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Topical Papers

Institute News

Departments

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INMM
INSTITUTE OF NUCLEAR MATERIALS MANAGEMENT

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Globally Promoting Best Practices for Nuclear Materials Management

By Nancy Jo Nicholas
INMM President

As a professional society, INNM provides a global forum for our members and other experts to explore and understand challenges to nuclear materials management in the changing global environment. INMM members help lead advances in nuclear materials management and disseminate best practices in nuclear safeguards and security.

In fall 2006, the INMM Materials Control & Accountability Technical Division and the Central Chapter collaborated to host an international workshop on best practices for nuclear material holdup monitoring. This was INMM's first topical workshop on holdup measurements in nearly two decades and it was, by all accounts, very successful. Many best practices were discussed and demonstrated throughout the workshop and this issue of the *Journal of Nuclear Materials Management* contains key papers from that workshop. In addition, several insightful technical papers have been presented at recent INMM annual meetings on management of nuclear material holdup.

WINS Update

INMM is partnering with the Nuclear Threat Initiative (NTI) to explore the development of a World Institute for Nuclear Security, or WINS. The WINS Steering Committee, an *ad hoc* committee of INMM Fellows chaired by John Matter, continues to collect input and ideas from interested parties about how to collect and disseminate best practices for nuclear security. In September 2007 they took part in a discussion hosted by NTI on possible organization structure and governance models for WINS. On October 24–26, 2007, INMM members also participated in a WINS pilot project on best practices in nuclear security at research reactor facilities in Oslo, Norway, hosted by the Ministry of Foreign Affairs of the government of Norway.

To help coordinate dissemination of best practices in nuclear safeguards and security, Matter led the development of a new "Best Practices" section for the INMM Web site. The inaugural Web pages for the section contain global best practices in nuclear security from two recent workshops organized by INMM to share best practices in MC&A and physical security: Nuclear Security Risk Management (Washington, D.C., May 2007, and Nuclear Materials Security (Prague, Czech Republic, June 2004).

Student Activities

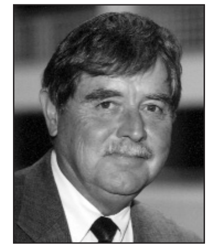
The INMM continues to grow and attract the next generation of nuclear materials management experts. One gratifying sign of this is the expansion of INMM student activities and chapters. Chapters at Texas A&M University, Mercyhurst College and the University of Missouri are active, and two other universities are in the process of establishing INMM student chapters. I'm extremely pleased to see the growing student participation in our annual meeting, regional chapter activities and workshops. This winter, INMM will co-organize the American Nuclear Society annual student conference to be held in late February at Texas A&M University. Special thanks go to James Miller, president of the Texas A&M INMM Student Chapter, for his work in coordinating the INMM section of the technical program for the conference. I'm looking forward to attending this student conference.

50th Anniversary

Our Institute is about to reach a very important milestone. The INMM was founded on May 17, 1958, and Dr. Ralph Lumb was elected as the first chairman of the INMM in October 1958. To ensure that this milestone does not go unnoticed, we have formed an *ad hoc* committee under the leadership of Ed Johnson to plan a year-long celebration of the INMM's 50th anniversary. This committee is preparing a brochure to highlight INMM's activities over the past fifty years, planning some special events to commemorate INMM's 50th anniversary at the July 2008 Annual Meeting, and other celebrations for the 50th Annual INMM Meeting, which will take place in July 2009.

The 49th INMM Annual Meeting will be held July 13–17, 2008, at the Nashville Convention Center and Renaissance Hotel in Nashville, Tennessee. Visit the INMM Web site at www.inmm.org for more information.

If you have comments, ideas or questions about INMM, I encourage you to e-mail me. My e-mail address at work is njnicholas@lanl.gov or contact INMM headquarters at inmm@inmm.org.



Best Practices in Holdup Measurements

By Dennis Mangan
Technical Editor

It was a year ago that we had a picture of Bob Keepin, former chair (now president) of the Institute, receiving a special award from the American Nuclear Society in recognition of more than forty years of work in safeguards. Bob, known as Mr. Safeguards at Los Alamos National Laboratory (LANL), passed away this past New Year's Eve. With the help of people from LANL, including INMM President Nancy Jo Nicholas and Past President Jim Tape, we are able to provide a memoriam for Bob in this issue. We plan to have a more in-depth memoriam in the summer issue of the *Journal*, which kicks off our Institute's fiftieth year anniversary.

This issue focuses six papers that were presented at the INMM-sponsored International Workshop on Best Practices in Material Holdup Monitoring, held in Oak Ridge National Laboratory, October 29 through November 3, 2006. Chris Pickett, the chair of the Materials Control and Accountability (MC&A) Technical Division, was extremely instrumental in making this highly successful workshop happen, and Cameron Coates, *JNMM* associate editor representing the MC&A Technical Division, was efficient and competent in arranging for the these articles. These two gentlemen deserve our thanks. In addition to the articles on holdup monitoring, we also have an interesting article addressing an alternative option to addressing the issues of the North Korea light-water reactor situation.

In the first article, *International Workshop on Best Practices in Material Holdup Monitoring,* Pickett and Coates summarize the workshop and set the stage for the papers that follow. In the second article, Ron Cherry (U.S. Department of Energy's National Nuclear Security Administration) provides an excellent summary of the holdup measurements from a global international perspective. In the third article, *Holdup Determinations Throughtout the Life Cycle of a Facility – An IAEA Perspective*. Shirley Johnson walks us through the various stages of a nuclear facility's life, from cradle to grave, and notes the importance that material holdup plays in the safeguards efforts. The fourth paper, *Thoughts on Holdup Measurements and Their Uncertainty,* by T. D. Reilly, J. K. Sprinkle, and S. Tobin provide interesting insights into the technical aspects of holdup measurements. In the fifth paper on holdup measurements, Reilly focuses on the use of gamma-ray assays of nuclear material to determine holdup. He takes us through the pros and cons of using gamma-ray assays for this application, and provides a historical perspective. The sixth paper is also very interesting. In *Holdup Characterization of the UO_2F_2 "Hockey Stick" Deposit Using CF-Source-Driven Transmission Imaging,* authors J.T. Mihalczo and T. Uckan discuss measurements they made at an Oak Ridge Gaseous Diffusion Plant on a section of a pipe in order to provide information to allow for a secure dismantlement of the pipe. The comparison of their predictions to what was actually found is amazing. The final hold-up measurements paper, *Programmatic Lessons Learned During Rocky Flats Holdup Measurements Support Site Closure"* by Frank Lamb conveys the magnitude of the holdup measurements that were performed at Rocky Flats, and touches on the personnel issues associated with this effort. In all, the papers on holdup measurements are interesting and educational to someone like me who is not intimately involved in the MC&A portion of our business.

The last article in this issue is also informative and interesting. In the thought-provoking, *A Return to Atoms for Peace: Provision of an Experimental Compact Liquid Metal Fast Reactor to North Korea,* the authors Lance Kim, Bethany Lyles, and Jay Fahlen begin their paper, "Should the United States negotiating strategy call for a new nuclear reactor deal in exchange for denuclearization by the Democratic Peoples Republic of Korea (DPRK), an experimental compact Liquid Metal Fast Reactor (LMFR) is an attractive option." They then address their reasoning for making this statement.

In our fall 2007 issue, we published a letter to the editor from Mark Maiello of Ossining, New York, USA. Maiello has requested that we correct an error in his letter. He asked that we provide the following: "Mark Maiello regrets an error made in his Letter to the Editor in the last issue of *JNMM*. Iran remains a signatory to the Nuclear Nonproliferation Treaty but *threatened* to pull out of the treaty in May 2006 contributing to the pressure put on the nonproliferation regime over the last few years." Also, because of limited space, we were not able to publish the references that Maiello provided with his Letter to the Editor. Should anyone want those references, contact me and I will see that they are provided.

I trust you find this issue of the *Journal* informative and interesting reading. Should you have any questions or comments, please feel free to contact me.

JNMM Technical Editor Dennis L. Mangan may be reached via e-mail at dennismangan@comcast.net.

International Workshop on Best Practices in Material Holdup Monitoring

C. A. Pickett and C. W. Coates
Oak Ridge National Laboratory, Oak Ridge, Tennessee USA

Abstracts

In fall 2006, the Oak Ridge National Laboratory (ORNL) hosted an INMM-sponsored International Workshop on Best Practices in Material Holdup Monitoring. This workshop represented the first time in more than twenty years that the international community had gathered to discuss pertinent holdup topics and needs. More than 100 people attended the workshop. Their expertise in the field ranged from novice to expert, and they shared their experiences throughout the week of the workshop.

Presenters discussed techniques that have been used worldwide to detect and characterize nuclear materials held up in processes and equipment and the policies used to report quantities detected. The primary goal of the workshop was to compile information on the best practices and lessons learned and to make this information available for sharing throughout the international community.

This paper discusses the information that was produced from four separate working groups (each composed of workshop attendees). Each group was tasked to determine what it believed to be the best practices in the field today and what issues needed to be addressed to move the field forward in the 21st century.

Introduction

The International Workshop on Best Practices for Holdup Monitoring was held at the Oak Ridge National Laboratory (ORNL) October 29 through November 3, 2006. There were 109 registered participants with about 20 percent of these from countries outside the United States. Attendees from Canada, China, Japan, Russia, and South Africa participated in addition to participants from countries of the European Union, the United Kingdom, and the International Atomic Energy Agency (IAEA). The attendees were a diverse group of individuals who ranged from measurement and policy experts to individuals wanting to learn more about the field.

This paper provides an overview of the material covered in the daily sessions and provides a summary of the conclusions from the working groups' efforts. It also provides a consensus of needs that the attendees identified.

Daily Schedule

The workshop opened with a keynote speech titled, "A Global Perspective on Nuclear Material Holdup Measurements," presented by Ronald C. Cherry of the Office of International Regimes and Agreements at the U.S. Department of Energy's National Nuclear Security Administration. Two sessions were held each day. The morning session was technical in nature and, as listed in Table 1, each day had a theme. Each technical session opened with an overview paper to set the stage for the remainder of the technical papers.

Following the last technical presentation, all speakers participated in a panel discussion, and the questions and answers were captured.

Table 1. Technical session themes

Day One	NDA and holdup review
Day Two	Measurement techniques
Day Three	Facility and process
Day Four	Closed-down and decommissioned facilities
Day Five	Best practices and needs

In the afternoon, the attendees either participated in a work session or toured the ORNL Safeguards Laboratory (only a small number of participants could be accommodated for each tour group). The afternoon sessions assigned attendees to one of four facilitated working groups where they developed a list of best practices for material holdup measurements and future needs. This was done in a structured manner to guide discussion and produce the required deliverables. Work session process and tasks are listed in Figures 1-3.

The facilitators were a key part in the discovery and presentation of the working group deliverables. Thanks to Bill Brosey, Ann Raffo-Caiado, Mike Ehinger, Leigh Gunn, Shirley Johnson, Gary Kodman, Don Kovacic, John Randolph, and Sammi Owens acting as facilitators the deliverables were met on schedule. Topics covered during the discussions in the groups working sessions can be seen in Table 2.

Figure 1. Session One

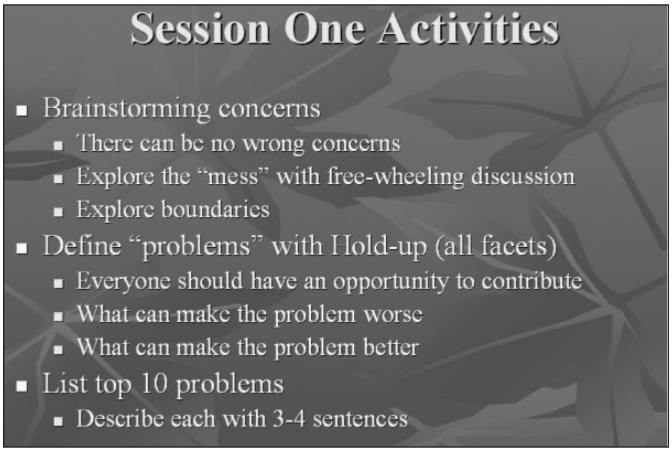


Figure 2. Session Two

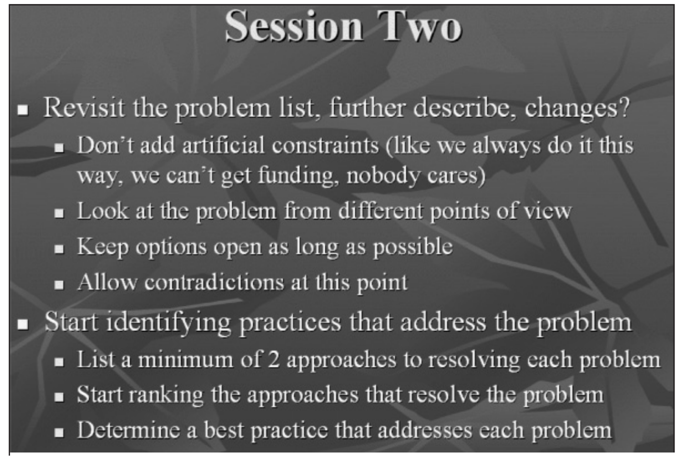


Figure 3. Session Three

Figure 4. Holdup demonstrations at ORNL Safeguards Lab

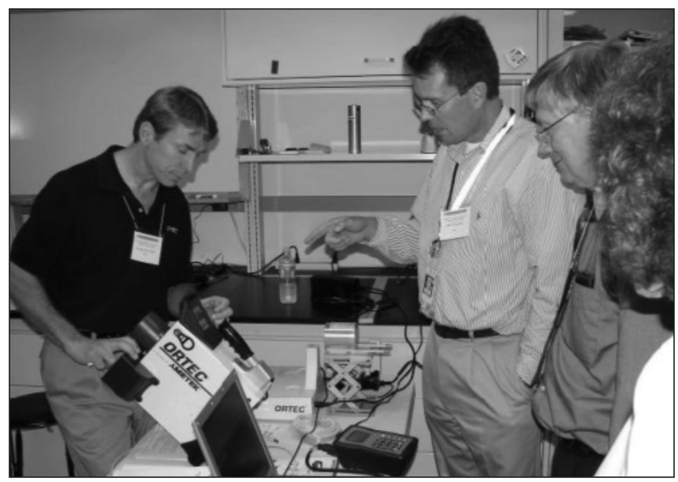


Figure 5. Steve Smith (ORNL) shows workshop participants the automated holdup measurement software HMS4.

Figure 6. Jim Bogard (ORNL) demonstrates NDA software for determining uranium enrichment.

Figure 7. Workshop participant performing simple gamma scan of a pipe array.

Figure 8. Ametek-Ortec representative demonstrating portable gamma-ray measurement system.

Figure 9. Alexander Solodov (ORNL) prepares to make a holdup measurement on a small round duct.

Figure 10. Workshop participants discussing portable NDA instruments shown by Canberra Industries.

Table 2. Topics of discussion during group sessions

• Measurement uncertainty	• Measurement quality
• Common vocabulary	• Identifying what is to be measured
• End states	• Understanding facility processes
• Integrating group needs	• Accounting/reconciliation
• Waste management	• Legacy to now and beyond
• Criticality safety	• Inadequate standards, difficulty
• Operations	• Developing standards and need new methods
• Authorization basis/safety	• Need mandate, directive to focus on bigger picture, long-term view Including cost benefit analysis
• MC&A/safeguards	
• Site licensing issues	
• Expense/cost savings	

The concept of the workshop was to demonstrate technologies offering an opportunity to get hands-on-experience using detection equipment with radioactive source materials in holdup configurations as well as general education. Each afternoon one group was selected on a rotating basis to observe technology demonstrations from sponsoring vendors conducted in the ORNL Safeguards Laboratory by ORNL staff. Figures 4-10 show a sampling of the demonstrations.

The last morning of the workshop was dedicated to presentations by each of the four working groups to the entire workshop participants. Each working group presented the results of their group's efforts at compiling best practices and future needs of holdup monitoring.

Technical Session One: Nondestructive Assay and Holdup Review

The first morning session began with a keynote talk and a series of papers presenting basic information on nondestructive assay (NDA) and holdup overview. The purpose of these presentations was to provide common ground with respect to terminology, NDA techniques, perspectives, and facilities. The list of papers and a sample of summary statements from the first day's panel discussion is presented in Table 3.

