Fall 2011 | Winter 2012 | Spring 2012 | Summer 2012 | Volume XL, Number 1

JNMM Journal of Nuclear Materials Management

Non-Profit Organization
U.S. POSTAGE
PAID
Permit No. 2066
Eau Claire, WI

INMM
INSTITUTE OF NUCLEAR MATERIALS MANAGEMENT
Published by the Institute of Nuclear Materials Management

JNMM Journal of Nuclear Materials Management

JNMM (ISSN 0893-6188) is published four times a year by the Institute of Nuclear Materials Management Inc., a not-for-profit membership organization with the purpose of advancing and promoting responsible management of nuclear materials.

SUBSCRIPTION RATES: Annual (United States, Canada, and Mexico) $200; annual (other countries) $270 (shipped via air mail printed matter); single copy regular issues (United States and other countries) $55; single copy of the proceedings of the Annual Meeting (United States and other countries) $175. Mail subscription requests to *JNMM*, 111 Deer Lake Road, Suite 100, Deerfield, IL 60015 U.S.A. Make checks payable to INMM.

DISTRIBUTION and delivery inquiries should be directed to *JNMM*, 111 Deer Lake Road, Suite 100, Deerfield, IL 60015 U.S.A., or contact Anne Czeropski at +1-847-480-9573; fax, +1-847-480-9282; or E-mail, inmm@inmm.org. Allow eight weeks for a change of address to be implemented.

JNMM Journal of Nuclear Materials Management

Topical Papers

INMM
INSTITUTE OF NUCLEAR MATERIALS MANAGEMENT

One Year Later

By Scott Vance
INMM President

It's hard for me to believe that I am already finished with my first year as president of this great organization. The year has gone very quickly for me. On a related note, thank you for the vote of confidence in my election for a second year—while the term of this office is normally understood to be two years, I do not take your vote for granted and appreciate the support that our members have provided to me over the past year.

As you may recall from my Annual Report, my assessment of the "State of the Institute" is that INMM is healthy by all of the normal metrics that might be used to determine our vitality—membership, finances, activities, and member involvement. I have a different question here, however: How am I doing? I outlined three broad goals for myself in my first column a year ago: complete the organizational transition to our new structure, increase industry participation in INMM, and faithfully represent INMM to the broader nuclear community.

Progress has been made with the integration of our activities under the new organizational structure established by the Executive Committee more then a year ago. I admit that progress may seem slow, but we are attempting to be very deliberate in our implementation. Our goal is not "change for change's sake," but make changes in the structure that better represent the state of the industry and allow us to better address the specific needs of our membership. The three individuals who have assumed the roles of oversight are all communicating with their various constituencies, and I believe that the benefit of these positions is going to become obvious in the near future, not only because it makes sense but also because the Executive Committee has appointed three excellent individuals to fill these roles.

I am especially pleased with the progress made with regards to industry involvement. One of the significant organizational changes made was to establish the Facility Operations Division to focus on industry involvement. This division made a fantastic first showing at the Annual Meeting, and is actively seeking suggestions on how to engage individuals who are tasked with nuclear materials management at operating facilities, both governmental and commercial. I am confident that this division will quickly develop into a strong participant in INMM and will lead to significantly greater involvement by this currently underrepresented group.

With regards to the third goal that I identified for myself last year, representing INMM to outside groups is actually not an easy task, because the expertise of INMM is varied and extensive; I believe it would be difficult for any one person to adequately represent the Institute. However, I have a fantastic Executive Committee to assist me with this task, and an excellent administrative staff that keeps me on track. I continue to commit to you that I will do my best to represent the organization with the respect it deserves.

One additional goal that I have set for myself over the remainder of my term is to increase the participation of nuclear lawyers in INMM. I hesitate to say that, because I am well aware of the collective groan that was just expressed. But the connection is obvious. Each annual meeting has numerous presentations dedicated to the exploration of legal aspects of nuclear materials management; this year, there were no fewer than fourteen. My involvement in the Nuclear Regulation Committee of the Energy Bar Association (NRC EBA) has highlighted the common interest between nuclear lawyers and INMM. During a recent discussion, members of the NRC EBA indicated that, among others, their top choices for upcoming meeting topics were the ramifications of the Fukushima incident on nuclear activities and the findings of the Blue Ribbon Commission on Nuclear Waste. These topics have a direct nexus with INMM. I plan to develop this relationship further over the coming year.

I hope that you were able to join us at the 2011 Annual Meeting. Once again, Ken Sorenson, Charles Pietri, the Technical Program Committee, the technical division chairs, and our headquarters staff all deserve recognition for an outstanding meeting, both in planning and execution. While you will find summaries of the plenary sessions and a few of the presentations included in this *Journal*, there is no way for us to convey the valuable personal interaction and camaraderie that come from participation. If you were there, I hope that you found it to be a professionally and personally rewarding week. If you were unable to join us, start planning now for the 2012 meeting in Orlando.

I look forward to another year representing the Institute, and, as always, I welcome any suggestions you may have regarding how I can be more effective as your president.

Scott Vance may be contacted at savance@tva.org

Wrapping Up the 52nd Annual Meeting

By Dennis Mangan
INMM Technical Editor

This fall issue of the *Journal*, as in the past fall issues, focuses on the Institute's Annual Meeting normally held in the July time Frame. Charles Pietri, Chair of the Technical Program Committee (which is responsible for structuring the technical program for our AM), provides us an interesting summary report of our 52nd Annual Meeting held in Palm Desert, July 17-July 21, 2011. Many of you who attend the Annual Meeting may not appreciate that many members, those who support the Institute by being officers and members at large of the Executive Committee (EC), those who are chairs of various standing and ad-hoc committees, chairs of our regional chapters and student chapters, our managing organization (the Sherwood Group), plus others who support the Institute, gather on the Saturday before the official opening of the meeting to review what has happened in the past and address what our Institute's future might include. Although we have three EC meetings each year (November, April, and the Annual Meeting), the EC meeting at the Annual Meeting by far has the largest attendance.

I believe you will find the article by plenary speaker, Herman Nackaerts, Deputy Director General and Head of the Department of Safeguards of the International Atomic Energy Agency (IAEA), *IAEA Safeguards: Cooperation as the Key to Change,* interesting and forward looking. The Roundtable discussion that follows the plenary speech, allowed a select few of our present and past officers and the assistant editor and associate editors that support the *Journal* to ask Nackaerts questions. He did a very credible job. His desire to implement significant change in the safeguards inspection culture at the IAEA has to be applauded.

In this fall issue, we publish the three J. D. Williams Student Paper Award winning articles of papers presented at the AM by students. There are the first- and second-place oral presentation awards and the first-place poster award. The first-place oral presentation paper is *Evaluating Advanced Fuel Cycle Proliferation Resistance Dynamics Using Isotopic Characterization Coupling* by Steven Skutnik of North Carolina State University, Raleigh, North Carolina, USA. The second-place oral presentation winner is *Experimental Method for Determining the Attenuation by Aluminum Cascade Pipes in the Presence of UF_6 Gas During Enrichment Measurements* by M.L. Lombardi of the University of New Mexico and Los Alamos National Laboratory, Los Alamos, New Mexico, USA. The first-place poster award is *Experimental Investigation of Temperature Effects on Radiation Portal Monitor Performance* by David Addington, also of North Carolina State University. These three papers, which are comprehensive and impressive, interestingly address proliferation concerns of nuclear materials. Also interesting is the fact that both North Carolina State winners had, as a co-author, Associate Professor Man-Sung Yim. Well done professor (and of course, students).

The last technical paper in this issue is *Fission Product Signatures from Variations in Reactor Power History,* by David Sweeney and Dr. William Charlton of Texas A&M University, College Station, Texas, USA. This paper is likewise impressive. However we did have some technical difficulty with equations/figures in our usual two column format. Some equations are too long and detailed, and some figures are not quite readable; however, we and the authors did the best collectively that we could.

This issue is the start of the 40th year anniversary of the *Journal*. In celebration of this year, we will include in each issue articles published in the past that we consider exceptionally interesting. In this issue we re-publish an article by Senator Pete Domenici (New Mexico, USA) of his speech to the George Bush Presidential Conference Center at Texas A&M University in November 2001, ten years ago, *America's Energy Challenge — The Nuclear Answer.* Unfortunately, with minor changes, he could give the same speech today.

An extremely interesting article is the *Taking the Long View in a Time of Great Uncertainty* by Jack Jekowski, our Industry News Editor and Chair of the Institute's new Strategic Planning Committee. Jekowski, in my opinion, is an impressive coordinated thinker, a definite asset to our Institute and this Journal.

Finally, there is a message that was made at the Executive Committee Meeting by the president of the Japan Chapter, Yoshinori Meguro, thanking INMM for its support and donations made to the American Red Cross following the Fukushima Daiichi nuclear power plant incident last March 2011 and the concerns Japan is addressing to improve safety of nuclear power plants.

I trust you will enjoy and find interesting this issue of *JNMM*. Should you have questions or comments please feel free to contact me.

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

Report of the 52nd INMM Annual Meeting – A Reflection on the Past

Charles E. Pietri, Chair
Technical Program Committee

As I was perusing some back issues of the *Journal of Nuclear Materials Management,* I came across my 1997 report, "Pushing the Limits." I just couldn't resist including some excerpts in this current report to share with you: "… we heard that there was so much to do [at the meeting] that there was little time to relax. [But] after all, we did have another successful golf outing and our first fun run-walk without detracting from the meeting program. We had a full house at the major technical sessions… In fact, trying to figure out the right [size] room causes us great anguish each year especially when there are potentially several concurrent large sessions and attendance varies from one session to another, even within a session…We just may be reaching our limits in space availability at the hotels we have been using… 229 papers were presented…35 sessions…21 posters…700 attendees. Did attendees… feel overwhelmed with information and involvement…at the annual meeting? We've had many comments to that effect but no one has suggested that it stop—no pain, no gain, I guess."

That was in 1997! We could say the same for the 52nd Annual Meeting except we had 1,144 attendees (including 124 students)—it was not a record-breaker from last year but close. We received 630 abstracts and 543 papers were presented (including fifty posters and fifty-seven student papers). There were seventy-eight sessions including the plenary sessions. Unfortunately, we had eighty-three withdrawals and four "no-shows." (In the latter case, it still disturbs me that some authors who do not present their submitted paper do not notify us, that for whatever reason, they will not be at the meeting. It adds an extra burden on the Session Chairs and attendees who were interested in the paper.)

The INMM 52nd Annual Meeting officially opened on Sunday, July 17, but the previous day the INMM Executive Committee met to discuss issues of importance to the Institute and future directions to explore; and, the annual meeting of the New Brunswick Laboratory Measurement Evaluation Program took place to review progress in this evaluation of international measurements to date. The Technical Divisions met to discuss issues of significance and plan for future activities. New to these meetings was the recently organized Facility Operations Division headed by Shirley Cox, Tetra Tech HEI.

Figure 1. Herman Nackaerts as Opening Plenary Speaker

INMM was pleased to have Dr. Herman Nackaerts, Deputy Director General, Head of the Department of Safeguards, International Atomic Energy Agency, speak July 18 in the Opening Plenary Session on "IAEA Safeguards: Cooperation as the Key to Change." His presentation was clear and decisive on how the IAEA plans to enhance their currently acceptable programs and practice with some positive changes to meet future demands.

Each year INMM holds a Roundtable to discuss issues with the Opening Plenary Speaker. Dennis Mangan, technical editor of the *Journal of Nuclear Materials Management (JNMM),* chairs this Roundtable, normally a luncheon interview. We had a very honest and open discussion with our plenary speaker Nackaerts that you can read in the *Journal* along with his written paper; these articles also will be found in the *Proceedings of the INMM 52nd Annual Meeting 2011.* (Please note that the *Proceedings* are now part of a fully searchable archive on the INMM Web site, www.inmm.org).

And, the Closing Plenary, "10th Anniversary of September 11, 2001: Changes in Nuclear Security," consisted of a panel of speakers who focused on nuclear security changes since that fateful September day to address the evolving threat environment and thoughts on what the future might bring. They were: George Moore, International Atomic Energy Agency; Lawrence Kokojko, U.S. Nuclear Regulatory Commission; Chris Price, United Kingdom Office of Nuclear Security; and Anita Nilsson, AN & Associates. A summary of these discussions is proposed for inclusion in the *Proceedings* and in the *Journal*. Amy Whitworth, NNSA, chair of the Government Industry Liaison Committee was instrumental in initiating this panel event; INMM President Scott Vance acted as moderator for the panel.

Please be aware that the following is merely a snapshot summary of a few highlights at the annual meeting; it is not meant to be comprehensive, and does not include all individuals, groups, and events.

INMM continues to value the input it gets from attendees regarding the annual meeting through the electronic survey but

Figure 1a. Closing Plenary Session Panel

is disappointed that the responses continue to be relatively small. For example, this year 27 percent of the attendees responded to the survey—generally the customary response. In 2010 it was 20 percent, 2009 (29 percent), 2008 (19 percent), 2007 (28 percent), 2006 (29 percent), 2005 (25 percent), 2004 (31 percent), 2003 (5 percent—the last year of the written survey). About 70 percent of the responders were INMM members in several membership categories. (An interesting note: this annual meeting was the first one for 36 percent of attendees, which is about the level seen for the past few years.) So, despite the fact that the response level has improved since we moved to electronic surveys, be aware that these findings may not be representative of the entire group of participants but only those who took enough time and interest to respond. **It still is very significant to note that more than 95 percent of the responders *continue* to indicate that the quality of the INMM Annual Meeting was judged as satisfactory (84 percent) or neutral (11 percent)—and 94 percent said that the program met their professional needs!** INMM Annual Meetings have consistently rated above 90 percent for many years. Furthermore, about 90 to 95 percent of the respondents thought that the quality of the papers was ***as expected or was better than expected.*** There were several isolated comments to the contrary but they were so small that we could not tally them meaningfully.

About 80 percent of the responders rated the **Opening Plenary** session as **meeting their needs or interesting** while 50 percent of the responders similarly rated the **Closing Plenary**—both about the same percentage as in the past few years. It was also noted that greater than 85 percent of the responders indicated that Closing Plenary speakers or topics did not influence their decision to attend the Annual Meeting. Rating the Closing Plenary, the last formal activity of the Annual Meeting, is difficult since about half of the meeting attendees were not present. Unfortunately, INMM is always faced with the fact that attendees leave the meeting early on the last day to travel home after nearly a week of intensive discourse.

The overall impression was that the 52nd INMM Annual Meeting was an excellent one as usual, at times exceeding our expectations but a few times not quite reaching them. In the latter instances, we take action to correct any real or perceived deficiencies. We have some very enlightening reports from session chairs in addition to informal comments received at the meeting along with the results of the electronic survey submitted to meeting attendees that will be evaluated further and action taken where warranted.

During the meeting we also had the usual activities such as the President's Reception, the Student Orientation and Reception, and the Student Career Fair (a very popular event). And the Tuesday evening Awards Banquet following the INMM Business Meeting was most interesting this year. Alexander Izmailov, Eleron: Nancy Jo Nicholas, Los Alamos National Laboratory; Larry Satkowiak, Oak Ridge National Laboratory, were inducted into the INMM Fellows group; Leah McCrackin, INMM's former executive director received a certificate of appreciation for her many years nurturing INMM and leading headquarters staff in support of the Institute; and Charles Pietri, HI-TECH Consultants, was presented with the first Charles E. Pietri Special Service Award.

Figure 2. Nancy Jo Nicholas receiving the Fellows Award (Left to right Ken Sorenson, Nancy Jo Nicholas, and Scott Vance)

Figure 3A. Certificate of Appreciation for Leah McCrackin (Left to right Ken Sorenson, Leah McCrackin, and Scott Vance)

Figure 3. Resolution of Respect for Darryl Jackson (Left to right, Scott Vance, Doris Jackson, Damon Jackson, and Ken Sorenson)

Sadly, several notable Resolutions of Respect were presented for Darryl Jackson, LANL; Don Six, retired; Donnie Glidewell, Sandia National Laboratory (SNL); Steve Dupree, SNL.

One of the side benefits of the Awards Banquet is to meet and greet friends and colleagues, relax and enjoy the social life a bit. As the writer of this report, I take the presumptuous privilege of inserting a photo of my choice from this banquet demonstrating the pleasant social life.

Figure 4. Bettina and Charles Pietri at the Banquet

As the INMM Annual Meeting grows larger, sometimes unexpectedly, we begin to encounter issues that did not exist previously and attempt to resolve them as soon as possible. The Annual Awards Banquet is such an example. Although we clearly indicated that the table reservation process was a means for the attendee to secure a table for the banquet and avoid the frantic rush at dinner time, we need to clarify further just what needs to be done to make it run smoothly. Again, we apologize for any inconvenience and discomfort that may have been caused.

At each Annual Meeting we encourage speakers to make their presentations better. There has been noticeable improvement over the years and we can attribute that improvement to Paul Ebel, BE Inc., who returns each year with his tutorial on how to present an animated, clear, and coherent paper. This year Ebel focused on providing guidance to English-speaking speakers on how to best communicate with our colleagues whose native language is not English. Conversely, some important concepts were elaborated for the non native English speakers to help them. We hope that these suggestions were considered as good advice for the speakers' benefit and not as criticism. Hopefully, Ebel will be back next year with some more helpful hints for better presentations in other areas.

I believe that we have resolved any remaining issues with the PowerPoint© projection systems for the speaker presentations using our professional audiovisual staff to manage the process. We introduced this process last year and it worked well. In this way we not only have a central source for loading individual presentations and easier access for the speakers to their actual presentations in the session but the availability of the professional staff for immediate assistance should incidents arise. Paul Ebel also continues to provide counseling and assistance as necessary.

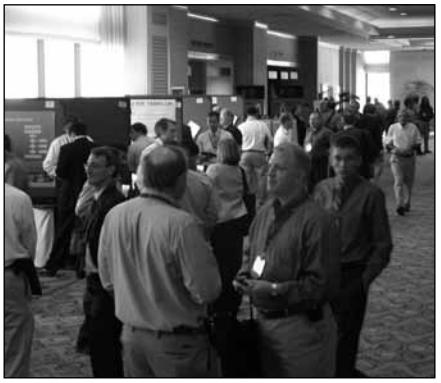
About 91 percent of the responders visited the Exhibits and rated the variety, schedule, and location good.

Our Poster Session was held in a spectacular location with plenty of room and visibility. The turnout for the posters was one of the best ever. Taner Uckan, ORNL, our Poster Session Chair, works hard to make this activity a continuing success. The quality of the posters and their content was high. Uckan believes our upgraded Poster Guide with more specific guidelines including example of acceptable posters may have been instrumental in improving the session. A suggestion has been made that we leave the posters up longer perhaps through most of the meeting—INMM plans to evaluate this proposal for next year. We appreciate your comments.

The competition for the **J. D. Williams Student Paper Award** resulted in: first place paper winner Steven E. Skutnik; second place M.L. Lombardi; and first place poster winner David A. Addington.

The New Member/Senior Member Reception on Monday evening was, as usual, a well-attended, successful event. New regular members and new Senior Members along with new student members had the usual opportunity to meet. Students, especially, were encouraged to become involved in both their technical divisions and local regional chapters.

Figure 5. Activity at the poster session



We provide this report of the INMM Annual Meeting for your information and entertainment. (Hopefully, you will find a bit of humor hidden in the text and photos.) Since we consider all comments, there appears to be a variety of perceptions about the meeting, its events, and activities, including a few that are totally erroneous and frivolous, INMM will be evaluating these comments and responding to them publicly later on in the year. We try to give a balanced perspective of what our attendees report at the Annual Meeting whether their perceptions are favorable or unfavorable. That's one of the most important ways we learn how to continually improve the Annual Meeting process. Some readers have criticized us for expressing other attendees' sentiments that are contrary to their beliefs—that is their right to do so, just as is the other parties' right to do the same. Our past performance demonstrates that each year we take action to resolve issues of significance and are dedicated to continuous improvement to enhance your stay at the meeting. Remember, it's *your* meeting!

This continuous improvement is reflected in the quality of the presentations, the efforts made by speakers to find surrogates to give their talks when they are unable to attend the meeting, and the participation of individuals who are not members of the Technical Program Committee who propose and orchestrate special sessions. However, we continue to see that the significant issues facing INMM

in managing the Annual Meeting program are excessive paper withdrawals after the Final Program has gone to press and even during the meeting; frequent speaker changes; "no-show" speakers; and late and absent final paper submittals; and finally, those folks who do not read the detailed manuals and guides we prepare to help everyone participate successfully. INMM encourages you to keep these obstacles to a *perfect* meeting in mind when planning to participate in our Annual Meeting. For example, we recognize that professionals have many obligations to meet, but please give your participation in INMM a prime priority! If you cannot meet the June 9 deadline for submitting your final paper, you may request a short extension if you provide me with a significant reason for the delay (cpietri@aol.com).

Each year the INMM president hosts a closed meeting with INMM leaders to explore issues to be addressed for the following year's Annual Meeting. Although the content of the meeting is quite serious we do find time to relax and enjoy the current success.

INMM wishes to recognize the efforts and accomplishments of those that make our Annual Meeting such a success year after year: all the 500-plus speakers who presented papers either orally or in the poster session; the Opening and Closing Plenary speakers; the Technical Program Committee members who reviewed 630 abstracts and placed them in sessions; D. L. Whaley's Registration Staff; President Scott Vance, Vice President Ken Sorenson along with the INMM Executive Committee for their support; Steve Ward, who managed our newly-formed photographic group, assisted by Shannon Lambert; Paul Ebel, with his educational stimulus; and, of course, our dedicated INMM headquarters staff, especially Jodi Metzgar, Leah McCrackin, Lyn Maddox, Kim Santos, Patricia Sullivan, and Jake Livsey, who made the meeting work. *(Now who did I forget?)*

Figure 6. Closeout Meeting

Next year we will be at steamy Orlando, Florida USA for our 53rd Annual Meeting: the Renaissance Orlando Resort at Sea World July 15-19, 2012. (Please, no complaints about the weather—stay in the beautiful recently refurbished hotel and attend the meetings, or soak a bit in the gigantic pool and refreshing Jacuzzis.) So, as I say each year, start planning for it now by completing your research, getting your subject approved by management in a timely manner, writing your abstract, and submitting it by February 1, 2012. Then write your paper and submit it early—certainly no later than the June 9, 2012 deadline. Remember, for those of you who are planning to organize a special session, you need to contact me by December 1, or sooner, and be prepared to attend the Technical Program Committee review meeting in February/March 2012. There can be no exceptions! If you wish to discuss any issues with me, please contact me at cpietri@aol.com.

On behalf of President Scott Vance, we look forward with great pleasure to your presence at the 53rd Annual Meeting next year—I plan to be there and will look forward to seeing you there, too.

IAEA Safeguards: Cooperation as the Key to Change

Herman M. G. Nackaerts
Deputy Director General and Head of the Department of Safeguards, International Atomic Energy Agency
Presented Monday, July 18, 2011, at the INMM 52nd Annual Meeting

Allow me to begin today's presentation with a quotation. Victor Hugo, the famous French poet, playwright, and novelist is reported to have said *"Nothing is more powerful than an idea whose time has come."* I believe that this sentiment is relevant to the evolution of the IAEA safeguards system: the time has come to make the implementation of safeguards more focused, less predictable and more adaptable. More focused on that which really concerns us; less predictable in terms of the timing and nature of verification activities; and more adaptable to changing situations. This requires an approach to safeguards implementation that focuses on the state as a whole and not just on the nuclear material and facilities that it declares to the agency—the so-called state-level approach.

At our Safeguards Symposium last November and, more recently, at ESARDA's annual meeting, I spoke about the need to change the safeguards system by fully embracing the state-level approach, the challenges inherent in trying to do so and the progress made by the Department of Safeguards so far.

Today, I want to expand on that change initiative, and to touch upon one aspect in particular: and that is the importance of the cooperative relationship between a state and the agency in the implementation of safeguards.

Setting the Scene

The IAEA is responsible for providing assurances to the international community that states are in compliance with their commitments to use nuclear material, equipment, and technology for peaceful, non-explosive purposes. Through its safeguards system it deters the proliferation of nuclear weapons, by detecting early the misuse of nuclear material and technology. These strategic objectives apply to all states with a Comprehensive Safeguards Agreement in place, whether they implement an Additional Protocol or not.

Unfortunately, experience has shown that the safeguards system has not been as effective as it should be, nor has it been implemented as efficiently as it could be. Despite the adoption of measures to strengthen the system over the years, events in a number of countries have demonstrated systemic deficiencies. In most of these cases, safeguards were implemented successfully at declared facilities, while *undeclared* nuclear activities took place unnoticed by the agency. If we are to move forward successfully, to maintain our capability to provide soundly-based safeguards conclusions, these deficiencies need to be properly addressed.

So, let's look at some of those deficiencies:

The assumption underlying the traditional safeguards system is that every state with a civil nuclear program, by virtue of being able to divert nuclear material to non-peaceful uses, poses a potential proliferation threat. On that basis, therefore, safeguards measures have been applied to nuclear material and associated facilities without differentiation. Moreover, although safeguards apply to *all* nuclear material and activities in a state, the agency's primary activity has concentrated on verifying the correctness of that which the state has *declared* to the agency. To that end we created a criteria-based safeguards system.

The result of implementing this system was that the number and type of declared facilities and the volume of declared nuclear material determined the nature, scope, and frequency of our verification activities according to predetermined criteria. Consequently, our in-field verification effort has been uniform and prescriptive. It concentrated on a handful of states. For example, under traditional safeguards, due to the size of their respective nuclear programs, 60 percent of the agency's verification effort was expended in just *three* states. In other words, the more a state declared, the more verification scrutiny it was subjected to, independent of the *real* proliferation risk posed by that state (a point I will revisit later).

So, although we were diligently verifying what a state declared to us, were we sufficiently addressing the overall purpose of that verification activity, namely, to prevent proliferation? In answering that question let me make the following points:

First, experience has shown that proliferation risk is not *only* associated with the amount of declared nuclear material that a state possesses or the number and type of declared facilities. Indeed, the major proliferation challenges have arisen in states with limited nuclear fuel cycle facilities, and involved previously exempted or undeclared nuclear material.

Second, under the traditional safeguards system there was no real assessment of risk *beyond* consideration of the type and amount of declared nuclear material.

Third, experience has also shown that the vast majority of states live up to their respective nonproliferation commitments.

Finally, the system was manifestly failing in its primary objective, namely, to detect activities that *did* raise potential compliance issues and proliferation concerns—such as those undertaken, for instance, in Iraq, Libya, Syria, and Iran.

Addressing the Need for Change

All of this would suggest that in order to fulfill our responsibility to continue to provide soundly based safeguards conclusions we must refocus our safeguards system to better address areas of real proliferation risk. It is time to improve the system's effectiveness and efficiency, and to invest our resources where they are most needed, not necessarily in states with the largest inventories of nuclear material. We need to broaden our outlook, to consider the whole picture of what a state may be doing and why.

This means moving away from such a heavy reliance on routine quantitative measurements and the mechanistic application of generic criteria. Instead, it requires taking into account a wide range of qualitative and quantitative factors, reaching an informed judgment based upon a detailed analysis and evaluation of all the information available to the agency, and then deciding to act accordingly. To do this, our focus needs to be on each state as a whole, rather than solely on the nuclear material and particular facilities within that state.

I am not talking about a revolution in our approach, because some of what I have mentioned has already been accepted and certain measures adopted, albeit in a partial and ad hoc fashion. What I am calling for is more akin to an accelerated *evolution* of safeguards: a step change, whereby we fully embrace the state-level concept and drive the process forward in a wholehearted and determined manner.

In doing so, we can build upon recent experience, particularly that associated with the development and implementation of integrated safeguards, where the state-level concept was first introduced. However, while we have been implementing state-level *integrated* safeguards in countries such as Canada and Japan, the way in which this system has been implemented has remained largely based on the application of the traditional criteria, albeit with somewhat more discernment.

Evolving the State-Level Concept

We want to optimize the benefits inherent in the state-level concept and to extend its application to cover all states, not just those under integrated safeguards. The overall aim is to provide the basis for a more effective safeguards system: one that is less predictable, more focused on areas of concern and more adaptable to the changing environment.

In short, the state-level approach to safeguards implementation will be based upon a continuous and comprehensive evaluation of all information about that state. And in the latter respect, we now have far more of such information available to us—whether from open sources, satellite imagery, environmental samples, or from the state itself. We now need to make better use of that information. We need to be able to optimize the collection, categorization, and storage of that information to ensure that we can efficiently assess and then extract everything of potential value from what has become a huge inventory. We then need to be able to conduct detailed analysis and a thorough evaluation of that information to identify risks and determine priorities.

The result of that evaluation is then used to establish a state-level approach specific to each state, one that identifies a range of safeguards measures necessary to meet state-specific objectives. These measures are subsequently selected and applied through an annual implementation plan. Considering the state-as-a-whole provides the opportunity to take state-specific factors into consideration in all stages of safeguards—design, implementation, and evaluation. And, supported by this process, an annual safeguards conclusion is drawn.

At this point I should emphasise that we will continue to respect the fundamental principles underlying the safeguards system. The same legal framework, setting out the legal obligations that apply to all states Parties to each safeguards agreement, will remain intact. Safeguards will continue to apply to all states on a non-discriminatory basis. What will be new is that within that overall rubric we will adopt customized state-level approaches for states, having taken into account the safeguards objectives to be met as well as a range of state-specific considerations.

Our *bottom line* will continue to be safeguards effectiveness. We cannot and will not sacrifice effectiveness in order to save money. Indeed, our goal is exactly the reverse. I would contest that we can become more effective by introducing efficiencies; the two can go hand-in-hand.

For example, the safeguards approach for each state must ensure that each potential acquisition path relevant to that state is considered, assessed and addressed in one way or another. Although nuclear material accountancy will remain of fundamental importance for deriving a conclusion on the non-diversion of nuclear material, we will be able to satisfy that objective in different ways, depending on the circumstances. Information on states and related agency evaluations, as provided for in Safeguards Agreements and Additional Protocols, will still be protected; and we will continue to draw independent and soundly-based safeguards conclusions.

Moving Forward

Obviously, pursuing a safeguards system that allows for differentiation in the application of safeguards in states can raise concerns about discrimination. To address this we need to establish clear and transparent processes, including those used for state evaluation, for developing individual state-level approaches, and for determining the annual verification activities to be undertaken for each state.

We need to develop a framework that links general state-level safeguards objectives to specific safeguards activities in a state in a way that reflects the establishment of risk-based priorities. Such a framework would involve a number of state-specific factors being taken into account. These factors can be of a technical nature, such as fuel cycle considerations

and the use of remote monitoring and unannounced inspections, while others can be of a non-technical nature, such as the history of safeguards implementation in the state, the degree of transparency within its nuclear program and the level of cooperation between the state and the agency.

It is this last point, the level of cooperation between the state and the agency that I want to address in my remaining remarks. A high level of cooperation between a state and the agency is crucial to making this approach work well. For example, the state through its state or regional system of accounting and control may have to provide more information to facilitate safeguards implementation, it may have to take additional measures to ensure the quality of the information provided, and it may have to be more responsive to agency requests for assistance and clarification. This will support a less predictable and less prescriptive verification regime.

Cooperation: Building Trust

Ensuring that the global nonproliferation regime is credible and effective should be in everybody's interest. It is the *joint* responsibility of all stakeholders in the safeguards and nonproliferation community to make it so. In this regard, it is essential that we all work together in helping the agency execute its mandate. In that spirit, the IAEA needs to forge strengthened partnerships with states and state authorities. We need to build upon that which is already working well and spread best practices more widely.

I want all states to regard the agency as a partner with whom they share the same objectives, rather than as a "necessary irritant" and safeguards as a "burden that must be borne." The more a state cooperates and "goes the extra mile," the less likely it will be for us to need to undertake routine, in-field verification activities: contrariwise, the less a state cooperates, the greater the likelihood that it will receive more attention from the agency, and from the international community as a whole.

We don't have to look any further than recent problem cases that have been reported to the Board of Governors, such as Iran, Syria, and the DPRK, each of which involved a lack of cooperation by the state.

You are all aware of Iran's consistent refusal to address the outstanding issues concerning possible military dimensions to its nuclear program and to Syria's lack of cooperation in addressing issues related to the Dair Alzour site and the other locations allegedly functionally related to it. While these are serious issues that need to be resolved, it is also vitally important that states not be given the impression that they can "get away with it" simply by not cooperating with agency requests for information or access. If they were to do so, this would seriously weaken the credibility of the agency's safeguards system: the Director General has pointed to this danger on numerous occasions.

To be fair, in both cases there have also been examples whereby a more cooperative approach has enabled the agency to resolve issues and draw conclusions. So there have been acknowledged benefits in greater cooperation, but it cannot be pursued on a selective basis.

