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INSTITUTE OF NUCLEAR MATERIALS MANAGEMENT

INMM Is a Bargain

By Scott Vance
INMM President

Before Christmas Sale! Black Friday Sale! After Christmas Sales! Spring Sale! All of us are looking for a bargain, and all of us feel good when we believe that we have paid less for something than it is actually worth. So let me demonstrate that INMM membership Annual Meetings, and workshops clearly fall within the "bargain" category.

While membership fees for many professional societies have continued to increase over the years, INMM's have remained constant—$50. Standard American Nuclear Society dues are currently $140. Regular members of the American Physics Society pay $129 annually. The Health Physics Society assesses $135 each year. Membership benefits for each of these organizations appear similar to INMM.

So, why are INMM dues so low? The answer is very simple. INMM has made a conscious decision to keep our membership dues low because we want to encourage fellow nuclear materials managers to become members. Increasing our membership benefits the organization as a whole by inherently increasing the knowledge base that the organization can access. While employers often see the benefit to sending employees to conferences that cover relevant topics and therefore often pay some or all of the cost associated with attendance, membership dues are often the responsibility of the employee. In order to encourage individuals to join the organization and participate in activities at the grassroots level, INMM chooses to keep these costs low. Incidentally, our dues do not cover the cost of the benefits that members receive from membership, such as an annual subscription to the *Journal of Nuclear Materials Management* and discounted registration fees to INMM-sponsored meetings. Attendance at the Annual Meeting alone recoups the cost of membership.

Most members obviously understand the "bargain" nature of our membership fees—we get very few comments about these fees. On the other hand, each year when we announce the registration fees for our Annual Meeting, the comments begin rolling in. For our 2011 meeting in Palm Desert, California, the Executive Committee has determined that Regular Members will be assessed a registration fee of $770 if they register early, and otherwise will be charged $820 if they wish to attend the full four and a half day meeting. This includes access to all technical sessions, public receptions, and a ticket to the banquet.

Again, how do other meetings that are similar in scope and length to INMM's annual meeting compare? The member registration fees for the American Nuclear Society's 2010 Annual Meeting were $730 for early registrants and $830 for registration at the door. Similarly, the member fees for the 2011 International High-Level Radioactive Waste Management Conference are $700 for early registration and $800 for registration at the door. These registration fees are not significantly different from those set for INMM's 52nd Annual Meeting.

The truth is, putting on a conference is an expensive undertaking. Proceeds from registration fees must not only pay for the immediate costs of the meeting, but also must cover all of the preparatory costs that are incurred throughout the year. INMM employs a professional staff of meeting planners who work year round to make sure that this one week runs flawlessly. In addition, the Technical Program Committee (TPC) meets in March each year to arrange for the technical program. Many of the costs of this meeting are born by the TPC members' employers, but INMM must still arrange for the meeting space and provide the mechanism for TPC members to review the abstracts that are submitted (that is, provide—and pay for—the online abstract review system). These and other costs are all covered by your meeting registration fees.

While we have no plans to run any sales on our membership or meeting registration fees, I hope that you will agree that these fees are a bargain. I understand that the ultimate decision about whether or not our fees are a bargain is one that you will have to make on your own, and I know from past experience that some of you will continue to feel that we have set our registration fees too high. But, I am confident that if you attend an INMM meeting with the intent of learning all you can about what's new in the field of nuclear materials management, you will find that you simply cannot get the volume and quality of information anywhere else. I can assure you that each year, when the Executive Committee sets INMM's operating budget, it carefully considers what the Annual Meeting registration fee must be to ensure that there are adequate funds to make the meeting both worthwhile and as economical as possible. I hope that you will agree with me that we accomplish that, and I hope to see you in Palm Desert.

Addressing the Terrorist Threat

By Dennis Mangan
INMM Technical Editor

This issue of the *Journal* contains three interesting and diverse articles. Coincidentally, two of them address the terrorist threat. As we all know, 9/11 changed many aspects of our lives, but as most of us can become complacent with the past, papers like these two remind us that we have to continue to be careful in all aspects of our lives.

The first article, *Separations and Safeguards Performance Modeling for Advanced Reprocessing Facility Design,* by Benjamin Cipiti of Sandia National Laboratories, addresses the "real-time accountability" of nuclear material at reprocessing plants. Although this concept has been pursued over the years, implementation is typically hampered by cost and equipment limitations. Using a model developed at Sandia National Laboratories, an evaluation of increasing the effectiveness of improved measurements was conducted for a reprocessing plant. The model is effectively a virtual test bed. The results were dependent on the material balance area evaluated. In one, there did not seem to be an increase in effectiveness with the addition of more measuring points within the MBA. The second article, authored by Mark Maiello of Wyeth is titled *Issues Concerning the Security and Continued Use of Cesium-137 Irradiators.* In this paper, the author addresses the terrorist-related issues with the salt-form of Cs-137 and explores alternative means for radiation generating purposes. It appears the fate of the use of Cs-137 salts still remains to be determined. In the third paper, *All Stocks of Weapons-Usable Nuclear Materials Worldwide Must be Protected Against Global Terrorists Threats* the authors, Matthew Bunn, associate professor of public policy at the Harvard Kennedy School, and retired Colonel-General E. P. Maslin, Russia's Ministry of Defense, outline a baseline set of adversary capabilities that all stocks of nuclear weapons, plutonium, and highly enriched uranium should be protected against no matter what country they are in. In their adversary capabilities, they include both insiders and outsiders and a range of potential tactics.

In our Industry News column, Jack Jekowski, our Industry News editor, and Ken Sorenson our INMM Vice President and chair of the INMM Strategic Planning Committee, join forces to answer the question, "How can the INMM support the growth of nuclear power and the international commercial fuel cycle while ensuring that it is managed in a way that minimizes proliferation concerns and maximizes security?"

Next fall's issue of the JNMM will initiate the *Journal's* fortieth anniversary year. Beginning with that issue and in the three subsequent issues, we plan to devote some space to celebrate this anniversary. Managing Editor Patricia Sullivan, Advertising Manager Jill Hronek, Assistant Technical Editor Markku Koskelo, and myself are developing various ways we to celebrate. If you have suggestions, feel free to contact me.

JNMM *Technical Editor Dennis Mangan may be reached at dennismangan@comcast.net.*

Separations and Safeguards Performance Modeling for Advanced Reprocessing Facility Design

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Abstract

The long-standing goal of domestic safeguards for reprocessing plants is the ability to track all nuclear material within a plant in real time, with high quality, and with minimal impact to cost and plant operations. In reality, this goal is hampered by the limitations and cost of deployment of plant-wide measurement technologies. Thus advanced safeguards systems rely on an optimization of measurement uncertainty, timeliness of detection, cost, and impact to operations. The Separations and Safeguards Performance Model, developed at Sandia National Laboratories, provides a platform for both evaluating and demonstrating these advanced systems. This transient model tracks elemental mass flow rates and bulk chemicals through a reprocessing plant and simulates materials accountancy and process control measurements. The model was used to evaluate the effectiveness of improved measurements and near real time accountability. The results of the modeling effort suggest that adding additional measurements to every vessel or component processing plutonium provides only marginal benefit to the safeguards system due to additional error buildup. Future work will need to examine if the costs are worth the benefit or if other techniques may provide more improvement.

Introduction

Materials accountancy in reprocessing plants traditionally relies on sampling and precise analytical measurements at the inputs and outputs of a material balance area (MBA). In-process measurements of actinides are taken for criticality and process control, but the measurement uncertainty may be limited. A plant flushout is required to account for the full plutonium inventory, yet this is very time-consuming and costly for plant operations. It typically occurs only periodically (annually) and so limits the timeliness of detection of material loss.

Materials accountancy can be improved in different ways, but three have been examined in this work. First, the measurement uncertainty on the inputs or outputs can be improved. However, most areas of the plant already achieve very low uncertainties, and the key area that requires improvement is incoming spent nuclear fuel (SNF). Second, the plant flushout could be performed more often or the plant could be designed in such a way to make interim inventories less onerous and more accurate. Frequent flushout would improve the timeliness of detecting a diversion, especially a protracted diversion. Finally, in-process measurements could be added to achieve near real-time accountability (NRTA). The main advantage here is that abrupt or protracted diversions could be detected much sooner, but the effectiveness is limited by the instrumentation that could be used.

Modeling provides a platform for examining these potential improvements to determine if they will be worth the impact on operations and cost. Because demonstration research facilities are unlikely, a virtual test bed has many advantages. The Separations and Safeguards Performance Model (SSPM) has been developed over the past few years at Sandia National Laboratories for this purpose. It was originally designed to provide a platform for testing advanced material control and accountability (MC&A) concepts. However, its use has expanded to include more detailed modeling of solvent extraction and process monitoring. The model provides a tool that other safeguards professionals can use for design and analysis. One of the advantages of this model is that it uses the Matlab Simulink platform, which many engineers use or can easily obtain. The model runs using a standard desktop or laptop PC.

The purpose of this paper is to first describe the SSPM including its various capabilities. Then a series of results is presented based on evaluating the potential improvements to the safeguards system. Example material loss scenarios are shown to demonstrate how these systems advance the current state of the art. Finally, the implications of these findings for facility design and technology needs are discussed.

It is important to note that this work is focused on domestic safeguards, so a primary emphasis is to design accountancy systems that will optimize the cost and operations to the plant operator. Also, in domestic safeguards, material loss scenarios encompass threats from external adversaries or insiders. Detection of state-sponsored proliferation is in the realm of international safeguards and outside the scope of this work. However, these concepts have overlap in both domains.

Separations and Safeguards Performance Model (SSPM)

The SSPM is a transient reprocessing plant model constructed in Simulink to describe the various processing vessels and measurement technologies.[1,2] Simulink is used for simulating dynamic systems and is most often used for digital signal processing. In this model, arrays are used to represent the various mass or volumetric flow rates of each stream. The base of the model tracks mass and volumetric flows throughout a uranium extraction (UREX+) reprocessing plant, but the specific plant design can be changed easily depending on the desired extraction steps. The model data are based on related work being performed as part of the U.S. Department of Energy's Fuel Cycle Research and Development (FCRD) Program, including data from Argonne National Laboratory's AMUSE code[3], the Spent Fuel Treatment Facility scoping study,[4] and the Engineering Alternative Study.[5] Bulk volume and mass flows are tracked along with mass flow rates of elements 1-99 on the periodic table. All of the separation steps were initially modeled using assumptions of the separations efficiency, but current efforts are examining more detailed modeling of the chemistry.

Figure 1 shows the front end of the reprocessing plant in Simulink, which includes all processes from fuel receipt through dissolution to the first accountability tank. This also makes up the first MBA. The main processing areas include SNF storage, hardware removal and chopping, dissolution and hulls wash, centrifuge, surge tank, and the accountability tank. These blocks contain subsystems that model the processing units. For example, the accountability tank is designed to accumulate material (using an integration function) until the maximum tank level is reached, at which point the incoming flow is turned off. The tank holds that level for two hours to ensure adequate mixing for sampling, and then the tank is emptied. Relays and switches are used to control the addition or subtraction of material.

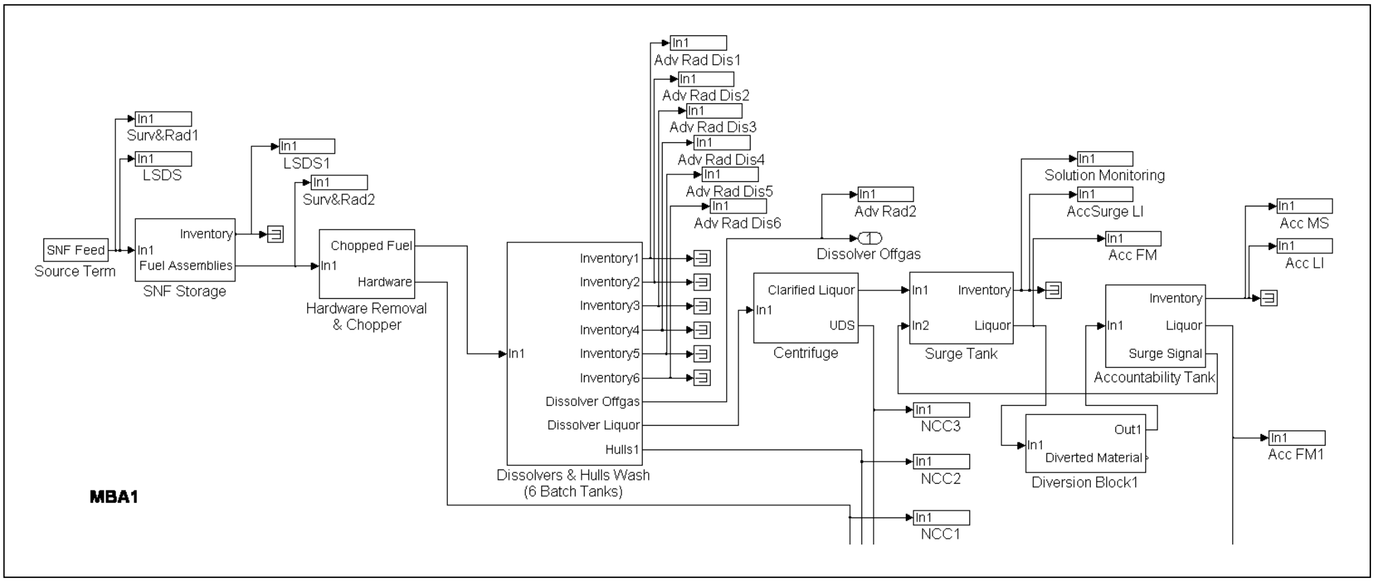
Most of the unit blocks in the model have input ports, one or more output ports, and an inventory port. The signals connecting to the inputs or outputs represent the actual material flow between units. The inventory port signal describes the total inventory in that processing unit or area as a function of time. The rectangular blocks that are connected to the process flow and inventory signals are measurement blocks.

The measurement blocks simulate any type of accountancy measurement by modeling flow meters, analytical sampling, level indicators, gross radiation measures, etc. Measurement uncertainty is defined by the user as standard deviations (σ) for the various locations. Both random (σ_r) and systematic errors (σ_s) are included. The model uses the σ's and a random number generator to apply an error to the true value. However, the random error changes every time a measurement is made while the systematic error is randomly assigned at the beginning of a run and held constant throughout the run. This assumption generates a bias to more adequately reflect actual operations.

The data generated from the measurement blocks is called in a different area of the model to perform material balances and to determine an overall standard error. A diversion block is also shown—this block can be moved to different locations within the model for examining the instrumentation response to material loss.

The second MBA includes all of the separation steps through product conversion. Figure 2 shows MBA2 in Simulink. This figure shows a UREX+ plant with three extraction steps. UREX separates uranium and technetium, TRUEX extracts the transuranics and lanthanide fission products, and TALSPEAK purifies

Figure 1. Front end model (MBA1) of the reprocessing plant in Simulink



the transuranics. Variations on extraction steps are rather easy to make in the model. The FCRD program is currently focusing on simplifying the processes, but it appears likely at this point that future U.S. reprocessing plants will separate out some combination of uranium and transuranics while placing all fission products into a high level waste form.

MBA2 also contains a large number of measurement blocks. Traditional accounting relies mostly on accountancy tanks at the end of the separations steps. However, this model also includes a large number of non-destructive analysis (NDA) measurements throughout that represent advanced instrumentation that may be used for NRTA. This will be discussed in more detail later.

