LA-UR-98-3617

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CONF-9809131--

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Submitted to: American Political Science Association Annual Meeting
September 3–6, 1998
Boston, Massachusetts



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# GLOBAL PLUTONIUM MANAGEMENT: A SECURITY OPTION

Presented at the American Political Science Association Annual Meeting
Boston, MA; Sept. 3-6, 1998

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## ABSTRACT

The U.S. surplus plutonium disposition program was created to reduce the proliferation risk posed by the fissile material from thousands of retired nuclear weapons. The Department of Energy has decided to process its Pu into a form as secure as Pu in civilian spent fuel. While implementation issues have been considered, a major one (Russian reciprocity) remains unresolved. Russia has made disposition action conditional on extracting the fuel value of its Pu but lacks the infrastructure to do so. Assistance in the construction of the required facilities would conflict with official U.S. policy opposing the development of a Pu fuel cycle. The resulting stagnation provides impetus for a reevaluation of U.S. nonproliferation objectives and Pu disposition options.

A strategy for satisfying Russian fuel value concerns and reducing the proliferation risk posed by surplus weapons-grade plutonium (WGPu) is proposed. The effectiveness of material alteration (e.g. isotopic, chemical, etc...) at reducing the desire, ability and opportunity for proliferation is assessed. Virtually all the security benefits attainable by material processing can be obtained by immobilizing Pu in large unit size/mass monoliths without a radiation barrier. Russia would be allowed to extract the Pu at a future date for use as fuel in a verifiable manner. Remote tracking capability, if proven feasible, would further improve safeguarding capability. As an alternate approach, the U.S. could compensate Russia for its Pu, allowing it to be disposed of or processed elsewhere. A market based method for pricing Pu is proposed. Surplus Pu could represent 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. The proposed strategy attempts to meet nonproliferation objectives by recognizing technical limitations and satisfying political constraints.

## BACKGROUND

The disposition of surplus plutonium in both Russia and the U.S. presents a major challenge. The U.S. has declared 52.2 MT of both weapons and reactor-grade plutonium excess to its security needs [1]. 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 [2].

The larger quantities of surplus highly enriched uranium (HEU) from weapons have proven far more manageable - both technically and politically. The U.S. has decided to blend down its HEU to low enriched uranium (LEU) for use in commercial reactors. The Russian government has moved faster to commercialize its HEU. Despite numerous hurdles the U.S. is now working with Russia to bring her uranium to the market. As of April last year Russia had delivered the equivalent of 21 tonnes of HEU to the U.S. [3].

Unfortunately, timely Pu processing has suffered from two barriers: 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 Pu can be made into a nuclear explosive [4].

Recognizing this physical reality, the so-called "Spent Fuel Standard" (SFS) was adopted. As recommended by the U.S. National Academy of Sciences, both countries have decided that their WGPu should be processed into a form that makes it as inaccessible and unattractive as Pu in spent fuel. The SFS could be met either by mixing the Pu with the radioactive waste it was originally extracted from (immobilization) or by burning the Pu in reactors. The U.S. is pursuing both options in parallel in its "dual track" program.

Meeting the Standard will be difficult as neither country has the required facilities and their construction will cost 100s of millions if not billions of dollars. Moreover, unlike the HEU case, making Pu disposition investments will not produce a profit. Without the means or the motivation there is little reason to believe that Pu disposition will proceed any time soon.

The expense of Pu disposition could certainly be justified on a security basis alone. However, due to national economic troubles, Russian finances are not available for Pu processing. The U.S. is apparently unwilling to fund Russian disposition efforts, particularly if funds are used to support the development of a Pu fuel cycle, something the U.S. as a matter of policy does not encourage [5].

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

This situation has lead to a stalemate. Russia appears content to store its Pu until conditions favor its use in reactors. However, the current turmoil in Russian political and economic affairs leads some to worry that the Pu is at risk of being stolen.

There is evidence to support this fear. 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 6 grams of Pu, a single gram of HEU, and approximately 500 grams of a Pu/U mixture [6]. The most significant was a case involving nearly three kg of HEU in December of 1994. This increases the pressure to either process the Pu into a more intrinsically secure matrix or to transfer it to a more stable environment.