While these two cases may be at the more extreme end of the spectrum, there have been other far less serious examples where insufficient cooperation has led to stalemate and mistrust. For instance, in the past the agency has had extensive discussions with some member states regarding the introduction of short notice random inspection regimes, the implementation of which would result in obvious gains to the agency and, I would say, to the state by way of efficiency and effectiveness. I am pleased to say that these states have now overcome their initial reluctance and accepted this approach to everyone's satisfaction.

To take another example: When the agency was obliged to implement a new policy for conversion plants in order to plug a hole in safeguards implementation in the front end of the fuel cycle, persuading certain member states to agree to it proved to be very time consuming. Eventually a new safeguards approach that addressed the problem satisfactorily was agreed in almost all countries: but it did require a lot of time and effort to get there.

I could also mention another case in which a state that was initially reluctant to provide information requested by the agency about historical activities, has now seen value in doing so, has consequently cooperated with the agency in this regard and, as a result, we are now close to drawing the broader conclusion for that state.

There are other examples in which the relationship between a state and the IAEA was initially *procedural* and *defensive*, but then transformed into a more productive and cooperative one—thereby allowing for the resolution of safeguards implementation issues to the benefit of both parties.

The level of cooperation with the state system of accounting and control of nuclear material is a key factor in the effectiveness of safeguards implementation in a state. I urge all member states to ensure that their SSACs receive the necessary support to do the job thoroughly and efficiently. Of course, some already do so.

To maximize the benefits inherent in the state-level approach to safeguards, ideally the relationship between the IAEA and a state should be seen as a partnership: one that has benefits for each party, and that is characterized by a high degree of openness and transparency, by the agency as well as the state. The advantages that accrue as a result will benefit the state, the agency, and the safeguards system as a whole.

For the IAEA, the safeguards system requires that we have a clear understanding of the overall nuclear profile of a state in order to provide soundly based conclusions concerning peaceful use. This requires, amongst other things, the provision of timely, accurate, and comprehensive information to support the understanding. Ideally, states should be willing and able to provide such informa-

tion, whether in response to agency requests or on their own initiative. For both operators and state authorities, I would like safeguards considerations to become a standard part of operating and licensing procedures; as is already the case for safety and security considerations.

I think that it is fair to say that one factor currently inhibiting the provision of all safeguards relevant information by a state, is the concern that the provision of *more* information about the state will lead to more verification activity by the IAEA within the state. However, as we better integrate all safeguards relevant information, particularly information arising from inspection activities, into the state evaluation process, the routine provision of comprehensive information should allow us to *reduce* routine verification effort in the field. For example, our consistency evaluations could be undertaken at headquarters rather than in the field. While there would be no automatic causality between more cooperation and less inspection, this would be the general expectation. Of course, any reduction would be buttressed by the understanding that if circumstances changed, or new information was received, the in-field verification activities could increase: such is the dynamic nature of continuous evaluation.

In short, if we have a consistent, transparent, and predictable picture of the nuclear program in a state, supported by analysis of all information, including the results of verification activities undertaken within the state, we should not need to go there as frequently for routine verification activities. Rather, we could redirect those resources to addressing safeguards issues in other states posing real proliferation concerns.

Conclusion

To sum up: in order to optimize its effectiveness and efficiency, we are adapting the safeguards system to fully implement the state-level concept. Such an approach involves looking at the state as a whole, allowing us to focus on issues of real proliferation concern and to customise our approach to the particular nuclear profile of each individual state. In order to demonstrate that we are applying safeguards fairly and objectively, we will ensure that we have processes and procedures in place, that they are used consistently and that they are transparent. As now, we will do so on the basis of each state's legal obligations. The alternative—to apply the system inflexibly to all states in exactly the same way, regardless of their nonproliferation credentials, record of cooperation with the agency, and degree of transparency—would be monumentally inefficient and, because it spreads scarce resources far too thinly, grossly ineffective: increasing the risk of the agency missing cases of non-compliance and thereby losing credibility. Such an outcome would be in no one's interest.

That is why the Department of Safeguards has now embarked on a two-phased approach to make the change happen. In the first phase—to be completed by the end of this year—we are better integrating the inspection-related activities of the Department with the comprehensive state evaluation process. In the second phase—to be completed by the end of next year—we are establishing the processes, procedures, and guidelines to support consistent implementation of the state-level concept and to enhance transparency.

My goal is to make the safeguards system more focused and adaptable while protecting the principle of non-discrimination and ensuring a high degree of transparency. To make this happen, the agency needs member states and other stakeholders to work with us in true partnership and in a spirit of cooperation to prevent the proliferation of nuclear weapons worldwide, working together to uphold international security.

Thank you.

JNMM Roundtable

July 18, 2011

Opening Plenary Speaker:
Herman Nackaerts
IAEA Deputy Director General,
Head of the Department of Safeguards

Roundtable Attendees:
Glenn Abramczyk
JNMM Associate Editor

Obie Amacker
Chair, Fellows Committee

Michael Baker
JNMM Associate Editor

Robert Curl
INMM Treasurer

Debbie Dickman
INMM Past President

Felicia Durán
JNMM Associate Editor

Leslie G. Fishbone
JNMM Associate Editor

Jack Jekowski, Chair
INMM Strategic Planning Committee
JNMM Industry News Editor

Markku Koskelo
JNMM Assistant Technical Editor

Dennis Mangan
JNMM Technical Editor

Steve Ortiz
INMM Immediate Past President

Chris Pickett
INMM Secretary

Charles Pietri, Chair
INMM Technical Program Committee

Bernd Richter
JNMM Associate Editor

Sam Savani
JNMM Associate Editor

Ken Sorenson
INMM Vice President

Gotthard Stein
JNMM Associate Editor

Patricia Sullivan
JNMM Managing Editor

Scott Vance
INMM President

Dennis Mangan: Welcome, Herman, to this Roundtable discussion. I thoroughly enjoyed your Plenary Speech, and I'm sure everyone around this table did as well. I'm hopeful that the questions asked in the Roundtable session will be interesting to you.

Leslie Fishbone: Apropos of the state-level safeguards, you emphasized that in various papers the application of state-level safeguards is for all states. Could you explain how that relates to states that do not have comprehensive safeguard agreements but rather have facilities under INFCIRC 66 agreements? I think there's a sense that state-level means that everything in the state would be covered and you try to implement safeguards most effectively and efficiently, and you can capitalize on knowing that everything is under safeguards. But that's certainly not the case for states with other than comprehensive safeguards agreements.

Herman Nackaerts: As described in various agency reports going back some ten years, the state-level concept is based on a comprehensive and continuous state evaluation and a state-level approach identifying a specific combination of safeguards measures for each individual state. While applicable to all States, the first wide-scale application of the concept was in the context of integrated safeguards. Integrated safeguards are implemented in those States that have a comprehensive safeguards agreement and an additional protocol in force and for which we have drawn the broader conclusion that all nuclear material remains in peaceful activities—meaning also that there are no indications of undeclared nuclear material or activities. The idea of integrated safeguards was to optimize safeguards activities conducted for a State under its comprehensive safeguards agreement and additional protocol in order to improve efficiency without undermining effectiveness by looking at the state as a whole. At this point, for other States—States with a comprehensive safeguards agreement (based on INFCIRC/153) but no additional protocol, and for States with INFCIRC/66-type safeguards agreements or voluntary offer agreements—while we conduct state evaluation for each State based on all available information, we continue to have safeguards implementation which is facility-based and driven by the safeguards criteria. This provides us with less room to determine how we utilize our resources. We could benefit a lot if we also started to fully implement the state-level approach in those states that have a comprehensive safeguards agreement but no additional protocol in force.

It is important that we look at the State as a whole and identify State factors or characteristics that would affect the determination of verification activities we need to carry out. Clearly in a state with a comprehensive safeguards agreement and an additional protocol in force, the AP itself and the broader conclusion are very important state factors influencing our verification activities. By extension, there's no reason not to do that also in the INFCIRC/66-type States. There was a presentation this morning on India and

its separation plan. I think that India is a good example of a state where we could do that as well. India has agreed to put all of its declared civil facilities under safeguards. Although we still have to develop the concept in more detail, we could maybe look at the fully declared civil cycle as a state within a state. What kind of conclusions can be drawn from it? Would we then continue to implement safeguards in India the way we do now? Could we also determine some state-specific factors that would allow us to perhaps change some things? Also, in the case of the five nuclear weapon states with voluntary offer agreements, we could think of a similar approach. John Carlson in his paper this morning touched a little bit on how that could be done.

All that said: let's not try running before we can walk. As our first priority we should concentrate on fully implementing a state-level approach in each of those states that already have integrated safeguards. I think there's a lot we can still improve there. Secondly, we should extend the state-level approach to states that have a comprehensive safeguards agreement but do not yet have additional protocols in force and have significant nuclear fuel cycle activities. I see these as our two priorities.

Robert Curl: I have a question more oriented toward the inspectors. I followed your comments with great interest this morning. One of the things that you mentioned is the issue of the inspectors having a good understanding of what they're supposed to be doing relative to the process and procedures, but not really having much of an understanding of what they're trying to accomplish, or what they're really hoping to get out of the inspection. I think this may have been systemic for a long time. It certainly was there when I was an inspector. Can you speak to how you are approaching that problem and getting this understanding and this feeling for what they're really trying to accomplish instilled into the inspectors?

Nackaerts: First, I want to say that we have many very good inspectors. This morning I gave an extreme example that does not represent agency inspectors as a whole. We have many, many good people who know perfectly well what they are doing. However, as a former inspector you may know that we, unfortunately, have had a system in place in which inspectors—if I can put it bluntly—were supposed to perform prescriptive routine verification tasks, tick the boxes, come back and report the results, and then let the director think and draw the conclusions. I think that this is an enormous waste of human resources. We have well trained and very experienced inspectors that are capable of making professional judgments. The organization could benefit a lot more if we fully used this potential. I want the inspectors to go into facilities and be more analytical; to come back with their own judgment about a situation; and to put forth their findings in a less mechanistic way than before—not just fill out the forms and prepare a standard inspection report, but to better analyze what they observe and draw conclusions from that inspection. This is going to require a big cultural change in the inspectorate. Therefore, we are looking into how to provide training to the existing inspectors so that they can embrace this new approach of being more like investigators rather than simply accountants. So we'll have to adjust training. Also, we will re-examine the profile of the newly recruited inspectors and modify our vacancy notices to attract people with the right kind of skills. We need not only to have specialists with knowledge about specific technologies, such as centrifuges, but also nuclear generalists with good knowledge about the whole fuel cycle. So we need people with a variety of skills and background. We are examining all this. We realize that the cultural change we are implementing is going to be a major undertaking.

Gotthard Stein: My question relates to the role of state-level safeguards as a common standard that should be applied for all different agreements: INFCIRC 153 alone, INFCIRC 153 and the Additional Protocol, INFCIRC 66, and Voluntary Offer Agreements for Nuclear Weapon States. One lesson again we can learn from the recent nuclear disaster in Fukushima is that we need appropriate and common standards for safety, security, and safeguards in all peaceful activities in all countries. Also the growing global nuclear energy market asks, as John Carlson mentioned in his presentation this morning, to have safeguards in nuclear weapon states even before other fixed commitments from FMCT or similar regimes are established. Do you think that state-level safeguards can offer the basis for such a common future standard?

Nackaerts: Although resource considerations are not driving the changes that we are implementing, the fact of the matter is that our resources are very limited for what we're doing. We need to use our resources in the best possible way so we are now re-examining how we allocate them. We ask ourselves: are we going to expend these resources in countries like the United States, UK, France, or China or Russia? I'm not sure that would be a good use of our resources right now. Of course, if we have special agreements such as the Plutonium Management and Disposition Agreement we honor the commitments that we make, and make the necessary resources available. However, in these current circumstances, our priority lies elsewhere than the states with voluntary offer agreements.

Bernd Richter: I want to raise the issue of denial of cooperation, which you raised in your speech. I think there must be a concern that the agency's position is weakened by denial of cooperation. So far, we have had two cases where a threatened state decided to destroy facilities. I mean in one case a declared facility, I think, and in the other case, an undeclared facility or construction site. To me it seems it is an unresolvable issue. Can you comment on this?

Nackaerts: With regard to the destroyed facility in Syria, our then Director General ElBaradei clearly condemned that. We regretted that force was used. This is not the way to do business. If states believe in our safeguards system, they should have confidence in us; if they have information that a facility is a nuclear reactor, they should tell us so that we can take necessary action. They should not first destroy the facility and only later on inform the agency that this might have been a nuclear facility. This didn't add to the credibility of the agency system. That is one issue. The other issue is about cooperation of states in the implementation of safeguards. It is true that currently two states, Iran and Syria, still trying to get away with it by not cooperating. DG Amano has been clear on that: This is negatively affecting the credibility of the safeguards system. It should be a concern to our member states—even more to them than us. We cannot accept that a state, by not cooperating, gets away with not complying with its safeguards obligations. So what can we do about it? I can only plead for the cooperation of all states. It is important that other states show a good example; that they are not defensive when we come with questions; they are not restrictive in their answers; and they're not trying to find legalistic excuses not to do certain things. We should all have the overall objective in mind and cooperate to that effect. As regards states that think they can get away with not cooperating, we need to continue to demonstrate that that is not acceptable. Certainly, the first thing we do, when we observe a reduction in cooperation, is to ask for more information and access. But ultimately we have to consider non-cooperation as non-compliance; as cooperation is in fact an obligation under comprehensive safeguards agreements. This is a complicated challenge. Fortunately, for the majority of the states—states that don't have anything to hide—it is already clear that it's in their interests to cooperate with us, be transparent, and to share information.

Charles Pietri: Actually, Bob asked the question I wanted to ask and get an answer to, but we got a good answer on it. But every plan is either successful or unsuccessful, depending on its implementation. Now, can I ask you what other internal obstacles or concerns do you have as far as getting the new approach accepted?

Nackaerts: Our first challenge has been, and still is, is to have good communication of our vision and of what we want to achieve. If my staff doesn't understand what I want to achieve as the boss, we'll never get anywhere. So when I took this position, the first thing I tried to do, together with my colleagues, is to formulate a clear vision of what we want to achieve and where we want to end up. Once you have that vision clearly defined, it's easier to get there. The other challenge is resistance to change. As with any change process in a big organization, some people like the comfort of the existing situation. They've been doing their job in a certain way for many years and, quite often, nobody has questioned this. So how do you convince them of the need to change, and that this change is in everybody's interest? How do we address resistance to change? We still have some inspectors who want to remain in their comfort zones, in their nice routine of things to do. They went on inspections, came back and reported standard verification results. We are now trying to have a complete change in approach, giving more room to personal initiative and judgment. We have to convince our inspectors of the usefulness of what we want them to do so they embrace the change. We have to assure them that this is not an attack on their position or their contract. So these are some of the difficult challenges we're trying to deal with. We also need to train the inspectors for the new approach—I touched on that a little bit with the previous answer. We have a new training program that we're going to implement. For people to understand what we want to do, I have engaged a senior change manager, whom some of you may know: James Casterton of Canada is now working in my office as senior change manager at the director level. By appointing him at a high level, I wanted to demonstrate that I am serious about the change I want to accomplish. And he's going to push these changes through. His task is to make this happen before the end of 2012. I also have a fantastic team of directors now. Most of them are relatively new to their post and all of them are really committed to what we want to do: people who can make this change happen. But I realize that it is a difficult job, and I know we have to work hard to get there.

Chris Pickett: As the agency transitions to what's been termed fully information driven safeguards, what are the tools and techniques that you see some of the inspectors and directors would need? And also, what practices do you plan to put in place for verifying the validity of information that may be coming from open sources?

Nackaerts: First of all, information driven or *fully* information driven—we still don't

know what we're going to call it. If you have suggestions for a good name, please share it with us. At first, we started to call it information driven safeguards. Then, we had a departmental meeting where we announced our plans and one of the inspectors stood up and said that he did not understand the term 'information driven safeguards.' What are we doing now or what have we been doing in the past? Was it 'emotional driven' safeguards? In fact, we've always been doing information driven safeguards. The only difference is that we now have access to much more information than before. So what we should be doing, first of all, is to integrate all the information that we have into one system. At the moment we have two almost independent processes. We have the state evaluation process that looks at all these kinds of information, such as open sources and satellite imagery. This has been a self-sustaining process that has had very little interaction with the routine inspection process that we're carrying out in facilities. There has been little interaction between the two processes. The first thing is to make sure that internally we integrate these two processes so that we can use all the information that we have in determining what activities we have to do in the field—and vice versa, to use the results from our activities in the field to determine what kind of other information we should seek in order to have a better picture. Regarding the tools we will need, we may need more specialized technical tools. In the old system we performed too many routine verification measurements, measuring the same things over and over again. We should have very precise tools for precise activities, for example, to determine the origin of nuclear material. Technology will remain an essential part of information driven safeguards implementation. However, we need different tools, tools that may be used less frequently and less routinely to help us acquire, analyze and store the information we seek.

Ken Sorenson: This morning you talked about the problem with undeclared facilities. Are you going to try to address that within the concept of this new approach? I think about the commercial fuel cycle and it will continue to expand, I'm confident, despite Fukishima. The question is, what role do you see for external groups in helping keep control of fuel cycle technologies and materials? Specifically the Nuclear Supplier's Group, for example. Is there a role that a group like that can play in helping the IAEA and the world mitigate and minimize proliferation?

Nackaerts: We hope to have better assistance from the Nuclear Suppliers Group. For whatever reason, it seems we don't. I'll have to find out what is the reason for that. In the agency, we have set up our own group for trade analysis in an effort to try to understand nuclear-related trade as it relates to safeguards. There is a lot of information out there but we find it difficult to access it. The agency and the various export control arrangements work in the same environment and for the same final objective of nonproliferation, so we should find ways to cooperate better to that effect.

Felicia Durán: Listening to your talk this morning, I was recalling an activity that the U.S. Nuclear Regulatory Commission underwent in the 1990s with their reactor oversight process. It's a similar type of process, they have inspectors that go out to do the reactor facilities and they have on-site inspections, and another inspection activities, until they really were looking at achieving the same goals that you're trying to achieve here—a more efficient use of their inspection resources. I think they were quite successful in improving their overall process, so I wanted to share that with you and reinforce and tell you that I really think this is a really good direction to be going in. I think you can expect a lot of success along those lines. The NRC was trying to set up the same sort of situation, where the facility provided more information, better information, to demonstrate that they were in line with all the NRC requirements. Then they have less inspection oversight at their facility. The other thought that I had as I was listening to your talk, and I'd like you to explain or comment on is that I think the IAEA is in a position here with this initiative to provide some strong leadership for safeguards, which is another of your key roles, and that some of the strategies and approaches that you're going to work at implementing will then filter down to the security operators and other state regulatory bodies so that you're all working towards the best use and most efficient uses of our resources and we're not engaging in activities that we're just doing for the sake of doing, as opposed to really providing added value to the work that we're responsible for. Do you have any insight along those lines?

Nackaerts: Thank you very much for your comment. It's very encouraging that you can quote examples where you have succeeded in doing something very similar to what we want to do. We can learn a lot from them. In Vienna we have an informal group called the 'Friends of Safeguards' whereby a number of member states interested in what we want to achieve get together and discuss with us and offer assistance in moving things forward. Maybe we could ask the United States to share some of its insights so we could learn from the experiences of the NRC and apply lessons learned when we make the changes to our own implementation. We want to make sure that we have sufficient cooperation from our member states and from facility operators. Therefore, we have started, for instance, discussions with the European Commission at the May

ESARDA meeting on how to make better use of their activities. To be able to do that, we need to determine how our respective systems should evolve. There is no such thing as a free lunch. We expect a lot from them: more information and better quality information. We hope they can embrace some of the things that we want to do as well. It's important that the operators and the states see the benefits for the global regime; that they do their part of the job; and that they don't see us only as an additional burden. I have already heard of good initiatives during these one and a half days that I have been here: for example, Finland, which has a project on the final storage of spent fuel, is working to make sure that the operators are fully involved from the very beginning. So yes, we have to do our part to reach them.

Markku Koskelo: Some of the answers to the question I had in mind have already come out with other questions. But it's very clear that you're pushing the state-level approach. It was very gratifying to hear that you want to make sure that you convey a very clear mission. And it was that clarity of mission that sort of started my question, because there are all these buzz words, including information driven safeguards, so it's not clear now where that is relative to state-level approach and you may answer back to some extent. But sort of as a follow-on question to that, even at the state-level approach, you now have the facility operators providing you with data. How can you make sure that the numbers and the data that they're providing you, in fact, are the same quality and the exact same thing from one facility or one country to another country? Isn't that a large job, to make sure that the number in fact means the same thing everywhere? Because that may not be a given.

Nackaerts: First of all, as you know, we deal mainly with state authorities—our official safeguards points of contact with the states—and through them, with operators. Therefore, it will be important that we work closely with SSACs and, where necessary, convince them that it's in their interest that they make sure that the operators have procedures and the right measurement systems in place, and that they provide good data to the state system in the first place. I have to say that some of them have to work much harder to ensure the quality of the data. I'm not saying that we will no longer carry out inspections and other verification activities. We will continue to visit regularly facilities and carry out verification activities there and independently collect and record data. We will not give that up. I want to make that point very clear for those who think that the new state-level approach means that we give up on-site inspections. This is not the case. Access to facilities is the most important asset that we, as an agency, have. If we have one added value compared to any other organization, then it is access to countries and their facilities. It would be unwise from our side to give up that access. So we will continue to carry out inspections. But we will make them smarter, not carrying them out in the very prescriptive way as before.

Jack Jekowski: Taking advantage of the Internet here while we're talking, I was able to download your twelve-year strategic plan and take a look at some of the data. And I see the state-level initiative, of course, is driven by that. This is a two-part question. One is how did you feel that planning process went? I noticed that you talked to scenario development in that planning process and how far have you taken that planning process? That's part one. Part two you may either not have to answer or scrub out when you do the final edit here. But that is, as I listened to your presentation this morning, it struck me, and then I see one of the first strategic objectives here is to deter the proliferation of nuclear weapons by detecting early the misuse of nuclear material or technology and providing credible assurances that states are honoring their safeguard obligations. The way that the United States and some other countries do that is through national technical means and human intelligence. Does the IAEA look down the road and see that with the changing landscape and the surreptitious nature of many nation states, that they are going to have to likewise implement a technical capability and perhaps an Intel capability to sustain a goal such as this?

Nackaerts: We are not going to set up our own MI-6 or CIA or equivalent—of course not. However, if member states have relevant information about activities in other states, we expect them to share it with us, as a lot of states do already. Third-party information is just one source of information that we have. It is clear that in the two cases that are currently discussed by the IAEA Board of Governors, we have been making use, to a certain extent, of intelligence information. While we do use intelligence information and people seem to get excited about it, I certainly don't want to over-emphasize its role. But when we have it, we use it as lead information. We keep it in the back of our minds and we confront the country with such information at the appropriate time.

As regards to the strategic plan, it was developed before I took up my current position, so I would not do justice to Jill Cooley, who led the work on that, by talking about the various steps. I understand that you're developing a strategic plan for the INMM, so I would encourage you to speak to Jill to find out how we went through that process. But I will say that the process and the result were very successful, to the degree that DG Amano has instructed other IAEA departments to adopt a similar process and to prepare their own long-term strategic plans.

Obie Amacker: Several times during your presentation and this discussion you have mentioned that the new approach is focused on reaching certain milestones by the end of 2011 and 2012. Have you thought about measures or metrics to evaluate your progress at the target points? How will you know if you were successful at meeting your defined objectives?

Nackaerts: We have established a detailed work plan and appointed a change manager to oversee the process. The beginning is difficult, as always. Early successes are important so that people see this is really happening. What have we achieved up to now? First of all, we have clarified our vision. This is important. We have communicated it to the department. We have made the state evaluation process collaborative, actively involving all departmental divisions. It is no longer the silo type of approach where every division did its own thing. This collective approach may not mean a lot to an outsider, but for us in the agency it means a lot. And the staff in the department is aware of this now. We have core state evaluation groups that, with representatives across divisions, are now responsible for preparing the state evaluation reports and producing state-level approaches. That is something we can already tick off the list. We have also put in place a "Red Team" system whereby state evaluation reports are evaluated afterwards to examine whether they're complete and correct and whether there are any gaps. This is to ensure the quality of those reports. Finally, we have reorganized the department, as of the first of July. It is more aligned with the work that we want to do. People can see this happening. We have a portal on our website where we place all the related documents and the new ways of working. People can see how things are improving. Having said that, we recognize that we still have a long way to go.

Fishbone: In implementing the state-level approach, I'm seeing discussions about dependence on technical factors, such as the fuel cycle, and also statements about dependence on non-technical factors. One non-technical factor that comes to mind and is very straightforward is whether a state adheres to the additional protocol or not. Can you mention other non-technical factors that would apply?

Nackaerts: This is, of course, still a work in progress. When I give you examples of factors, it's not an exhaustive list. Of course, the status of a state's legal undertakings is very important, and it's easily measurable. For example, does the state have an additional protocol in force? Do they have national authorities to communicate with the agency? The legal situation is probably the most important state factor. Another factor, which we want to take into account, is the level and quality of the cooperation between a state and the agency. There are ways to measure this. Does the state provide us with reports and declarations in a timely manner? Is the information correct and complete? That's easily measurable. Whether the state facilitates agency access is also measurable. Does the agency have to argue over every inspection or does the state proactively welcome them? This is about transparency. It's also measurable. With respect to the designation of inspectors, does the state object to inspectors the secretariat has hired and the board has approved? Do they issue long-term visas to our inspectors? These are not purely technical things, but they're very objective things that can be measured. This is the kind of road we want to embark on, to try and determine these state factors. This is the next phase in our work. We are currently actively thinking about it, and hope to have a more comprehensive approach by next year.

Sam Savani: I found your talk very interesting and informative and I thought you did a very good job of outlining your change plan that you want to go forward with. It's going to be challenging because you're talking about changing the culture here. I was curious, does the agency ever wonder or have a problem or issue or concern with anyone participating. They may not be there to help the cause, but they are there to collect information so they can go back to their countries and use the info for their personal gain.

Nackaerts: I will not say it is a problem, but it is a concern. The agency is not a career organization, so we have people from different states that spend some time at the agency and then go back to their home state. So the objectives and liability of some individuals may be an issue of concern. What can we do about it? We can try to work out certain people's possible motivations and avoid potential problems. For example, we wouldn't put inspectors of a particular nationality to inspect certain states. One can try to take some measures, without being formal, to address these concerns. Confidentiality of information is a big issue. Many people, many states, many organizations may have different reasons to leak information or pass on information. So that is an internal challenge we're having in the agency. No matter what safeguards system you're implementing, you will be confronted with such challenges and have to find ways to handle them. This issue is not linked to the change process I want to implement. It is more a general fact of life we have to deal with.

Michael Baker: I'd like to follow up on an earlier comment. Several of us in the room are technology developers. You mentioned that you would like to have your department be able to select tools as needed. Can you to expand upon what tools you are missing today that you would like to be able to select from?

Nackaerts: That is a question that I'm not very prepared for, but I can give you some examples. In one example, we're building a new nuclear material laboratory. When I looked at what that new laboratory should do in the future, I was told it should do the same as it had always done. I asked myself whether this was the right thing to do. Why should we build a laboratory for the next 30 plus years that does exactly the same thing as before: analyzing samples and determining the concentration and isotopic composition of nuclear material? The real issue is where the material comes from—much more than its concentration. We need forensic measurements to determine the origin of material. In the case of Syria, we needed to identify whether the material came from a conversion plant in Syria or another country. So we were looking at ratios of impurities and other signatures—not our usual type of analysis. We should have access to forensic technology. Whether we need to have it ourselves in the agency, or just know where to go for that type of analysis, is another matter. In a number of discussions during this meeting, it has been said that we need more remote transmission of data and that we need to make sure that the information is genuine and not tampered with. This is certainly something we want to achieve. As for an overview of our technical R & D needs, we want to look at our R & D program in a more systematic way. Jill Cooley and her concepts and planning division are currently identifying our R & D needs and developing a long-term R&D plan—the same division that developed the long-term strategic plan. This will ensure that the R & D plan is fully integrated with the strategic plan. You will also note that the coordination of member state support programs has also been moved from our technical division into the same conceptual division.

Debbie Dickman: Well, as you might guess, since I am involved with the education and training committee, my question would come back to training and the cultural changes that you need to make in the inspector mindset. I'm wondering have you started down that pathway in analyzing what the training is now and what you would like it to accomplish later, and how you plan on approaching that and implementing changes?

Nackaerts: We have started looking at it. I had a meeting last week with our training section. I asked them to specifically make sure that the next introductory course for new safeguards inspectors, starting in February 2012, is focused on this new regime that we want to put in place. This is one practical change initiative. At the same time, through management guidance, inspectors will start to understand the direction in which we want to go. This is also part of training. When I joined the agency, I was made responsible for a number of sensitive countries. I pushed the inspectors to do a lot more investigation and analysis—things that are not directly inspection related. Some of them were very reluctant to do that. They said, "I'll do it, but I really don't have much time because I have to get on with my real work." They considered their real work to consist of going on an inspection and ticking the boxes. As long as management doesn't send the right messages, this will never change. If management doesn't push the inspectors and doesn't reward those inspectors who are ready to do the more investigative work, we will never get anywhere. That's also part of the cultural training: making sure that they get the right feedback and rewarding them when they do the right thing. And then they will understand, when they go on an inspection, that we don't expect these five additional measurements, but something else. In another example: the preparation of the annual safeguards implementation report has been a very bureaucratic process. In some cases, inspectors have been so concerned with satisfying the requirements of our internal safeguard effectiveness evaluation group that they basically have carried out their activities in the field with the blind objective of *passing* their facilities in terms of goal attainment. For them, this was the real work. Some of them forgot to be curious: instead, acting rather like robots. I don't want to generalize. Please don't misunderstand, but this has been the environment. So we have to send the message that there's more information out there that we want inspectors to observe and take note of.

Steve Ortiz: My question is along those lines. The state-level concept you said, is doing more of this. Then you talk about fixed or steady budget and resources. It takes more time to get more data and more analysis, more time and more people. So are you going to do fewer inspections each year? How are you going to address that?

Nackaerts: I stated in my presentation that we spend 60 percent of our effort in three countries. I'm not convinced that these are the three countries that pose the biggest proliferation risk. There is a reasonable expectation that we do less in countries that do not pose a proliferation risk. We have some margin of maneuver in this respect. I was interested to see in one of the presentations that someone had already calculated what it would mean to reduce by a certain factor our activities in Ja-

pan and to use those resources elsewhere. So other people are thinking about it. This is good, and I can certainly use such information. So yes, we will have to reduce some for the sake of efficiency—but never at the expense of effectiveness.

Pickett: In your job today, what is your biggest worry or concern that you lose the most sleep over?

Nackaerts: My biggest worry is Iran, honestly. I want to be sure that we find the truth. I have information that points to a possible military dimension of Iran's nuclear program. That information is largely based on intelligence information. It is very convincing. It seems very credible and comprehensive. But on the other hand, I cannot verify it. Iran is claiming that this is all false and fabricated, and that they don't have such a program. I don't want to be part of a game between states that may escalate into an inter-state conflict and end up in a war somewhere. I want to find the truth. If something prevents me from sleeping, it is that.

Scott Vance: I really don't have a question, but more a comment about the last question you had in the general session, which was a gentleman who stood up. I honestly don't know him. But he asked how INMM can support what you do. My statement to you is I know you are familiar that we have a very close relationship with the IAEA and would hope to maintain that. Our chapter in Vienna, we call it the IAEA Chapter. We try to support that chapter very much and we want to encourage that relationship. So I appreciate you being here and I appreciate you meeting with us here today, and I hope that our relationship is the same as it was or has been, so I appreciate that.

Nackaerts: Thank you.

Mangan: I want to thank you very much for taking the time to meet with us today. I really enjoyed listening to your answers. Your attitude is just refreshing; it's absolutely refreshing. That doesn't mean that previous DDG's weren't refreshing but this certainly has a different atmosphere to it than what we're used to. So take care, and I think all of us here will continue to cheer you on.

Evaluating Advanced Fuel Cycle Proliferation Resistance Dynamics Using Isotopic Characterization Coupling

Steven E. Skutnik and Man-Sung Yim
North Carolina State University, Raleigh, North Carolina USA

Abstract

A method for enhancing nuclear fuel cycle proliferation resistance (PR) assessment through the direct coupling of nuclear materials depletion and decay analysis is presented in this paper. This direct coupling of nuclear materials analysis with PR evaluation affords new avenues of PR evaluation, including the evaluation of the cycle-level sensitivity to factors such as reactor type, fuel enrichment, and fuel burnup, all of which result in changes to materials properties that cascade throughout the system. This analysis can be useful to identifying the conditions under which nuclear energy systems show a heightened PR sensitivity and warranted further characterization. This paper extends prior work in the coupling technique; in addition to making use of a more sophisticated material attractiveness evaluation and a stage weighting sensitive to the material mass flow of the system, further categories of systems are evaluated. A demonstration analysis is applied to three classes of fuel cycles across varying parameters: open cycles consisting of no actinide recycle, modified open cycles with limited actinide recycling, and fully closed cycles in which all actinides are recycled as fuel. While the Fuzzy Logic Barrier Model developed at North Carolina State University shall be used as a demonstration platform for this effort, this technique can be applied to enhance many models for fuel cycle PR assessment.

