An Evaluation of the Proliferation Resistant Characteristics of Light Water Reactor Fuel with the Potential for Recycle in the United States

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EXECUTIVE SUMMARY

The Advanced Fuel Cycle Initiative within the Department of Energy has been formulated to perform research leading to advanced fuels and fuel cycles for advanced nuclear power systems. Some of this research is focused on Light Water Reactor (LWR) fuels with the potential for recycle. As part of this research, program management convened a committee of internationally recognized experts to evaluate the nonproliferation characteristics of this fuel. This nonproliferation review committee was chartered to report to the Advanced Nuclear Transmutation Technology Subcommittee of the Nuclear Energy Research Advisory Committee (NERAC).

The review committee concluded that:

- The research and development being conducted on advanced fuels in the AFCI program on the UREX process has the potential for a major nonproliferation advance and can raise the bar with respect to proliferation resistance,

- The time integrated proliferation resistance measure of a fuel cycle intended to transmute minor actinides, if properly designed, has the potential to be roughly equal to that of the Spent Fuel Standard; the Inert Matrix fuel cycle is particularly notable in this regard,

- Recycling higher actinides for additional intrinsic proliferation resistance and employing highly advanced or ideal safeguards features for additional extrinsic proliferation resistance has the potential to increase the proliferation resistance measure of the more vulnerable points in the fuel cycle to approximately that of the Spent Fuel Standard,

- It is inappropriate to focus all attention on the recycling step as the only point of vulnerability in the overall fuel cycle. The enrichment step is also a point of

nonproliferation concern, since a lack of sufficient safeguards at this step could allow the production of weapons-usable uranium, and

- Elements of highly advanced safeguards features and innovations are under consideration in the research and development being performed on the UREX process and actinide transmutation in the AFCI.

The review committee recommends that the AFCI conduct research along several lines in order to realize the goal of increasing proliferation resistance measures associated with recycle. They include:

- Continuing research and development leading to the use of neptunium as a doping agent to produce Pu-238 during irradiation in the reactor, thereby degrading the isotopic composition and deliverable-weapon usefulness of discharged plutonium, as a means to increase intrinsic proliferation resistance,

- Continuing research and development on other fuel systems with the capability to degrade the plutonium isotopic composition, such as Inert Matrix Fuel, thereby reducing the deliverable-weapon usefulness of the discharged plutonium, and so increasing intrinsic proliferation resistance,

- Continuing research and development leading to the use of advanced fuels containing higher actinides, such as Am-241, to increase the radiation barrier and thereby increase intrinsic proliferation resistance,

- Ensuring that advanced safeguards techniques, leading ultimately to Ideal Safeguards, are incorporated into all steps (including enrichment) in the design process in order to increase extrinsic proliferation resistance, and

- Ensuring that plutonium and neptunium streams are retained together in order to utilize the daughter product Pa-233 as a tracer in the safeguards system to increase extrinsic proliferation resistance.

If the research, design, and development being considered in AFCI should prove successful, the UREX process -- combined with advanced safeguards and fuel systems that employ material doping to provide radioactive tracers and degrade the plutonium isotopic composition, or degrade plutonium isotopic composition by the use of inert materials -- will have a high proliferation measure. It can potentially increase the proliferation resistance measure of a closed cycle to roughly that of the Spent Fuel Standard. Research and development on advanced fuel systems with intrinsic and extrinsic nonproliferation attributes as defined above should continue to be pursued in the AFCI.

The effect of plutonium isotopic composition on the usefulness of plutonium in a deliverable weapon was not considered in detail in this study, but will be evaluated in separate studies. Nonetheless, some fuel systems have the inherent capability to provide this attribute and so research and development on fuel systems with these characteristics is recommended.

I – INTRODUCTION

The Advanced Fuel Cycle Initiative (AFCI) of the Department of Energy has been formulated to perform research leading to advanced fuels and fuel cycles for advanced nuclear power systems. One of the objectives of AFCI is to determine if partitioning and transmutation of spent nuclear fuel will reduce the burden on the geologic repository. The AFCI program is periodically reviewed by the Advanced Nuclear Transmutation Technology (ANTT) subcommittee of the Nuclear Energy Research Advisory Committee (NERAC). This report contains a review of the general nonproliferation attributes of several advanced approaches to close the fuel cycle on which AFCI is performing research. This nonproliferation review was performed for the ANTT subcommittee.

II – BACKGROUND

Dealing with spent nuclear fuel is one of the long-standing issues associated with commercial nuclear power. The approach currently being taken by the United Sates is to store the spent nuclear fuel from the once-through cycle in a geologic repository at Yucca Mountain. Research is also being performed on advanced fuels and fuel cycles. A goal is to arrive at a closed fuel cycle that would not increase the risk of proliferation while simultaneously reducing the need for a second geologic repository. An additional benefit is that plutonium will be destroyed by burning in reactors and the amount of plutonium in the nuclear fuel cycle will decrease to a minimal equilibrium value. Otherwise, it will continue to grow as long as nuclear power exists and remain at the final value essentially forever as a magnet for potential proliferators.

Consequently, the Department of Energy (DOE) decided to constitute a committee consisting of internationally recognized professionals in this field to study the proliferation risks associated with closing the fuel cycle in the United States. The charter given to the committee is attached as Appendix A. In brief, the committee (hereafter referred to simply as the Committee) was asked to review alternative fuel forms for a fuel for Light Water Reactors (LWRs) with the potential for recycle and to

assess their nonproliferation attributes. In the original charter for the Committee, this fuel was identified as Series One and is a mixture of the isotopes of uranium, plutonium, neptunium, and possibly other constituents. The fuel is to be developed for potential recycle in LWRs with the intent of destroying plutonium and other minor actinides as rapidly as possible. This approach will use the existing fleet of LWRs, rather than waiting for the development of advanced reactors. The characteristics of this fuel to be evaluated, as stated in the charter to the Committee (Appendix A), include:

(a) Constituents required in the fuel.
(b) The level of intrinsic proliferation resistance,
(c) The fabrication difficulty,
(d) The reprocessing and potentially increased refabrication difficulty, and
(e) The acceptability of the fuel to operations of commercial nuclear power plants.

The objective of the Committee was to provide additional input to the ANTT subcommittee chaired by Dr. Burton Richter. The ANTT is a subcommittee of the NERAC, which serves to review and evaluate research being conducted by the AFCI. The ANTT provides programmatic recommendations for research directions to the AFCI. In the course of this review, the Committee considered approaches for closing the current commercial fuel cycle in the United States in a manner that would not increase, and possibly would decrease, the proliferation risk relative to that of the open fuel cycle. The result of this assessment could be used to guide future nuclear fuel cycle research directions.

Similar but not identical work is being performed within the Generation IV program. The Proliferation Resistance and Physical Protection (PR&PP) subcommittee is reviewing the proliferation resistance associated with the reactor designs being developed by Generation IV [Petersen]. Although addressing the same problem, the PR&PP study is a longer-term assessment extending over several years. In addition, the PR&PP is using a more analytical approach somewhat similar to the approach used for Probabilistic Risk Analysis (PRA) to assess the safety of nuclear power

plants. Based upon constructive interactions between the two groups, the Committee believes that the two approaches are consistent in objectives and nicely complement one another.

III – HISTORICAL PERSPECTIVE

Preventing the proliferation of nuclear weapons has been part of the policy of the United States for more than half a century. Each and every decade has had its successes and its failures. The original United States policy of Secrecy and Denial, codified in the Atomic Energy Act of 1946, was intended to ensure that additional nuclear weapons states did not develop. The approach was to limit nuclear cooperation. Subsequent to this, the Soviet Union became the second nuclear weapons state in 1949 and the United Kingdom became third nuclear weapons state in 1952.

The apparent failure of this policy led to a complete reversal of the approach taken by the United States. The Atoms for Peace Initiative served as the cornerstone for a new policy of controlled cooperation. This policy was codified in the Atomic Energy Act of 1954. To ensure that nuclear cooperation proceeded in an acceptable manner, the major nuclear nations founded the International Atomic Energy Agency with a charter to both promote peaceful uses of nuclear energy and to provide an effective safeguards regime against its abuse.

While it was hoped that this approach would prevent the development of new nuclear weapon states, such was not the case. France became the fourth nuclear weapons state in 1960 and China became the fifth in 1964. This led to a consensus by the major nuclear nations that additional international provisions were needed, which ultimately resulted in the formulation of the Treaty for the Nonproliferation of Nuclear Weapons (NPT) in 1968.

In 1974, India became the sixth nuclear weapons state, causing repercussions that ultimately led to the Once-Through Cycle in the United States. One action was the Nuclear Nonproliferation Act (NNPA) of 1978 that tightened export controls and constrained subsequent arrangements. Another was the Nonproliferation Alternatives System Assessment Program (NASAP), which came up with conclusions that hold to this day [DOE 1980]. Still another was the International Nuclear Fuel Cycle Evaluation (INFCE) that, while not arriving at identical conclusions, did acknowledge the beneficial nonproliferation attributes of the Once-Through Cycle [IAEA 1980]. A subsequent study, the Management and Disposition of Excess Weapons Plutonium [NAS 1995], articulated the Spent Fuel Standard that has been the s*ine qua non* of proliferation resistance in the United States for more than two decades.

It is useful to review the conclusions of NASAP [DOE 1980] because they relate directly to the current research on advanced nuclear fuel systems in AFCI and Generation IV. They stated that current and future nuclear power systems can be made more proliferation resistant and that:

(1) All nuclear fuel cycles entail some proliferation risk; there is no technical fix,

(2) There are substantial differences in proliferation resistance among fuel cycles if they are deployed in non nuclear weapon states,

(3) Technical and institutional proliferation resistance features can help, and

(4) The vulnerability to threats by sub-national groups varies among fuel cycles.

It is interesting to note that the distiction between the characteristics of the nuclear fuel cycle, its location, and its acceptability were being drawn over twenty years ago. This distinction was drawn more recently in a speech by President Bush to the National

Defense University [Bush 2004]. A similar proposal has been put forth by Dr. Mohamed ElBaradei, the Director General of the International Atomic Energy Agency [IAEA 2003].

The present report focuses on the first and third conclusions, that is, while there is not technical fix, there are technical and institutional features that can increase proliferation resistance considerably.

IV – COMMITTEE COMPOSITION AND OPERATION

Given the charter contained in Appendix A, the first task was to select an appropriate committee to undertake the stated mission. The criteria for selection of committee members included recognized expertise in reactor physics, fuels, chemical processing (separations technology), non-proliferation matters (including safeguards), and the commercial aspects of fuel manufacturing. The latter was important to assure that any recommendations supplied by the committee would be acceptable to the current reactor fuel manufacturing community. We were fortunate to obtain acceptances from world experts in the disciplines desired. The membership, affiliation, and expertise are shown below:

Member	Organization	Country	Expertise
Pascal Baron	CEA	France	Reprocessing and Safeguards
Christine Brown	BNFL	UK	Fuels, Safeguards, Nonproliferation
Bruce Kaiser	WGI	USA	Fuels Manufacturing
Bruce Matthews	LANL	USA	Safeguards
Takehiko Mukaiyama	JAIF	Japan	Reactor Physics, Fuel Cycles, Safeguards
Ronald Omberg	PNNL	USA	Reactor Design and Nonproliferation
Lee Peddicord	Texas A&M	USA	Fuels, Fuel Cycles
Massimo Salvatores	CEA	France	Reactor Physics, Fuel Cycles, Nonproliferation
Alan Waltar	PNNL	USA	Chairperson

As the table above indicates, the makeup of the Committee was international and so it was prudent to minimize the number of full committee meetings. Consequently, only two formal meetings were held and both were limited to necessary discussions. However, numerous telephone communications and e-mails were used to supplement these meetings.

The first meeting was held in Washington DC on 12 and 13 December 2002. The primary purpose of the first meeting was to lay the background for the work of the committee. In addition, this meeting included a review of:

- The current AFCI approach to reactor design for actinide destruction,
- The current AFCI approach to actinide recycle,
- Alternative approches for plutonium burnup,
- The current status of Mixed Oxide (MOX) fabrication technology, and
- Current thinking on advanced safeguards approaches.

The second meeting was held in Washington DC on 1 and 2 May 2003. The primary purpose of the second committee meeting was to review alternative advanced fuel cycles and advanced safeguards technologies most applicable to the current situation in the United States. Presentations were made to the committee on:

- The current status of UREX separation technology,
- Quantative proliferation assessment methodologies,
- Technological approaches for advanced safeguards technology,
- The impact of minor actinide additions in fuel fabrication,
- The status of Inert Matrix Fuel (IMF), and
- The current status and technology involved in the DUPIC process.

In addition to the above full committee meetings, smaller meetings were held with the PR&PP committee working on nonproliferation assessment of Generation IV reactors as well as the Chair of the ANTT subcommittee.

V – FUEL CYCLES REVIEWED

Whereas there are a wide number of fuel cycles that might be considered for possible adoption of Series One fuel in the United States, the Committee focused attention on only four that essentially span the space. These were:

- The classical PUREX/MOX cycle being implemented in Europe, Russia and Japan,

- The UREX process with actinide separation and recycle on which research is being conducted in the United States in the AFCI,

- The DUPIC process, which is largely an intrinsic approach, and is being studied in the Republic of Korea, and

- The IMF approach, which uses a fuel that does not contain U-238 and so does not produce plutonium, but rather burns and degrades its composition, an approach that is being studied in Switzerland.

CLASSICAL PUREX/MOX

The PUREX/MOX approach for LWRs was adopted in Europe during the late 1970s. Large investments have made by COGEMA in France and by BNFL in the United Kingdom at reprocessing plants at La Hague and Sellafield, respectively. The PUREX approach is based on the historical aqueous process originally developed for the

extraction of plutonium from spent fuel for nuclear weapons. When used for LWR MOX recycle, the plutonium separated during reprocessing is combined with uranium and refabricated into oxide pellets. These pellets are then loaded into fuel rods, the fuel rods are combined into fuel assemblies, and the fuel assemblies are reloaded into LWRs.