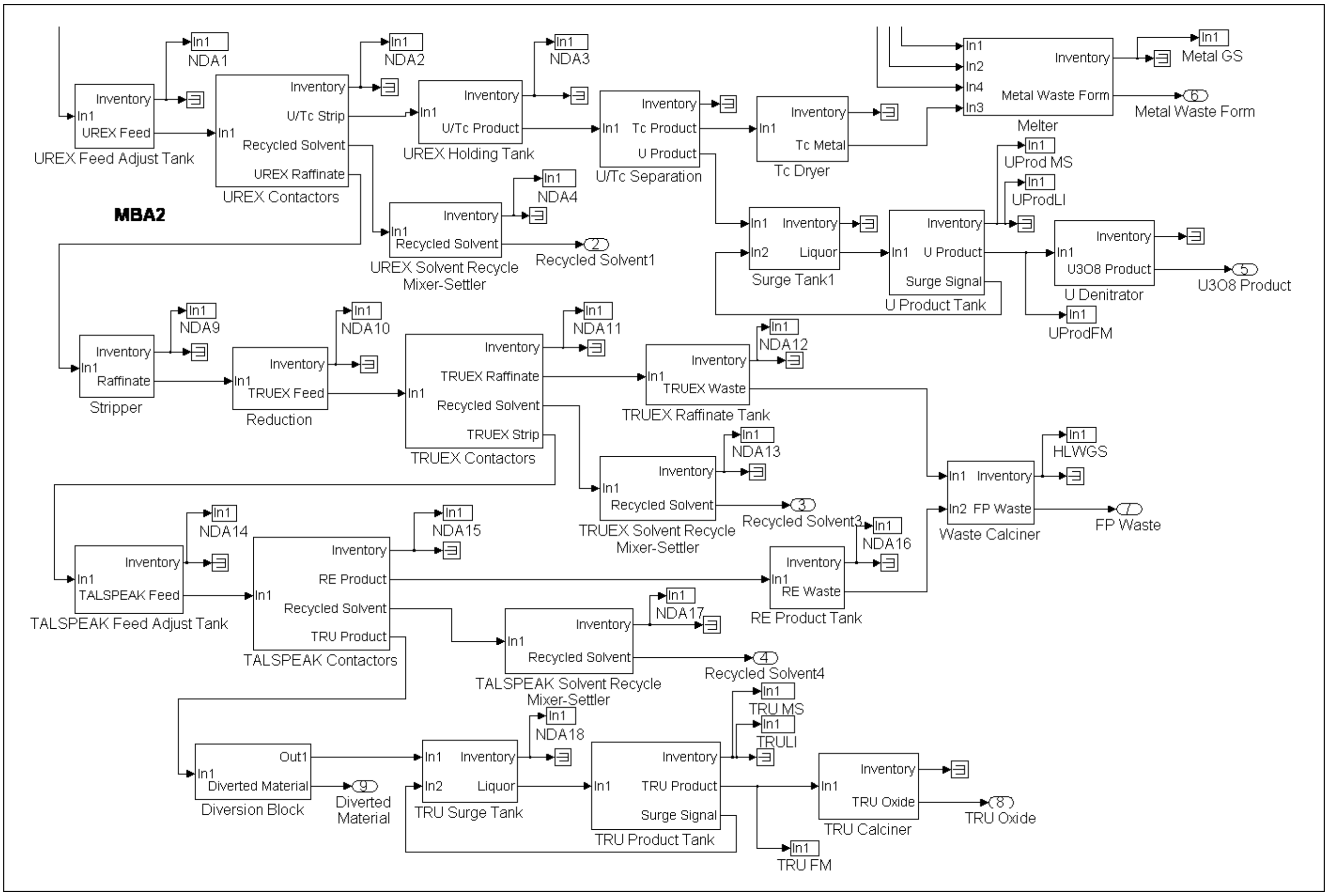
A typical measurement block is shown in Figure 3. The window shown on the lower left allows the user to input a random and systematic error for the measurement. The measurement block then uses those σs and a random number generator to apply errors to the measurement. The algorithm is set up so that many measurements of the same value will generate a distribution around the true value with the user-defined standard deviation. Each measurement block output contains both the simulated measurement and the combined random and systematic error on that measurement.

Inventory Balances

The measurement blocks shown in the previous section produce a large amount of data that is used in the model to perform inventory balances. The model only measures plutonium, but expansion of the measurement outputs to include other elements is straight-forward. Manipulation of the data can get complex due to the variety of instrumentation. For example, an accountability tank measurement is a combination of tank volume and a plutonium concentration measurement. The level indicator can provide data continuously, whereas the concentration measurement is taken once per batch, which occurs about every eight hours. On the other hand, a non-destructive measurement of plutonium may provide total plutonium content in a more continuous fashion. Matching up batch and continuous measurements in an inventory balance requires the use of signal delays in the model.

For each MBA, a subsystem was created in the model to take all of the measurement data to calculate a plutonium inventory difference (ID). Because the error of each measurement is also tracked, the total standard error of the inventory difference (SEID) is calculated. Finally, a cumulative sum of the inventory difference (CuSum ID) is calculated.

Figure 2. Extraction steps (MBA2) in Simulink



The ID measurement is the sum of the inputs with the sum of the outputs and change in inventory subtracted out—this is calculated over a set time period. The CuSum ID measurement is the sum of all the previous ID measurements, but Simulink allows for this value to be calculated in a simpler way. Instead, the CuSum ID is the integrated sum of the inputs with the integrated sum of the outputs and the sum of the vessel inventories subtracted out.

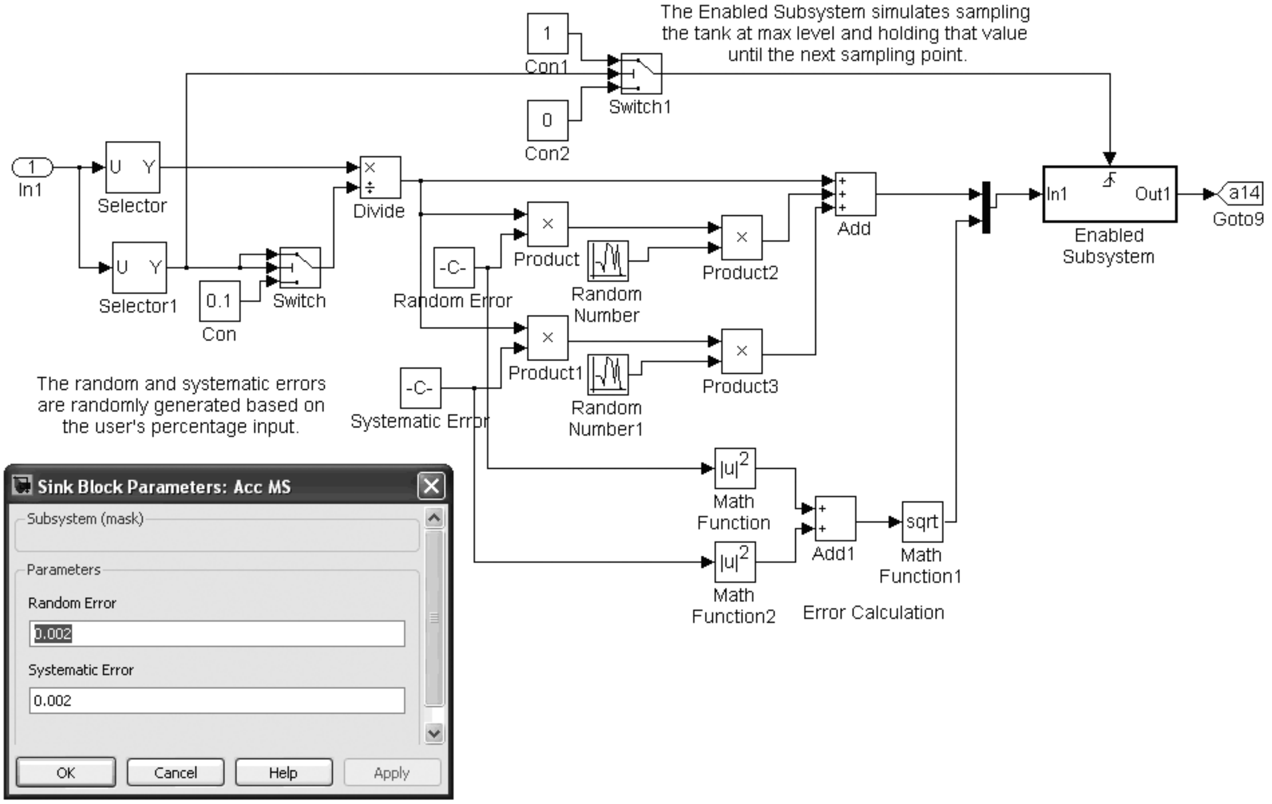
Error propagation is calculated first per ID measurement. For each measurement in the model, the random and systematic σs are added (using the sum of squares method). Then for Pu calculations that require two measurements (such as tank level and concentration), a multiplicative error propagation is used to calculate the correct σ. Then all of the variances for the measurements that go into the ID measurement are added. It is important to note that the inventory measurement errors are effectively counted twice because the change in the inventory requires two measurements. The square root of this final value then is the SEID at 1σ. For the CuSum standard error, the sum of squares method was used to add the final SEID from each balance to all the previous ones.

The model runs in time units of hours. Graphing functions are used to monitor the ID, SEID, and CuSum ID as the model runs. The model can be setup to perform these calculations as often as is appropriate. Due to the random scatter of the simulated measurements, the ID values fluctuate around a true value. The following sections will show what the fluctuation looks like in the results. Simple visual examination of the results can yield a great deal of information about the current MC&A system. However, for an advanced system statistical tests are required to set alarm conditions for material loss.

Potential Improvements to the Safeguards System

The three different options for improving accountancy were modeled using the SSPM: the improvement of the SNF measurement on the front end, the incorporation of additional plant flushouts, and the addition of an NRTA system for plutonium tracking. In all cases, various diversion scenarios were added to the model to determine the response and compare results.

Figure 3. Typical measurement block for an analytical sample



The Enabled Subsystem simulates sampling the tank at max level and holding that value until the next sampling point.

The random and systematic errors are randomly generated based on the user's percentage input.

Random Error: 0.002

Systematic Error: 0.002

Improving the Front End Measurement

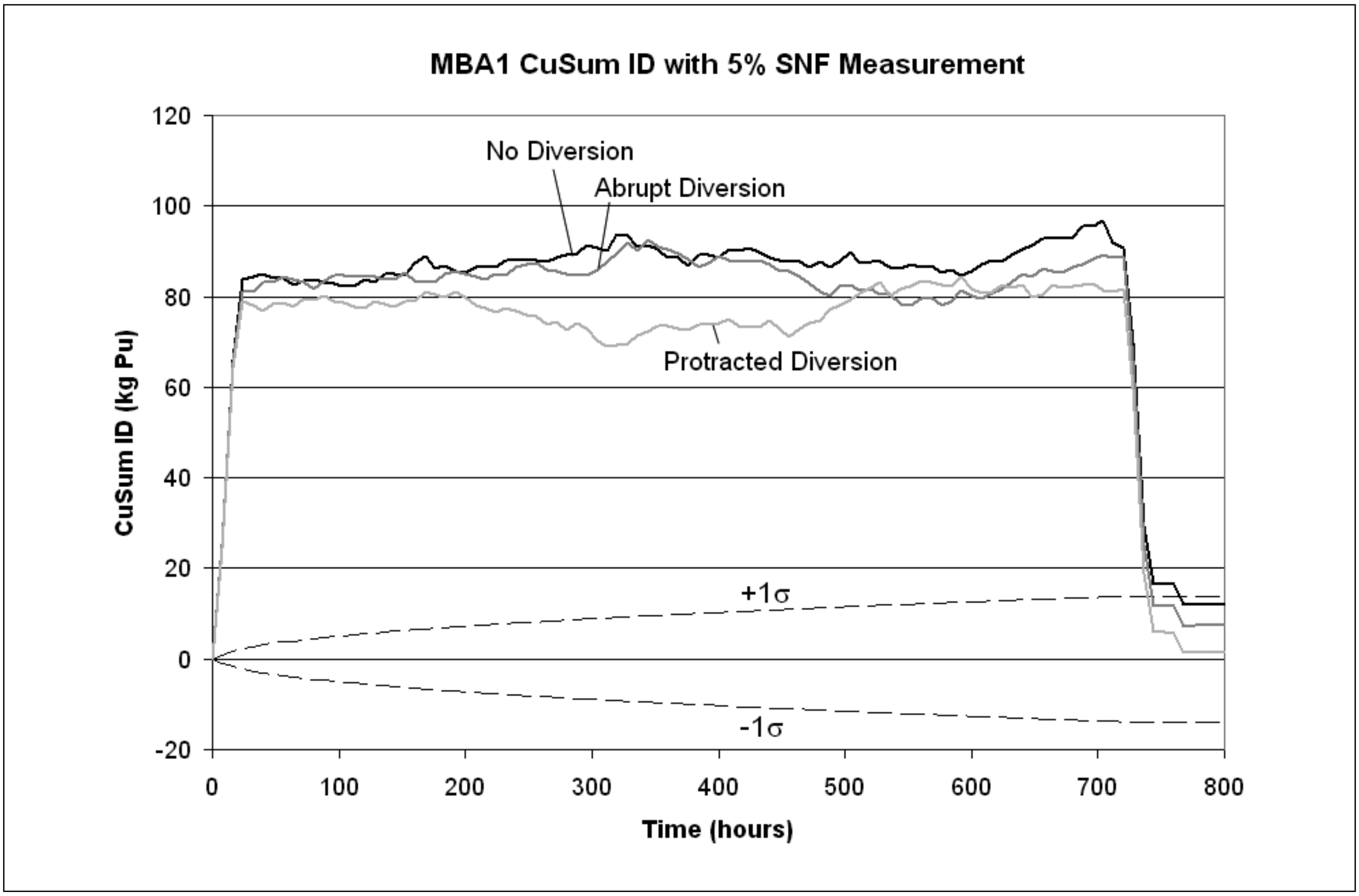
The front end MBA has been a significant limitation of MC&A due to the difficulties of measuring fuel while in solid or partially dissolved form. Estimates of actinide content can be made using the fuel history, decay time, and burnup codes like ORIGEN/SCALE [6], but these estimates have high uncertainty and usually exhibit a significant systematic error. Because measurements have never been able to achieve the high degree of accuracy and precision of analytical measurements from accountancy tanks, the traditional material balance, usually referred to as shipper/receiver differences, has not achieved a desirable detection sensitivity. Item monitoring, containment, and surveillance are used for additional assurances for safeguards on the front end until the fuel is dissolved.

New techniques are being examined to decrease the uncertainty on the SNF measurement,[7] but there is value in determining the impact this will have on the plant. The front end of the SSPM was modeled assuming a typical measurement at the accountability tank and for the three waste products (hulls, undissolved solids, and hardware), as well as solution monitoring techniques for the surge tank. An NDA measurement was added in simulation to the incoming spent fuel to examine the effect of adding a more precise measurement. The uncertainty was set at both 5 percent and 1 percent (for both σ_r and σ_s) to determine detection limits.