Introduction

With the growing interest in development and expansion of nuclear energy systems, proliferation resistance (PR) assessment has become an essential tool both in benchmarking the relative PR performance of novel fuel cycle technologies and configurations, and as for developing new and more effective proliferation safeguards. Such a need is acutely important in that the intrinsic proliferation resistance of nuclear fuel cycle systems can vary significantly between different fuel cycle configurations.

Given that fuel cycle PR is inherently related to the physical characteristics of materials within the system, PR assessment exercises require ready access to the changing isotopic inventories throughout the system under consideration. As these properties are generally a function of high-level operational parameters of the fuel cycle (such as enrichment, burnup, and isotopic separation strategies), PR can logically be evaluated as a function of such cycle parameters. In as much, PR is thus arguably a dynamic system property given that changes in material properties (due to changes in said cycle parameters) permeate throughout the fuel cycle system.

Evaluating PR as a dynamic system property affords several advantages; chief among these is the ability to evaluate the operating conditions under which the system PR is most sensitive, thus warranting more detailed characterization of safeguards performance.

This study extends prior work in developing the isotopic coupling technique for PR analysis,[1] incorporating a more sophisticated evaluation of isotopic attractiveness and a new stage weighting system that accounts for material mass flows through the system, as well as other improvements to the PR model used for this demonstration. PR dynamics for both current and advanced nuclear fuel cycles shall be evaluated, falling into three categories: open fuel cycles, modified open cycle (MOC) consisting of limited actinide recycle and MOX fuel fabrication using both conventional and advanced separations techniques (PUREX and UREX+ series) as well as re-irradiation of PWR fuel in a CANDU reactor (DUPIC),[2,3] and finally a closed cycle consisting of full actinide recycle in fast-spectrum reactors. Proliferation resistance is evaluated along several key operational parameters of the chosen fuel cycles, including fuel burnup and actinide separation strategies.

Methodology

Model Used for PR Evaluation

The detailed mechanics of the Fuzzy Logic Barrier (FLB) model have been discussed at great length prior[4,5,6] and thus shall not be presented specifically in this paper as it is not the focus of this study, but rather simply a demonstration platform. However, a short discussion shall be made of the use and features of this model to facilitate its use for this purpose.

The basis for the FLB model lies in the evaluation of eleven intrinsic barriers to proliferation, as identified by the TOPS committee,[7] given as Table 1. Each barrier is independently evaluated for each nuclear fuel cycle stage and assigned a linguistic ranking, from Ineffective (I) to Very High (VH). These linguistic rankings then correspond to a fuzzy number. The fuzzy numbers corresponding to each barrier effectiveness ranking are combined for each level and the resulting stage fuzzy numbers can then be combined into an aggregate system fuzzy number.[4]

Table 1. Intrinsic barriers to proliferation in nuclear energy systems, as defined in Reference 7

Physical barriers	Technical barriers
Isotopic attractiveness	Facility unattractiveness
Chemical separation difficulty	Facility accessibility
Radiological hazard	Available mass
Material mass & bulk	Facility diversion detectability
Material detectability	Skills, expertise, & knowledge
	Time

Figure 1 gives the breakdown of relative barrier weights used for this analysis, based on the assumption of a relatively unsophisticated state (e.g., lacking a fully developed nuclear fuel cycle or advanced industrial infrastructure) in a covert diversion attempt.

Isotopic Characterization Coupling

As discussed in prior works,[1,8] the evaluation of PR dynamics rests in the direct coupling of isotopic characterization analysis (performed through codes such as ORIGEN-S[9]) with models for fuel cycle PR. Using a generalized series of fuel cycle facility types, nuclear fuel characterization analysis in SCALE can be automated through the use of discrete parameters; the dynamic properties of fuel can thus be carried through the system (including the subsequent decay, separation, and re-irradiation of materials). The OASIS module for SCALE is used to facilitate this process of fuel analysis;[10] a corresponding OASIS input deck is constructed for each fuel cycle level, which are then assembled into a single system input deck. The fuel analysis is then executed in SCALE, where the isotopic, radiological, and thermal data for each position are retrieved for each respective fuel cycle level, thus enabling PR analysis as a direct function of the evolving physical properties of the fuel. This coupling process is diagrammed as Figure 2.

Stage Weighting and Mass Flow

Determining the weight contributions of individual fuel cycle stages is a multi-step process, accounting for factors such as the total heavy metal inventory between fuel cycle subsystems, heavy metal mass flow between subsystems, and the concentration of fissile materials between individual stages.

First, the nuclear energy system is broken up into constituent subsystems based upon heavy metal inventories (e.g., actinides). This premise of this assumption is in that heavy metal inventories are generally invariant for non-reactor stages (e.g., given the long

Figure 1. Barrier weighting used in FLB analysis

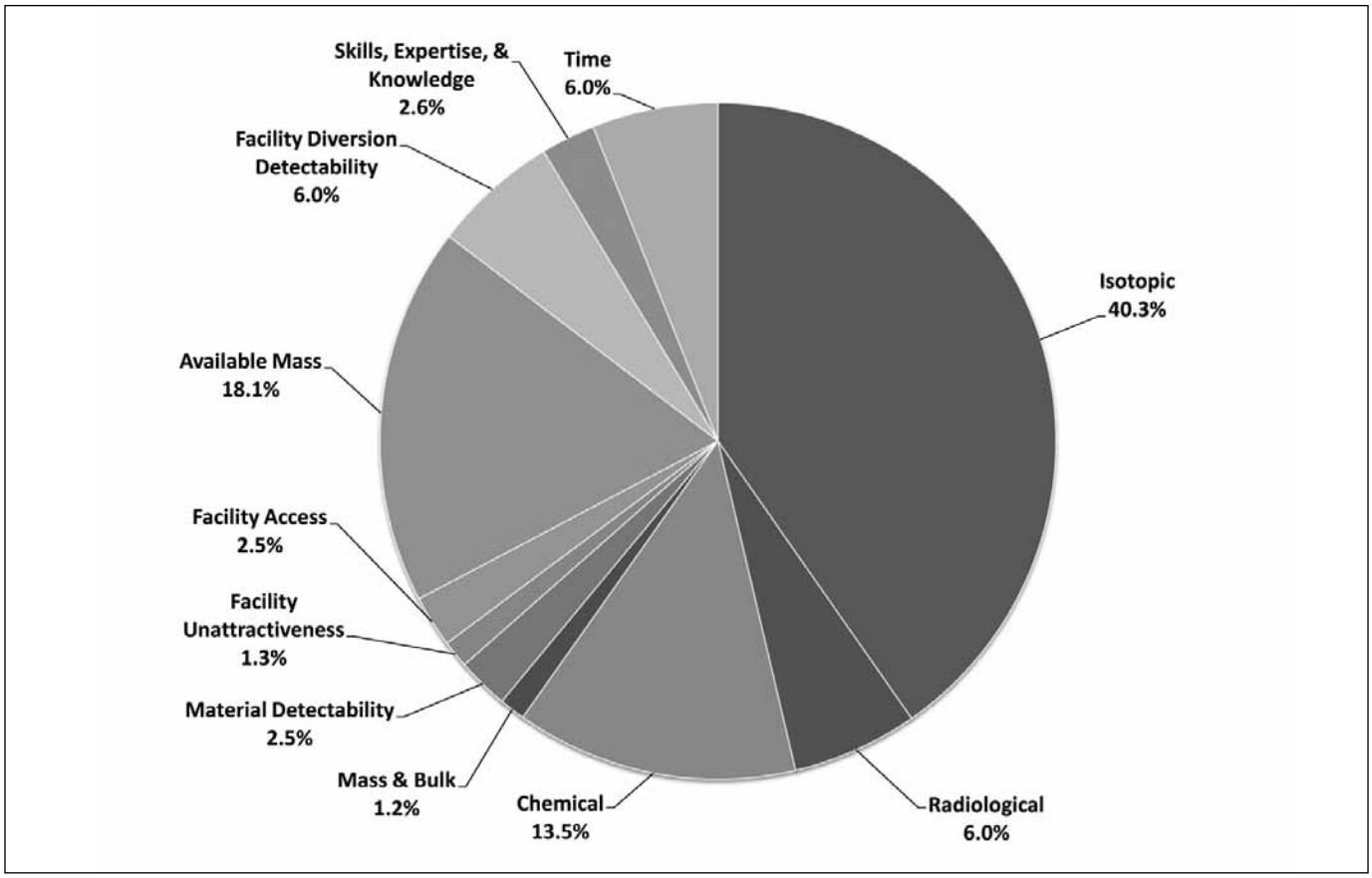
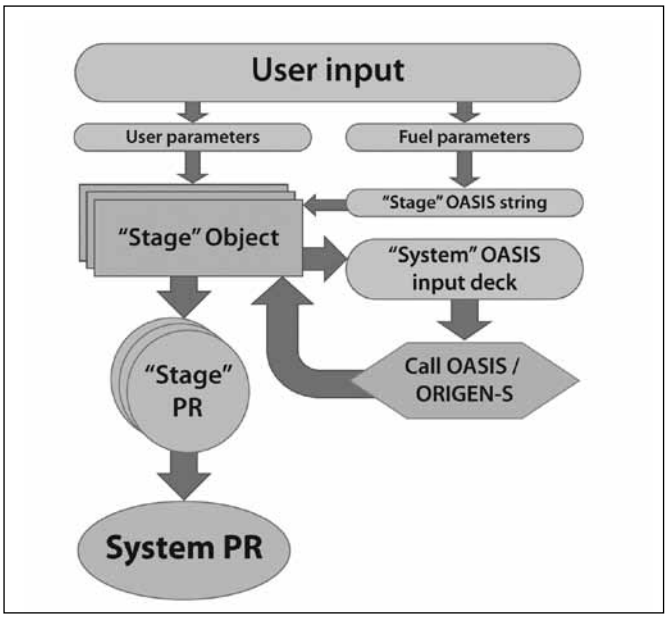


Figure 2. Coupling of isotopic analysis using the OASIS module for SCALE.[10,9] User data is used to generate case input data for isotopic transmutation/decay in SCALE (using the OASIS module for input) for each fuel cycle stage; ORIGEN-S data is then extracted for the respective stages and used to generate stage PR values and a subsequent system PR value.



half-lives of actinides); thus the only substantial changes are due to fission and transmutation (both of which occur during irradiation). Thus, a LWR-OT cycle would have two subsystems, consisting of all stages before irradiation (including enrichment, fuel fabrication, etc.) and then all post-irradiation stages (e.g. spent fuel handling and disposal). For "modified open" and closed cycles, additional subsystems are added based on subsequent re-irradiation stages; for example, a MOX system consists of a pre-irradiation subsystem, a post-LWR irradiation subsystem (including spent fuel handling, reprocessing, and MOX fuel fabrication), and a post-MOX irradiation subsystem. See Figure 3.

Second, a mass balance is applied to the system in order to account for material flow between subsystems, namely by the calculation of the required fuel mass input per unit of electricity produced (i.e., $\frac{kg}{TWhe}$), similar to studies performed by the NEA.[11] For "modified open" and closed cycles, this mass balance is used to then calculate the equilibrium share of electricity production by calculating the amount of available TRU for MOX and FBR fuel fabrication. The mass flow required (and hence available electricity fraction) is thus a function of two parameters: the TRU inventory of LWR fuel and the burnup of fuel in the secondary irradiation stage (dictating the amount of fuel required per unit energy). Assumptions of reactor electrical conversion efficiency are taken as those given in Reference 11.

The weighting between subsystems is thus the ratio of heavy metal inventories scaled by the electricity production factor; this relationship is defined as Equation 1, where $EF_{reirrad}$ is the electricity fraction from the re-irradiation cycle (calculated from the available mass flow), HMi is the heavy metal mass inventory in the given subsystem, and NSS is the number of subsystems.

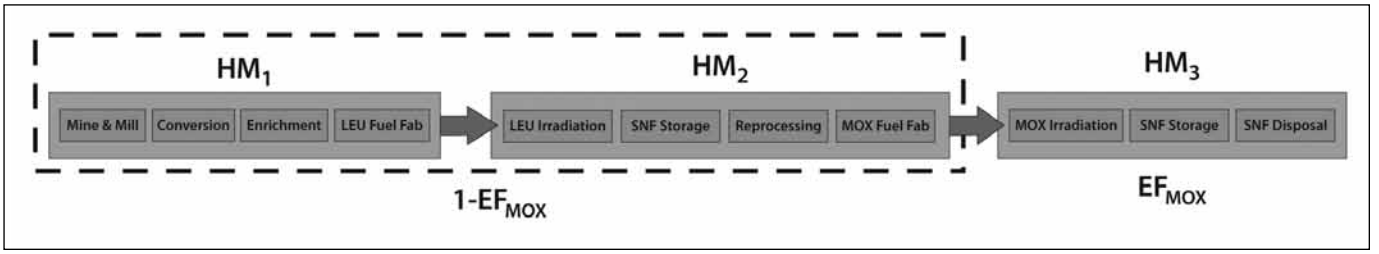
$$W_i = \begin{cases} \frac{HM_i}{\sum_{i}^{N_{SS}} HM_i} \cdot (1 - EF_{reirrad.}) & \text{Pre-reactor \& LWR stages} \\ \frac{HM_i}{\sum_{i}^{N_{SS}} HM_i} \cdot (EF_{reirrad.}) & \text{Re-irradiation stages (MOX \& FBR)} \end{cases} \quad (1)$$

For example, if the electricity production ratio from MOX fuel is 11 percent (as would be the case for equilibrium mass flow with UO_2 and MOX fuel burnups of 60 $\frac{GWd}{MTU}$ / $\frac{GWd}{MTHM}$[11]), the weight of each subsystem is calculated from the subsystem heavy metal inventory (based on the equilibrium material mass flow) and then scaled accordingly by the electricity fraction. Thus, the MOX weight would be scaled by 0.11, and the pre-reactor and post–LWR weights would be scaled by 0.89. The subsystem weighting thus takes into account varying mass flow, giving greater prominence to stages with a higher overall flow of fissile materials.

The rationale for this choice of weighting system is twofold. First, the goal of such a system is to be able to account for differences in heavy metal mass flow between different systems. As fuel burnup increases, the overall mass flow per unit electricity ($\frac{kg}{TWhe}$) decreases, thus shifting the overall balance of the actinide inventory in the system. Second, for systems employing actinide recycle, the heavy metal mass flow at equilibrium is limited by the available material for recycle (i.e., transuranics in uranium fuel). The electricity fraction (EF) explicitly accounts for this mass balance, adjusting the weight of re-irradiation stages accordingly.

To adjust for the difference in critical mass requirements between ^{235}U and Pu, the International Atomic Energy Agency (IAEA) standard of 25 kg for one significant quantity (SQ) of ^{235}U is used with 8 kg for Pu. Given that mixtures of Pu and

Figure 3: Example of mass weighting calculation for a modified open cycle with MOX fuel



minor actinides show little difference in the overall bare sphere critical mass (BSCM), the sum of the TRU mass is taken from the subsystem inventory and thus scaled by $\frac{25}{8}$ in order to compare enriched uranium inventories to TRU inventories. Individual constituents of the subsystems (stages) are then weighted by the fraction of fissile material within the heavy metal inventory of the stage (i.e., the fraction of ^{235}U and ^{239}Pu to the total mass flow). The net result is that stages with higher concentrations of fissile materials (such as post–enrichment, post-irradiation, and reprocessing) show a higher importance than those with relatively low concentrations (e.g., pre-enrichment and reprocessing wastes).

The stage weights within each subsystem are normalized for the individual subsystem, as are the subsystem weights themselves. Each stage weight is scaled by its corresponding subsystem weight to produce a net stage weight; thus, the total sum of stage weights is unity.

Isotopic Attractiveness Evaluation

Given both the significant weight placed upon the isotopic barrier and its broad range of potential values (given the space of fuel burnups and actinide co-recovery strategies considered), a robust system for evaluating material attractiveness is required. For the purpose of the FLB model used in this demonstration, the isotopic barrier is evaluated through an adaptation of the Figure of Merit approach developed by Bathke, et. al., at Los Alamos National Laboratory.[12] Having been developed in consultation with weapons experts, the FOM approach represents a highly robust metric for evaluating material attractiveness.[12]

The material attractiveness ratings of the FOM_1 range from 0 (unattractive) to 3.0 (preferred); these values were translated into linguistic values roughly corresponding to those found in Reference 12, given as Table 2.

Table 2. Fuzzy number correspondence to FOM_1[12]

FOM1	Fuzzy Rank	Weapons Utility[12]
> 3.00	I	
2.66-3.0	L-	Preferred
2.33 – 2.66	L	
2.00 – 2.33	L +	
1.66 – 2.00	M-	
1.33 – 1.66	M-	Attractive
1.00 – 1.33	M+	
0.66 – 1.00	H-	
0.33 – 0.66	H	Unattractive
0.00 – 0.33	H+	
< 0.00	VH	

FOM_1 is evaluated based upon three physical parameters: the material bare sphere critical mass (M, in kg), radiological dose at one meter (D, from one-fifth of the critical mass), and finally the heat generation rate of the material (h, inW/kg). FOM_1 is defined as Equation 2.[12]

$$FOM_1 = 1 - \log_{10}\left(\frac{M}{800} + \frac{Mh}{4500} + \frac{M}{50}\left[\frac{D}{500}\right]^{\frac{1}{\log_{10} 2}}\right) \quad (2)$$

While the radiological dose and heat generation rate can be calculated directly from the material inventories (i.e., from ORIGEN-S), the calculation of the BSCM is not easily automated. Creating a broad space of burnup and material mixture combinations, the BSCM was found for each configuration in a criticality search using MCNPX.[13] From this data, a regression analysis was performed to produce a correlation for the bare sphere critical mass. For this correlation, the mass fraction of plutonium in the stream was found to first order to be the most significant term, showing an inverse-power relationship with the BSCM. The ^{239}Pu vector was found to be a second-order scaling factor, also showing an inverse power relationship. Between these two variables, an extremely good fit to the BSCM values observed across the broad space of material mixtures can be achieved.

The quality of fit for the BSCM correlation is shown in Figure 4; in general, the correlation provides an excellent fit to the BSCM data obtained in MCNPX for a wide range of mixture conditions, with $\bar{R}^2$ =0.9940. The quality of the fit declines slightly for very high dilution factors (i.e., lower values of the plutonium mass fraction), however overall the fit shows a very good agreement over the space of the data, thus enabling an automated calculation of the FOM_1 value for any isotopic mixture.

Results and Analysis

Open Cycles

Figure 5 shows a comparison of the system PR for a LWR and a CANDU HWR once-through cycle. However these differences are not large, particularly for the CANDU cycle. For the LWR cycle, the differences in material attractiveness are most pronounced at higher burnups (>40 $\frac{GWd}{MTU}$); these changes cascade throughout the remainder of the fuel cycle, producing the observed differences in system PR. One observes that burnup has a noticeable but relatively limited effect upon system PR. Taking a cross-section of the centroid values of the stage PR fuzzy numbers (Figure 6), differences in stage PR in post-irradiation (due to varying material attractiveness and radiological hazard) drive differences in system PR, conforming to intuitive expectations.

Figure 4. Regression analysis fits (lines) to bare-sphere critical mass data (points) obtained through criticality searches upon material mixtures using MCNPX; BSCM data in kg.[13] Nuclear composition data generated using SCALE [9]. $\bar{R}^2 = 0.9940$.

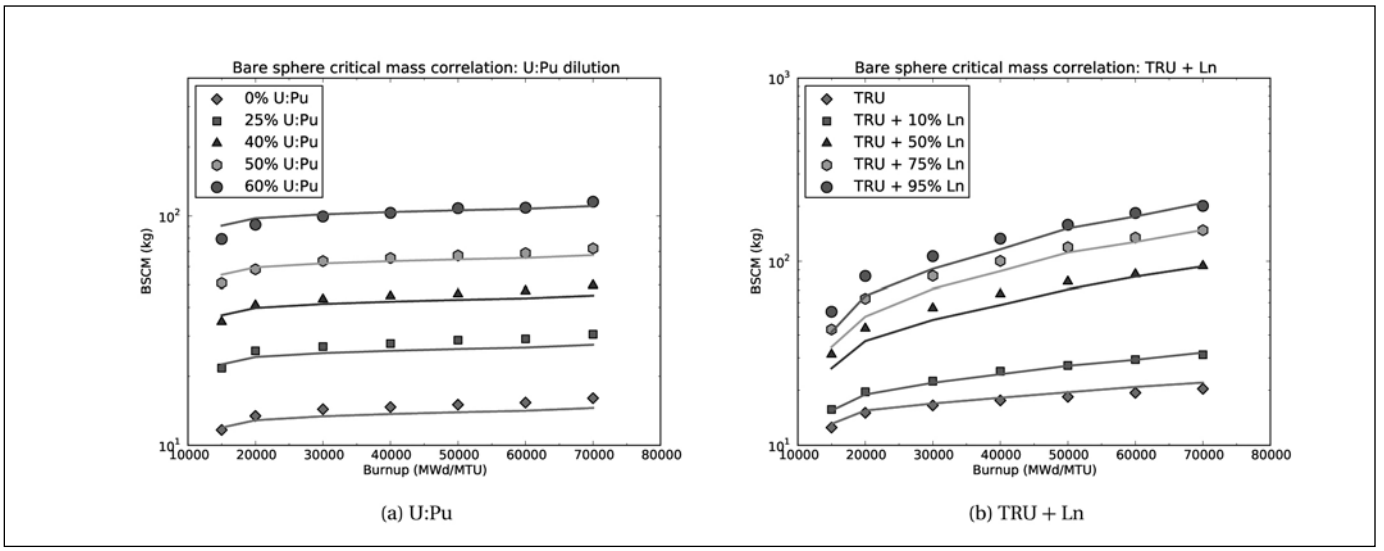
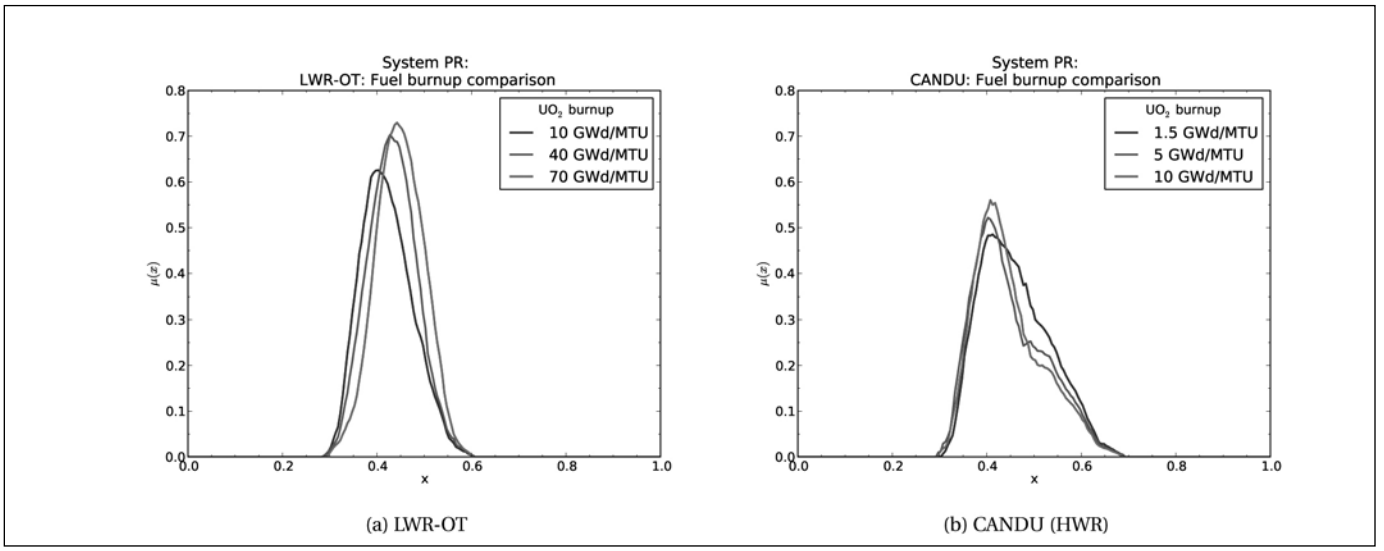


Figure 5. System PR comparison for (left) LWR once-through cycle, (right) CANDU HWR cycle



Modified Open Cycles

Figure 7 shows a comparison of the system PR as a function of UO_2 burnup for four "modified open" cycles; a traditional PUREX cycle (with plutonium-only recycle), COEX (with 50 percent co-extraction of uranium with plutonium), advanced UREX (UREX+1a, where plutonium is coextracted with minor actinides), and finally DUPIC (Direct Use of spent PWR fuel in CANDU), where LWR fuel is dry processed to remove volatile fission product gases and then re-irradiated in a CANDU reactor.[2]

A clear bifurcation in the system PR is evident for several MOC scenarios considered, with the lower PR peak being comprised of the reprocessing-related stages, where intrinsic barriers are least effective and a second, higher PR peak is composed of intact fuel stages (e.g., where chemical and radiological barriers are more effective). By contrast, while a minor penalty is incurred for the DUPIC cycle due to the downgrading of the radiological barrier in dry processing, the overall PR of the DUPIC cycle is the highest of the MOC options, approaching that of the reference LWR-OT case.

Figure 6. System PR decomposition for (left) LWR-OT cycle and (right) CANDU HWR cycle

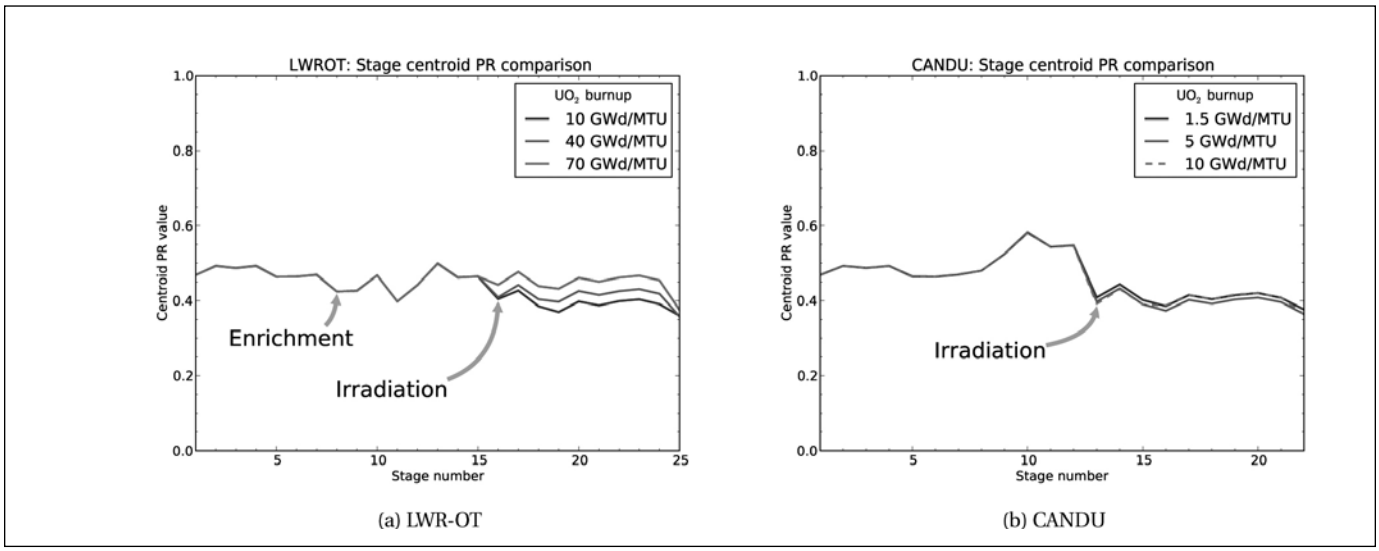


Figure 7. System PR comparison for (clockwise from top-left): PUREX (Pu only), COEX (50 percent U:Pu), DUPIC, and UREX+1a (Pu + MA)

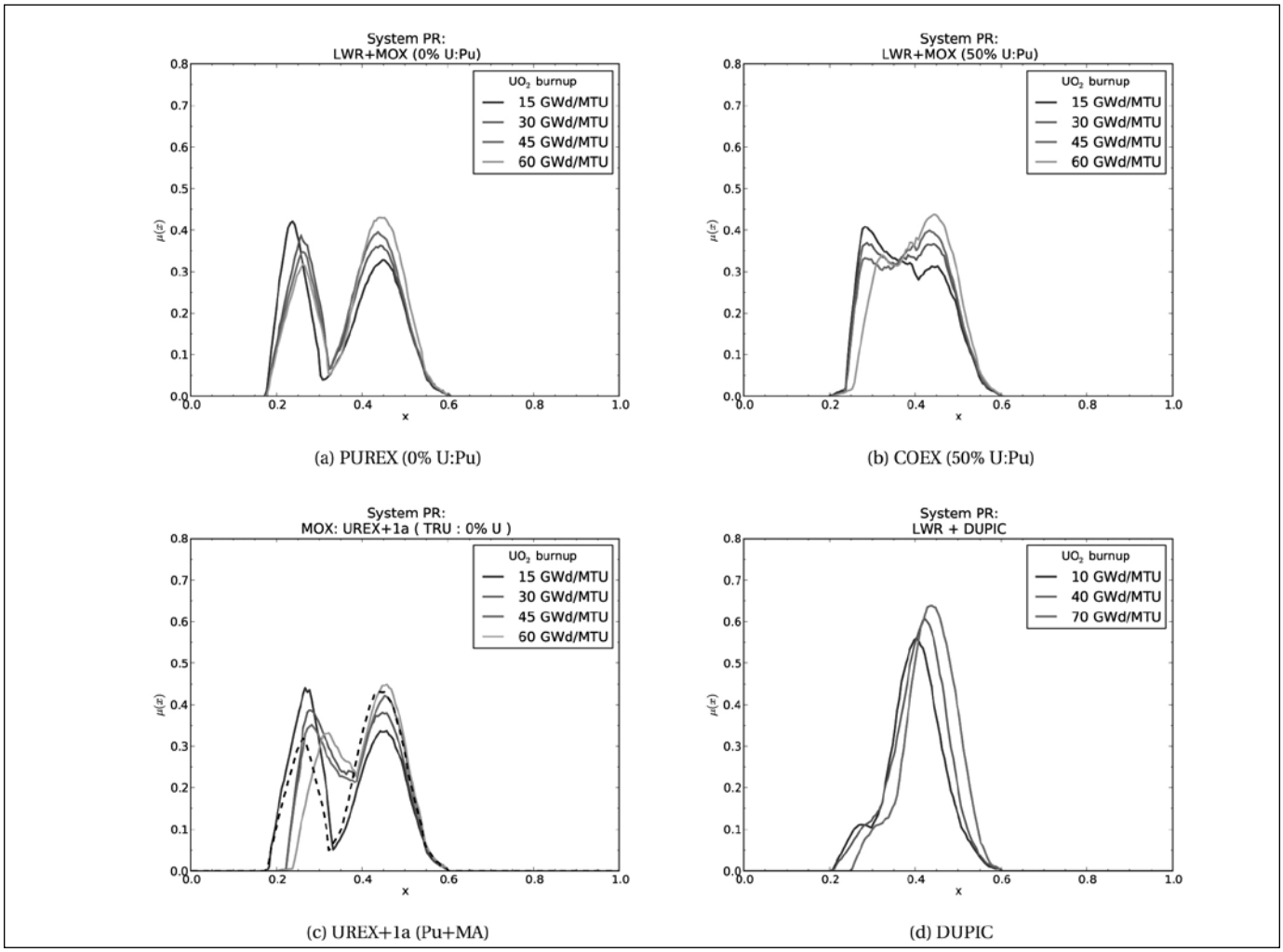
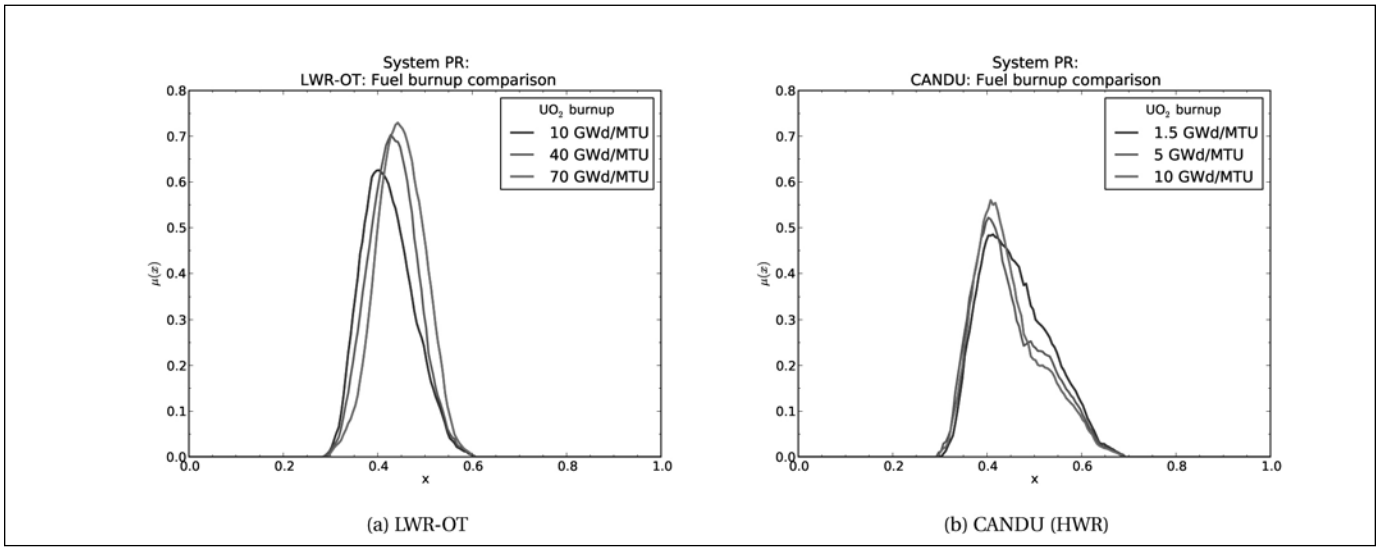


Figure 8. System PR comparison for LWR + fast burner reactor (50 percent conversion ratio) for actinide recovery using (left) UREX+1 and (right) Pyroprocessing



As was the case for the once-through cycles, burnup shows a nominal effect on system PR for most cases, being most pronounced at both higher UO_2 fuel burnup values and with the co-extraction of transuranic species (whose inventory scales as a function of burnup, affecting the heat generation rate of the mixture). Changes in the attractiveness of the plutonium vector are small over the burnup space considered, and therefore burnup appears to have only a minor effect on system PR in PUREX and COEX-based cycles. This effect is slightly more pronounced for the DUPIC cycle (in part due to the larger burnup range), although it is still relatively constrained.