Belgium was actually the first country to start burning MOX fuel, but substantial amounts of MOX fuel are currently being burned in France, Germany, and Switzerland. In 1989, MOX was being used in thirteen thermal reactors in Europe [OECD 1989]. Both Russia and Japan have adopted this cycle as their preferred approach. The Japanese currently have a large reprocessing plant at Rokkosho nearing completion. All these plants rely on either EURATOM or IAEA safeguards. Over time, the French and the British have made continual improvements in the safeguards technology employed in these plants. The Japanese intend to carry this tradition of continual improvement forward by employing the most advanced safeguard approaches at the Rokkosho plant.

From a nonproliferation point of view, proponents argue that the system works well. Even though plutonium does exist in a pure state at some points in the separations process, strict safeguards measures are in place and there has been no diversion of plutonium in any part of this fuel cycle. Opponents argue that such technology is not appropriate for wide global use because of the potential for access to separated plutonium at some points of the fuel cycle.

To date, plutonium has been recycled once in LWRs, although numerous studies are underway to determine the number of recycles that may be practical. The limiting factor, other than economics, is the degradation of safety coefficients in the reactors themselves (such as the control rod worth, coolant temperature coefficient, and the coolant void coefficient). However, several concepts that allow multiple recycles have been shown to be feasible.

UREX WITH ACTINIDE SEPARATION AND DESTRUCTION

The UREX process being developed in the U.S. extracts uranium as a pure stream, with over 99.9% purity having been demonstrated in small pilot scale models. In this process the plutonium is not separated into a pure stream but always contains some neptunium, and the process could be configured such that this stream might include some higher transuranic isotopes as well. The most troublesome high-heat fission products, strontium and cesium, can separated as a separate stream. Technetium and iodine are likewise removable as a separate stream. Transmutation of the higher actinides is an integral part of this approach and the ultimate objective is to relieve the load on the geologic repository at Yucca Mountain. Transmutation could be accomplished either by recycling the higher actinides in LWRs or in Generation IV reactors.

There are several advantages associated with the UREX process combined with actinide separation and transmutation. By separating the uranium, cesium, strontium, plutonium, and minor actinides, and by transmuting the plutonium and minor actinides, it will:

- Reduce the mass per unit of spent fuel that must be ultimately stored in a geologic repository such as Yucca Mountain,

- More importantly, it will reduce the heat load per unit of spent fuel that must be put into the repository,

- It will significantly reduce or eliminate the need for additional repositories.

This is accomplished by separating Sr-90 and Cs-137 and storing them separately, and also by separating Am-241 and other higher actinides and either recycling them in LWRs or storing them above ground for later use in Generation IV reactors.

In the current research programs on the UREX process, plutonium and neptunium will remain together in a single stream. This provides a stream signature from a daughter product of neptunium that can be used to increase real-time detection capability. When this is combined with smaller material balance zones, the potential exists to increase nonproliferation attributes considerably.

This technology is currently only at the laboratory scale, but research plans are being developed for pilot scale experiments that will both demonstrate the process and the nonproliferation characteristics associated with the UREX technology.

DUPIC

A process intended to use spent fuel from Light Water Reactors in CANDU reactors is being developed in the Republic of Korea. This process is called Direct Use of Plutonium in CANDU Reactors, or DUPIC. The Republic of Korea is in the unique position of having several Light Water Reactors and several CANDU reactors operating in their power reactor fleet with approximately the correct distribution to support the DUPIC fuel cycle. Since the Republic of Korea is a very small country, geographically, and is very heavily populated, their ability to site an underground repository is especially difficult. Further, the spent nuclear fuel discharged from their LWRs still has sufficient fissile content to be loaded into their CANDU reactors. This unique combination provides considerable incentive for them to devise a way to postpone the waste disposition issue by reconfiguring the spent nuclear fuel from their LWRs into fuel that can be burned in their CANDU reactors.

The DUPIC concept separates only the volatile fission products and so any handling and subsequent refabrication must be performed in a highly radioactive environment. The Korean Atomic Energy Research Institute (KAREI) has constructed a large hot cell facility to conduct research and development on the entire DUPIC process. They

have conducted pilot tests of several assemblies of the new fuel in their CANDU reactors, and thus far, the tests have been encouraging.

The feasibility of adapting their process for use in the United States, however, is highly problematical. The United States does not have CANDU reactors. To implement such a process the United States would have to reload the fuel fabricated with the DUPIC process into existing LWRs. This would require the additional step of blending either plutonium or U-235 into the fuel system. And given the expense associated with employing hot fuel fabrication, the DUPIC process would be almost assuredly be opposed by the commercial fuel fabrication infrastructure in the United States.

INERT MATRIX FUEL

When large-scale nuclear reactor systems were envisioned as a result of President Eisenhower's Atom for Peace address to the United Nations in December 1953, there was general consensus that within a few decades inexpensive supplies of U_3O_8 would be diminished to the point that breeder reactors would become a necessity. Hence, the concept of purposely burning up plutonium would have been in total contrast to any national policy. However, given the combination of a much slower commitment to nuclear power than originally envisioned, plus the continuing availability of relatively inexpensive uranium, the policies of most nations (including that of the United States) are generally focused on either burning plutonium or storing it as spent nuclear fuel in a geologic repository.

In Switzerland, serious consideration is now being given to significantly reducing the plutonium produced by LWRs. The fundamental philosophy is to develop a fuel system such that the net production of plutonium is either zero or negligible. That has led them to a program based on non-fertile fuels, or fuel without U-238 in it, often called Inert Matrix Fuel (IMF). Stated differently, their approach is to load a fraction of the LWR core with non-fertile fuel that is incapable of producing plutonium. The Paul Scherrer Institute is carrying out research on diluents to mix with plutonium for one

subsequent recycle such that no additional plutonium is generated in the subsequent burn [JNM 2003]. Diluents such as zirconium oxide and magnesium oxide are under active consideration. With the approach currently being considered in Switzerland, reprocessing is required and so a pure plutonium stream will exist at some point in the fuel cycle.

Analyses performed to date indicate that this approach can burn in a single cycle most of the plutonium loaded into a non-fertile fuel rod. At least as important, it can degrade the plutonium isotopic composition considerably. While it may be possible to develop a nuclear weapon using this composition, it appears that nuclear weapon states have not considered it desirable as the fissile material in a deliverable weapon. Assessing the usefulness of degraded plutonium isotopic in a deliverable nuclear weapon was not part of this study, but will be assessed in separate studies.

As there is little irradiation data on the performance of IMF fuel, additional research needs to be performed. Also, additional research and design analyses need to be performed on the amount of IMF that can be loaded into a reactor core while still maintaining acceptable safety coefficients. Nevertheless, such a system could become a practical interim measure for reducing separated plutonium stockpiles and degrading plutonium isotopic composition.

THORIUM BASED FUEL

The use of thorium based fuels as a means to improve proliferation resistance was studied in both NASAP [DOE 1980] and INFCE [IAEA 1980]. At that time, almost all concepts used HEU as the fissile material and intended to recycle the U-233 produced by the fertile thorium. As such, they added some intrinsic proliferation resistance because of the 2.6 Mev gamma far down the Th-232 chain, but not enough to offset the need for of HEU. Studies have recently been performed on thorium fuel systems on the Once-Through Cycle with more proliferation resistance [ANFM 2003]. Analyses on these systems shows that, with a seed and blanket concept, uranium with an

enrichment of less than 20% can be loaded and less plutonium is produced and its isotopic composition is highly degraded. Similar studies are being performed on cycles with reprocessing that are intended to bring the transuranics into equilibrium and reduce the load on the geologic repository. These systems have similar nonproliferation characteristics. Thorium based systems, while promising, were not reviewed by the Committee since they are not part of the Series One fuel under consideration in the AFCI program. Their nonproliferation characteristics may, however, be reviewed by the PR&PP effort that is part of Generation IV.

VI – OBSERVATIONS

NO SILVER BULLET

In reviewing the input provided, the Committee reaffirmed what is already known regarding proliferation resistance; namely, there is no silver bullet. If nuclear power is to be employed to produce electricity, there will always be some potential for fissile materials to be removed from somewhere in the commercial fuel cycle for non-peaceful purposes. It is important to note, however, that diverting special nuclear material from the back end of the commercial nuclear fuel cycle has not been the route to a weapons state. Rather weapons states have emerged through the use of dedicated facilities or though the abuse of research facilities. The use of the CIRUS research reactor by India is an example of the latter.

We might inquire why the closed fuel cycle has not been successfully used so far for illicit purposes. First, the isotopic quality of plutonium discharged from a power reactor is considerably less desirable for weapons use than plutonium from a production reactor, where it is discharged early to prevent the buildup of Pu-238 and Pu-240. Secondly, in the life cycle of a fuel element, there is only a short time during the reprocessing step that fissile fuel is in either pure or relatively pure form, and there are internationally-accepted IAEA safeguards systems protecting such material (assuming that the nation state is a signatory to the Nuclear Nonproliferation Treaty).

Nonetheless, such safeguards are not absolute guarantees and any improvement in the nonproliferation regime (either technical or institutional) is warranted and welcome.

The charter of this Committee was to focus on Series One fuel, defined earlier in the AFCI as fuel discharged from LWRs with the potential for recycle, and so this study concentrated on the back end of the fuel cycle. Hence, plutonium is the principal special nuclear material of concern. The Committee does recognize, however, that a uranium isotopic enrichment step is necessary to provide the initial fuel load. Therefore, potential vulnerabilities in the front end of the fuel cycle will be briefly discussed later in this report.

FUEL CYCLES ARE UNIQUE TO NATIONAL SITUATIONS AND INFRASTRUCTURE

Given the sensitivities and philosophies associated with non-proliferation issues, perceptions sometimes arise that the approach taken by any nation on the nuclear fuel cycle will establish an immediate precedent for subsequent actions of other nations. This perception is especially prevalent for the United States, given the dominant role that the United States plays in the global economic balance. But regardless of perceptions, the fact is that each nation has a different set of drivers regarding the nuclear fuel cycle and these determine its national behavior.

In the 1970s and 1980s, both France and the United Kingdom perceived a large and growing market for fuel recycle services. This perception may have been enhanced when the United States decided to forgo reprocessing in the late 1970s. Both France and the United Kingdom made substantial investments in reprocessing capability at La Hague and Sellafield, and have since sold and preformed reprocessing services for several nations. The driving force was market share and market positioning in what, at the time, was envisioned to be a large and profitable international market.

The Republic of Korea, as mentioned previously, has few possibilities for a geologic repository but does have a unique incentive to process fuel discharged from their

LWRs for refabrication and insertion into their CANDU reactors. This provides additional energy from the original fuel investment, along with a process to both enhance significant intrinsic proliferation resistance and delay the time for ultimate repository disposal of waste products.

The Swiss have developed a political mandate to not build up excess plutonium stocks or put separated plutonium into a repository. This has led them to an approach with the potential to burn down plutonium stocks as rapidly as possible. To achieve this, research is being conducted collaboratively by the Paul Scherer institute and the nuclear utilities on fertile-free fuel.

An important driving force in the United States, on the other hand, is to maximize the use or capacity of Yucca Mountain and avoid the need for a second geologic repository. Given the lengthy process to select and characterize a site for a geologic repository, there is little incentive to go through the process for a second siting any time soon. Hence, studies are being carried out in the United States to investigate fuel cycles that have the potential to enhance the lifetime of Yucca Mountain.

The fuel cycles reviewed by the Committee are all located in nations with long-established nuclear traditions and infrastructures. These nations all have agencies such as the DOE, CEA, UKAEA, or JAEC with long experience in the nonproliferation regime. They have experts on IAEA and EURATOM safeguards, international treaties such as the Treaty on the Nonproliferation of Nuclear Weapons, as well as experts on the nuclear fuel cycle. These nations tend to be suppliers of reactors, fuel, and other fuel cycle services and do so within the existing nonproliferation regime.

ALL FUEL CYCLES INCORPORATE PROLIFERATION RESISTANCE BUT DO SO BY DIFFERENT MEANS

Tempting though it may be, it is inappropriate to glibly label some fuel cycles as proliferation resistant and others as not. All fuel cycles of which the Committee is aware, that are either operating or being considered for operation in responsible politically stable countries, do incorporate proliferation resistance of considerable significance.

It is true that some are more proliferation resistant than others. For instance, the DUPIC process incorporates intrinsic measures to an exceptional degree. All SNM must be contained within a hot cell during the entire reprocessing and fuel fabrication process because of the intense radiation barriers. However, intense radiation fields do not absolutely preclude the possibility of proliferation. Indeed, it is possible to attain a significant measure of proliferation resistance without relying upon intense radiation fields. The EURATOM and IAEA safeguards employed at La Hague and Sellafield attest to both the acceptance and utility of extrinsic approaches. In addition to the natural physical and radiation barriers present, IAEA cameras and other detection devices are strategically located in numerous places throughout the process to constantly monitor the flow of material. The UREX process being proposed for the U.S. will incorporate all of these safeguards, plus many more. This will be outlined later in this report.

ONCE-THROUGH FUEL CYCLES USE THE SPENT FUEL STANDARD AS A BASIS

The current practice in the U.S. is the Once-Through fuel cycle. Although spent fuel is stored for several years at the reactor sites, the current policy dictates that it will be sent to Yucca Mountain for permanent disposal. Since proliferation resistance is not

absolute (any more than safety is absolute), the Spent Fuel Standard has become a reference point for comparing the proliferation resistance of any other fuel cycle.

INTRINSIC PROLIFERATION RESISTANCE OF THE ONCE-THROUGH CYCLE IS DECREASING WITH TIME

At this point we must clearly recognize that simply placing spent nuclear fuel into a geologic repository does not "solve" the nonproliferation problem. The radiation barrier surrounding the spent nuclear fuel continually decays away. Since plutonium has a half-life much longer than the fission products (with the exception of Tc-99 and I-129), this naturally leads to what some people refer to as a "plutonium mine" if left in place long enough. The intrinsic proliferation resistance of the once-through cycle clearly decreases with time.

IMPLICATIONS OF THE TIME DEPENDENCE OF PROLIFERATION RESISTANCE

To illustrate the time-dependence of proliferation resistance, Figure 1 shows the intrinsic proliferation resistance measure of a fuel assembly for the Once-Through Cycle versus the Closed Cycle (Recycle). The ordinate neglects the short-lived fission products and is arbitrarily set to unity based upon decay of the long-lived fission products such as cesium and strontium. The radiation field surrounding the assembly displayed by the ordinate is consistent with that of the Spent Fuel Standard. Whereas there are several factors that influence the total proliferation resistance, the decline of the radiation barrier is the most obvious. Since the primary radiation barrier is supplied by Sr-90 and Cs-137 for the first several decades, the illustration of Figure 1 is constructed around a 30-year half life. Hence, the proliferation resistance measure drops to about 25% of its original value in two half-lives, i.e. 60 years.

