PROLIFERATION RESISTANCE OF ADVANCED SUSTAINABLE NUCLEAR FUEL CYCLES

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ABSTRACT

Intrinsic and extrinsic proliferation barriers of a pyroprocess-based nuclear fuel cycle are discussed. While technical characteristics of the process raise new challenges for safeguards, others naturally facilitate the implementation of more integrated schemes for unattended continuous monitoring. In particular, the concept of operations accountability and model-assisted methods are revisited. While traditional safeguards constructs, such as material control and accountability, place greater emphasis on input/output characterization of nuclear processes, a model-based discrete event accountability approach could explicitly verify not only facility use but also internal operational dynamics. Under the proposed remote integral safeguards approach, transparency can be achieved efficiently, without divulging competitive or national security sensitive information.

Keywords: nonproliferation, safeguards, transparency, operations accountability, pyroprocessing

1. INTRODUCTION

To put the need for development of nonproliferation technologies in perspective, consider the following: In the second half of this century, hundreds of reactors will be burning recycled fuel as they supply a significant fraction of the electricity needs of major industrialized nations around the world. This is neither the fanciful thinking of nuclear engineers nor the nightmare of anti-nuclear activists, but the inescapable conclusion of many of the most respected global energy system analysts [1]. An expanding world population and rising expectations of citizens of emerging economies will stimulate a global energy demand that can only be met if nuclear makes up a significant fraction of the supply mix. Restrictions on carbon emissions will only add urgency to reducing reliance on fossil-fueled power plants.

Financing, construction, startup and operation of hundreds of new-generation nuclear power plants will take place over an appreciable time period. Just as today's commercial nuclear technology was introduced in the 1960's and 1970's after 10-20 years of development, introduction of this new generation of nuclear plants will have to begin within the next two decades. That means that the research that goes forward today will provide the technology that will be deployed; there simply is not time to delay development in the hope that something better will come along. Ensuring that the right technology features are developed is the aim of the United States' international "Generation-IV" initiative as well as major national programs in France, Japan, Russia and elsewhere. In addition to being economically competitive, robustly safe, efficiently using natural resources, and responsibly managing the radioactive waste, the next generation of nuclear power systems will have to successfully allay legitimate concerns about their potential misuse in nuclear weapons material production.

The fact is that all countries with advanced nuclear energy R&D programs have a vested national interest in enhancing the proliferation resistance of future nuclear power systems. Without some means of assuring transparent nuclear operations, international deployment of a new generation of nuclear power plants could be delayed until severe economic or environmental impacts result. With large-scale deployment requiring the introduction of fuel recycling facilities as well as the reactors, the technological underpinnings of an acceptable global nonproliferation regime will become even more essential. Transparency of operations needs to provide country-to-country and formal international assurance of the absence of illicit activities, but it also should provide timely data that are accessible to any concerned group, even in third-party countries.

Providing that level of transparency is a theoretical and technological challenge, but it is made even more difficult by conflicting interests. Technology providers want to capitalize on their research and development investments by protecting patents and intellectual property. Host nations have an obligation to physically protect nuclear materials, a job made more difficult by providing detailed information about the location and state of such materials to potential adversaries such as terrorist groups. In view of these conditions, it is postulated that transparency can be more easily adopted internationally when it emphasizes openness and dissemination of information on triggered operating events within the facility rather than on detailed material inventory data. Disseminating the former information appears less sensitive than circulating the latter data. Moreover, if it is to be accepted, providing adequate transparency cannot require excessive capital investment or annual operating cost, incur significant interference to plant operations, or divulge information that would compromise the security of nuclear materials.