Given the implementation hurdles a reassessment of disposition objectives and options appears warranted. In the following section a definition of proliferation risk is proposed which identifies three factors contributing to risk and how material processing can affect each one. This information is then used to critique the effectiveness of the current disposition strategy at reducing risk and identify areas for improvement.

## PROLIFERATION RISK

If proliferation risk reduction is desired, a detailed understanding of what is meant by risk is needed. Proliferation risk was taken to be dependent on three factors: desire, ability and opportunity. 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 storage matrix represents:

- something I want to some degree (defined by my ability to use it and alternate sources of the fissile material);
- something I have some prospect of successfully obtaining (defined by the presence of safeguards, security, physical form, tracking potential, etc...);
- and given a degree of opportunity, I will acquire it.

The bullets above describe the three risk factors respectively: desire, ability and opportunity. Both desire and capability are directly affected by the material characteristics of the Pu. Opportunity is indirectly affected by material form in that processing may allow for direct, multilateral verification and safeguarding. Certain processing steps also take longer to implement and are more prone to delays, potentially leaving Pu in a state of questionable security. Removing ambiguity by securing Pu in a transparent manner can deter proliferation attempts as well.

Each of the listed factors is needed for proliferation risk to exist, however their relative contribution is unknown. Nonetheless, a successful disposition strategy should (where possible) make the Pu less desirable, more difficult to use, and be implemented such that opportunities for diversion are minimized.

Material processing will also have asymmetric affects on disparate proliferators. The objectives as well as the resources and expertise available to a proliferator will determine the relative impact of any modification of the Pu. The impact of various physical alterations on risk will be discussed in this context.

### Desirability

The material processing of surplus 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. Desirability addresses the proliferators regard for the material assuming it could be successfully diverted. Disposition processing can degrade the utility of the Pu or make alternate sources more attractive but the impact is limited.

Processing the Pu out of pit form would diminish the usefulness of the material from a military readiness perspective. Pit processing (converting the Pu 'pits' into oxide or metal) would eliminate the direct reinsertion of the Pu into a weapon, forcing it to be remachined. (For extracting Pu from pits a dry separation process termed the Advanced Recovery and Integrated Extraction System (ARIES) has been developed.) For a host state, any Pu that was not in pit form, would possess no military value in a use-or-lose combat scenario. In addition, if limited pit refabrication capacity existed, ARIES processing would demonstrate commitment to treaty obligations as swift reversal would be impossible.

Another benefit of pit processing would stem from the elimination of all design information. This would impact a non-nuclear weapons state or a subnational group, which is likely to have design challenges. Reductions in the expected yield and the confidence of successful weapon production may dissuade certain less skilled proliferators from attempting diversion.

Altering the isotopic makeup of the Pu might affect desirability for a host-state. Isotopic dilution (e.g. by inserting the Pu in a reactor) may be capable of de-militarizing the material for service in the host nation's existing weapons infrastructure. While new weapons could be designed for low-grade Pu, in the current nuclear test ban environment that may be unacceptable, forcing new material to be produced. However, only nations that have a refined taste for Pu 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 Pu [7]. As they cannot pick and choose their fissile material, and would likely be satisfied with one or two explosives of uncertain yield, isotopics would not affect their desire in a meaningful way.

If isotopic manipulation is deemed irrelevant, the most additional processing can do to reduce attractiveness is to force recovery and purification through chemical processing. A so-called chemical barrier alone (achieved by commingling Pu in a multi-element material matrix) could result in the same degree of host state deterrence as a radiation barrier. The combination of an operational reprocessing facility and concerns over criticality safety would quite likely result in a "clean" Pu matrix being processed in the remote facility. In that sense, a matrix that forced the use of such a solvent extraction facility should be viewed as equivalent to radioactive spent fuel.

Lacking industrial facilities, if a proliferator is willing to accept clumsy and slow laboratory scale reprocessing, the addition of a radiation barrier will not reduce the attractiveness of the material. Crude separations are capable of reducing the radiation dose rate by several orders of magnitude. It seems that if even a contaminated quantity of Pu could be obtained, a means for purifying it would be found.

Ability

Another component of proliferation risk is the proliferators' estimated and actual capability to successfully transfer the Pu off-site. Dispositioned Pu will be placed in a storage facility for monitoring. The material form of the Pu can affect the ease of safeguarding and/or off-site removal. This can dramatically decrease the proliferator's expectations for success and thereby the proliferation risk.