Three different runs were examined for this study all for an 800-hour run with flushout at hour 720 (one month)—a no diversion case, an abrupt diversion case at hour 300, and a protracted diversion from hour 300 to hour 600. In each of the diversion cases, a total of 8 kg plutonium was removed. (The plant throughput is about 5 kg of plutonium per hour.) Figure 4 shows the CuSum ID for the three cases with σ_r=σ_s=5 percent for SNF. The solid lines show the CuSum ID for the three cases, and the dotted lines show the total measurement uncertainty (+/-1σ). The CuSum ID has a strong positive deviation at the beginning of the run as material is building up in the process vessels (and because measurements are not in place to determine these quantities). The measurement uncertainty bounds then are only applicable when a flushout occurs at the end of the run. The uncertainty grows with time because the cumulative sum is dependent on all previous time steps.

The variation in the CuSum ID is significant, and the error bounds at 1σ go beyond 8 kg of plutonium in about eight days (192 hours). With no diversion, a deviation is seen at plant

Figure 4. Cumulative sum of the Pu inventory difference (CuSum ID) with a σr=σs=5 percent SNF measurement: no diversion, abrupt diversion of 8 kg Pu at hour 300, protracted diversion of 8 kg Pu from hour 300 to hour 600



flushout due to the measurement error. (Note that this deviation is just as likely to be negative.) The abrupt and protracted diversions would not have been detected.

The same set of runs was calculated using a SNF measurement with $\sigma_r=\sigma_s=1$ percent. Figure 5 shows the results, again for the three cases. This time, the error bounds reach 4 kg of plutonium after thirty days. Both the abrupt and protracted diversion would be detected, but protracted diversions on the order of two months or more would probably be hidden in the uncertainty.

These results suggest that a SNF measurement on the front end provides little value unless $\sigma_r=\sigma_s<1\%$ can be achieved. However, even at 1 percent a plant flushout would probably need to occur every month or so (as in the examples shown here) in order to reset the measurement uncertainty, or measures/estimates of material in the interim vessels will be needed.

Increasing Plant Flushouts

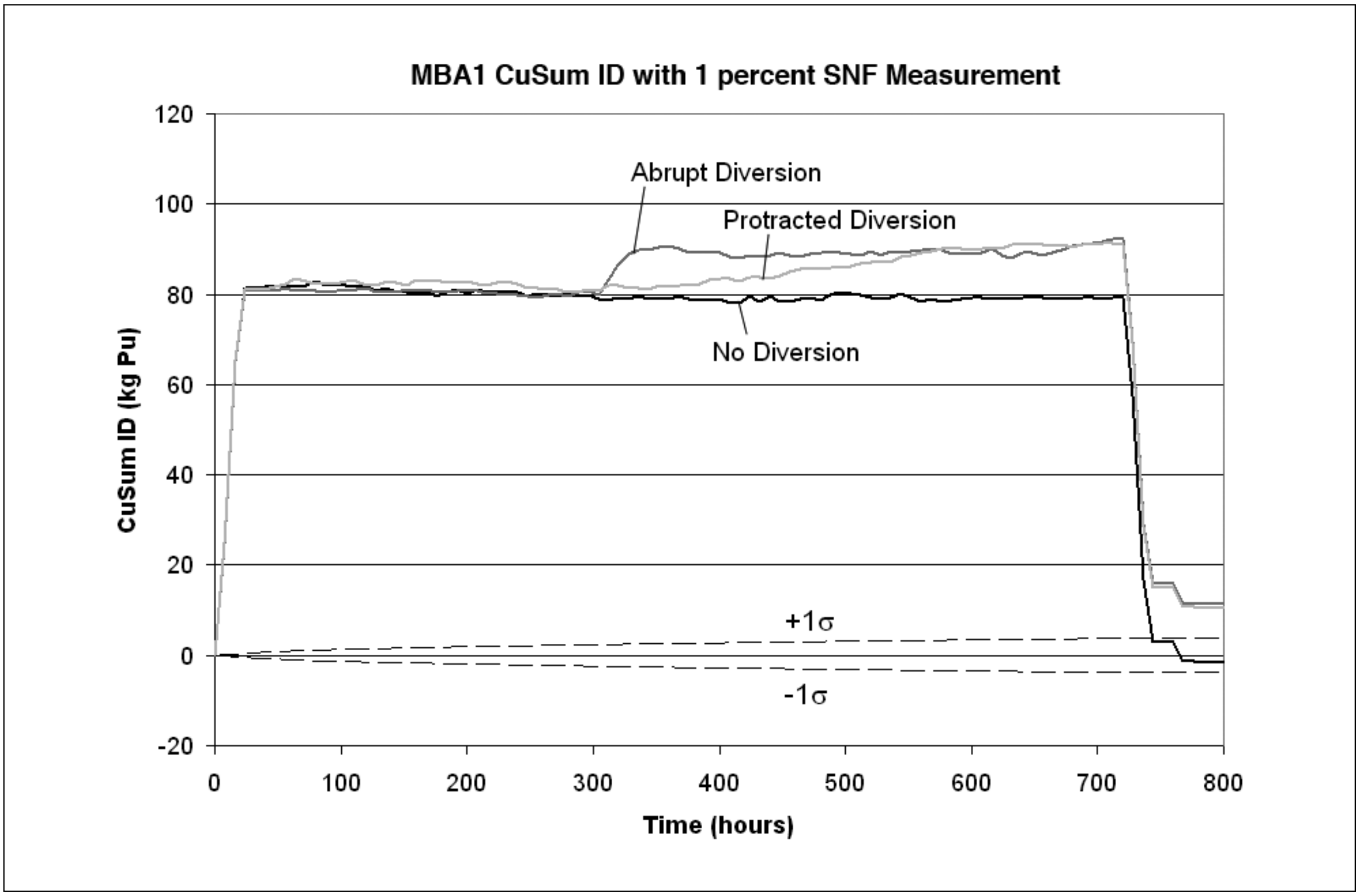
When in-process inventory measurements are not available, a flushout is the only way to close an inventory balance. Increasing the frequency of flushouts improves the timeliness of detecting material loss from both abrupt and protracted diversions. However, the uncertainties of the input and output measurements will still place a limit on the maximum length of a protracted diversion that can be detected. The difficulty is that flushouts have a significant impact on the plant by reducing the number of operational days.

Other techniques may be used to provide the information of a flushout without completely emptying the plant. The Sellafield Mixed Oxide Plant provides an example of NRTA based on windows of opportunity.[8] These windows are time periods when the entire plant inventory can be measured—more specifically, they are times when no transfers are taking place between processing units. When all the plant material is located in vessels that can be measured, an inventory can be calculated. The idea is that processing operations would be interrupted for only a short period of time to get a full inventory. This type of system may be useful for future plant design with the goal of minimizing the interruption time as much as possible.

Achieving NRTA

NRTA has been achieved in a limited manner in existing plants. The Plutonium Inventory Measurement System is an example of an NRTA system in one portion of the Rokkasho Reprocessing Plant. This system consists of 142 neutron detectors in the plu-

Figure 5. Pu CuSum ID with a 1 percent standard deviation SNF measurement, no diversion, abrupt diversion of 8 kg Pu at hour 300, protracted diversion of 8 kg Pu from hour 300 to hour 600



tonium conversion and finishing areas to track total Pu inventory continuously. The system is able to measure total plutonium in that area with an uncertainty (1σ) of 6 percent.[9] However, this design is for relatively pure processes—the applicability of these systems changes when considering an entire reprocessing plant with mixed solutions.

One of the goals of this work was to determine what it would take to design a high-quality plutonium NRTA system and how effective it would be in improving safeguards. NRTA requires tracking of material at all locations in the plant, so in a strict sense it would require some type of measurement on every vessel and estimates or measures of material in pipes. The large number of measurement blocks as shown previously in Figures 1 and 2 were used for this evaluation. However, implementation on a large scale commercial facility will face many challenges. NRTA systems need to be designed to keep costs down and to minimize the impact on plant operations. For this reason, NRTA optimization was also part of this study.

Four different methods for optimizing NRTA have been identified:

1. *Confirmatory Measurements* – Confirmatory measurements can be used in processing vessels that are only expected to contain trace quantities of plutonium. Examples include vessels in the solvent treatment system that contain solvent which has been stripped of nuclear material. Because these measurements only need to detect that plutonium is not present, gamma spectrometers or neutron detectors (reasonably cost-effective equipment) could be used.
2. *Solution Monitoring* – Existing plants take advantage of solution monitoring to compute concentrations of material in surge tanks around accountability tanks. Very accurate concentration data is available from the accountability tank, and concentrations in adjacent vessels can be calculated based on volumes and mass transferred from solution monitoring.
3. *NDA Instrumentation* – Many areas in the reprocessing plant contain small quantities of actinides. For example, the high-level waste streams are expected to only contain small percentages of plutonium. For low quantities, NDA instrumentation, even at σ_r=σ_s=5-10 percent will be adequate for NRTA. NDA instrumentation has less of an impact on plant operations than sampling and destructive techniques.
4. *Advanced Analytical Instrumentation* – A small number of additional tanks will have plutonium content high enough to require low uncertainty measurements, but these areas can benefit by the development of new instrumentation. Hybrid K-Edge Densitometry is used currently for accountability,[10] but more automated systems may speed up the measurement turnaround time. The TARIS (Thermal Atomization Resonance Ionization Spectroscopy) technique can perform high quality analytical measurements of mixed samples with a turnaround time on the order of minutes as opposed to hours.[11] Microcalorimetry or ultra high resolution spectroscopy may provide an NDA technique for measuring actinides at high quality[12]. The last two techniques are in the research and development phase but may be ready for use in the next several years.

By taking advantage of all these techniques, a high quality plutonium NRTA system was simulated for the two MBAs. This design is somewhat dependent on whether or not the advanced technologies are proven, but it serves as a point design for future plants.

MBA1 NRTA

Table 1 describes the NRTA measurement mapping in detail. Because in the previous sections, only the σ_r=σ_s=1 percent SNF measurement detected both abrupt and protracted diversions, this same uncertainty was used for the in-process measurements. The optimization discussed above was used to minimize the additional instrumentation required. A SNF measurement with item accounting can determine the Pu content in the SNF storage area. The surge tank uses solution monitoring. The chopper and centrifuge can be drained of material when NRTA balances occur. The only additional measurements required are on the six dissolver tanks.

The SSPM was used to evaluate both the SEID for this particular instrumentation mapping and to examine the instrumentation response to material loss. The uncertainties in the measurements of incoming fuel and at the dissolver tanks drive the overall uncertainty. These uncertainties lead to a significant

Table 1. NRTA instrumentation list for MBA1

Measurement Point	Puσ_r	Puσ_s	Mode	Volume σ_r	Volume σ_s
Incoming SNF	1.0%	1.0%	Batch	N/A	N/A
Dissolver Tanks (x6)	1.0%	1.0%	Continuous	N/A	N/A
Surge Tank	1.0%	1.0%	Solution Monitoring	0.1%	0.1%
Hardware	5.0%	2.0%	Continuous	N/A	N/A
Hulls	5.0%	2.0%	Continuous	N/A	N/A
Undissolved Solids	5.0%	2.0%	Continuous	N/A	N/A
Accountability Tank	0.2%	0.2%	Batch	0.1%	0.1%

amount of deviation in the CuSum ID measurement even when no diversion has occurred.

Figure 6 shows a one-month run with the same three cases as performed above—no material loss, an abrupt diversion at hour 300, and a protracted diversion from hour 300 to 600. For the diversion tests, 8 kg of plutonium were removed. The figure shows that the abrupt diversion would likely be detected due to the significant drop off, and the protracted diversion would not be detected. However, based on the previous section result which showed that a $\sigma_r=\sigma_s=1$ percent SNF measurement alone could detect both abrupt and protracted diversions, it is somewhat unclear how much value NRTA is adding. A benefit of NRTA is that it could detect an abrupt diversion at startup which would otherwise be masked by the effect of the process line filling up. However, other techniques like solution monitoring and estimates from data collected during cold startups may be able to provide this detection capability without requiring NRTA. Future work will need to investigate this issue in more detail.

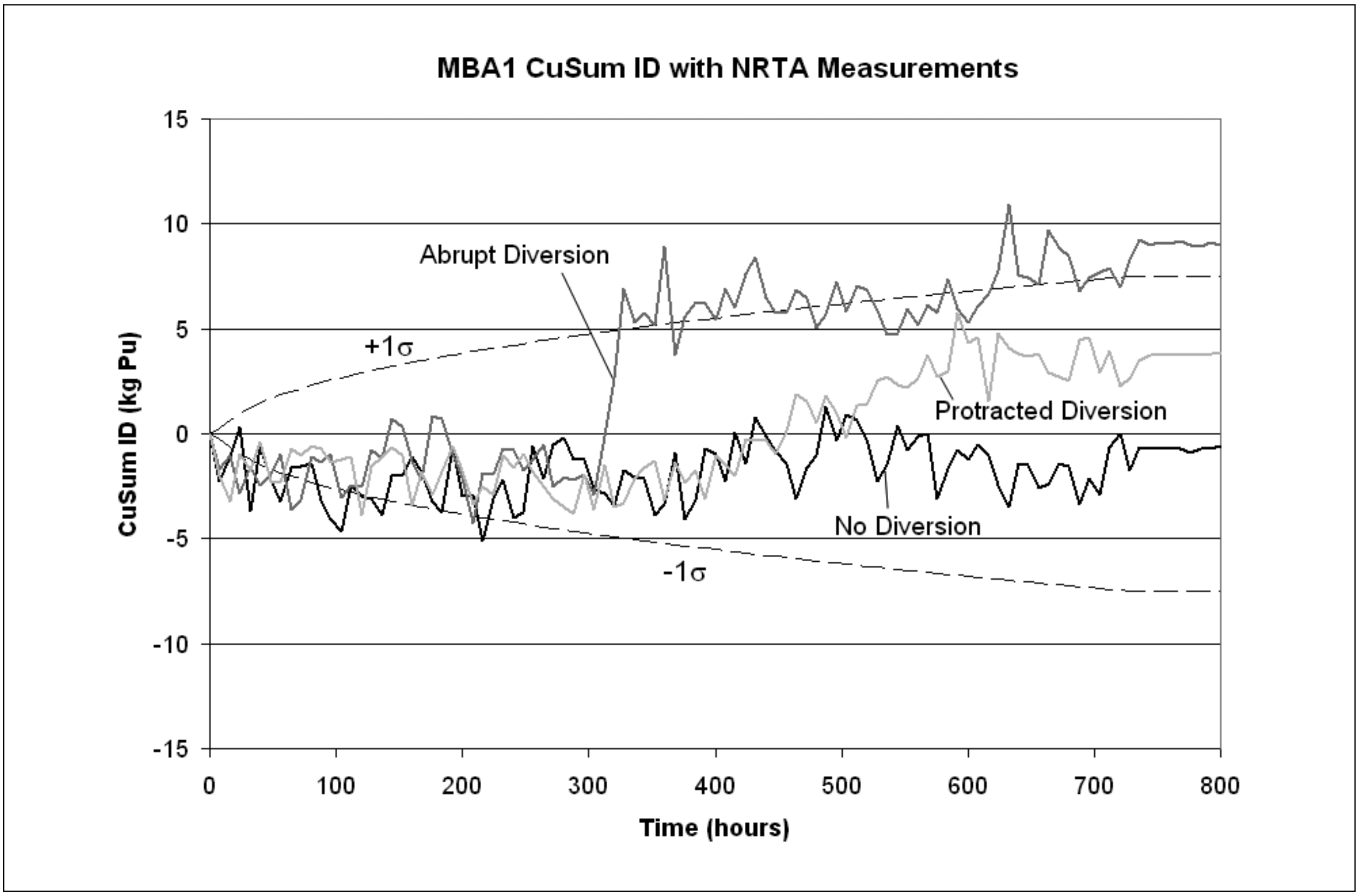
The additional measurements add more uncertainty to the error bounds, and thus the additional measurements required for NRTA provide limited value to the system. Given that the measurement uncertainties assumed for the dissolver tanks were much lower than what would probably be achieved today, a real system would have worse results. Preliminary conclusions suggest that NRTA on the front end does not appear to be very effective, and resources might be best spent on other safeguards techniques.

