear weapon. Processing pits out of weapon form would ease barriers to verification and safeguarding by eliminating geometric design information, while reducing the desirability of the plutonium to certain proliferators by preventing direct reinsertion in a weapon. These benefits are meaningful and can be obtained independently of decisions regarding further processing.

The proposed strategy attempts to meet nonproliferation objectives by recognizing technical limitations and satisfying political constraints. The reasoning used to develop the strategy is outlined in the sections that follow. A brief background on fissile-material disposition is given to further describe current challenges. The underlying factors contributing to the proliferation risk from surplus plutonium are then identified. An assessment is made of the effectiveness of physical alteration (e.g., isotopic, chemical, etc.) in reducing the attractiveness of the material and decreasing a proliferator's ability to divert it. Based on this assessment, a strategy for Russian disposition is proposed, and conclusions are discussed.

BACKGROUND

The disposition of surplus plutonium in both Russia and the United States presents a major challenge. The United States has declared 52.2 MT of weapons- and reactor-grade plutonium excess to its security needs.[7] While a similar Russian declaration has not been made, plutonium available for disposition in Russia will be at least this much and could be several times greater.[8]

The larger quantities of surplus highly enriched uranium from weapons have proven far more manageable—both technically and politically. The United States has decided to blend down its highly enriched uranium (HEU) to low-enriched uranium (LEU) for use in commercial reactors. The Russian government has moved aggressively to commercialize its HEU, agreeing to sell 500 MT of HEU to a US company over a twenty-year period.

Unfortunately, timely plutonium processing has suffered from two barriers: there is no denatured (non-explosive-usable) form and no market incentive to process the material. Blending HEU down is a relatively easy and effective means of eliminating its weapons usability. However, virtually any isotopic mixture of plutonium can be made into a nuclear explosive.[9]

In recognition of this physical reality, the Spent Fuel Standard was adopted. As recommended by the US National Academy of Sciences, both Russia and the United States have decided that their surplus plutonium should be processed into a form that makes it as inaccessible and unattractive as the plutonium in spent fuel. It was noted that going beyond the Standard would not be justified unless the same treatment was performed on the much larger stocks of plutonium presently found in spent fuel.

No measurable parameters were established to determine compliance with the Standard. However, both burning the plutonium in reactors (the mixed-oxide fuel or MOX option) and commingling the plutonium with the radioactive waste it was originally extracted from (the immobilization option) have been judged as meeting the SFS by the Department of Energy. The United States is pursuing both options in parallel in its “dual track” approach.

Meeting the Standard will be difficult as neither country has the required facilities and their construction will cost hundreds of millions if not billions of dollars. Moreover, unlike commercializing HEU, plutonium processing will not produce a profit. With neither means nor financial motivation there is little reason to believe that plutonium disposition will proceed with urgency.

The expense of plutonium disposition could certainly be justified on a security basis alone. Due to national economic troubles, however, Russian finances are simply not available for plutonium processing. The United States is reluctant to fund Russian disposition efforts, particularly if funds are used to support the development of a plutonium fuel cycle, something the United

States as a matter of policy does not encourage.[10]

While the immobilization option may have a better chance of obtaining US financial support, Russia has firmly rejected it. Russia contends that the high energy content of plutonium cannot and should not be ignored. Disposing of this resource is therefore illogical and unacceptable, in their view.

This situation has led to stagnation. Russia appears content to store its plutonium until conditions favor its use in reactors or the disposition effort is subsidized internationally. In the meantime, the turmoil in Russian political and economic affairs creates a risk that the plutonium could be stolen. During Senate testimony in 1996, John Deutch, then director of the Central Intelligence Agency, described four confirmed thefts of weapons-usable material. This included thefts of six grams of plutonium, a single gram of HEU, approximately 500 grams of a plutonium/uranium mixture, and most significant, a case involving nearly 3 kg of HEU in December 1994.[11] These incidents increase the pressure to either process the plutonium into a more intrinsically secure storage form or transfer it to a more stable environment.

Given the implementation hurdles, a reassessment of nonproliferation objectives and Russian plutonium disposition options appears warranted. The following section proposes a measure of proliferation risk, by identifying two factors that contribute to the risk of theft or diversion, and discusses how material processing affects each one. This information is then used to generate an effective disposition strategy that would produce a secure plutonium storage form without requiring US investments in a Russian plutonium fuel cycle.

PROLIFERATION RISK

In order to reduce proliferation risk, we need a detailed understanding of what is meant by risk. In this analysis, proliferation risk is taken to depend on two factors: desire and ability. The greater the motivation and the ability of a group to divert fissile material if given the opportunity, the greater the perceived risk.