As long as the material remains in the country, no material processing will prevent host state retrieval. However, processing the Pu into an easily monitored and safeguarded form may somewhat reduce the prospects of successful diversion by other proliferators as security forces could be notified immediately. Therefore, ARIES type processing would increase security as the presence of classified information, which hamper international safeguarding efforts, would be eliminated. Safeguarding would also have some deterrence for the host state as the international community would be alerted of any removal.

Beyond pit processing the most important factor appears to be the use of unit/size and mass to hamper on-site manipulation and off-site transport by requiring industrial size equipment. This can be achieved by fabricating the Pu into large glass or ceramic monoliths. Even then the D.O.E.'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 few people on the ground" [8]. Nonetheless, relative to small objects, such a monolith would be much easier to guard.

To the extent a radiation field forces the use of heavily shielded equipment to handle the Pu, it would be effective at reducing the ability to divert. However, the Red Team notes that "none of the alternative final forms emit radiation fields large enough to require shielding for dedicated aggressors" [9]. An aggressor that is willing to take a non-incapacitating dose of a few hundred rem will not be deterred. The assessment 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. They estimate 10 year old spent fuel to possess a dose rate of 1000 rem/hr at 1 meter. In any regard the protection offered will decay with Cs-137 possessing a half-life of 30 yrs.

Opportunity

While material form is important, when and where Pu is processed and stored also affects proliferation risk. This relates to the strength of institutional control. The longer weapon's grade material is stored in an insecure or volatile environment the greater the cause for concern.

Material processing could greatly reduce the opportunity for proliferation. As execution of the present disposition alternatives will require decades, the near-term focus has been on safe, secure storage. However, as mentioned previously, storage in pit form may not allow adequate verification and safeguards. In addition, observer presence may be intermittent. For perhaps unrelated political purposes, inspectors may simply be forced out of storage facilities. Independent direct verification would be desirable under such circumstances. Processing into a non-classified form would allow for such verification if the final form were suitable for non-destructive evaluation. If the present instabilities in Russia are believed to exist indefinitely, the benefits of a non-pit storage form become larger.

While processing beyond ARIES may be pursued for other reasons (e.g. to reduce the ability to divert), if would not further reduce the opportunity for proliferation as it has been defined here. The potential benefits (in terms of reducing proliferator opportunity) of material processing are attained exclusively by the production of a directly verifiable form for storage in an internationally safeguarded facility.

Further, if pit processing were delayed due to the unavailability of these additional processes, pursuing the SFS options could prolong exposure to the present risks. Low Pu fuel fabrication and high-level waste (HLW) vitrification capacity would have the same impact. Given the limited benefits of a radiation barrier, the risk of processing delay should be carefully weighed.

## DISPOSITION STRATEGY NEEDS

An effective disposition strategy must be capable of addressing identified threats in a timely manner. The greatest risk appears to be the sub-national threat from unsecured Pu in Russia. The D.O.E. Nonproliferation Assessment describes the impact on Russian programs for disposing its Pu as a "major motivation for U.S. Action" [10]. In addition, the Red Team Vulnerability Report characterized the threat from unauthorized parties to the "greater near-term concern," compared to host nation retrieval [11]. While other nonproliferation objectives should not be ignored, this prioritization should drive strategy formulation. It appears therefore that the focus should be on finding solutions that can swiftly secure Russian Pu.

Having discussed the effectiveness as well as the limitations of material processing at reducing risk in the prior section, we can critique disposition options. The present U.S. disposition strategy (dual track) adopts a material standard that, if executed, would certainly reduce the risk from each country's surplus Pu.

However, the adoption of the Spent Fuel Standard as the only acceptable form for long-term Pu disposition may impede the processing of any Russian material. The SFS requires Russia to either treat Pu as fuel or as a waste. Doing so hampers cooperation for the reasons mentioned previously. Under such conditions stagnation seems predictable.

The present plan for addressing the near-term Pu risks while long-term disposition options are readied appears to be pit storage. By pursuing options that require large capital projects with significant schedule vulnerabilities we may be inadvertently accepting indefinite pit storage. This is undesirable for the reasons mentioned above: verification/safeguarding difficulties, and the greater attractiveness for all proliferators of Pu in pit form.