Nonproliferation analysts find it useful to describe intrinsic and extrinsic proliferation barriers, the former implying innate features of a given technology that are difficult to defeat; the latter implying features of a national and international safeguards regime [2]. Taken together, these system characteristics can be used with other factors to perform a qualitative risk assessment. Given the financial constraints on imposing such extrinsic barriers as frequent International Atomic Energy Agency (IAEA) inspections, developers of new-generation nuclear technology will be pushed to optimize the inherent proliferation resistance of the technology to achieve an acceptable proliferation risk level. This can be most effectively accomplished by including such features in the design criteria, rather than back fitting plant designs to include safeguards technologies. In attempting to describe how transparency-enabling technology might be integrated with a new nuclear energy system, we have chosen to describe its application to a specific system—a fuel processing facility for a metal-fueled fast reactor. This is a natural selection since such a system is the most developed among new nuclear energy concepts with intrinsic nonproliferation characteristics.

Dry (i.e., non-aqueous) processing technology has captured interest in part due to the inherent difficulty of extracting weapons-useable plutonium from any step in the process. These processes typically involve highly radioactive species accompanying the heavy metal product, making both the process and the product unattractive for use in weapons programs. In addition, this technology can facilitate the implementation of novel safeguards concepts of accountability that combine traditional material accountancy tools with complementary operations-observability methods to accomplish robust process accountancy and transparency.

Several dry processing technologies have been proposed worldwide. For example, Argonne National Laboratory introduced a dry process for the treatment of spent fuel that involves molten salt electrorefining at 500 C. Development of this process, hereinafter referred to as the pyroprocess, began nearly 20 years ago. Operations with irradiated metallic fuel have been going on successfully for four years [3]. A similar process being investigated in Japan is aimed at nitride or metal fast reactor fuel [4]. In Russia, there is considerable interest in dry processes for a variety of fast reactor fuels [5].

Regardless of the particular dry processing technology adopted, it is postulated that the effective deployment and commercialization of dry processing technology will depend in part on the nonproliferation and transparency measures integrated into the fuel treatment design. It will also depend on its safeguards acceptance by the IAEA and whether the particular verification mechanisms adopted are achievable and affordable. In support of more direct and feasible safeguards measures, the additional provision in the Model Protocol Additional to Safeguards Agreements [6] with respect to facility operations reporting is an enabling element for achieving improved nuclear transparency.

The fuel treatment facility considered in this paper may either be collocated with one or more reactors and dedicated solely to them or be a central facility serving several distributed reactors. In the latter central plant scheme, the required larger capacity would most likely be achieved through replication of processing equipment rather than through increased equipment size. Reliance on a process line replication to obtain increased throughput results from criticality considerations and the expected difficulty in scaling up the key process equipment pieces anticipated in dry processes. In these larger installations, with many operations occurring concurrently and generating a larger number of operational events, the benefits of relying on model-based methods for online negative verification of illicit nuclear activities become even more evident as discussed below.

2. PROLIFERATION RESISTANCE ATTRIBUTES OF PYROPROCESSING

Proliferation resistance attributes include the nature of the treatment process, the type of material being processed and equipment used, isotopic composition, difficulty of chemical separation, mass and bulk, the type, number, and location of required sensory devices, the accuracy and integration of measurements, and, in general, the process plant design features. Several of these technical barriers associated with the pyroprocess are discussed below.

2.1 Physical-based Proliferation Deterrents

The inherent resistance of the pyroprocessing technology to illicit fissile material production or the overt removal of fissile material is of primary interest. Inherent attributes enhancing proliferation resistance include its radioactivity signature and tight operating requirements. Contrary to currently implemented aqueous reprocessing with its complex piping network that connects many different processing cells, pyroprocessing is relatively observable with only a few machines that can be collocated in a single cell with few penetrations though which material can be moved. In addition, highly radioactive species remain with the process material throughout the entire fuel cycle, yielding only a partially decontaminated product for recycling. Carrying out undetected proliferant activities would be difficult because essentially all operations must be conducted remotely in an inert-atmosphere hot cell. Some intrinsic characteristics of the recycled plutonium product that contains most of the transuranics and a significant fraction of fission products are: lethal radiation fields, high specific heat generation, and high neutron emission rates. These characteristics would severely complicate the handling, machining, and assembly of the fissile material, making it unsuitable for weapons use. Contact-handled operations with any of the pyroprocess materials are simply not feasible. Highly automated processes are envisioned in commercial deployments, which might add to the proliferation resistance of the final plant design. Additionally, automated data acquisition and verification systems should provide less opportunity to falsify data. But all of these features must be established and subjected to peer review before their benefits will be fully accepted.