Table 3. Workshop Presentations—Monday

Paper	Presenter
Global Perspective (NNSA HQ)	R. Cherry
NDA and Holdup General Kickoff	J. Sprinkle
Basics of Process Holdup	C. Gariazzo
Holdup Measurements and Procedures	D. Reilly
Facility/Process Characterization Basics	V. Longmire
Closed-Down and Decommissioned Facilities (U.S. Perspective)	F. Lamb
Holdup Determinations Throughout the Life-Cycle of a Facility (an IAEA Perspective)	S. Johnson

Sample summary statements from panel discussion:

- The total amount of special nuclear material (SNM) measured is generally a monotonically increasing function of the number of holdup measurements.
- The more time spent on a single measurement, the better answer one expects for that measurement result.
- Old truisms are not necessarily reliable:
  - What you don't know can hurt you.
  - Rely on cleanout or alternative measurements.
  - Even experts get fooled.

The following considerations will determine how large or small the holdup term is in the material-balance equation and, thus, in the inventory difference:

- the form of the holdup material,
- the layout of the process,
- the ability to insert measurement instruments into or around the process equipment, and
- installation of measurement equipment or infrastructure prior to the introduction of the nuclear material.

Technical Session Two: Measurement Techniques

The second session focused on measurement techniques. The list of papers and a sample of summary statements from the daily panel discussion are presented in Table 4.

Table 4. Workshop Presentations—Tuesday

Paper	Presenter
Measurement Techniques Kickoff	K. Frame
Plutonium Holdup Measurements at Pacific Northwest National Laboratory	A. Mozhayev
Holdup Measurement in a Reprocessing Facility	T. Iwamoto
Ulba Holdup Measurement	D. Reilly
Comparison of Two Measurement Techniques for Determining the Total Holdup at a Large Fuel Fabrication Facility	T. Wenz/S. Tobin
Experiences in IAEA Usage of the *In Situ* Object-Counting Software (ISOCS) for Uranium Holdup Verification	L. Bourva

Sample summary statements from panel discussion:

- Material, geometry, accuracy, and facility operations dictate the measurement technique needed.
- Holdup measurement is essential, but the complete measurement is limited because of the complex processes.
- A process-monitoring system like Portable In-Line Measurement System (PIMS) is needed for large-scale plants in order to provide credible safeguards assurance that the plant is operated as declared, and that possibilities for undetected removal of nuclear material from processes could be eliminated.
- Measuring holdup takes a long-term commitment.

Technical Session Three: Facility and Process Characterization

The third session focused on facility and process characterization. The list of papers and a sample of summary statements is presented in Table 5.

Session Four: Closed-Down and Decommissioned Facilities

The fourth session focused on closed-down and decommissioned facilities. The list of papers and a sample of summary statements from the daily panel discussion is presented in Table 6.

Table 5. Workshop Presentations—Wednesday

Paper	Presenter
Facility and Process Characterization Kickoff	F. Lamb
Facility and Process Characterization at Rocky Flats and LANL	V. Longmire
Lessons Learned from the Holdup Measurement Program at the K-25 Site	R. Hagenauer
Facility and Process Characterization at the Y-12 National Security Complex	G. Pfennigwerth
Holdup Measurements in a 24-in.-diam Pipe at the K-29 Enrichment Plant	J. Mihalczo
Automation of Holdup Assay	A. Solodov
Sample summary statements from panel discussion: • Holdup measurements are not easy. • New hardware and software does make it easier for the next holdup program. • Much development work is still needed. • The use of measurement "pulse points" at the most sensitive accumulation points may be useful as indicators of change. • Subdivision of process systems into functional sections may aid process monitoring. • Estimation of uncertainty is important to understanding the reported data. • Combining holdup measurements with safety screening improves safety assessments and reduces overall effort.	

Table 6. Workshop Presentations—Thursday

Paper	Presenter
Closed-Down and Decommissioned Facilities Kickoff	Y. Ferris
Closed-Down and Decommissioned Facilities Hanford PFP Experiences	M. Talbot/M. Minette
Closed-Down and Decommissioned Facilities SRS FB Line Experiences	R. Lynn
Determination of Measurement Locations During Transition out of Operational Status	F. Lamb
Contrasting Facility Holdup Measurements from Operating to Decommissioned	B. Douglass
Holdup Measurements on Pu Glove/Boxes Using DIPSIM®	P. Ronaldson

Sample summary statements from panel discussion:
• Portable NDA becomes a valuable characterization tool that enables work to focus on the right things:
  • facilitates waste determination, transuranic (TRU) vs. low-level waste (LLW);
  • enables direct load of TRU waste into waste containers; and
  • facilities focusing on decontamination efforts.
• Developing a process for radiological characterization of the Department of Transportation (DOT) Surface Contaminated Objects can help to screen LLW efficiently.
• The holdup program supports nuclear criticality safety and materials control and accountability (MC&A) for site closure.
• Holdup measurements provide an important tool for terminating safeguards.
• Prior expectations and visual inspections can be misleading and should be used carefully.	

Session Five: Workshop Wrap-Up

The fifth session focused on presenting results of the work sessions from each group individually with a follow-on discussion of the results. A sample listing of significant best practices is presented in the following list.

- Compare NDA numbers with actual material removed from the process to verify quantity and validate the model.
- Use measurement experience to promote better practices that minimize uncertainty to as great a degree as possible.
- Ensure stakeholder involvement in facility design and holdup measurement planning.
- Be creative, flexible, and open to revising the plan as work proceeds and new information becomes known.
- Imitate (or adapt) the Rokkasho approach to implementing safeguards in initial facility design.
- Cradle-to-grave life-cycle cost analysis results in significant cost savings when safeguards is designed into original facility.

Problem areas identified:

- Lack of standardization in holdup measurement terminology throughout the nuclear community
- Facilities have not been designed with holdup determination and minimization in mind. This includes uncertainties in holdup locations, difficult access for measurements, as well as lack of access for visual inspection.
- Inadequate research and development for holdup measurement techniques, including remote unattended measurement/monitoring systems. Remote monitoring reduces resource requirements and radiation exposure.
- Different stakeholders of holdup measurement campaigns, such as safeguards, criticality safety, waste management, and health physics have conflicting needs and objectives.
- Holdup measurements impact plant operations and production schedules. This frequently leads to inadequate support for holdup measurement campaigns, a resistance to change current practices, and acceptance of substandard results.
- Due to classification or proprietary issues, information cannot always be shared, thus hampering efforts to better understand measurement uncertainty.
- Integrated and user-friendly software is not available for holdup measurement analysis, record-keeping, and reporting.

- Limited selection of equipment specifically designed for holdup measurement, including non-nuclear techniques
- Lack of international guidelines, standards, and criteria for holdup measurement and calculation including precision and accuracy goals
- Limited availability of calibration reference material for holdup measurements and inadequate guidelines for development.

The following is a listing of needs developed by the groups:

- The development of methods and equipment to lower uncertainties associated with holdup measurements (extremely high priority)
- Standardized documenting and reporting of measurement results, including measurement uncertainties
- Issuance of the ASTM Standards on NDA measurement control for holdup
- Regular international sessions at the American Nuclear Society or INMM meetings to provide feedback on holdup measurement experience
- Funding for fabrication and characterization of reference and working standards
- A team of holdup measurement consultants who could go to the sites to help set up systems for the sites
- A group of holdup experts to function as a center of excellence or to operate a hotline
- Definition of terms related to holdup and clarification on how these terms are used in describing holdup and in-process inventory measurements
- Ensuring that money for NDA research and development is spent in the most efficient manner

Conclusion

Evaluation forms for the workshop were given to all conference attendees with nearly 80 percent responding. Nearly all of the comments were very positive, but two comments provided universal suggestions that need to be addressed. The first comment expressed a need to keep the momentum going and make sure that another twenty years does not pass before a workshop is held on this subject. The MC&A and International Safeguards Technical Divisions of INMM will work to make this happen.

The second comment referred to a need for providing greater access to reference materials and source documents. The INMM is working to address this need as well, by considering a repository for this information on its Web site. Establishing this repository is consistent with the goals of INMM to promulgate best practices.

Acknowledgements

The authors would like to express their gratitude to the multitude of individuals who contributed to the success of the workshop including: 1) the Technical Program Committee; 2) all who prepared and presented technical papers; 3) the session chairs [James Sprinkle, Frank Lamb, and Yvonne Ferris]; and 4) the Facilitators [Bill Brosey, Mike Ehinger, Leigh Gunn, Shirley Johnson, Gary Kodman, Don Kovacic, Ana Raffo-Caiado, John Randolph, and Sammi Owens] and the Central Chapter members and ORNL Staff who without whose logistics support the workshop could not have occurred (Brenda Gouldy, Janie McCowan, Teresa McKinney, Shannon Morgan, and Donna Sneed, Amy Wilson, and Peggy York). Oak Ridge National Laboratory is operated by UT-Battelle, LLC, for the U.S. Department of Energy under Contract No. DE-AC05-00OR22725.

A Global Perspective on Nuclear Material Holdup Measurements

Ronald C. Cherry
Office of International Regimes and Agreements, U.S. National Nuclear Security Administration, Washington, DC USA

Abstract

This paper presents an overview of uses of nuclear material holdup measurements and describes why they are important for nuclear material control and accounting. As technology advances, subject matter experts retire, and nuclear power enjoys a resurgence, the sharing of holdup measurement best practices contributes to optimal allocation of resources and reduces proliferation risk. The sharing of best practices is an ideal platform from which to reinvigorate the technology base using an up-to-date R&D program.

Why Holdup Measurements Are Important

As those interested in material accounting know, holdup measurements serve many purposes related to the safe and secure operation of nuclear facilities. First, they are an important part of a nuclear plant's material control and accountability (MC&A) system and play a key role in providing assurance of the security of nuclear material. As such, holdup measurements make an essential contribution to the effectiveness of national safeguards systems.

Second, holdup measurements contribute to criticality safety. Even when criticality safety is not an issue, these measurements can help to detect deposits of material, such as low-enriched uranium, in process equipment that could have an impact on a facility's operational efficiency.

A third contribution that holdup measurements make is in the area of nuclear facility decontamination and decommissioning (D&D). Important D&D activities that rely on these measurements include inventory difference reconciliation and close out of the final material balance for safeguards, criticality safety and process cleanout, and waste management.

Fourth, at the international level, holdup measurements play an important part in enabling the International Atomic Energy Agency (IAEA) to independently verify inventories at nuclear facilities. For instance, experts from the United States and other countries have participated in a multilateral collaboration with the IAEA and Kazakhstan to strengthen MC&A systems in that country, including the measurement of holdup at the Ulba Metallurgical Plant. Another recent collaboration involved the successful application of a holdup measurement technique to the measurement of wastes in storage at a nuclear facility in Japan. While quite different in their details, these cases both illustrate the contribution holdup measurements can make to the implementation of IAEA safeguards, and to the ability of the agency to verify that nuclear materials declared by states remain in peaceful uses.

Fifth, just as holdup measurements contribute to the IAEA's ability to verify declared nuclear programs, they also can play an important role in helping verify the dismantlement of nuclear programs. This was true in Iraq and more recently in Libya, where holdup measurement techniques and portable equipment were used in connection with the disablement or removal of nuclear facilities and equipment associated with those countries' undeclared nuclear programs.

Finally, insofar as holdup measurements support the safe and secure operation of nuclear facilities, and help the IAEA provide assurance of states' compliance with nonproliferation obligations, they can be an important factor in fostering public acceptance of peaceful nuclear power programs. This is an important consideration as the United States and other countries look ahead to a global renaissance in civil nuclear power.

Evolution of Holdup

Measurements The INMM last sponsored a workshop on nuclear material holdup measurements in 1988. Significant progress has been made since then, much of it as a result of advances in facility and process designs outside the United States. The development of advanced, highly automated nuclear facilities in some countries has helped push the state-of-the-art in technologies for measuring and monitoring in-process nuclear materials. In the United States, the recent emphasis within the U.S. Department of Energy complex on facility shut-down and decommissioning has also provided opportunities to improve holdup measurements. The technology has evolved from the use of portable instruments to measure specific items or equipment in a facility, to techniques for measuring holdup in entire areas of a plant, to the use of installed systems to continuously monitor flows and in-process inventories. In the implementation of IAEA safeguards, the combination of installed systems with unattended or remote monitoring holds the potential for more effective verification, with reduced impact on the facility operator and the agency.

Why Best Practices are Important

The developments over the past two decades, in facility and process design and in measurement techniques, have led to the accumulation of considerable experience on the part of subject matter experts—valuable experience that could be lost unless steps are taken now to consolidate and record the lessons those experts have learned.

In his address to the 2005 INMM Annual Meeting, Charles Curtis called the identification of best practices and the institutional infrastructure to support them "indispensable elements of nuclear materials security."[1] The recent workshop is evidence that the INMM has taken his challenge seriously and is working to respond to it. One may argue that in the case of holdup measurements, the challenge of establishing best practices is especially daunting. How these measurements are performed is affected by the unique design and operational history of facilities and process equipment, and by the specific needs the measurements will serve. In 1988, Jim Sprinkle of Los Alamos was quoted in the *Journal of Nuclear Materials Management* as saying, "Some people consider holdup measurements to be a black art. I prefer the description of holdup measurements as lots of hard work requiring extensive training and careful observation."[2] While hopefully the general perception of these measurements has improved over the years, I am confident his comments about hard work, training, and careful observation remain true today.

In a recent exchange regarding best practices for holdup measurements, Jim Sprinkle noted the importance of advance planning; the assessment of costs versus benefits; having a clear understanding of the end-use of the measurements (e.g., D&D, safeguards, safety); careful attention to measurement uncertainties, and the value of having subject matter experts working as a team with the facility.

How to Promote Best Practices

There are many ways by which nuclear safeguards practitioners can promote best practices. Curtis in his address to the INMM in 2005 called for the creation of an organization similar to the World Association of Nuclear Operators. The INMM and Curtis' organization, the Nuclear Threat Initiative (NTI), are now working to develop a concept tentatively called the World Institute of Nuclear Security, or WINS. As described in the *INMM Communicator,* WINS "would promote best practices in nuclear security, and provide an institutional infrastructure to help put these best practices in place in nuclear facilities throughout the world."[3]

The establishment of WINS, or something like it, would be a major advance in the effort to promote best practices. But there are other things we can do, as well. The most obvious is the 2006 International Workshop on Best Practices Workshop in Material Holdup Monitoring, and other events like it sponsored by the INMM, such as the two workshops that the Institute and NTI sponsored in 2004.

In addition to workshops that focus on specific topics, the Institute could hold a meeting or series of meetings each year, perhaps in conjunction with its Annual Meeting, to foster international consensus among technical experts on issues related to best practices. The Institute could also establish a cross-cutting working group on best practices, with representation from all its technical divisions. These ideas are probably not new. They would certainly not take the place of an initiative like WINS, but they might complement it and they demonstrate the contributions that the INMM can make to this cause.

As noted in the *INMM Communicator,* international support is essential in order for WINS—or indeed any effort of this nature—to succeed.[3] This leads me to believe that another logical mechanism for promoting best practices would be through bilateral cooperation, and multilateral engagement, for instance through IAEA Member State Support Programs. Earlier I mentioned examples of activities that have been carried out under IAEA auspices that supported advancements in the development and implementation of holdup measurements. Through its bilateral cooperation arrangements, NNSA has been involved in numerous projects to develop improved methods for measuring holdup. Notable examples include our cooperation with Japan at uranium and plutonium processing facilities in that country, and collaboration with Argentina to develop and demonstrate holdup measurement methods for its gaseous diffusion enrichment plant at Pilcaniyeu.

Ultimately, however, the promotion of best practices will depend not on any one project or initiative, but on the international consensus that best practices are important. And if we all agree they are important, then we should seek to capitalize on all the resources, new or existing, available to us to promote them.

Best Practices and the Technology Base

In a field like nuclear material holdup measurements, best practices and technology are two sides of the same coin. Advancements in nuclear materials processing technologies and designs have both driven and enabled the evolution in technology for these measurements. At the same time, however, the technology will only be effective if it is in the hands of safeguards practitioners with the right subject matter expertise. As we work to define best practices for holdup measurements, I would encourage you to think in the broadest possible terms about what would be needed to support them.