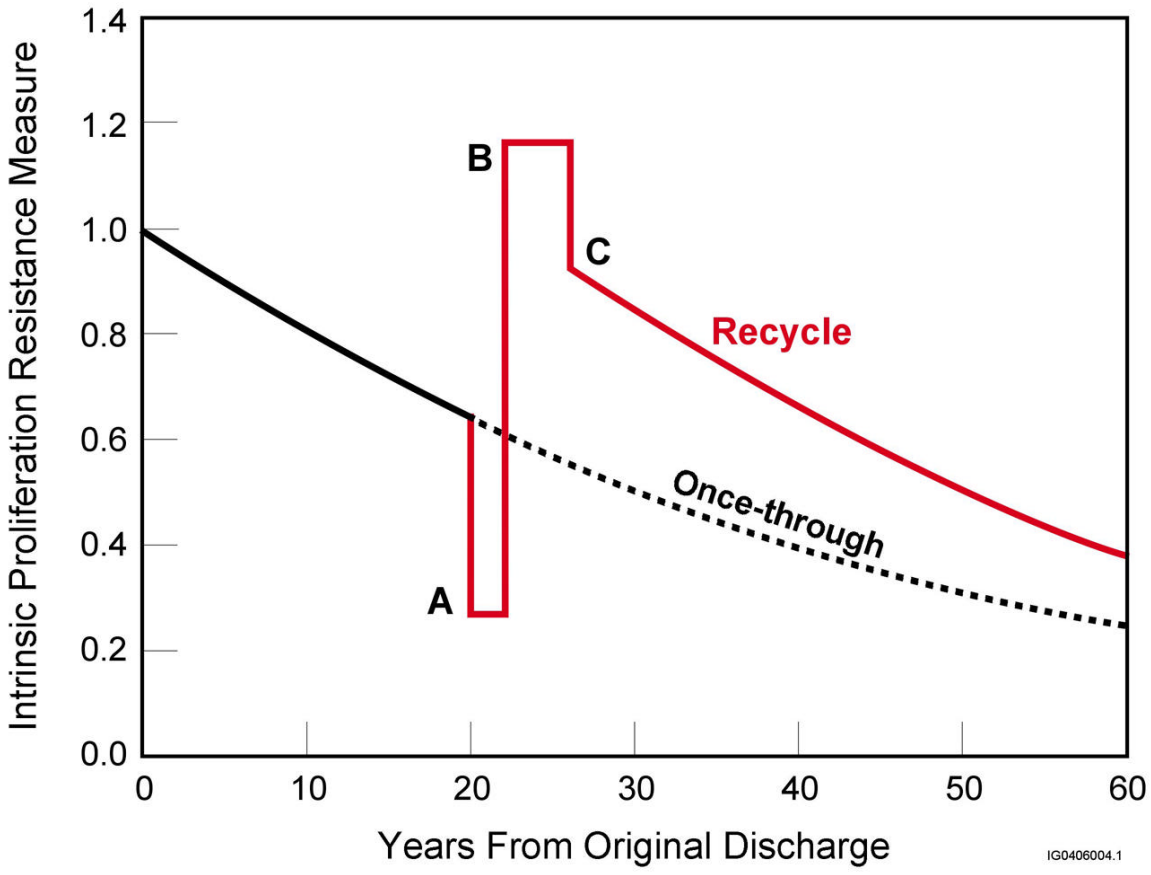

Figure 1 – Intrinsic Time-Dependent Proliferation Resistance Measure of a Single Fuel Assembly

If, on the other hand, the subject fuel assembly is taken to a reprocessing plant and the fissile ingredients are extracted, put into a new fuel assembly, and then inserted into a reactor for an additional burn, the proliferation resistance changes significantly. Point A on the illustration indicates the drop in proliferation resistance during chemical processing. There are several reasons for the decrease in proliferation resistance measure at this point: the loss of item accountability when the fuel pins are chopped and the uranium oxide is leached from them, the loss of the radiation barrier when fission products are extracted, and the increased difficulty in accountability while the special nuclear material is in liquid form. When fissile material is put back into a solid fuel form, however, the proliferation resistance of this fuel assembly increases—primarily due to reversal of the above items. When placed back into a reactor, the

proliferation resistance is highest because the radiation barriers are exceptionally high and any attempts at access are easily detected. That is designated as point B. Point C represents the time of discharge of the fuel from this second burn cycle. The proliferation resistance drops, because the physical protection of the reactor is gone, as well as the exceptionally intense radiation level. However, the proliferation resistance at that point is considerably higher than would be the case if that fuel assembly had been sitting in a Once-Through Cycle, since the radiation barrier has been restored by the second burn. At that point, the assembly is assumed to cool and the radiation barrier drops according to the fission product decay.

The key observation to be drawn from this comparison is that the integrated proliferation resistance of recycling the fuel could be greater than the Once-Through Cycle—even if assessed over just the first 50 to 100 years. This is in stark contrast to the mantra often espoused by those who oppose recycle on the grounds that it cannot be tolerated for nonproliferation concerns.

We hasten to say, however, that there is a time interval during the fuel recycle process where the proliferation resistance measure of the fuel assembly is lower than the Once-Through Cycle; namely, point A. Further, in any large operation, point A will always exist somewhere in the overall system. Hence, any illegitimate access would likely focus attention on point A (i.e. the most vulnerable point) if other barriers (guns, gates, and guards) didn't exist in sufficient force.

In that regard, we first note that the duration of the reprocessing step is limited in time. We used a time frame of two years in this illustration, although any given fuel assembly would experience a considerably shorter time in a fully commercial operation. The actual magnitudes of points A, B, and C were developed using a nonproliferation analysis technique known as Multi-Attribute Utility Analysis [Charlton 2004]. This technique has been under development for the last two decades [Heising 1980 and Charlton 2003]. While highly analytical in nature, it does have the ability to identify vulnerable points in the fuel cycle and provide a quantative assessment of the

extent of this vulnerability. It thereby allows the designer, the researcher and the developer of technology to concentrate their efforts on those areas where they will be most productive. In terms of Figure 1, it is to reduce the gap between the Once-Through cycle and point A. This gap reduction can be achieved by either advanced safeguards (extrinsic measures) of by recycling higher actinides (intrinsic measures).

With respect to advanced safeguards, one can take advantage of evolutionary improvements from the present systems in the United Kingdom and France. Based upon their experience, new designs can incorporate smaller material balance zones and can utilize improved technology for the measurement of special nuclear material concentrations. Such measures have been included in the new Rokkosho plant in Japan, and recent studies indicate that additional improvements can be obtained.

The AFCI program is currently conducting research and development of the UREX process that will remove essentially all of uranium as the first step in the extraction process. This will allow the use of a plasma-atomic emission spectroscopy approach capable of measuring remaining materials much more accurately due to the absence of resonance U-238 peaks. Also, substantially increased sensitivity is available to measure beta and gamma emissions from the remaining material once the Sr-90 and Cs-137 is removed. If Np-237 is left with the plutonium, as in the current flowsheet, it is possible to use the gamma signal from Pa-233 (a daughter product of Np-237) to monitor the plutonium stream and detect potential diversion. Finally, smaller control volumes are part of the basic design, a key factor in assuring accountability. This is partially accomplished by using centrifugal contactors for the plutonium-neptunium extraction step. Such contactors are smaller than comparable containers for either the mixer-settler or pulsed column approaches previously used, and the extraction step is much faster. In addition, reducing control volumes by limiting the number of intermediate tanks is also employed.

There are undoubtedly other technical innovations that can be considered for incorporation into the separation steps to provide enhanced safeguards. One such

technology is based upon the use of a nuclear resonance fluorescence approach under active development by Passport Systems. Based on the sensitivities that their developmental process has been able to achieve to date, this looks like a promising technology for potential incorporation into the new reprocessing plant. Such technologies may allow continuous monitoring of special nuclear material, a very significant improvement over previous methods.

Incorporation of the appropriate blend of technologies at point A could substantially reduce proliferation concerns at this point of vulnerability—thereby further enhancing the proliferation resistance characteristics of Recycle versus the Open (or Once-through) fuel Cycle. This potential is illustrated in Figure 2.

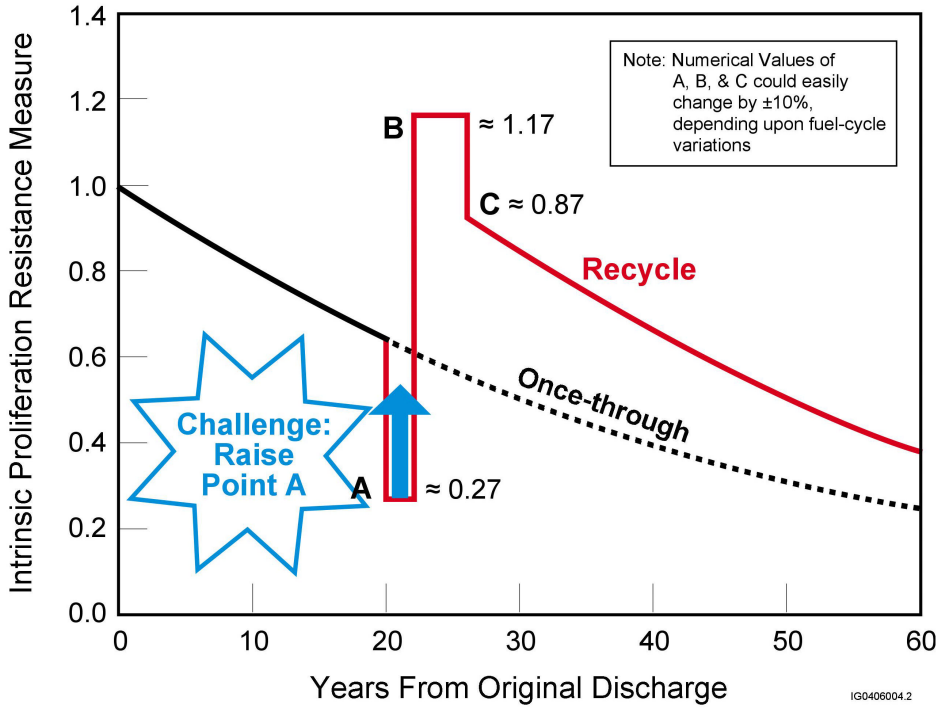

Figure 2 – Potential Impact of Improved Safeguards

A COMPARISON OF THE PROLIFERATION RESISTANCE OF VARIOUS FUEL CYCLES

The Committee recognizes the fact that numerous approaches have been developed for providing metrics to evaluate the proliferation resistance of various fuel cycle systems. To date, there has not been any particular set of metrics that has enjoyed universal acceptance. However, the Multi-Attribute Utility Analysis approach developed within the AFCI program by Professor Charlton [Charlton 2004] appeared to the Committee to contain sufficient capability to at least provide a reasonable comparison of various fuel cycle options. Hence, we asked Professor Charlton to run calculations for the four scenarios considered in this report; namely, PUREX/MOX, UREX/MOX, DUPIC, and IMF. Given the substantial differences in these four approaches, we felt that a comparison of the proliferation resistance of such cycles should provide valuable perspective.

The Multi-Attribute Utility Analysis has the advantage of allowing the user to employ a variety of weighting factors, selected to best represent the relative importance of the various factors contributing to nonproliferation effectiveness. For the cases presented in this report, we used the weighting factors listed in Table I (page 36). These values were obtained by Professor Charlton via systematic consultations with numerous nonproliferation experts from the U.S. weapons laboratories.

Figure 3 shows in some detail the proliferation resistance measure calculated by Professor Charlton for the standard PUREX/MOX cycle and the Once-Through Cycle. We use this as a reference point, since the PUREX/MOX cycle is in actual commercial use in major parts of Europe and it will be shortly employed in Japan. We need to emphasize at the outset that one should not place too much emphasis on the absolute values presented. There are many weighting factors that the user needs to specify in conducting such an analysis. The particular factors chosen for this illustration were derived by Professor Charlton, based on substantial input from many non-proliferation experts from several institutions who participated in this AFCI endeavor. Hence, we should have at least some degree of confidence in the approach. It is important to

note the time-dependence of the proliferation resistance and then be able to compare the changes in such resistance for different fuel recycling options.