From the perspective of a proliferator, surplus plutonium in a given storage form represents:

- something I want to some degree (defined by my ability to use it and alternate sources of the fissile material); and
- something I have some prospect of successfully obtaining (defined by the presence or absence of safeguards, security, ease of handling, tracking potential, etc.).

Both desire for the plutonium and ability to obtain the material are directly affected by the physical characteristics of the plutonium host form. The objectives of as well as the resources and expertise available to a proliferator will determine the relative impact of any physical modification of the plutonium by the host state (i.e., the owner of the plutonium and storage facility, either the United States or Russia).

The ability to obtain plutonium is further constrained by the presence of safeguards, through the application of material control and accounting as well as physical protection procedures. Material form can impact both the application and the expected effectiveness of safeguards.

Both desire and the ability to divert are needed for proliferation risk to exist; however, their relative importance is unknown. Nonetheless, a successful disposition strategy should (where possible) make the plutonium less desirable and more difficult to divert, and be implemented such that opportunities for diversion are minimized. The effect of processing on the risk of diversion by various proliferators will be discussed in the following section.[12]

Desirability

Desirability involves the proliferator's regard for the material, assuming it could be successfully diverted. The material processing of surplus weapons-grade plutonium (WGPu) would do relatively little to reduce the ultimate desirability of the material to a subnational proliferator, but could impact a host state under certain conditions. Disposition processing can degrade the utility of the plutonium or make alternate sources more attractive, but the impact will be limited.

The first step in any disposition program will be to extract the plutonium from the pit. Pit disassembly and conversion (converting the extracted plutonium into an oxide powder) makes it impossible to reinsert the plutonium into a weapon without remachining. A dry separation process, termed the Advanced Recovery and Integrated Extraction System (ARIES), has been developed for this purpose. In ARIES, the pit is bisected and the plutonium extracted using a hydride/dehydride process. The plutonium is collected in a crucible and, if so desired, converted to an oxide product.

For a host state, any plutonium that is not in pit form possesses no military value in a use-or-lose combat scenario. ARIES processing would also demonstrate commitment to treaty obligations because swift reversal would be impossible as long as only limited pit fabrication capacity exists.

Another benefit of pit processing would stem from the elimination of important design information. This could make the plutonium less attractive to a non-nuclear weapon state or a subnational group, because they are likely to face design challenges. Reduced confidence in the production of a weapon as well as the expected yield may dissuade certain less-skilled proliferators from attempting a theft.

Altering the isotopic makeup of the plutonium might affect desirability for a host state. Isotopic dilution (e.g., from exposing the WGPu to neutrons in a reactor) may render the material useless for service in the host nation's existing weapons infrastructure. While new weapons could be designed for low-grade plutonium, in the current nuclear test ban environment that may be unacceptable, forcing new material to be produced. However, only nations that have refined requirements for plutonium and possess alternate sources of fissile materials would be affected by isotopic degradation. Non-host states, even with limited technical skill, can produce a dependable (albeit low-yield) design that utilizes low-grade plutonium.[13] As they cannot pick and choose their fissile material and would likely be satisfied with one or two explosives of uncertain yield, the isotopics of the plutonium would not affect their desire in a meaningful way.

The most additional processing can do to reduce attractiveness is to force a proliferator to perform plutonium recovery and purification operations. This would be achieved by chemically combining plutonium with various other elements in a host form—a so-called chemical barrier to proliferation. If some of the added elements are radioactive, a radiation barrier would also be present. The radiation could force the construction of a large, remotely operated facility for plutonium recovery. However, this is true only if a large quantity of plutonium were stolen and a high extraction rate were desired. For a case where only a few weapons are needed, small batch operations could reduce radiation exposures, and crude separations capable of reducing the radiation dose rate by several orders of magnitude could be employed. If a proliferator is willing to accept clumsy and slow laboratory-scale reprocessing, the addition of a radiation barrier will not dramatically reduce the attractiveness of the material.

A scenario where the host state diverts the plutonium in order to reconstitute its arsenal is the only case where large quantities of plutonium would be involved. Even then, the combination of an operational reprocessing facility and concerns over criticality safety would quite likely result in a "clean" plutonium matrix (one that lacked other radioactive elements) being processed in the remote facility. In this situation, a clean host form could be viewed as equivalent to radioactive spent fuel because the same processing facility would be used.

Ability

The other component of proliferation risk is the proliferator's estimated and actual ability to successfully transfer the plutonium offsite. Each host state will presumably place its dispositioned plutonium in a storage facility for monitoring. The material form of the plutonium can affect the ease of safeguarding and/or off-site removal, and can dramatically decrease the proliferator's expectations for success, thereby deterring an attempt.