The operating parameters particular to pyroprocessing, such as high-temperature conditions and inert atmospheres, are also important inherent elements increasing the proliferation resistance of the process. At the current level of understanding, production of weapons-suitable plutonium material seems to be impossible by simply modifying the process. Diversion scenarios would require new processes, additional equipment, and out-of-the-cell processes that should be readily detectable. Use of in-cell aqueous processes to purify fissile material would be incompatible due to atmosphere compositions present in pyroprocessing.

2.2. Model-based Item Accountability and Processing Transparency

To assess whether a given State is meeting its international commitments under a given nonproliferation regime, positive and negative verification activities are conducted. Positive verification is used to verify a declared existence; e.g., that all declared materials are properly accounted [7]. On the other hand, negative verification is used to verify an absence; e.g., that no undeclared activity is present. Traditional safeguards practices, such as material control and accountability (MC&A), have been directed to positive verification. However, recent undetected proliferant incidents (such as the events in Iraq and North Korea) have revealed the weakness of relying solely on positive verification [8]. Consequently, there is a growing international interest on the further development and application of negative verification technologies.

The role of containment and surveillance (C/S) and similar methods in negative verification is seemingly important to accommodate pyroprocessing. In contrast to aqueous processes, the inspectability and material accountability in dry processing for positive verification purposes are relatively more difficult. While the process in the main is item accountable, with discrete material movements, the electrorefiner is an exception. Further, it has long been recognized that input fissile specification is more difficult without the accountability or dissolver vessel that is common in aqueous systems [9]. These areas require, and have received, special attention. To provide adequate safeguards for these dry processes, extensive measures of negative verification are then anticipated with more than customary reliance on discrete sensory information (such as C/S monitors) and less dependency on material accountability at key points in the process.

The pyroprocess is mainly a batch process, where electrorefiners and cathode processors are the major equipment pieces. In this process, an electrorefiner partially separates uranium and plutonium electrolytically both from each other and from the bulk of the fission products and a cathode processor vaporizes and collects any salt adhering to the deposit. Throughout the process, discrete material items (rather than continuous flows) are transferred among processing steps. The significance of an item in safeguards terminology has already been recognized for some time [10]. For example, regardless the treatment technology used, fuel assemblies have been accounted for as unique items traveling through the system until they are disassembled or again after they are fabricated. This item accountability approach has been proven to be an effective safeguards method. In dry processing, one can further capitalize on this discrete material handling nature not only at the reactor or storage sites of the fuel cycle but also within treatment operations in order to enhance proliferation resistance of the process.

First, as individual entities are transferred among processing steps, the innate ability to monitor and account for material is increased. This increased observability facilitates material balance and enhances proliferation resistance not only between accounting areas, but also between process/equipment steps, as more material tracking is conducted within a detection period. Increased access to inner processing segments also results in enhanced sensitivity to detection of frequent covert diversions of small quantities of material, shorter holdup times, and the potential for faster counter-diversion responses.

Second, the information retrieved from recorded manipulation of identifiable items can be used to detect facility misuse. Traditionally, MC&A systems characterize a process from an input/output description of material balance calculations. Accountability effectiveness (hence diversion) is thus determined by statistically comparing inventory difference against specified limits. While within-limit uncertainties may suggest that operations have been conducted as expected, accountability data are not explicitly used to verify plant operations. In order to complement safeguards activities based solely on material balance calculations, the discrete items produced under dry processing can be individually tracked and made to trigger discrete process events during their transit. Given these observed event sequences and associated operations models, model-based methods can be employed to explicitly correlate observed process behavior to declared operations, providing an additional avenue to detect suspected facility misuse. When the logical description of process operations is enriched with timed and other continuous valuation information, the timed event sequence generated can be further used to detect abnormal (and possibly proliferant) operating modes that violate time or quantitative expectations. An operations model-assisted approach is then concerned not only with the system input/output behavior but also with its internal operations dynamics. Thus, model-based methods may significantly increase the ability of a safeguards construct to detect undeclared nuclear activities or material diversion at declared sites.