MBA2 NRTA

The second MBA is considerably larger than the first, but because the fuel is dissolved in this MBA, low measurement uncertainties can be achieved with sampling. The optimization strategies become much more important. Table 2 describes the instrumentation locations in detail. In general, all locations with significant Pu content were assumed to have $\sigma_r=\sigma_s=0.2$ percent while locations with little or trace Pu content were assumed to have σr=σs=10 percent.

Batch mode refers to points when both a Pu concentration measure and a tank volume measurement are used. In continuous mode, a total Pu measurement is assumed (in many cases this may not be realistic, but was assumed to simplify the model). Previous work[1] has examined optimization strategies for this MBA to find that a vast majority of the required NDA measurements on the in-process inventories do not require low uncertainties. The

Figure 6. MBA1 Pu CuSum ID with NRTA—no diversion, abrupt diversion of 8 kg Pu at hour 300, protracted diversion of 8 kg Pu from hour 300 to hour 600



quantity of plutonium in many processing vessels is so small that $\sigma_r=\sigma_s=10$ percent is adequate. It was assumed that a standardized neutron counting technique would be used in these locations. However, three additional tanks within the process contain large enough quantities to require analytical sampling and low uncertainty measurements—the Stripper, Reduction Vessel, and TALSPEAK Feed Adjust Tank. Also, the UREX Feed Adjust Tank and TRU Surge Tank can take advantage of solution monitoring to minimize additional instrumentation.

Again, the SSPM was used to evaluate a no diversion, abrupt diversion, and protracted diversion case. Figure 7 shows the results. In this comparison, the total measurement uncertainty is less than the first MBA because the key measurement points with large quantities of Pu are at low uncertainty. The abrupt and protracted diversions are clearly seen, which suggests that NRTA on MBA2 is effective.

The total measurement uncertainty reaches 2 kg at 1σ after 30 days, but at 2σ the uncertainty reaches 8 kg after about 60 days. Without NRTA, the total measurement uncertainty is almost exactly the same, suggesting that the material balance is dominated by only a few key areas in the MBA. The advantage of NRTA, though, is that it improves the timeliness of detection.

Discussion

Facility Design Implications

In MBA1, the addition of a Pu measurement on SNF with $\sigma_r=\sigma_s=5$ percent was not able to detect abrupt or protracted diversions in a thirty-day run. With $\sigma_r=\sigma_s=1$ percent, an abrupt diversion was detected, but a monthly plant flushout would be required to detect protracted diversions. NRTA on the front end adds little value due to the buildup of measurement errors. Given that the additional NRTA measurements of the dissolver tanks will be incredibly difficult to achieve, NRTA on the front end may not be the best option. A high-quality SNF measurement on the front end is still desired, but other techniques for improving safeguards should be examined.

Future plant designs could focus on interim inventories of MBA1 that minimize lost processing time as much as possible. Such systems will require a pause in operations to drain all dissolver tanks. The choice of batch versus continuous dissolvers should take this need into account. The loss of twelve hours of processing time every two weeks may be a reasonable goal as it will only result in a 3.6 percent loss of productivity.

In MBA2, the NRTA system was more effective because the fuel is in solution throughout the process. The total measurement uncertainty does not change significantly with NRTA, but the timeliness of detection improves. However, because the measurement errors go beyond 8 kg of Pu in about two months (at 2σ), plant flushouts or interim plant balances will still be required at least every two months. With or without NRTA, very long protracted diversions (on the order of months) are unlikely to be detected.

Technology Needs

High-precision mass spectrometry measurements continue to

Table 2. NRTA instrumentation list for MBA2

Measurement Point	Puσ_r	Puσ_s	Mode	Volume σ_r	Volume σ_s
Accountability Tank	0.2%	0.2%	Batch	0.1%	0.1%
UREX Feed Adjust	0.2%	0.2%	Continuous	N/A	N/A
UREX Contactors	10.0%	10.0%	Continuous	N/A	N/A
UREX Holding Tank	10.0%	10.0%	Continuous	N/A	N/A
UREX Solvent Rec.	10.0%	10.0%	Continuous	N/A	N/A
TRUEX Stripper	0.2%	0.2%	Continuous	N/A	N/A
TRUEX Reduction	0.2%	0.2%	Continuous	N/A	N/A
TRUEX Contactors	10.0%	10.0%	Continuous	N/A	N/A
TRUEX Raffinate	10.0%	10.0%	Continuous	N/A	N/A
TRUEX Solvent Rec.	10.0%	10.0%	Continuous	N/A	N/A
TALSPEAK Feed Adj.	0.2%	0.2%	Continuous	N/A	N/A
TALSPEAK Contactors	10.0%	10.0%	Continuous	N/A	N/A
TALSPEAK Solvent Rec.	10.0%	10.0%	Continuous	N/A	N/A
RE Product Tank	10.0%	10.0%	Continuous	N/A	N/A
Waste Calciner	10.0%	10.0%	Continuous	N/A	N/A
TRU Surge Tank	0.2%	0.2%	Continuous	N/A	N/A
TRU Product Tank	0.2%	0.2%	Batch	0.1%	0.1%

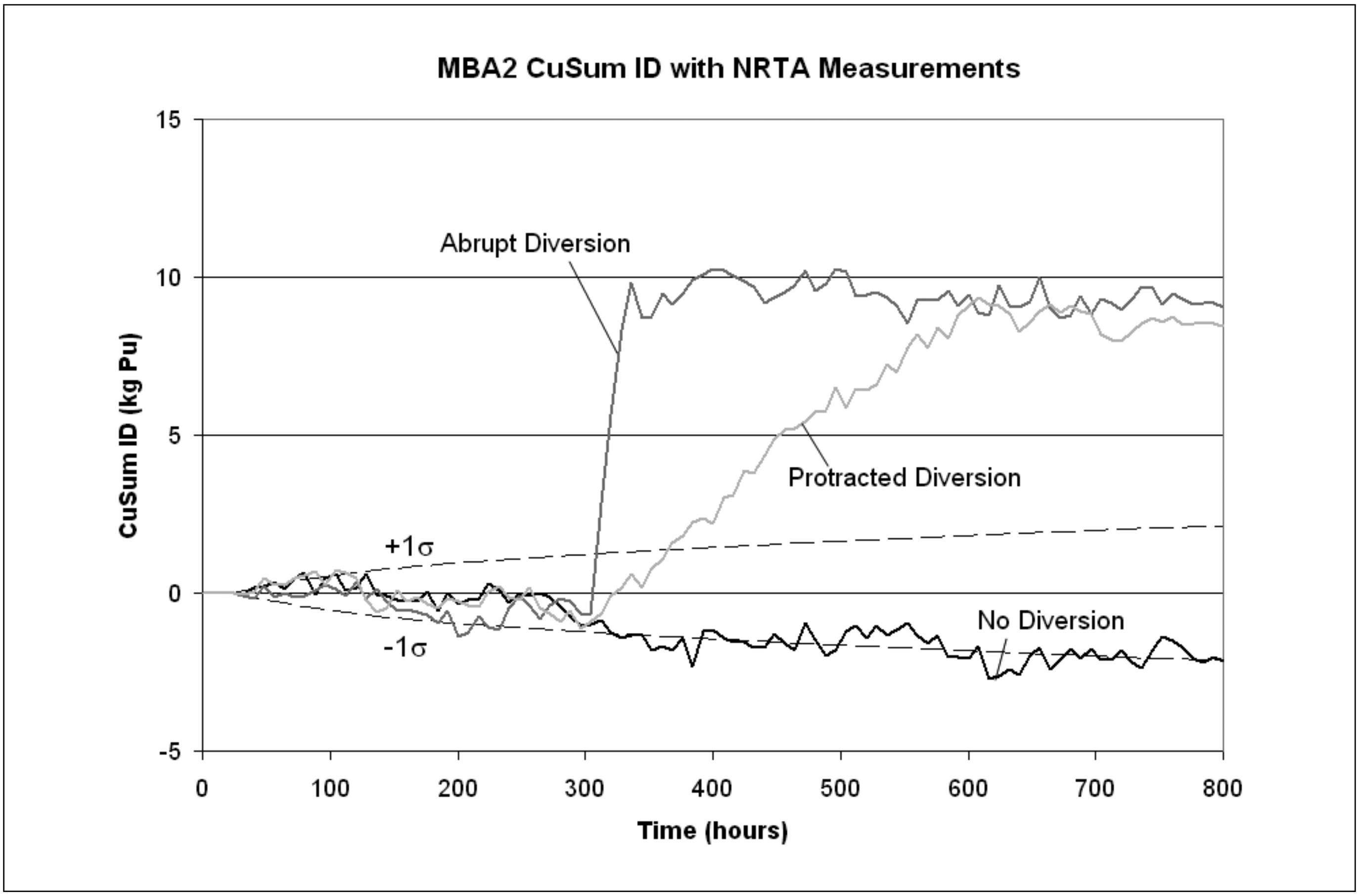
form the basis for accountancy. The number of key measurement points will increase slightly because the UREX+ designs produce more products than the traditional PUREX process. However, the proposed use of more frequent interim inventory balances may require more rapid turnaround time for sample analysis. Advanced technologies that can drastically speed up the analytical time could save on costs. More rapid HKED systems, the TARIS concept, or other techniques for automating the measurement (such as ion chromatography directly coupled to the mass spectrometer) will be important to investigate. Techniques like Microcalorimetry that may provide low uncertainty measurements non-destructively could replace sampling in many areas. An advanced measurement of actinides in SNF on the front end will also improve the safeguards regime if the measurement standard deviation can reach 1 percent.

Conclusion

This work suggests that adding additional measurements to every vessel or component processing plutonium provides little benefit on MBA1. On the other hand, periodic plant inventories that require draining of material to key interim tanks may be a much more effective use of resources. NRTA was more effective on MBA2 by improving the timeliness of detection. Much of the additional NRTA instrumentation in MBA2 can use NDA techniques with σs on the order of 10 percent, and only a few additional high quality sampling points will be required. MBA2 will also require interim inventories to minimize error buildup for protracted diversion detection. The challenge then is to improve the facility design to be able to provide these interim inventories with minimal impact to plant operations.

This conclusion does not provide significant technology leap from the current state-of-the-art at reprocessing plants, but it is hoped that it will provide more direction on the design of future plants. Future work will examine the interim inventory strategy in more detail using the SSPM. This will likely require improvement of the model detail regarding processing times and the operation of individual processing units.

Figure 7. MBA2 Pu CuSum ID with NRTA—no diversion, abrupt diversion of 8 kg Pu at hour 300, protracted diversion of 8 kg Pu from hour 300 to hour 600



Acknowledgements

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Issues Concerning the Security and Continued Use of Cesium-137 Irradiators

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Abstract

Sources of Cs-137 greater than 27 Ci (1 TBq) in activity are classified as "Radionuclides of Concern" by the U.S. Nuclear Regulatory Commission (NRC). They fall under "increased controls" that require the owners of these sources to initiate preventative measures to decrease the probability of unauthorized and malevolent use. These controls have been implemented over the past several years at some cost to the responsible owners who use Cs-137 for radiobiological research, medical and pharmaceutical research, blood irradiation, and agricultural sample sterilization. The use of Cs-137 is advantageous in many of these applications and aside from the security concerns, has few negative issues. However, because Cs-137 comes in *salt* form as the easily dispersible chloride CsCl, the NRC had been directed by the U.S. Congress to investigate if it could be replaced. The results of a National Research Council investigation requested by NRC and an NRC-sponsored public workshop provide an interesting insight into the conflicting needs of source users, regulatory/security oversight, and the financial implications of replacement with other radiation generating devices. This paper is a summary of the security concerns regarding the use of CsCl and the NRC's approach to mitigating those concerns based on the 2008 NRC workshop and subsequent NRC publications.

Large Cesium Sources Identified as Possible Threat

The National Academies recommended in late January 2008 that large radioactive sources of cesium-137 (Cs-137) be replaced.[1] The primary reason is that cesium-137 is in the chemical form cesium chloride (CsCl), a common *salt* in chemical parlance. Unfortunately, it is generally agreed that this makes the CsCl attractive for terrorists because it could be dispersed into the air by explosives. Decontamination of soil and urban surfaces such as concrete can be problematic and is predicted to be expensive. The radioactive qualities of Cs-137 also enhance its vulnerability. It has a fairly long radioactive half-life of thirty years, meaning that it would take that long for half of the starting amount to become non-radioactive. It also means that the radiation exposure rate from the cesium will not diminish to 50 percent of its initial value until thirty years have past. Cs-137 is an emitter of penetrating gamma-rays that require lead-shielding to protect those that use it. The radioactivity of the Cs-137 sources of concern here can produce potentially lethal exposure rates if they are removed from the accompanying shielding. According to the U.S. Nuclear Regulatory Commission (NRC), there are 1,101 device termed irradiators currently in use for various forms of research or for irradiation of the U.S. blood supply (Table 1).[2] In response to the National Academies recommendation, the NRC held a public workshop on September 29 and 30, 2008, attended by 200 interested people near its headquarters in Rockville, Maryland, USA.[3] The discussions revealed several issues that argue against an all-out ban and replacement of these radioactive sources.

Alternate Forms of Cesium Need Time for Development

Nuclear reactors in Mayak, Russia, are primary producers of cesium-137 as CsCl. It is distributed in the United States by Reviss, a Russian/United Kingdom joint venture based in the UK.[4] The radioactive sources are installed into irradiators that provide the shielding, timing electronics, and mechanical means to safely use

Table 1. U.S. NRC Statistics of Cesium-Based Devices (2008) (From Reference 2)

Application	IAEA Category*	Number of licensees	Number of Devices	Percent of Total Activity
Blood Irradiators	1-2	327	575	33.6
Research Irradiators	1-2	265	526	66.0
Calibrators	2	61	104	0.4
		Total of irradiators	1101	
		Grand total of all devices	1205	

* The IAEA category is based on a "D" value for Cs-137 of 3 Ci and the ratio of actual source activity (A) to D. Category 1 = A/D ≥ 1000. Category 2 = 1000 > A/D ≥ 10. The IAEA also considers the practices involving the sources when assigning a category.

the radiation. These devices are manufactured by such companies as Best Theratronics of Ottawa, Canada.[5] They are used in many facilities worldwide to irradiate materials for sterilization purposes but are also employed for radiobiological and pharmaceutical (oncology) research. One of the most important functions they serve is the irradiation of human blood to prevent detrimental immunological responses after transfusions. The use of radiation practically eliminates the risk of this "graft versus host disease." To perform these irradiation tasks efficiently, the sources must be large to produce high exposure rates that facilitate the rapid irradiation of large quantities of blood. Therefore, irradiator sources are generally of the order of 2000 Curies (74 TBq) or larger. These are primarily classified by the IAEA as "category 1" or due to the presence of less activity as "category 2" sources capable of doing great harm by means of their high (unshielded) exposure rates.[6]

Although forms of cesium such as pollucite [the chemical form of pollucite (Cs,Na)2Al2Si4O12•(H2O)] may be considered as a replacement for the chloride form, manufacturing facilities such as the Mayak complex in Russia would need several years to retool in order to produce it. As of the workshop date, the development and manufacturing costs of an alternate form had not been assessed.