Processing the plutonium into a more easily monitored and safeguarded form would reduce the prospects of a successful theft because security forces could be notified immediately. Multilateral safeguarding would have some deterrent effect on the host state because the international community would be alerted of any removal. Safeguarding the material in an open manner could also deter proliferation attempts by removing ambiguity regarding the security of the material. ARIES-type processing would increase security by eliminating classified design information, thereby making it more likely that host states would accept multilateral safeguarding.[14]

Processing the plutonium into an unclassified form would also simplify the direct verification of plutonium storage (i.e., the confirmation of declared plutonium locations and concentrations via measurements performed on the host form). For perhaps unrelated political reasons, inspectors may periodically be denied access to storage facilities. Being able to independently verify declarations under such circumstances would be desirable.

Beyond pit processing, the most effective means for reducing diversion ability appears to be increasing the size and mass of storage units to hamper on-site manipulation and off-site transport. This can be achieved by fabricating the plutonium into large glass or ceramic monoliths that require industrial-size equipment to be moved. Some have questioned this benefit. The DOE's Proliferation Vulnerability Red Team Report cautions: "In all cases, it is estimated that intrinsic resistance to theft could be overcome in 15 to 30 minutes by one heavy lift helicopter and a few people on the ground."[15] Nonetheless, relative to small objects, such a monolith would be much easier to safeguard and clearly raises a significant barrier to a successful theft.

The addition of radioactive fission products could provide an effective barrier but appears to provide little functional benefit beyond that produced by a large-unit-size/mass matrix. The National Academy of Sciences notes that a radiation barrier would reduce a proliferator's chances for a successful theft by forcing remote handling of the plutonium-loaded matrix.[16] When the plutonium has been fabricated into sufficiently large forms, however, proliferators face the burden of using large equipment for on-site manipulation regardless of additional radionuclides. Such heavy-lifting equipment could be fitted with crude shielding rather easily. The marginal benefit due to the presence of radiation would appear to be small.

Setting aside the possibility of shielding, a radiation barrier could incapacitate a thief during a theft attempt if the radiation level was sufficiently high. For the MOX option, the radiation barrier could be effective for a period of several decades after irradiation. While potentially effective, adding the radiation barrier could take several decades due to insufficient fuel fabrication and reactor capacity. The timing of the benefits, and the risks associated with leaving the plutonium in pit form, should be carefully weighed when considering the role of a radiation barrier in Russian disposition.

A simplified example allows the radiation barrier issue to be explored in more detail. Assume a whole body dose upwards of 500 rem (a "rem" is a measure of radiation absorption and its impact on the human body) is needed to provide a measure of confidence that a person would be incapacitated within roughly half an hour, a reasonable period of time for a successful theft.[17] Further assume that the final plutonium storage form delivers a dose rate of 1000 rem/hr at one meter from the surface (comparable to 10-year-old spent fuel). If a thief were at an average distance of one meter from the material for 30 minutes, she or he would have somewhat less than 30 minutes before radiation effects would be expected to appear. Assuming these effects would manifest themselves in an inability to function physically, and she or he had not yet transferred the plutonium off-site, the radiation would have served as an effective barrier.

This hypothetical case illustrates the complexity and the limits of the radiation barrier. There are numerous relevant factors: the dose required for timely incapacitation; the dose rate of the plutonium matrix itself; the duration of the theft; and the thief's success at using shielding and distance from the matrix. Each factor is subject to debate or is presently unknown. What is known is that whatever the dose rate deemed necessary to incapacitate, the plutonium storage form will drop below it eventually.[18] Therefore, whatever effectiveness a radiation barrier does provide will subside with time.[19]

Finally, while material form is important, when and where plutonium is processed and stored also affects proliferation risk. This relates to the strength of institutional control. The longer weapons-usable material is stored in an insecure environment, the greater the cause for concern. Therefore a disposition strategy that transferred plutonium to a more stable environment would effectively reduce the ability for theft.

DEVELOPING AN EFFECTIVE DISPOSITION STRATEGY

An effective disposition strategy should be capable of addressing identified threats in a timely manner. For the United States, insecure plutonium in Russia has caused the greatest concern. The "major motivation" for US disposition action, as stated in the DOE Nonproliferation Assessment, is to produce reciprocal action in Russia.[20]

As illustrated in the preceding section, characterizing a disposition strategy as effective requires specifying the proliferator that the strategy is aimed at defeating. In the present case, the proliferator of concern is the subnational organization, which is distinguished by its lack of alternate sources of fissile material and by its desire for one or a few crude nuclear weapons. The DOE Proliferation Vulnerability Red Team Report characterized the threat from unauthorized parties to be the "greater near-term concern," compared to host nation retrieval.[21] It appears therefore that priority should be given to finding solutions that can swiftly secure Russian plutonium.