If pit storage is viewed as unacceptable, what sort of material processing should be pursued? What strategy might eliminate the stagnation? When it comes to Pu disposition, less processing may produce more security. If a Pu 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 disposition to proceed in a more timely fashion.

Processing decisions should be made with specific, functional objectives in mind. Verification and safeguarding objectives have already been discussed. The ability to detect, track and retrieve diverted material could be another functional requirement. It has been said that, "The current inability to locate a nuclear device without intelligence cueing is perhaps the greatest limitation of our neutralization capability" [12]. Indeed, the D.O.E.'s Nonproliferation Assessment stated that the *primary* benefit of the radiation barrier was its ability to aid the detection of Pu *after* a theft [13]. The impact of material form on detection capability should be further explored.

The critical component of an effective disposition strategy may not even be a technical solution. The opportunity for diversion may be dramatically reduced if Pu was removed from Russia for processing in another country. This would require addressing Russia's desire to extract the fuel value of its Pu. If this issue could be resolved a great deal of flexibility could be added to disposition negotiations.

Finally, today's disposition decisions must be made with an eye to the future. The world may change in ways that will dramatically affect the realized proliferation 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 RGPu is also of proliferation concern. Either occurrence could produce an environment where the expense of continued processing of WGPu is difficult to justify.

This does not mean that one should wait for other risks to hopefully 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 Pu in an optimum form 20-30 years from now does nothing to address today's risks. Sub-optimum forms that can produce near-term payoffs can serve as insurance against future unknowns.

## A NEW APPROACH TO PU DISPOSITION

The following strategy is proposed to reduce the near-term risk of subnational or NNWS diversion in the near term. The U.S. should adopt the following priorities:

- negotiate a bilateral agreement with Russia to process surplus Pu pits into non-classified forms immediately.

- accommodate Russian fuel value concerns in order to allow removal and/or further material processing.

It is proposed that the U.S. and Russia address their mutual proliferation concerns by agreeing to initiate bilateral processing of their surplus WGPu pits immediately. Assuming it could be executed in a verifiable manner, the benefits of removing the material from classified pit form are too large to ignore and should be executed in short order.

Pit conversion/Pu recovery operations could be initiated immediately if sufficient shipping/receiving facilities along with glove box and ventilation systems were available [14]. The availability of such facilities in Russia is unknown. The operational start time for the ARIES process, is estimated at 7 years [15]. It is possible that such processing could be done faster and cheaper in Russia.

The processing of Pu out of pit form, easing verification and safeguarding efforts, reduces 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.

While eliminating the design information and making direct verification possible is valuable, if the Pu is to be stored indefinitely further material changes may be warranted to reduce the ability of a proliferator to successfully steal the material. However, additional processing of Russian Pu will not be possible unless Russian fuel value issues are addressed.

Two means for accommodating Russian interests are proposed:

1. allow for the conditional retrieval of Pu in the future for use in energy production:

    - fabricate a 'clean' Pu storage form absent of fission products;

    - immobilize Pu to form a high unit size/mass matrix via a can-in-can or similar approach[1];

    - do not require the addition of HLW in the future; and

    - add integral off-site tracking capability; or

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[1] The can-in-can alternatives first immobilize Pu 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.

2. financially compensate Russia for the potential value of the material as a nuclear fuel;

   - stored Pu represents access to nuclear fuel at a fixed price, this can be replicated and valued as a position in the uranium market;

   - purchased Pu can be disposed of or removed from Russia for dispositioning.

Further details and the merits of this proposal are discussed below.

<u>Secure Pu Storage Form</u>

Processing Pu into a non-fission product storage form would provide virtually all the security benefits attainable by additional material processing. For all but the host-state proliferator on-site manipulation and removal is a major barrier. Processing the Pu to a high unit-size and mass matrix is effective at forcing 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 Pu, 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 M of the can-in-can variants [16]) we should add it even though the benefits are debatable.[2] This would be true if money was available for the processing. In Russia a radiation barrier means building the infrastructure for a Pu fuel cycle. As financiers, including the U.S., are unwilling to invest in such facilities, the cost in terms of disposition progress becomes excessively high.