Usefulness of Cesium Irradiators Complicates Security Issues

Other issues were discussed by the academicians, manufacturers, health physicists, source recovery companies, and other varied users of irradiators that attended the workshop. These issues fall into several categories:

- *Scientific Concerns* – The exposure that the Cs-137 gamma rays delivered to cells and cell components such as DNA has been well characterized. The linear energy transfer (LET) of gamma-rays is crucial to radiobiological research and has been the *de facto* standard for at least three decades. A change to X-rays would require that some form of *equivalency* be achieved between the results obtained with Cs-137 and X-rays. Cesium-137 radiation also delivers its radiation energy to small experimental animals in a well-known way that is crucial to certain types of research. By using the same form of radiation and at the energy of the radiation emitted from Cs-137, laboratories worldwide can compare data and assess the quality of their experiments. Considering the amount of radiobiological data so far amassed, the research science contingent at the workshop argued strongly against replacing the sources with radiation generating machines. One scientist explained that X-rays could be used in some research protocols but any experiments that detect the direct effects of radiation cannot use alternatives to Cs-137. One argument against X-ray machines is that they cannot generate the high radiation energies that can be achieved with Cs-137. These alternative X-ray producing devices are unlike the machines used in hospitals and clinics for diagnostic and therapeutic purposes because they confine the beam to a small chamber that holds cell samples or small animals. Studies are underway to determine the suitability of replacing Cs-137 with these new X-ray irradiators.[7, 8]
- *Financial Concerns* – Plaguing scientists and other users of Cs-137 irradiators are the costs of purchasing and maintaining X-ray irradiators. A Cs-137 irradiator is simple in design compared to an X-ray irradiator. An X-ray irradiator uses an X-ray tube that will wear out from thermal and radiation stress. The quality of the radiation produced is a function of the X-ray tube age. Therefore, the calibration of its output exposure rate is more frequent than for a Cs-137 irradiator. The upfront costs for X-ray irradiators are also expensive relative to Cs-137 irradiators. They cost about \$145,000 to \$180,000 and that cost is supplemented by service agreements in the range of \$10,000 to \$20,000 per year.[7] Similar figures were compiled by non-profit organizations that perform blood banking services (Table 2). With the view in mind that the cesium irradiators would be decommissioned by the NRC, America's Blood Centers estimated the phase-out cost and included the expenditure incurred for replacement with X-ray generating machines (Table 3).[9] The total expenditures are considered excessive for not-for-profit organizations. Other stakeholders claimed that Cs-137 irradiators, with their relatively low maintenance costs and long source half-lives, have paid for themselves many times over.
- *Alternative Technologies* – From a security perspective, X-ray machines specially built for research or blood irradiation are preferred to Cs-137 sources because there is no source to destroy or steal. But there are other issues concerning their use. Due to their electromechanical nature, they are more costly to operate than irradiators. Since they use more electricity than a Cs-137 based irradiator (mainly to energize the X-ray tube), they have a relatively larger operating carbon footprint. They are more sophisticated than a source-based irradiator and as indicated by some operating data, current models do have a tendency to malfunction more frequently than Cs-137 based irradiators.[10] Their life spans are expected to be shorter as well (five to ten years vs. twenty to thirty for Cs-137 based devices). However, this has not dissuaded X-ray machine manufacturers from attempting to take market share from source-based irradiator manufacturers. One of the best known manufacturers of X-ray irradiators is Rad-Source.[11] They are making in-roads with some customers that apparently can conduct biomedical research without Cs-137. But, the needs of all blood banks cannot be met with these devices at present. The speed of X-ray irradiation is currently a limiting factor for some high-throughput blood banks (see below under Health Concerns).

Another isotopic alternative to Cs-137 is the radionuclide Cobalt-60 (Co-60). It has a much shorter half-life (only about five years). That means the sources would have to be replaced more frequently increasing costs to users and to some extent the vulnerability to terrorists. Cobalt-60 also requires about twice as much shielding as an equivalent Cs-137 source does. [12] Thus potential purchasers of irradiators must consider the user of reinforced floors or floors with a load-rating capable of withstanding the heavier mass of a shielded Co-60 source. On the scientific side, energies of Co-60 gamma-rays are not considered viable alternatives to those of Cs-137 for certain types of research.

Linear accelerators have been mentioned as alternatives to Cs-137 for research purposes and even for blood irradiation. However, use of these devices for either purpose, though technically feasible, [13] means that users must compete for time on an expensive clinical device that is primarily devoted to patient care. [14] Other issues arise such as the irradiation of research animals, which would require that they be transported from research space into treatment areas. The speed of and quality of blood irradiation by a device not designed for that purpose must also be a concern.

- *Dosimetry* – This is a major concern for X-ray devices. Radiation derived from Cs-137 is basically mono-energetic (a 0.662 Mev gamma-ray; the beta emission is usually filtered out). Typical diagnostic X-ray machine energies (orthovoltages) are about 140 kVp to 400 kVp (note that X-ray machines produce a spectrum of energies from 0 to the maximum tube voltage). At lower photon energies, the photoelectric scattering effect dominates over the Compton effect. In general, higher photon energies penetrate further and interact via the Compton effect. There will be a difference in the delivered dose of the relatively low energy X-rays as a function of depth in the target compared to the Cs-137 or Co-60 photons. Therefore, because attenuation generally decreases with higher photon energy, the dose delivered from a Co-60 source is higher at the same depth in a target volume compared to that from Cs-137 photons or machine produced X-rays. An attempt to deliver the same dose to a small animal (a small target volume) from Co-60 would require modifications to the irradiation protocol that uses Cs-137 or X-rays. Achieving the same end-point using a large animal (a larger target volume) such as a dog may be much easier to meet.

  Another problem is that of achieving a uniform dose in the research animal. It is difficult to achieve with X-rays due to the photoelectric effect and the consequent disparity of the dose to bone and the dose to water (a substitute for soft tissue). At the photon energy of Cs-137 gamma-rays, this ratio is about 0.96 providing a nearly uniform dosimetry across the differing tissues. In order to minimize these issues, X-ray tubes must be redesigned to reach 0.5 MeV. Such a tube is perhaps three to four years away and ideally, should be offered at an affordable cost to research institutions.
- *Health Concerns* – As mentioned above, irradiation of banked blood is commonly performed to eliminate graft-versus-host disease—a rare but fatal condition. To prevent complications associated with the storage of transfused blood (potassium will leak over time from red blood cells that have been irradiated), hospitals perform as-needed or "stat" irradiations of blood. For example, children's hospitals must use irradiated blood within twenty-four to forty-eight hours due to the potassium leakage problem. The banning of cesium-based irradiators would force such hospitals to change blood irradiation and storage procedures to accommodate the slower irradiation capability of X-ray machines. Typically, up to six blood bags may be irradiated in two to three minutes in a Cs-137 irradiator. A Best Theratronics/Nordion Raycell X-ray machine only holds two blood units and may require five minutes to achieve a similar radiation exposure level. [15]
- *International Use and Security Issues* – Irradiators are used worldwide. A meeting representative from the U.S. Department of Agriculture (USDA), who uses these devices in Guatemala, explained the need to irradiate insects (to sterilize them reproductively) for about twenty-two hours per day, seven days a week.[16] He could only achieve about 700 operating hours weekly using Rad-Source Inc. X-ray machines to accomplish this task. A cost of $50,000 was quoted for tube replacement. The USDA investigated implementing their own machine shop to train their engineers to do repair and tube installation in order to avoid these high costs.

  Cesium-based machines are in use in many third world countries where security and oversight by regulating authorities may be questionable. Here, replacement by X-ray machines is even more problematic because electricity supplies may be unreliable. Yet, the irradiation of blood supplies is still a necessity which strongly argues for maintaining Cs-based irradiators in overseas operation despite the security concerns. An employee of Best Theratronics pointed out that medical personnel in such countries as Pakistan, India, China, and Japan do not see the use of Cs-137 irradiators as a security issue. He suggests that an education campaign is needed to enlighten users globally about the potential misuse of these radiation sources.[17]
- *Disposal Problems* – The Cs-137 sources in irradiators are of relatively small volume but can be *concentrated* to contain many hundreds or thousands of Curies of radioactivity. When the concentration is greater than 4,600 Curies per gram (170 TBq/g), the source, if considered for disposal would be a "Class C" waste. Unfortunately, a Class C radioactive waste repository has not yet been approved in the United States thus complicating the results of any ban or confiscation of these sources. Short-term storage at a government facility such as the Department of Energy's Los Alamos National Laboratory was suggested but the issue of transportation to accomplish this storage also has its share

of problems. For example, stakeholders expressed the need for the federal government to bare the transport costs, which now include provisions for security when the source is removed from the owner's site. A cask suitable for transport of these highly radioactive sources was retired by the NRC on October 1, 2008, leaving only a certified type available for import/export use with sources under the care of Best Theratronics.[18] Reviss also has an approved import/export cask. Conceivably, the high-level waste packages of some radioactive waste processors can be used if they were to be certified by NRC for domestic transport of CsCl.[19] Thus, the confiscation of these sources for interim storage would be extremely challenging due to the current shortage of U.S. government approved transport casks.

Government Security Programs in Place

A federally funded program to provide security upgrades to cesium-based irradiators was implemented in the fall of 2008.[20] A combined effort of the U.S. Department of Energy, the National Nuclear Security Administration (NNSA), the Department of Homeland Security, the NRC, and several private organizations such as the Organization of Agreement States and a few manufacturers, this program focuses on improving the protection of domestic cesium irradiators. The upgrades include security training and an assessment of the current security that is being provided by the irradiator owner/operator. The hardware typically installed at deficient sites includes motion detectors, radiation sensors, tamper seals, audible alarms, and guard force communications and protection equipment.

To protect the United States from radiological dispersal devices and other threats using radiation as a weapon, the Global Threat Reduction Initiative (GTRI) was established in 2004 under NNSA. It was preceded in 2002 by a similar program also under NNSA called the Off-Site Recovery Program (OSRP). GTRI, like OSRP, is a radioactive source recovery program that operates primarily in the United States. The sources of concern are those at risk for theft because they are considered surplus, otherwise unwanted, or were abandoned. Since 1997, these NNSA programs have secured more than 20,000 radioactive sources of varying types (not just Cs-137) from medical, educational, agricultural, research, and industrial facilities. GTRI also works to recover orphaned sources internationally.[21] The costs for operations within the United States are carried by the U.S. government. The IAEA, host governments and international donors supplement overseas operations.[22] A National Source Tracking System was also recently implemented to maintain a renewable database of ownership, location and technical information of Category 1 and 2 radioactive sources.[23]

NRC Ruling Places Emphasis on Security over Phase-out

The NRC has formed a "Radiation Source Protection and Security Task Force that includes a "CsCl Working Group." In March 2009, this working group recommended the following:

1. Immediate phase-out of CsCl is not possible
2. Stepped phase-out could be possible
3. Certain challenges related to a phase-out must be overcome
    a. Economic incentives are lacking to develop alternative Cs-137 chemical forms
    b. New forms may not be successfully utilized with irradiator manufacturers
    c. Phase-outs can have detrimental effects on the blood supply
    d. A disposal pathway for large Cs-137 sources must be developed.
4. Time would be needed to implement replacement technologies (X-ray machines) and to develop the disposal pathway
5. Interim security measures continue to be important and relevant[2]

In two *NRC News* publications (numbers 08-223 and 09-074) the NRC recommended enhancing the security of cesium chloride-based irradiators rather than banning them.[24, 25] The earlier publication (08-223) de-emphasized the replacement of the sources while the later encouraged research to develop an alternate form of Cs-137. For the time being security enhancements have won out over the banishment of the irradiator. These units provide necessary services relatively inexpensively. A ban currently presents too many technical and financial obstacles that would disrupt many organizations that own and operate these devices under NRC or agreement state licenses. Thus, the secu-

Table 2. Costs of Irradiators Owned by America's Blood Centers (From Reference 9)

Type	Number of Devices	Average Purchase Price ($US)	Average Operating Costs ($US)	Average Anticipated Lifespan (y)
Cs-137	65	107,272	9,230	25
X-Ray	13	149,747	20,375	10
n *	80**	47	56	68

*Number of devices for which data was supplied
** Two irradiators use Co-60

rity measures that were first implemented by law several years ago by NRC for these "sources of concern"—the "increased controls" requirements—must be enforced and the licensees subject to periodic inspections by NRC and agreement state regulators.[26] These regulations require that those needing unattended access to irradiators undergo fingerprinting, a Federal Bureaus of Investigation (FBI) criminal background check with submission of the fingerprints to NRC, and the establishment of a program to support the security of the irradiator including a documented agreement with local law enforcement to provide assistance in the event of malevolent act involving the irradiator, and the protection of the aforementioned personnel information.

Conclusion

Until manufacturers develop a more secure, less dispersable form of Cs-137 or improve non-source technologies for blood irradiation such as cabinet X-ray machines, irradiator units will be subject to scrutiny by regulatory agencies (NRC and agreement state radiation protection agencies) concerned about their security and potential misuse. Complicating this issue is the cost of irradiator decommissioning, source disposition, X-ray machine replacement and associated costs of preventative maintenance and repair. The latter issues are especially difficult for non-profit blood centers, hospitals, and university research institutions and even for other, better-funded organizations such as pharmaceutical corporations that must budget for this contingency at the expense of other projects. The NRC has acted cautiously and reasonably via the information collected at its well run 2008 workshop. However, the final chapter on the fate of CsCl sources still remains to be written.

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	Average Cost per Device ($US)	Total Cost for 65 Devices* ($US)
Estimated Remaining Value in Cs-137 for an Average 12-year Remaining Life Span	54,491	3,541,915
Decommissioning Cost	12,237	803,205
Purchase Cost of X-ray Irradiator	149,747	9,733,555
Additional Operating Costs Per Year For a 10-year Period for an X-ray Irradiator vs. Cs-137	11,145	7,244,250
Total	227,740	21,322,925

*Number of Cs-137 irradiators at ABC facilities in 2008

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All Stocks of Weapons-Usable Nuclear Materials Worldwide Must be Protected Against Global Terrorist Threats

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Abstract

The danger of nuclear terrorism is real enough to justify urgent action to reduce the risk. Some terrorist groups are actively seeking nuclear weapons and the materials to make them; it is plausible that a technically sophisticated terrorist group could make a crude nuclear bomb if it acquired enough highly enriched uranium (HEU) or plutonium; important weaknesses in nuclear security still exist in many countries and thefts of HEU and plutonium have already occurred; nuclear smuggling is very difficult to interdict; and the consequences of a terrorist nuclear detonation would be immense and far-reaching. Nuclear thieves could strike in any country. In this article, we outline a baseline set of adversary capabilities that *all* stocks of nuclear weapons, plutonium, or HEU should be protected against, no matter what country they are in, including both insiders and outsiders and a range of potential tactics. We recommend that countries facing more substantial adversary threats put even more capable security systems in place. The article calls for international cooperation Countries facing more capable adversaries should provide protection going beyond the baseline level we describe. The article calls for international cooperation, including technical and financial assistance where needed, to ensure that at least this baseline level of protection is in place for all nuclear weapons, plutonium, and HEU worldwide.