Third, online discrete event (DE) information correlated with given operations models can be used to verify that the actual material transit scheduling maximizes nonproliferation goals without compromising product performance. For example, when both driver and blanket materials are recycled under a sustainable nuclear power regime, the preferable operating practice may not be to dedicate electrorefiners exclusively to either fuel type but to mix them. This plan of operation should make fissile material from blanket products less attractive for weapon use by contaminating it with driver material usually characterized with undesirable isotopic concentrations and high levels of fission products. By using material flow control measures based on DE models, it should be readily possible to detect unauthorized scheduling of blanket material to a particular electrorefiner with the intent of producing an intermediate product that incorporates weapon grade plutonium, though in a highly radioactive matrix.

Finally, a DE approach to monitor process operations can automatically integrate diverse sensory information in the context of declared operations, thus providing more details about the workings of nuclear systems and significantly improving their safeguards transparency properties. Sensory devices may include C/S monitors, nondestructive assay (NDA) instruments, near-real-time MC&A systems, and process monitoring and control systems. The integration of operational events with security alarms triggered by physical protection systems could also be facilitated, thereby strengthening nonproliferation barriers and enabling prompt neutralizing responses to a broader range of proliferant scenarios. This integration of sensor information would occur in a synchronized manner, providing a continuous correlated record of in-cell nuclear activities. As automation and standardization of (multiple) process lines are adopted to increase their diversion resistant attributes, the capability to rely on operations models to deny willful misuse of material and facilities should be increasingly practical and beneficial. Taken together, the features of the model-based construct could provide the potential for a transparent nuclear fuel cycle.

2.3 NDA Accountancy Measurements

As mentioned the previous section, operational data should be incorporated within a monitoring approach in order to strengthen safeguards verifications. Mass measurements, such as those taken during material transfers, can be used to determine the internal system state to assure, for example, that nuclear material follows predetermined routes.

While these measurements can signal material movements, they may not be sufficient to indicate the composition of what was moved. Analytical samples are often collected for this purpose. However, the inherent nature of pyroprocessing hinders the accessibility of collecting representative samples for analyses at various process locations. In addition, destructive analyses may be overly expensive, time consuming, and intrusive during production operation.

NDA techniques can potentially provide automated information on material and activities, with minimal intrusion. Besides supporting process control objectives, these techniques are employed throughout the nuclear fuel cycle for verification of special nuclear material (SNM) presence and isotopic content. For example, a signature detector would look for signatures (e.g., gamma ray energies, neutron emission intensity and multiplicity) specific to particular SNM sources and quantities. Unfortunately, intrinsic pyroprocessing characteristics complicate NDA implementation, excluding few possible locations. For example, it may be feasible to use neutron interrogation methods to monitor the fissile contents of the cladding waste. Scrap material containing modest amounts of gamma emitters may also be assayed quickly. Similarly, online measurements of volume and SNM concentration in the electrolytic cells can significantly improve the estimation of residual inventories (process holdups) and the prompt detection of abnormal accumulation of fissile material in the electrorefiners.

The application of NDA techniques is often discarded due to their inadequate accuracy under some applications to reliably provide high precision verification of isotopic composition of materials. These situations often arise in positive verification efforts. Contrary to that assumption, the level of accuracy required for operations accountancy (rather than material accountancy) should be lower, opening more possibilities for the effective use of NDA methods. However, the pyroprocess would have to be better characterized before NDA techniques can be applied routinely with a reliability acceptable for purposes of IAEA accountability.