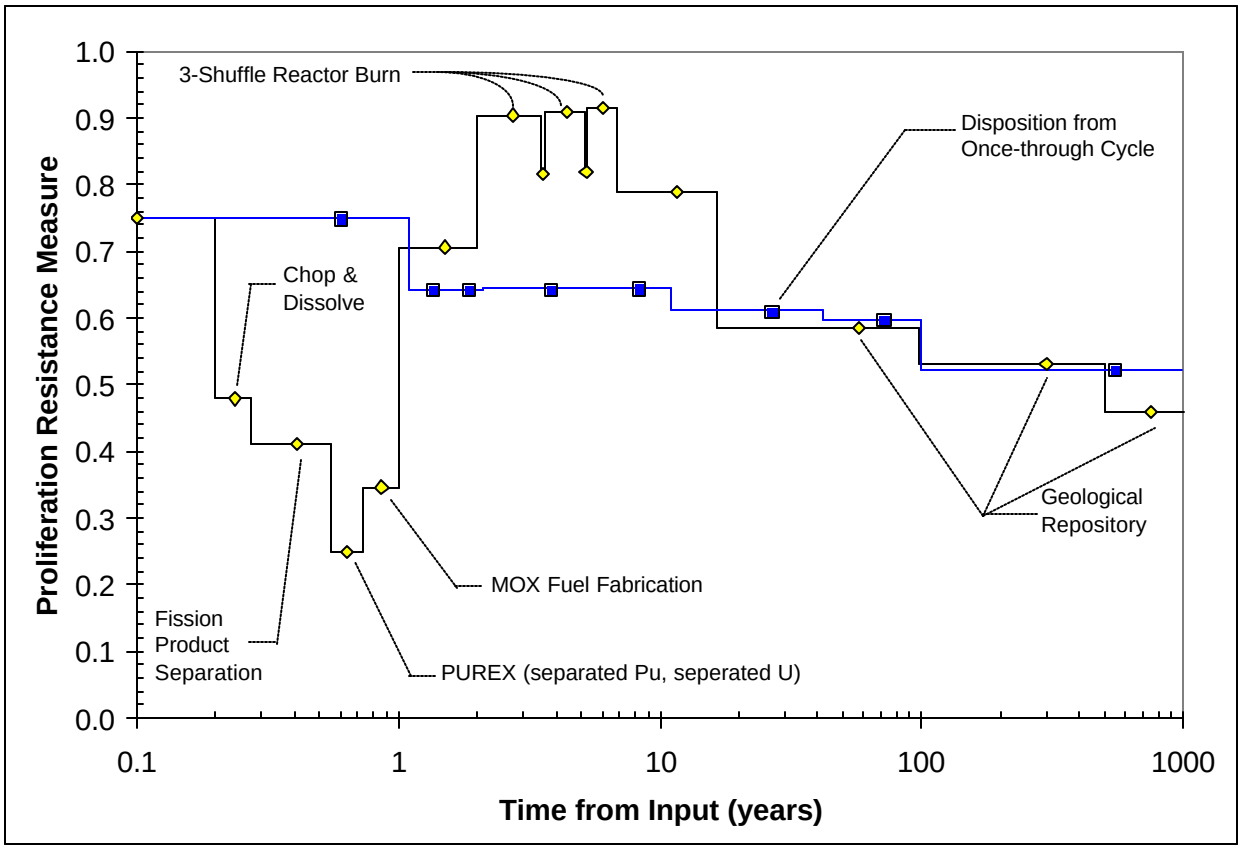

Figure 3 – Relative Proliferation Resistance Measure as a Function of Time for the PUREX/MOX Process (back-end of once-through cycle shown for comparison)

Figure 3 shows the proliferation resistance measure of the assembly as it changes while it moves through the various steps of PUREX reprocessing, MOX re-fabrication, reactor burning, and ultimate disposition in a repository, all with traditional safeguards. The Once-Through Cycle is shown for comparison. The proliferation resistance measure of 0.75 at the start of the analysis reflects fuel that has been discharged and

allowed to cool for twenty years. We should note that the time is recorded logarithmically—certainly convenient for understanding the time-dependence of the steps taking place over a short time interval, but perhaps misleading if one wants to obtain a long-term perspective of proliferation resistance.

We note from Figure 3 that the proliferation resistance measure drops when the assembly is mechanically chopped and dissolved in the processing plant. The proliferation resistance drops further when the fission products are separated out (since the principal radiation barrier has been removed). The lowest value of the proliferation resistance measure occurs when the plutonium is separated out as a pure stream from the uranium.

Once the plutonium is blended with uranium in the form of a MOX fuel element, the proliferation resistance measure begins to rise due to item accountability. The proliferation resistance rises substantially when the new MOX fuel elements are inserted into the reactor for recycle. At this point, the proliferation resistance measure is higher than that of the Once-Through Cycle. This position provides the maximum physical protection and the highest radiation barrier. This particular scenario assumes that the fuel is shuffled three times during the overall burn cycle. Hence, there is a drop in the proliferation resistance measure when the reactor cover is off for refueling and fuel shuffling. Finally, the fuel assembly is discharged from the reactor, sent to storage for a 10-year cool-down, and then put into geologic storage. The small drop in the proliferation resistance measure over the longer term (500 years and beyond) is due primarily to the loss of the radiation barrier and heat production capability. For several hundred years, however, the proliferation measure is quite similar to that of the Once-Through Cycle.

Figure 4 contains a comparison of the proliferation resistance measure as a function of time for the four cycles under consideration. Although these four fuel cycles are quite different, they do not have monumental differences in their proliferation resistance

measure. The proliferation resistance value of the PUREX/MOX cycle is, indeed, the lowest during processing, but not substantially different than either the UREX/MOX cycle or the IMF cycle. Over almost all of the time period, the IMF has the highest proliferation resistance measure because of its ability to burn plutonium without creating more as well as its ability to degrade the plutonium isotopic composition considerably. The values shown for the IMF could be higher than shown if future studies indicate that plutonium with a highly degraded isotopic composition is not desirable in a deliverable weapon. The DUPIC cycle does show more proliferation resistance during reprocessing and refabrication, due to the constant radiation barrier that remains throughout the processing steps. However, the proliferation resistance measure for DUPIC is less than the other three cycles once the fuel is recycled and eventually placed in the repository because of the higher generation of plutonium in the CANDU cycle. This observation suggests that a total focus on the reprocessing step itself, a temptation that has attracted the attention of many opponents of closing the fuel cycle, may be inappropriate.

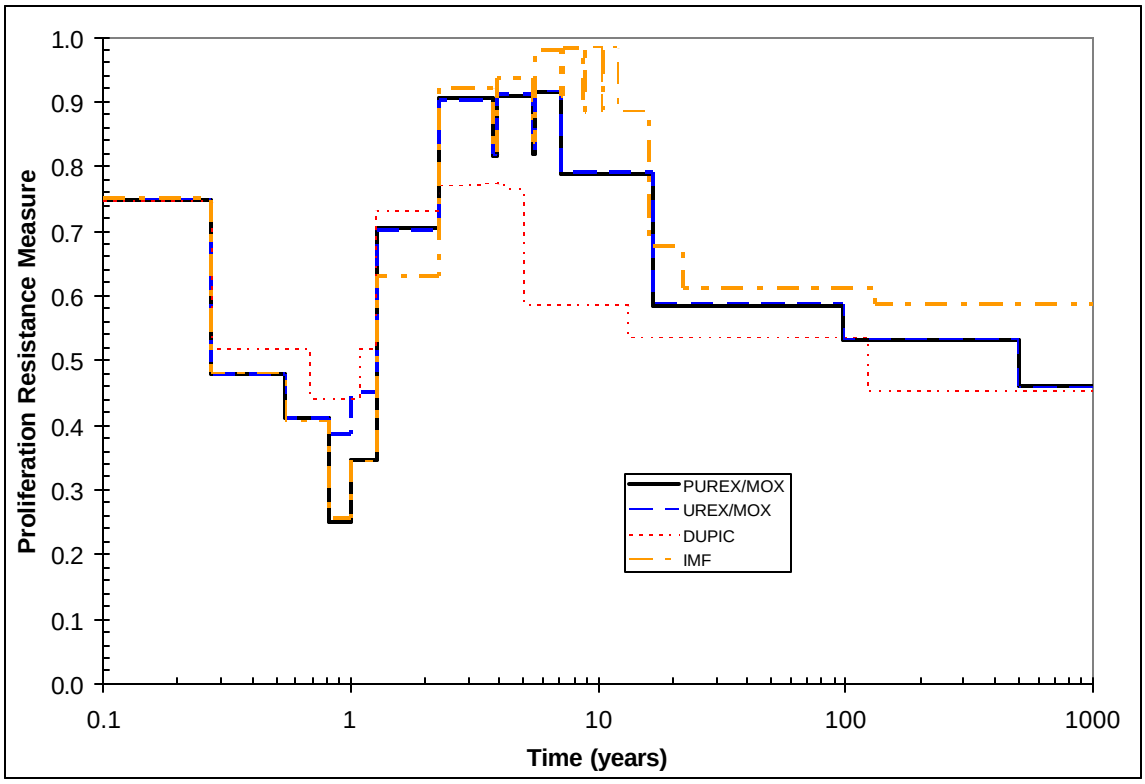

Figure 4 – Proliferation Resistance Measure of a Single Fuel Assembly as a Function of Time for Four Fuel Cycles

IMPLICATIONS OF OTHER PARTS OF THE FUEL CYCLE

The primary focus of the present study was the back end of the fuel cycle. But without taking into account the entire fuel cycle, it is possible to draw misleading conclusions. Figure 5 shows the entire fuel cycle and places the proliferation resistance of the back end of the cycle into perspective. The back end of the fuel cycle in this case is the UREX process with neptunium doping and typical IAEA safeguards as specified in INFCIRC/153 [IAEA 1972].

Note that enrichment and reprocessing are the two vulnerable regions of the fuel cycle, with reprocessing being slightly more vulnerable than enrichment with typical IAEA

safeguards. But the magnitude of either depends upon the safeguards employed as shown by the brackets in the figure. The reference case for both enrichment and reprocessing in this figure is based on typical IAEA safeguards as defined in INFCIRC/153 [IAEA 1972]. The safeguards ranges for both enrichment and reprocessing show the effect of variations in the applications of these safeguards. At the upper end of the safeguards range, the proliferation resistance of the UREX process with neptunium doping is roughly equivalent to that of enrichment with typical safeguards. And also at the upper end, the proliferation resistance of the UREX process with neptunium doping is roughly equivalent to that of spent fuel in the geologic repository. Stated differently, the proliferation resistance measure of UREX with neptunium doping and highly advanced safeguards is roughly equivalent to the Spent Fuel Standard. Neptunium doping consists of adding neptunium to both the fresh fuel and to the recycle fuel to build up Pu-238 as quickly as possible.

The proliferation resistance measure is affected by the level of safeguards and the physical characteristics of the facility. Specifically, the following extrinsic attributes influence safeguards effectiveness and the proliferation resistance measure:

(1) Frequency of measurement
(2) Measurement uncertainty
(3) Percent of the processing steps that use item accounting
(4) Probability of unidentified movement
(5) Physical barriers

To evaluate the range over which safeguards can change the proliferation resistance values, four safeguards levels were studied: (a) no safeguards, (b) typical IAEA safeguards as defined by INFCIRC/153, (c) enhanced safeguards as defined by INFCIRC/540 [IAEA 1997], and (d) highly advanced or ideal safeguards. These four application levels determine the range of safeguards indicated by the brackets in Figure

5. Ideal Safeguards include features and innovations that are being considered in research and development being performed on the UREX cycle in the AFCI program. Examples of features contributing to Ideal Safeguards are:

(1) Continuous real-time monitoring,
(2) Measurement uncertainties below 0.2% (essentially achievable only with mass spectrometry) with a material unaccounted for (MUF) of less than 0.02 of a Significant Quantity per month,
(3) A containment/surveillance system that decreases the probability of unidentified movement of material to below 0.2%, and
(4) Physical barriers that limit human access to the material at all times during processing, except initial input and the final product, to the extent practical.

While the application of Ideal Safeguards to the UREX cycle will require additional research and development and may increase the facility and production cost, they are not unrealistic. Additional UREX research and development, combined with advances in computational and communications systems, could very well make this goal achievable in the near future. As a step toward this goal, the AFCI program is currently engaged in discussions on the application of Enhanced Safeguards to the program as defined in INFCIRC/540.

Research and development is currently being conducted on both neptunium and americium doping in the AFCI. With neptunium doping, neptunium is added to both the fresh fuel on the front end of the fuel cycle and to the recycle fuel on the back end. With americium doping, Am-241 is not separated during the UREX process and so is only added to the recycle fuel. The effect of doping with both elements is shown in Figure 6. Note that adding both elements raises the proliferation resistance of the UREX process to the extent that its proliferation resistance is almost equivalent to that of the geologic repository at longer times. And with Ideal Safeguards, the conclusions noted earlier hold.

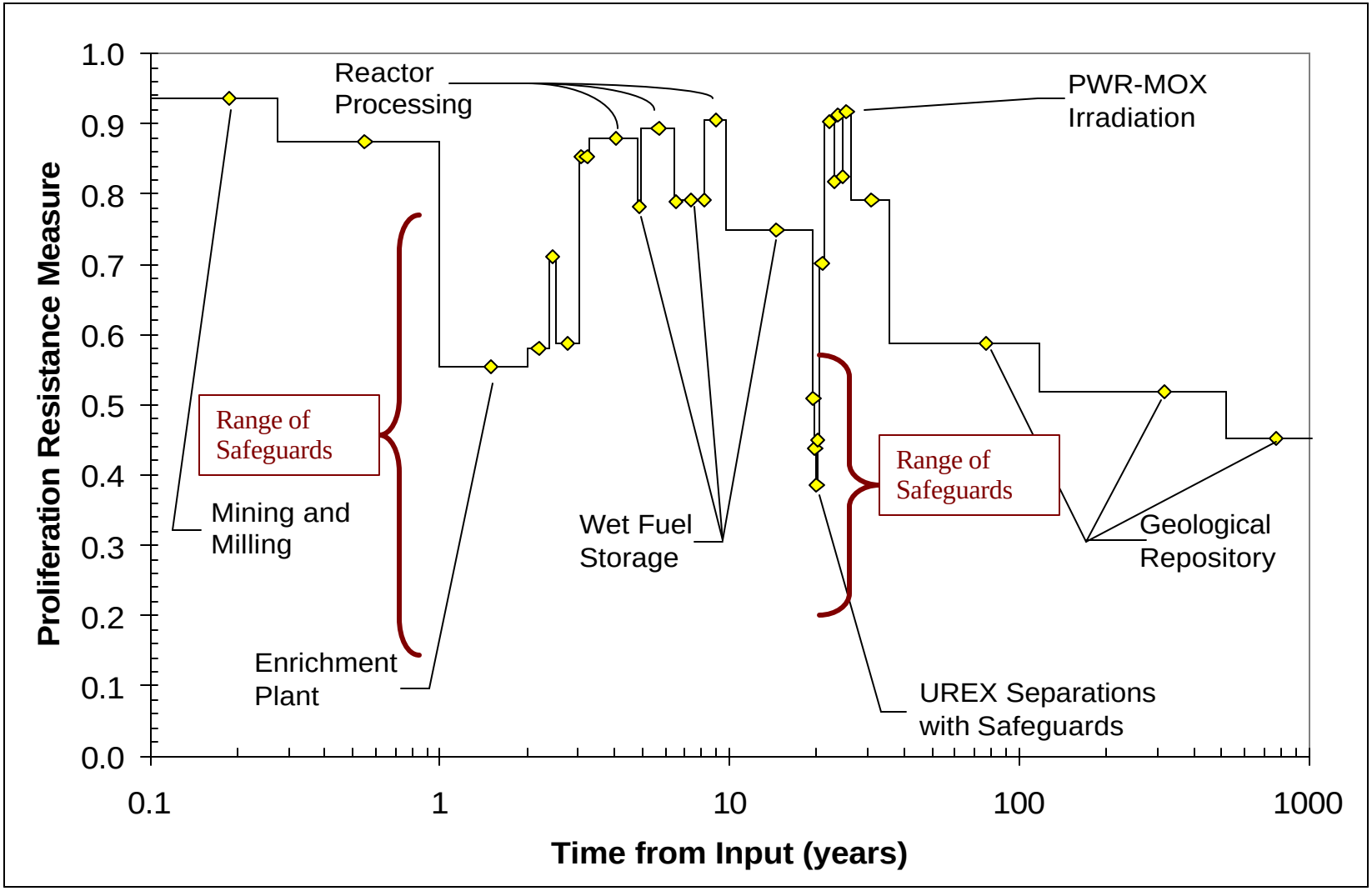

Figure 5 – Proliferation Resistance Measure of a Single Fuel Assembly for All Steps in the Fuel Cycle with UREX and Neptunium Doping