Introduction

> *"We must ensure that terrorists never acquire a nuclear weapon. This is the most immediate and extreme threat to global security. One terrorist with one nuclear weapon could unleash massive destruction.... So today I am announcing a new international effort to secure all vulnerable nuclear material around the world within four years."*
> -U.S. President Barack Obama, Prague, 5 April 2009

> *"We have firm knowledge, which is based on evidence and facts, of steady interest and tasks assigned to terrorists to acquire in any form what is called nuclear weapons, nuclear components."*
> - Anatoly Safonov, Special Representative of the Russian President for International Cooperation in the Fight Against Terrorism and Transnational Organized Crime, Interfax, 27 September 2007 (translation by Simon Saradzhyan)

In April 2010, leaders and senior officials from forty-seven countries agreed that "nuclear terrorism is one of the most challenging threats to international security," and called for a four-year effort to secure all vulnerable nuclear material worldwide.[1] No one knows the real probability of a terrorist attack with a nuclear bomb. But the evidence of terrorist efforts to get the nuclear materials and expertise needed to make a crude nuclear explosive is sufficiently troubling, and the consequences of such an event sufficiently grave, to justify urgent action to reduce the risk.

Nuclear Terrorism is a Genuine Danger

Several unfortunate facts shape the risk the world faces.[2] First, some terrorists are actively seeking to acquire nuclear weapons, and the plutonium or HEU needed to make them. Osama bin Laden has called the acquisition of nuclear weapons or other weapons of mass destruction a "religious duty," and al-Qaeda operatives have attempted to buy nuclear material and recruit nuclear expertise. Two senior Pakistani nuclear weapon scientists associated with Ummah Tameer e-Nau (UTN) network, for example, personally met with bin Laden and Zawahiri to discuss nuclear weapons. In the 1990s, the Japanese terror cult Aum Shinrikyo, which launched the nerve gas attack in the Tokyo subway in 1995, also sought nuclear weapons. There is clear evidence that Chechen terrorists have pursued radiological "dirty bombs," and at least suggestive indications of their interest in actual nuclear bombs as well—and there are deep links between some Chechen terrorist factions and al Qaeda.[3] With at least two terrorist groups having pursued nuclear weapons in the last two decades, the world should not expect that they will be the last.

Second, repeated assessments by the U.S. government and other governments have concluded that it is plausible that a sophisticated terrorist group could make a crude nuclear explosive—capable of destroying the heart of a major city—if they got enough plutonium or HEU.[4] A "gun-type" bomb made from

HEU, in particular, is basically a matter of slamming two pieces of HEU together at high speed.

One study by the now-defunct congressional Office of Technology Assessment summarized the technical reality: "A small group of people, none of whom have ever had access to the classified literature, could possibly design and build a crude nuclear explosive device... Only modest machine-shop facilities that could be contracted for without arousing suspicion would be required."[5] Indeed, even before the revelations from Afghanistan, U.S. intelligence concluded that "fabrication of at least a 'crude' nuclear device was within al-Queda's capabilities, if it could obtain fissile material."[6]

The hardest part of making a nuclear bomb is producing the needed plutonium or HEU—a task that took up more than 90 percent of the effort in the U.S. Manhattan Project. Making their own nuclear material is almost certainly beyond terrorist nuclear capabilities—so if the stocks controlled by states can be appropriately secured and kept out of terrorist hands, nuclear terrorism can be prevented.

It is important to understand that making a crude, unsafe, unreliable bomb of uncertain yield that might be carried in the back of a large van is a dramatically simpler task than designing and building a safe, secure, reliable, and efficient weapon deliverable by a ballistic missile, which a state might want to incorporate into its arsenal. Terrorists are highly unlikely to ever be able to make a sophisticated and efficient weapon, a task that requires a substantial nuclear weapons enterprise—but they may well be able to make a crude one. Their task would be easier if they managed to recruit knowledgeable help, which they have been actively attempting to do.

Third, there is a real risk that terrorists could get the plutonium or HEU needed to make a nuclear bomb. Important weaknesses in nuclear security arrangements still exist in many countries, creating weaknesses that outsider or insider thieves might exploit. HEU-fueled research reactors, for example, sometimes located on university campuses, often have only the most minimal security measures in place. One recent review of research reactors that had received U.S.-sponsored security upgrades identified research reactors that were wholly dependent on off-site response forces to respond to a theft attempt, but had never exercised the capabilities of those forces; a reactor that conducted no search of vehicles leaving the site for potential nuclear contraband; a reactor for which the national regulatory agency had not established any nuclear security requirements; and a reactor where no background checks were performed before allowing access to nuclear material.[7] In countries such as Pakistan, even substantial nuclear security systems are challenged by immense adversary threats, both from nuclear insiders—some with a demonstrated sympathy for Islamic extremists—and from outside attacks that might include scores or hundreds of armed attackers. In the end, all countries where these materials exist—including the United States and Russia—must regularly reassess whether the security they have in place is sufficient to meet the evolving threat.

As a result of such security weaknesses, there have been eighteen incidents of theft or loss of HEU or separated plutonium confirmed to the IAEA by the states concerned.[8] In February 2006, Russian citizen Oleg Khinsagov was arrested in Georgia (along with three Georgian accomplices) with 79.5 grams of 89 percent enriched HEU, claiming that he had kilograms more available for sale; in March 2010, two Armenians were arrested in Georgia with 18 grams of similar 89 percent enriched HEU.[9] What we do not know, of course, is how many thefts may have occurred that were never detected; it is a sobering fact that nearly all of the stolen HEU and plutonium that has been seized over the years had never been missed before it was seized. There have also been alarming intrusions. In 2007, for example, at the Pelindaba nuclear facility in South Africa, where hundreds of kilograms of weapon-grade HEU are located, two teams of armed men attacked from opposite sides of the site: one of the teams got through a 10,000-volt security fence, disabled intrusion detectors without detection, proceeded to the emergency control center (where they shot one of the workers on duty), and spent forty-five minutes inside the guarded perimeter without ever being engaged by site security forces.[10]

Fourth, it would be extremely difficult to stop terrorists from smuggling nuclear material or a crude nuclear weapon to its target. A nuclear bomb might be delivered, intact or in ready-to-assemble pieces, by boat or aircraft or truck. The length of national borders, the diversity of means of transport, the vast scale of legitimate traffic across borders, and the ease of shielding the radiation from plutonium or especially from HEU all operate in favor of the terrorists. Building the overall system of legal infrastructure, intelligence, law enforcement, border and customs forces, and radiation detectors needed to find and recover stolen nuclear weapons or materials, or to interdict these as they cross national borders, is an extraordinarily difficult challenge.[11]

Fifth, even a single terrorist nuclear bomb would be a catastrophe that would change history. The heart of a major city could be reduced to a smoldering radioactive ruin, leaving tens or hundreds of thousands of people dead. Terrorists—either those who committed the attack or others—would probably claim they had more bombs already hidden in other cities (whether they did nor not), and the fear that this might be true could lead to panicked evacuations, creating widespread havoc and economic disruption. Some countries may feel that nuclear terrorism is really only a concern for the countries most likely to be the targets, such as the United States. In reality, however, such an event would cause devastating economic aftershocks throughout the world—global effects that in 2005 then-UN Secretary-General Kofi Annan warned would push "tens of millions of people into dire poverty," creating "a second death toll throughout the developing world."[12]

It is also important to emphasize that the nuclear industry itself has a huge interest in preventing nuclear terrorism. A terrorist nuclear bomb, or a major sabotage of a nuclear facility—a "security Chernobyl"—would doom any prospect for gaining the public, government, and utility support needed for large-scale growth of nuclear power, putting tens or hundreds of billions of dollars in future revenue at risk. In some countries, it might even lead to pressures to close major operating facilities.

The good news is that there is no convincing evidence that any terrorist group has yet gotten a nuclear weapon or the materials and expertise needed to make one. Moreover, making and delivering even a crude nuclear bomb would be among the most technically challenging and complex operations any terrorist group has ever carried out. There would be many chances for the effort to fail. But given a history of terrorist efforts to get a nuclear bomb, and the dire consequences should they ever succeed, there can be no room for complacency. All countries must take action to reduce the risks of nuclear theft and terrorism to the lowest practicable level.

Nuclear Thieves Could Strike in Any Country

Unfortunately, international terrorists have demonstrated that they have global reach. Everyone recalls the attacks in the United States, in Moscow and Beslan, in London, and in Madrid. But it is important to recall that al Qaeda-linked conspiracies have been uncovered in some of the "safest" countries, from Canada to Belgium to the Netherlands. Japan has experienced homegrown terrorism with weapons of mass destruction from Aum Shinrikyo—and in the years to come, such groups could arise in other countries.

Al Qaeda bombed the U.S. embassies in Kenya and Tanzania not because they had any special quarrel with Kenya or Tanzania but because they were particularly vulnerable targets that would hurt the United States. Similarly, terrorists will seek nuclear material for a bomb wherever they think the combination of their strength and the security systems' weakness makes it easiest to get. They do not have to steal it in the country that is the ultimate target. No country should believe that because it has never been threatened by Islamic extremists it need not provide stringent security for its nuclear material. In a very real sense, vulnerable weapons-usable nuclear material anywhere is a threat to everyone, everywhere.

All Nuclear Stockpiles Must be Protected Against Plausible Adversary Threats

Clearly, the capabilities of terrorists and thieves vary from one country to another. A nuclear security system sufficient to reduce the risk of nuclear theft or sabotage to a low level in Canada may not be sufficient in Pakistan. Each country with nuclear weapons, plutonium separated from spent fuel, or HEU must ensure that these stocks are effectively protected against the spectrum of outsider and insider capabilities that are most plausible in their country. These stocks should be protected against two sets of capabilities: first, capabilities that terrorists and criminals have shown they can bring together in that country (with whatever additional capabilities that country's intelligence agencies believe are most likely), and second, a set of capabilities that international terrorists might be able to bring to bear in any country. To accomplish this, countries controlling these stocks should establish and enforce rules that require that these stocks be protected against particular sets of adversary capabilities, known as the design basis threat, (DBT), as described in IAEA recommendations and guidance.[13] Ideally, the threat assessment process should include experts who have access to all relevant threat information available to the state, and who are independent of those operating the nuclear facilities. The DBT should be reviewed regularly to ensure that it reflects an up-to-date assessment of the evolving threat. Of course, a balance must be drawn between the costs of security and the threats the security system can protect against—and different participants in these discussions will often have different views as to where that balance should be drawn.

Outlining a Nuclear Security Baseline

As just noted, facing terrorists with global reach, there are adversary capabilities that *all* stocks of nuclear weapons, plutonium, or HEU must be protected against, no matter what country they are in. In our view, all such stocks should *at least* be protected against:

- A modest group of well-trained outside attackers, capable of operating as more than one team, with armaments that might include automatic weapons, rocket-propelled grenades,[14] and explosives;
- A well-placed insider, with knowledge of the security system, who might carry out a theft himself or herself, or might provide passive or active assistance to outsiders;
- Deception attacks, where thieves might, for example, have military uniforms and forged identification papers, or even forged documents authorizing material to be removed from a site for shipment;
- Bombs that could be carried on a person's body, or in a car or van; and
- Unusual vehicles or routes.

Several elements of this list are particularly important. First, it is essential that all countries with nuclear materials and facilities include the possibility of an insider in the DBT that facilities must be able to protect against. All of the real cases of theft of HEU or plutonium whose origins are documented were perpetrated by insiders or with the assistance of insiders. Hence, it is essential to maintain a strong personnel reliability program that conducts background checks before giving employees access to nuclear weapons, materials, or nuclear security information, and that also includes ongoing monitoring so that suspicious changes in behavior may set off warnings. But even where effective personnel reliability programs are in place, it is still essential to protect against insider theft. Some managers may believe that their employees are trustworthy and they could never have an insider problem at their facility. In some countries (including the United States) operators are allowed to assume that employees participating in the full personnel reliability program would not *actively* participate in a theft attempt (though they might provide information to outsiders, or disable an alarm). But it should be remembered that even trustworthy insiders could be coerced. In one case in Northern Ireland, for example, a bank had a security system that required two senior officers of the bank to work together to open the vault—but a gang kidnapped the families of two of the senior officers of the bank, and sure enough, they opened the vault.[14] Where practical, it may even be desirable to require operators to at least explore options that would make theft attempts involving more than one insider more difficult and risky.

The possibility of more than one team is also important. Unless the defenders are appropriately prepared for such possibilities, one team might create a major diversion to draw the defenders away while the other carried out the theft. Or one team might be assigned to prevent the response force from arriving in a timely way (for example by mining a road and then sniping at those trying to clear the obstacles). Imagine, for example, if the site relied on an external police response and there were to be another attack in a local town that preceded the facility attack.

With respect to vehicles and routes, much depends on the specifics of the particular site. Sites on the coast should be protected against attacks arriving from the sea (as in the recent attack in Mumbai). Sites in urban areas with buildings close by that are not controlled by the operator should consider whether tunneling into the facility is a realistic possibility; there have been repeated cases of that tactic being used to steal millions of dollars from otherwise well-guarded banks. Sites that rely heavily on layers of barriers for delay should consider whether they have adequate protection in the event that thieves arrive or depart with a helicopter, bypassing the barriers—a tactic that criminals have used in jailbreaks in several countries, though also one that introduces another step that the attack force has to take, with additional risks of its own.

Each of these types of adversary capability has been repeatedly demonstrated in terrorist attacks and thefts from guarded non-nuclear facilities around the world. Indeed, the Pelindaba incident described above—two teams attacking from opposite sides, apparently with insider knowledge of how to defeat the intrusion detectors—makes clear that this is a realistic level of threat against which stockpiles of nuclear weapons, plutonium, or HEU worldwide must be protected.[15]

Providing effective protection against at least this spectrum of potential adversary capabilities should be considered a "best practice" in implementing DBT methodology that should be adopted by all. Countries and operators who do *not* believe their stocks of weapons-usable nuclear materials need to be protected against such threats need to ask themselves what makes them so confident that thieves could not apply such capabilities in attempts to steal their nuclear stocks—and whether it is justified for them to endanger other countries and the nuclear industry as a whole by providing less security than other operators do.

Countries and operators should not use a DBT that represents a single point estimate of the threat, but rather should protect against a spectrum of possibilities. A theft attempt involving a small number of people with convincing official uniforms and paperwork is not a *lesser* attack than a dozen attackers arriving with guns blazing, it is a *different* attack, requiring different types of defensive procedures.