The present Russian plan for addressing the near-term risks while SFS options are readied appears to be storage in either pit form or as recast metallic spheres. Pursuing disposition options that require large capital investments with significant operational vulnerabilities may thus lead to indefinite, or at least extended, storage in pit form. While the recast forms would be a meaningful improvement, their attractiveness and small size would still present safeguarding challenges, particularly in a country troubled by economic and political turmoil.

If the default storage options are viewed as unacceptable, what sort of material processing could be pursued? When it comes to Russian plutonium disposition, less processing may produce more security. If a plutonium storage form marginally below the SFS could be produced without contentious fuel-cycle investments in Russia, a net security benefit could be produced by allowing plutonium to be dispositioned in a more timely fashion.

Plutonium processing decisions should be made with specific, functional objectives for reducing the proliferation risk posed by this material. Verification and safeguarding criteria should be adopted and met. The ability to detect, track, and retrieve diverted material could be an additional functional requirement for a plutonium storage form. As the Center for Strategic and International Studies has noted, "The current inability to locate a nuclear device without intelligence cueing is perhaps the greatest limitation of our neutralization capability."[22] While it is a difficult task, processing the plutonium into a more readily traceable form would provide obvious benefits.[23]

Disposition decisions must also be made with an eye to the future. The world may change in ways that will dramatically affect the nonproliferation benefits of disposition actions. The diffusion of uranium enrichment technology (e.g., centrifuge and laser technology) over the several decades of disposition may dominate the long-term proliferation risk posed by surplus WGPu. The buildup of separated reactor-grade plutonium (RGPu) is also of proliferation concern. Either occurrence could produce an environment where the expense of extensive processing of WGPu is difficult to justify.

This does not mean that one should do nothing in the expectation that other risks will swamp those of surplus WGPu. The uncertainty means that we should focus on simple actions that can be taken in the near term to address known proliferation risks. Spending large amounts of time and money to place plutonium in an optimal form 20 or 30 years from now does not address today's risks and may not address the nonproliferation needs of the future. Sub-optimum storage forms that produce near-term payoffs can provide useful insurance against future unknowns.

A NEW APPROACH TO PLUTONIUM DISPOSITION

The following strategy is proposed to reduce the proliferation risk posed by surplus WGPu in Russia. First, the United States should pursue the negotiation of a bilateral agreement with Russia to process surplus plutonium pits into non-weapon storage forms. In addition, the United States could propose to accommodate Russian fuel-value concerns in order to allow removal of surplus plutonium from Russia and/or further material processing. This approach would reduce both the desirability of the plutonium and the potential for diversion, in a timely manner.

The United States and Russia should begin to address their mutual proliferation concerns by committing to disassemble their surplus pits and extract the contained WGPu as soon as possible. Assuming pit disassembly could be done with sufficient transparency to be confident of the weapons origin of the plutonium, the benefits of removing the material from pit form are significant and should be the immediate priority.

The processing of plutonium out of pit form would ease multilateral verification and safeguarding and reduce the opportunity for diversion by all would-be proliferators. The prospect of direct reinsertion in a weapon is also eliminated. As this act would be the first step for any disposition option, it would appear that every effort should be made to decouple this activity from other disposition decisions and move forward swiftly.

Russia has apparently already taken steps in this direction by recasting some of its pits. While this is desirable, it does raise some transparency concerns related to potential future arms control agreements. If such agreements require accounting for the number of pits disassembled, it may be difficult to prove the recast plutonium came from an actual weapon. Detection systems are currently being designed to provide confidence, without divulging classified information, that plutonium entering the disposition process is of weapons origin.

With sufficient transparency in place, the Russian pit disassembly efforts could be expanded. In the United States, pit disassembly and conversion operations will require sufficient shipping and receiving facilities, along with glove box and ventilation systems.[24] The operational start time for the ARIES process is estimated at seven years.[25] With siting and regulatory authority issues settled, US and Russian efforts could be scaled to match any level of warhead disassembly.

While steps that create obstacles to reinsertion and improve prospects for outside verification are valuable, if the plutonium is to be stored indefinitely, further material changes may be warranted to reduce the ability of a proliferator to steal the material. However, additional processing of Russian plutonium will not be possible unless Russian fuel-value concerns are addressed.

Two alternative means for accommodating Russian interests are proposed:

(1) Allow for the conditional future retrieval of plutonium for use in energy production:
- fabricate a "clean" plutonium storage form absent of fission products;
- immobilize plutonium to form large-unit-size/mass matrices via a "can-in-can" or similar approach;[26]
- do not require the addition of high-level waste (HLW) in the future; and
- if proven feasible, add integral off-site tracking capability; or

(2) Financially compensate Russia for the potential value of the material as a nuclear fuel:
- replicate the value of stored plutonium, which represents access to nuclear fuel at a fixed price, as a position in the uranium market;
- purchase plutonium at the price calculated in this manner; and
- dispose of the purchased plutonium.