2.4 Process and Environmental Monitoring

Pyroprocessing's intrinsically sophisticated technology as well as stringent operational requirements should increase the safeguards reliance on operational data as an effective proliferation barrier. For example, pyroprocessing requires high-purity inert gas atmospheres, with very small amounts of impurities such as oxygen or water vapor, in order to produce acceptable product and scrap material yields. Only a limited number of closely monitored transfers of fuel, equipment, and supplies are scheduled to maintain the required atmospheric purity. Therefore, unauthorized entries should be readily detectable using process instrumentation otherwise installed for monitoring cell atmosphere contamination. The qualification and integration of operational data with safeguards measurements offered by model-based constructs are postulated to lead to significant enhancements in the openness and transparency of nuclear operations.

Monitoring product and waste constituents should also facilitate detection of unauthorized activities. For example, resulting salt and cadmium waste streams are expected to contain a known percentage in heavy metals. Any deviation from the expected values may indicate facility misuse. Similarly, the fissile isotopic composition of the product is closely monitored, regardless of its low attractiveness for nuclear explosive applications. Very simplistically, a reduction in the mass ratio of Pu in the product (e.g., by changing the electrorefiners' operating conditions) could indicate that this material is being accumulated in the electrorefiners' salts for subsequent unauthorized collection and removal.

Environmental monitoring is a powerful safeguards tool that makes it almost impossible for undeclared nuclear activities to go unnoticed at declared sites [11]. Consequently, it will be an important cornerstone of negative verification safeguards technology for the deployment of future advanced fuel cycle systems. This technique relies on an input/output characterization of process operations. It is based on the fact that no industrial process can prevent minute traces of material from escaping into the environment where they can be collected by established sampling techniques and sent to off-site laboratories for analysis of physical, chemical, and isotropic properties. The exact emissions would depend on the type of facility, the specific technology chosen (for fuel design and treatment), and the systems and care applied to minimize them. Treatment plants, for example, are expected to produce more telltale emissions than nuclear reactor sites. In these plants, gaseous products (e.g., krypton and tritium) are released from fuel chopping operations. Difficult to be trapped, the released gasses can be monitored for safeguards purposes as they pass through the ventilation stack. For its implementation, the IAEA currently has established environmental sampling protocols. This technique has evolved rapidly within the past decade and eventually may help assure the absence of illicit nuclear activities even at undeclared sites. Environmental monitoring integrated with advanced safeguards systems provides a major deterrent to clandestine fissile material production.

In general, the carefully controlled atmospheres and filtered ventilation systems present in pyroprocesses may complicate the application and effectiveness of environmental monitoring. Periodic analysis of purification devises, such as HEPA filters, and of swipes, such as smears, may be routinely incorporated to strengthen the sensitivity for detecting facility misuse. However, the baseline environmental fingerprints or signatures resulting from pyroprocessing operation as a function of facility throughput must be first sufficiently established and characterized before environmental monitoring can be internationally accepted at commercial sites.

3. RESEARCH AND DEVELOPMENT AREAS

Although the IAEA has traditionally sought to emphasize material accountancy as the safeguards measure, there is a significant trend toward an increased reliance on complementing strategies, such as NDA, C/S, and dynamic operations accountancy model-assisted methods. This initiative entails integrating not only traditional MC&A data but also C/S and operational information such as equipment status, material transfer logs, cell atmosphere measurements, and security alarms. Just as the overall technical objective of traditional safeguards translates to the testing of the hypothesis of no diversion, the objective of strengthened safeguards translates to the testing of the hypothesis that there is no undeclared nuclear activity [12]. Testing of these hypotheses can only be accomplished through direct observation. Strengthened safeguards thus strives for a new kind of observational vantage point incorporating state declarations and confirmatory observations regarding nuclear-related activities.

Toward this end, an advanced design for remote safeguards monitoring would also include operating information from material handling equipment, such as cranes, manipulators, and robots, and from radiation monitors, including the radiation level and direction of material movement, as integral elements. The retrieved sensory information then quantified as discrete events would be integrated and analyzed under the context of declared operations models to detect undeclared material movement within the facility. However, the incorporation of operating data (with associated sensors) and model-assisted methods must be first accepted for international verification before its routine application in unattended continuous monitoring safeguards systems. Similarly, the use of advanced technology to remotely monitor the movements of nuclear material should be demonstrated through a series of field trials in nuclear facilities employing dry processing technologies.