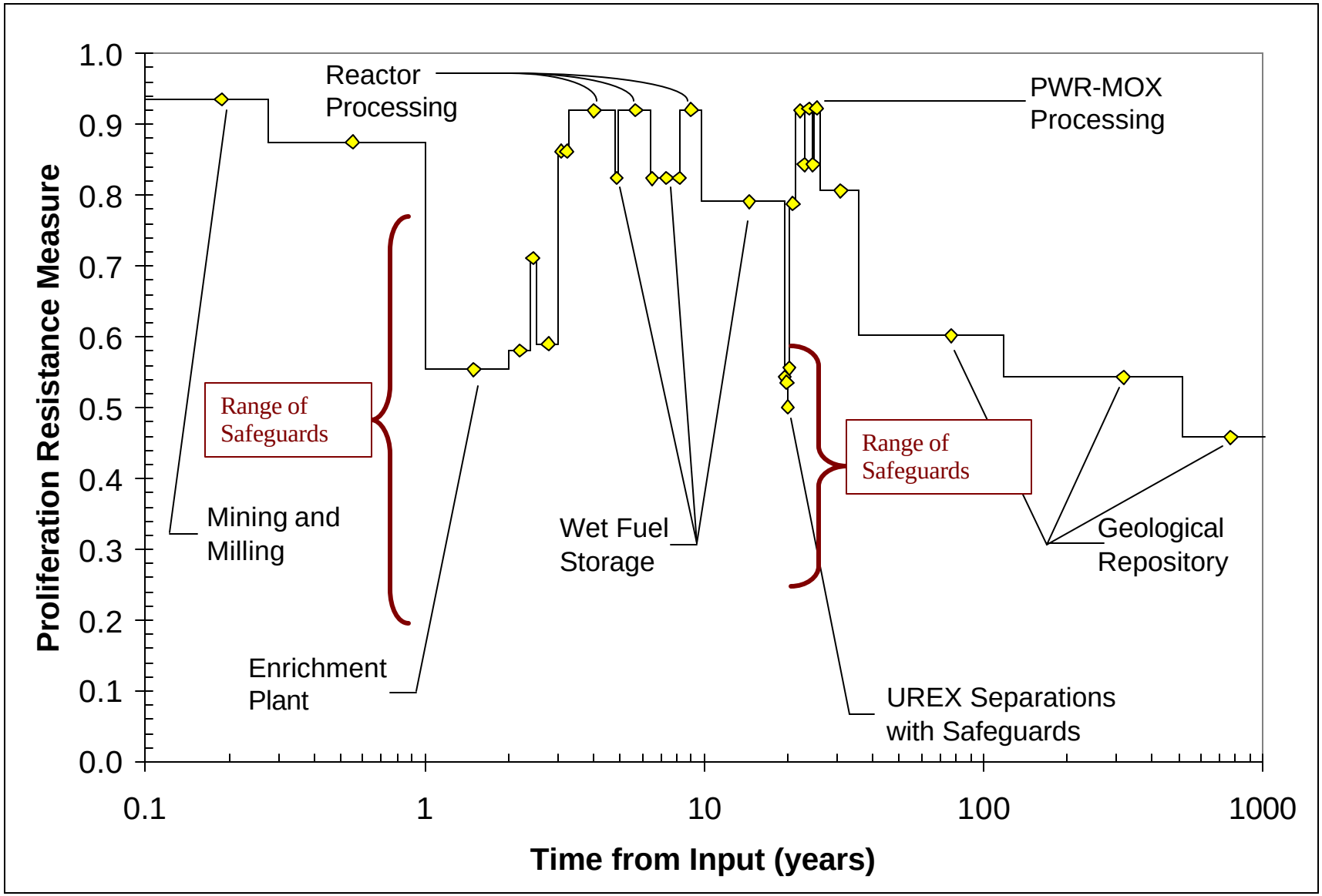

Figure 6 – Proliferation Resistance Measure for All Steps in the Fuel Cycle with Both Neptunium and Americium Doping

In addition to the time-dependent measure of proliferation resistance discussed above, a time integrated measure can also be developed [Charlton 2004]. Given a system that involves a sequence of processes, *i=1,2,3,...I*, the total nuclear security measure (*NS*) for the system can be determined using the following:

$$NS = \frac{\sum_{i=1}^{I} m_i \cdot \Delta t_i \cdot PR_i}{\sum_{i=1}^{I} m_i \cdot \Delta t_i} \ .$$

In this equation, m_i is the amount of material in process *i* in Significant Quantities (SQ) and ? t_i is the time the material is in process *i* at the static proliferation resistance value of PR_i for process *i*.

The static proliferation resistance value of process *i* is given by

$$PR_i = \sum_{j=1}^{J} w_j u_j(x_{ij})$$

where w_j is the weight for attribute *j*, u_j is the utility function for attribute *j*, and x_{ij} is the input value for the utility function for attribute *j* in process *i*. Each of the attributes (along with their overall measure and weighting factors) for the present assessment is given in Table I [Charlton 2004]. Items (1) through (6) might be described as intrinsic measures as they are inherent to the material or system while items (7) through (14) might be described as extrinsic measures because they are administrative or engineering measures.

TABLE I

Measures, Attributes, and Weights for the Present Assessment Methodology

Measure	j	Attribute	Weights
Attractiveness Level	1	DOE attractiveness level (IB through IVE)	0.10
	2	Heating rate from Pu in material (Watts/kg)	0.05
	3	Weight fraction of even Pu isotopes	0.06
Concentration	4	Concentration (SQs/MT)	0.10
Handling Requirements	5	Radiation dose rates (rem/hr at a distance of 1-meter)	0.08
	6	Size/weight	0.06
Type of Accounting System	7	Frequency of measurement	0.09
	8	Measurement uncertainty (SQs per year)	0.10
	9	Separability	0.03
	10	% of processing steps that use item accounting	0.05
Accessibility	11	Probability of unidentified movement	0.07
	12	Physical barriers	0.10
	13	Inventory (SQs)	0.05
	14	Fuel load type (Batch or Continuous Reload)	0.06

The total nuclear security measure is a time and mass weighted average of the proliferation resistance measure. The mass values used are in Significant Quantities, which are defined by the International Atomic Energy Agency (IAEA) as: 8 kg for plutonium, 25 kg for high-enriched uranium, 75 kg for low-enriched uranium (LEU), 25 kg for Np-237, 25 kg for Am (as an element), and 20,000 kg for thorium (as an element). Note that this methodology accounts for a variety of possible weapons materials and uses the unit of Significant Quantities to normalize between them. The total nuclear security measures for the systems under review in this study are shown in Table II below for the first 100 years [Charlton 2004]. In each case, typical IAEA safeguards are assumed [IAEA 1972].

Conventional thinking says that any closed fuel cycle will have a lower total nuclear security measure than the Once-Through Cycle. In Table II, however,

three fuel cycles have a total nuclear security measure at least equal to or slightly greater than that of the Once-Through Cycle. While the increase is not large, it does contradict conventional wisdom that any recycle will have a lower total nuclear security measure. The three fuel cycles with a higher measure are the IMF fuel with the UREX process, UREX with neptunium doping, and UREX with neptunium and americium doping. The reasons are largely due to plutonium consumption and isotopic degradation in the case of the IMF, plutonium isotopic degradation due to Pu-238 buildup in the case of UREX with neptunium doping, and Pu-238 buildup and the radiation barrier in the case of UREX with neptunium and americium doping. Note that the IMF has the highest proliferation resistance measure, followed by UREX with doping. A more detailed discussion of the Multi-Attribute Utility Analysis methodology used in this report is provided in Appendix C.

TABLE II

Total Nuclear Security Measures Integrated Over One Hundred Years

Cycle	Total Nuclear Security Measure
Once-Through PWR Cycle	0.657
LWR MOX w/ PUREX	0.641
LWR MOX w/ UREX	0.644
Inert Matrix Fuel w/ UREX	0.746
UREX with Np Doping	0.664
UREX with Np and Am Doping	0.665

VII – RECOMMENDED APPROACH

After considerable deliberation, the Committee concluded that the baseline approach under development by the United States should be acceptable from a nonproliferation point of view since it contains many proliferation-resistant attributes. The approach can be summarized as further developing the UREX process to extract essentially all of the uranium from the spent nuclear fuel, separating Sr-90 and Cs-137 as well as Tc-99 and I-129, separating the higher actinides such as americium and curium, and separating plutonium and neptunium together in the same stream for recycle. The Sr-90 and Cs-137 would be stored above ground long enough to decay to insignificant levels or used for commercial purposes. The actinides would be recycled using transmutation fuel loaded into existing LWRs or stored above ground for eventual use in a Generation IV reactor. Preliminary calculations indicate that the actinides could be stored in a manner that would be self-protecting for about fifty years. Very little waste would be stored in the geologic repository – thus increasing the capacity of Yucca Mountain and significantly reducing or eliminating the need for a second repository.

This approach, with properly incorporated nonproliferation attributes, has the potential to raise the nonproliferation bar. One of the advantages of retaining neptunium with plutonium is to burn the neptunium along with the plutonium. Another is to take advantage of the Pa-233 daughter product of Np-237, such that the 312 KeV photon provides a constant and readily detectable tracer for monitoring the plutonium stream. Further, the transmutation of Np-237 in the reactor produces some Pu-238, which contributes to intrinsic proliferation resistance due to both spontaneous fission and to the heat generated by alpha decay. This could make the material less attractive for weapons applications. This has the advantage of raising the value of Point A in Figure 2 using a purely intrinsic approach.

Other approaches that degrade the plutonium isotopic composition and also burn considerable amounts of plutonium, such as the IMF, have the potential to raise the nonproliferation bar further. IMF has the largest potential in this regard, but will require additional research and development. There is a scarcity of irradiation data on such fuels, and although preliminary research and development is being conducted by AFCI, additional research has been recommended [Richter 2004].

Adding higher actinides to the recycled fuel, such as americium or curium, would substantially enhance proliferation resistance. Although the results are not conclusive, recent research and development indicates that adding americium may increase difficulties associated with fabrication [Willson 2004]. Additional research and development has been recommended [Richter 2004] and will be conducted, and this may show that americium bearing fuel can be readily fabricated, but such is not the case at the present. Therefore inclusion of americium or curium is not recommended for LWR fuel with the potential for recycle at this time, although future research and development could change this.

The recommendations above are largely intrinsic, but extrinsic proliferation resistance attributes can also be used to raise Point A in Figure 2. These would involve institutionalizing proliferation resistance attributes as part of the fundamental design process. As an example, such attributes should be a fundamental part of the Functions and Requirements and the design would be reviewed against such requirements. This would ensure that advanced safeguards technology would be incorporated into the design whenever practical. It would also ensure that smaller material balance zones would be incorporated into the design to the extent practical. Designer ingenuity and innovation in the proliferation resistance area should be incorporated in a systematic manner early in the design process.

It is possible, of course, that policy or other considerations may dictate a strategy for raising the proliferation resistance bar other than the one outlined in this report. Should this be the case, it may be necessary to consider an alternate nonproliferation strategy. There may be merit in giving serious consideration to the concept of reactor states and fuel cycle states. The former category would include any nation that desires access to nuclear power, but lacks the historical record of governmental stability and accountability necessary to take on the burden of the full fuel cycle. Such nations would have reliable access at reasonable cost to fuel for civilian reactors so long as they do not engage in enrichment and reprocessing [Bush 2004]. The primary attributes of such a system would be that any nation sincerely desiring the benefits of nuclear power could have such access without the need to make the heavy investments necessary to undertake the establishment of the entire fuel cycle infrastructure. The nonproliferation attributes are obvious.

VIII – CONCLUSIONS

The Committee concluded that the research and development being conducted on advanced fuels in the AFCI on the UREX process has the potential for a major nonproliferation advance and can raise the bar with respect proliferation resistance. Specifically:

- The research and development being conducted on advanced fuels in the AFCI program on the UREX process has the potential for a major nonproliferation advance and can raise the bar with respect to proliferation resistance,

- The time integrated proliferation resistance measure of a fuel cycle intended to transmute minor actinides, if properly designed, has the

potential to be roughly equal to that of the Spent Fuel Standard; the Inert Matrix fuel cycle is particularly notable in this regard,

- Properly recycling higher actinides for additional intrinsic proliferation resistance and employing highly advanced or ideal safeguards features for additional extrinsic proliferation resistance has the potential to increase the proliferation resistance measure of the more vulnerable points in the fuel cycle (both enrichment and reprocessing) to approximately that of the Spent Fuel Standard, and

- Elements of highly advanced safeguards features and innovations are under consideration in the research and development being performed on the UREX process and actinide transmutation in the AFCI.

Research, design, and development along these lines as well as designs that incorporate Ideal Safeguards have the potential to raise the proliferation resistance bar significantly. If this research, design, and development should prove successful, it can potentially raise the proliferation resistance measure of a closed cycle to roughly that of the Spent Fuel Standard.