Closed Cycles

Figure 8 compares the effect of UO_2 fuel burnup for "fully closed" systems consisting of a fast burner reactor (with a conversion ratio of 50 percent), using strategies of advanced UREX (UREX+1, where transuranics are co-extracted with lanthanides) and pyroprocessing (where it is assumed transuranics are coextracted with uranium and a small amount of transuranics).

Burnup appears to have a stronger impact on system PR for the fully closed cycle, particularly for the advanced UREX scenario, due to the larger burnup range evaluated and the greater overall consumption of fissile inventories.

Additionally, the effect of burnup is more pronounced in the closed cycle case than in the once-through case due to a longer overall cascade produced in the post-irradiation (and subsequent re-irradiation) stages for the closed cycle; this is evident in Figure 9, which gives a cross-section of the stage fuzzy number centroid values of such a cycle. From Figure 9, one observes that the largest change in intrinsic PR occurs between 40 and 70 $\frac{GWd}{MTU}$; the impact of burnup on PR is most clearly evident in the actinide recovery stages (e.g., where the TRU inventory, which is burnup-contingent, has the greatest discriminating impact on material attractiveness due to the heat generation rate). The differentiation in material attractiveness is more subdued as a function of burnup for the pyroprocessing case, namely due to the saturation of decreased material attractiveness at lower burnups. This comes from the co-extraction of uranium (inflating the bare sphere critical mass) as well as the inclusion of minor actinides (increasing the heat generation rate).

Conclusion

A method of enhancing nuclear fuel cycle proliferation resistance assessment through direct coupling with materials characterization analysis (via SCALE) has been demonstrated. In doing so, it is thus possible to directly evaluate the dynamics of PR, including *cascade* effects due to changes in material properties as a function of total fuel burnup, which has been previously identified as a matter of interest in such studies.[1,8,14] This study extended prior work in the coupling technique,[1] refining the materials attractiveness characterization (using the Figure of Merit technique developed by Bathke and others[12]) and stage weighting procedure. A subsequent analysis was made for novel fuel cycles, including DUPIC[2,3] and fast-spectrum reactor-based cycles.

Through this analysis, uranium fuel burnup showed overall minor effect upon system PR, manifesting most significantly for extended burnup ranges (e.g., over 40 $\frac{GWd}{MTU}$) and for longer cascade chains, such as those found in partially closed and fully closed fuel cycles. Additionally, uranium burnup acts as a proxy for minor actinide isotopic inventories in processes that involve the coextraction of transuranics (e.g., UREX+1a, pyroprocessing, etc.).

The overall system PR for class of fuel cycle is compared as Figure 10 for fixed fuel burnups. Overall, the LWR once-through cycle remains the baseline standard for intrinsic proliferation re-

Figure 9. System PR decomposition for LWR + FR cycle using (left) UREX+1 and (right) pyroprocessing for actinide recovery

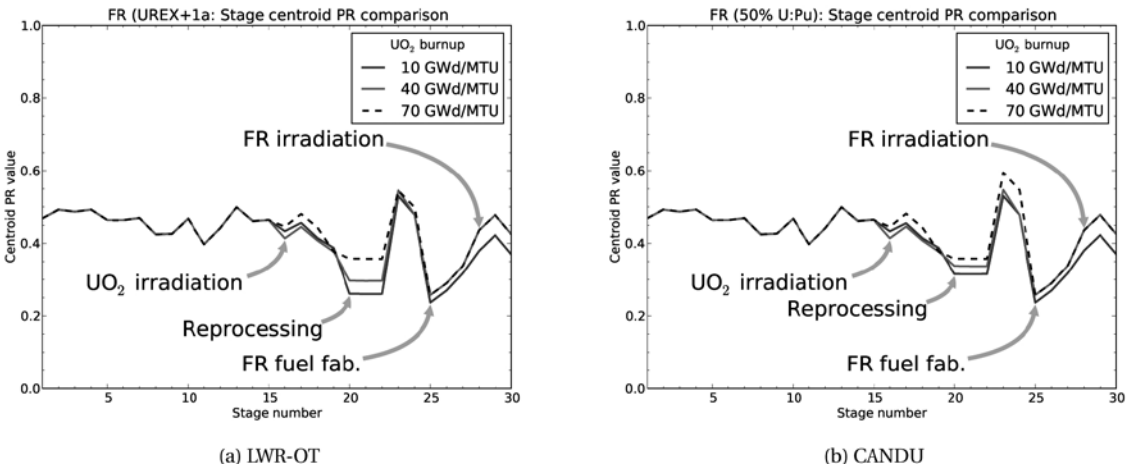
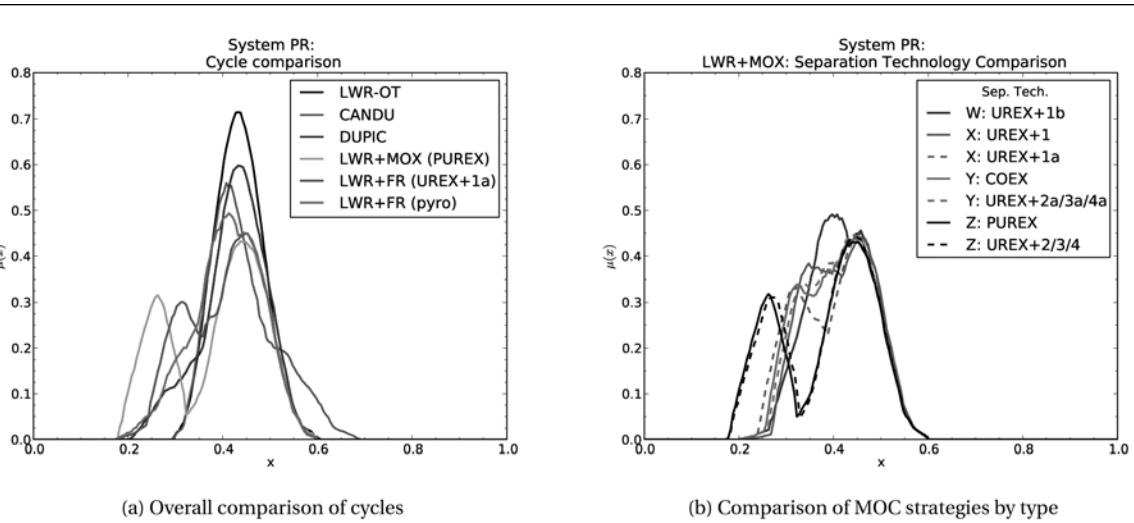


Figure 10. PR comparison of fuel cycle systems evaluated. Uranium & MOX fuel burnup fixed at 60 $\frac{GWd}{MTU}$ 60 $\frac{GWd}{MTHM}$; FBR fuel burnup of 90 $\frac{GWd}{MTU}$; CANDU and DUPIC fuel burnup of 10 $\frac{GWd}{MTU}$.



sistance. However, one observes that the DUPIC fuel cycle combines the advantages of further consumption of plutonium in used nuclear fuel without isolation of plutonium in the fuel cycle; in as much, the system PR of the DUPIC cycle approaches that of the LWR-OT case. Finally, fully closed fuel cycles (such as the fast reactor cycle) appear to show a noticeable PR advantage over partially-closed cycles, given the fact that both plutonium is not isolated (lessening material attractiveness) and the higher overall degree of actinide consumption in the fast cycle.

This relative comparison is further summarized as Table 3; the system PR values for each system are reduced to the centroid mean value for simple pointwise comparison. Likewise, a system rank is established through the use of a fuzzy outranking procedure in order to assign a relative linguistic ranking of overall system PR.[15]

Acknowledgments

This research was performed under appointment to the U.S. Department of Energy Nuclear Nonproliferation International Safeguards Graduate Fellowship Program sponsored by the National Nuclear Security Administration's Office of Nonproliferation and International Security.

Table 3. Summary of system centroid PR and rank values for selected fuel cycle systems

System	Burnup ($\frac{GWd}{MTU}$ / $\frac{GWd}{MTHM}$)	Centroid	Rank
LWR-OT	40 /—	0.4327	M+
	70 /—	0.4489	M+
CANDU HWR	10 /—	0.4462	M
MOX: PUREX	60 / 60	0.3853	L+
MOX: COEX	60 / 60	0.4069	M–
MOX: UREX+1a	60 / 60	0.4060	M–
DUPIC	40 /	10 0.4085	M
	70 / 10	0.4335	M+
FBR: UREX+1a	40 / 90	0.3988	M–
	70 / 90	0.4157	M
FBR: Pyro	40 / 90	0.4090	M
	70 / 90	0.4094	M

References

1. Skutnik, S., and M.-S. Yim. 2010. Enhancing Nuclear Fuel Cycle Proliferation Resistance Assessment through Direct Coupling with Nuclear Materials Characterization Analysis, *Proceedings of the INMM 51st Annual Meeting.*
2. Park, J. J., M. S. Yang, K. K. Bae, H. B. Choi, H. D. Kim, J. H. Kim, and H. S, Park. 2000. Technology and Implementation of the DUPIC Concept for Nuclear Spent Fuel in the ROK. Technical report, Korea Atomic Energy Research Institute.
3. Ko, W. I., and H. D. Kim. 2001. Analysis of Nuclear Proliferation Resistance of DUPIC Fuel Cycle. *Journal of Nuclear Science and Technology,* 38(9):757–765.
4. Li, J., M.-S. Yim, and D. McNelis. 2008. Assessing Proliferation Resistance of Nuclear Fuel Cycle Systems Using a Fuzzy-Logic Barrier Method. *Nuclear Technology,* 3(162):292–307.
5. Skutnik, S.E., M.-S. Yim, and J. Li. 2008. Reevaluating Barrier Attribute Analysis for Non-Proliferation Applications Using Fuzzy Logic. *Transactions of the American Nuclear Society,* 99:205–207.
6. Skutnik, S., J. Li, M.-S. Yim, and D. McNelis. 2009. Evaluating Proliferation Resistance and Security Needs of Nuclear Fuel Cycle Technologies Through a Fuzzy-Logic Barrier Model, *Proceedings of the INMM 50th Annual Meeting.*
7. TOPS Task Force. 2001. Technological Opportunities to Increase the Proliferation Resistance of Global Civillian Nuclear Power Systems (TOPS). Technical report, Nuclear Energy Research Advisory Committee (NERAC).
8. Skutnik, S.E., and M.-S. Yim. 2011. Assessment of Fuel Cycle Proliferation Resistance Dynamics Using Coupled Isotopic Characterization. *Nuclear Engineering and Design.* (Article in press).
9. Oak Ridge National Laboratory. 2009. *SCALE: A Modular Code System for Performing Standardized Computer Analyses for Licensing Evaluations,* ORNL/TM-2005/39, Version 6.0, Vols. I-III edition, January 2009.
10. Skutnik, S.E., and I. C. Gauld. 2009. OASIS: A Simplified User Interface for Advanced Fuel Cycle Analysis in SCALE. *Transactions of the American Nuclear Society,* 101:243–244.
11. Nuclear Energy Agency (NEA). 2006. *Advanced Nuclear Fuel Cycles and Radioactive Waste Management,* Organization for Economic Cooperation and Development (OECD), NEA no. 5990.
12. Bathke, C. G., B. B. Ebbinghaus, B. W. Sleaford, B. Collins, K. R. Hase, K. S. Bradley, J. R. Ireland, A. W. Prichard, M. Robel, G. D. Jarvinen, B. W. Smith, R. Wallace, and M. W. Johnson. 2009. An Assessment of the Attractiveness of Material Associated with a MOX Fuel Cycle from a Safeguards Perspective, *Proceedings of the INMM 50th Annual Meeting.*
13. LANL. *MCNP User's Manual*, la-cp-05-0369 edition, April 2005. Available from Radiation Safety Information Computational Center at Oak Ridge National Laboratory as CCC-74.
14. Charlton, W. S., R. F. LeBouf, C. Beard, S. Landsberger, and M. Whitaker. 2007. Proliferation Resistance Assessment Methodology for Nuclear Fuel Cycles. *Nuclear Technology*, 157:143–145.
15. Facchinetti, G., R. G. Ricci, and S, Muzzioli. 1998. Note on Ranking Fuzzy Triangular Numbers. *International Journal of Intelligent Systems,* 13:613–122.

Experimental Method for Determining the Attenuation by Aluminum Cascade Pipes in the Presence of UF_6 Gas During Enrichment Measurements

M. L. Lombardi
University of New Mexico and Los Alamos National Laboratory, Los Alamos, New Mexico USA

A. Favalli, K. D. Ianakiev, and C. E. Moss
Los Alamos National Laboratory, Los Alamos, New Mexico USA

Abstract

We previously reported on calculations for a proposed method of determining the thickness of a pipe in a gas centrifuge enrichment plant (GCEP) when an empty pipe measurement is not feasible.[1] This method uses an X-ray tube for transmission measurements and a LaBr3 scintillation detector on the opposite side of the pipe. Two filters, molybdenum (Mo, K-edge 20.0 keV) and palladium (Pd, K-edge 24.35 keV) are used to transform the bremsstrahlung spectra produced by the X-ray tube into more useful spectra each with a sharp peak. The maximum energies of the peaks are determined by the K-edges of the filters. The attenuation properties of the UF_6 allow us to determine wall thickness by looking at the ratio of selected regions of interest (ROIs) of the Mo and Pd transmitted spectra. Feasibility studies were performed using analytical calculations, and filter thicknesses were optimized. In order to experimentally validate our attenuation measurement method a UF_6 source with variable enrichment and pipe thickness was built. We describe the experimental procedure used to verify our previous calculations and present recent results.

Introduction

Gas centrifuge enrichment plants (GCEPs) are a common, relatively economical method for enriching uranium to levels suitable for use as fuel in power reactors. However, GCEPs are proliferation concerns because such plants, in addition to producing UF_6 at enrichments useful for power production, could also be used to enrich the UF_6 to the much higher levels needed for nuclear weapons production. Enrichment to a higher level can be accomplished with little to no modification of the process being used. Therefore, enrichment monitoring is a necessary technology that has been used for many years and is currently being improved.

Traditional enrichment measurement methods, such as the continuous enrichment monitor (CEMO),[2] use a radionuclide source such as ^{109}Cd or ^{57}Co. These systems rely on passive measurement of the 186-keV gamma-rays from ^{235}U to measure enrichment, and a transmission measurement to determine the gas density. The ratio of ^{235}U (measured by the number of 186-keV counts) to the total U gives the enrichment.[3] A fairly low energy source is needed so that attenuation in the gas can be measured.

Using an X-ray tube as a transmission source for UF_6 gas enrichment monitoring eliminates the costly requirement of replacing the traditional gamma-ray source after it decays. Typically the source itself must be replaced every two to four years. An X-ray tube does not need to be replaced because the expected lifetime is many years. In addition, it can be turned off for system maintenance and no source handling is required.

Pipe Wall Thickness Concerns

In an operating enrichment facility, it is often not feasible to directly measure an empty pipe in order to calibrate for pipe thickness, as was possible with the Blend Down Monitoring System (BDMS).[4] With the CEMO method, an empty pipe calibration needs to be performed periodically in a laboratory, with a pipe of similar composition to the one being measured in the facility.[2] Depending on the enrichment and pressure of the gas in the pipe, small variations in pipe thickness could easily cause the measured enrichment to fall outside of the acceptable range. The calibration error caused by differences in the wall thickness between the calibration and facility pipe was analyzed in detail and reported previously.[5, 6] Continuous, unattended monitoring is also desired. For these reasons, a method of determining the pipe-wall thickness while the UF_6 gas is inside is needed. Once the pipe thickness is known, the gas pressure can be determined with another transmission measurement. Since the attenuation in the aluminum pipe is much greater than in the gas, small differences in pipe thickness from facility to facility or even pipe to pipe will greatly affect the UF_6 gas density results.

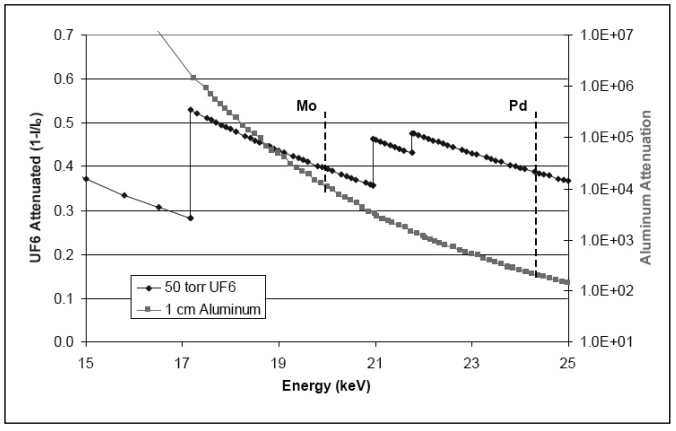
We use the following formula to determine the enrichment of the UF_6 gas:[7]

$$E = K \cdot \frac{I_{186}}{\ln\left(I/I_0\right)}\% \qquad (1)$$

Where I_{186} is the intensity of the 186-keV peak acquired by a passive measurement, and I and I_0 are obtained by transmission measurements, with and without attenuation by the UF_6 gas. K is a calibration constant. Traditionally, an empty-pipe measurement was used to determine the attenuation by the pipe without any gas present (I_0). Another option is to use a facility declaration of the gas pressure. Since the purpose of enrichment monitoring is to detect facilities that are trying to hide improper use, facility declarations may not be trustworthy. Therefore, we propose a two-energy X-ray transmission method for pipe thickness determination in those cases where empty-pipe measurements are not feasible.

We perform two transmission measurements of the header pipe at energies with closely matched attenuation in the UF_6 gas. Looking at the ratio of these two transmitted spectra will enable us to determine the attenuation in the aluminum pipe because the attenuation in the gas should cancel out. This is possible because we select two transmission energies in the uranium L-edge region, as shown in Figure 1. While the attenuation factor in the UF_6 gas is nearly equal, the aluminum pipe wall attenuation varies by a factor of about 50.

Figure 1. Attenuation as a function of energy in UF_6 gas and the Al pipe.



Notch Filter Material Selection

One advantage of using an X-ray tube with notch filters is that this method allows for flexibility in selecting transmission energies. Traditionally, the 22-keV silver X-ray from a decaying ^{109}Cd source was used to measure attenuation in the UF_6 gas. There are not many available choices that have both an optimum energy and a long enough half-life to be useful. With the X-ray method, a wide range of transmission peak energies is available. However, there is a trade-off between attenuation in the gas and attenuation in the pipe, which is large for such low energies. For the transmission measurement that determines the UF_6 gas density, we have attempted to maximize the attenuation in the gas and minimize the attenuation in the pipe. We use the highest energy possible that will still give acceptable attenuation results in the gas. For the pipe thickness measurement, however, it is more important to be able to cancel out attenuation in the gas, using the two-measurement technique described previously. Because this is a one-time measurement to characterize the pipe before a series of relatively short monitoring enrichment measurements are performed, longer count times are acceptable, allowing lower energies to be used.

Table 1 shows a number of options for X-ray transmission notch filter materials compared with two traditionally used radioisotopes. This table compares some of the data previously presented,[5] with a new material, Mo. The table also includes K-edge energies of the various materials, and attenuations in 5-mm wall thickness Al pipe. Also shown are attenuations in 10-cm of UF_6 gas at 50 Torr (typical of a downstream pipe header) and at 5 Torr (typical of an upstream header before a pump). We also explored Zr (K-edge 18-keV) because of its similar attenuation in UF_6 to Ru, but the attenuation in the aluminum pipe would have been impractically large. It is important to note the similar attenuation of Mo and Pd in the UF_6 gas, both at 5 and 50 Torr. Because of these properties, we selected Mo and Pd as our two notch filter materials. All further discussions will focus on these two materials.

Experimental Setup

Notch Filters

We fabricated the filters, shown in Figure 2a, by cutting the 0.1-mm thick sheets into 32-mm squares and affixing them to aluminum rings which can be mounted directly above the flux monitor for the X-ray beam. This mounting is shown in Figure 2b, with a close-up of the flux monitor diode in Figure 2c. The X-ray tube is mounted on the other side of the steel circular plate seen in Figure 2b, with a hole through the middle ensuring all of the beam hits the filter and is directed through the flux monitor.

Figure 2a. Some of the notch filters attached to their mounting rings
Figure 2b. A filter in place. Next, the flux monitor mounting will be screwed in, fixing the entire setup.
Figure 2c. Close-up of the flux monitor; this side faces the X-ray tube

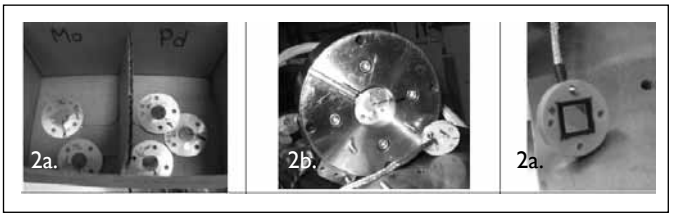
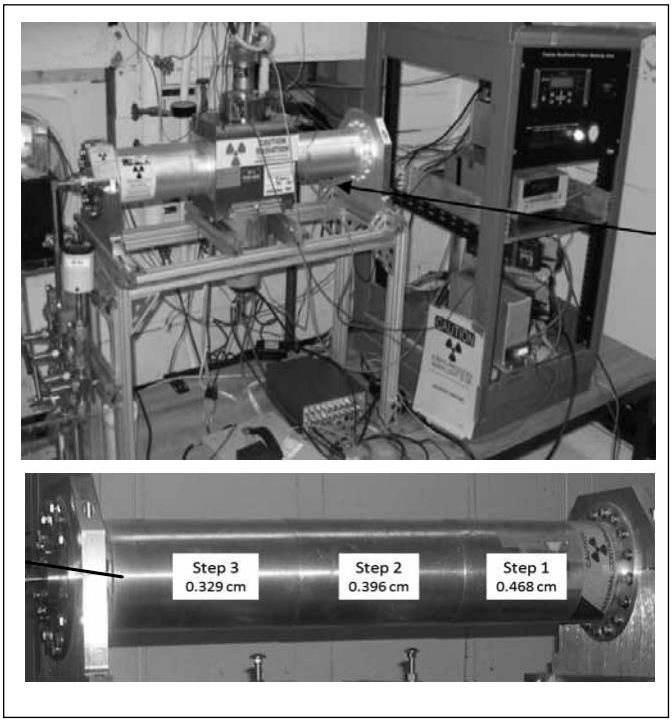


Table 1. Filter selection data

	X-ray Filter		Isotopic Source	X-ray Filter				Isotopic Source
	Mo	Ru	Cd-109	Pd	Ag	Cd	Sn	Am-241
K-edge (keV)	20.00	22.10	22.16	24.40	25.50	26.70	29.20	59.50
Attenuation Factor in Al	12322.2	1085.9	1028.8	198.3	109.5	62.1	26.2	2.13
Attenuation Factor in UF_6, 50 torr	1.63	1.86	1.86	1.63	1.55	1.47	1.36	1.05
Attenuation Factor in UF_6, 5 torr	1.05	1.06	1.06	1.05	1.04	1.04	1.03	1.005

The thicknesses used for testing were 0.3, 0.4, and 0.5 mm of each notch filter material. Analytical calculations indicate that the optimum thicknesses of both Mo and Pd for this experiment are between 0.4 and 0.5 mm. Figure 3 shows the complete experimental setup, with a close-up of the pipe with three wall thicknesses.

Figure 3. Our laboratory UF_6 source. This source has three different pipe wall thicknesses and allows variable UF_6 gas pressure and enrichment.



Low Dead-Time Spectrometer

For these measurements, we used a planar ½-inch thick by three-inch diameter lanthanum bromide (LaBr3) spectrometer. This detector is capable of handling the higher dead times that we anticipate when performing attenuation measurements comparing spectra with molybdenum and palladium filters. We also used a Canberra's Lynx digital signal analyzer to further help with the possible high dead times that we may encounter.

In order to be able to accurately compare spectra taken with different notch filters, we use the same X-ray tube high voltage and beam current. Because of the low count rates seen in the transmission peak when using the Mo filters, tube settings were optimized for molybdenum while attempting not to adversely affect the Pd spectra. We found that as long as the cutoff voltage of the X-ray tube was kept above the K-edge of the notch filter, the width of the peak is not affected. Since the tube settings were optimized to get a reasonable count rate with the Mo filter, some higher count rates were seen with the Pd filter using the same settings. The $LaBr_3$ detector was easily able to handle all observed count rates.

Analytical Analysis

Figure 1 shows that the attenuation in the pipe walls as a function of energy drops much more steeply than the attenuation in the UF_6 gas. The energies near the Mo and Pd K-edges have almost equal attenuation in the gas, but the attenuation differs by a factor of about 50 in aluminum. For this reason, the thickness of the pipe must be known very precisely in order to calculate the gas density, and from this, the enrichment. The following error propagation analysis provides the precision needed in the pipe thickness measurement in order to end up with an accurate enrichment measurement.

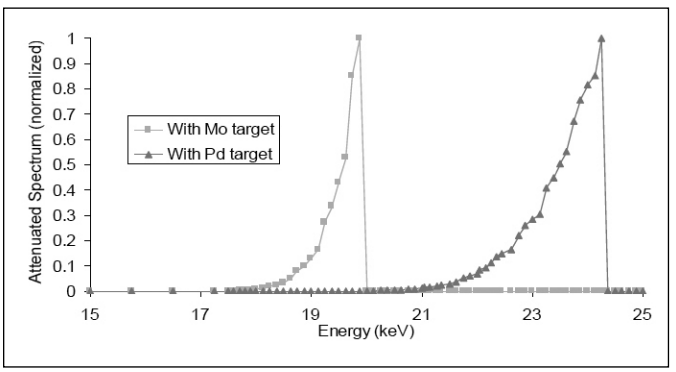
We use the following analytical formula to determine the transmitted spectra:

$$I_0(E) = k \cdot \left(\frac{E_c}{E} - 1\right)^{n} \cdot \exp\left[-\mu_{filter}(E) \cdot \rho_{filter} \cdot d_{filter}\right] \cdot \exp\left[-\mu_{Al}(E) \cdot \rho_{Al} \cdot d_{Al}\right] \cdot \exp\left[-\mu_{UF6}(E) \cdot \rho_{UF6} \cdot d_{UF6}\right] \quad (2)$$

Where k is a scaling constant, E_c is the cutoff energy (determined by the high voltage), n is an empirical coefficient depending on the anode material, and $\mu(E)$, ρ, and d are the mass attenuation coefficient, density, and thickness, respectively. This equation is the energy-dependent bremsstrahlung yield of the x-ray tube[8] multiplied by the exponential attenuation in the notch filters, the aluminum pipe, and the UF_6 gas.

Figure 4 illustrates the spectra as calculated from Equation 2, on a normalized scale. The ratio of these transmitted spectra is used to determine the pipe-wall thickness, since the gas attenuation factors cancel. We can adjust the average energy of the peaks by varying the filter thicknesses.

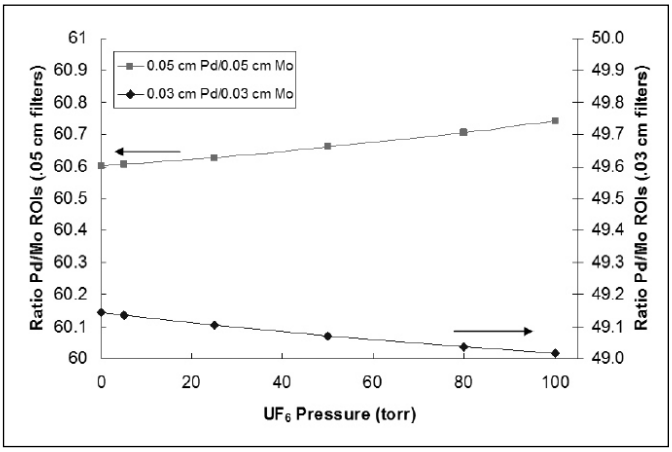
Figure 4. Transmitted spectra, as calculated in Equation 2, with filter thicknesses of 0.05 cm



In the ratio of the two transmitted spectra (one with each filter), the gas attenuation factors should cancel. The ratio of Equation (2) with Pd and Mo is simplified to one without the gas attenuation term. Because we selected the filter thicknesses and the operating voltage of the X-ray tube, we can solve for the attenuation in the aluminum, thereby determining the thickness of the pipe. To perform this calculation we looked at a pre-selected region of interest (ROI) for each spectrum. Figure 5 demonstrates two examples of ratios of these ROIs, as a function of gas pressure.

A slope of zero in Figure 5 would indicate a combination of Mo and Pd filter thicknesses with results that are independent of UF_6 gas pressure. Because the lines for the two thicknesses used have opposite slopes, there is an optimum thickness somewhere in between the two shown. For implementation in a facility, we intend to determine the range of filter thicknesses that would

Figure 5. Ratios of the transmitted spectra, as a function of UF_6 gas pressure. The Al pipe wall was 5 mm thick



yield an acceptably low sensitivity to changes in gas pressure. By doing so, we could go into a facility *blind* and calibrate our system on an operational pipe. The factor of 50 to 60 is mostly from the difference in attenuation in the aluminum pipe at the two transmission energies.

Experimental Results

We took a series of measurements, varying a number of factors. We used two different notch filters at each measurement setting; Mo and Pd. Three thicknesses of each filter material were used: 0.3 mm, 0.4 mm, and 0.5 mm. The transmission measurements were performed on three pipe thicknesses, as shown in Figure 3.

With the matrix of measurements described above, we looked at filter thicknesses to find the optimum combination that was most independent of gas pressure. Figure 6 shows the ratios of transmitted Pd/Mo spectra as a function of UF_6 gas pressure, for our three pipe thicknesses. These data were taken with a 0.4 mm thick Pd filter and a 0.3 mm thick Mo filter. The ratio of these transmitted spectra vs. gas pressure has slopes closest to zero over the range of pipe thicknesses for which we tested. The fact that the slope of these lines is very close to zero in all three cases shows that these ratios are largely independent of gas pressure.

With the transmission ratios shown here, we have determined a calibration curve (Figure 7) with which we can measure a transmission ratio on an unknown aluminum pipe thickness and determine its thickness. To do this we simply need to make two measurements on the pipe, one with a 0.3 mm Mo filter and one with a 0.4 mm Pd filter. The thickness of the pipe can then be determined from the ratio of the peaks generated. We have shown that this measurement can be performed for any gas pressure that falls within the expected range of a working header pipe in a GCEP.