In my opinion, a fundamental part of the infrastructure that should accompany best practices is what I refer to as the "technology base," comprising the full range of resources—equipment, laboratories, and, most important of all, people—needed to sustain effective safeguards. Today the need to strengthen the safeguards technology base may be greater than ever. In 2005, shortly before Curtis called on the INMM to take up the challenge of best practices, a panel of experts sponsored by the American

Physical Society completed a study on nuclear power and proliferation resistance. This panel concluded that much of what the United States is doing today in international safeguards involves the implementation or transfer of technologies that resulted from research and development (R&D) done ten to twenty years ago. In this regard, the panel concluded, "A robust safeguards R&D program is the single most significant technical investment that can be made to enhance the proliferation resistance of nuclear power in the near term."[4]

The need for expanded investment in safeguards R&D—and here I am referring particularly to *international* safeguards R&D—could become even more acute as a result of the Global Nuclear Energy Partnership (GNEP), and other initiatives that have been put forward to expand the role of nuclear power while reducing proliferation risks. As Adam Scheinman, director of NNSA's Office of Nonproliferation and International Security, noted at the IAEA's 2006 International Safeguards Symposium, one of GNEP's goals is to develop and deploy the most advanced international safeguards technologies and systems, and investments in this area are needed and likely overdue. GNEP can help catalyze this investment in international safeguards.[5]

Conclusion

Since the 1988 INMM workshop was held on holdup, significant advancements in technology have been made. As the subject matter experts who have been involved in so much of this R&D retire, we face the possibility of losing invaluable knowledge and experience. At the same time, we are now seeing the beginnings of a renaissance in nuclear power and, in GNEP and other similar initiatives, the prospect for an even greater global expansion in the peaceful uses of nuclear energy.

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Holdup Determinations Throughout the Life Cycle of a Facility–An IAEA Perspective

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Abstract

The determination of *holdup* within a facility is a concern to operators, state authorities and to the International Atomic Energy Agency (IAEA). However, the definition and the need for determination and verification of this material are somewhat different. The IAEA considers any material within a process, whether in operations or shut-down, as in-process holdup, or more precisely as inventory. As for the different roles, the operator and state must determine or estimate the amount of holdup in a facility and provide an inventory declaration to the IAEA. The IAEA then must verify that declaration. However, verification of in-process holdup can be very challenging due to inaccessibility, inadequate measurement technology and the fact that the material may be flowing through the process. For this reason, the IAEA depends on verified design features and operating parameters to provide added assurance to all measurements and to provide reliable estimations where measurements are not possible. This paper outlines the need for both design and material verification throughout the life cycle of a facility.

Introduction

The Department of Safeguards within the International Atomic Energy Agency (IAEA) is mandated to develop and implement safeguards approaches for all types of nuclear facilities. Those having bulk material in loose form, whether solid, liquid, or gas, present a significant challenge when implementing verification and monitoring methods. This is particularly challenging if the material is within a process of a facility such as an enrichment, conversion, fuel fabrication, or spent fuel reprocessing plant. The nuclear material within these processes is referred to as in-process holdup or inventory and the safeguards applied to it may vary depending on the life cycle of the facility. The life-cycle phases as viewed by the IAEA are:

- Pre-construction (design and planning) Phase
- Construction Phase
- Commissioning Phase
- Operating Phase
- Maintenance/Modification Phase
- Shutdown Phase
- Closed-down Phase
    - State of Preservation
    - State of Decommissioning
- Decommissioned for Safeguards Purposes

The definition of holdup, as stated in the IAEA Safeguards Glossary,[1] is "nuclear material deposits remaining after shutdown of a plant in and about process equipment, interconnecting piping, filters, and adjacent work areas. For plants in operation, the holdup is the amount of nuclear material contained in the process. It is also referred to as in-process inventory." This international safeguards definition may differ from that of an operator and state in that the goals and concerns are quite different. An operator and the state must be able to determine or estimate the in-process holdup (inventory) in order to prepare a declaration to the IAEA. The IAEA must have methods to independently verify that declaration.

Appropriate verification and/or monitoring measures must be implemented from the first introduction of nuclear material into a process until the process has been cleaned out and the facility closed-down. Since physical measurement of the nuclear material is not always possible, special in-process methods must be applied such as near-real-time accountancy (NRTA) or process monitoring. In many instances indirect verification is based on verified process design and operational information. Therefore, the design of the process and verification of that design is a critical part of establishing inventory holdup verification methods. Examination and verification of the process design must begin with the design phase and continue throughout the entire life cycle of a facility.[2,3]

Pre-Construction Phase

Definition

The Pre-Construction Phase of a facility begins when the decision is first made to construct a nuclear facility. During this phase the design is finalized, a site is identified, and contractors are selected.

Holdup Determination

Since in-process holdup can present a significant challenge for verification, the development of a safeguards approach and the associated methodology must start early in the life of large and/or complex facilities. It is during this early phase of a facility that the locations and accessibility of inventory needs to be anticipated.

Some questions that need to be answered are:

- What is the estimated holdup during normal operations?
- What is the estimated holdup during shut-down?
- What are the proposed process clean-out procedures and what amount of residual holdup is expected?
- How can these inventories be measured?
- Where will there be unmeasurable inventories (UMI)?

The design information available during this phase is preliminary but provides a starting point for planning potential R&D tasks, equipment procurements, and human resource needs.

Construction Phase

Definition

The Construction Phase of a facility begins with the preparation of the site and continues until the entire facility or parts of the facility are constructed and ready for commissioning. This phase includes manufacturing and assembling the components of a nuclear facility, the erection of civil works and structures, the installation of components and equipment, and the performance of some factory or vendor tests.

Holdup Determination

As construction of a facility progresses, parts of the process will be accessible for design verification. Many of these parts of the process may not be accessible when construction is complete and/or during operations. It is during this time that holdup in vessels, piping, pumps, sampling pots, and transfer systems can be calculated or estimated based on verified design features. In-process measurement and monitoring equipment are also installed that will provide independent verification of inventory and operating conditions. It is also an opportunity for the IAEA to identify potential locations where material may accumulate and where direct measurement of the material might not be possible. This latter is UMI and will require a verification approach that relies on material accounting, process design, and operating conditions.

Commissioning Phase

Definition

The Commissioning Phase of a facility, or part of a facility, begins after completion of construction and before the facility is considered to be functional. During commissioning the facility systems and equipment undergo extensive acceptance testing by the operator to ensure that the facility functions as designed. This stage may include the use of nuclear material for testing.

Holdup Determination

Facility commissioning activities provide an opportunity for the IAEA to verify both the operator and IAEA measurement and monitoring systems, including both installed and portable equipment. Calibration of vessels provides refinement of the design estimates previously made and helps to define the distribution of material throughout a process. Participation in "first time through" activities provides information on expected operating process holdup and start-up losses. Testing of clean-out procedures also provide vital information on residual holdup that cannot be removed during a normal process clean-out.

Operating Phase

Definition

The operating phase of a facility, or part of a facility, begins after commissioning is completed and when nuclear material has been introduced to the main facility, or support facility, so that it may function for its designed purpose.

Holdup Determination

During operations the IAEA is required to periodically verify the inventory of the facility at a specified "cut-off-time." Depending on the type of facility and operating procedures the in-process holdup may be verified as a flowing or a static inventory. A certain portion of the inventory can be verified by sampling and analysis or by in-line or on-line measurement and monitoring systems. However, a flowing inventory provides a very specific challenge and often needs to be enhanced with the use of NRTA, which applies statistical analyses to the declared holdup compared to the expected holdup based on flow declarations. This method can also provide added assurance that the expected UMI does exist and its quantity is within a specified uncertainty.

Maintenance/Modification Phase

Definition

The Maintenance/Modification Phase of a facility, or part of a facility, may coincide with other phases, such as the Operating or Shutdown Phases. These activities may introduce safeguards significant design changes.

Holdup Determination

During maintenance and modification activities design changes may be introduced by the operator either intentionally or unintentionally. Therefore, observation, verification, and follow-up of these operator activities are required to determine if any changes in design have altered the distribution of material or holdup capacity of the process. This is particular important if the previously established UMI quantity may have been changed as a result of upgraded systems, rerouting of flows or change in operating conditions.

Shutdown Phase

Definition

The Shutdown Phase of a facility, or part of a facility, normally involves the interruption of operations for a period of time exceeding one month for facilities handling unirradiated direct-use material and three months for all other facilities. During this phase the facility, or part of a facility, is not in operations, contains nuclear material and could be restarted in a short time should the operator choose to do so.

Holdup Determination

During a shutdown the quantity of in-process holdup can vary greatly from facility to facility. Some facilities may shutdown with operating levels of material in the process, others may do a run-down or rinse-out, and others may do a clean-out with the material being collected in verifiable locations. The IAEA must first confirm the shut-down procedures being used and, if necessary, carry out material verification during their implementation. In-process inventory verification methods, which are used during operations, may not be applicable during a shut-down. This is particularly true with methods such as NRTA that rely on flow verification to determine the expected in-process holdup and its uncertainties.

Closed-down Phase

Definition

"A closed-down facility or closed-down location outside facilities means an installation or location where operations have been stopped and the nuclear material removed but which has not been decommissioned (INFCIRC/540)." A closed-down facility can be in a:

State of Preservation—where all essential equipment remains in operating condition and decommissioning activities have not begun.

State of Decommissioning—where the essential equipment is being removed or rendered inoperable according to a plan and schedule.

Holdup Determination

The IAEA does not currently have a defined nuclear material quantity by which a facility can be declared as cleaned out and closed down. It is the operator and state that declares that a facility is cleaned out, that all material has been shipped from the facility and that the inventory is zero. It is then the IAEA's responsibility to verify that the process has been cleaned out to the extent possible and that all measurement and monitoring systems indicate only residual holdups which are below detection capabilities. The most important activity in confirming the existence or non-existence of significant process holdup is a statistical evaluation of the cumulative material-unaccounted-for (Cu-MUF), over the lifetime of the facility. A large Cu-MUF, taking into account measurement uncertainties, could indicate un-recovered inventory remaining within the process.

As equipment is removed during decommissioning and more intense cleaning is performed, previously undeclared inventories may be found. In such a case, they are measured and adjustments to the accountancy records of the facility are made. This is followed by new declarations to the IAEA and subsequent adjustment to the MUF.

Decommissioned for Safeguards Purposes

"A decommissioned facility or decommissioned location outside facilities means an installation or location at which residual structures and equipment essential for its use have been removed or rendered inoperable so that it is not used to store and can no longer be used to handle, process or utilize nuclear material (INFCIRC/540)." These requirements may differ from those for radiological decommissioning.

Conclusion

Holdup, whether it is called in-process, static, flowing, residual, operating, cleaned-out, or un-measurable, for international safeguards it is inventory that must be measured, monitored, estimated, or determined to be *negligible* for accountancy purposes or non-recoverable. In order to do this requires a safeguards effort throughout the life cycle of the facility.

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Thoughts on Holdup Measurements and Their Uncertainty

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Introduction

Holdup measurements are challenging, in part, because they are not performed in a controlled environment such as a laboratory. They do not present standardized containers, the measurement geometry is uncontrolled, and they are generally performed in nuclear material process areas surrounded by unknown and uncontrolled backgrounds. Holdup measurements are often considered an art. Alternatively, they can be considered an underdetermined mathematical problem. Either way, these characteristics indicate that it may be difficult to reliably estimate holdup measurement uncertainties.

One should first consider the definition of holdup. It has been defined as undeclared inventory, in-process inventory, a residue remaining after cleanout, or the process contents before cleanout and recovery. While this presentation is pretty much independent of which definition is used, specifically it addresses the other factors in estimating holdup measurement uncertainty, clearly much confusion or error can result from a discussion between two parties with different definitions of nuclear material holdup.

Most mature measurement methods in regular usage in the nuclear fuel cycle undergo evaluations to assess measurement errors.[1] Sufficient data now exist to include an assessment of holdup errors. This paper documents a variety of holdup measurement experience in facilities for highly enriched uranium (HEU), Pu, and low enriched uranium (LEU). In addition, experience from training courses using calibration materials to simulate holdup is included.

What is a Holdup Measurement?

Before one can assess measurement uncertainty, one must define the measurement. In addition to the assorted definitions of holdup, holdup measurements have been described in various ways including:

- a treasure hunt
- detective work
- on-the-spot improvisation
- hundreds of detailed, repetitive (and possibly boring) measurements

These descriptors indicate the expectations one might have regarding the uncertainty in a given situation. In the authors' experience, holdup measurements are never requested just to spend money or keep personnel busy. They are requested in the hope of saving money or of finding a valuable asset. The resultant measurement uncertainty is coupled with how much the customer wants to pay. A rapid scan for hot spots will likely have larger uncertainty than methodical, replicate measurements that cost more to perform. However, there is no guarantee that increased funding and effort will provide an improved rate of return. The fuel cycle has ample examples of increased funding not yielding the desired improvements. With the additional measurement challenges found in holdup measurements, the use of highly skilled professionals is one way to improve the odds of getting better quality results, with reduced measurement uncertainties.[2]

Why Measure Holdup?

The desired uncertainty can be related to the amount of money to be spent performing the measurement, while the amount of money available is related to why the measurement is being performed. Possible reasons for performing holdup measurements include:

- Economics
- Criticality safety
- Health hazard (D&D)
- Safeguards

Special nuclear material is valuable. Some estimates place its cost per gram higher than gold or platinum. Facilities find it important to be interested in economics, in where their valuable assets are, and in how easy it is to retrieve them for use. If the cost to retrieve and use the asset is lower than the cost to buy new assets, and there is sufficient funding to retrieve the material, then the facility is generally interested in retrieval. The uncertainty in how much there is to retrieve is a component in this decision.

If the reason for measuring holdup is criticality safety, one must improve the measurement uncertainty as more material is located, particularly if kilogram quantities are localized in unsafe geometries. However, if the quantities being measured are orders of magnitude below the criticality safety limits, large measurement uncertainties, with correspondingly lower measurement costs, are acceptable.

Many nuclear material accounting systems assume that measurements have a constant percentage error, and the holdup results are expected to fit into this same simplistic model. Overlaid on these considerations is the limitation of budget: What is the customer able to pay and what is he willing to pay for. Before starting measurements, it is important to clarify the customer's needs and expectations with respect to the assay uncertainty.

Many sources of measurement error are present independent of the expectations or future use the customer might have for the measurements. However, the customer's expectations can play a significant role in how much effort is expended in considering sources of error.

Sources of Error

The most significant source of error in nuclear holdup assay is usually the lack of knowledge about the geometry of the deposit being measured. Incorrect guesses about the material location and distribution, followed by guesses about the intervening attenuators can lead to significant bias in the reported results. While the bias can be either positive or negative, experience shows that the reported results are more generally biased low.

There are several models for acquiring and analyzing holdup data;[3-5] all have simplifying assumptions that may cause significant bias. A lack of well-characterized or representative calibration materials can be treated adequately. Incorrect treatment of background is often not recognized until after the results are reported. Counting statistics can be handled using standard techniques, consequently it is usually the smallest source of uncertainty and occasionally the only one reported.

When corrections are made for these or other effects, it is useful to keep track of the possible errors due to incorrect assumptions. In general, it is prudent to remember that one has less control over the measurement process and the measured item than one has in a laboratory.

Means to Estimate Measurement Uncertainty

Assuming one has the resources and funding, there are several means to determine holdup assay uncertainty. Some can be applied during the measurement, some are based on (facility-specific) experience, and the best relies on actual cleanout and recovery of the nuclear material during the assay campaign. Then the cleaned-out items are remeasured and the mass difference compared with the cleanout mass. It can be hazardous to apply bias corrections to holdup measurement results based on cleanout results. The better approach is to improve the measurement procedure and the analysis model.

Replicate measurements can give information about precision. Sometimes adding more measurement points per item can yield information about the suitability of the analysis model. Alternatively, if one measures the item from several directions or several source-to-detector distances, suitability of model specific parameters or geometries can sometimes be assessed.

Sometimes one has the option to vary the assumptions in the model and see the effect on the result. While changing from aluminum to steel for the intervening material (when one does not know what it is other than opaque) has little effect when the material is 0.1 mm thick, it can have a substantive effect for a thickness of 2 cm. One can also vary geometric assumptions like compare the results from assuming the deposit to be a line viewed from distance x, to those obtained by assuming a point at distance y, or use the same model geometry at two distances.