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APPENDIX A

Committee Charter

PROLIFERATION RESISTANT CHARACTERISTICS OF RECYCLE FUELS
Advanced Fuels Cycle Institutive – Series One
Light Water Reactor Recycle Fuel

Charter and Purpose

Background:

This activity is in response to questions raised by the Advanced Nuclear Transformation Technology (ANTT) sub-committee of the Nuclear Energy Research Advisory Committee (NERAC) on the level of proliferation-resistance of Series One, Light Water Reactor (LWR) recycle fuel consisting of plutonium/neptunium, and possibly other constituents, which may improve the proliferation-resistance. This panel is to report on its findings to the ANTT sub-committee Chairperson, Dr. Burton Richter.

Charge:

The "panel" is charged to review alternative fuel forms for Series One LWR containing mixtures of plutonium, neptunium, and possibly other constituents in order to assess their nonproliferation characteristics. Among these characteristics will be: (a) constituents required in the fuel, (b) the level of intrinsic proliferation resistance, (c) the fabrication difficulty added, (d) the reprocessing and re-fabrication difficulty added, and (e) the acceptability of the fuel to operators of commercial nuclear power plants. The "panel" should provide opinions on various technical options to be considered for LWR proliferation-resistant fuel that it deems sufficiently to qualify as proliferation-resistant fuel, that is, the fuel would be an unattractive and undesirable proliferation route.

The "panel" is also asked to comment on the likely nature of the design features of the reprocessing and fuel fabrication plants that would be required in the context of the current national and international political environment.

A report summarizing the findings of the "panel" should be completed and forwarded to the ANTT Chairperson.

APPENDIX B

Brief Biographical Sketches of Committee Members

Pascal Baron has an Engineer degree in Chemical Engineering obtained in 1980 at the Ecole Nationale Supérieure des Industries Chimiques at Nancy (France). He entered at the CEA/Fontenay-aux-Roses in 1982 as a chemical engineer in charge of computer modelling of the PUREX process. Pascal Baron's main fields of interest concerns the development of solvent extraction processes, including the PUREX, DIAMEX, SANEX *etc…* processes. He is author or co-author of more than forty articles published in international journals and in the proceedings of international conferences. In his field, he is an expert recognised at the National and International levels.

Dr. Christine Brown completed her first degree in Chemistry at the University of Glasgow. After doing so, Christine undertook post-graduate research studies in the field of X-ray crystallography at the University of Oxford. She then joined the United Kingdom Atomic Energy Authority (UKAEA) in 1971as a research assistant, specializing in the use of electron beam optics to study the effects of neutron irradiation on Fast Reactor core structural materials and fuels. In 1988 she was appointed Manager of the Radiation Damage Department at Dounreay in the North of Scotland and in 1991, was appointed coordinator and Head of Technical Area for the UK Fast Reactor Core Materials Program. In 1993, following the termination of the UK Fast Reactor R&D program, Christine joined the Thermal MOX fuel fabrication team at Sellafield and, following the transfer of this project to British Nuclear Fuels Limited (BNFL) in 1994, joined BNFL as Technical Specialist. She is now Head of Technical, MOX at Sellafield.

Dr Bruce Kaiser has a broad and deep technology background in all aspects of commercial nuclear fuel manufacturing, gained from working in all aspects of the nuclear fuel business. He has authored 10 successful patents with another now 10 pending, and over 22 technical papers. Dr. Kaiser obtained a B.S. degree in physics, and both an M.S. and Ph.D. in nuclear engineering from the University of Florida.

From 1977 to 1983 he held senior engineering positions in Westinghouse Hanford and GE nuclear fuel manufacturing. In 1986 he accepted a position as Chemical Science Department Manager at Battelle's Pacific Northwest National Laboratory in Richland, WA. where he won many science awards and doubled the size of the business. He then accepted a position at GE that led to Manager of Fuel Manufacturing Operations. In that position, he restructured the manufacturing and laboratory operations, introduced new products, and reduced cost by 30% while increasing output by 50% and reducing cycle time by 80%. He managed the day to day operations, producing about $300 million worth of nuclear fuel for commercial power reactors world wide each year. Dr. Kaiser then became Vice President of Nuclear Fuel for ABB, where he modernized the

manufacturing and supporting laboratory facility and increased business orders by $1.2 billion—while reducing costs by 30% and process cycle time by 60%. By closely working with the NRC, he succeeded in removing the business from their watch list.

Dr. R. Bruce Matthews has a Ph.D. in Materials Science from the University of Wales. He was recently appointed as a member of the Defense Nuclear Facilities Safety Board, which oversees the safe operation of the Nation's nuclear weapon plants. Dr. Matthews spent eight years as a Research Scientist at Atomic Energy of Canada where he developed advanced nuclear fuels and structural materials. He subsequently spent two years as a Research Scientist at Pacific Northwest Laboratory working on proliferation resistant fuels for advanced nuclear power systems. Dr. Matthews was a line and program manager at Los Alamos National Laboratory and was involved in programs on stockpile stewardship, nuclear materials disposition, and space and terrestrial nuclear power systems. Dr. Matthews was Director of the Nuclear Materials Technology Division and had overall responsibility for facility operations, base technologies, and program execution involving plutonium and other actinide materials at the Plutonium Facility and the Chemistry Metallurgy Research Building. In 2000, Dr. Matthews received a Senior Scientific Manager Return to Research grant at the University of California at Santa Barbara. Dr. Matthews is the author or co-author of more than eighty journal publications, conference proceedings and technical reports.

Takehiko Mukaiyama is the Director of the Jakarta Liaison Office of the Japan Atomic Industrial Forum and is supporting and advising the Indonesian nuclear authorities for introducing nuclear power in Indonesia as well as for collaboration between Japan and Indonesia in nuclear science and technology.
After graduating from the University of Tokyo, Department of Nuclear Engineering, he joined the Japan Atomic Energy Research Institute in 1965 and engaged in fast reactor physics experiments. He was appointed in 1992 as Head of the Fast Reactor Physics Laboratory of JAERI. During this period, he developed containment and surveillance systems for IAEA Safeguards and served as Consultant for IAEA Safeguards.
From 1976 to 1978, he served as Visiting and Guest Scientist at the Laboratory of Laser Energetics of the University of Rochester, USA for the laser fusion project.

He led the OMEGA Program which was the partitioning and transmutation program of Japan and served as Chairman of the Research Committee on Partitioning and Transmutation of the Nuclear Society of Japan from 1993 to 1999.

He was appointed as Director of the Neutron Science Center of JAERI in 1996 and was responsible to develop a grand designing of a high-power proton accelerator complex for neutron scattering and accelerator-driven system (ADS).

This project was accepted for funding in 2001 after he retired from JAERI in 1999. Construction of the world's most powerful proton accelerator complex will be completed in 2007 under the J-PARC Project.
From 1999 to 2001, he served as Scientific Consultant for JA

Dr. Ronald P. Omberg is the manager of a project to plan the closure of the last three operating weapons-grade plutonium production reactors in the Russian Federation. He has a Ph.D. in Nuclear Engineering from the University of California at Berkeley. He has managed organizations that were principal contributors to analyses performed during the Nonproliferation Alternatives System Assessment Program (NASAP) and the International Nuclear Fuel Cycle Evaluation (INFCE). He has served on official delegations representing the United States at meetings on the international nuclear fuel cycle and nuclear non-proliferation in London, Paris, Brussels, Bonn, and Vienna. For ten years, he managed an organization that provided expert analyses in these areas and has served on expert working groups convened by the Organization for Economic Cooperation and Development (OECD) in Paris and the International Atomic Energy Agency (IAEA) in Vienna. For many years, he was one of the contributors to the Yellow Book and Red Book published by the OECD. He also provided technical support to the National Academy of Sciences' study on Weapons Plutonium Disposition. Dr. Omberg is the author or co-author of more than one hundred journal publications, conference proceedings and technical reports.

Professor Kenneth L. Peddicord is Vice Chancellor for Research and Federal Relations of The Texas A&M University System, and Professor of Nuclear Engineering at Texas A&M University. His received the B.S. degree in Mechanical Engineering from the University of Notre Dame in 1965, and the M.S. in 1967 and Ph.D. in 1972 in Nuclear Engineering from the University of Illinois at Urbana-Champaign. From 1972 to 1975, he was employed as a Research Nuclear Engineer at the Eidgenössisches Institut für Reaktorforschung (the Swiss Federal Institute for Reactor Research), now the Paul Scherrer Institut, in Würenlingen, Switzerland. From 1975 to 1981, Dr. Peddicord was Assistant Professor and Associate Professor of Nuclear Engineering at Oregon State University. From 1981 to 1982, he served as Visiting Scientist at the EURATOM Joint Research Centre in Ispra, Italy. In 1983, he joined the faculty of Texas A&M University as Professor of Nuclear Engineering. At Texas A&M, he has served as Head of the Department of Nuclear Engineering, Associate Dean and Interim Dean of the College of Engineering, Assistant Director and Director of the Texas Engineering Experiment Station, and Associate Vice Chancellor of The Texas A&M University System. Since 2003, he has been Vice Chancellor. He has published over 200 research articles, papers and reports. His technical interests include nuclear engineering education, advanced nuclear fuels, nuclear materials safety, the disposition of weapons plutonium, nuclear generated hydrogen and the hydrogen economy, and Generation IV nuclear systems.

Dr. Massimo Salvatores is the Research Director at the Commissariat a l'Energie Atomicque (CEA), Cadarache, France. He now serves in the dual role of scientific advisor for the Engineering Research Division at Argonne National laboratory and as scientific advisor to the Director of the Nuclear Energy Division of CEA. Dr. Salvatores holds a PhD in physics from the University of Turin (Italy). After theoretical and experimental research work performed in the '60s and '70s at the Italian Atomic Energy Commission and at Argonne National Laboratory, he began his career at CEA leading the shielding group for the SUPERPHENIX design and then headed the physics laboratory in charge of the SUPERPHENIX startup. experiments He then headed the Reactor and Fuel cycle Physics Division at the CEA Cadarache, in charge of both LWR and FR theory and experiments. In the '90s he chaired the Nuclear Science Committee and the Joint Evaluated Nuclear Data File (JEF) project of the OECD-NEA. Dr. Salvatores has led numerous national and international studies of Pu management and recycling, and of Partitioning and Transmutation technology. These studies included theoretical and experimental work on the Accelerator-Driven Systems as well as other innovative radioactive waste management strategies.

Dr. Salvatores is a member of the Scientific Council of the CEA, and was awarded the "Grand Prix Ampere" of the French Academy of Sciences, the American Nuclear Society (ANS) Nuclear Technology Award, and is a Fellow of the ANS. He has more that 200 articles on various aspects of reactor physics and nuclear fuel cycles and has served as Editor or Advisory Editor on a number of scientific journals such as Nuclear Science and Engineering and Nuclear Engineering and Design. He has also served as Professor at the National Institute for Nuclear Sciences and Technology (INSTN) and has teaches courses at the Ecole National Superieure de Chimie in Paris.

Dr. Alan E. Waltar is Director of Nuclear Energy at the Pacific Northwest National Laboratory (PNNL) and is responsible for engaging the extensive professional nuclear capabilities of PNNL to support efforts in revitalizing nuclear energy at the global level. Earlier, he served as Professor and Head of the Nuclear Engineering Department at Texas A&M University (1998-2002). He also served as President of the 16,000 member American Nuclear Society (1994-95), and is a Fellow of the ANS. He holds a B.S. in electrical engineering from the University of Washington, an M.S. in nuclear engineering from the Massachusetts Institute of Technology, and a Ph.D. in engineering science from the University of California at Berkeley. Dr. Waltar was elected the Founding President of the Eagle Alliance, a nationwide educational movement to revitalize nuclear science and technology in America. He is author of the classic textbook, Fast Breeder Reactors, which - along with the Russian translation edition - has become the standard international text in the field. His latest book, AMERICA THE POWERLESS: Facing Our Nuclear Energy Dilemma, was written to ease public fears regarding nuclear energy. He is currently finalizing the book, RADIATION AND MODERN LIFE: Fulfilling Marie Curie's Dream, which is planned for publication in November, 2004 by Prometheus

Books to document the multitude of beneficial applications of radiation to modern life.

APPENDIX C

Proliferation Resistance Methodology

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Abstract

A study of the time-dependent proliferation resistance of seven commercial nuclear fuel cycles was considered. These cycles consisted of a variety of closed fuel cycles and also considered several levels of safeguards in place at the enrichment and reprocessing facilities. The proliferation resistance methodology developed by Charlton *et al.* and funded by AFCI was used for the analysis. A description of that methodology is given. Increases in proliferation resistance were noted due to both safeguards level and characteristics of the material in process in each cycle. Dramatic increases in proliferation resistance were noted for enrichment plants when safeguards were implemented. Also, large increases in proliferation resistance were noted for both the PUREX and UREX reprocessing plants. Incremental increases in proliferation resistance were noted at other points in the cycles due to degradation in plutonium quality and decreases in plutonium quantity/concentration; however, none of the cycles considered demonstrated any ability to completely eliminate a proliferation risk due to the use of nuclear fuel for the production of electricity.

Introduction

We measure the effect that any technology has on the potential for nuclear proliferation using its **proliferation resistance**. The term proliferation resistance is often difficult to define.[1-3] The most useful definition appears to be that "proliferation resistance is a measure of the relative increase in barriers [both intrinsic to the material or process and extrinsic (or engineered)] to impede the proliferation of nuclear weapons either by diversion of material by a state in possession of a system or theft of material by a terrorist or sub-national group". It is common for experts to disagree on the effectiveness of different attributes to increasing these barriers; however, there are a number of attributes that are commonly agreed upon. These include:

1. Extraordinary reduction in the quantity of special nuclear material (SNM), which includes plutonium (Pu) and high enriched uranium (HEU), increases proliferation resistance.

2. Avoidance of separated SNM streams (e.g., maintaining the plutonium physically mixed with minor actinides and/or fission products) increases proliferation resistance.
3. Designing the material or process such that it can be more readily safeguarded (in terms of both material accountancy and containment/surveillance) increases proliferation resistance.

Systems for assessing proliferation resistance have been studied previously by various researchers with mixed success.[4-14] The results from these studies have yielded a considerable expertise in studying proliferation resistance and allow for a database of expert opinions concerning the importance of various attributes. In many cases, the researchers were interested in analyzing the proliferation resistance of a particular reactor concept or separations technology. However, this often will ignore the effect of the overall cycle.