Tracking devices, encapsulated in the storage matrix itself, could provide a new form of deterrence for would-be proliferators. A 'beacon' from such a device could be used to locate and retrieve the Pu should it be diverted. A detectable signal would be quite useful during the initial transport off-site, before the transmitter could be removed. The design of such a device has not been explored in any detail, however the absence of highly radioactive elements would appear to make this option more feasible.

Perhaps the largest benefit of this approach, as well as its motivation, is its potential to gain Russian acceptance. Because HLW is not included in the matrix, retrieval would not produce additional wastes to be vitrified. This would reduce the costs of extracting the material for commercial use. In essence a Pu ore would be fabricated that could be mined at a later date (in a safeguarded manner). As the immobilization would not be supporting

[2] In the U.S. HLW might be included to reduce Pu disposal costs. Fewer canisters of Pu would need to be disposed of if they were included in the HLW canisters already scheduled for disposal.

a Pu fuel cycle, this activity could be financially assisted by the U.S. The combination of retrievability and financial aide may be sufficient to garner Russian support.

By completely separating Pu disposition from other fuel cycle activities processing could 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 would promote additional near-term benefits.

This proposal could also be formalized into a surplus plutonium storage standard which could be applied globally. Other states possessing separated Pu may eventually wish to disposition their excess Pu. Such a matrix would give them an alternative other than mixed oxide (MOX) fuel or mixing with HLW.[3] Indeed the country may have neither alternative at its disposal. Such a form could be used to demonstrate a commitment to arms reduction, ease safeguarding and storage costs, and give verifiable proliferation resistance.

Financial Compensation

Russia may decide that even immobilizing the Pu without fission product is not acceptable. 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? A Pu valuation methodology that may be acceptable to both Russia and the U.S. is proposed.

*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.

Chow estimates that a Pu cycle will be competitive when $U_3O_8$ sells for \$160/lb [17]. This assumes today's European reprocessing and MOX fabrication costs. The current price of $U_3O_8$ is around \$9.20/lb.[4] Uranium has never sold for more than \$50/lb $U_3O_8$. It seems that Pu recycling will not be economically justifiable for some time.

However, the economics of burning WGPu differs considerably from the economics of pursuing a Pu fuel cycle. While an evaluation of future Pu fuel cycle investments must include an assessment of all costs, particularly reprocessing, Pu 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 Pu would obviously be much more competitive. However it still must be fabricated into fuel, which is much more expensive than uranium fuel fabrication.

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[3] Plutonium is mixed with uranium for burning in reactors, thus the name mixed oxide or MOX fuel.
[4] Published Trade Tech value 4/30/98.

In a 'free Pu' scenario, Pu fuels become attractive at a much lower price of uranium. When the price of $U_3O_8$ is just $15.84/lb, MOX fuel is the cheaper alternative.[5] This 'breakeven' price is still higher than the price of uranium today but is much lower than the price needed for Pu fuel cycle competitiveness.

Nonetheless, the analysis demonstrates that Pu is at best valueless today. Uranium can be purchased, enriched, and fabricated into fuel for less than the cost of Pu fuel fabrication. This supports the view that Pu 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 Pu. Plutonium could be worth holding onto if one believes it will be valuable in the near future. The present value of Pu should therefore include its potential future worth.

The value of separated Pu 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 Pu breakeven point. This means that Pu will amass value in the future.

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

What is needed in an objective or market based assessment of the potential future worth of Pu. If such a framework could be accepted, global market data could be used to determine the value of Pu rather than subjective predictions. 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 impacts their cost of electricity production. It is in their interest therefore to negotiate with coal producers to assure that they have access to coal at a fixed low price. In this way the utilities can reduce their risk of 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 and buy coal at the

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[5] This value was calculated using published market values for SWU (Trade Tech) and assumes thermal use in a once-through cycle. Ironically Pu is most valuable in a once-through cycle without reprocessing. Fuel costs are a higher fraction of production costs in this cycle.

agreed upon price. Otherwise the utility will let the agreement 'expire' and simply purchase coal at market prices. The contract that the utility purchased is insurance against the potential high price of coal.

Storing Pu is a similar strategy for providing insurance against high fuel prices - in this case nuclear fuel. One kg of Pu 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 right or 'option' to purchase an asset in the future.[6] 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.