Further details and the merits of each approach are discussed below.

Secure Plutonium Storage Form

Processing plutonium into a non-fission-product storage form would provide virtually all the security benefits attainable by material processing. For all but the host state, on-site manipulation and removal is a major barrier to diversion. Processing the plutonium into units with large size and weight would force potential proliferators to employ industrial equipment for handling purposes. While the resulting matrix would not possess a radiation barrier, the radiation barrier is not expected to significantly reduce the attractiveness of the plutonium or unduly hamper a skilled proliferator's ability to steal the material.

It could be argued that given the relatively low marginal cost of adding a radiation barrier for the immobilization option (an estimated $390 million beyond the cost of ARIES processing for the can-in-can variants[27]), we should add it even though the benefits are debatable.[28] However, adding a radiation barrier in Russia means building the infrastructure for a plutonium fuel cycle, which is expensive and likely to delay plutonium disposition.

Tracking devices, encapsulated in the storage matrix itself, could provide a new form of deterrence to would-be proliferators. A beacon from such a device could be used to locate and retrieve the plutonium should it be diverted. A detectable signal would be advantageous during the initial transport offsite, before the transmitter could be removed. Although the design of such a device has not been explored in any detail, the absence of highly radioactive elements that could damage the device would appear to make this option more feasible.

Perhaps the largest benefit of this immobilization approach is its potential to gain US and Russian support. Because HLW is not included in the matrix, retrieval would not require further handling of aqueous, radioactive waste. This would reduce the costs of extracting the material for commercial use. In essence, a plutonium ore would be fabricated that could be mined at a later date (in an internationally safeguarded manner). As the immobilization would not be supporting a plutonium fuel cycle, this activity would not conflict with other US nonproliferation goals and could be financially supported by the United States without criticism. This cooperation may provide the basis for swift disposition action.

Completely separating Russian plutonium disposition from other fuel-cycle activities enables processing to be performed independently. Progress would not be tied to potentially precarious HLW vitrification activities or civilian reactor operations. Plutonium could be immobilized at virtually any pace through the use of multiple process lines and/or higher capacity systems.

This proposal could also be formalized into a surplus plutonium storage standard that could be applied globally. Other states possessing separated plutonium may eventually wish to disposition their excess plutonium. The matrix described here would give them an alternative other than MOX fuel or mixing with HLW. Indeed, some countries may have neither alternative at their disposal. This alternate storage form could enable these states to demonstrate a commitment to arms reduction, ease safeguarding and storage costs, and give verifiable proliferation resistance.

Financial Compensation

Russia may not accept the idea of immobilizing the plutonium, even with no requirement to add fission products. In such a scenario, an outright purchase, similar to the HEU deal, would be attractive. But how does one value a commodity that is not traded in the marketplace? I propose a plutonium valuation methodology that may be acceptable to both Russia and the United States.

Plutonium Economics

Recent evaluations have concluded that the plutonium fuel cycle is not competitive with once-through alternatives. It is simply cheaper to produce electricity from uranium fuels. The price of uranium must rise dramatically before a plutonium fuel cycle is economically competitive with a once-through uranium cycle.

A recent study estimates that a plutonium cycle will be competitive when U3O8 sells for $160/lb.[29] This assumes today's European reprocessing and MOX fabrication costs. The current price of U3O8 is around $9.20/lb,[30] and it has never sold for more than $50/lb. It thus seems that plutonium recycling will not be economically justifiable for some time.

However, the economics of burning WGPu differs considerably from the economics of pursuing a plutonium fuel cycle. While an evaluation of future plutonium fuel-cycle investments must include an assessment of all costs, particularly reprocessing, plutonium from weapons could be viewed as an essentially free resource. The cost of producing the WGPu was paid for long ago by defense agencies. Free plutonium would obviously be much more competitive. However, it still must be fabricated into fuel, which is much more expensive than uranium fuel fabrication.

In a "free plutonium" scenario, plutonium fuels become attractive at a much lower price of uranium. When the price of U3O8 is just $15.84/lb, MOX fuel is the cheaper alternative.[31] This break-even price is still higher than the price of uranium today, but is much lower than the price needed for plutonium fuel-cycle competitiveness.

Nonetheless, the analysis demonstrates that plutonium is at best valueless today. Uranium can be purchased, enriched, and fabricated into fuel for less than the cost of plutonium fuel fabrication. This supports the view that plutonium has no economic worth.

However, this assessment ignores a significant point: present economic conditions will not hold forever. Global depletion of uranium may tilt the economic scale in favor of plutonium. Plutonium could be worth holding onto if one believes it will be valuable in the future. The present value of plutonium should therefore include its potential future worth.