The curve was fit to the two outer points taken on steps 1 and 3 of the pipe. Point 2 is superimposed on the fit. Using this fit, we were able to calculate the thickness of step 2 as 0.393 mm. This is less than 1 percent error from the measured thickness of 0.396 mm.

Figure 6. Ratios of transmitted Pd/Mo spectra as a function of UF_6 gas pressure, for three pipe thicknesses

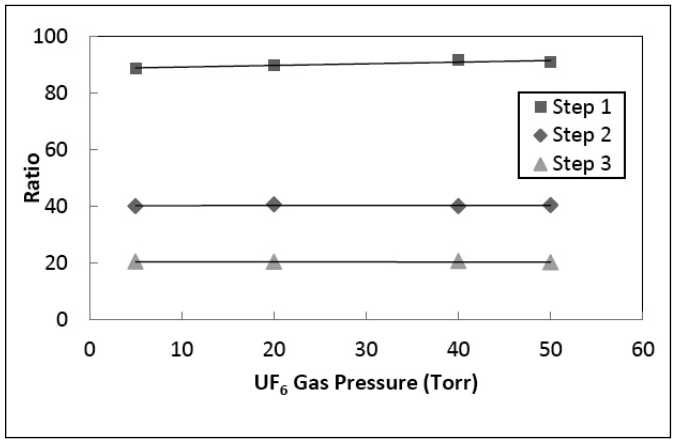
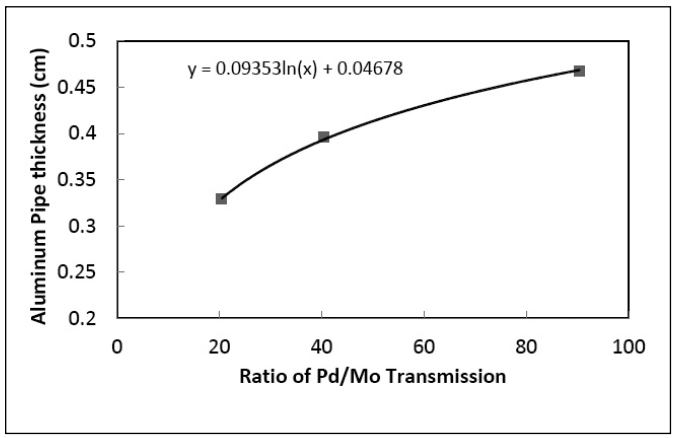


Figure 7. Pipe thickness calibration curve. With a measured transmission ratio we can use this curve to determine an unknown aluminum pipe thickness. The fit shown is based on the outer two points only.

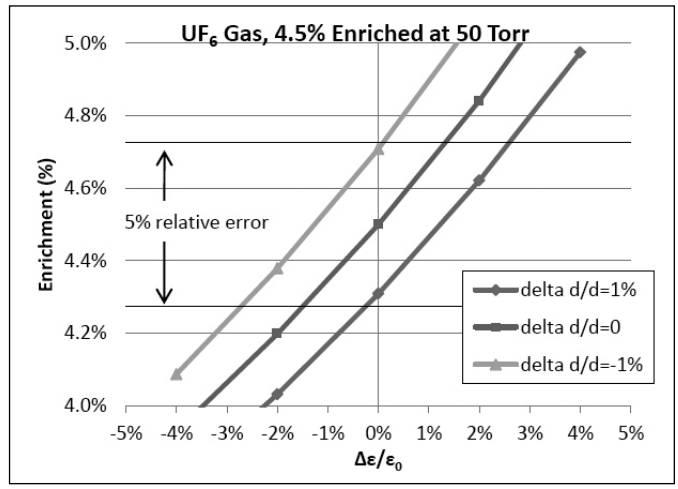


Error Analysis

The following error analysis examines the effect of our measured 1 percent error in wall thickness on the feasibility of keeping the enrichment measurement within the 5 percent relative error limit set by nuclear safeguards mass balance requirements.

The previously reported CEMO calibration is based on an initial laboratory calibration with the same type of pipe as the one in the GCEP.[2] While the composition of the pipe material is kept within very tight tolerances, the pipe geometry may differ significantly due to the extrusion manufacturing process. For instance, a typical pipe with a 100-mm inside diameter (ID) and 4-mm wall thickness has a +/-0.4 mm tolerance on the wall thickness. Because the attenuation in the pipe is much higher than attenuation in the UF_6 gas, any difference in the pipe thickness between the calibration pipe and header pipe in the plant could lead to a significant calibration error. Using an analysis similar to the analysis for the transmission error reported previously,[6] we determine the calibration error caused by our measured 1 percent error in the wall thickness. For simplicity, we do not consider errors associated with the statistical and systematic errors of the count rate in the 186-keV and transmission peaks. The enrichment formula including the calibration and instrumental errors has been discussed in great detail previously.[5]

Figure 8. Example of enrichment values calculated as described for UF_6 gas at 4.5 percent enrichment and 50 torr pressure. These values were calculated at a transmission energy of 30 keV.



With our measured 1 percent error in wall thickness, the maximum instrumental error allowable was calculated, in order to keep the enrichment measurement within the 5 percent relative error limit set by mass balance requirements. Figure 8 shows one of the plots used to calculate this error for a transmission energy of 30-keV. The enrichment measurement error is approximately symmetrical for positive and negative errors in pipe thickness measurement.

This calculation was repeated over a range of transmission energies, with the results shown in Figure 9. Note that if the wall thickness error is fixed, as in our case at 1 percent, the maximum allowable instrumentation error decreases with increasing energy.

Finally, we show an enrichment calculation as a function of transmission energy in Figure 10, with the instrumentation error fixed at 1.5 percent and wall thickness error at 1 percent. A notch filter such as Sn, which has a K-edge at 29.2 keV, would be optimal in this case.

Conclusions

This report has described a method for determining cascade header pipe thickness with an enrichment monitor based on an X-ray source and a LaBr3 detector. The various possible X-ray filters and isotopic sources were reviewed, and molybdenum and palladium were chosen based on initial analytical calculations. These analytical calculations showed that the ratio of transmitted spectra should be completely independent of UF_6 gas pressure when the notch filter thicknesses are optimized.

Figure 9. Calculated values of the maximum allowable instrumentation error vs. energy, for the enrichment result to be correct within 5 percent. This is for a fixed error in wall thickness of 1 percent.

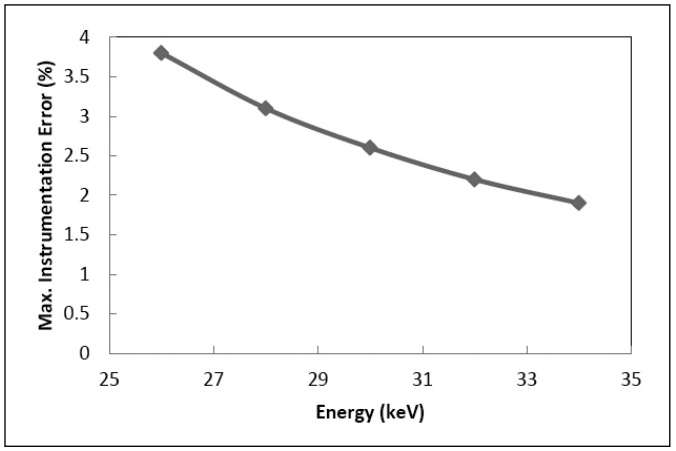
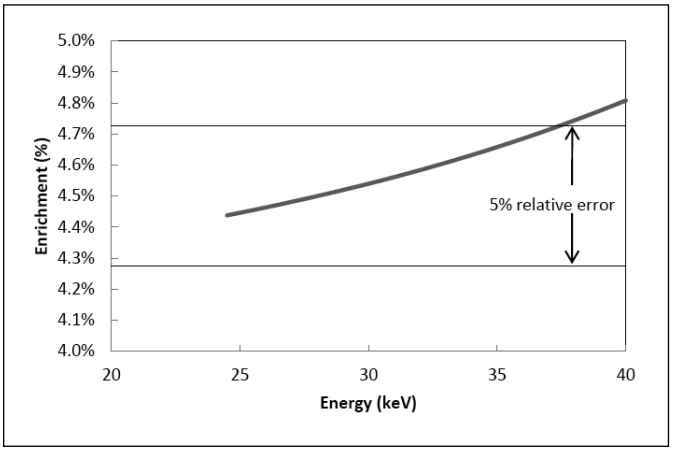


Figure 10. Enrichment calculation as a function of transmission peak energy, including the combined error factor described in the error analysis section



We determined that a combination of 0.4 mm Pd and 0.3 mm Mo notch filters gave the ratio of transmission spectra that was most independent of UF_6 pressure in the pipe. Using these notch filters, we were able to create a calibration curve using our UF_6 source with three pipe thicknesses. This curve allows us to determine pipe thickness simply by measuring the ratio of two transmission measurements. This one-time measurement could be completed in less than an hour, and once the calibration has been performed for a specific measurement location it is not necessary to ever perform it again.

Once the pipe thickness is determined, we can switch to an unattended mode of operation, with a transmission energy selected to maximize transmission through the pipe but still have measureable attenuation in the gas. Then we simply need a single transmission measurement to determine the gas density. We intend to make more measurements with additional pieces of aluminum pipe to verify that the thickness determination method works for other "unknown" thicknesses.

Acknowledgments

This work was supported by the U.S. Department of Energy National Nuclear Security Administration Office for Nonproliferation Research and Development (NA-22).

References

1. Lombardi, M. L., J. M. Goda, K. D. Ianakiev, and C. E. Moss. 2010. Determining the Thickness of Aluminum Cascade Pipes in the Presence of UF_6 Gas, *Proceedings of the INMM 51st Annual Meeting.*
2. Packer, T. W., and M. R. Wormald. 1994. Continuous Monitoring of Variations in the 235U Enrichment of Uranium in the Header Pipework of a Centrifuge Enrichment Plant, report, SRDR-R221 UK A00623.
3. Kerr, P. L., D. A. Close, W. S. Johnson, R. M. Kandarian, C. E. Moss, and C. D. Romero. 1999. IAEA Verification Experiment at the Portsmouth Gaseous Diffusion Plant: Report on the Cascade Header Enrichment Monitor, LA-13557-MS.
4. Close, D. A., R. E. Anderson, W. S. Johnson Jr., R. M. Kandarian, P. L Kerr, C. E. Moss, C. D. Romero, G. W. Webb, C. R. Whitley, and L. A. Trujillo. 1999. Calibration of the Enrichment Monitor for HEU Transparency, *Proceedings of the Sixth International Meeting on Facilities Operations-Safeguards Interface.*
5. Parker, R. F., T.R. Hill, B.P. Nolen, M.T. Paffett, Martyn T. Swinhoe, B. Boyer, C. E. Moss, K. D. Ianakiev, J. M. Goda, and H. Nguyen. 2009. Progress in Development of an Advanced Enrichment Monitor Based on Transmission Measurements with an X-ray Source and NaI(Tl) Spectrometer, *Proceedings of the INMM 50th Annual Meeting.*
6. MacArthur, D. W., B. Boyer, G.A. Sheppard, M. T. Swinhoe, T. Hill, C. E. Moss, K. D. Ianakiev, T. Marks, B. S. Alexandrov. 2008. New Generation Enrichment Monitoring Technology for Gas Centrifuge Enrichment Plants, *Proceedings of the INMM 49th Annual Meeting.*
7. Reilly, D., N. Ensslin, H. Smith, Jr., and S. Kreiner. 1991. Passive Nondestructive Assay of Nuclear Materials, United States Nuclear Regulatory Commission, Washington, D.C.
8. McCall, G. H. 1982. Calculation of X-ray Bremsstrahlung and Characteristic Line Emission Produced by a Maxwellian Electron Distribution, *Journal of Physics D: Applied Physics*, 15, 823.

Experimental Investigation of Temperature Effects on Radiation Portal Monitor Performance

David A. Addington, Jr. and Man-Sung Yim
North Carolina State University, Raleigh, North Carolina USA

Kenneth G. Baird III and Peter J. Chiaro, Jr.
Oak Ridge National Laboratory, Oak Ridge, Tennessee USA

Abstract

Radiation portal monitor (RPM) systems are deployed around the world in order to help detect and deter the movement of illicit nuclear material. Because these systems are often deployed in remote locations or on borders, they are exposed to and must tolerate a wide range of ambient temperature. Therefore, discovering temperature dependent behavior in RPM-type detectors is increasingly important as more systems are deployed and the global political climate places a premium on ensuring that illicit trafficking of special nuclear material (SNM) and other radioactive material is detected.

In this paper, results from an experimental investigation of the temperature dependence of two RPM detectors' behavior are presented. Four hypotheses are examined, and a discussion of the results is included as well. The results presented in this paper demonstrate that the root cause of these detectors' temperature dependence is the photomultiplier tubes. Furthermore, the results provide evidence that dark current formation in the photomultiplier tubes significantly impacts the background count rate of detectors, which in turn decreases the detectors sensitivity to low energy gamma sources such as SNM.

Introduction

Understanding the effects of environmental factors on the performance of radiation detectors is critical to an analysis of detector effectiveness. One example of the importance of this understanding is in the deployment of radiation portal monitor (RPM) systems. RPM systems are deployed in remote locations around the world in unprotected environments. The components of these systems must withstand extreme variations in ambient temperature without compromise to, or degradation of, detection capability.[1] Given the harsh climates endured by RPMs and other radiation detectors, it is desirable to understand how they respond to their environments.

Identifying potential shortcomings in performance due to temperature would aid in the prediction of detector vulnerabilities and provide recommendations for circumventing the vulnerabilities. The experimental portions of this study have focused on RPM systems because of their increased deployment in various climates. Collaboration with Oak Ridge National Laboratory (ORNL) and the use of their climate chambers have made testing the temperature effects on performance of these systems possible. The experiments to be performed include efficiency measurements and spectrum analysis during temperature cycles typical of American National Standards Institute (ANSI) testing.[2] The experiments seek to uncover any temperature dependence in the RPM's performance and to examine the specific components responsible for any change in detector performance. This study will use results from the experiments involving RPMs to augment the existing understanding of performance degradation in radiation detectors due to temperature.

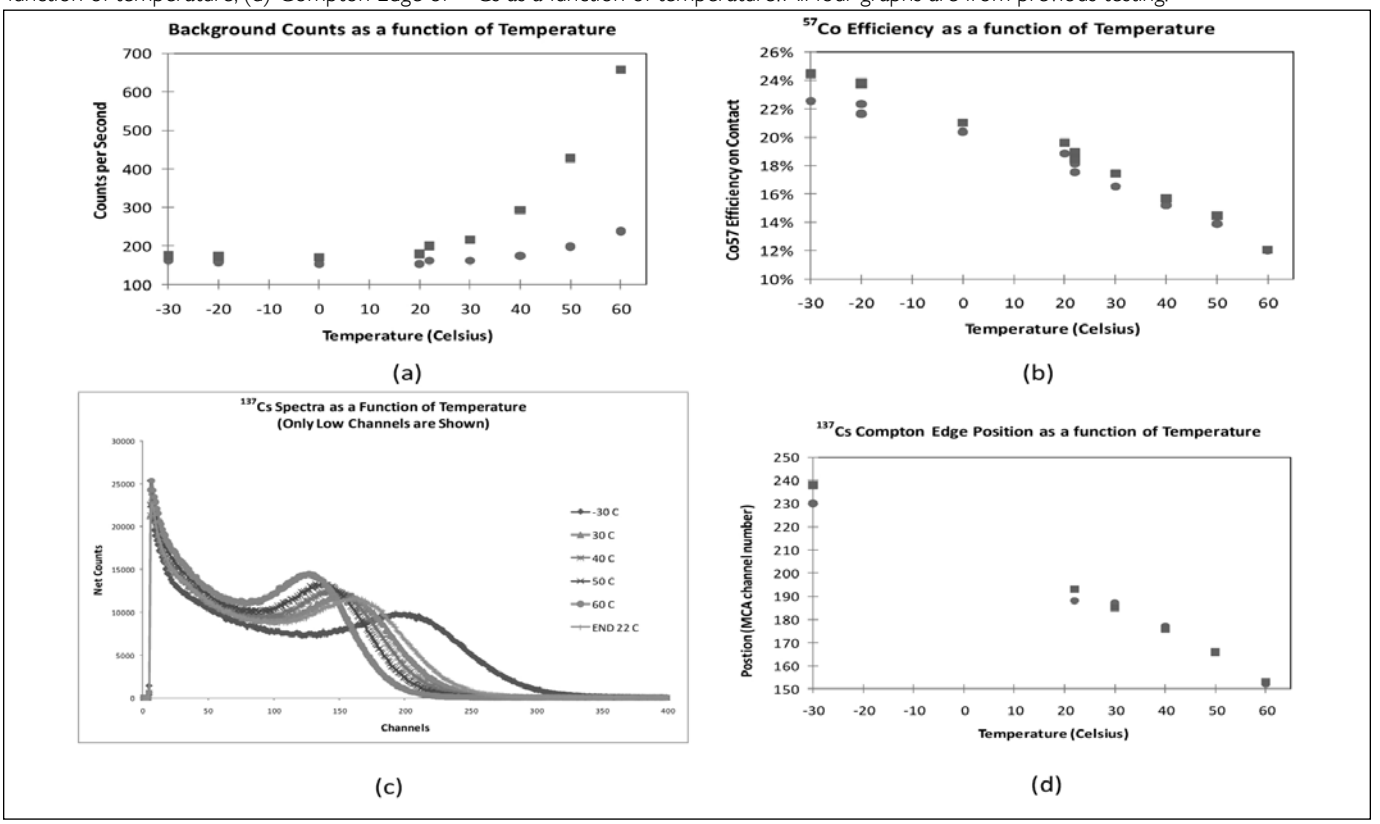
This paper hopes to provide important insights for deployment of RPM type detectors in nuclear security applications. Specifically, it is hoped that this study will explain how detector performance is affected by temperature, elucidate potential shortcomings in performance that are attributable to this temperature dependence, and provide suggestions for identifying and minimizing the temperature dependence.

Relevant Testing Previously Performed

Previous temperature tests involving RPM systems that were performed at Oak Ridge National Laboratory (ORNL) have shown that the background count rate increases with temperature, and that both the ^{57}Co efficiency and the gain of the detector are temperature dependent.[3] The temperature dependence of the efficiency was shown by repeated efficiency measurements at 10°C steps during a temperature cycle ranging from -30°C to 60°C. Similarly, the temperature dependent gain shifts were measured by examining the position of the Compton edge of ^{137}Cs using a multi-channel analyzer at -30°C and also at 10°C steps from 20°C to 60°C. Figure 1 highlights the temperature dependence seen in this previous round of tests at ORNL.

Clearly, the results in Figure 1 (a) show an increase in the background count rate as the temperature increases. In addition, Figure 1 (b) shows that the sensitivity to ^{57}Co decreases as the temperature increases, which implies that the efficiency is a func-

Figure 1. (a) Background count rate as function of temperature, (b) ^{57}Co Efficiency as a function of temperature, (c) ^{137}Cs Spectra as a function of temperature, (d) Compton Edge of ^{137}Cs as a function of temperature. All four graphs are from previous testing.[3]



tion of temperature. Figure 1 (c) and (d) show the temperature dependence of the Compton edge of ^{137}Cs. As the temperature is increased from 22°C, the Compton edge of the spectrum is shifted to the left of the 22°C position, but the -30°C spectrum, and thus the Compton edge, is shifted to the right of the 22°C position. These shifts demonstrate that the gain decreases as the temperature increases.

Thus the results in Figure 1 clearly show that the performance of the RPM system tested is temperature dependent. Further investigations are warranted to determine the root causes of the observed performance change.

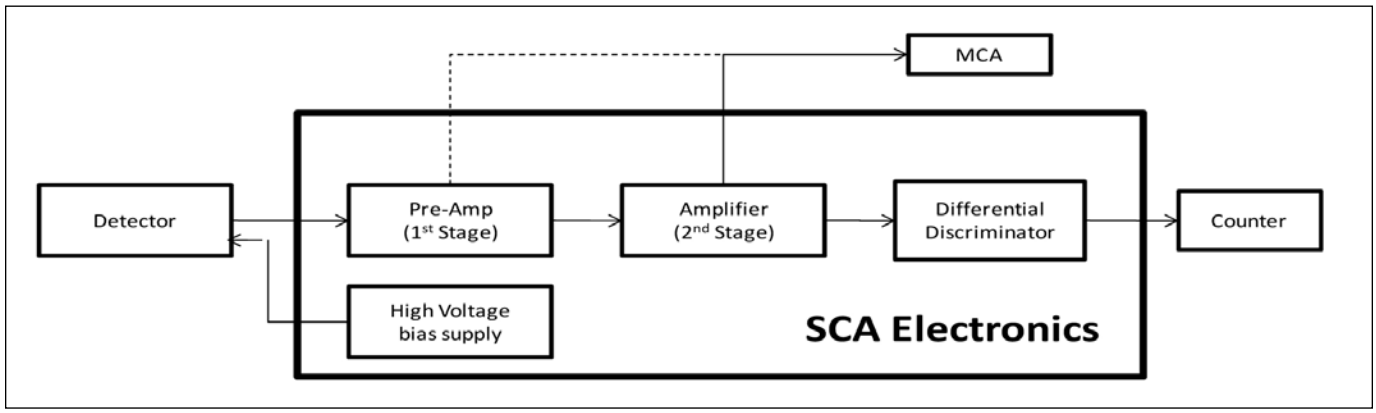
Experimental Setup

In the experiments presented in this paper, two gamma detectors—each having a photomultiplier tube (PMT) and coupled polyvinyl toluene (PVT) plastic scintillator—were tested for temperature dependence in the range of 22°C to 50°C. These gamma detectors were taken from a currently deployed RPM system and were powered using electronic components supplied by the manufacturer of the RPM system. The voltage pulses from the detectors were analyzed by the manufacturer's specific single-channel analyzer (SCA) and a generic multi-channel analyzer (MCA). The manufacturer's SCA provided the high voltage bias to both gamma detectors tested, as well as the dual operational amplifier and dual comparator needed to perform typical SCA functions. During operation, the HV setting controls the pulse height coming from the PMT, which is input to a fixed gain pre-amplifier (first stage). The signal then feeds into a fixed gain amplifier (second stage) that attenuates the curve to provide the final pulse shape. The pulse is then sent to a differential discriminator. If the peak pulse amplitude falls between the lower-level discriminator (LLD) and upper-level discriminator (ULD), then a logic pulse is sent from the SCA to a separate component where the logic pulses are counted. The output from the counter was displayed and recorded in counts per second format. A simplified detector setup is shown in Figure 2.

The discriminator window for the SCA used was set to correspond to energies between 22 keV and 144 keV, and a Tukan 8k MCA with resolution set to 1,024 channels served as the MCA for spectrum collection. A Russell's model RD-125-605-605-AC environmental chamber at ORNL provided temperature control for these experiments. The interior dimensions of the chamber are 5 feet x 5 feet x 5 feet allowing the gamma detectors to be placed inside the chamber in a horizontal configuration.

A wall penetration was used to pass Bayonet Neill-Concelman (BNC) and miniature high voltage (MHV) cables from the PMT to the pre-amplifier and high voltage supply respec-

Figure 2. Simplified signal chain for the gamma detectors used during these experiments. This chain was modified for some experiments in order to allow spectrum collection from the Pre-Amp using the MCA.



tively for experiments conducted with the electronics placed outside the chamber. When the electronics were placed inside the chamber, the same wall penetration was used to pass data collection cables from the electronics to a laptop placed outside the chamber. Any components outside the chamber were maintained at room temperature regardless of the temperature inside the chamber, while all components inside the chamber experienced the controlled environment set by the chamber's temperature profile.

Experimental Procedure

The testing phase began by placing the two gamma detectors inside the environmental chamber, with all other components outside of the chamber. With the temperature held at 22°C, the detectors were calibrated as specified by the manufacturer. After calibration the detectors' sensitivity to ^{57}Co was examined by taking efficiency measurements. The results of these measurements are shown in Table 1.

Table 1. Measured ^{57}Co efficiencies (at 22°C) for the two gamma detectors prior to testing

^{57}Co Source Activity		
3.44 E+06 Bq (93 MicroCuries)		Creation Date: 5/1/2005
1.48 E+04 Bq (0.4 MicroCuries)		Test Date: 3/9/2011
Pre-Test Gamma Detector Efficiency Calculations		
Detector	Net Gamma CPS	Detector Efficiency
1	2201	29.8%
2	2056	27.8%

Following the initial calibration, the detectors were examined during a series of temperature cycles. Each temperature cycle followed a simple profile that was based on the following:

Hold at room temperature (20°C) for two hours
Raise by 10°C/hr to +30°C and hold for 1 hour
Raise by 10°C/hr to +40°C and hold for 1 hour
Raise by 10°C/hr to +50°C and hold for 2 hours
Lower by 10°C/hr to +40°C and hold for 1 hour
Lower by 10°C/hr to +30°C and hold for 1 hour
Lower by 10°C/hr to +20°C and hold indefinitely

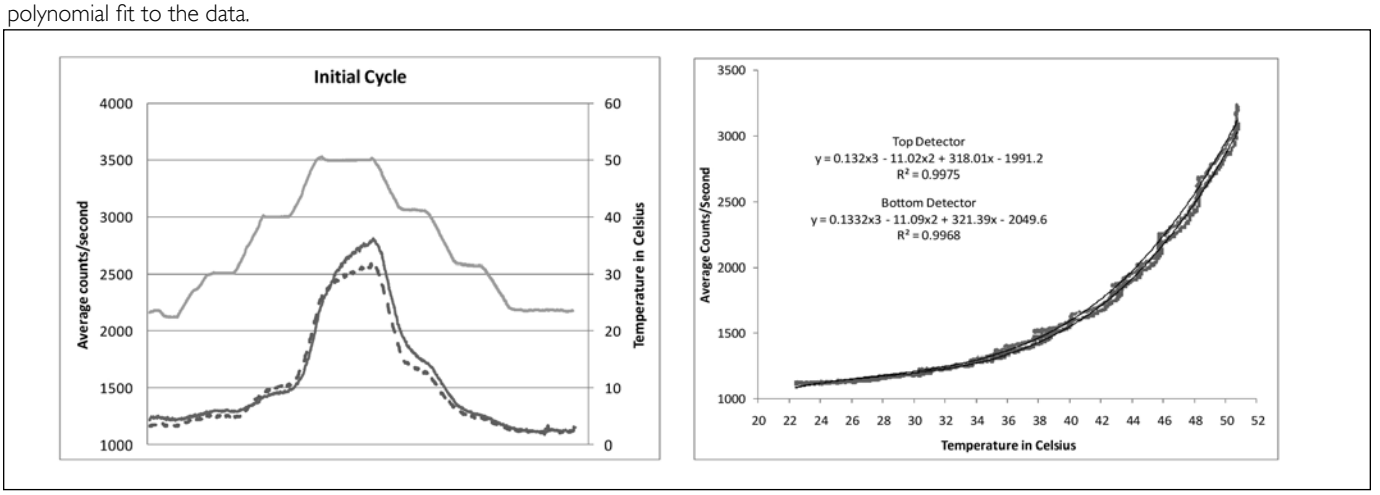
For a subset of the temperature cycles, the end of this profile was modified to include a ramp to 50°C followed by a hold at 50°C so that measurements could be retaken while the temperature was holding at 50°C.

During the temperature cycles, the gamma background count rate was logged in order to expose any temperature dependence in the detectors' reported background measurements. This experiment was repeated multiple times while examining the effect that changing high voltage settings, replacing system components, and exposing other system components to the cycling temperature had on any temperature dependence in the background count rate. In addition, background spectra were collected at 20°C, 50°C, and at thirty-minute intervals during a subset of the experiments. The spectra collected provide supplemental data not typically recorded for gross-count detector systems that help to further identify and examine any temperature dependent behavior. In order to identify any temperature dependent behavior in the detectors, and to examine the contribution of individual system components to this behavior, the following hypotheses were tested:

1. The detectors evaluated exhibit temperature dependent behavior.
2. The specific SCA chosen was not the cause of the temperature dependent behavior.
3. The high voltage bias is a determining factor in whether the detector exhibits temperature dependent behavior.
4. The PMT is the system component that determines the temperature dependence of the detector.

The first hypothesis was tested during the first cycle using manufacturer specified settings. The second hypothesis was tested

Figure 3. Average background count rate during the initial temperature cycle. The figure on the left shows both temperature and the background count rates as the cycle progressed. The top "step-like" curve in this figure is the temperature, the other solid curve is the bottom detector, and the dashed line is the top detector. The figure on the right shows the count rates as a function of temperature, and also contains a third order polynomial fit to the data.



by replacing the older manufacturer's SCA used during the initial cycle with a new SCA from the manufacturer. The third hypothesis was tested by raising and lowering the high voltage bias to the detector. The fourth hypothesis was tested by cutting the PVT scintillator off of one of the PMTs and comparing the cut-off PMT's behavior to that of the remaining intact detector.

Experimental Results

Hypothesis 1

The initial test in this experiment examined the gamma background count rate of the two detectors as the temperature cycled from 22°C to 50°C. Figure 3 shows the average background gamma count rate, calculated over successive one minute periods, in counts per second for both gamma detectors during the temperature cycle. These average count rates are referenced to the left vertical axis. Also included in the figure is a plot of the chamber temperature in Celsius during the cycle that is referenced to the right vertical axis. It is clear from the figure that the background count rates show significant temperature dependence, and furthermore the figure shows that as the temperature approaches the maximum cycle temperature of 50°C, this dependence becomes even more dramatic. The statistical significance of this data was tested using a two-way Analysis of Variane (ANOVA) test, which showed with high confidence that the individual detector's count rates were dependent on both the detector characteristics and the temperature.

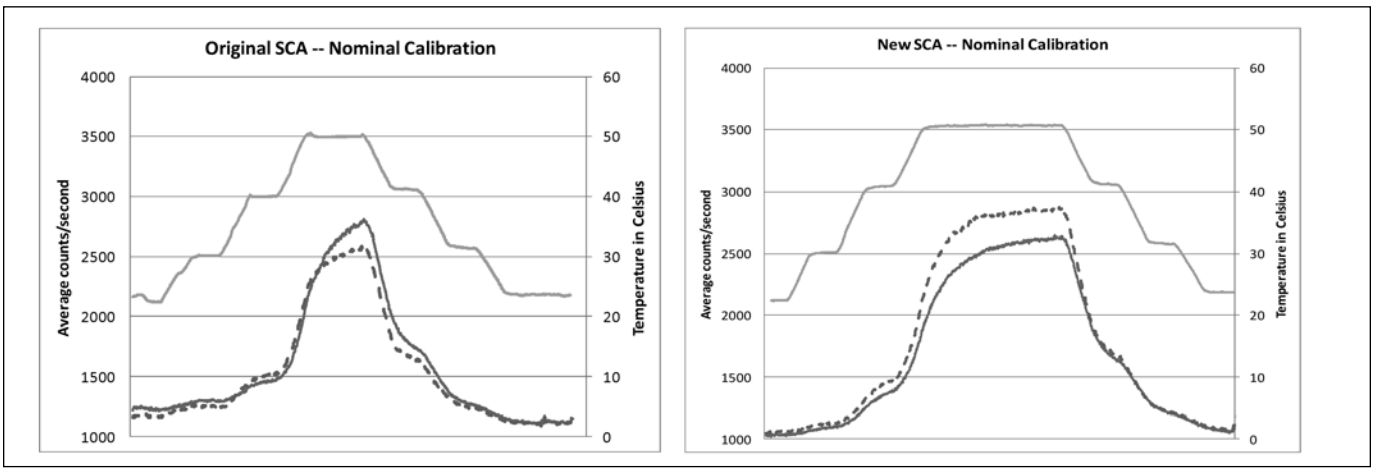
The results from the current experiment and data collected from previous temperature tests performed at ORNL confirm the hypothesis that the RPM's gamma detectors exhibit temperature dependent behavior. The remaining experiments presented in this paper focus on the background count oscillations that occurred during the initial temperature cycle performed and use these oscillations to examine the corresponding hypotheses.

Hypotheses 2

The second hypothesis explores whether the magnitude of the background count oscillations was dependent on the individual SCA provided by the manufacturer and on the temperature dependence of the electronics inside the SCA. To test the hypothesis that the results were not unique to the original SCA, a different SCA unit was used to verify the temperature response seen by the SCA used in the original cycle. Furthermore, in order to test the effect that the ambient temperature experienced by the SCA had on the background count oscillations, this new SCA was placed inside the climate chamber with the detectors. Ideally, this hypothesis should have been tested in two steps: replacing the original SCA for one cycle, and then placing the new SCA inside the chamber for the next cycle. However, due to time constraints these two tests were performed as one. The results from this experiment are shown in Figure 4 and are compared with results from the original cycle.