Previous researchers who have analyzed complete fuel cycles have noted that difficulties arise in comparing one cycle to another especially when one considers the cycle as a dynamic process where material is constantly in a state of change (either chemically, physically, or radiologically). One of the primary objectives of this work was to study a method that might overcome this dynamic process difficulty. This was accomplished by focusing the proliferation resistance assessment not on the facilities or processes within a fuel cycle but on the material moving through a fuel cycle. Since proliferation resistance is primarily associated with the diversion or theft of nuclear material, this appeared to be a logical focus.

In this case, we simply track the proliferation resistance of a unit mass of material input into a fuel cycle all the way from its initial input through its eventual disposal. The assessor determines the actual termination time of the assessment. One of the major advantages to this analysis philosophy is it avoids one of the primary difficulties of proliferation resistance assessments, which is that the three commonly agreed upon adages to proliferation resistance mentioned above are often at odds with one another. For example, separating pure streams of plutonium would decrease the proliferation resistance of a fuel cycle; however, if this resulted in the ability to destroy extraordinary amounts of plutonium in inventory, it would increase proliferation resistance. Determining how these factors offset one another is complicated if a consistent time dynamic is not considered.

The general philosophy developed here is to view the proliferation resistance of a material input into a system as a function of time. The proliferation resistance of the material can then be tracked as a function of its history. In the separations case above, it would be shown that the proliferation resistance of the material would decrease during the time it is in the separation process; however, after significant transmutation its proliferation resistance would increase again. Since the philosophy of this methodology focuses on tracking the history of a unit mass fuel input, the resulting proliferation resistance is the resistance for the unit mass of fuel not for the lifetime of any facility. In a detailed analysis, scenarios involving changes in the initial material input could be completed to determine the overall resistance of the cycle when operational characteristics are changed.

This information alone provides a useful tool for decision makers, but it was also deemed necessary to generate a methodology for aggregating this dynamic process into a single measure which would help decision makers compare fuel cycle technologies. This was achieved by considering the proliferation resistance value as if it was a probability (i.e., it relates the probability per unit mass of input and per unit time that proliferation would be avoided). The time-dependent proliferation resistance values can then be aggregated into a single metric (in this case termed the *total nuclear security*) for a single cycle.

The model developed here was based on work performed in collaboration with Sandia National Laboratory (SNL), Los Alamos National Laboratory (LANL), and the Amarillo National Resource Center (ANRC) as part of an ATW/AAA/AFCI working group. The attributes and weights developed from that effort were then modified as part of a collaborative effort with Oak Ridge National Laboratory (ORNL) to provide a broader focus on the methodology and include a greater degree of safeguards related metrics. The assessment methodology developed based on these collaborations is described in the following section.

Proliferation Resistance Analysis Methodology

A methodology based on Multi-Attribute Utility Analysis (MAUA) was developed to allow for relative comparisons of proliferation resistance for different fuel cycles and facilities.[17–18] This method uses a variety of attributes in determining its measures. MAUA has been used previously for decision analyses related to the nuclear industry.[10, 18–20] It has been shown to provide a viable means for assessing systems with diverse (and often conflicting) attributes. Proliferation resistance for a nuclear fuel cycle is one such system.

The method described here uses a series of attributes to determine a proliferation resistance measure for each step in a process flowsheet. Each of the attributes has some weighting which determines its importance in the overall assessment. Each attribute also has an associated utility function that relates changes in the value of the attribute to its overall effect on the proliferation resistance measure. This method is focused on preventing host nation diversion, theft by an insider, or theft by an outsider. It is important to note that this methodology does not provide any results necessary to assess technology misuse (i.e., the export of technology to some group or state which then misuses that technology to proliferate nuclear weapons). The goal of this methodology was to generate a nuclear security measure that would involve as diverse a set of attributes as was needed for allowing discrimination between different commercial nuclear fuel cycles.

Assessment Methodology Formulation

Given a system which involves $i=1,2,3,...I$ processes, we can determine the total nuclear security measure (NS) for the system using the following:

$$NS = \frac{\sum_{i=1}^{I} m_i \cdot \Delta t_i \cdot PR_i}{\sum_{i=1}^{I} m_i \cdot \Delta t_i} \quad (1)$$

where m_i is the amount of material in process i [in significant quantities (SQ's)] and $? \ t_i$ is the time the material is in process i at the static proliferation resistance value of PR_i for process i. The total nuclear security measure is a time and mass weighted average of the proliferation resistance measure. The mass values used are in SQ's which are defined by the International Atomic Energy Agency (IAEA) as: 8 kg for Pu, 25 kg for HEU, 75 kg for low-enriched uranium (LEU), 25 kg for ^{237}Np, 25 kg for Am (as an element), and 20000 kg for Th (as an element). Note that this methodology accounts for a variety of possible weapons materials and uses the unit of SQ to normalize between them.

The static proliferation resistance value of process i is given by

$$PR_i = \sum_{j=1}^{J} w_j u_j(x_{ij}) \quad (2)$$

where w_j is the weight for attribute j, u_j is the utility function for attribute j, and x_{ij} is the input value for the utility function for attribute j in process i. Each of the attributes (along with their overall measure and weighting factors) is given in Table I.

TABLE I
Measures, Attributes, and Weights for Assessment Methodology

Measure	J	Attribute	Weights
Attractiveness Level	1	DOE attractiveness level (IB through IVE)	0.10
	2	Heating rate from Pu in material (Watts/kg)	0.05
	3	Weight fraction of even Pu isotopes	0.06
Concentration	4	Concentration (SQs/MT)	0.10
Handling Requirements	5	Radiation dose rates (rem/hr at a distance of 1-meter)	0.08
	6	Size/weight	0.06
Type of Accounting System	7	Frequency of measurement	0.09
	8	Measurement uncertainty (SQs per year)	0.10
	9	Separability	0.03
	10	% of processing steps that use item accounting	0.05
Accessibility	11	Probability of unidentified movement	0.07
	12	Physical barriers	0.10
	13	Inventory (SQs)	0.05
	14	Fuel load type (Batch or Continuous Reload)	0.06

Utility Functions for Each Attribute

Utility functions were constructed for all of the attributes in Table I. These utility functions are used in Eq. (2). Each of these utility functions requires input from the user in the form of either a numerical value (for instance, a heating rate such as "2.03 W") or a text string (for instance, an attractiveness level such as "IIID"). These utility functions were constructed using expert knowledge within a multi-organization working group concerning the effects of each input on the proliferation resistance of the material in process. Efforts were made to include a series of intrinsic and extrinsic measures that reflect material attractiveness as well as "safeguardability". A description of each utility function and the required input data for their implementation is given below.

DOE Attractiveness Level (j=1)

The utility function for DOE Attractiveness Level of the material is a constructed scale shown in Table II. The categories of material correspond to form and quantity of material from DOE M474.1-1.[21] This measures the quality of material in process and weighs materials with lower qualities higher on a proliferation resistance scale. Thus, unattractive materials would be less likely to be stolen or diverted by a proliferator. As can be seen from Table II, this is a roughly linear scale. Attractiveness level is generally considered one of the most important metrics for proliferation resistance; thus, the overall methodology developed here is essentially a linear scale and the resultant score should be viewed in that light. Also, note that it was assumed that category IA material (assembled weapons and test devices) would never be present in any cycle considered.

TABLE II
Utility Function (u_1) for DOE Attractiveness Level (x_1)

		Category			
		I	**II**	**III**	**IV**
Attractiveness	**B**	0.00	0.05	0.10	0.15
	C	0.15	0.25	0.35	0.45
	D	n/a	0.40	0.65	0.90
	E	n/a	n/a	n/a	1.00

This metric is a high level metric combining quantity and type of material. Thus, the DOE Attractiveness Level provides a baseline for a judgment of intrinsic material barriers. The other intrinsic barriers below are provided to allow for better discrimination than would be possible with only this metric alone.

Heating Rate from Pu (j=2)

This metric accounts for the increased difficulty of designing an explosive device with a high heat source.[22] This could include the requirement for careful management of heat in the device (such as channels through the high explosive to allow for heat removal). The utility function for this metric is as follows:

$$u_2(x_2) = 1 - \exp\left[-3\left(\frac{x_2}{x_{2,\max}}\right)^{0.8}\right] \quad (3)$$

where x_2 is the heating rate from the plutonium in the material (in Watts/kg of Pu) and $x_{2,max}$ is the maximum possible heating rate (set to be 570 Watts/kg which is the heating rate of pure ^{238}Pu). A plot of this utility function is shown in Fig. 1. If the quantity of Pu/HEU in the material is identically zero, the utility function value for this metric is set to unity.

Weight Fraction of Even Pu Isotopes (j=3)

The concentration of even Pu isotopes (especially ^{240}Pu and ^{238}Pu) can complicate the construction of a nuclear explosive.[22] ^{240}Pu has a high rate of spontaneous fission and can significantly increase the probability of pre-initiation in a nuclear explosive device. The utility function for this metric is as follows:

$$u_3(x_3) = 1 - \exp\left[-3.5(x_3)^{1.8}\right] \quad (4)$$

where x_3 is the weight fraction of even Pu isotopes and is given by

$$x_3 = \frac{sum\ of\ \ even\ Pu\ isotopes\ (g)}{sum\ of\ \ all\ \ Pu\ isotopes\ (g)}. \quad (5)$$

A plot of this utility function is shown in Fig. 2. If the quantity of Pu/HEU in the material is identically zero, the utility function value for this metric is set to unity.

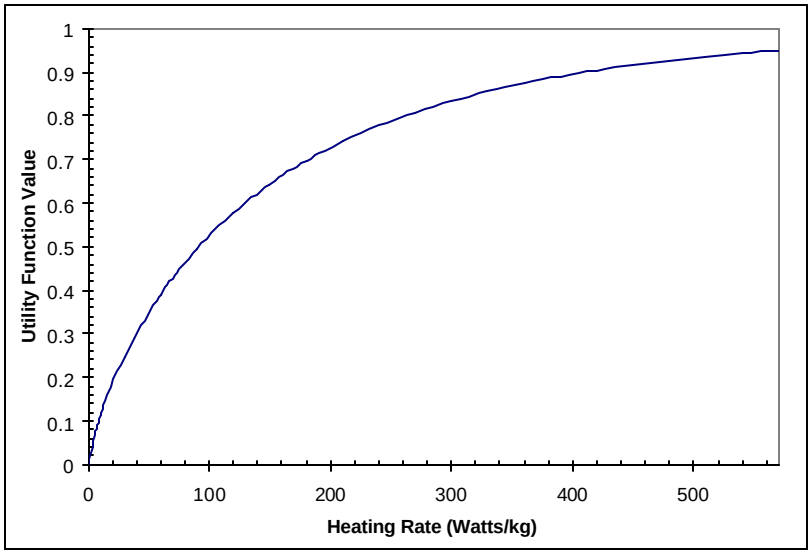

Fig. 1. Heating rate utility function.

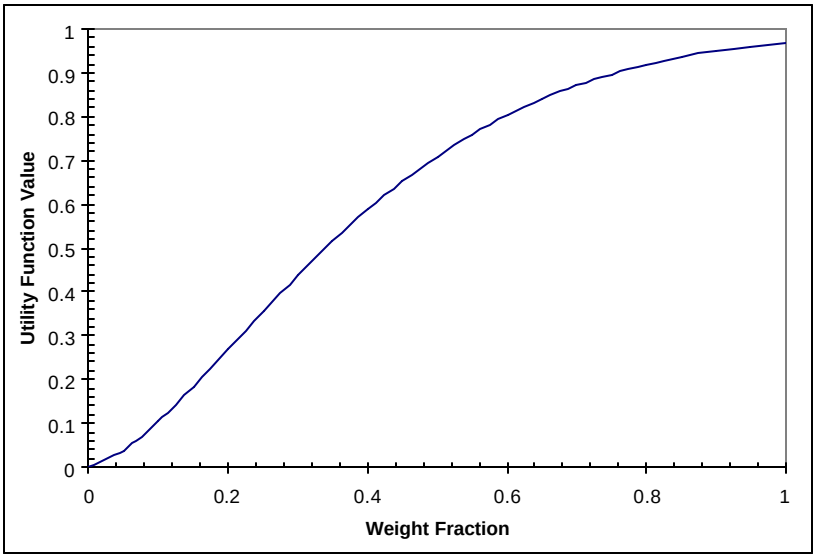

Fig. 2. Weight fraction of even Pu isotopes utility function.

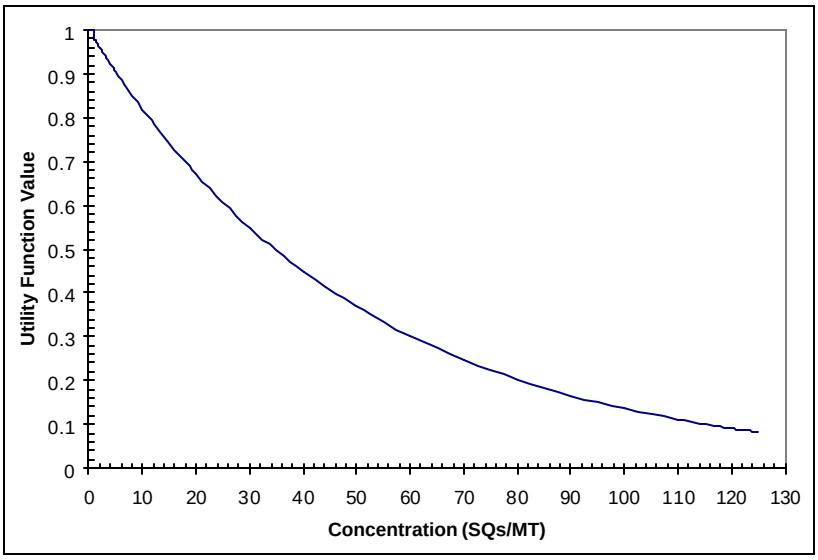

Fig. 3. Concentration of fissile material utility function.