Implementing the Recommended Level of Protection

Of course, establishing a requirement that operators be able to protect against such a DBT is only the first step. Operators must then develop and implement security designs, plans, and procedures capable of protecting against the full spectrum of possibilities included in the DBT. Regulators must review these arrangements to confirm that they really will provide effective protection against the DBT. Assessments of operators' security arrangements should include a range of testing, including not only component tests—such as tests to ensure that detectors detect intrusions, or that response forces arrive in response to a call—but also exercises designed to test the full system's ability to defeat intelligent adversaries. In the United States, for example, "force-on-force" exercises testing sites' protection against outsider attacks—sometimes using laser-tag weapons to avoid anyone actually being shot in the exercise—have often revealed important weaknesses in security systems that looked good on paper. Exchanging approaches to getting the maximum value out of such exercises while maintaining appropriate safety for both facilities and personnel could be an important area for exchange of best practices between countries.

Facilities will inevitably vary in their abilities to maintain effective security against a spectrum of threats of this kind. Military organizations have long focused on security for their operations and are generally already protected against these kinds of threats—though the focus at both military and civilian facilities must always be on constant vigilance and continual improvement. For large commercial facilities, we believe that effective security can be achieved and maintained for a cost that represents a small fraction of total operating budgets. Companies must take responsibility for effective nuclear security as an essential part of corporate risk management, just as they already do in the case of nuclear safety. For small research reactors with little operating revenue, however, the costs of protecting against the kinds of threats outlined in this paper may seem prohibitive. We believe that governments, which generally already subsidize the operation of such reactors, should pay for their security, to the extent that governments believe their continued operation provides a benefit to society worth the cost. The costs of security will also provide an additional incentive to convert from the use of HEU to other fuels that do not require such stringent protection.

International Nuclear Security Cooperation and Agreements

Countries should work together, including providing technical and financial assistance where needed, to ensure that this baseline level of protection is in place for all nuclear weapons, plutonium, and HEU worldwide—and that countries facing more substantial adversary threats put even more capable security systems in place. Achieving that goal should be the centerpiece of the four-year international effort to secure nuclear stockpiles worldwide called for by the Nuclear Security Summit and unanimously endorsed by the U.N. Security Council.[17] The cooperation between the United States and Russia, which has led to substantial improvements in physical protection, material control, and material accounting at many sites, demonstrates what can be accomplished.

International agreements and recommendations should be modified to call for all nuclear weapons, plutonium, and HEU to have effective protection against such a baseline set of adversary capabilities. The current version of the IAEA physical protection recommendations, drafted in 1999, already calls on states to base their nuclear security approach on a DBT; the new revision in the process of being published offers somewhat more specific recommendations on how countries should develop and use their DBTs, but does not offer a baseline level of security states should adopt, such as that outlined in this paper.

A strong argument can be made that states are already legally obligated to provide something like this level of security. UN Security Council Resolution 1540 requires all states to provide "appropriate effective" security and accounting for any nuclear weapons or weapons-usable nuclear materials they may have—but no one has yet defined precisely what this requires. If the words "appropriate effective" mean anything, they should mean that nuclear security systems would effectively protect against the threats that terrorists and criminals have shown they can pose. Thus one possible definition would be that to meet its UNSCR 1540 physical protection obligation, every state with nuclear weapons or weapons-usable nuclear materials should have a well-enforced national rule requiring that every facility with a nuclear bomb or a significant quantity of nuclear material must have security in place capable of defeating a specified DBT including outsider and insider capabilities comparable to those terrorists and criminals have demonstrated in that country (or nearby).[18] Even in particularly safe countries, as argued above, the DBT should not be less than two modest teams of well-armed and well-trained outsiders, possibly in collaboration with one insider.

This approach has the following advantages: the logic is simple, easy to explain, and difficult to argue against; the approach is general and flexible enough to allow countries to pursue their own specific approaches as long as they are effective enough to meet the threats; and at the same time, it is specific enough to be effective and to provide the basis for questioning, assessment, and review. If the leading nuclear states could agree on a common interpretation of what UNSCR 1540 requires—including a minimum design basis threat that all nuclear weapons or weapons-usable nuclear materials everywhere should be protected against—that would, in effect, create a binding global nuclear security requirement. The leading nations agreeing to such a requirement should then launch an intensive effort to persuade other states to bring their nuclear security arrangements up to the agreed level and help them to do so as needed.[19] Similarly, nuclear exporters should consider requiring that plutonium or HEU they export, or produced from materials they export, be protected to at least the level described in this paper. Ultimately, effective nuclear security should be part of the "price of admission" for doing business in the international nuclear market.

The danger of nuclear terrorism is real. Action to reduce the risk is essential. But no nation, however powerful, can prevent nuclear terrorism on its own. The task requires international cooperation, involving all those with stockpiles to secure and resources and expertise to help secure them. Ensuring that all stockpiles of nuclear weapons, plutonium, and HEU worldwide are effectively protected against the most plausible terrorist and criminal threats is the first and most important step, holding the potential to greatly reduce the risk the world faces, at a cost that is far smaller than the potential cost of failure to act.

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End Notes

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3. For a summary of the publicly available evidence, see Matthew Bunn And Anthony Wier, With Joshua Friedman, "The Demand For Black Market Fissile Material," In *Nuclear Threat Initiative Research Library: Securing The Bomb* (Cambridge, Ma., 2005), available at www.nti.org/e_research/cnwm/threat/demand.asp (accessed 30 October 2009). See also the alarming account of Al Qaeda's nuclear weapons efforts, extending well beyond the collapse of the Taliban regime in Afghanistan in late 2001, in George Tenet, *At The Center Of The Storm: My Years At The CIA* (New York: HarperCollins, 2007), pp. 259–80. While Tenet's credibility has inevitably been undermined by the faulty intelligence on Iraq, none of the assertions in his chapter on Al Qaeda and nuclear weapons has been publicly challenged.
4. Throughout this paper, references to plutonium and HEU, or to weapons-usable nuclear materials, refer to materials separated from the intensely radioactive fission products in spent fuel. In international parlance, the IAEA refers to these as "unirradiated direct use materials."
5. U.S. Congress, Office of Technology Assessment, *Nuclear Proliferation And Safeguards* (Washington, D.C.: Ota, 1977) http://www.princeton.edu/~ota/disk3/1977/7705/7705.pdf (accessed 30 October 2009), p. 140. Ota reached this conclusion long before the internet made a great deal of relevant information much more widely available.
6. Commission on the Intelligence Capabilities of the United States Regarding Weapons of Mass Destruction, *Report to the President* (Washington, D.C.: WMD Commission, 2005), http://www.gpoaccess.gov/wmd/index.html (accessed 30 october 2009), p. 276.
7. U.S. Congress, Government Accountability Office, *Nuclear Nonproliferation: National Nuclear Security Administration Has Improved the Security of Reactors in Its Global Research Reactor Program, But Action Is Needed to Address Remaining Concerns,* GAO-09-949 (Washington, D.C.: GAO, September 2009), http://www.gao.gov/new.items/d09949.pdf (accessed 30 october 2009).
8. For the International Atomic Energy Agency's most recent list of incidents confirmed by the states concerned, see *IAEA Illicit Trafficking Database* (Vienna: IAEA, 2008) http://www.iaea.org/newscenter/features/radsources/pdf/fact_figures2007.pdf (accessed 28 october 2009). Perhaps the best available summary of what is known and what is not known about nuclear and radiological smuggling is "Illicit Trafficking in Radioactive Materials," in Mark Fitzpatrick, Ed., *Nuclear Black Markets: Pakistan, A.Q. Khan, and the Rise of Proliferation Networks: A Net Assessment* (London: International Institute for Strategic Studies, 2007), pp. 119-138. (Lyudmila Zaitseva, principal author.)
9. For an especially useful account of the 2006 case, see Michael Bronner, "100 Grams (and Counting): Notes From The Nuclear Underworld" (Cambridge, Mass.: Project on Managing the Atom, Harvard University, June 2008). (The case involved roughly 100 grams of uranium oxide, of which 79.5 grams were uranium.) For an account of the 2010 case, see Julian Borger, "Nuclear Bomb Material Found for Sale on Georgia Black Market," *Guardian,* November 7, 2010 http://www.guardian.co.uk/world/2010/nov/07/nuclear-material-black-market-georgia).
10. The team that entered the site left via the same point at the fence by which they arrived. Their familiarity with how to disable the intrusion detectors and with equipment at the emergency control center strongly suggests they had help from someone with insider knowledge. They have never been identified or captured. For a description of this event, see Bunn, *Securing the Bomb 2008*, Pp. 3-4, And "60 Minutes: Assault on Pelindaba," *CBS News,* 23 November 2008, http://www.cbsnews.com/stories/2008/11/20/60minutes/main4621623.shtml (accessed 30 October 2009).
11. For a useful discussion emphasizing the ease with which terrorists might follow different pathways to deliver their weapon, see allison, *Nuclear Terrorism: The Ultimate Preventable Catastrophe.* For a more optimistic view of the potential of these parts of a defensive system, see levi, On Nuclear Terrorism.
12. kofi annan, "a global strategy for fighting terrorism: keynote address to the closing plenary," in *the international summit on democracy, terrorism and security* (madrid: club de madrid, 2005; available at http://english.safe-democracy.org/keynotes/a-global-strategy-for-fighting-terrorism.html as of 18 june 2008).
13. International Atomic Energy Agency, *The Physical Protection of Nuclear Material and Nuclear Facilities,* INFCIRC/225/rev.4 (corrected) (Vienna: IAEA, 1999) http://www.iaea.or.at/publications/documents/infcircs/1999/infcirc225r4c/rev4_content.html (accessed 30 October 2009), and International Atomic Energy Agency, Development, Use, and Maintenance of the Design Basis Threat: Implementing Guide, Nuclear Security Series No. 10 (Vienna: IAEA, 2009), http://www-pub.iaea.org/mtcd/publications/pdf/pub1386_web.pdf (accessed 30 october 2009). A fifth revision of INCIRC/225 is in the process of being published.
14. Unfortunately, rocket-propelled grenades are widely available to terrorist groups, and have been used extensively in Lebanon, in Iraq, in Afghanistan, and elsewhere. Fortunately, in the case of defending fixed sites such as nuclear facilities, simple and cheap defenses—such as strong wire mesh in front of a wall to be protected—can cause the grenade to detonate harmlessly away from the wall. See "Systems

Under Fire," (Video), U.S. Department of Energy, Office of Independent Oversight and Performance Assurance, 2003.

15. For a more detailed discussion of possible routes toward effective global nuclear security requirements, see Bunn, *Securing the Bomb 2008,* pp. 147-157. For a good introduction to the Northern Bank case, see Chris Moore, "Anatomy of a £26.5 Million Heist," *Sunday Life,* 21 May 2006. The thieves also used deception in this case, appearing at the bank managers' homes dressed as policemen. One of these managers, however, was later charged with participating voluntarily in the crime; he denied the charge.
16. For a description, see Bunn, *Securing the Bomb 2008,* pp. 3-4, and "60 Minutes: Assault on Pelindaba," *CBS News,* 23 November 2008, http://www.cbsnews.com/stories/2008/11/20/60minutes/main4621623.shtml (accessed 30 October 2009).
17. U.N. Security Council, Resolution 1887, 24 September 2009, http://daccess-ods.un.org/access.nsf/Get?Open&DS=S/RES/1887 percent20(2009)&Lang=E&Area=UNDOC (accessed 30 October 2009).
18. For an initial cut at defining the essential elements that must be included for nuclear security and accounting systems to meet the obligation to be "appropriate effective," see Matthew Bunn, "'Appropriate Effective' Nuclear Security and Accounting—What is It?" presentation to "'Appropriate Effective' Material Accounting and Physical Protection," Joint Global Initiative/UNSCR 1540 Workshop, Nashville, Tennessee, 18 July 2008, http://belfercenter.ksg.harvard.edu/files/bunn-1540-appropriate-effective50.pdf (accessed 30 October 2009).
19. For a more detailed discussion of possible routes toward effective global nuclear security requirements, see Bunn, *Securing the Bomb 2008,* pp. 147-157.

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  1. Jones, F.T. and L. K. Chang. 1980. Article Title. *Journal* 47(No. 2): 112–118. 2. Jones, F.T. 1976. *Title of Book*, New York: McMillan Publishing.
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Taking the Long View in a Time of Great Uncertainty
Focusing on the Nuclear Fuel Cycle

By Jack Jekowski
Industry News Editor

Ken Sorenson
INMM Vice President

In the last edition of *JNMM*, Jack Jekowski wrote of the challenges that the world faces relative to proliferation and arms control concerns, and how these issues may impact future paths for the INMM. In that we asked the question: "What should be the role of INMM in a world defined by the new 'international order' and how should we prepare today to fill that role?" This article extends the discussion with a focus on another aspect of the INMM strategic planning effort: how can the INMM support the growth of nuclear power and the international commercial nuclear fuel cycle while ensuring that it is managed in a way that minimizes proliferation concerns and maximizes security?

The Nuclear Renaissance—How Strong Is It?

There is debate over the strength of the nuclear renaissance. In fact, one could take a snapshot anywhere in the world to make a case one way or the other. In the United States, for example, the excitement of the nuclear renaissance has diminished with the difficulties in the Loan Guarantee Program, the continued low cost of natural gas, and the difficulties licensing a geologic repository. Meanwhile, nuclear expansion continues apace in Asia with interest being expressed in many other parts of the world. Following is a short overview of the commercial nuclear power industry.

Reactors

(Data supplied for this section from the World Nuclear Association, http://www.world-nuclear.org/, October 2010.) There are 441 reactors generating 376 GWe of electricity internationally; 14 percent of the world's electricity generation. There are currently fifty-eight reactors under construction and 489 additional reactors either planned or proposed. New construction is somewhat offset by plant closings. Between 1996 and 2009, forty-three reactors closed and forty-nine started operation. It is also projected that an additional sixty plants now operating will close by 2030. However, with plant life extensions being granted, coupled with the new builds, it is expected that there will be a net increase in nuclear generating capacity the first half of this century.

Strategic implications of this growth:

- The scale is truly international: Of the fifty-eight new reactors currently under construction, twenty-three are in China, ten in Russia, six in South Korea, and only one in the United States.
- The supply chain supporting the non-nuclear and nuclear materials needed to construct and operate these plants requires an expanded international network of suppliers.
- Commercial reactor technology is being consolidated into only a few multinational companies.
- Safeguards and security issues associated with this international growth creates a challenge for reducing proliferation.
- The increase in commercial nuclear power generation juxtaposed with the potential for proliferation of nuclear technology and materials creates a special responsibility for the weapons states to assume leadership roles in managing the commercial growth of nuclear power.

Enrichment Facilities

(Data supplied for this section from the WISE Uranium Project, http://www.wise-uranium.org/, September 2010.) Enrichment of natural uranium as the feedstock for nuclear fuel is the first step in the fuel cycle that has potential for serious safeguards and security implications. Changing separation technology from gaseous diffusion to centrifuge and laser techniques, formation of multinational companies, and facilities owned by nationalities other than the host country all contribute to a challenging environment for safeguards and security.

Demand for enriched uranium, coupled with planned closings of some existing sources, has fueled a robust growth in this part of the fuel cycle, some of it unwanted, as seen with Iran and DPRK. In the United States alone, traditional sources of enriched uranium are quickly diminishing. The United States receives about 40 percent of its enriched uranium from Russia through the Megaton to Megawatts Program. This source is scheduled to be cut in half in 2013. To address current and projected domestic demand, the United States has four new enrichment facilities that are being built or are in the design phase.