The results in Figure 4 show that the oscillations are not dependent on the SCA chosen or the ambient temperature it is exposed to. The background count rates for each of these two experiments exhibited similar increases as the temperature increased during each cycle. The variations between the amplitudes of the background count rates for the old and new SCA are due to uncertainties inherent in the calibration procedure. However, the trend of increasing count rate with temperature is the same for both SCAs. Another difference between the two cycles is the temperature profiles themselves. During the study presented in this paper, the decision was made to extend the temperature hold at 50°C three hours longer than originally planned in order to allow the detectors to be closer to thermal equilibrium at 50°C. The result of this extension was that the count rate continued to increase as the temperature held at 50°C, demonstrating that the system had not reached thermal equilibrium at the end of two hours.

Figure 4. Comparison of the oscillation in gamma background count rates for the original and new SCA. The top "steplike" curve in each figure is the temperature, the other solid curve is the bottom detector and the dashed line is the top detector. Note that the hold at 50°C for the New SCA cycle is three hours longer than the original cycle.



Hypothesis 3

Because thermionic emissions in PMTs are typically in the same very-low-energy range that these detectors are optimized for,[4] the increase in count rates with temperature was thought to be a result of thermionic noise in the PMT. Furthermore, the contribution of the thermionic noise is somewhat dependent on the high voltage,[5] so this hypothesis sought to find a high voltage setting that would decrease the magnitude of the thermionic emissions and result in a decrease in the magnitude of the background count rate oscillations. A variety of high voltage settings were tested using the same temperature cycle as the initial nominal calibration test. None of the settings tested resulted in better count rate stability over the temperature range. The results from three test cases are shown in Figure 5: a nominal high voltage setting, a slightly lower than nominal high voltage setting, and a slightly higher than nominal high voltage setting.

The results in Figure 5 show that the two alternative high voltage settings presented did not solve the temperature dependence of the count rate. For each calibration with lower than nominal high voltage, the oscillations became slightly more pronounced, similar to what is seen in Figure 5 for the 970 V setting. In addition, if the high voltage setting was increased enough that peak pulse height of ^{137}Cs as measured by an oscilloscope was greater than 2.0 V, the second stage amplifier and differential discriminator became saturated, which rendered the count rate meaningless. The high voltage setting of 1,101 V which is presented in Figure 5 seemed to have small improvements in one detector's count rate oscillation, but this small improvement was negated by a slight exacerbation of the other detector's oscillation. If time had permitted, the experimenter would like to have explored other high voltage settings that were greater than the nominal high voltage setting but below the settings that resulted in saturation of the second stage and differential discriminator.

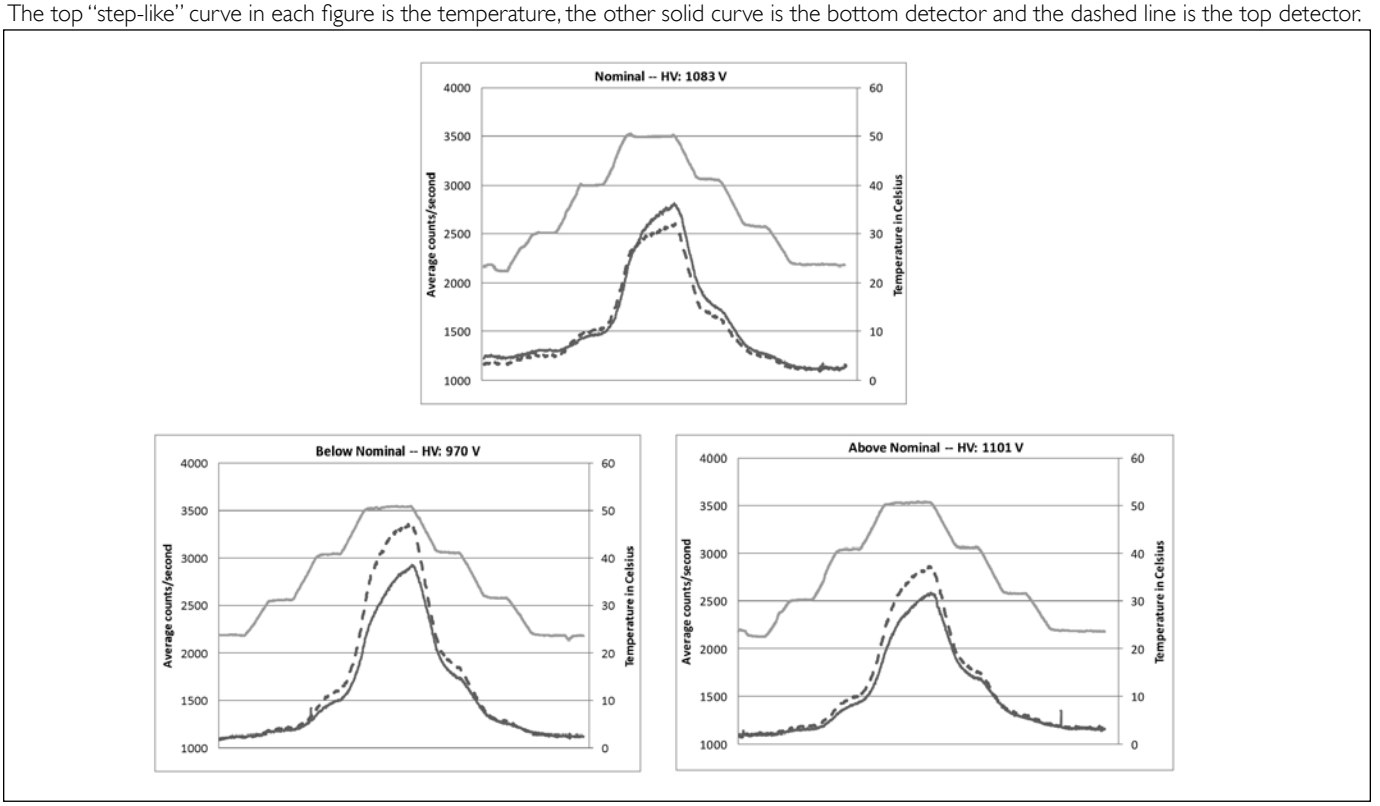
Hypothesis 4

The testing of the previous three hypotheses suggests that the temperature dependent behavior is due to the gamma detectors themselves. Since the detector is made up of two components—a PVT scintillator and a PMT—the fourth hypothesis examines these components individually. In order to test the hypothesis that the PMT was the component responsible for the temperature dependent count rate oscillations, a PMT was cut off of its corresponding PVT scintillator. Both the remaining intact detector and the cut-off PMT were placed in the environmental chamber and cycled through the same temperature profile used in the other tests in this study. Not only was the background count rate recorded during the cycle, but background spectra were collected during the cycle as well. The results from this test are shown in Figure 6. The figure on the left shows the average background count rate recorded from both the intact detector and the cut-off PMT. The figure on the right shows spectra which were collected from the cut-off PMT as the temperature cycled from 22°C to 50°C and then back.

The results in Figure 6 show that the PMT is likely the component that is primarily responsible for the temperature dependence of the gamma detectors. Notice that the background count rate recorded from the cut-off PMT follows the exact trend that the intact detector does.

This behavior demonstrates that the oscillations seen in the background count rate originate in the PMT. Also, the difference between the two curves is relatively constant, which suggests that the scintillator's temperature dependence is minimal compared to that of the PMT. The difference in the amplitude of each curve shows that the scintillator superimposes actual count rates onto the dark current created in the PMT. The result of this additive factor is a higher count rate, but one that follows the same oscillating pattern dictated by the temperature dependence of the PMT.

Figure 5. Comparison of the oscillation in gamma background count rates for nominal, below nominal, and above nominal high voltage settings. The top "step-like" curve in each figure is the temperature, the other solid curve is the bottom detector and the dashed line is the top detector.



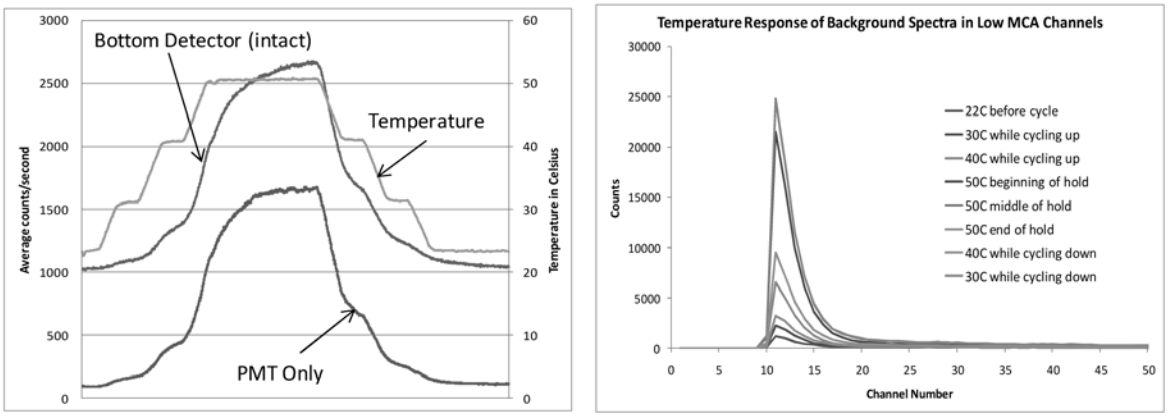
The figure on the right side of Figure 6 shows the background spectra collected from the cut-off PMT. It appears that a misalignment of the MCA's lower level discriminator results in the left-edge of the spectra representing non-physical behavior. Despite this issue, the parts of the spectra that are not affected by the MCA's lower level discriminator still demonstrate some important behaviors. The amplitudes of the spectra show that as the temperature increases, the counts in each spectrum increase, and conversely, the counts in each spectrum decrease again as the temperature returns to room temperature. Furthermore, the increase in the amplitudes of the spectra collected is located in channels corresponding to very-low-energy gamma radiation, suggesting that the counts from the cut-off PMT are dominated by dark current due to thermionic emissions.[4] It is assumed that if the MCA's lower level discriminator were properly aligned that the spectra would show real counts in channels below channel 10. However, the position of the right-edges of the spectra are unaffected by the misalignment, and thus it is not expected that more counts would fall in higher-energy channels. Therefore, the conclusion is that the spectra shapes indicate that the source of the increased count rate is a mechanism consistent with thermionic emissions.

Discussion of Results

The results of this experiment demonstrate the temperature dependence of the detectors used in some RPM systems; specifically, the background count rate in the tested detectors is clearly temperature dependent. An apparent temperature dependence that appeared in each of the tests was the oscillation of the gamma background count rate in each detector. Since many RPM systems employ a gross-count alarm algorithm in which the sensitivity of the detector decreases as the background count is increased, this temperature dependence directly affects the performance of the RPM detectors by making them less sensitive at high temperatures.[6] In addition, the temperature dependence observed in previous experiments would further degrade the detector's overall performance in gamma radiation based detection of SNM at high temperatures.[3]

It is not surprising that the results point to the PMT as the component that drives the oscillations in background counts that were discovered in these experiments, since the temperature dependence of PMTs is a known issue.[4,7,8,9] The increase in spectrum counts in low-energy channels as temperature increases and the increase in count rate with increasing temperature are both consistent with dark current produced by thermionic emission in the PMT.[4] Furthermore, the results from the testing of the fourth hypothesis strongly suggest that the PMT is the primary component responsible for the count rate increases as the temperature increases.

Figure 6. (i) Background count rate for the intact detector and the PMT with no PVT scintillator, (ii) Background spectra as a function of temperature



Conclusions

The results presented in this paper demonstrate that the gross count detectors that are used in many RPM systems exhibit temperature dependent behavior. Furthermore, this paper identifies that the temperature dependence of these RPM systems exists in the coupled PMT and PVT scintillator detectors and is not significantly influenced by the temperature dependence of the other electrical components of the RPM system. It is clear from the results presented that the oscillations in count rates that have been observed are driven by the temperature dependence of the PMT. As the temperature of the PMT increases, the dark current created in the PMT begins to drive the count rate up. The result is a false elevation of the gamma background counts and thus an increase in the source activity needed to create an alarm. Combined with the temperature dependent decrease in sensitivity to low-energy gammas such as ^{57}Co,[3] the increase in the background count rate leads to decreased performance in the detection of SNM.

Therefore, this study provides justification for the continued exploration of the temperature dependence of the detectors' behavior. Important questions that should be asked in future investigations include: Operationally, why do some detectors exhibit significant temperature dependence, while others do not? Can the background count oscillations be induced in detectors that previously did not show evidence of count rate oscillations? Are there any settings not explored in this study that can alleviate the oscillations in detectors that do exhibit this behavior?

Until the answers to these questions can be addressed, a temporary solution to the temperature dependence is to minimize the maximum temperature experienced by the detectors, particularly the PMT. The implementation of this solution can be as simple as providing shade to the RPM systems. By limiting direct exposure to sunlight the amount of solar heating can be minimized. A more complex solution involves active cooling systems, similar to those used in many high resolution detectors,[4] which can keep the detector at a low temperature regardless of the environmental temperature.

While this study focuses on RPM systems, the results identify temperature dependent behaviors of the gamma detectors used in these and other systems. Therefore, the results and conclusions presented in this paper are applicable to many other gross-count detector systems that employ similar detection schemes.

References

1. Siciliano, E. R., J. H. Ely, R. T. Kouzes, B. D. Milbrath, J. E. Schweppe, and D. C. Stromswold. 2005. Comparison of PVT and NaI(Tl) Scintillators for Vehicle Portal Monitor Applications, *Nuclear Instruments and Methods in Physics Research A,* 550: 647-648.
2. ANSI N42.35. American National Standard for Evaluation and Performance of Radiation Detection Portal Monitors for Use in Homeland Security.
3. Addington, D., K. Baird, and P. Chiaro. 2011. Temperature Test Report for a Pedestrian Radiation Portal Monitor used in Nuclear Security Applications (OUO), ORNL/TM-2011/128. Report is in final stages of editing.
4. Knoll, G. F. 2002. *Radiation Detection and Measurement* (Third Edition), Wiley, New York.
5. Hamamatsu Photonics K. K. 2006.Photomultiplier Tubes: Basics and Applications (Third Edition), Electron Tube Division, 67-72.
6. Ely, J. H., R. T. Kouzes, J. E. Schweppe, E. R. Siciliano, D. Strachan, and D.R. Weier. 2005. The Use of Energy Win-Dowing to Discriminate SNM from NORM in Radiation Portal Monitors, *Nuclear Instruments and Methods in Physics Research A* 560: 373-387.

7. Ball, W. P., R. Booth, and M. MacGregor. 1957. Temperature Coefficients in Scintillating Systems, *Nuclear Instruments,* 1, 71-74.
8. Singh, A. S., and A. G. Wright. 1987. The Determination of Photomultiplier Temperature Coefficients for Gain and Spectral Sensitivity using the Photon Counting Technique, IEEE Transactions on Nuclear Science, 34:1, 434-437.
9. Kinard, F. 1957. Temperature Dependence of Photomultiplier Gain, *Nucleonics*, 15, Number 4, 92-97.

Fission Product Signatures from Variations in Reactor Power History

David J. Sweeney and William S. Charlton
Texas A&M University, College Station, Texas USA

Abstract

A method for uniquely determining power history characteristics of spent fuel assemblies based on the concentration of various fission products in the fuel assembly has been developed. It is envisioned that this method could be used as a transparency aid at reprocessing facilities to verify the identity of spent fuel assemblies. Specific fission product concentrations measurably vary as a result of differences in reactor power history. A discussion of the physical properties of various fission products responsible for concentration differences along with the mechanisms by which these properties produce concentration differences is presented. Several different mechanisms based on variations in the physical properties are illustrated through simplified models. These models led to the identification of an extensive list of possible monitor ratios. A case study was also performed to assess the distinguishing capabilities of the given monitors. The variations between cases include modifications to specific power, the number of shutdowns, and the duration of the shutdowns while maintaining a constant final burnup. For all but one of the cases a monitor ratio is shown to vary by at least 20 percent from the base case while some ratio differences for cases with simple modifications reached 300 percent. This paper concludes with a proposed technique for using the presented monitor ratios to verify the identity of spent fuel assemblies based on differences in reactor power history.

Introduction

The power history of a spent fuel assembly may be used to uniquely identify the assembly. The power history experienced by a fuel assembly is dependent on core power, assembly position within the core, and other factors. These dependencies result in a unique power history for each assembly. A method to verify the power history of a fuel assembly could provide additional transparency for international safeguards applications. Further, if such a method were based on fission product signatures, the method's susceptibility to deception would be minimized. The use of fission products to determine spent fuel parameters such as actinide concentrations, fuel burnup, fuel age, reactor type, fuel type, and initial fuel enrichment has been demonstrated previously.[1-8] There has also been some preliminary work on power history determination from fission products.[9,10] Building from the prior fission product analyses, research was conducted to determine a method for power history identification based on fission product signatures.

Analytical Models

To determine ideal monitor properties, analytical models of potential monitor isotopes were constructed. Both radioactive and stable monitors were considered for this analysis.

A model was derived for radioactive fission product monitors following the assumed decay scheme shown in Figure 1(a). The radioactive monitor is produced directly from fission and has an arbitrary decay constant, λ_R, and neutron absorption cross-section, $\sigma_{a,R}$. The concentration of the radioactive monitor, N_R, for any time t within a given time step is given by:

$$N_R^i(t) = \frac{\rho_U P_s^i}{\overline{E_R}\lambda_{R,eff}}\left[\frac{Y_{f,U235}^R}{1+R^{-1}} + \frac{Y_{f,Pu239}^R}{1+R}\right] \tag{1}$$

$$\left[1 - e^{-\lambda_{R,eff}(t-t_{i-1})}\right] + N_R^{i-1} e^{-\lambda_{R,eff}(t-t_{i-1})}, \text{ for } t_{i-1} < t < t_i$$

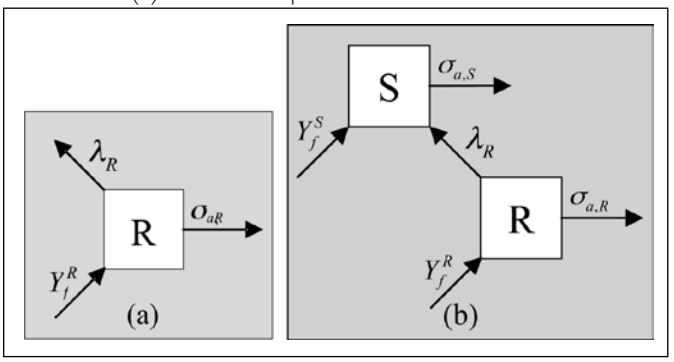
where

$$\lambda_{R,eff} = \lambda_R + \frac{\sigma_{a,R}\rho_U P_s^i}{\overline{E_R}\,\overline{\Sigma_f}},$$

$$R \equiv \frac{\sigma_{f,U235}\overline{N_{U235}}}{\sigma_{f,Pu239}\overline{N_{Pu239}}},$$

ρ_U is the density of uranium in the fuel, P_s^i is the specific power of timestep i, E_R is the average energy released per fission, $\overline{\Sigma_f} = \sigma_{f,U235}\overline{N_{U235}} + \sigma_{f,Pu239}\overline{N_{Pu239}}$ is the average macroscopic fission cross-section, $\sigma_{f,x}$ is the microscopic fission cross-section of isotope x, $Y_{f,x}^R$ is the fission yield of the radioactive fission product isotope from the fission of isotope x, $\sigma_{a,R}$ is the neutron absorption cross-section of the radioactive fission product isotope, and λ_R is the decay constant of the radioactive isotope.

Figure 1. Assumed decay schemes for (a) radioactive fission product monitor and (b) stable fission product monitor



Equation 1 is piecewise continuous over *i* timesteps for which specific power is assumed constant.

A model was derived for a stable fission product monitor in which the stable monitor is produced directly from fission and through the decay of a single radioactive parent isotope. The radioactive parent isotope is also produced directly from fission and has a decay constant, λ_R, and neutron absorption cross-section, $\sigma_{a,S}$. The stable monitor isotope also has a neutron absorption cross-section, $\sigma_{a,S}$. This decay scheme is shown in Figure 1(b). The concentration of the stable monitor, N_S, is then given by (2)

$$N_S^i(t) = \frac{\rho_U P_s^i}{\overline{E_R}\sigma_{a,S,eff}}\left[\frac{Y_{f,U235}^S}{1+R^{-1}} + \frac{Y_{f,Pu239}^S}{1+R}\right](1-e^{-\sigma_{a,S,eff}(t-t_{i-1})})$$

$$\lambda_R\left\{\frac{\rho_U P_s^i}{\overline{E_R}\lambda_{R,eff}}\left[\frac{Y_{f,U235}^R}{1+R^{-1}} + \frac{Y_{f,Pu239}^R}{1+R}\right]\left[\frac{(1-e^{-\sigma_{a,S,eff}(t-t_{i-1})})}{\sigma_{a,S,eff}} + \frac{(e^{-\sigma_{a,S,eff}(t-t_{i-1})} - e^{-\lambda_{R,eff}(t-t_{i-1})})}{(\sigma_{a,S,eff} - \lambda_{R,eff})}\right] + \frac{N_R^{i-1}(t_{i-1})(e^{-\lambda_{R,eff}(t-t_{i-1})} - e^{-\sigma_{a,S,eff}(t-t_{i-1})})}{(\sigma_{a,S,eff} - \lambda_{R,eff})}\right\}$$

$$+N_S^{i-1}(t_{i-1})e^{-\sigma_{a,S,eff}(t-t_{i-1})}, \text{ for } t_{i-1} < t < t_i$$

$$\sigma_{a,S,eff} = \frac{\sigma_{a,S}\rho_U P_s^i}{\overline{E_R}\overline{\Sigma_f}}.$$

where

These models were tested using simple fuel burnup scenarios to ensure that the models replicated expected results.

Model Verification

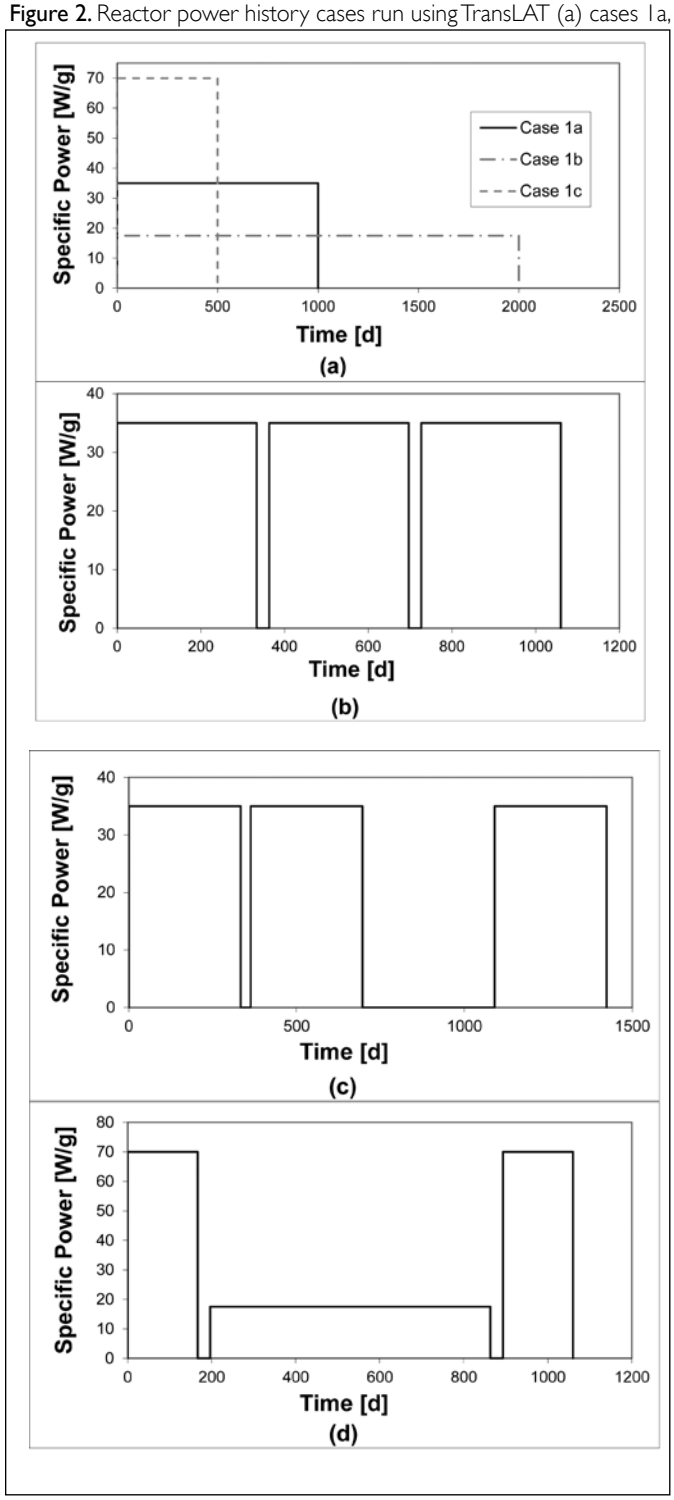
These models were benchmarked against concentration values generated by TransLAT for two sets of radioactive parent and stable daughter nuclide pairs. TransLAT is part of the modular software system TransFX produced by TransWare Enterprises Inc.[11] TransLAT couples advanced particle transport theory methods with arbitrary geometry modeling techniques. TransLAT was successfully benchmarked for its fission product isotope generation capabilities in a prior study.[12] The cross-sections and fission yield values used in the analytic models were taken from the ORIGEN 2.2 PWRPUU library. ORIGEN 2.2 is the Oak Ridge Isotope Generation Code that uses a deterministic method for determining isotope generation and depletion and has been successfully benchmarked elsewhere.[13,14]

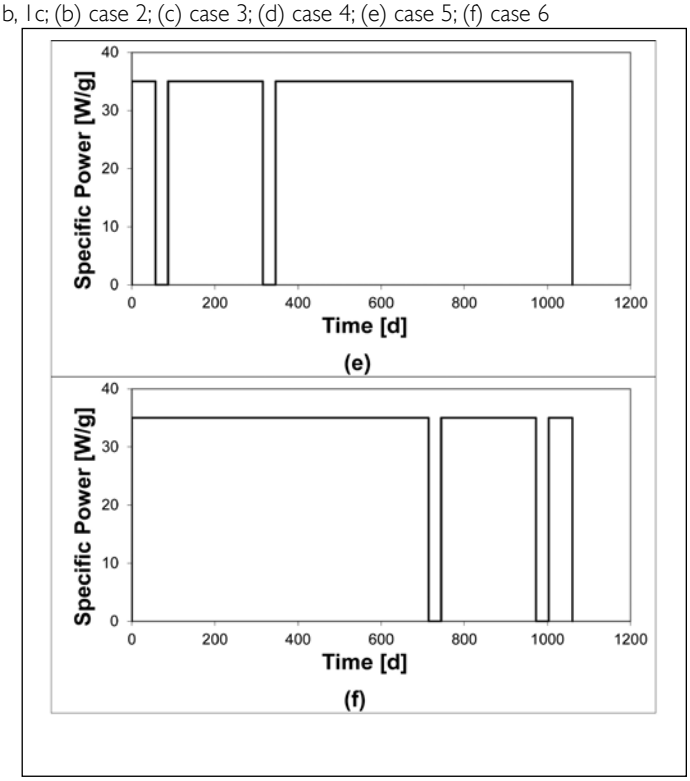
Several TransLAT cases were run and compared to values of several fission products predicted by the analytic models. The TransLAT cases run used a PWR pin cell based on the Calvert Cliffs No. 1 nuclear power reactor modified to adjust the fuel to moderator ratio of the pin cell so that it corresponds to the fuel-to-moderator ratio of the entire assembly.[12] Figure 2 illustrates the power histories simulated with TransLAT.

All cases run have a final burnup of 35 GWD/MTU. The first three cases, Case 1a, Case 1b, and Case 1c are all straight burns with no shutdowns. Case 1a is the base case run with a constant specific power of 35 W/g. Case 1b and Case 1c halve and double the specific power of Case 1a to 17.5 W/g and 70 W/g respectively. Case 2 adds two thirty-day shutdowns to the base case maintaining the original 35 W/g specific power. Case 3 adds an additional cooling cycle, of equal length to the burn cycles of Case 2, and an additional thirty-day shutdown period. This recreates a four-cycle core load where fuel assemblies experience a three burn cycle rotation with one cooling cycle out of the reactor. This is a common practice in the nuclear power industry.[15] Case 4 reverts to the shutdown scenario of Case 2, but varies the specific power from 70 W/g, 17.5 W/g, and back to 70 W/g for the burn cycles. It should be noted in Case 4 that the total burnup of each burn cycle remains the same while the actual time of each burn cycle varies inversely with specific power. Case 5 and Case 6 vary from Case 2 by adjusting when the shutdowns occur. In Case 5 the shutdowns occur at fuel burnups of 2 GWD/MTU and 10 GWD/MTU whereas in Case 6 the shutdowns occur at 25 GWD/MTU and 33 GWD/MTU.

The primary concern for benchmarking the analytic models was functional behavior in response to power history variations as opposed to absolute accuracy with respect to the concentration values from TransLAT. The analytic models derived are general and make several assumptions. Further, the values of some parameters used in the models were obtained from ORIGEN 2.2 and are not necessarily equal to the values of the same parameters used by TransLAT. The models were used to construct a guide for identifying potential monitor isotopes. As long as the model results behave similarly to those from TransLAT with respect to

Figure 2. Reactor power history cases run using TransLAT (a) cases 1a, 1b, 1c; (b) case 2; (c) case 3; (d) case 4; (e) case 5; (f) case 6

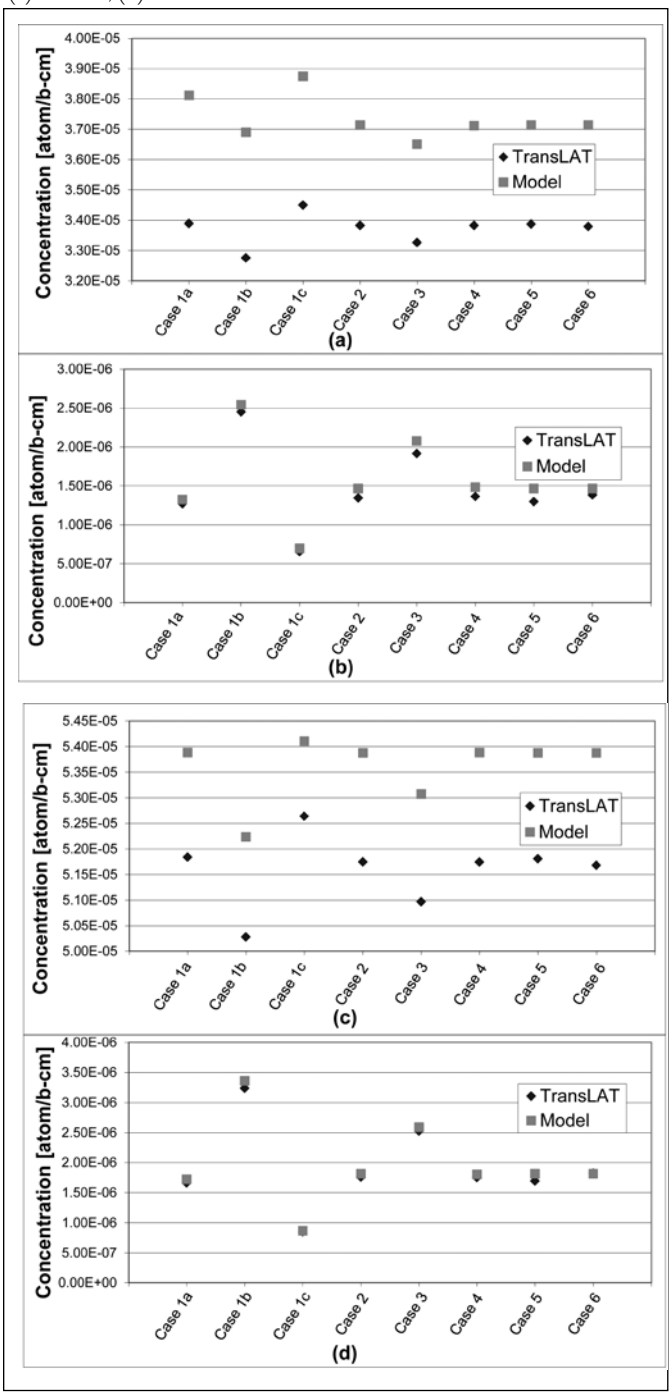




power history variations, the guides produced from the models will be applicable. Figure 3 compares the behavior of the models to the behavior of TransLAT in response to the power history variations described for Cases 1-6 for the radioactive and stable daughter nuclide pairs Sr-90, Zr-90, Cs-137, and Ba-137. Figure 4 shows the error of the models relative to TransLAT.