The value of separated plutonium depends on its storage costs relative to the price of uranium. For example, if storage costs are negligible, then even though it may take many years, eventually the price of uranium will rise above the plutonium break-even point. This means that plutonium will amass value in the future.

Accepting that plutonium could have future worth does not by itself solve the problem. Valuing plutonium using traditional methods relies on predictions of the future price of uranium: when it will rise or fall, and by how much. These predictions vary widely. Russian plutonium investment plans reflect their view of impending uranium scarcity, while the United States feels confident that uranium will remain plentiful for some time. These conflicting expectations will produce contradictory estimations of plutonium value, leaving disposition at its present impasse.

What is needed is an objective or market-based assessment of the potential future worth of plutonium. If such a framework could be accepted, global market data, rather than subjective predictions, could be used to determine the value of plutonium. A relatively new method for valuing assets that derive their value from other assets can be used for this purpose.

Plutonium Valuation via Options Theory

In some industries, the price of a single input is critical to the cost of production. For example, for coal-burning utilities, the price of coal affects their cost of electricity production. It is therefore in their interest to negotiate with coal producers to ensure that they have access to coal at a fixed low price, reducing their risk in producing electricity.

Rather than agreeing to purchase the coal outright, a utility can purchase the *right* to buy a certain amount of coal at a low price on a future date. If the price of coal is higher than the contracted price on that date, the utility will exercise its right, or option, and buy coal at the agreed-upon price. Otherwise the utility will let the agreement "expire" and simply purchase coal at market prices. The option contract that the utility purchased is insurance against the potential high future price of coal.

Storing plutonium is a similar strategy for providing insurance against high fuel prices—in this case nuclear fuel. One kilogram of plutonium can be used to offset an equivalent amount of enriched uranium. Stockpiling plutonium is one way to guarantee access to nuclear fuel at a fixed price in the future. This strategy pays off if the price of uranium goes up in the future. It is exactly the same as negotiating with uranium suppliers for the right to buy uranium fuel at a fixed price in the future. In both cases the risk of high fuel prices is eliminated.

The question remains: "how does one value this right to purchase?" Economists have developed a quantitative theory for pricing contracts that give the holder the option to purchase an asset in the future.[32] This approach uses the historical behavior of the asset's price to calculate option value. This parameter is determined directly from market data and does not rely on predictions of future price behavior.

I have used this option approach to value separated WGPu. Factors that are important in addition to the historical behavior of uranium prices are the current price of uranium, the break-even price, and the option execution date. The break-even price was mentioned above and can be calculated based on the costs of uranium and plutonium fuels. The execution date must be chosen and should represent the time at which the plutonium could be burned in reactors.

Results

By assuming that possessing plutonium is as valuable as possessing the right to an equivalent amount of uranium at a low price, we can calculate a market-based value for plutonium. If we assume that the infrastructure for burning plutonium will be available in 10 years, 50 MT of WGPu has a value of $263 million today.[33] While a store of plutonium is relatively worthless today, the ability to use it to avoid higher fuel costs in the future is indeed valuable.

The calculated value is dependent on when you believe the plutonium could be burned in reactors (the option execution date). While this date is a matter of opinion, the results of the analysis show that no matter what time is assumed, the value of plutonium is bounded. For the case above, this value is $524 million for an option with an infinite execution date.

It should be noted that there are costs associated with holding plutonium that would not affect a purely financial agreement. Storage costs increase with time and can be much higher than the option value of the plutonium. Assuming a low storage cost of $400/kg/yr, indefinite storage would have a present cost of $250 million. At a storage price of $1000/kg/yr, the cost of storing WGPu exceeds the maximum value of the option. Storage costs are capable of eliminating any market value of the material.

Regardless of the calculated value, the option framework provides a means for guiding negotiations. It allows both the United States and Russia to move beyond their polarized views of plutonium economics. The methodology values plutonium by capturing its *potential* worth (important to Russia) while providing a pricing mechanism based on hard market data rather than disputable assertions (important to the United States). For this reason, both parties may find this approach acceptable.

Implementation Issues

Fuel-value compensation could take one of several forms. Russia could be paid the calculated cash value of its plutonium, or receive the option contract guaranteeing uranium at a fixed price in the future. This contract could then be immediately sold in the marketplace or held for potential execution in the future. Either way, Russia will have extracted the energy value of its plutonium.

Accepting the option contract as payment may be more appealing. With this alternative, one need not accept the theory underlying options valuation, only that the value of plutonium depends on the value of uranium. As the price of uranium rises, the value of plutonium rises and so does the value of an option to buy uranium at a low price.

Holding an option contract as compensation for plutonium might require some sort of collateral. The HEU that the United States is purchasing from Russia might prove useful for this purpose. An equivalent amount of the HEU could be blended down, paid for, and stored in Russia until the execution date of the option. In this way, any risk that the terms of the contract will not be upheld can be avoided.