Intelligent guessing and the experience of subject matter experts can be useful in estimating measurement uncertainty. Many operators have experience showing where significant deposits have previously existed, and many measurement experts can apply lessons learned from other situations. The input from subject matter experts who have been able to adjust their measurement results and procedures based on cleanout values is invaluable, just as learning how to accept +/- 25 percent as being a very good uncertainty.

Reported Accuracy

The precision, which is inversely related to the random error variance, can be readily determined for all NDA measurements including holdup. Because of the many measurements performed, the overall precision of holdup measurements is usually of the order of a few percent or less. However, the accuracy or systematic error variance is very difficult to determine, because it is difficult to know the true mass of nuclear material held up in the equipment of a complex facility. Often, the accuracy estimate for a holdup campaign is simply the "best guess" based on judgment and experience. Such estimates are typically in the range of 25 percent to 50 percent, because of the many unknown factors and assumptions required to calculate the nuclear material mass. In some cases, e.g., gloveboxes, known standards can be introduced and measured in addition to the holdup. In a few cases, an effort was made to clean out and recover the measured material that was then analyzed destructively and compared with the measured holdup. A complete cleanout is usually difficult and costly, but this is the best way to determine holdup assay accuracy.

In the early 1980s, a holdup measurement campaign was conducted at a shut down part of the Portsmouth Gaseous Diffusion Plant (PGDP) in Piketon, Ohio. Gamma-ray measurements were made with a collimated NaI detector and neutron measurements with a portable slab detector. A total of approximately 250 stages (converter, cooler, compressor, and piping) were measured during the campaign. Afterwards, three cells (twelve stages each) were cleaned out and the uranium recovered. The U was also measured and recovered from an isolated converter. The results from this are summarized in Table 1. Because the gamma measurements only covered the converters, they should only be compared with the neutron assay of the isolated converter. These results are typical of what one finds in such holdup studies.[6]

Several bias estimates for gamma-ray holdup measurements have been reported. There is a stigma often associated with holdup uncertainty connected to the difficulty in obtaining

Table 1. Evaluation of PGDP holdup assay

Cell	n kg U[a]	γkg U[b]	Recovery kg U
A	177	45	120
B	32	3	28
C	29	12	25
isolated converter	9	10	7

a. *The neutron counters were not well collimated and measured an entire stage and double-counted the cooler.*
b. *Gamma-ray measurements covered only the converters.*

results of quality similar to those obtained from NDA in well controlled situations. Many typical results from these difficult-to-measure situations are not publicly documented.[7] The following are summaries of gamma-ray-based nuclear material holdup measurements at multiple facilities. The percentages are the holdup results divided by reference values. The reference values are typically from measurements based on cleanout and recovery of the items measured for holdup.

- HEU processing 14 percent - 118 percent
- Pu processing 10 percent - 157 percent
- LEU processing 91 percent - 156 percent

The Rocky Flats Environmental Technology Site (RFETS) is located near Denver and contained 802 facilities. The Rocky Flats plant, which manufactured plutonium parts for nuclear weapons, was closed in 1989 and subjected to a ten-year cleanup campaign that ended in 2005 when RFETS was turned into a national wildlife refuge. During this period, 3.5×10^5 m^2 of buildings were dismantled and more than 220 kg of plutonium holdup measured by a staff of fifteen. Holdup measurements included nearly 7 km of ductwork (~3 gPu/m), 1497 gloveboxes, and more than 300 plutonium process tanks. Gamma-ray measurements were performed using HPGe and Bismuth Germanate detectors and the Generalized Geometry Holdup (GGH) procedures. All of the measured equipment was cleaned out and the recovery values can be compared with the pre- and post-cleanout NDA holdup measurements. The cleanout data were generally within 20 percent of the measured holdup. Some specific building values are listed in Table 2.[8]

Table 2. RFETS holdup data

Building	Holdup/Recovered Pu
B-371 Gloveboxes	1.09
B-307 Ductwork	1.06
B-779 Total Holdup	1.13
B-A Total Holdup	1.17
B-B Total Holdup	0.97
B-C Total Holdup	1.04
B-D Total Holdup	1.03

A six-year study was conducted on the accuracy and precision of holdup measurements using the GGH (gamma ray assay) approach to measure simulated holdup situations with well known nuclear material standards. A series of simulations were fabricated for this study and a holdup training course; they included a pipe array, a steel pipe, an aluminum pipe, a rectangular ventilation duct, a V-Blender, and a contaminated spot on a floor. These were *salted* with U or Pu fuel rods, U metal foils, and small cans of UO_2 or PuO_2. Table 3 summarizes the results of this study which included measurements made by many people from students to holdup experts. The results shown here are "best case" vis-à-vis holdup assay accuracy.[9]

Table 3. GGH holdup assay evaluation

	^{235}U[a]	^{239}Pu[a]
Pipe array	0.90	0.72
V-blender	1.22	1.02
Al pipe	1.03	0.97
Steel pipe	0.97	1.47
Floor spot	0.96	n/a
Duct	1.07	0.96

a. *Number listed is the average ratio of measured U or Pu to the reference value.*

A new holdup assay technique has been demonstrated in a uranium centrifuge enrichment plant and a MOX fuel fabrication facility. Distributed Source Term Analysis involves Monte Carlo modeling of the neutron field in a facility and sampling the actual neutron distribution with a portable neutron detector. While the data set is small, there are preliminary uncertainty estimates for DSTA:

Plutonium—precision 20 percent, bias 150 percent-400 percent measured high due to wrong source term

Uranium—precision 4 percent (long counting times), bias 104 percent – source term was well known.

For the DSTA approach to be successful, one must know well the chemical and isotopic composition of the deposits and it must be acceptable that this approach does not pinpoint deposit locations.[10]

Summary

- In general, holdup measurement uncertainties are larger than those for other NDA methods.
- Occasionally, with judicious use of cleanout and recovery, modeling, and data interpretation, uncertainties as good as 5 percent have been reported.

- The total amount of spent nuclear material measured is generally a monotonically increasing function of the number of holdup measurements. One should expect a decreasing rate of return after an initial modest effort when additional resources are applied to the measurements.
- The more time spent on a single measurement location, the better answer one expects for that measurement result, up to a point.
- The previous two generalizations are not reliable:
  - What you don't know can hurt you.
  - Rely on cleanout or alternative measurements whenever possible.
- Even experts get fooled.
- Additional funds might be best spent on cleaning out hot spots and comparing recovery to the holdup measurements to improve data collection procedure and analysis models.

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Gamma-Ray Assay of Nuclear Material Holdup

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Introduction

The term *holdup* refers to the nuclear material deposited in the equipment, transfer lines, and ventilation systems of processing facilities. Reprocessing, fuel fabrication, conversion, and enrichment require very large facilities that can contain hundreds of kilometers of pipes and ducts, pumps, ovens, centrifuges, filters, and diffusers. During years of operation, significant quantities of uranium and/or plutonium can build up in this equipment. Operators need to know the location and amount of holdup for reasons of accountability, criticality safety, radiation safety, waste management, and efficient plant operation. Sometimes the term holdup is also applied to in-process inventory, if this must be known for verification or accountability purposes. Holdup is difficult to measure and while it is usually a small fraction of plant throughput, it can often amount to many kilograms of nuclear material and this limits the accuracy of the nuclear material balance within the facility. A diverter could, in principle, remove one or more significant quantities (SQ) of HEU or plutonium and hide the loss in the uncertain material balance caused by holdup deposits within the plant. International Atomic Energy Agency (IAEA) safeguards inspectors rarely attempt to measure holdup; although they have participated in a holdup measurement campaign at the Ulba Fuel Fabrication Plant in Ust-Kamenogorsk, Kazakhstan. Reference 1 presents a good summary of holdup measurements.[1]

Holdup measurements must cover a range of material types. Process history determines which materials may be deposited. The range of deposit thickness, presence of different material types (isotopic mixtures), and chemistry influence and complicate holdup measurements. The range of ^{235}U enrichment in some facilities includes depleted (0.3 percent) up to 97 percent, and that of ^{240}Pu at other facilities ranges from 2 percent to 45 percent. Because the equipment in large facilities is extensive, the total holdup may be large, even if deposit thicknesses are small.

Holdup measurements are usually made using gamma-ray techniques, although neutron detectors are also used. There is some experience with thermoluminescent dosimeters (TLD) to measure holdup deposits in gloveboxes or heavy equipment where it is difficult to insert gamma-ray detectors. Such dosimeters usually receive most of their dose from X-rays or low-energy gamma-rays, so the results are more susceptible to attenuation or geometry effects than those obtained with gamma-ray detectors. However, measurement performance can be comparable if the TLDs are carefully calibrated using mockups of the equipment to be measured.[2] Gamma rays have several advantages over neutrons in measuring holdup, because they are easily collimated allowing the locations and distributions of deposits to be defined. The gamma-ray peaks confirm the identities of the isotopes present. Multiple isotopes and elements can be measured independently and simultaneously by choosing the detector and peaks appropriately. Shielded gamma-ray detectors and the required electronics can be small and lightweight so that measurements can be performed in locations that are difficult to access.

Gamma-Ray Signatures and Equipment

Faced with a mix of material types for plutonium or uranium, the resolution provided by germanium or Peltier-cooled CdTe should be considered if there are possible biases from spectral interferences. When process knowledge is unable to specify isotopics, these high-resolution detectors may be required for preliminary surveys. When isotopic composition is sufficiently well known and interferences unlikely, even low-resolution scintillators (sodium iodide-NaI, bismuth germanate-BGO) can make useful holdup measurements. Table 1 lists the gamma-ray peaks commonly chosen to measure the nuclides of interest.

Table 1. Common Gamma Rays for Holdup Analysis

Isotope	E_γ (keV)	Intensity (γ/g-sec)
^{238}Pu	153	5.9×10^6
^{235}U	186	4.32×10^4
^{241}Pu - ^{237}U	208	2.04×10^7
^{239}Pu	414	3.42×10^4
^{241}Am	662	4.61×10^5
^{238}U	1001	73

If scintillators like NaI or BGO are used, it should be noted that they exhibit a strong gain dependence on temperature. The effective gain of NaI may drop by one to three percent per ten-degree increase in centigrade temperature. A simple and practical stabilization technique is to regularly measure a gamma-ray source to compensate for drift. The 60-keV gamma ray from ^{241}Am ($t_{1/2}$ = 460 y) is commonly used as a reference peak.

Figure 1. Comparison of the γ-ray spectra from a sample containing 94 percent ^{239}Pu using four different detectors

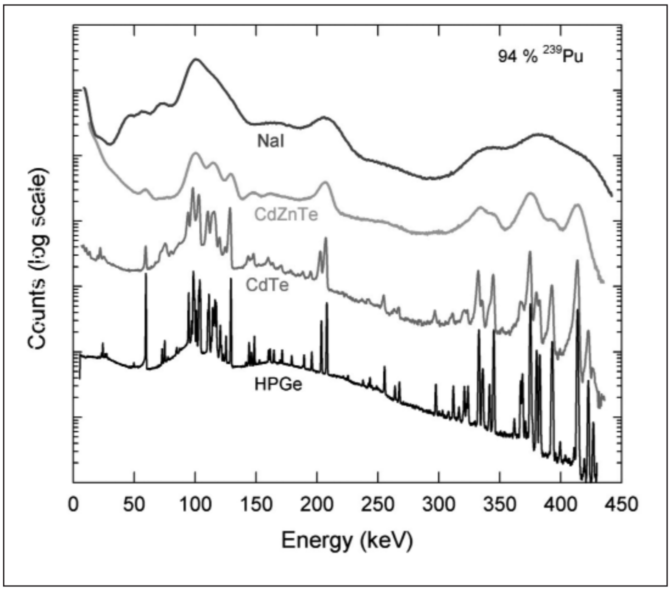

Figure 2. The Peltier-cooled CdTe detector is shown measuring Pu isotopic composition in a glovebox.

Figure 1 shows the gamma-ray spectrum from low-burnup (93 percent ^{239}Pu) plutonium measured with four different detectors (NaI(Tl), coplanar-grid cadmium-zinc-telluride (CPG CZT), Ge, and Peltier-cooled CdTe). The detector most commonly used for holdup measurements is NaI(Tl). A NaI thickness of 1.25 cm absorbs 80 percent of ^{235}U gamma rays at 186 keV. A thickness of 5 cm absorbs 85 percent of ^{239}Pu gamma rays at 414 keV. The intermediate-resolution CZT is equal in sensitivity to the 2.5-cm-diameter NaI despite its limited size. Cubic crystals as large as 1.5 cm on a side absorb up to 95 percent and 40 percent of gamma rays at 186 and 414 keV.

Interferences can add unwanted counts to the assay peak. Detectors with improved resolution and peak shape reduce bias from interference. The use of Ge detectors is generally not possible because of their weight. Recent progress with CdZnTe detectors is favorable for portable gamma-ray measurements.[3] A large CZT detector can resolve interfering gamma rays from the ^{232}Th decay chain that appear in recycled uranium, e.g. the gamma ray at 238 keV. It is not resolved from the 186-keV gamma ray in NaI, but it does not interfere in Ge or CZT. Gamma-ray peaks from ^{241}Pu-^{237}U (332 keV), ^{241}Am (323-335 keV, 662 keV), and ^{237}Np-^{233}Pa contribute to bias in the NaI assay of ^{239}Pu at 414 keV. Many of these effects are readily addressed with CZT, or other recently improved detector materials.

The recent availability of Peltier-cooled CdTe detectors with crystals larger than 1 cm^3 has made gamma-ray isotopic analysis of uranium and plutonium truly portable. Figure 1 illustrates the good energy resolution of CdTe. Figure 2 illustrates the compact dimensions of the CdTe detector, shown measuring plutonium isotopic composition in a glovebox. The range of CdTe for isotopic analysis covers 3 percent to 30 percent ^{240}Pu; it also covers ^{235}U from 0.1 to ~80 percent, and MOX. A 15-minute count with a CdTe detector measures the ^{240}Pu fraction to 2 percent and the ^{235}U fraction to 3 percent.

Generalized Geometry Holdup (GGH) Assay Method

A. Assumptions and Constraints

The Generalized Geometry Holdup (GGH) method categorizes each geometry, no matter how complex, as a series of simple point, line, or area deposits.[4] This is illustrated in Figure 3 below. The GGH assay method was developed to simplify the analysis of holdup measurements performed with NaI(Tl). It can, however, be applied to any detector. The analysis of holdup data using GGH requires the following constraints:

1. Radiation shielding is used on the back and sides of the crystal.
2. A cylindrical collimator is installed on the front of the crystal.
3. The detector is positioned so that the deposit can be approximated as:
    a. a small point source, or
    b. a narrow, uniform line source (length >> width), or
    c. a uniform area source.
4. Measurements are performed at a known distance r between the detector and the deposit.

B. Calibration

The calibration of the GGH method determines the relationship between the count rate of the measured gamma ray and the mass of the isotope of interest. Calibration of the assay of a point, line, or area deposit is accomplished with a point source. The response for each gamma-ray peak is measured with this source positioned

Figure 3. Illustration of point (a), line (b), and area (c) holdup deposits

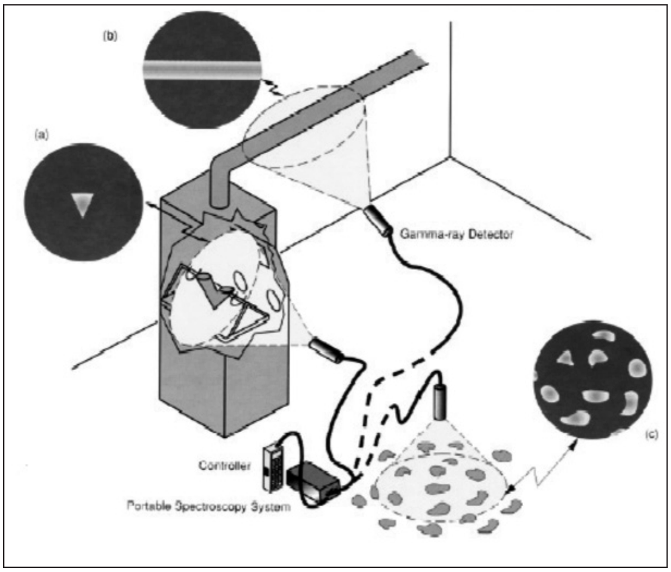

Figure 4. GGH applied in a uranium facility to measure an overhead duct

on the detector axis at a known distance from the crystal. Measurements are also performed with the source displaced at fixed intervals from the crystal axis to obtain the two-dimensional radial response of the detector. These data are used to obtain the calibration for the assay of the specific isotope mass in a point, line, or area deposit.