Strategic implications of uranium enrichment technology development and plant construction:

- The supply chain is increasingly transnational.
- Protection of nuclear technologies

- becomes more difficult as multinational companies operate in foreign countries.
- New technologies such as laser separation may introduce new challenges in monitoring.
- International transportation of enriched UF_6 will increase.
- Establishment of an international "fuel bank" to satisfy fuel needs while reducing the requirement for a complete fuel cycle in emerging nuclear power states.

Waste Management Facilities

There is one licensed and operating high-level waste disposal facility in the world. The Waste Isolation Pilot Plant (WIPP) located in Carlsbad, New Mexico, USA, is designed to dispose of the U.S. inventory of transuranic waste generated from weapons production during the Cold War. While the world nuclear power generators are working hard to site a consolidated repository for commercial high-level waste and spent fuel, the fact that such a site has not even been licensed, let alone made operational, points to the technical, regulatory, and institutional difficulties such a facility faces. Nowhere is this clearer than in the United States where work on the Yucca Mountain Repository has been stopped and a Blue Ribbon Commission has been established to take a "re-look" at all potential disposal options as well as alternative fuel cycle options.

Strategic implications of extended storage:

- As storage inventories continue to expand and time frames for long-term storage are extended for the foreseeable future, special security issues for this material, which is typically stored on-site, become a growing concern.
- Transportation of spent fuel may increase significantly as the government and utilities evaluate the feasibility of consolidated, centralized storage.
- Orphaned spent fuel stored at deactivated nuclear sites may have special security concerns over extended storage times.

Bilateral Agreements

Concomitant with the global expansion of the commercial nuclear fuel cycle, government-to-government agreements are growing in number and complexity. These agreements serve to strengthen in-country competencies in nuclear technologies and position countries for nuclear power generation.

All the nuclear weapons states are engaged in bilateral agreements with non-weapon states including some agreements that are not with signatories to the Nonproliferation Treaty. It is not unusual for a single country to have multiple agreements with different countries, such as Jordan, which has signed bilateral nuclear cooperation agreements with nine different countries.

Strategic implications of bilateral agreements:

- Challenges of applying International Atomic Energy Agency (IAEA) controls consistently across a spectrum of situations that include signatories and non-signatories to the Nonproliferation Treaty.
- Multiple bilateral agreements for one country may create challenges in consistent application of safeguards and security protocols.

Addressing Safeguards and Security Concerns in the Commercial Fuel Cycle

Nuclear Suppliers Group

The Nuclear Suppliers Group (NSG), which has forty-six member states, was formed to control the export of nuclear material and technologies that could be used for weapons development. In general, specific listed items can be exported to non-weapon states only if IAEA safeguards are agreed upon and used. Of particular note, India was granted a waiver last year from NSG rules forbidding trade with non-NPT member states upon India's pledge that it would not share sensitive nuclear material or technology and that it would uphold its moratorium on further nuclear testing.

IAEA

The IAEA has a clear role in safeguards and security of nuclear material and technologies. As the international consensus organization in the control of nuclear materials, it develops standards and recommendations (e.g., INFCIRC 225), conducts inspections, and administers surveillance programs at nuclear facilities around the world. Its role will become more critical and complex as the nuclear renaissance gains momentum around the world.

WINS

The World Institute for Nuclear Security (WINS) is headquartered in Vienna and was established in 2008 with the objective of promoting and sharing best security practices. In its short life, WINS has grown to 450 corporate and individual members from more than fifty-two countries. Through its membership, WINS develops and publishes best practices guides and sponsors workshops on safeguards and security. WINS can provide an effective bridge between the commercial sector and regulator in the development of best practices across the operational envelope of the fuel cycle.

Nuclear Weapons States

As the primary repositories of nuclear technologies across the entire fuel cycle, the weapons states have a special responsibility to ensure that export of these technologies and associated nuclear materials and equipment is done in a way that conforms to international protocols (e.g., IAEA and NSG). With the expansion of bilateral agreements and the sharing of nuclear technologies, it becomes paramount that these protocols are followed and strengthen, when needed. The permanent five weapons states are in a unique position to support the adherence to and consistent application of these protocols.

Non-compliant States

The continued disregard by Iran and DPRK to international demands for termination of their enrichment and weapons programs presents a special challenge to the world, and will be watched closely by other nation-states that have similar agendas.

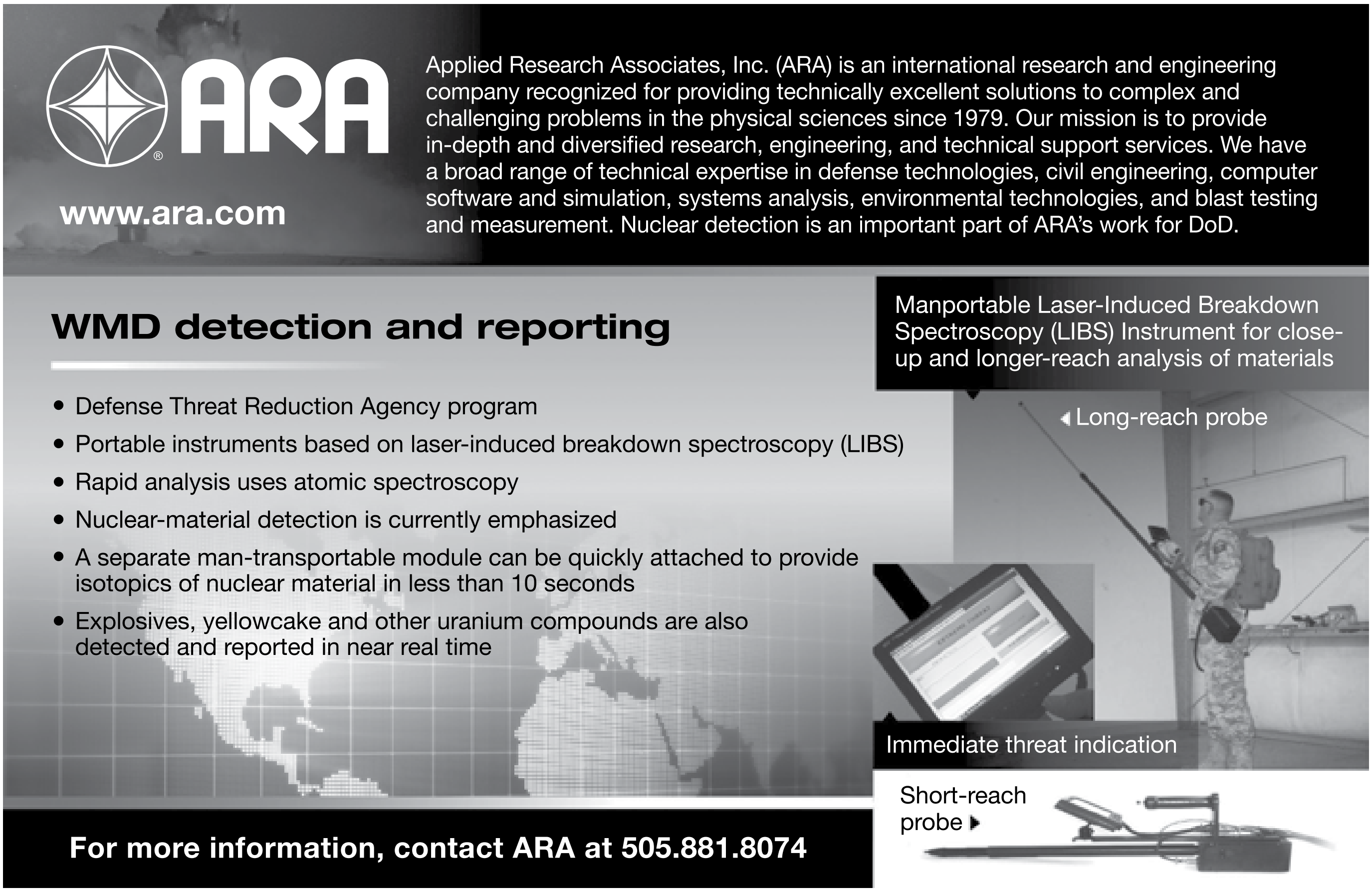
INMM – Where Do We Fit In?

In its fifty-plus years, the INMM has been flexible in addressing, developing, and promoting best practices in the management of nuclear materials. As part of the strategic planning effort conducted last year, INMM performed an externalities analysis; that is, a snapshot of the nuclear weapons and commercial nuclear power environments in real time, with a look into the future. While addressing nuclear arms control, nonproliferation, safeguards, materials control and accountability, physical protection, transportation, and waste management, the Strategic Planning Working Group felt that the commercial nuclear fuel cycle needed special emphasis in the Institute.

As a result, a new technical division was formed: Facilities Operations. The focus of this new division will be addressing the best practices for safeguards and security for commercial operations in light of all the external forces discussed above. Part of the Facilities Operations Division's role will be strengthening the INMM's relationship with other organizations to leverage positive impact on the nuclear fuel cycle. For example, the INMM is currently working with WINS to develop a more structured relationship to increase the effectiveness of both organizations. In addition, the INMM is working to strengthen its relationships with the American Nuclear Society (ANS) so that complementary areas of expertise can be combined to achieve overall success.

There are many challenges but also many opportunities for the INMM to constructively contribute to the peaceful expansion of nuclear energy across the globe while focusing on the imperative goal of safeguarding and securing all nuclear materials, equipment, and technologies.

We encourage *JNMM* readers to actively participate in these strategic discussions, and to provide your thoughts and ideas to the Institute's leadership. With your feedback we hope to explore these and other questions in future columns, addressing the critical uncertainties that lie ahead for the world and the possible paths to the future based on those uncertainties.



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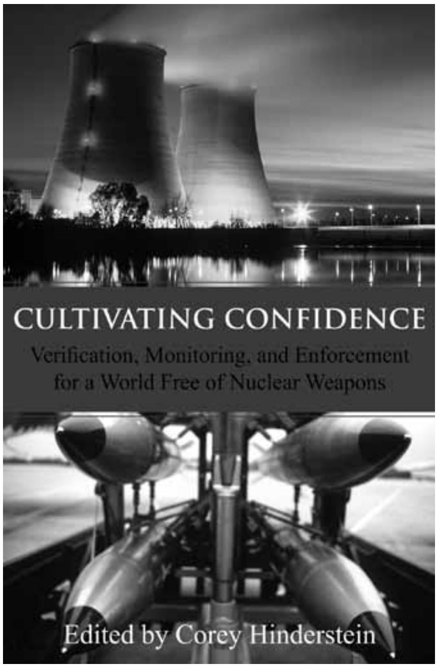
Book Review

by Walter Kane,
JNMM *Book Review Editor*

Cultivating Confidence
edited by Corey Hinderstein

The total abolition of nuclear weapons worldwide is an idea whose time has come. U.S. President Barack Obama spoke in support of this measure in April 2009, and earlier, four distinguished Americans—George Schultz, William Perry, Henry Kissinger, and Sam Nunn—in two editorials in the *Wall Street Journal* in 2007 and 2008, issued a manifesto proposing this initiative. There are compelling reasons for this initiative—the enormous destructive power of these weapons, the risk of their use by accident or by a subnational group that has acquired one or more of them, and the capabilities of conventional weapons which render them unnecessary.

The elimination of nuclear weapons is evidently a formidable task, but one with incalculable rewards. The problem, in simple terms, is to eliminate or de-weaponize thousands of tons of high enriched uranium (HEU) or plutonium when 25 kilograms of HEU or 8 kilograms of plutonium can destroy a city. *Cultivating Confidence* is a valuable "owners' manual" that addresses in detail the programs and procedures that will be necessary to attain this goal.



This work begins with a detailed review by Corey Hinderstein, of the Nuclear Threat Initiative, of the problems to be addressed and the corresponding policies and institutions necessary to reach the goal of nuclear disarmament. This section is followed by nine individual sections on individual areas of the required program by individuals with experience and expertise in these respective areas. These are:

1. Edward Ifft—"Political Dimensions of Defining Effective Verification."
2. Harald Muller—"Enforcement of the Rules in a Nuclear Weapon—Free World."
3. Annette Schaper—"Verifying the Nonproduction and Elimination of Fissile Material for Weapons."
4. James Fuller—"Going to Zero—Verifying Nuclear Warhead Dismantlement."
5. Steinar Hoibraten and Halvor Kippe—"Establishing Non-Nuclear Weapon States' Confidence in Verification."
6. Everet H. Beckner—"Verifying the Noproduction of New Nuclear Weapons."
7. Steven P. Andreasen—"Verifying Reduction and Elimination of Tactical Nuclear Weapons."
8. Thomas E. Shea—"The Role of the IAEA in a World Reducing Stocks of Nuclear Weapons."
9. Ralf Wirtz—"Role and Responsibility of the Civil Sector in Managing Trade in Specialized Materials."

INMM members should find this work both interesting and useful, a milepost along the road to the vitally important goal of total nuclear disarmament. In this area, we have seven billion stakeholders. The authors of this important contribution deserve our heartfelt thanks.

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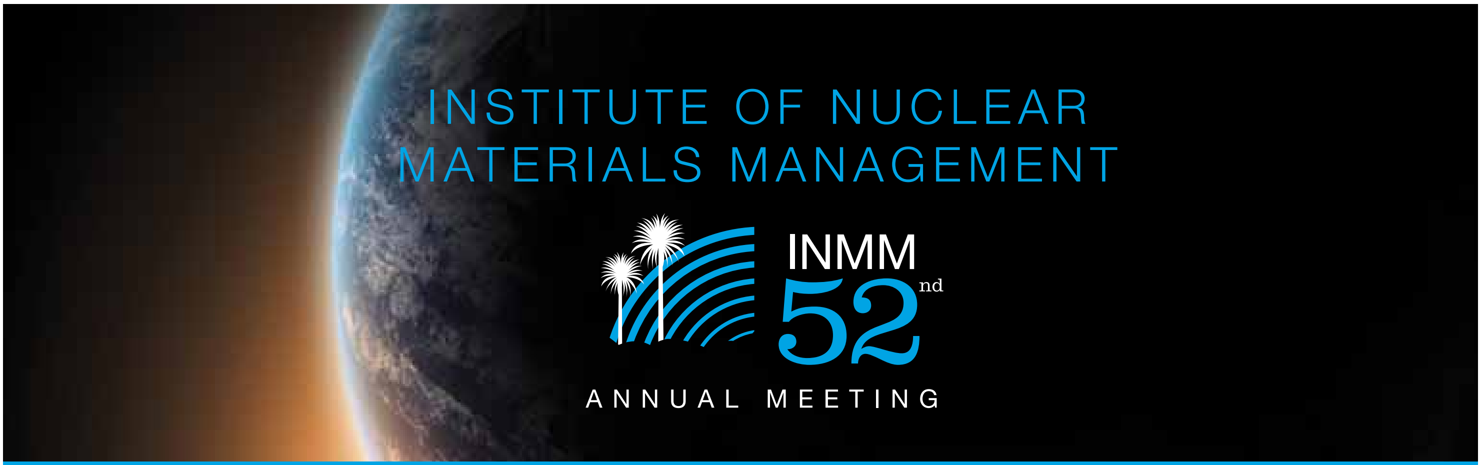

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