As dry processing has distinctive features that make it well suited to complementary safeguards measures, a rigorous systematic framework should be developed where the safeguards observability and transparency properties of nuclear facilities can be measured, analyzed, optimized, and monitored within a given operations policy and institutional structure. In particular, a safeguards model-based method based on DE theory could facilitate the design of inherently observable systems and the implementation of online monitoring systems that enforce *a priori* observability and transparency specifications through the integration of plant observations with declared operations. By formulating nuclear safeguards concepts in the context of a mathematically rigorous framework, safeguards attributes, such as observability, detectability, and diagnosability, can be systematically designed and quantified. The remote integration and validation of observed events with respect to the admissible operational behavior defined for the monitored nuclear facility should exhibit tamper-proof characteristics and minimal impact on operations, without significantly affecting SNM physical protection costs. The development of such a formal method should significantly contribute in many critical design activities including: i) to determine minimum observability requirements (such as minimal set of sensors, types, and locations) for detecting and diagnosing undeclared activities or potential unauthorized diversions of nuclear material; ii) to improve the transparency and observability properties of nuclear facilities; iii) to uncover safeguards limitations of nuclear designs; and iv) to detect undeclared or illicit facility use at real time by validating online observed events against declared operations. The distinctive discrete nature of material handling in pyroprocessing is conducive for implementing such a DE safeguards approach.

Transparency implementation issues, such as what type of information would be disclosed, how this information would be transmitted, and who would be able to access the information, must be investigated and negotiated among interested parties. It is envisioned that a hierarchical safeguards architecture, with different layers of observability attributes, would be present in a global implementation. Located at the top of this hierarchy would be the public, with the capability to access reassuring but uncompromising safeguards data about any declared nuclear fuel cycle located around the world. These remote observers may be grouped in several safeguards classes, with each class defining the type of information it can receive and share. However, much work, both conceptual and practical, is still needed in this area.

4. CONCLUSION

Ultimately, fast reactors, with associated fuel recycling technology, are necessary for the development of sustainable nuclear energy systems. To the extent that proliferation resistance is an issue, it is also argued that, aside from more favorable economics, the enhanced intrinsic and potential extrinsic proliferation-resistance attributes of dry processing would enable fast reactors to become accepted within an international nonproliferation regime. With regard to intrinsic features, the inseparability property of U and Pu should be thoroughly tested within the context of a cooperative international program. Only in this context can the limits of such claims be tested, understood, accepted, and included in any new international safeguards regime of greater transparency. As to extrinsic properties, it seems clear that recent developments in system theory and information technology have yet to be fully embraced in national and international safeguards. In fact, it appears appropriate to reexamine the integrated role of operations accountability and C/S methods as a safeguards measure to compensate for some of the inherent limitations of material accountability in dry processes. Dry processes bring the possibility of discrete item accountability, a material and operations tracking approach that could rely on richer DE formulations and model-based analysis methods, that is postulated as an entirely new thrust toward a transparent safeguards regime. Given adequate priority, an IAEA safeguards regime can be developed for electrometallurgical-based treatment processes that takes into account the application of effective model-based and C/S-liked measures. Combined with the rapidly evolving power of waste and environmental monitoring, these new techniques should ensure the timely detection of any misuse of a nuclear facility or the materials contained therein. Future safeguards systems and tools are then envisioned with more powerful analytical capabilities and greater effectiveness and transparency beyond current IAEA safeguards requirements. Demonstration of both intrinsic and extrinsic safeguards should proceed concurrently with prototype demonstration of dry processing. With the current multilateral interest in this technique, it is time to explore international benchmark activities in transparent safeguards that might set the stage for next-generation nuclear power deployments.

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