C. Performing the GGH Measurement and Assay

Using the GGH method to determine uranium or plutonium holdup requires a portable spectroscopy system and a calibrated detector. Because count times are often very short (5–15 s), the random uncertainty can be large for individual measurements. Propagating the uncertainties of the many measurements to get the total holdup in a piece of equipment greatly reduces the random error.

The initial assay result is the specific isotope mass for a point, line, or area deposit. Three additional corrections are required for equipment attenuation, finite-source dimensions, and the self-attenuation of the deposit. In recent measurements of ^{239}Pu holdup in bulk-processing equipment using the 414-keV gamma ray, the equipment attenuation correction factor varied from a low of 1.1 (lead-lined gloves) to a high of 6.2 (steel plates on a glovebox floor[4]).

Holdup Measurement Systems

The Integrated Holdup Measurement System at the Y-12 HEU plant in Oak Ridge, Tennessee, is a good example of a comprehensive holdup measurement system.[5] To measure HEU holdup within the plant, Y-12 has identified many thousands of measurement points, each indicated by a bar code. Operators carry a small multichannel analyzer (MCA), a collimated NaI detector, and a handheld bar code reader with a data logger/controller. Thousands of locations are measured each month. Data from the data logger is downloaded into a computer running a program called Holdup Measurement System version 4 (HMS4). This has been used successfully for more than seven years. An extensive study was made of system performance using simulated holdup situations such as pipes, ducts, and V-blenders with known U or Pu sources. Figure 4 below shows a technician at Y-12 measuring an overhead duct.

Figure 5 shows a similar measurement system in use at a plutonium processing facility. In this case a telescoping pole, such as used by house painters, is needed to position the NaI detector near the overhead pipes and ducts. Figures 6 and 7 show other ^{235}U holdup measurements in a uranium processing facility using Ge, CZT, and NaI detectors. Figure 6 shows a very large overhead duct being measured with a portable Ge detector weighing ~10 kg with collimator. Figure 7 shows CZT and NaI detectors weighing ~1 kg each with collimators. The greater portability of the room-temperature detectors is essential for most holdup measurements.

The Rocky Flats Plant near Denver, Colorado, was built to process plutonium and produce *pits*, which are the fission core of thermonuclear weapons. The plant ceased operations in 1993, and has now been dismantled, cleaned, and converted into an environment park. During its operating lifetime (~50 y), Rocky Flats accumulated large quantities of plutonium in the gloveboxes, filters, calciners, pipes, and air duct systems of several major processing buildings. This holdup was a significant health and criticality safety concern, and at times was a major contributor to the material unaccounted for (MUF) for the facility. During the decommissioning of the processing buildings, the holdup measurement campaigns were among the largest and most

Figure 5. A compact NaI detector is shown during measurements of plutonium deposits in overhead ducts.

Figure 6. A large overhead duct is measured from below with a collimated Ge detector.

Figure 7. Measurements of 235U deposits in a filter system performed with CZT and NaI

extensive ever reported. The holdup measurement teams pioneered the use of low-resolution BGO detectors, and the use of measurements made with the detectors in contact with pipes or ducts. Although this approach is more susceptible to uncertainties in material distribution than the GGH methodology, it allows routine measurements to be made more quickly. As buildings were decommissioned and the process lines were removed and cleaned out, it was often possible to obtain comparisons between the measured holdup and cleanout values. The overall results of numerous measurements of extended equipment lines tended to be unbiased.[6]

Accuracy of Gamma-Ray Holdup Measurements

The precision or random error can be readily determined for holdup measurements. Because of the many measurements performed, the overall precision is usually of the order of a few percent or less. However, the accuracy or systematic error is very difficult to determine, because it is difficult to know the true mass of nuclear material held up in the equipment of a complex facility. Often, the accuracy estimate for a holdup campaign is simply the "best guess" of the measurement team based on judgment and experience. Such estimates are typically in the range 25 percent to 50 percent or more, because of the many unknown factors and assumptions required to calculate the nuclear material mass. In some cases, e.g., gloveboxes, known standards can be introduced and measured in addition to the holdup. In a few cases, an effort was made to cleanout and recover the measured material, which was then analyzed destructively and compared with the measured holdup. A complete cleanout is usually difficult and costly, but this is the best way to determine holdup assay accuracy.

In the early 1980s, a holdup measurement campaign was conducted at a shut down part of the Portsmouth Gaseous Diffusion Plant (PGDP) in Ohio. Gamma-ray measurements were made with a collimated NaI detector and neutron measurements were made using large slab detectors. A total of approximately 250 stages (converter, cooler, compressor, and piping) were measured during the campaign. Afterwards, three cells (twelve stages each) were cleaned out and the uranium recovered. The U was also measured and recovered from an isolated converter. The results from this are summarized in Table 2. Because the gamma-ray measurements only covered the converters, they should only be compared with the neutron assay of the isolated converter. These results are typical of what one finds in such

Table 2. Evaluation of PGDP holdup assay

Cell	n kg U[a]	γ kg U[b]	Recovery kg U
A	177	45	120
B	32	3	28
C	29	12	25
isolated	9	10	7
converter			

a. *The neutron counters were not well collimated and measured an entire stage and double-counted the cooler.*

b. *Gamma-ray measurements covered only the converters.*

holdup studies.

A six-year study was conducted on the accuracy and precision of holdup measurements using the GGH approach to measure simulated holdup situations with well known nuclear material standards. A series of simulations were fabricated for this study and a training course; they included a pipe array, a steel pipe, an aluminum pipe, a rectangular ventilation duct, a V-blender, and a contaminated spot on a floor. These were *salted* with U or Pu fuel rods, U metal foils, and small cans of UO_2 or PuO_2. Table 3 summarizes the results of this study, which included measurements made by many people ranging from students to holdup experts. The results shown here are "best case" vis-à-vis assay accuracy.[7]

Table 3. GGH Holdup Assay Evaluation

	^{235}Ua	^{239}Pua
Pipe array	0.90	0.72
V-blender	1.22	1.02
Al pipe	1.03	0.97
Steel pipe	0.97	1.47
Floor spot	0.96	n/a
Duct	1.07	0.96

a. *Number listed is the average ratio of measured U or Pu to the reference value.*

Conclusion

Holdup measurements provide important information for the operator to use in operating their facility and in their accounting system. The measurement results and the associated uncertainties are used in multiple ways, typically by personnel who are not measurement specialists. Most holdup measurements are made with gamma-ray based systems, these systems have evolved over the years as the technology improves and as the user needs change to yield tools that are easier are faster to use. Some measurement uncertainty results were discussed. They are not of the quality generally obtained by fixed instrumentation in dedicated counting rooms, and they may not be a reliable indicator of the quality of future measurements.

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Holdup Characterization of the UO_2F_2 "Hockey Stick" Deposit Using Cf-Source-Driven Transmission Imaging*

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Abstract

A method had to be developed that could fully characterize the mass, shape, location, and composition of a large deposit of enriched (3.5 wt percent ^{235}U) uranyl fluoride (UO_2F_2) in a hockey-stick-shaped section of pipe in the K-29 building of the former Oak Ridge Gaseous Diffusion Plant so that a strategy for safe removal of the pipe could be developed. This large deposit had been formed by leakage of humid air into the UF_6 process gas lines over a period of years. The resulting UO_2F_2 is hygroscopic, readily absorbing moisture from the air to form hydrates of the form $UO_2F_2 \bullet nH_2O$. The ratio of hydrogen to uranium can vary from 0 to 16, and its presence can have significant nuclear criticality safety impacts for large deposits. To properly determine the appropriate course of action for removing the pipe, the following properties had to be determined by a nonintrusive technique: (1) the distribution of the fissile material within the pipe, (2) the total mass of the deposit, and (3) the amount of hydration present. The Nuclear Materials Identification System (NMIS) (previously developed for identification of uranium weapons components in storage containers) was used to successfully characterize this deposit. The distribution, mass, and hydrogen to uranium (H/U) ratio obtained from NMIS agreed with the visual observations after the section of pipe containing the deposit was disassembled. Earlier attempts using conventional gamma-ray spectrometry had predicted more than twice the mass (1,300 kg) and a symmetric distribution of material in the pipe. This paper discusses the details of how NMIS was used to image this deposit and briefly describes some of the improvements that have been incorporated into the NMIS imaging capability since the time of this measurement that make it more useful for nuclear material control and accountability, arms control and nonproliferation, and counterterrorism applications.

Introduction

The Oak Ridge Gaseous Diffusion Plant was built during World War II as part of the Manhattan Project. Its original purpose was the production of enriched uranium, using the gaseous diffusion process, for use in atomic weapons. During its more than forty-year history, the plant produced enriched uranium for the commercial nuclear power industry before it was permanently shut down in 1987. Since that time, restoration of the environment and reclamation of materials have been major activities at the site, renamed the East Tennessee Technology Park in 1997. The K-29 gaseous diffusion building, operated for more than thirty years, was one of the buildings slated for decontamination and decommissioning (D&D) along with other enrichment buildings at the site. Preliminary work indicated that characterization of uranium bearing deposits in various pieces of equipment in the building would be necessary to develop viable D&D strategies.

The holdup characterization described here was performed in 1998 and 1999 by active neutron and gammaray time-of-flight (TOF) transmission measurements through a process pipe using a time tagged ^{252}Cf spontaneous fission source that emits prompt gamma rays and prompt neutrons.[1] The prompt gamma rays and prompt neutrons from ^{252}Cf fission are separated in time, and thus both neutron and gamma radiographs were obtained. This methodology was originally developed at the Oak Ridge Y12 National Security Complex (Y-12) for identification of uranium weapons components in storage containers.[2] It was applied to a large deposit at the K-29 building.[3] This deposit, which came to be known as the "hockey stick" deposit because of the shape of the section of pipe in which it occurred, existed in a 17-ft.-long, 24-in.-outside-diameter process gas line (Figure 1). This deposit was in the B outlet of Unit 2, Cell 7. Nondestructive assay measurements using gamma-ray spectrometry and neutron counting indicated that the hockey stick deposit contained approximately 1300 kg of material enriched to 3.3 wt percent ±0.6 wt percent ^{235}U, uniformly distributed along the pipe. The deposit was formed as a result of a steady wet air leak into the system over a number of years from the 20in. diameter double disc gate valve, visible to the left in the picture in Figure 1. To properly assess the nuclear criticality safety requirements[4] and to provide information that would allow formulation of a safe method to remove the deposit, a characterization of the deposit distribution, its hydration, and its total mass was necessary. This gamma ray and neutron transmission imaging was used for this holdup measurement.

Since the time of these measurements in 1998 and 1999, the use of NMIS with imaging has advanced by use of many more

Figure 1. Process gas line containing the hockey stick deposit and the 20-in-diameter double disc gate valve that was the source of the wet air leak into the system.

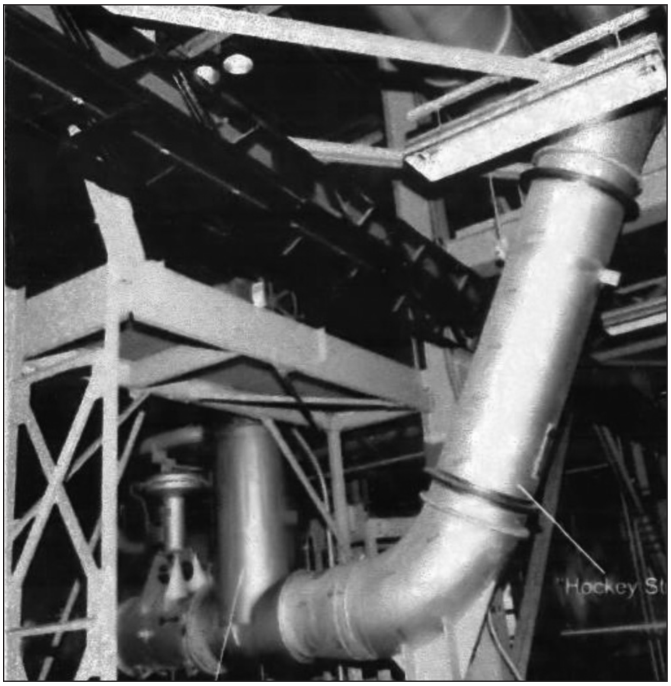
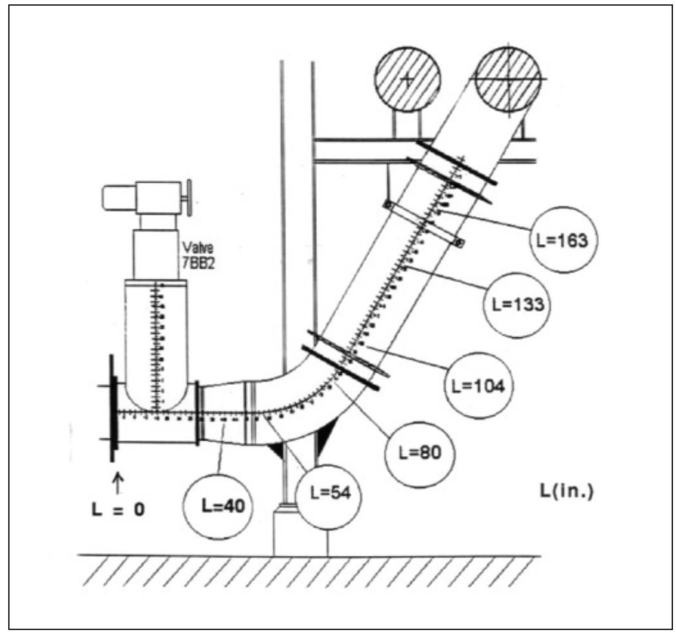


Figure 2. Sketch of the system showing measurement locations



detectors and small portable Deuterium/Tritium (DT) neutron generator with an embedded pixelated alpha detector which make it much more useful for nuclear material control and accountability (such as holdup measurements and fissile receipts and inventory)[5]. This advanced practical system, demonstrated at Y12 for NMC&A, arms control and non proliferation, and counter terrorism applications, can easily identify gun assembled, implosion fission, and thermonuclear weapons and distinguish between them.

Hockey Stick Description

The hockey stick deposit was adjacent to a 20-in.-diameter double disc gate valve visible on the left of the photograph in Figure 1. From the valve, an expanding section of pipe increases in diameter to 24 in., where it attaches to a 24-in.-diameter elbow. The elbow changes the direction of the pipe upward at an angle of ~55 degrees to the riser section of the pipe. The distance from the valve to the upper part of the riser is 15 ft. A sketch of the hockey stick with dimensions marked along the pipe is given in Figure 2.