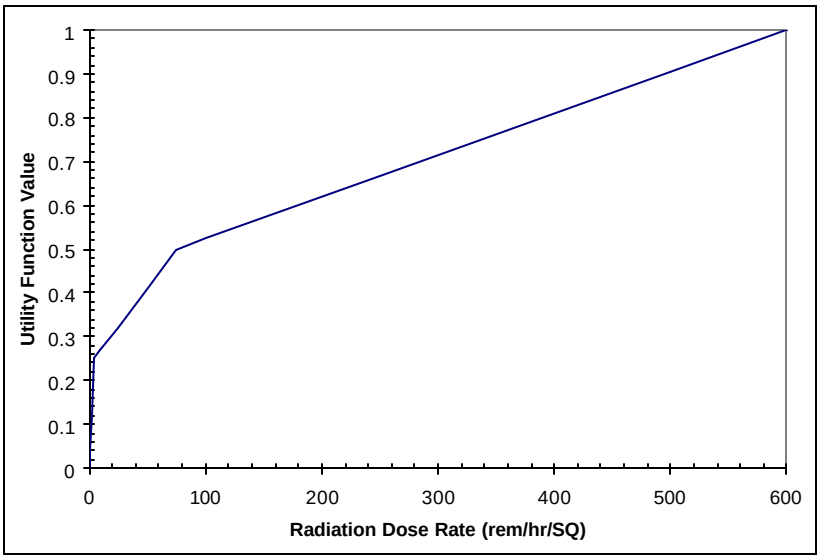

Fig. 4. Radiation dose rate utility function.

Concentration (j=4)

The Concentration metric considers the concentration of fissile material in the process step. Higher concentration materials will be more attractive since a lower mass (or volume) of material would need to be diverted or stolen to acquire a useable mass of SNM or ANM (Alternate Nuclear Material, defined as separated ^{237}Np or Am). The metric uses the number of SQ's of material per metric ton as its input value. The SQ definitions of the IAEA are used (i.e., 8 kg for Pu, 25 kg for HEU, 75 kg for LEU, 25 kg for Np-237, 25 kg for Am, and 20000 kg for Th). The utility function for this metric is as follows:

$$u_4(x_4) = \begin{cases} 1, & if\ x_4 < 0.01 \\ \exp\left[-20.5\left(\dfrac{x_4}{x_{4,\max}}\right)\right], & if\ x_4 \geq 0.01 \end{cases}$$

(6)

where x_4 is the concentration for the material (in SQs/MT) and $x_{4,max}$ is the maximum possible concentration. The maximum possible concentration was calculated assuming that the material was pure plutonium metal (or $x_{4,max}$=125 SQs/MT). A plot of this utility function is shown in Fig. 3.

Radiation Dose Rates (j=5)

The utility function for radiation dose rate is given by

$$u_5(x_5) = \begin{cases} 0, & if\ x_5 \leq 0.2 \\ 0.0520833x_5 - 0.010416 & if\ 0.2 < x_5 \leq 5 \\ 0.0035714x_5 + 0.232143 & if\ 5 < x_5 \leq 75 \\ 0.0095238x_5 + 0.428571 & if\ 75 < x_5 \leq 600 \\ 1, & if\ x_5 > 600 \end{cases}$$

(7)

where x_5 is the dose rate concentration in rem/hr/SQ for the unshielded material. Figure 4 shows the utility function in graphical form. If the quantity of SNM or ANM in the material is identically zero, the utility function value for this metric is set to unity.

The utility function for Radiation Dose Rate was developed based on acute biological effects of whole-body radiation dose to the potential proliferator. High dose rate materials would be hazardous to handle and may require the use of expensive and unique equipment. Extremely high dose rate materials would also provide a danger to the physical well-being of the proliferator especially if acute effects incapacitated the proliferator in a short time frame. Thus, this metric combines a small effect on proliferation resistance for lower dose rates (above a threshold of 200 mrem/hr/SQ) for the costs of specialized equipment and a larger effect on proliferation resistance for high dose rates which would quickly incapacitate a proliferator. It is assumed that above a threshold of 600 rem/hr/SQ, there is no continued increase in proliferation resistance since death is certain in all cases.

Radiation dose rates for the example problems used here were calculated using photon emission rates from ORIGEN.[23] The photon emission rates were then transformed into radiation dose rates assuming the source was a uniform line source of photons in air (i.e., the axial radiation profile was ignored) and impinging on a 70 kg reference man.[24] This should provide a reasonable approximation for a fuel assembly; however, if the item in process is significantly different than a fuel assembly, more accurate calculations should be used. The simplified method used here was employed only to acquire results for comparison and testing of the assessment technique.

Size/Weight (j=6)

The utility function for Size/Weight is a simple binary function. In this case, the utility function is accounting for the size or weight of a single unit in process (e.g., a fuel assembly). Large or extremely heavy items would prove more difficult for the proliferator to steal or remove without detection. An input of "yes" (for >2 ft^3 or >200 lbs) corresponds to one and an input of "no" corresponds to zero, that is:

$$u_6(x_6) = \begin{cases} 1, & if\ x_6 = "yes" \\ 0, & if\ x_6 = "no" \end{cases}.$$

(8)

Frequency of Measurement (j=7)

This attribute measures the frequency with which material inventory in the facility is measured. The utility function for Frequency of Measurement of the material of concern is a constructed scale shown in Table III. The scale was chosen to reflect a decrease in proliferation resistance as the frequency of measurement decreases. Continuous monitoring of the material of concern, albeit difficult to achieve, would be the ideal situation. Material accounting on an annual basis (or never) would be the worst scenario. In this case, a potential proliferator would have ample time between measurements to get away with a quantity of nuclear material and fabricate a weapon before its absence is detected. In some cases, a material is considered under continuous measurement when its theft or diversion would be immediately recognized (for instance, fuel under irradiation in a PWR).

Measurement Uncertainty (j=8)

The utility function for measurement uncertainty is given by:

$$u_8(x_8) = \begin{cases} 0, & if \ \ x_8 > 1 \\ 1 - x, & if \ \ x_8 \le 1 \end{cases} \quad (9)$$

where x_8 is the measurement uncertainty in SQs/year. The measurement uncertainty (in percentage) was multiplied by the bulk throughput in SQs/y to acquire the input value (x_8). Measurement uncertainties, which are dependent upon the material form, were obtained from 2000 IAEA target values.[25] It was assumed that there were no measurement uncertainties for material which can be accounted for using item accounting.

TABLE III
Frequency of Measurement Utility Function

Frequency of Measurement (x_7)	**Utility Function Value (u_7)**
Continuous	1.0
Hourly	0.95
Daily	0.85
Weekly	0.75
Monthly	0.5
Quarterly	0.25
Annually	0.1
Never	0.0

TABLE IV
Separability Utility Function

Fuel Form (x_9)	**Utility Function Value (u_9)**
Pu/HEU metal solid	0.00
separated Pu/HEU solution	0.20
mixed Pu solution (contains minor actinides, U, and/or fission products) or LEU solution	0.50
Solid fuel w/out structural materials	0.75
Solid fuel with structural materials	1.00

Separability (j=9)

The utility function for separability is a constructed scale shown in Table IV. As the material becomes more separated (and thus more conducive for production of weapons), the proliferation resistance value decreases. Solid fuel with structural materials is the best form for the nuclear material since it requires a significant amount of processing before it could be used in weapons manufacturing.

% of Processing Steps that Use Item Accounting (j=10)

This metric uses the following utility function:

$$u_{10}(x_{10}) = (x_{10})^3 \quad (10)$$

where x_{10} is the fractional percent (expressed as a number between 0 and 1) of steps that use item accounting. This weights processes that use item accounting higher than those that rely upon complicated material balance systems.

Probability of Unidentified Movement (j=11)

The degree to which surveillance is utilized in the facility will determine if material can be moved without a record of the movement. The surveillance used could include video cameras, automatic bar code readers, global positioning system devices, metal detectors, radiation portable monitors, and other radiation detection equipment. The utility function for the probability of unidentified movement of materials is given by:

$$u_{11}(x_{11}) = \frac{1}{2} - \frac{1}{2}\tanh\left[(4x_{11}) - 2\right] \quad (11)$$

where x_{11} is the probability (expressed as a number between 0 and 1) that a significant quantity of material can be moved without detection by the surveillance system. A plot of this utility function is given in Fig. 5.

The input value for this utility function would require a detailed vulnerability assessment for the material in a facility. For many hypothetical cases, there may not be sufficient information to generate this assessment. In these cases, it is suggested that the utility function be set to unity for all cases to be compared. The attribute will then not affect the relative comparisons.

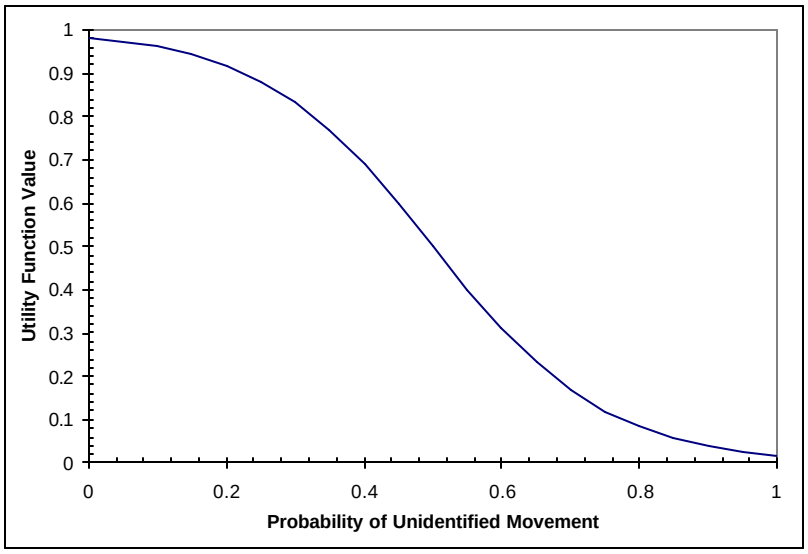

Fig. 5. Probability of unidentified movement utility function.

Physical Barriers (j=12)

The utility function for physical barriers is a constructed scale shown in Table V. The scale was chosen to reflect a decrease in proliferation resistance as the difficulty in accessing the material decreases. "Inaccessible" implies that the material cannot be physically accessed (for instance material being irradiated in a PWR). A "canyon" refers to a completely enclosed, underground structure to which it is very difficult to gain access. A "vault" refers to a large structure that impedes access to the material (a spent fuel pool was considered a vault in this work). "Secure" refer to sealed containers in which material may be stored (this could include drums or barrels). "Remote" would refer to any system in which its location alone makes it inaccessible to the proliferator (a geological repository is typically one example of this). "Hands-on" refers to engineered configurations in which the material can be at least indirectly handled (i.e. very limited physical barriers, such as a glove-box).

Inventory (j=13)

Each facility will maintain some inventory of fissile material. The size of this inventory will likely impact the attractiveness of the facility to a potential proliferator (and thus increase the risk of the material in process being targeted); however, above some point the difference between one large inventory and another large inventory becomes meaningless. The Inventory metric is used to discriminate between facilities that would maintain a large inventory from those with a small inventory of fissile material. This metric is most important for facilities with very small inventories (especially those with less than one SQ in inventory). The utility function for this metric is given by

$$u_{13}(x_{13}) = \begin{cases} 1, & \text{if } x_{13} < 1 \\ \left[\dfrac{(30 - x_{13})^{1/3}}{7.18}\right] + 0.574, & \text{if } 1 \le x_{13} \le x_{13,\max} \\ 0, & \text{if } x_{13} > x_{13,\max} \end{cases} \quad (12)$$

where x_{13} is the total facility inventory (in SQs) and $x_{13,max}$ is the maximum possible inventory (set at 100 SQs). A plot of this utility function is shown in Fig. 6. The maximum possible inventory is an arbitrary value. It is possible (even reasonable) for a facility to have a larger inventory than this on

site (e.g., the PANTEX plant in Amarillo); thus, it was necessary to include the upper-bound conditional on Eq. (12).

TABLE V
Physical Barriers Utility Function

Physical Barrier (x_{12})	**Utility Function Value (u_{12})**
Inaccessible	1.00
Canyon	0.90
Vault	0.75
Secure	0.50
Remote	0.25
hands-on	0.00

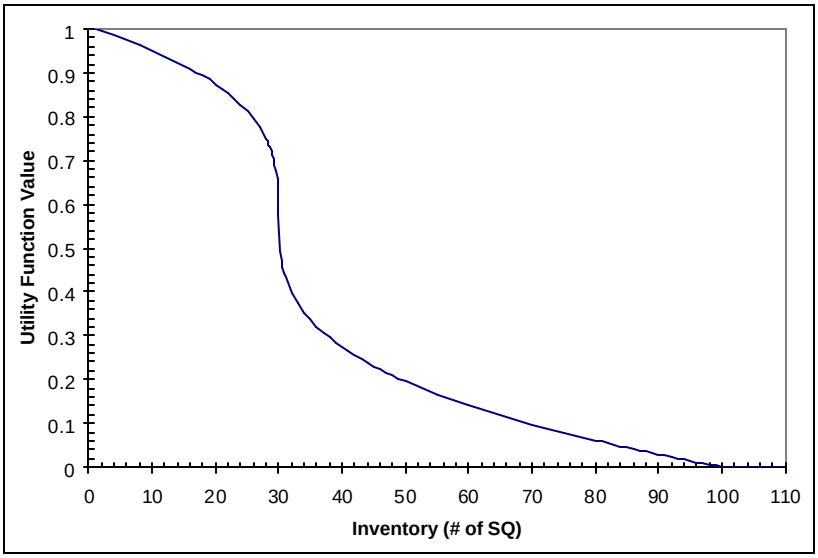

Fig. 6. Inventory utility function.

Fuel Load Type (j=14)

The Fuel Load Type requests an input of "continuous" or "batch" fueled. The utility function for the fuel load type metric is a simple binary function. An input of "continuous" corresponds to a utility function value of zero and an input of "batch" corresponds to a utility function value of one.

Determination of Weighting Factors for Each Attribute of Each Sub-Objective (w_{jk})

The weighting factors for each attribute were determined by soliciting input from twenty-four individuals in the fields of nuclear security, nonproliferation, international security, nuclear safeguards, nuclear smuggling, and law enforcement. This was done via a written questionnaire. Originally thirty-two questionnaires were distributed; however, only twenty-four were returned completed. The results of these questionnaires have been compiled to generate an unbiased set of weighting factors for use in the assessment methodology. This is sufficient data to allow for good reliance on the weightings factors; however, the weighting factors can easily be altered based on current trends or the bias of the assessor and stakeholders.

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