This option approach has been used to value separated WGPu. Factors that are important in addition to the historical behavior of uranium prices are: the current price of uranium, the breakeven price, and the option execution date. The breakeven price was mentioned above and can be calculated based on the costs of uranium and Pu fuels. The execution date must be chosen and should represent the time at which the Pu could be burned in reactors.

*Results*

By assuming that possessing Pu 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 Pu. If we assume that the infrastructure for burning Pu will be available in 10 years, 50 MT of WGPu has a value of $263M [18]. While being relatively worthless today, its ability to avoid higher fuel costs in the future is indeed valuable.

The calculated value is dependent on when you believe the Pu 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 Pu is bounded. For the referenced case, this value is $524 million for an option with an infinite strike date.

It should be noted that unlike an agreement, there are costs associated with holding Pu. Storage costs increase with time and can be much higher than the option value of the Pu. Assuming a low storage cost of $400/kg/yr, infinite storage would have a cost of $250M. 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.

[6] There is extensive literature on option pricing beginning with the work of Black and Scholes in 1973.

Regardless of the calculated value, the option framework provides a means for guiding negotiations. It allows both U.S. and Russia to move beyond their polarized views of Pu economics. The methodology values Pu 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 U.S.). 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 her Pu or receive the 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 Pu.

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

Holding a contract as compensation for Pu might require some sort of collateral. The HEU that the U.S. 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 expiration date of the option. In this way, any risk that the terms of the contract will not be upheld can be completely avoided.

*Compensation Impact on Disposition Flexibility*

Having addressed the fuel value issue, several Pu disposition alternatives may become more attractive. Immobilizing the Pu for disposal or irretrievable storage in Russia may become possible. The U.S. could financially aid the processing and allow disposition to move ahead swiftly.

Alternatively, the Pu could immediately be moved to a mutually agreed upon third state. Both U.S. and Russian WGPu could be transferred via military escort to safe storage until Pu processing can be executed. This reciprocal action would demonstrate both countries' commitment to Pu 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 U.S. or Russia.

The problem of the displaced RGPu would remain but seems more manageable. As Russian WGPu will have already been compensated for, Russia will not require its share of RGPu to be returned. If the Europeans do not want the displaced Pu the U.S. could eventually take it for dispositioning in the U.S.[7] This would also address Russian concerns over immobilizing U.S. WGPu without altering its isotopic composition. The Pu returned to the U.S. would possess the degraded isotopics of RGPu.

## CONCLUSIONS

Separated weapons-grade Pu in insecure storage represents a global security risk. If the U.S., Russia and the global community is interested in promoting timely Pu disposition a reassessment of alternatives and priorities appears warranted. By clearly articulating nonproliferation goals and measures, effective disposition alternatives can be identified.

Removing Pu from pit form and placing it in a safeguarded facility would reduce the ability and opportunity of any proliferator to divert the material. It can and should be done as expediently as possible. A major obstacle to further disposition processing is Russian fuel value concerns. The U.S. disposition strategy should be modified to reflect this reality.

In order to provide economic motivation and flexibility in Pu disposition negotiations, the U.S. should consider compensating Russia for the potential fuel value of its weapons-grade plutonium. By relying on a market-based assessment of Pu value, delays stemming from irreconcilable views of the nuclear future can be avoided. Compensating Russia for the peaceful fuel value of its Pu would allow a wider range of options to be considered including disposal or removal.

Processing Pu into the proposed 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 high unit size/mass would reduce the likelihood of successful diversion and the inclusion of off-site tracking capability would provide a new form of deterrence.

Unfortunately, the impression that the SFS forms under investigation leave plutonium in a 'self-protecting' matrix is false. Whatever protection a radiation barrier is purported to provide will decay with fission product inventory. Material processing options that could provide tangible, near-term security benefits while failing to meet the SFS should be explored.

Finally, by completely separating Pu disposition from other fuel cycle activities its execution could begin immediately. Disposition operations would also be more dependable as processing would proceed concurrent with arms control obligations, not the schedules of facilities possessing alternate missions. Proposals of this nature should be seriously considered.

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[7] Storing Pu can be expensive and Am-241 (from Pu-241 decay) must be extracted for safe handling during fuel fabrication. By swapping WGPu with the dirtiest RGPu the Europeans can avoid these costs. The U.S. could take this RGPu and dispose of it in its immobilization program.

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