Instrumentation and Measurement Theory

The NMIS, developed at Y-12 for identification of uranium weapons components in storage containers, was used for these measurements. The NMIS configuration for this application consisted of an external ^{252}Cf spontaneously fissioning source in a parallel-plate ionization chamber; two fast 9.5 x 6.5 x 10.2-cm-thick plastic scintillation detectors (encased in 0.63-cm-thick lead on front face and sides) for measuring the arrival of neutrons and gamma rays; a custom-built, PC-based five channel data acquisition and control board that had a sampling capability of up to 1 GHz; and a standard PC to process and display the data. The signals from the californium ionization and the detectors were transmitted a considerable distance to an uncontaminated area where the data were accumulated. The ^{252}Cf ionization chamber served as a timed source of spontaneous fission neutrons and gamma rays. Neutrons and gamma rays emitted from the spontaneous fission event traversed the pipe and deposited with no interaction (transmission), were scattered within the material, or initiated the fission chain multiplication process. The later processes prevented the source particles from reaching the detectors. The detectors measured the time distribution of counts that occurred after the initiating fission in the source. Because the time of fission is marked by the pulse from the source ionization chamber, the energy of the neutron is determined from the measured time it takes to travel the known distance between the source and detector using the nonrelativistic kinetic energy equation—a neutron time-of-flight (TOF) measurement. Gamma rays that are directly transmitted travel the same speed regardless of energy, thus their arrival at the detector after spontaneous fission is based solely on the separation between the source and detector. Gamma rays that are scattered arrive later in time than those that are directly transmitted, in essence providing a collimated source without having to heavily shield the detector (i.e., collimation by timing rather than lead). The method can be applied in high background radiation areas as

Figure 3. Photograph of the piping with the californium source and detector mounted on the fixture at the location closest to the gate value

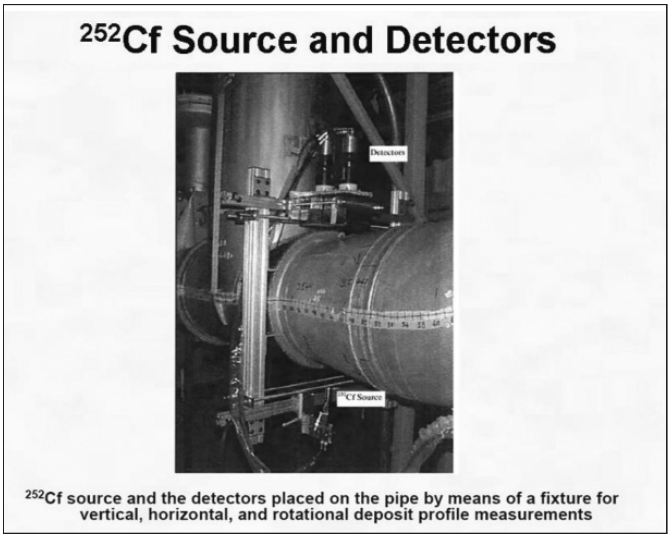
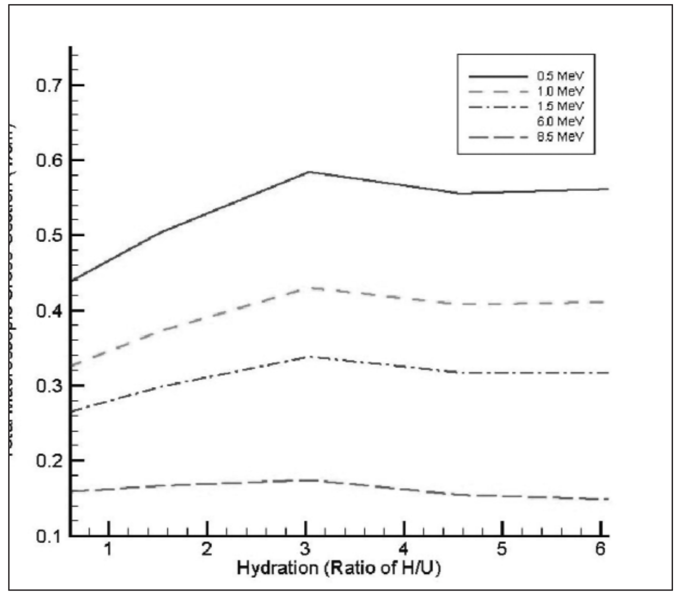


Figure 4. Total macroscopic neutron cross-sections at E = 0.5, 1.0, 1.5, 6.0, and 8.5 MeV

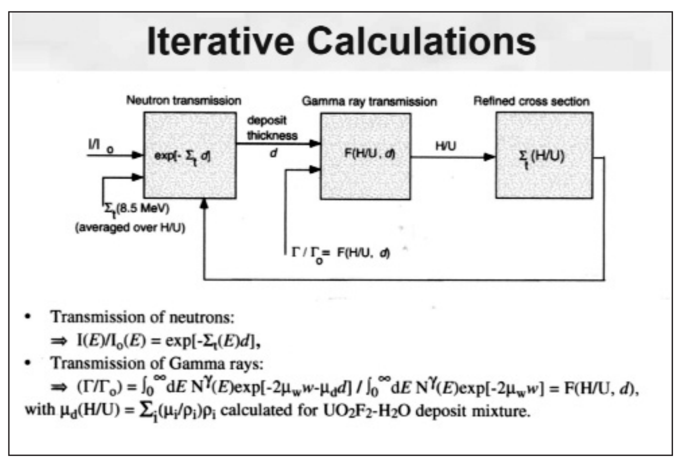


any background radiation is uncorrelated in time with the source. The time correlated signature is equivalent to the right half of the cross-correlation function between the source and detector and is essentially a randomly pulsed neutron measurement.[1]

As UO_2F_2 hydrates, the material density changes as a result of the displacement of the dense uranium component by the relatively light hydrogen. The material density can change by about a factor of four over the full range of hydration, making a normal transmission measurement determination of the material properties impossible, because what would be measured would be the product of the thickness and the attenuation coefficient. The ^{252}Cf provides a timed source of neutrons and gamma rays, thus providing two simultaneous measurements. A photograph of the californium source on the bottom of the pipe and two detectors mounted on a fixture on the top of the pipe is shown in Figure 3. The fixture allowed the source and detectors to be simultaneously traversed both horizontally (show in Figure 3), vertically, and also rotationally around the pipe. To achieve a vertical scan, the fixture was rotated 90° on the pipe and the source and detectors traversed vertically. In this way the transmission was measured for a wide variety of paths through the deposit. Detailed measurements were performed at distances of 40, 54, 80, 104, 133, and 163 in. from the gate valve. In analyses to estimate the mass along the whole pipe, linear interpolation was used between measurement locations.

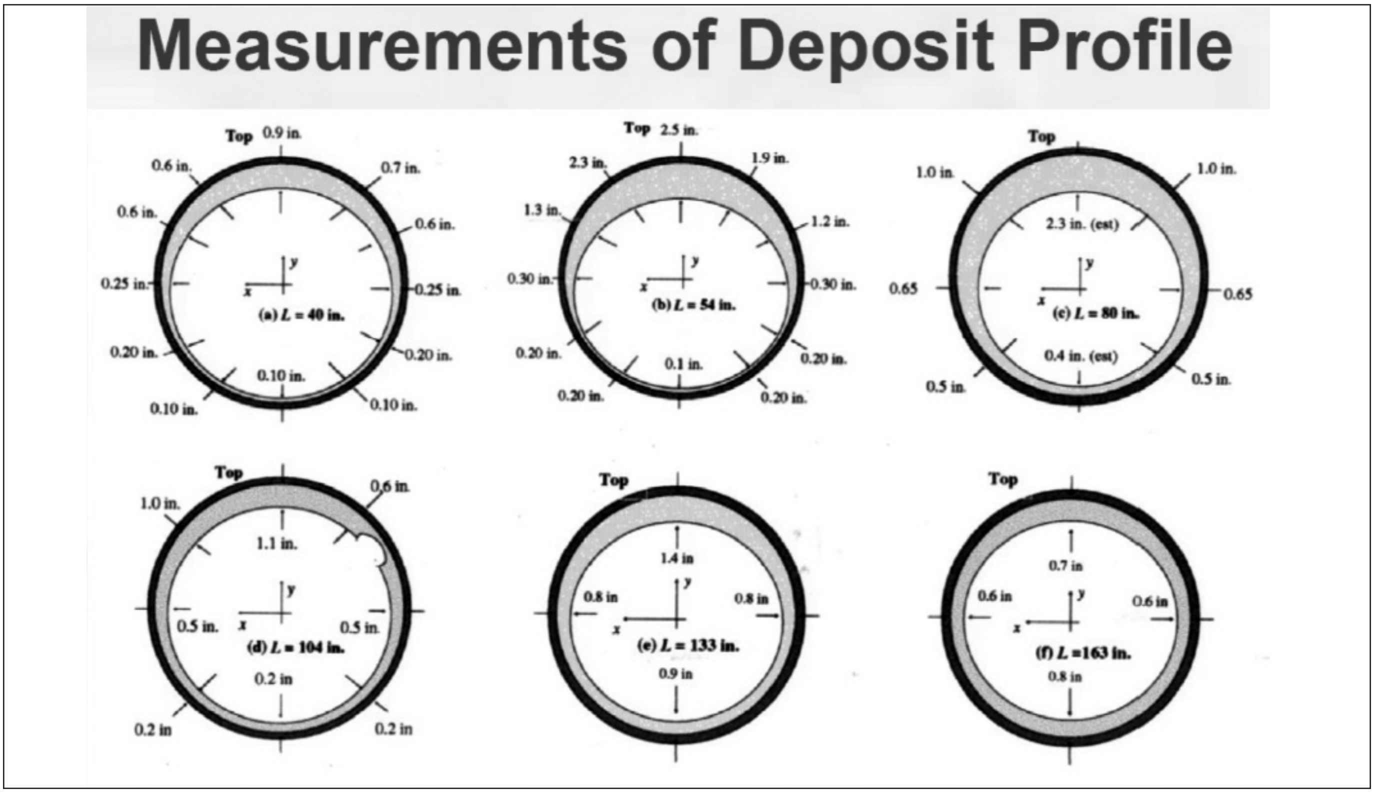
In the first measurement, high-energy neutrons (> 8 MeV) were used to measure the deposit thickness and construct a profile of the deposit distribution. This is possible because the neutron total interaction cross-section above 6 MeV is essentially flat with hydration, varying by less than 10 percent. Above 1.5 MeV, the hydrogen cross-section rolls off sharply, leaving the ^{235}U and ^{238}U cross sections to dominate. However, the relative abundance of the hydrogen is much greater than the uranium and these two

Figure 5. Iterative calculations for determining thickness and density from measured transmissions



competing effects offset each other, leading to the relatively flat total neutron interaction cross-section shown in Figure 4. At low energies the total macroscopic cross-section is sensitive not only to slight changes in hydration, but to slight perturbations in the incident neutron energy, denoted by the large separation between the three cross-sections at low energy (0.5, 1.0 and 1.5 MeV). At high energies (above 6 MeV) the cross-sections, in addition to being essentially flat, are only weakly affected by perturbations of the incident neutron energy. This is important because it demonstrates that small timing uncertainties (1 ns) in the TOF measurement, which are related to the measured neutron energy, will not have a significant effect on the calculation of material proper-

Figure 6. Deposit distributions inside the pipe at locations of 40, 54, 80, 104, 133, and 163 in.



ties. Because the total interaction cross-section (above 6 MeV) is approximately constant and can be calculated for any hydration (density), the deposit thickness can be determined from the ~8 MeV neutron transmission measurements.

Because the geometry is now known from the neutron transmission measurements, the second measurement (gamma-ray transmission) can be used to determine the density, which is related to the deposit hydration. The gamma-ray cross-sections are highly Z-dependent, making the gamma-ray transmission measurement well suited for determining the density. Due to the fast timing resolution of the NMIS system (1 ns), gamma rays that are scattered or interact arrive later in time than those that are directly transmitted, in essence providing a perfectly collimated source to measure the material mass attenuation coefficient. However, because all transmission gamma rays arrive at the detector at the same time regardless of energy, it is necessary to use a prompt fission gamma-ray spectrum-weighted approach to determine the material properties. Using the estimate of the deposit thickness obtained from the neutron data, the mass attenuation coefficient, which is distinctly related to the deposit density or hydration, is then determined. The values of I_0 were obtained from identical measurements with an identically shaped short section of pipe that did not contain any deposits. This resulted in removing the effects of the pipe from the transmission. The measurement results were then refined by a series of iterative calculations as depicted in Figure 5.

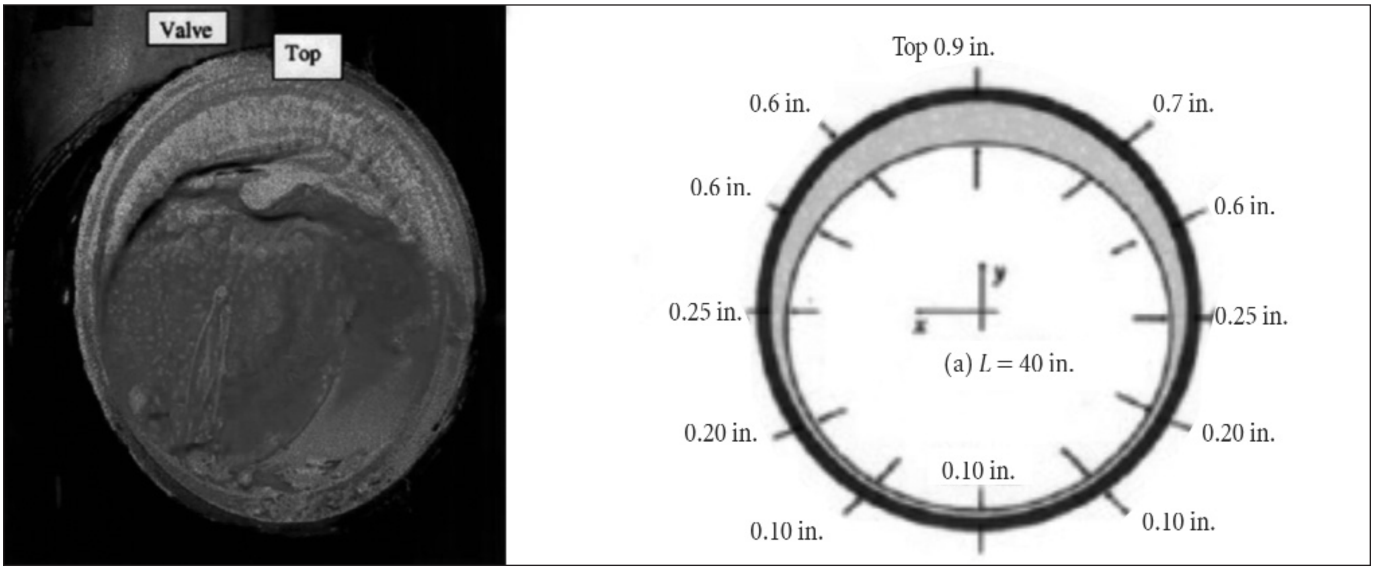
The process begins by assuming a constant total macroscopic cross-section for neutrons (which in fact varies by about 10 percent over the range of hydration). Once the thickness is determined from the neutron portion of the measurement, the hydration is calculated from the gamma portion of the measurement. This hydration is then used to refine the neutron cross-sections and obtain a new thickness from the neutron data. This new estimate of the thickness is then reapplied to the gamma transmission measurement for a new estimate of the hydrogen to uranium ratio, denoted as H/U. This process continues until values of the thickness and hydration are acceptably converged.

Measurement Results

The measured distributions of material deposited inside the pipe at various locations are given in Figure 6.

In the lower sections of the pipe the major portions of the deposit were on top of the pipe. This has still not been explained. The missing material in the upper right from the measurements at a location of 104 in. was confirmed when the pipe was eventually disassembled. Originally the plan was to drill a hole in the top of the pipe and insert a boroscope and take pictures of the inside of the pipe. After persistence in explaining that the measurements were correct and the deposit was mainly at the top of

Figure 7. Deposit profile measurements and observation during disassembly of the hockey stick



the pipe, the project team decided to drill the hole in the bottom of the pipe for the boroscope photograph. The active interrogation measurements determined that the H/U ratio was 3.60 ± 0.24 for one detector and 3.40 ± 0.25 for the other detector. Because the color of such deposits varies with H/U ratio, the color of the deposit from the boroscope photographs could be used to determine the H/U ratio. The H/U ratio indicated by the color in the boroscope photographs was 3.4, which agrees very well with the measurements. The low H/U ratio alleviated some criticality safety concerns. A photograph of the pipe after it was cut is compared with the measured distribution of the deposit in Figure 7.

The total mass of the deposit from the active interrogation measurements was 552 ± 93 kg for one detector and 532 ± 90 kg for the other. The measured mass of the removed deposit after it was collected into storage containers was ~ 479 kg, which agrees with the results from these active interrogation measurements. These masses were considerably lower than the values from gamma-ray spectrometry measurements that estimated the mass at more than 1,000 kg, uniformly distributed. The measured distributions were asymmetric towards the top of the pipe.

Based on this characterization, deposit removal proceeded safely.

Conclusions

The total mass of the deposit from the active interrogation was 552 ± 93 kg from measurements with one detector and 532 ± 90 kg for the other. The measured mass of the removed deposit after it was collected into storage containers was ~ 479 kg which agrees with the result from these active interrogation measurements. These masses were considerably lower than the values from gamma-ray spectrometry measurements that estimated the mass at ~ 1,300 kg and uniformly distributed. The measured distributions were asymmetric towards the top of the pipe. The active interrogation measurements determined that the H/U ratio was 3.60 ± 0.24 for one detector and 3.40 ± 0.25 for the other detector. Since the color of the deposit varies with H/U ratio, the color of the deposit from the boroscope photographs indicated that the H/U ratio was 3.4 which agreed very well with the measurements. Based on this characterization the deposit removal proceeded safely.