Compensation Impact on Disposition Flexibility

Once the fuel-value issue has been addressed, several plutonium disposition alternatives may become more attractive. Immobilizing the plutonium for disposal or irretrievable storage in Russia may become possible. The United States could financially aid the processing and allow disposition to move ahead swiftly.

Alternatively, the plutonium could immediately be moved to a mutually agreed-upon third state. Both US and Russian WGPu could be transferred via military escort to safe storage until plutonium processing can be executed. This reciprocal action would demonstrate both countries' commitment to plutonium disposition and eliminate concerns over present instabilities.

This approach would work well in conjunction with a plan to burn surplus WGPu in European reactors. The WGPu could be swapped with stockpiles of RGPu scheduled for fabrication into MOX fuel in existing European facilities. In this way, WGPu processing could begin much more quickly than in either the United States or Russia.

The problem of the displaced RGPu will remain but seems more manageable. As Russian WGPu will have already been compensated for, Russia will not require that its share of RGPu be returned. If the Europeans do not want the displaced plutonium, the United States could eventually take it for dispositioning.[34] This would also address Russian concerns about the United States immobilizing its WGPu without having altered its isotopic composition. The plutonium returned to the United States would possess the degraded isotopics of RGPu.

CONCLUSIONS

Separated weapons-grade plutonium in insecure storage represents a global security risk. Given the obstacles to timely plutonium disposition in Russia, a reassessment of alternatives and priorities appears warranted. This viewpoint has put forward an assessment of nonproliferation goals and measures in order to identify effective disposition alternatives.

Removing plutonium from pit form and placing it in an internationally safeguarded facility would reduce the ability of any proliferator to divert the material. This can be done separately from other disposition activities and should be pursued as expeditiously as possible. A major obstacle to further disposition processing is Russian fuel-value concerns. The United States should consider alternate strategies for addressing these concerns in case the MOX option in Russia proves difficult to implement.

In order to provide economic motivation and flexibility in plutonium disposition negotiations, the United States could compensate Russia for the potential fuel value of its WGPu. Using a market-based assessment of plutonium value could avoid delays stemming from irreconcilable views of the nuclear future. Compensating Russia for the peaceful fuel value of its plutonium would allow a wider range of alternatives, including disposal or removal, to be considered.

Processing plutonium into a clean storage form is an alternate means of addressing Russian energy concerns. This would allow Russia to save the material for fuel while providing virtually all the proliferation risk reduction attainable by material processing. The large unit-size/mass would reduce the likelihood of successful diversion, and the inclusion of an effective off-site tracking capability would provide a new form of deterrence.

The lack of a radiation barrier has less impact on security than one might expect. Whatever protection a radiation barrier provides may take decades to achieve and will decay with the fission product inventory. It is not clear that the marginal benefits of introducing such a barrier outweigh the costs. Material processing options that could provide tangible, near-term security benefits while failing to meet the SFS should be explored at least as a contingency plan.

Finally, if plutonium disposition were completely separated from other fuel-cycle activities, its execution could begin more rapidly. Questions of interfacing properly with energy production activities would be eliminated. Disposition operations would also be more dependable because processing would proceed concurrent with arms control obligations, not according to the schedules of facilities that possess alternate missions. Given the risks created by current conditions in Russia, desire for a perfect solution should not prevent us from taking imperfect but useful steps that can be implemented quickly.

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[1] United States and Russian Federation, "Joint Statement of Principles For Management and Disposition of Plutonium Designated as no Longer Required for Defense Purposes," Moscow, September 2, 1998.

[2] US Department of Energy (DOE), Office of Fissile Material Disposition, *Technical Summary Report for Surplus Weapons-Usable Plutonium Disposition*, DOE/MD-0003 Rev. 1, 1996, p. ES-1.

[3] Moscow Summit Participants, "Moscow Nuclear Safety and Security Summit Declaration," April 20, 1996.

[4] $200 million was included in the FY99 Omnibus Emergency Appropriations Act (H.R. 4328) to aid Russian disposition efforts.

[5] Tarun Reddy, "Group Fears Russian Plutonium Will Be Used For MOX Plants," *Inside Energy/with Federal Lands*, October 26, 1998, pp. 8-9.

[6] White House, Fact Sheet, "Nonproliferation and Export Control Policy," September 27, 1993.

[7] DOE, Office of Fissile Material Disposition, *Feed Materials Planning Basis For Surplus Weapons-Usable Plutonium Disposition* (Springfield, VA: National Technical Information Services, 1997), p. 1.