As seen in Figure 3 and Figure 4, the models are reasonably accurate relative to the results of TransLAT. (The reader should note that the scales of Figure 3 (a), (b), (c), and (d) are different. The figures were zoomed independently to better illustrate how the response of the models parallel the response of TransLAT to variations in power history). The differences between the results could be caused by the models using fission product parameters obtained from ORIGEN 2.2 instead of those used by TransLAT. This was done because the values from ORIGEN 2.2 were more readily available. Further, the primary purpose of these models is to build intuition into the response of fission product concentrations to variations in reactor power history. Thus the behavior of the models is of greater importance than their accuracy. Figure 3 shows that both the radioactive and stable models track the behavior of TransLAT very well. This validates the use of the derived models.

Figure 3. Model benchmarking results for (a) Sr-90, (b) Zr-90, (c) Cs-137, (d) Ba-137



Reactor Power History Variation Scenarios

The analytical models above were used to understand how the decay constant and cross-sections influence the concentration of potential monitors in response to power history variations. Table 1 shows the ranges of values used for the half-lives and cross-sections of the potential monitor models in this analysis.

Table 1. Ranges of parameters varied for potential monitor models

	Radioactive Monitor	Stable Monitor
Parent Half-Life [yr]	N/A	0.0055-40,000
Parent Cross-section [b]	N/A	1-10,000
Monitor Half-Life [yr]	0.0055-40,000	N/A
Monitor Cross-section [b]	1-10,000	1-10,000

While varying the parameters as described in Table 1, both models were applied to power history scenarios that varied specific power and shutdown time. The total burnup for the power history scenarios was held constant at 35 GWd/MTU. The first power history scenario consisted of a single irradiation cycle with a constant specific power and no shutdowns. The constant specific power was varied from 1–110 W/g. The second power history scenario consisted of three irradiation cycles of equal burnup with variable specific power and no shutdowns. The specific powers of the first and third cycles were held constant at 100 W/g while the second cycle specific power was varied from 10–100 W/g. The third power history scenario involved three burn cycles of equal burnup divided by shutdowns of variable duration. The total shutdown time was varied between 20 d – 2000 d and evenly divided between the two shutdowns. The specific power of each cycle for the third scenario was held constant at 35 W/g.

Monitor Property Ranges

Differences in final monitor concentrations generated through the power history variation analyses led to identification of ideal values of monitor properties. Useful ranges of monitor properties are shown in Figure 5.

Physical Mechanisms Underlying Concentration Differences

The ranges of useful monitor properties are determined by the value of $\lambda_{R,eff}$, $\sigma_{a,S,eff}$, and the time duration of the irradiation. Since in all scenarios the final burnup was constant, the total amount of monitor isotope atoms produced by fission was also constant. However, the amount of each isotope lost via absorption or decay or produced via parent decay varies depending on the specific power history. The implications of $\lambda_{R,eff}$ will be explored separately below for the radioactive monitor and the stable monitor.

Figure 4. Ratios of Model Values to TransLAT Values

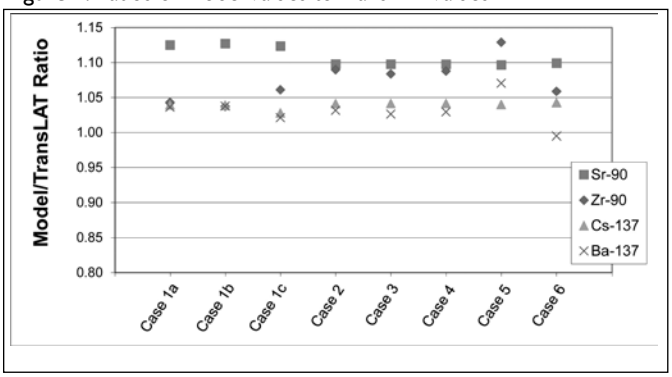
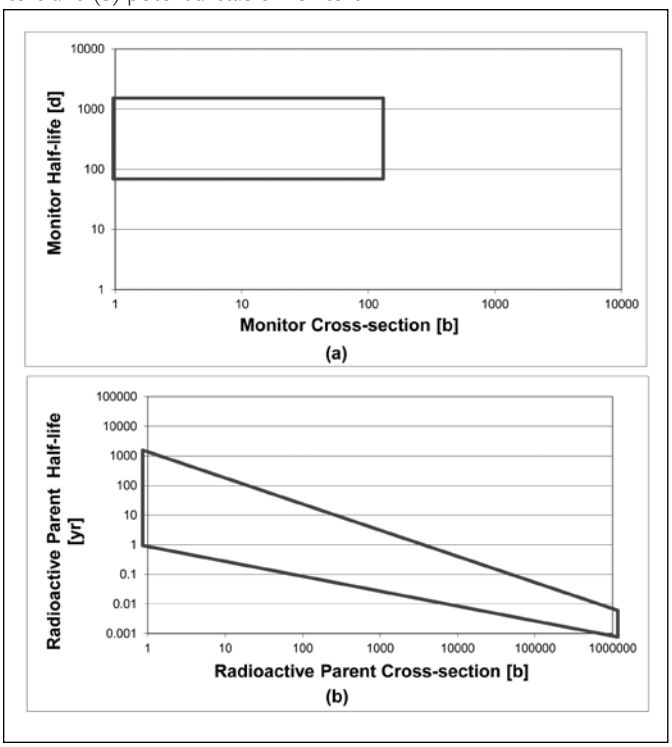


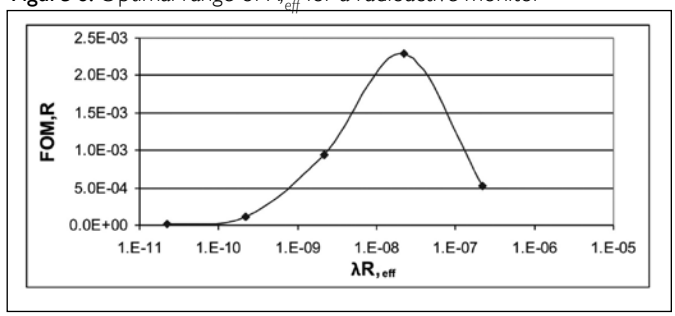
Figure 5. Useful property ranges for (a) potential radioactive monitors and (b) potential stable monitors



Radioactive Monitor

Concentration differences in radioactive monitors from variations in power history were found to be a result of an optimal destruction mechanism of the monitor. The destruction mechanism of the radioactive monitor is controlled by the effective decay constant $\lambda_{R,eff}$. If $\lambda_{R,eff}$ is too small, a negligible amount of destruction will occur and concentration will not vary with power history. However, if $\lambda_{R,eff}$ is too large the monitor will decay too rapidly leading to saturation of the monitor at a concentration proportional to the current specific power and loss of measurable signal after shutdown. A Figure of Merit (FOM,R) was defined for the radioactive monitor as

Figure 6. Optimal range of R_{eff} for a radioactive monitor



$$FOM,R = \frac{N_R^i\left(t_i, P_s^i = 10\ \text{W/g}\right) - N_R^i\left(t_i, P_s^i = 100\ \text{W/g}\right)}{N_R^i\left(t_i, P_s^i = 10\ \text{W/g}\right)} * 100 * N_R^i\left(t_i, P_s^i = 10\ \text{W/g}\right) \quad (3)$$

where the power history consists of a single irradiation cycle to 35 GWd/MTU. This FOM,R accounts for the increased percent difference for large values of $\lambda_{R,eff}$. This FOM,R is plotted against $\lambda_{R,eff}$ in Figure 6.

The limits shown in Figure 5(a) can be derived from Figure 6 and an examination of Equation 1. The limits of $\lambda_{R,eff}$ from Figure 6 were directly applied to the monitor half-life. The influence of cross-section on radioactive monitor concentration is not as clear as cross-section is coupled to specific power as seen in the definition of $\lambda_{R,eff}$. Substituting for specific power by $P_s^i = BU_i(t\text{-}t_{i-t})^{-1}$ in Equation 1 and referring to the exponential quantity $\lambda_{R,eff}$, $(t\text{-}t_{i-t})^{-1}$ one sees that if decay is negligible relative to absorption, irradiation time will cancel:

$$\lambda_{R,eff}(t - t_{i-1}) = \frac{\sigma_{a,R}\rho_U BU_i}{\overline{E_R}\,\overline{\Sigma_f}}.$$

If decay is not relatively negligible then a large cross-section will shift $\lambda_{R,eff}$ above the optimal range. As such minimal cross-sections are desirable as shown in Figure 5(a). It is noteworthy that the optimal range of $\lambda_{R,eff}$ is approximately inversely proportional to the reactor period.

Stable Monitor

Concentration differences in stable monitors from variations in power history were found to be a result of an optimal production mechanism from the decay of the monitor's radioactive parent. Production via parent decay is represented by the second term in Equation 2. In order for concentration differences to occur in the stable monitor, the rate of production via decay of the parent must be sufficiently limited so that irradiation time (as specified by specific power) determines the amount of production via decay. If the rate of decay is too fast, total time will not impact the amount of production. The properties of the radioactive parent determine the amount of stable monitor production via decay.

Figure 7. Optimal range for a stable monitor with (a) = 0.001 b and (b) 10,000 b

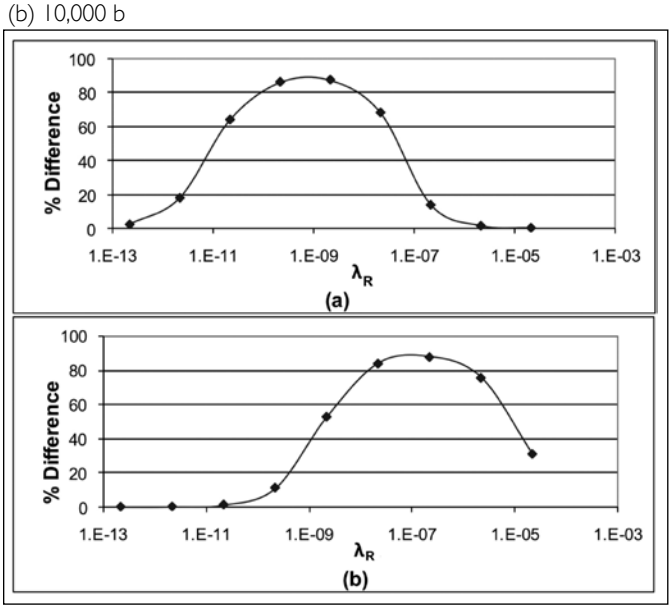
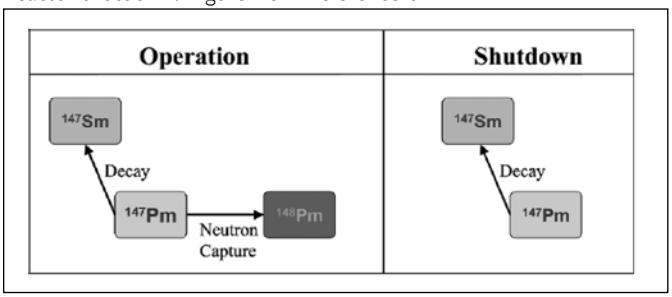


Figure 8. Illustration of significant parent absorption cross-section leading to an increase of stable monitor concentration as a result of reactor shutdown. Figure from Reference 6



For an appropriate discussion of how the properties of the radioactive parent limit production via decay the parent destruction rate $\lambda_{R,eff}$ must be resolved into its components of decay, λ_R, and absorption, $\sigma_{a,R} \cdot \lambda_R$ directly limits production via decay. There is thus a range of λ_R for which production will be sufficiently limited but not so limited that production will be negligible. The percent difference between final monitor concentrations produced from a single irradiation cycles to 35 GWd/MTU with specific powers of 10 W/g and 100 W/g is plotted against λ_R in Figure 7 for two values of $\sigma_{a,R}$: (a) $\sigma_{a,R}$ = 0.001 b and (b) 10,000 b.

Neutron absorption by the radioactive parent serves as competition for production via decay. This competition serves to drive the useful range of λ_R to higher values. This is illustrated in Figure 7(b) by increasing the value of $\sigma_{a,R}$ to 10,000 b. The optimal range of parent half-life and $\sigma_{a,R}$ shown in Figure 5(b) reflect the useful range of λ_R as influenced by $\sigma_{a,R}$. Another effect of the competition provided by absorption is a boost in concentration experienced by the stable monitor as a result of reactor shutdowns.[6] This concept is illustrated by Figure 8.

If the cross-section is large enough to move the useful parent property range to the far right of Figure 5(b), the presence of reactor shutdowns will no longer be reflected in the stable monitor concentration. In this case, the useful parent half-life is so short that all parent atoms will immediately decay if not removed through an absorption reaction. A monitor with these parent characteristics would reflect only variations in non-zero specific power, i.e., such a monitor would not be affected by the amount or length of shutdowns. The parent daughter pair of Xe-135 and Cs-135 exhibit the properties required of a specific power only monitor. Comparison of the Cs-135 concentration and the potentially highly shutdown sensitive Sm-147 concentration (depicted in Figure 8) may directly isolate total shutdown time.

Potential Monitors

Based on the half-life ranges of potential radioactive monitors and the radioactive parents of potential stable monitors given, a potential monitor list was developed. Tables 2 and 3 list potential radioactive and stable monitors respectively.[16]

Table 2. Potential radioactive monitors

Potential Monitor	Monitor Half-Life [d]
Ru-106	372.3
AG-110m	249.8
Sn-119m	293
Sn-123	129.2
Sb-125	1006.67
Te-127m	109
Cs-134	753.725
Ce-144	284.6
Pm-147	957.541

Table 3. Potential stable monitors

Potential Monitor	Radioactive Parent	Parent Half-Life [yr]
Rb-85	Kr-85	10.76
Zr-90	Sr-90	28.78
Pd-106	Ru-106	372.3
Sb-123	Sn-123	0.3540
Te-125	Sb-125	2.758
I-127	Te-127m	0.2986
Ba-134	Cs-134	2.065
Ba-137	Cs-137	30.07
Nd-144	Ce-144	0.7797
Sm-147	Pm-147	2.6234
Eu-151	Sm-151	90
Gd-154	Eu-154	8.593
Gd-155	Eu-155	4.75

Monitor Confirmation

The results of the power history case study described in Figure 2 above modeled in TransLAT were used to determine the sensitivity of each potential monitor to changes in power history. Figure 9 and Figure 10 illustrate the percent difference from the base case for the potential monitor isotope concentration of the other cases. The monitor isotopes would likely be measured by mass spectroscopy. To avoid fractionation effects, each monitor will be measured relative to another isotope of the same element.[17] As such the figures relate the data as ratios which were selected to maximize the differences with the base case. Tables of the numerical data represented in the figures below and other figures in this paper are reported elsewhere.[18]

Figure 9. Differences in potential radioactive monitor ratios resulting from power history variations simulated by TransLAT case study

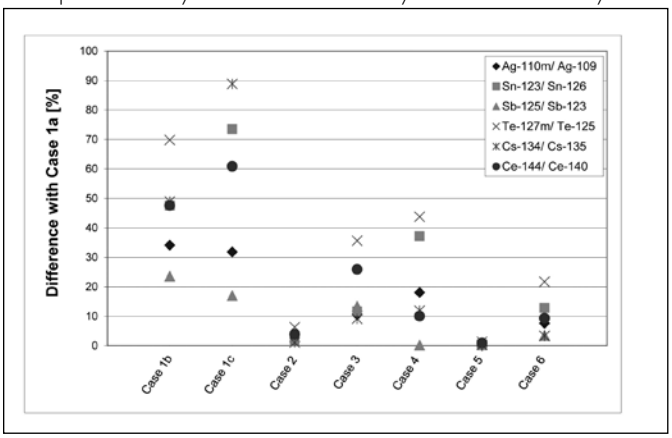
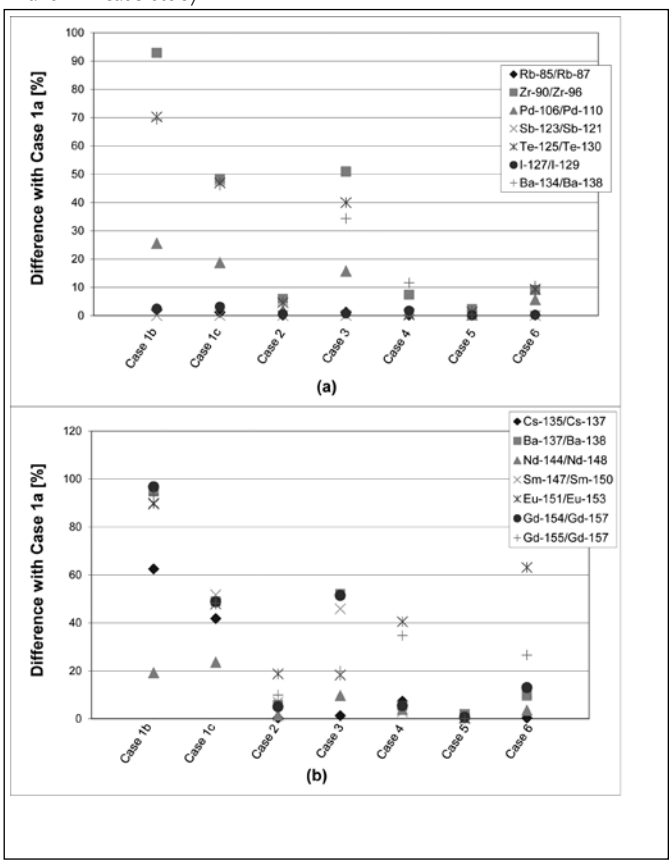


Figure 10. Differences in potential stable monitor ratios (a) set 1 and (b) set 2 resulting from power history variations simulated by TransLAT case study



As seen in the Figure 9 and Figure 10, those potential monitors that do not show significant variation include Rb-85, Sb-123, and I-127. These three isotopes likely did not show variation because the radioactive parent responsible for the expected differences has multiple states with different half-lives. Thus the parent state with the half-life necessary for daughter variation was likely not the dominant parent state. As a result daughter concentration was controlled by a parent nuclide state without the necessary characteristics and the daughter behaved as such. Additionally, Sn-119m remains unconfirmed because it was not included in TransLAT's nuclide library. A ratio including Pm-147 was not included because the element Pm has no stable isotopes. Thus, while it may be a useful signature, its measurement via mass spectrometry would be complicated, and it was not considered as a potential monitor isotope.

The concept of using Cs-135 as a specific power only monitor was proven by the results shown in Figure 10. Significant differences for the Cs-135/Cs-137 ratio from Case 1a were seen for only the cases in which the specific power was adjusted: Case 1b, Case 1c, and Case 4. This makes Cs-135 unique among the other monitors and potentially very useful to the full characterization of reactor power history.

The Cs-135/Cs-137 monitor ratio may be used to isolate the specific power independent of any shutdowns during reactor operation. A generic mathematical representation of power history as a function of time may be written as

$$P_s(t) = \begin{Bmatrix} P_{s1},\ t_0 \le t < t_1 \\ P_{s2},\ t_1 \le t < t_2 \\ P_{s3},\ t_2 \le t < t_3 \\ P_{s4},\ t_3 \le t < t_4 \\ P_{s5},\ t_4 \le t < t_5 \\ P_{s6},\ t_5 \le t < t_6 \\ P_{s7},\ t_6 \le t < t_7 \end{Bmatrix}. \quad (4)$$

Full specification of $P_s(t)$ in this case requires the determination of seven unknown specific powers and seven unknown times. Regardless if any of the individual specific powers are set to zero, as it is in the case of a reactor shutdown, the monitor ratios still depend on all intervals and specific powers shown in Equation 4. This is illustrated in the concentration models developed

and the case study results presented above. However, due to the extremely short half-life of its parent Xe-135, the Cs-135 concentration does not depend on the shutdowns. Assuming $P_{s2} = P_{s4} = P_{s6} = 0$, i.e., shutdowns occurred; these specific powers can be removed from an equation describing the representative power history for the concentration of Cs-135. Further since the time intervals involved are no longer continuous, they can be replaced by time differences, denoted tb for burn time, such that Equation 4 can be rewritten as

$$P_{s,Cs-135}(t) = \begin{Bmatrix} P_{s1}, \text{ for } t_{b1} \\ P_{s3}, \text{ for } t_{b2} \\ P_{s5}, \text{ for } t_{b3} \\ P_{s7}, \text{ for } t_{b4} \end{Bmatrix}. \quad (5)$$

The amount of unknowns has now been reduced from seven specific powers and seven times to four specific powers and four time durations. Not only is this a far simpler system to solve, but it also can be used to gain information about the removed shutdowns. To illustrate this concept an abstract mathematical representation can be given as

$$\begin{Bmatrix} P_s(t) \\ Information \end{Bmatrix} - \begin{Bmatrix} P_{s,Cs-135}(t) \\ Information \end{Bmatrix} = \begin{Bmatrix} Shutdown \\ Information \end{Bmatrix}. \quad (6)$$

Using a signature based on a fission product whose concentration is highly dependent on shutdown time, such as Sm-147, for the first term in Equation 6 would optimize the extraction of shutdown information. A more detailed version of Equation 6 could serve as an additional basis for iteration in the applications of this work.

It was also found that ratios of a stable daughter to its radioactive parent provided significant sensitivity to changes in power history. This effect is caused by the inverse proportionality of their concentrations in response to power history variations. This relationship was exploited using ratios of ratios. For example [Eu-151/Eu-153]/[Sm-151/Sm-147] is more sensitive to changes in power history than Eu-151/Eu-153. Figure 11 illustrates the differences of the double ratios with the base case.

Significant differences with Case 1a are seen in the ratios listed for all but Case 5. This is a result of the signature of the early shutdowns effectively being washed out by a long final burn cycle. However, all of the other cases show differences with Case 1a for at least several monitor ratios that are above the estimated error for fission product generation by TransLAT of 10 percent-20 percent.[12] This proves the viability of the listed ratios with differences greater than the TransLAT error as power history monitors. Table lists the ratios with the most significant differences for use as power history signatures.

The work above showed that there were fission products that could serve as reactor power history monitors. Previous sections

Figure 11. Increased differences using potential daughter-parent monitor double ratios (a) set 1 and (b) set 2 resulting from power history variations simulated by TransLAT case study

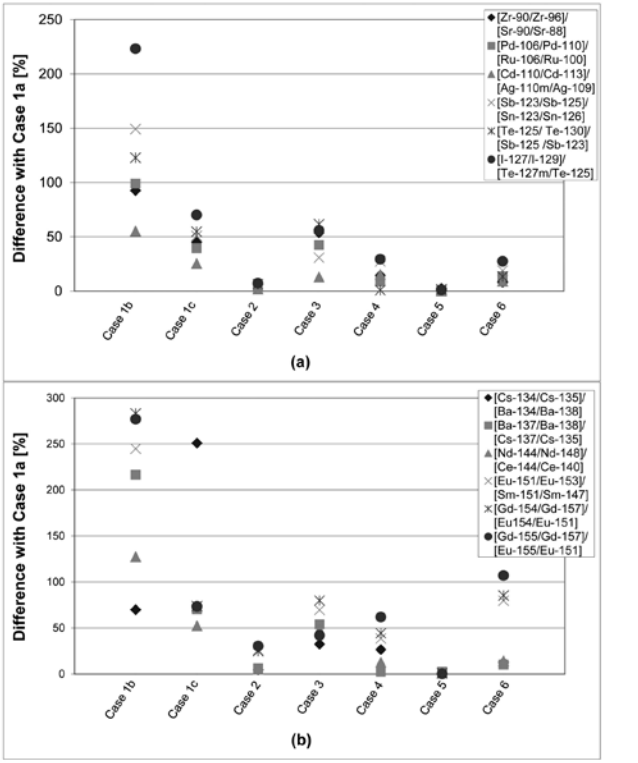


Table 4. Suggested reactor power history signatures

Signature Type	Signature Ratio
Radioactive	Te-127m/Te-125
	Ce-144/Ce-140
	Sn-123/Sn-126
Stable	Eu-151/Eu-153
	Gd-155/Gd-157
	Gd-154/Gd-157
	Sm-147/Sm-150
	Cs-135/Cs-133
Double	[Gd-155/Gd-157]/ [Eu-155/Eu-151]
	[Gd-154/Gd-157]/ [Eu-154/Eu-151]
	[Eu-151/Eu-153]/ [Sm-151/Sm-147]

established a range of ideal monitor properties as a guide to selecting potential monitors. With potential monitors identified, a case study involving eight different power histories was simulated with TransLAT. This case study computationally validated the use of the suggested monitors as power history verification signatures.

Conclusion

The goal of this study was to develop a method to uniquely identify a spent fuel assembly based on fission product signatures. Such a method would be useful as a transparency aid for international safeguards to help protect against possible diversions of spent nuclear fuel. In order to guide the search for potential monitors and as a tool for understanding the physics involved, concentration models as a function of power history were developed for both radioactive and stable monitors. Fission products were identified with potential for use as reactor power history monitors. The key properties for identification included the absorption cross-section of the fission product and the half-life of the parent nuclide. Potential monitors identified were tested through a power history case study simulated with TransLAT. Monitors displaying a distinguishable concentration difference as a result of power history variations were catalogued, and several such ratios displayed significant concentration differences.

Potential Applications

Based on the results of this study, a verification regime could be developed for the identity of a given fuel assembly that uses the reactor operator's report for power history experienced by that fuel assembly. The first objective of the verification process would be to obtain the signature ratios listed in Table 4. The signatures are assumed to be determined by mass spectrometry analysis of spent fuel dissolutions obtained from commercial reprocessing facilities or other institutions conducting spent fuel analysis. A system for obtaining such samples at a commercial facility must be developed that minimizes disruptions to the facility and costs incurred. Assuming such a system exists, the verification of power history and thus fuel assembly identity begins with obtaining the desired signatures from a spent fuel assembly.

The remaining task of the verification procedure is to generate expected signature ratios for comparison with actual signature ratios measured in the spent fuel assembly. Using the power history provided in the reactor operator's report and the models developed above, one may generate estimated signature ratios for comparison. However, doing so entirely based on the reactor operator's report creates unnecessary dependencies of other parameters used in the models. As described in the introduction, methods exist for determination of final fuel burnup, initial enrichment, fuel age, and reactor type. Knowledge of burnup, enrichment, and reactor type allows for determination of the burnup averaged concentrations of U-235 and Pu-239 without referring to the reactor operator's report. Knowledge of the fuel age also allows for the correction of inconsistencies in the ratios involved due to isotope depletion or accumulation as a result of radioactive decay during any post-irradiation cooling. Other necessary parameters involved in the concentration models are fission product yields and cross-sections. These parameters may be obtained from existing data libraries such as those used by ORIGEN 2.2. It is also possible to generate yields and cross-sections through physics codes such as TransLAT with reactor models based on the obtainable parameters and assuming a generic power history, such as that given in the operator's report. Using burnup averaged values for yields and cross-sections will reduce the importance of an accurate power history for the determination of these parameters. If necessary, the yields and cross-sections can be refined through an iterative process if the actual monitor ratios determined from the spent fuel diverge from those obtained using the power history from the operator's report. Extracting all possible information from the fuel itself as opposed to depending on the reactor operator's report eliminates excess degrees of freedom for deception by the potential proliferator. With this in mind, the verification method is simply comparing measured ratios against estimated ratios based on the power history provided by the reactor operator's report. Any inconsistencies merit further, more detailed investigation.

Another use of this work could be to independently determine a fuel assembly's power history without using the operator's report for verification. To do so would necessitate that all initial parameters be determined from the spent fuel as discussed above. After the desired power history signatures have been analyzed, it may be possible to create an iterative scheme based on an assumed generic power history. Such a generic power history could consist of three irradiation cycles divided by two shutdowns in which the specific powers and the lengths of cycles were allowed to vary during iteration. However, prior to the full scale iteration it may be possible to isolate pieces of the power history independently. The concentration of fission products with short half-lives will saturate to a level proportional to the specific power of the final irradiation cycle. Though the concentration signal would rapidly deteriorate, the specific power of the final irradiation cycle would be a useful origin for full power history characterization. As discussed, the Cs-135/Cs-137 signature could be used to isolate information about the shutdown time. With information about the final irradiation specific power and the shutdown time known, iteration on the generic power history system could be done until the estimated signature ratios matched the measured signature ratios to within specified tolerances. The full iteration system could involve several generic power histories with the overall best fit to all the measured signature ratios taken to be representative of the actual power history of the spent fuel assembly.

Future Research

A fully functioning system for the identification of a spent fuel

assembly based on its power history still requires much work to be done. A deeper understanding of the power history monitor nuclides involved and exactly what can be determined with the given ratios is necessary. This study identified monitor isotope ratios that change with power history while burnup remains constant. The next step is to do a computational study that begins with given monitor ratios. The task of this study should be to determine how well the inverse problem of reconstructing power histories of varying complexity given some set of monitor ratios with some attributed uncertainty can be accomplished.

Given that reactor power history can be adequately recreated using the monitor ratios, it may be possible to move to experimental validation. Experimental validation of the concentration differences from actual fuel samples as a result of power history variations is necessary. Experimental validation could also help improve the models and codes used to calculate the monitor nuclides suggested here and enhance the distinguishing capability of the proposed verification system. Further it is likely that mass spectrometry measurement is not well developed for all the suggested monitors. The analysis techniques for obtaining the suggested ratios need to be refined and standardized especially if this system is to be employed on an international or commercial basis.

An analysis of deception or spoofing techniques designed to defeat such a verification system would be useful. As seen in Case 5, long final irradiation cycles could reduce monitor differences from early power history variations. The exploitability of such limitations should be explored. Other research, analysis, and technological development may also be necessary prior to the implementation of the proposed future identification system. However, the information given here demonstrates that such a system is possible and can serve as a guide for future efforts.

References

1. Persiani, P. J., and R. G. Bucher. 1989. Implementation of Isotope Correlation Technique for Safeguards, *Proceedings of the 11th ESARDA Annual Symposium on Safeguards and Nuclear Materials Management.*
2. Koch, L., A. Cricchio, and F. Gerin. 1972. Isotope Correlations of Heavy Isotopes and Fission Products for Consistency Checks and Data Generation, European Institute for Transuranium Elements, *Karlsruhe*, April 1972.
3. Charlton, W. S. 2001. Monitors for the Prediction of Alternate Nuclear Material Concentrations for Pressurized Water Reactor Spent Fuel, *Nuclear Technology*, v. 136, no. 1.
4. Charlton, W. S., B. L. Fearey, C. W. Nakhleh, T. A. Parish, R. T. Perry, J. Poths, J. R. Quagliano, W. D. Stanbro, and W.B. Wilson. 2000. Operator Declaration Verification Technique for Spent Fuel at Reprocessing Facilities, *Nuclear Instruments and Methods in Physics Research, Section B: Beam Interactions with Materials and Atoms,* 168:1, 98-108.
5. Charlton, W. S. 1999. Burnup Determination and Age Dating of Spent Nuclear Fuel using Noble Gas Isotopic Analysis, *Transactions of the American Nuclear Society,* 1999 v. 81, 312-13.
6. Scott, M. 2005. Nuclear Forensics: Attributing the Source of Spent Fuel Used in an RDD Event, Master's Thesis, Texas A&M University, Nuclear Engineering Department.
7. Charlton, W.S., and J. Poths. 2003. Capability of Ruthenium Isotopes in Distinguishing Spent Reactor Fuel Type and Burnup, *Journal of Nuclear Materials Management,* 31: 2, 5-9.
8. McAninch, J. E., I. D. Proctor, N. J. Stoyer, and K. J. Moody. 1997. Viability of Long-Lived Fission Products as Signatures in Forensic Radiochemistry, Lawrence Livermore National Laboratory, UCRL-ID-126425.
9. Sweeney, D. J., and W. S. Charlton. 2007. Reactor Power History from Fission Product Signatures, *Proceedings of the INMM 48th Annual Meeting.*
10. Sweeney, D.J., and W. S. Charlton. 2008. Physical Mechanisms for Fission Product Concentration Differences from Variations in Reactor Power History, *Proceedings of the INMM 49th Annual Meeting.*
11. 2001. *TransFX Computer Software Manuals: Advanced Particle Transport Software Using Three-DimensionalDeterministic Methods in Arbitrary Geometry*, TransWare Enterprises.
12. Sweeney, D.J., and W. S. Charlton. 2010. Benchmarking TransLAT for Fission Product Generation, *Proceedings of the PHYSOR Conference.*
13. Croff, A. G. 1980. A User's Manual for the ORIGEN2 Computer Code, ORNL/TM-7175, Oak Ridge National Laboratory.
14. Charlton, W. S., W. D. Stanbro, and R. T. Perry. 2000. Comparisons of HELIOS, ORIGEN2, and Monteburns Calculated 241Am and 243Am Concentrations to Measured Values for PWR, BWR, and VVER Spent Fuel, *Journal of Nuclear Science and Technology,* 37:7.
15. Cochran, R. G., and N. Tsoulfanidis. 1990. *The Nuclear Fuel Cycle: Analysis and Management,* American Nuclear Society, Inc.
16. Baum, E. M., H. D. Knox, and T. R. Miller. 2002. *Nuclides and Isotopes 16th Edition,* Knolls Atomic Power Laboratory.
17. Alonso, J. I. G., D. Thoby-Schultzendorff, B. Giovanonne, J. Glatz, G. Pagliosa, and L. Koch. 1994. Characterization of Spent Nuclear Fuel Dissolver Solutions and Dissolution Residues by Inductively Coupled Plasma Mass Spectrometry, *Journal of Analytical Atomic Spectrometry,* 9.
18. Sweeney, D. J. 2008. Reactor Power History from Fission Product Signatures, Master's Thesis, Texas A&M University, Nuclear Engineering Department, December 2008.