It was successfully demonstrated that the NMIS imaging capability provides a reliable method for nonintrusive characterization of hydrated uranyl fluoride deposits. The radiographic characterization can be performed when neither the material mass nor density is known, and it can be successfully applied in environments where other methods fail due to high background radiation conditions or self-shielding effects.

Since the time of these measurements in 1998 and 1999, the use of NMIS with imaging has been advanced through modifications to the equipment and configuration, including use of many more detectors and a small portable deuterium-tritium neutron generator with an embedded pixelated alpha detector which make it much more useful for nuclear material control and accountability (such as holdup measurements and fissile receipts and inventory).[5] This advanced practical system, demonstrated at Y12 for nuclear materials control and accountability, arms control and nonproliferation, and counterterrorism applications, can easily identify gun assembled, implosion fission, and thermonuclear weapons and distinguish between them.

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Programmatic Lessons Learned During Rocky Flats Holdup Measurements Supporting Site Closure

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Abstract

The purpose of this report is to document the history of holdup measurements at the Rocky Flats Environmental Technology Site (RFETS) and to supply lessons learned from the management, training, staffing, and documentation of those measurements. Nuclear material holdup can build up in any location where fissile material is processed or handled; it can be found in ducts, pipes, filter plenums, tanks, gloveboxes, storage areas, pumps, filters, and even floors and walls. Holdup measurements at RFETS were primarily performed using the nondestructive assay technique of gamma-ray spectroscopy by the generalized geometry holdup technique. Holdup measurements were performed for material accountability and safety purposes. RFETS was closed in 2005. During its last fifteen years, advancements in holdup measurements were evaluated, implemented, or discarded. Key lessons learned are documented here.

Introduction

Prior to 1989, the only routine measurements of fissile material holdup performed at Rocky Flats Environmental Technology Site (RFETS) were tank and pipe scans to verify compliance with nuclear material safety limits. Additional gamma-ray surveys of holdup were performed on an irregular basis. Need for a dedicated holdup measurement team became clear in 1990 when the Defense Nuclear Facilities Safety Board Recommendation 90-6 was accepted by the secretary of the U.S. Department of Energy (DOE) and an implementation plan was issued. The implementation plan called for specific tasks to "reduce the probability of a criticality accident and maintain an acceptably low level of risk to the workers and the public." Task 1 of the implementation plan called for determination of fissile material accumulation through a phased approach of detailed measurements for areas indicated as containing significant holdup. The implementation plan also called for validation of the ductwork assay results by use of calorimetric assay of material removed from the ducts.

The task of forming a holdup measurement team was performed by Jerry McKamy. Of the original personnel hired for this task during 1990 and 1991, approximately 50 percent continued in this field for close to fifteen years. The attrition rate was such that twenty people were hired in the first five years in order to maintain a staffing level of ten. When the staffing level was increased to fifteen in 2001, the retention rate was less than 50 percent. Reasons for staff turnover included that holdup measurements can be repetitive and do not offer the degree of accuracy or precision found in fixed NDA systems.

Fortunately, numerous site NDA scientists spent significant time mentoring team members. John Fleissner trained the team in gamma-ray spectroscopy tailored specifically for holdup measurements. The members of the holdup measurements team attended numerous off-site courses in nondestructive assay, gamma-ray spectroscopy, radiation detection, and measurement control.

Lesson Learned: The effort to convert NDA professionals to holdup measurements personnel was problematic. Site NDA professionals were willing to work with and train new team members as long as the interaction was clearly short term but the majority of site NDA professionals did not choose to support holdup measurements full time. The attitude was "why work so hard for a plus or minus 50 percent measurement when calorimetric assay results are considered to be within 2 percent of the true value?" Thus, the holdup team was formed of individuals with a variety of work histories.

Measurement Campaigns

Conducting holdup measurements at RFETS was an iterative and learning process consisting of several campaigns. Those campaigns are discussed below.

Exhaust Ductwork Measurements

The RFETS holdup measurement team developed and implemented a systematic, phased program for assessing nuclear material process holdup in site exhaust ductwork. The method selected expanded on the generalized geometry holdup (GGH) methods developed at the Los Alamos National Laboratory (LANL). A width-model technique was developed while Phase I measurements were being conducted and was implemented for Phase II duct measurements at the site. The width-model technique used the ratio of bottom and top measurements to calculate the width of the deposit at each measured location.

Phase I measurements provided a gross estimation of the maximum possible amount (i.e., upper bound) of fissile holdup material in specific locations selected by the RFETS Criticality

Engineering group. Phase II was developed in an effort to provide measurements with a higher degree of accuracy and precision in order to quantify the total duct holdup material. Phase II measurements were used to evaluate the nuclear and criticality safety of individual ductwork flowpaths, to provide an upper bound for the nuclear material quantities needed to validate building safety reviews, to identify ducts containing more than 400 grams of plutonium (the threshold mandating remediation), and to establish an accountability inventory of ductwork holdup.

Lessons Learned: In the early start-up effort of the holdup measurement team, two significant errors in data analysis and reporting were identified. The first was due to poor communications of actual measurement configuration to the data analyst, who was not part of the measurement team. The analysis error caused under-reporting by greater than 50 percent for a section of ductwork. Corrective actions included using a computer program for data entry instead of copying to paper, which improved accuracy in data transmission. Also, the data analysts were required to be part of the measurement teams to improve the knowledge of the measurement configuration. The second 'growing pain' mistake in the first year occurred as a result of equipment configurations prevalent at RFETS. In this case, an overhead plutonium storage area was located close enough to the exhaust duct being measured to significantly increase the holdup results for the ductwork. The corrective actions for this problem lead to the use of the width-model method of ductwork measurements.

Untoward Area Campaign

By July 1991, all ductwork holdup characterization was complete and the primary task of the holdup measurement team was to re-measure remediated areas as cleanout occurred. LANL conducted a peer review of the program and data analysis improvements were incorporated into the measurement program. Comparison data became available as cleanout and re-measurement occurred.

The Duct Remediation Program Plan was written in early 1991. In the development of this remediation plan, a decision was made to include gloveboxes as part of the exhaust ductwork system. As a result, holdup measurements of gloveboxes in one major production building (Building 707) were planned and performed. The remediation plan recommended identification of all potential holdup locations. The scope of work included all equipment and systems connected to the exhaust ductwork. Holdup measurements were required for locations where an expert review team evaluated that holdup was likely to exceed the 400-gram ductwork system threshold. The measurement campaign was completed in 1993 and the measurement results were added to the site holdup inventory. A criticality assessment reported in July 1993 that "a criticality due to plutonium holdup in untoward areas is not possible, because of the expected configuration of the plutonium."

Attribute Scan Program

Attribute scan measurements were performed in 1995 by the holdup measurement team in an effort to prioritize and plan for measurements needed to quantify all remaining holdup. These scans consisted of a single gamma-ray count assay and background count at an identified location on each glovebox in the processing facilities. These scans followed the measurement control, standard traceability, and training requirements for accountability measurements. As items were scanned, the results were compared to background measurement results for that location. Locations were evaluated for statistical differences between assay results and the background count rate. The evaluation of the scan results was used to prioritize quantification measurements.

Lesson Learned: The highest scan results did generally indicate the gloveboxes with the highest amounts of holdup. However, for buildings where knowledgeable subject matter experts (SME) were available, the SMEs did a better job of identifying locations with high holdup than the attribute scans did. In the one major processing building where no knowledgeable SME was identified, the attribute scans proved very useful in identifying which areas were most likely to contain elevated amounts of holdup. The use of scanning techniques was valuable for piping, but of limited use for more complex equipment. Scans should not be used to eliminate equipment from complete characterization.

High Holdup Campaign

In 1996, quantification of holdup at RFETS became focused on assaying areas identified in the scan campaign as having high amounts of holdup. Compliance with the DOE requirement that holdup be quantified where feasible was achieved by this graded approach. Glovebox and equipment locations were selected using several criteria; (1) attribute scan results, (2) consultations with knowledgeable site personnel or SMEs, and (3) video characterizations where available. This campaign was completed June 30, 1998, consisted of thousands of individual measurements of high holdup locations, included a variety of special requests for holdup measurements, and doubled the site holdup inventory.

Lesson Learned: The use of knowledgeable personnel and SMEs was a successful tool for selecting areas with high holdup. The SME for one building identified approximately 80 percent of the total holdup in the building in 25 percent of the process equipment. This SME had worked in the building more than thirty years and had been the operations manager for more than ten years.

Facility Characterization

To support the final closure activities of RFETS, holdup measurements were completed in all buildings to characterize any remaining holdup inventory. The measurement schedule was coordinated with, and prioritized according to, the site plans to deactivate and decontaminate each building prior to demolition and environmental restoration. The results were initially used as part of evaluating safeguards and security requirements. As the holdup material was cleaned out, the quantity of holdup remaining in each building was used by safety organizations to support reduction in safety requirements.

Locations characterized included all gloveboxes, hoods, and all equipment in the gloveboxes and hoods, the ductwork system, tanks, pipes, and rooms that were expected to contain fissile material. Removal of in-process material and product were required prior to holdup characterization. The measurement results were evaluated by an SME to document expert opinion of the safeguards category of the holdup material. The safeguards categories were determined by the form and density or concentration of the material as well as how removable it was. Additional measurements were required to quantify remaining holdup in areas after cleanout activities were performed.

Prior to downgrading or terminating safeguards and security requirements, "wall-to-wall" scans of a facility were performed to demonstrate that holdup was not in unexpected areas and that any remaining holdup quantities were below thresholds requiring safeguards or security measures. These wall-to-wall scans were required as part of verifying the total MAA inventory for safeguards and accountability categorization. Large quantities of holdup were removed from all processing buildings, possibly eliminating the need for a security area. Numerous activities, including verifying that remaining holdup did not exceed acceptable amounts were performed. In each case, initial measurements and SME evaluation indicated that holdup totals did exceed the quantities which would allow a security downgrade. Cleanout efforts and additional characterization measurements were performed.

Lessons Learned: (1) The SME determination was routinely conservative. In one case, the holdup in a plenum was determined by the SME to be less than 10 percent plutonium. An oversight team believed that the material was more likely to be greater than 10 percent plutonium by weight. During the actual material removal, all containers measured less than 10 percent plutonium by weight, confirming the initial SME evaluation. (2) The resources required to measure all equipment for facility characterization and measure the majority of individual items removed from gloveboxes were underestimated. The holdup measurement team had to increase equipment and personnel by 50 percent to support mission critical tasks.

Training of Measurement Personnel

The holdup measurement team (HMT) personnel were extremely fortunate to receive both formal and informal training from a series of mentors. From the start of the team, an annual written training plan was submitted to the manager of the material control and accountability (MC&A) organization for approval. Training combined discussion, lectures, simulation, and on-the-job training.

Qualification records of the HMT personnel performing instrument setup, measurements, calibration, and measurement control was documented and maintained by Rocky Flats Training Records. Training and qualification required an average of one year per employee. Completion of the LANL Safeguards and Technology Program "Nondestructive Assay of Special Nuclear Material Holdup" was a requirement for qualification beginning in 1990. Advantages of the Safeguards and Technology Program holdup training were the excellent instructors, the well thought out mockups modeling real world situations, the freedom from interruptions, and the confidence building of comparing results with those of teams from other sites.

The benefits of a very thorough training program included an excellent safety record with no on-the-job injuries in more than ten years and proficiency that resulted in timely and accurate holdup measurement support.

Lesson Learned: The LANL Safeguards and Technology Program holdup training offered benefits beyond those achievable with a mock-up training facility at the site. Adding attendance of that program as a requirement for qualification was a key to the success of the RFETS holdup team.

Holdup Accounting

The site accounted for duct material as "reportable inventory" beginning in 1991. Holdup results from gloveboxes and tanks were entered into the accountability database after the external peer review determined that the method was qualified for accountability purposes. The HMT produced and updated a holdup inventory report every two months with values for all holdup locations measured to date. The HMT holdup inventory was adjusted to account for all new measurements, re-measurements, and removals. Included in the report were the building number, the specific location, the gram quantity and 95 percent uncertainty, and the date the individual measurement was reported. As the MC&A organization developed measurement criteria for categorizing areas or determining when safeguards could be reduced or terminated, measurement data to compare against those criteria were added to the report.

As cleanout work in the buildings accelerated, material custodians requested the HMT report be produced once a month. By receiving and reviewing the holdup inventory report monthly, the custodians were able to insure that the data agreed with current building conditions. The HMT and MC&A personnel performed monthly comparisons of the inventory by item to ensure consistent holdup tracking. The individual in the MC&A organization responsible for maintaining the holdup account was separate from the MC&A custodian, who verified the physical conditions of the holdup.

A special account was created within the accountability database for each building with a single item in that account representing the total holdup inventory for the facility. The individual items or locations reported in the HMT inventory report were combined into the single item. This allowed the MC&A organization to track the difference between the total holdup measured in place and the measured value of the holdup material after it was removed.

Lessons Learned: (1) Most MC&A personnel have indicated that the holdup inventory should have been listed individually in the accountability database rather than placing the bulk holdup grams from the holdup inventory report into the accountability database as a single item per account. (2) The custodian must perform walk-through inspections no less than monthly to monitor holdup locations and to determine if there have been holdup removals. If there have been partial removals, the item should be adjusted by the estimated percent removed. The percent removed estimate should be performed following visual verification by the custodian. (3) In final stages of a facility closure, holdup removal is happening very rapidly. The custodian needs to frequently monitor the building account to track items being repacked or added to existing containers and ensure the needed information is captured on appropriate paperwork.

Summary

In summary, available evidence indicated that holdup measurement results at RFETS were consistently accurate within 20 percent and were typically conservative. The holdup measurement team measured approximately 220 kilograms of plutonium holdup at RFETS. Safety was a major priority, demonstrated by no lost-work time injuries. By the time buildings were ready for demolition, the holdup inventory was reduced to zero grams. Measurements were used for material control and accountability, criticality safety, and nuclear safety purposes. Holdup measurements proved to be a key part of the $7 billion efforts of deactivation, decontamination, demolition, and remediation for the safe, cost effective closure of RFETS.

A Return to Atoms for Peace: Provision of an Experimental Compact Liquid Metal Fast Reactor to North Korea

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Abstract

Should the United States' negotiating strategy call for a new nuclear reactor deal in exchange for denuclearization by the Democratic People's Republic of Korea (DPRK), an experimental compact Liquid Metal Fast Reactor (LMFR) is an attractive option. To arrive at this conclusion, several reactor options are considered in the context of a future reactor deal. Most importantly, the view that advanced reactor systems are long-term options too premature to contribute to current policy issues is explicitly challenged. A number of objectives including energy security, proliferation resistance, safety, and political feasibility are identified that will improve the viability of a reactor deal with the DPRK.

Compared against these objectives, the compact LMFR is a major leap forward with distinctive features well-suited for a new reactor deal. First and foremost, the reactor provides proliferation resistance through strong inherent physical barriers and new reprocessing technologies. Second, the removable reactor module is readily integrated into multilateral supply arrangements that invalidate the pretext for domestic enrichment and reprocessing capabilities. Third, this reactor provides long-term energy security and significantly reduces the frequency of demands for fuel cycle services. Fourth, should the agreement fail, the reactor module can be removed or, conceivably, be destroyed by force with minimal public health consequences. Fifth, the compact LMFR is expressly designed for sites like the DPRK with limited energy infrastructure. Lastly, all members of the Six Party Talks can be engaged in this reactor project by virtue of existing collaborations, expertise, and interest in advanced nuclear energy systems.

These distinctive features form the basis of a new reactor deal that incorporates carrots and sticks to achieve nonproliferation objectives while deterring non-cooperation. The three elements of this new deal focus on 1) conferring prestige through multilateral cooperation, 2) creating incentives for cooperation, and 3) deterring non-cooperation. First, an international reactor project involving all members of the Six Party Talks will confer prestige to the DPRK and may motivate verifiable denuclearization. Second, the high energy value of nuclear fuel in the LMFR may draw nuclear material away from military applications. Finally, the ability to remove or destroy the reactor creates strong and credible sanctions for non-cooperation and offers greater political flexibility.

This new deal requires strong commitments from members of the Six Party Talks to overcome the political liability associated with delays in reactor development, counter DPRK attempts to cheat, and assure the supply of nuclear material and fuel cycle services. By locking down existing nuclear materials in this reactor and discouraging the DPRK from retaining or producing nuclear material, this deal prevents the situation from deteriorating and offers an opportunity for progress by engaging all members of the Six Party Talks.