[8] Matthew Bunn and John Holdren, "Managing Military Uranium and Plutonium in the United States and the Former Soviet Union," *Annual Review of Energy and the Environment* 22 (Palo Alto: Annual Reviews Inc., 1997), p. 413.

[9] National Academy of Sciences, *Management and Disposition of Excess Weapons Plutonium* (Washington DC: National Academy Press, 1994), p. 32.

[10] White House, Fact Sheet, "Nonproliferation and Export Control Policy," September 27, 1993.

[11] John Deutch, Director of Central Intelligence, Statement for the Record to the Permanent Subcommittee on Investigations of the Senate Committee on Government Affairs, March 20, 1996.

[12] In this paper the term diversion includes theft by an unknown party as well as diversion by the host state.

[13] DOE, *Nonproliferation and Arms Control Assessment of Weapons-Usable Fissile Material Storage and Excess Plutonium Disposition Alternatives*, DOE/NN-0007, 1997, p. 38.

[14] Russia regards the isotopics of its WGPu as classified information. ARIES-type processing would obviously not eliminate this information. However, the elimination of geometric information would loosen the restrictions associated with multilateral verification and safeguards activities.

[15] Sandia National Laboratories, *Proliferation Vulnerability Red Team Report*, SAND97-8203 1996, Ch. 5, p. 40.

[16] National Academy of Sciences, *Management and Disposition of Excess Weapons Plutonium: Reactor-Related Options* (Washington DC: National Academy Press, 1995), p. 225.

[17] The incapacitating dose of 500 rem is taken from a review of the table presented in Sandia National Laboratories' *Red Team Report*, Ch. 4, p. 11. The table in that document was extracted from United Nations Scientific Committee on the Effects of Atomic Radiation, *Sources, Effects and Risks of Ionizing Radiation* (New York: United Nations, 1988). The assumed dose is a nominal value, consistent with published dose-effect relationships for acute radiation exposure, and was assumed for the purpose of discussion.

[18] After roughly 10 years, the dose rate from spent fuel falls by 50 percent every 30 years. This is due to the decay of cesium-137.

[19] Sandia's *Red Team Report* goes on to estimate that dose rates of several thousand rem/hr at 1 meter would be needed to produce lethal effects during the execution of a theft. Spent fuel would fall below this level sooner than the 10 years used in the example.

[20] DOE, *Nonproliferation and Arms Control Assessment*, p. 9.

[21] Sandia National Laboratories, *Red Team Report*, Ch. 2, p. 1.

[22] S. Mullen, chair, Nuclear Black Market Task Force, Center for Strategic and International Studies, Washington, DC, Statement to the US Senate Permanent Subcommittee on Investigations, Senate Committee on Government Affairs, March 13, 1996.

[23] Notably, the DOE *Nonproliferation and Arms Control Assessment* (p. 54) stated that the "larger" benefit of the radiation barrier was its ability to aid the detection of plutonium after a theft had occurred.

[24] Lawrence Livermore National Laboratory, *Fissile Material Disposition Program, Alternate Technical Summary Report: Vitrification Can-in-Canister Variant*, UCRL-ID-122659 L-20216-1, 1996, Ch. 2, p. 21.

[25] DOE, *Technical Summary Report*, Ch. 5, p. 10.

[26] The can-in-can approach immobilizes plutonium in small canisters of glass or ceramic. The cans are then placed in a rack in a larger container that is eventually filled with molten glass.

[27] DOE, *Technical Summary Report*, Ch. 5, p. 10.

[28] If implemented in the United States, HLW might be included simply to reduce plutonium disposal costs. Fewer canisters of plutonium would need to be disposed of if they were included in the HLW canisters already scheduled for disposal.

[29] Brian Chow and Kenneth Solomon, *Limiting the Spread of Weapon-Usable Fissile Materials* (Santa Monica: RAND, 1993), p. 36.

[30] Published *Trade Tech* value, April 30, 1998.

[31] This value was calculated using market values published by *Trade Tech* for separative work units (SWUs) expended in uranium enrichment and assumes thermal use in a once-through cycle. Ironically plutonium is most valuable in a once-through cycle without reprocessing. Fuel costs are a higher fraction of production costs in this cycle.

[32] There is extensive literature on option pricing, beginning with F. Black and M. Scholes, "The Pricing of Commodity Contracts," *Journal of Political Economy* 81, No.3 (1973), pp. 637-54.

[33] Kory Sylvester, "Weapons-Grade Plutonium Disposition: An Alternate Immobilization Strategy," Ph.D. diss., MIT, 1997, p. 148.

[34] Storing plutonium can be expensive, and if sufficient americium-241 has grown in from plutonium-241 decay, the plutonium must be purified before fuel fabrication. By swapping WGPu with the RGPu, the Europeans can avoid these purification costs. The United States could take this RGPu and dispose of it in its immobilization program.