During this year, the Journal of Nuclear Materials Management *celebrates its 40th anniversary. As part of that celebration, we will reprint some of what we consider to be our more significant articles from the past forty years.*

We begin with this article by U.S. Senator Pete V. Domenici, which was based on a speech he gave at the George Bush Presidential Conference Center at Texas A&M University.

This article was originally published in Volume 30, No. 3, of the Journal of Nuclear Materials Management.

The Need for Nuclear Energy—Four Years After the Harvard Speech

America's Energy Challenge—The Nuclear Answer

U.S. Senator Pete V. Domenici
New Mexico USA
George Bush Presidential Conference Center
Texas A&M University
November 19, 2001

Earlier this year, blackouts in California were front-page news. There was serious discussion about our energy crisis.

The situation eased in the last few months thanks to mild weather and increased conservation. The economic slowdown after the terrorist actions will also depress energy needs for awhile. But while the urgency of an energy crisis has abated somewhat, the basic facts haven't changed. Our nation and the world are facing immense shortfalls in energy, both in the short term and even more so in the long term.

In October 1997, I gave a speech at Harvard that anticipated the severity of the energy problems for both this nation and the world. In that speech, I called for a national dialogue on nuclear power. I'd like to contrast that with another speech given that same month by President Clinton as he laid out his strategy for negotiations at Kyoto. He talked about renewables, conservation, and his deep concerns about emission of greenhouse gases—but he never said one word in that speech about nuclear. By ignoring nuclear energy, he dismissed the largest source of clean electricity we have today, or will have for a long time.

Today we have a different administration. Thanks to the leadership of President Bush, we also now have a realistic energy policy that recognizes the need to increase all sources of energy. I am very pleased that nuclear energy figures prominently in his plan. (In passing, I should note that I won't take time here to discuss the unfortunate choices made by the Senate majority party to avoid committee debate on a legislative version of the president's energy plan.) The Vice President's National Energy Policy stated that*: The Policy Development Group recommends that the President support the expansion of nuclear energy in the United States as a major component of our national energy policy.*

President Bush accepted that recommendation without hesitation. In his speech releasing and endorsing the National Energy Policy, he noted that: *"America should expand a clean and unlimited source of energy—nuclear power"* and added: *"By renewing and expanding existing nuclear facilities, we can generate tens of thousands of megawatts of electricity, at a reasonable cost, without pumping a gram of greenhouse gas into the atmosphere."*

In contrast to President Clinton's speech, my Harvard speech certainly mentioned the "nuclear" word—considerably more than once. I discussed several concerns and challenges, with perhaps the most critical issue being the focus of anti-nuclear groups only on the risks involved with nuclear. They simply don't discuss its benefits, or discuss the solid technical solutions for the risks. Unfortunately, their actions do not help the public toward a balanced view of this complex issue.

This issue is hardly unique to nuclear energy. Energy production, by any technology, represents a trade-off between risks and benefits. The public must have information to fairly judge both sides of this equation for each energy source. With that kind of comparison, which you and your colleagues can help to frame, nuclear energy fares very well. From this debate, and from continued progress on many fronts, I believe that nuclear energy will play an increasing role in future domestic and global electrical supplies.

As you know, there's a long list of real benefits from nuclear energy, fundamental to its superb record in supplying clean, reliable, low cost electricity. In fact, its operating costs are among the lowest of any source, even 10 percent below coal.

The output of nuclear plants has risen dramatically since the 1980s. In 2000, our plants generated over 91 percent of their maximum output. Since the 1980s, our average unit output has increased by over 20 percent. That's equivalent to gaining over twenty new nuclear plants without building any.

Safety has been a vital focus, as evidenced by a constant decrease in the number of emergency shutdowns, or "scrams," in our domestic plants. In 2000, for the fourth year in a row, the number of unscheduled reactor shutdowns was zero. Another example of the exemplary safety of well-run nuclear reactors is our nuclear navy. They now operate about ninety nuclear powered ships. Over the years, they've operated about 250 reactors. They've accumulated over twice the number of reactor-years as our civilian sector without any significant in-

cidents. They are welcomed into over 150 major foreign ports in over fifty countries, only excluding New Zealand.

Some question the safety of nuclear plants in light of the recent terrorist attacks. I concur that it is appropriate that we carefully evaluate the safety of all major nodes of our critical infrastructures—chemical plants, electrical transmission systems, pipelines, oil tank farms, and nuclear plants, to name a few. But we need to remember that nuclear plants are probably the most hardened commercial structures in the world. In addition, critics of nuclear energy need to remember that we and our allies control the fuel supplies for nuclear energy. That's in stark contrast to petroleum-based fuels where the fuels are largely controlled by sources outside the United States who will consider their own best interests ahead of ours.

In my view, it just doesn't make sense to conclude that any potential target that cannot be hardened against any and all acts of war should be abandoned, as some of the antinuclear groups might suggest for nuclear plants. With that line of reasoning, we should be abandoning airplanes and high buildings.

Instead, I think the president's leadership is taking us on precisely the correct course—to work diligently to root out the causes and sources of terrorism around the world. Only then can we return to enjoying the lifestyle that we value and that we want to preserve for our future generations. Some have sought to limit nuclear energy by arguing that transportation of spent fuel is too dangerous. These arguments are being raised again in light of the terrorists' actions. Indeed, such transportation must be done with great care, but it's also something that we already do very well. There has never been a breach in a spent nuclear fuel container during almost 3,000 American shipments covering 1.6 million miles.

The environmental benefits of nuclear energy are immense. It is essentially emission free. We've avoided the emission of more than two billion tons since the 1970s. A recent Japanese study showed that nuclear was the lowest electricity source in overall carbon dioxide emissions except hydropower. The inescapable fact is that nuclear energy is making a vital contribution to our environmental health and security.

In fact, we could be doing much more with nuclear energy to promote the health of our environment. For example,

France generates 76 percent of its electricity from nuclear. That helps France achieve spectacular results for minimal emissions of carbon dioxide. Their emission of CO2 per dollar of GDP is almost three times lower than ours.

Since that speech at Harvard, many of you in this room participated in the national dialogue that followed. From that dialogue and many concrete actions, the nuclear industry of 2001 bears little resemblance to that of 1997.

In 1997, it was a real challenge to find a headline talking about the future of nuclear energy. There was little optimism for re-licensing, and any talk about a new plant would have been dismissed as lunacy.

Many factors contributed to this dramatic shift. I think that Harvard speech helped. Congressional initiatives helped and support in Congress is now much stronger. The president's strong support for nuclear energy is a key development. And initiatives, including some that I helped to encourage, to streamline the Nuclear Regulatory Commission also helped. Today there's real enthusiasm for expanded use of nuclear energy.

Today, six nuclear plants have been re-licensed to add up to twenty years to their service. These six studies took between seventeen and twenty-three months. That's in contrast to the old NRC that took eight years studying one application for an enrichment plant.

There are fourteen re-licensing applications pending at the NRC now. And there are twenty-six renewal applications expected in the next few years.

I've also been approached by several utilities who tell me to expect three applications for operating licenses of new plants by the end of 2002. Around the world, there are ninety-three new reactors planned by 2016, thirty-seven are under construction today. Eight are scheduled for operation in 2002.

Earlier this year, when I have introduced extensive legislation to support and encourage future nuclear energy development, I found many senators eager to help. Eighteen senators joined me in cosponsoring this bipartisan legislation—a most impressive number. Nuclear energy is included in several other energy bills as well.

For the current fiscal year, nuclear energy is well supported, including:

- $17.5 million for university support to ensure educational resources needed for nuclear power,
- $7 million for nuclear energy plant optimization to improve reliability and productivity of our 103 existing nuclear power plants,
- $32 million for nuclear energy research,
- $7 million to continue work on advanced reactors including Generation IV,
- $5 million for cost-shared programs with industry to support new licensing applications at the Nuclear Regulatory Commission,
- $18 million to continue the research on improved understanding of the health impacts of low doses of radiation,
- $5 million for continued joint work with Russia on high temperature, gas-cooled reactors,
- $10 million for our Nuclear Regulatory Commission to prepare to license new plants, and
- $50 million for research on reprocessing and transmutation to reduce quantities and toxicity of final waste forms

In closing, I'd like to discuss two specific areas. One involves the largest remaining roadblock to rebirth of a new era for nuclear energy. The second involves my vision for the role of nuclear energy around the world.

Perhaps the most frustrating area of challenge for future use of nuclear energy involves our lack of credible strategies to deal with spent fuel. The barriers to progress in this area are entirely

political, and not technical. This is one area that I fear could doom our nation's prospects for future use of nuclear energy if we don't make faster progress.

We continue to focus on Yucca Mountain as a permanent repository, despite the fact that it is not obvious that permanent disposal of spent fuel is in the best interests of all our citizens. It's even less obvious to me that we should equate the terms "spent fuel" and "waste."

Depending on our future demands and options for electricity, we may need to recover the tremendous energy that remains in spent fuel. Furthermore, strong public opposition to disposal of spent fuel, with its long-term radiotoxicity, may preclude use of repositories that simply accept and permanently store spent fuel rods.

For these reasons, I favor centralized storage for a period of time in a carefully monitored, highly secure, fully retrievable, configuration. At a minimum, this type of storage could allow concentration of the spent fuel from its seventy plus locations around the country into one or more centralized, tightly controlled storage areas.

Such a monitored storage facility can allow future generations to evaluate its own needs for energy and decide on appropriate reuse of spent fuel or final disposition. In a very real sense, this facility would represent a national nuclear fuel reserve for future generations.

Congress has worked very hard to make progress on the spent fuel issues. Last year, a bill passed both houses of Congress by large margins that created an "early receipt facility" in Nevada; it also created an office within the department to seriously evaluate strategies for spent fuel. The vote for passage was 253-167 in the House and 64-34 in the Senate—those are both impressive margins. Unfortunately, President Clinton vetoed this bill, and the veto override vote failed in the Senate by a single vote. That office would have studied alternative management strategies for spent fuel, including both reprocessing and transmutation. We need to do the research today that can allow tomorrow's leaders to decide whether some forms of reprocessing and transmutation can lead to reduced risks and enhanced benefits from nuclear energy.

Transmutation, as part of an integrated national or international strategy for spent fuel, could dramatically alter the radiotoxicity of final waste products destined for a repository and allow recovery of much of the residual energy in spent fuel. This option might involve systems utilizing both existing or new reactors, plus accelerators, to develop a new fuel cycle. I've successfully championed a major research program for this effort, Advanced Accelerator Applications or AAA, which is funded at $50 million this year. If this program is successful, we can recover the residual energy in spent fuel. We would also produce a final waste form that is no more toxic, after a few hundred years, than the original uranium ore. If we reach that goal, I think public concerns about waste will be dramatically reduced.

I was very pleased that the president endorsed these studies in the National Energy Policy which:

"recommends that, in the context of developing advanced nuclear fuel cycles and next generation technologies for nuclear energy, the United States should reexamine its policies to allow for research, development and deployment of fuel conditioning methods (such as pyroprocessing) that reduce waste streams and enhance proliferation resistance. In doing so, the United States will continue to discourage the accumulation of separated plutonium worldwide."

In addition, the new policy also stated:

"The United States should also consider technologies, in collaboration with international partners with highly developed fuel cycles and a record of close cooperation, to develop reprocessing and fuel treatment technologies that are cleaner, more efficient, less waste-intensive, and more proliferation resistant."

Before closing, I'd like to mention my vision for a major future role for nuclear energy. It involves the increasing globalization of the world's economies. I don't believe that the world can develop in the peace and harmony that we all want unless the large differences between the "have" and "have-not" nations are addressed.

The standards of living for billions of people lag the Western world by extremely large factors. Reliable sources of electricity underpin the economies of the developed world. They are one of the factors determining each nation's standard of living and are certainly one of the prerequisites for modernization in all developing nations. As you are well aware, there is now a vast gulf in energy usage per capita between Western nations, especially the United States, and the developing world.

I firmly believe that globalization offers immense benefits to the American people. We benefit from a network of global trading partners. These partners help create markets for our high technology products. But this will happen only if the rest of the world increases its standards of living to levels that closely match our own. And that won't happen unless they have access to clean, reliable, low cost sources of electrical power.

Nuclear energy, appropriately designed to avoid proliferation concerns and operate in absolute safety, can play a major role in energizing the rest of the world. It can be one of the solutions to providing global energy needs and helping to bring many of the poorer economies into the 21st century.

In closing, I want to commend Texas A&M University on a tremendous record of achievements in your first 125 years of existence. Your strong program in nuclear engineering is most impressive. Programs like yours are essential for training the next generation of young scientists and engineers who will be the ones evaluating, building, and operating the new nuclear plants that can continue to provide us with the benefits of nuclear technologies in the next millennium.

Taking the Long View in a Time of Great Uncertainty

The Changing Face of INMM at the 52nd Annual Meeting

By Jack Jekowski
Industry News Editor and Chair of the INMM Strategic Planning Committee

For those of us fortunate enough to have attended the INMM 52nd Annual Meeting in Palm Desert, California, USA, we were able to witness first hand a changing face of INMM that has long-term strategic impact for the Institute.

Most obvious was the ever-increasing participation of students in our Annual Meeting (of the 1,150 attendees, 124 were full time students, with 71 papers presented by those students). Many of these students are not only actively engaged in their student chapters (now numbering ten chapters), but are also becoming a voice within the Institute itself, participating in Executive Committee meetings and other events during the week.

Also, the Institute continues to see increasingly vibrant participation by the international community (forty-two countries were represented by 240 registered attendees). Most notable in this regard were the 20th Anniversary celebration of the Brazilian-Argentine Agency for Accounting and Control of Nuclear Materials (ABACC) hosted by the International Safeguards Division (ISD) during a break during the Sunday afternoon technical division meeting; the heavily attended ISD technical sessions during the week; and a remarkable technical session on Tuesday afternoon with representatives from several Middle East nations discussing their active plans for nuclear power production and alignment with safeguards as practiced by the International Atomic Energy Agency (IAEA).[1]

Another *change* we are witnessing is the increased visibility of smartphones, iPads, netbooks, laptops, and social networks, the use of which have grown over the years among the participants of our meetings. The INMM itself issues timely daily email updates during the annual meeting on events for each day, and offered an Internet café for participants in the main conference area. In the spring 2011 "Taking the Long View" column, the growing use of social networks worldwide and the importance of understanding this new communications medium in the 21st century was discussed. In discussions with students at this year's INMM Annual Meeting, there was enthusiastic support for an INMM-specific social network that was suggested in that column. This is a strategic issue that the Institute will have to address if it wishes to fully engage the new generation in the coming years.

This year's annual meeting also reflected the new strategic organizational realignment within the Institute, including a wide range of technical and policy papers presented under the auspices of the new Facilities Operations Technical Division. The meeting also provided a venue for the official launch of the new Strategic Planning Committee.

All of these visible cues in the annual meeting environment reflect upon the changing strategic landscape of the Institute, and should serve as important indicators to leadership in the development of strategies to ensure a vibrant future for the organization.

Strategic Planning Committee Activities

The formation of the new Strategic Planning Committee this year provides yet another mechanism to address the impact of this changing face of INMM on the future of the Institute. The author has been appointed by the Executive Committee to chair the Strategic Planning Committee, and similar to the other new Committees that were formed this year, a draft charter has been created, and initial membership in the committee established. Some initial tasks for the committee have been identified by the EC, including:

40th Anniversary of *Journal of Nuclear Materials Management*

This year marks a major milestone for our Institute's *Journal*[2]–four decades of publications that document the history of our organization and the technical work that has contributed to the Institute's Mission of encouraging:

- The advancement of nuclear materials management in all its aspects,
- The promotion of research in the field of nuclear materials management,
- The establishment of standards, consistent with existing professional norms,
- The improvement of the qualifications of those engaged in nuclear materials management and safeguards through high standards of professional ethics, education, and attainments, and the recognition of those who meet such standards, and
- The increase and dissemination of information through meetings, professional contacts, reports, papers, discussions, and publications.

Just as the original INMM Organizational Strategic Planning Working Group (OSPWG) was formed to examine the structure of the Institute on its 50th Anniversary, some questions have been posed by *Journal* Technical Editor Dennis Mangan and Managing Editor Patricia Sullivan on the 40th anniversary of *JNMM* that the EC agreed it would like the Strategic Planning Committee to explore:

- Are we continuing to provide a valuable resource to the membership with the *Journal* in its current form?
- How do we challenge our member-

ship to increase their contributions of technical papers for peer review and publishing in the *Journal*?

The Strategic Planning Committee will explore these questions, and also examine the historical contributions made by the *JNMM* over the past forty years to be able to assess what future changes regarding the *Journal* might better serve the Institute. Feedback on these questions is welcome.

Organizational Implementation

With the formal implementation of the new organizational structure approved by the EC last year, the Institute is now poised to face the challenges of the second decade of the new millennium. Achieving success in meeting those challenges, however, will require the full engagement of the Institute's membership, and assistance to those in newly created positions to ensure the goals set forth in the restructuring plan are implemented. The Strategic Planning Committee has been tasked by the EC to assist in the publicizing and deployment of the new structure. This will include increased communications with the Institute membership through the chapters and technical divisions, and working with the new technical division/committee chairs to ensure effective implementation. As with any significant organizational change, this will require establishing roles, responsibilities, and authorities, seeking feedback from the membership, and adapting to a dramatically changing world environment.

Developing Cooperative Partnerships

Another strategic issue being explored by the Institute is the collaboration with other organizational entities that can offer support on critical issues. In the past the Institute has worked closely with the Nuclear Threat Initiative (NTI), the World Institute for Nuclear Security (WINS), the European Safeguards Research and Development Association (ESARDA), and other national and international organizations and entities; and continues to strengthen those relationships. It has also been proposed that the Institute explore additional collaborative efforts with the American Nuclear Society (ANS), particularly in areas of mutual interest such as engaging student populations, nuclear facility operations, and other areas of mutual interest. The Strategic Planning Committee is currently collecting planning and mission documents from a wide range of those organizations with related mission components, expanding upon efforts undertaken by the original OSPWG, to identify common opportunities for collaboration. These results will be shared with the EC and the membership for comments. Again, any suggestions or feedback from membership would be welcomed.

Call for Interested Members to Join the Strategic Planning Committee

The draft Charter for the Strategic Planning Committee establishes membership of the Committee at twenty, reflecting a diversity of membership across the Institute. Currently, we have eleven members officially on the Committee, leaving nine openings. In discussions with the EC, it has been agreed to focus our recruitment efforts for the remaining positions on representation from our international and student chapters. The EC has also suggested the addition of an INMM Fellow to the committee. Interested members of the Institute should contact the author for consideration as a member of the new Committee.

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 issues in future columns, addressing the critical uncertainties that lie ahead for the world and the possible paths to the future based on those uncertainties.

Jack Jekowski can be contacted at jpjekowski@aol.com.

End Notes

1. In fact, the past four or five years have been signature "anniversary" years – the 50th Anniversary of the IAEA in 2007 (celebrated that year by the INMM in Tucson); the 50th Anniversary of the INMM two years ago, also in Tucson; the ABACC anniversary this year; and also, the upcoming 40th Anniversary of the *Journal of Nuclear Materials Management (JNMM)*. All these historic milestones are testimony to these institutions' continued importance in the world of nuclear materials management, but also speak to the increasing importance of engaging our students and younger generation in the creation of a new and vibrant future for the Institute. During the coming year we will look back upon this history so that lessons learned can be carried forward, enabling us to better prepare for an uncertain future.
2. There is an excellent summary of the history of the *JNMM* on the INMM website, under the heading Publications.

Statement to the INMM Executive Committee Meeting by Yoshinori Meguro

President, INMM Japan Chapter
Senior Advisor, Japan Atomic Power Company

Saturday, July 16, 2011

Mr. Chairman, Ladies and Gentlemen. Good morning.

First of all I appreciate the opportunity to give a word of gratitude to INMM.

As president of the Japan Chapter, I would like to express our sincere appreciation for INMM's endeavors on taking a leadership role in support to Japan through the Red Cross and so on. All of us are very excited about your thoughtfulness and moving forward to reconstruct our country.

When the earthquake hit at 2:46 p.m. on March 11, the 137th session of the Japan Chapter's Executive Committee was in session in my office in Tokyo. The meeting was adjourned immediately after the first shock. Due to the disaster, some planned events, such as the technical workshop was rescheduled, but we are going forward with the Chapter's regular annual meeting in Tokyo, November 10-11, 2011.

I would like to try to explain the current situation of the Fukushima Daiichi NPP accident and its related issues. All of the fifteen nuclear power reactors, including Fukushima Daiichi, located on the Pacific coast of northeast Japan were shocked by a Richter Scale Magnitude 9 earthquake. But all reactors were safely shutting down by automatic emergency shutdown function and once had started the reactor cooling system used by RHR system.

Unfortunately, however, Station Blackout occurred from stopping the electric power supply from outside caused by the massive earthquake, and also emergency power supply failed by 45 feet height of the tsunami that hit one hour after the first earthquake.

As a result, the Fukushima Daiichi Nuclear Power Plants were induced by loss of cooling capability and meltdown of reactor core.

At the same time, a large amount of fission products such as iodine-131, cesium-147, etc., (approximately 770,000 tera Bq) were discharged into the neighboring region when it blew out of the reactor building due to the explosion of hydrogen gasses. Then, the accident was assessed as Level 7 of INEW.

Consequently, more than 80,000 residents within a 12.5 mile radius of the Fukushima site have been evacuated and remain so, even four months after the tragedy occurred.

Tokyo Electric Power Company twice updated the Road Map for Recovery schedule on June 17, which is aimed at achieving stable cooling of the reactor core by the middle of July as the initial phase, and cold shutdown is expected by the end of December. In order to accelerate this schedule, TEPCO is making its best effort to process more than 100,000 tons of water that is highly contaminated with radioactive fission products accumulated at this site, and a reduction of the radiation dose rate.

The initial phase will be finished tomorrow (Sunday, July 17) and official expect to get good results.

I would also like to take this opportunity to express our sincere appreciation for the assistance from the United States, France, and so on, and in particular the cooperation with the United States called Operation Tomodachi.

Currently our country is realizing the necessity of strengthening countermeasures for earthquake and tsunami, and the

security of our emergency power supply.

On July 11, our government outlined a plan to introduce a two-stage stress test to determine the safety of nuclear plants. Whether to restart the currently idled plants will be decided based on primary assessments and all nuclear reactors will undergo a second-stage safety review to decide if they should be kept in operation. Nuclear plants will face endurance tests to see how much they can endure in a "phenomenon that exceeds presumed" situation, such as a massive earthquake or tsunami.

Both the assessments will be conducted by utility companies, confirmed by the government's Nuclear and Industrial Safety Agency, and approved by the Nuclear Safety Commission.

Thirty-five nuclear power reactors out of fifty-four units in Japan are out of service. This will cause a shortage of electric power supply during the summer and our government has started restricting electricity consumption by 15 percent by large-lot users in the service areas of Tokyo and the Tohoku Electric Power Co.

Nuclear development worldwide was dealt a heavy impact by the unparalleled accident and core meltdown. I would like to express my sincere apologies as someone involved in nuclear development.

We fully realize that nuclear energy is essential for a secure, stable future energy supply. Therefore our government and utility companies intend to make further improvements to nuclear safety by deeply reflecting on this accident, and introducing the results of this study.

Furthermore, we will put our best effort forth on strengthening safeguards for the peaceful use of nuclear energy, and maintaining nuclear security. Lastly I would like to ask all INMM members to continue to provide guidance to us.

Once again, we thank you for your friendship, which shows to us that we stand together with all of you to attain the significant goal of the reconstruction of Japan.

Thank you for your attention.

Submit your articles to the peer-reviewed *Journal of Nuclear Materials Management.*

Put your work before your peers
Network with others
Make yourself more competitive

To submit your paper:

1. ***Read the Author Submission Guidelines below.***
2. ***Email your paper in a Word document to JNMM Managing Editor Patricia Sullivan at psullivan@inmm.org.***
3. ***Respond promptly to review comments.***
4. ***Remember: JNMM is published four times a year in English. All graphs and images are published in black-and-white. References should follow Chicago Manual of Style guidelines.***

Questions?
Contact JNMM Managing Editor Patricia Sullivan at psullivan@inmm.org.

The quarterly JNMM is the premier international journal for the nuclear materials management profession. JNMM readers are the leaders in the field. They work in government, industry and academia around the world.

REACH THIS IMPORTANT AUDIENCE.

Author Submission Guidelines

The *Journal of Nuclear Materials Management* is the official journal of the Institute of Nuclear Materials Management. It is a peer-reviewed, multidisciplinary journal that publishes articles on new developments, innovations, and trends in safeguards and management of nuclear materials. Specific areas of interest include facility operations, international safeguards, materials control and accountability, nonproliferation and arms control, packaging, transportation and disposition, and physical protection. *JNMM* also publishes book reviews, letters to the editor, and editorials.

Submission of Manuscripts: *JNMM* reviews papers for publication with the understanding that the work was not previously published and is not being reviewed for publication elsewhere. Papers may be of any length. All papers must include an abstract.

The *Journal of Nuclear Materials* Management is an English-language publication. We encourage all authors to have their papers reviewed by editors or professional translators for proper English usage prior to submission.

Papers should be submitted as Word or ASCII text files only. Graphic elements must be sent in TIFF, JPEG or GIF formats as separate electronic files and must be readable in black and white.

Submissions may be made via e-mail to Managing Editor Patricia Sullivan at psullivan@inmm.org. Submissions may also be made via by regular mail. Include one hardcopy and a CD with all files. These submissions should be directed to:

Patricia Sullivan
Managing Editor
Journal of Nuclear Materials Management
111 Deer Lake Road, Suite 100
Deerfield, IL 60015 USA

Papers are acknowledged upon receipt and are submitted promptly for review and evaluation. Generally, the author(s) is notified within ninety days of submission of the original paper whether the paper is accepted, rejected, or subject to revision.

Format: All papers must include:

- Author(s)' complete name, telephone number and e-mail address
- Name and address of the organization where the work was performed
- Abstract
- Camera-ready tables, figures, and photographs in TIFF, JPEG, or GIF formats. Black and white only.
- Numbered references in the following format:
  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.
- Author(s) biography

JNMM is published in black and white. **Authors wishing to include color graphics must pay color charges of $700 per page.**

Peer Review: Each paper is reviewed by at least one associate editor and by two or more reviewers. Papers are evaluated according to their relevance and significance to nuclear materials safeguards, degree to which they advance knowledge, quality of presentation, soundness of methodology, and appropriateness of conclusions.

Author Review: Accepted manuscripts become the permanent property of INMM and may not be published elsewhere without permission from the managing editor. Authors are responsible for all statements made in their work.

Reprints: Reprints may be ordered at the request and expense of the author. Contact Patricia Sullivan at psullivan@inmm.org or +1-847-480-9573 to request a reprint.

THE INSTITUTE FOR NUCLEAR MATERIALS MANAGEMENT IS PLEASED TO ANNOUNCE THE INMM 27th SPENT FUEL SEMINAR

XXVII

Spent Fuel Management Seminar

January 31 – February 2, 2012
Crystal Gateway Marriott, Arlington, VA USA

Register at www.inmm.org

DON'T MISS THIS IMPORTANT EVENT IN NUCLEAR MATERIALS MANAGEMENT

www.inmm.org

SPONSORED BY THE
INMM PACKAGING, TRANSPORTATION AND
DISPOSITION TECHNICAL DIVISION
IN COOPERATION WITH THE U.S. NUCLEAR
INFASTRUCTURE COUNCIL

INMM
INSTITUTE OF NUCLEAR MATERIALS MANAGEMENT

Calendar

December 6–8, 2011
Human Reliability in Nuclear Security Workshop
Castle Green Hotel
Cumbria, UK
Supported by the INMM, WINS, and the UK Government—Foreign and Commonwealth Office (FCO) via the UK—National Nuclear Laboratory.
Information and registration at http://www.inmm.org/Upcoming_Events/2604.htm
Contact: Institute of Nuclear Materials Management
+1-847-480-9573
E-mail: inmm@inmm.org

January 31–February 2, 2012
27th Spent Fuel Seminar
Crystal Gateway Marriott
Arlinton, VA USA
Sponsor: INMM Packaging, Transportation and Disposition Technical Division in partnership with the U.S. Nuclear Infrastructure Council
Contact: Institute of Nuclear Materials Management
+1-847-480-9573
E-mail: inmm@inmm.org
Web site: www.inmm.org

February 6–8, 2012
6th Annual Workshop on Reducing the Risk from Radioactive and Nuclear Materials
Washington, DC USA
Sponsor: INMM Nonproliferation and Arms Control Technical Division
Contact: Institute of Nuclear Materials Management
+1-847-480-9573
E-mail: inmm@inmm.org
Web site: www.inmm.org

May 14–16, 2012
Applying the IAEA State-Level Concept Workshop
University of Virginia
Charlottesville, Virginia USA
Sponsor: INMM International Safeguards Technical Division and the Northeast Chapter
Contact: Institute of Nuclear Materials Management
+1-847-480-9573
E-mail: inmm@inmm.org
Web site: www.inmm.org

July 15–19, 2012
53rd INMM Annual Meeting
Renaissance Orlando Resort at SeaWorld
Orlando, Florida USA
Sponsor: Institute of Nuclear Materials Management
Contact: INMM
+1-847-480-9573
Fax: +1-847-480-9282
E-mail: inmm@inmm.org
www.inmm.org

August 18–23, 2013
PATRAM 2013
Hilton San Francisco Union Square
San Francisco, California USA
Hosted by the U.S. Department of Energy, the U.S. Nuclear Regulatory Commission, and the U.S. Department of Transportation in cooperation with INMM
http://www.patram.org

Cut the Threat Posed by the World's Most Dangerous Weapons

For forty years, the **Arms Control Association** has provided decision-makers, scholars, media, and the general public with accurate and timely information on biological, chemical, and nuclear weapons and the best methods to halt their spread and prevent their use, such as the dismantling of U.S. and Russian nuclear missiles.

Information is influence. Help us set the course for effective arms control solutions by supporting our work. Membership includes:

- Original news reporting and analysis in our monthly journal, ***Arms Control Today.***
- In-depth interviews with top policymakers.
- And so much more!

Visit **www.armscontrol.org/discount** to save 20% on an ACA membership or *Arms Control Today* subscription.

Arms Control Association
ACA
Recipient of the 2010 MacArthur Award

Arms Control TODAY

Follow us on:

Decommissioning?

The new AURAS-3000 Box Counter from ORTEC will make short work of those bulky free release construction waste containers!

www.ortec-online.com/solutions/waste-assay.aspx

- Free Release Assay of large waste containers up to 3 m^3: B25 ISO Box, smaller boxes with demonstrated regulatory compliance.[1]
- Container Weights up to 6000 kg, with on-line weighing to 3000 kg and 1 kg resolution.
- Full Quantitative Assay of all detectable gamma emitters, with non-gamma emitter estimates by correlated scaling factors.
- FAST: High sensitivity, large area integrated HPGe detectors (85 mm diameter) achieve rapid release levels.
- Individual and averaged activity AND MDA reporting.
- Highly automated.
- Extensive Safety Protection.
- Tested to EMC, Electrical and Safety standards.

[1]http://www.ortec-online.com/download.asbx?AttributeFileId=0b1f5761-c46b-4901-91ac-e0b810655b6a

801 South Illinois Ave., Oak Ridge, TN 37831-0895 U.S.A. • (865) 482-4411 • Fax (865) 483-0396 • ortec.info@ametek.com
For International Office Locations, Visit Our Website
www.ortec-online.com

ORTEC®

AMETEK
ADVANCED MEASUREMENT TECHNOLOGY