Introduction

A key stipulation of the now-defunct 1994 Agreed Framework (AF) was the provision of two light-water reactors (LWR) to the Democratic People's Republic of Korea (DPRK).[1] Strained U.S.-DPRK relations following, *inter alia*, revelations of a clandestine DPRK uranium enrichment program and delays in reactor construction led to the collapse of the AF and the reactor deal.[2] The Six Party Talks (6PT) between the United States, China, Japan, Russia, the DPRK, and the Republic of Korea that emerged to tackle the resulting crisis have made little progress. The provision of a reactor remains a point of contention. The September 19, 2005, 6PT Joint Statement papered over the dispute by leaving the discussion of a new reactor to an "appropriate time" that must be preceded by verifiable disarmament and a "sustained commitment to cooperation and transparency."[3] Following the October 2006 nuclear test by the DPRK, progress in the 6PT negotiations was stalled by the DPRK's "excessive" energy demands.[4] In February 2007, the DPRK tentatively agreed to cease further nuclear weapons material production in exchange for energy aid of an unspecified nature.[5]

Should U.S. negotiating strategy call for a new reactor deal, understanding the strengths and drawbacks of available technological options is imperative. To this end, we discuss several different reactors, highlight characteristics relevant to a future reactor deal, and outline elements of a new deal. In particular, we challenge the view that advanced reactors are long-term options[6] too premature to contribute to current policy issues. After considering several reactor systems, we argue that the provision of an experimental compact liquid metal fast reactor (LMFR) to the DPRK is an attractive option.

The LWR Deal

The AF stipulated the provision of two LWRs supplied under the umbrella of the Korean Peninsula Energy Development Organization (KEDO), an international consortium involving South Korea, Japan, the European Union, and the United States.[7] Initial DPRK opposition focused on the "unproven safety and performance characteristics" of the Korean Standard Nuclear Power Plant LWR design despite its demonstrated operational and safety record.[8] One interpretation suggests that the DPRK views a reactor deal as a litmus test for U.S. attitudes and intentions toward the DPRK rather than a necessity.[9] The difficulty of integrating a 1,000 megawatt electric (MWe) LWR into the DPRK's antiquated electricity grid (roughly 10 GWe total with only a few GWe operating reliably)[10] supports such an interpretation.

LWRs themselves can be effectively safeguarded against theft, diversion, and clandestine irradiation by classical safeguards methods. Escaping detection by safeguards is unlikely given the difficulty of covertly moving intensely radioactive LWR spent fuel or clandestinely irradiating material in the core to produce high quality plutonium (Pu). The Reactor Grade Plutonium (RGPu) contained in spent fuel can be used as a nuclear explosive,[11] but this material is relatively unattractive for theft and diversion since it requires a more sophisticated weapons design when compared against weapons grade plutonium (WGPu). Though WGPu can be produced if one has unfettered access to the core of a LWR, classical safeguards and non-cooperative verification measures (e.g., satellite imagery[12]) can provide indications of such reactor operations.

The more troubling aspect of LWRs is their dependence on sensitive fuel cycle technologies, namely enrichment and reprocessing that can be used to produce material for a nuclear explosive. Operating a LWR that requires refueling every twelve to eighteen months creates strong incentives to acquire enrichment and other front-end fuel cycle facilities. In the longer term, reprocessing facilities are desired for energy security and radioactive waste management. Possession of a LWR, therefore, provides a pretext for building important elements of a nuclear weapons program. Though assured supplies of nuclear fuel[13] provide an institutional measure to reduce these incentives, the possibility of politically motivated supply interferences creates insecurities. In view of these insecurities and the possible failure of institutional measures, a greater reliance on inherent technological barriers is preferable.

Alternative Technologies

A number of alternative reactor technologies could be substituted for a LWR. Relevant reactor characteristics are highlighted followed by a summary of objectives for an improved reactor deal with the DPRK.

Heavy Water Reactor (HWR)

A HWR fueled with natural uranium (NU), such as the CANDU design, obviates the need for enrichment and eliminates the pretext for enrichment facilities. On the other hand, frequent online refueling multiplies opportunities to produce Pu by diverting low burnup fuel or by clandestinely irradiating targets. Additionally, the heavy water required for HWR operations could be redirected to a production reactor capable of producing WGPu. Though a HWR reactor can be effectively safeguarded, tracking numerous transfers of fuel bundles requires more intensive and costly safeguards in comparison to a LWR.

Pebble Bed Modular Reactor (PBMR)

The smaller PBMR reactor (~100 MWe) is more readily integrated into the DPRK's transmission infrastructure than a LWR and its modular design allows for future expansion. Though requiring enriched fuel, reprocessing the PBMR's coated particle fuel to extract Pu is difficult. While this is an attractive feature with regard to nonproliferation objectives, coated particle fuel technology may preclude a closed fuel cycle and limit sustainability. Furthermore, the use of nuclear-grade graphite and its potential use in a graphite-moderated Pu production reactor are problematic. And, like the HWR, frequent online refueling multiplies opportunities for clandestine irradiation of targets.

Floating Nuclear Power Plants[14]

Despite the fact that a complete assessment of this concept is dependent on the type of reactor employed on a floating platform, the possibility of removing the reactor from the state raises intriguing counterproliferation options should the deal go sour. Though somewhat unconventional, the excellent safety record of the modern nuclear navy and U.S. experience with the Sturgis floating reactor lends confidence to this concept.

Objectives

The following criteria for judging a future reactor deal with the DPRK derive from, in addition to general nonproliferation concerns, the preceding discussions of alternative technologies and the failed AF.

Reduce

- Incentives for acquiring fuel cycle technologies
- Access to dual use materials (graphite, heavy water, etc.)
- Opportunities for clandestine irradiation, theft, and diversion
- Material attractiveness (RGPu vs. WGPu, etc.)
- Power output

Increase

- Safety
- Sustainability and energy security
- Tolerance to the failure of institutional measures
- Amenability to safeguards and institutional measures
- Counterproliferation options
- Modular design

Compact Liquid Metal Fast Reactor

The innovative compact LMFR satisfies the objectives outlined above and is well suited for a new reactor deal with the DPRK. A proposal by Toshiba to demonstrate its compact LMFR design in Alaska creates an opportunity to deploy this system in the near future.[15] In the remainder of this paper, we describe important characteristics of compact LMFR technology and discuss the use of this reactor as the basis for a new reactor deal.

General Characteristics

All compact LMFR design variants share a number of features including proliferation resistance, passive safety, a long-life core, and modular design. Consider, for example, the Encapsulated Nuclear Heat Source (ENHS) developed primarily by the University of California at Berkeley, Lawrence Livermore National Laboratory, Argonne National Laboratory, Westinghouse, and three South Korean research organizations.[16] The ENHS is a modular, low power density (50-100 MWe), fast reactor cooled by naturally circulating molten lead. The ENHS was expressly designed for deployment in developing countries and remote sites with limited energy and nuclear infrastructures[17] – an apt description of the DPRK.

Energy Security: The ENHS Fuel Cycle

The essentially self-sustaining, long-lived core of the ENHS guarantees energy security well into the foreseeable future. The initial core load consists of low-enriched uranium (LEU) or, more likely, a mixture of RGPu and NU. Plutonium is bred *in situ* and the core is designed to operate for about twenty years at full power. After two decades, the reactor module (consisting of a sealed vessel containing the fuel embedded in the solidified lead coolant) is removed for reprocessing. Proliferation-resistant reprocessing technologies remove fission products while leaving actinides commingled. NU or depleted uranium (DU) is added as makeup, fuel is refabricated and the sealed reactor module is reinserted for another twenty years of full power operation. Except for the makeup of NU or DU, the core is essentially self-sustaining due to plutonium breeding.

Proliferation Resistance

This reactor design features inherent physical barriers that limit core access and restrict the availability of sensitive nuclear materials. Furthermore, a state's reliance on multilateral fuel cycle services is more politically palatable due to a dramatic reduction in the reactor's dependence on these services.

Physical Barriers to Proliferation

Theft and diversion from the core and clandestine irradiation are physically difficult, time consuming, and readily detected. Stealing or diverting nuclear material from the core requires shutting down the reactor, removing the bulky lead-filled reactor module, cutting through the sealed reactor vessel, removing the solidified lead coolant, and cutting fuel elements anchored to a grid plate. Clandestine irradiation is a similarly elaborate task. Unlike other fast reactor concepts, the absence of a fertile blanket in the ENHS eliminates this route for dedicated Pu production. Many of these actions are readily observable (via safeguards or satellite imagery) and can be addressed before the action is successful. Since reprocessing technologies leave actinides commingled, the fuel is no more attractive for theft and diversion than spent LWR fuel. The possibility of misusing these reprocessing technologies to separate fissile material must be fully evaluated. Theft and diversion during transportation is also unlikely due to the bulk and radioactivity of the reactor module.

Multilateral Fuel Cycle Services

The removable core is amenable to multilateral fuel cycle systems[18]—an essential feature for use in the DPRK to limit incentives for acquiring sensitive fuel cycle technologies. The sealed reactor module can be shipped abroad for reprocessing and fuel refabrication, obviating the need for fuel handling and fuel cycle equipment in the host country. Attempts to tamper with the sealed reactor module in the DPRK would be easily detected and construed as a violation of safeguards agreements. Furthermore, the long-lived, self-sustaining core increases the acceptability of multilateral supply by reducing the frequency of demands for sensitive fuel technologies and minimizing the system's sensitivity to supply disruptions. Fuel cycle technologies are only required for the initial fuel load and again every twenty years when the reactor module is replaced (as opposed to every twelve to eighteen months for a LWR). The time between refuelings provides ample opportunity to renegotiate fuel supply arrangements should a politically motivated supply interruption occur.

Inherent Safety and Counterproliferation

The inherently safe design of the ENHS has obvious safety and reliability benefits, but also creates less obvious counterproliferation options. With few moving parts and natural circulation cooling, one of the few conceivable methods of permanently damaging the reactor is by deliberate attack. While a full vulnerability analysis must be performed, the reactor could conceivably be disabled by force with minimal, if any, consequences to public health.

Technical Uncertainties

The unproven experimental nature of this reactor design introduces significant technical uncertainty that impacts the viability of a new reactor deal. Fabricating fuel from reprocessed ENHS fuel requires development. Furthermore, the degradation of materials over the twenty-year lifetime of the reactor module is poorly understood in the harsh chemical and radiation environment of a nuclear reactor core. The inaccessibility of the core and the opaque lead coolant also pose maintenance issues in the event of, for example, a fuel element failure. Fuel handling equipment could be located in the state to repair problems, but this increases the accessibility of the core. Though such failures could be solved by replacing the core module, an unknown core module failure rate creates financial uncertainties and energy insecurities.

Elements of a New Deal

The distinctive characteristics of the innovative ENHS design provide the basis for a new reactor deal. In addition to exchanging a reactor for denuclearization, this deal incorporates carrots and sticks unique to this type of reactor to encourage nonproliferation objectives and deter non-cooperation. The three elements of this new deal focus on 1) conferring prestige through multilateral cooperation, 2) creating incentives for cooperation, and 3) deterring non-cooperation.

Prestige and Multilateral Cooperation

The DPRK's participation in an international project to develop a cutting-edge technology that in some respects is the fission equivalent of ITER[19] will confer prestige and international recognition to the DPRK. If the DPRK political leadership interprets the project as a signal of positive U.S. intent, the DPRK may overlook technical uncertainties in the reactor's design and agree to denuclearize. Backing by all members of the 6PT to develop the reactor and to assure access to nuclear fuel and fuel cycle services increases the credibility of this deal.

Incentives for Cooperation

Fuel Matching

While the DPRK has enough material for about six nuclear weapons,[20] this is insufficient for the ENHS, which requires approximately seventeen tonnes of Pu.[21] Thus, other members of the 6PT must provide the majority of the fuel. A fuel-matching program could be structured such that suspected DPRK stockpiles are relinquished for use in the ENHS. Alternatively, the deal could require a minimum quantity of material provided by the DPRK without which the reactor deal would not go forward.

Energy Security

The long-term energy security provided by the ENHS vastly increases the value of nuclear material for peaceful uses and may draw out material from military applications. Although the DPRK may prefer an ENHS over a LWR, the benefits of energy security must outweigh the benefits of nuclear weapons to draw out material from the DPRK weapons program. This may be impossible as the DPRK may be fanatically determined to retain their nuclear weapons. Maximizing the value of nuclear material in peaceful uses remains the best course of action in view of this possibility; generating confidence that the reactor will operate as advertised is essential to achieve this end. Otherwise, additional measures are necessary to reduce the benefits of nuclear weapons or to impose greater costs for possessing nuclear weapons.

Deter Non-Cooperation

Strong disincentives that impose costs for non-cooperation are necessary to deter non-cooperation and overcome uncertainties in material quantities. Non-cooperative actions include the continued production or withholding of nuclear material. The further production of material can be dissuaded by establishing a cut-off date for relinquishing fuel beyond which additional fuel stockpiles would not be considered for incorporation into the reactor. To induce compliance, this measure must be coupled with intrusive verification of denuclearization backed by credible threats of punishment. One such sanction is the removal of the ENHS reactor module or the reactor's destruction by force. The possibility of attacking an operating ENHS with minimal consequences to public health increases the credibility of this option. However, the potential for a DPRK military response against U.S. forces and allies in the region may lead to escalation, deter U.S. military action, and reduce the feasibility of this threat.

Failure Modes

Juche

While the ENHS fuel cycle vastly reduces the frequency of demands for fuel cycle services, notions of self-reliance, or juche, may drive the DPRK to demand reprocessing facilities and additional supplies of nuclear material to sustain the ENHS and fuel additional ENHS modules. Although this type of reactor makes dependence on assured supplies more acceptable, any country would prudently anticipate the failure of such institutional measures. For instance, the DPRK may restart their PUREX reprocessing facilities to refuel the ENHS. If this were to occur, locating a proliferation-resistant reprocessing system in the DPRK in exchange for the shutdown of the PUREX facility may be tolerable. Generating more LEU or RGPu to start additional ENHS modules is more problematic as this will require enrichment or conventional reactors and reprocessing. Consequently, assured supplies of fuel are essential to minimize incentives for acquiring these technologies. Similar issues exist with all reactor designs, but greater dependence on multilateral supplies is more tolerable with an ENHS.

Motivation

The possibility that the DPRK is determined to possess nuclear weapons no matter what carrots are offered must also be considered. Should the DPRK accept the deal as proposed, they may nonetheless take steps to ensure that the deal fails and pin the blame on members of the 6PT. Delays in reactor development will be a key issue in this scenario. As with the LWR deal, every opportunity will be taken to portray the lack of progress as evidence of foot-dragging by the United States, and the DPRK may become increasingly reluctant to denuclearize. The strong backing of all members of the 6PT, especially those more closely allied with the DPRK, will be necessary to reassure the DPRK that progress is being made, dispel accusations of foot-dragging, and compel the DPRK to continue cooperating.

Political Feasibility

The political feasibility of this proposal requires more in-depth analysis, but is inevitably confounded by political ideology and interpretations of DPRK intentions. For instance, Wit, Poneman, and Galluci describe two schools of thought in the United States: realists vs. idealists. The former prefer to make the best out of a bad situation while the latter describe the DPRK as habitual cheaters determined to maintain their nuclear weapons program.[22] Using these concepts as a springboard, we will attempt to describe, perhaps naïvely, how the various states may view this new proposal on its technical merits, present alternative views and describe how potential pitfalls might be overcome.

DPRK Perspective

The DPRK political leadership could view this project favorably on its technical merits. Not only does an ENHS provide greater energy security and satisfy North Korean notions of juche, the prestige of developing and hosting an innovative international reactor project could be irresistible. On the other hand, the DPRK may regard this as an attempt to swindle them with an unproven reactor technology. To overcome this uncertainty, all members of the 6PT must emphasize the prestigious nature of this project and assure the DPRK that all five parties are committed to developing the ENHS. Without such commitments, the DPRK may fear that the reactor will never be operational and thus not worth any concessions.

U.S. Perspective

Realists in the U.S. government should favor the deal as it attempts to improve the situation by locking down current nuclear stockpiles and preventing further production. Idealists who believe the DPRK leadership to be inveterate cheaters are unlikely to be swayed. Both camps will be concerned by the untested nature of the reactor and the inevitable accusations of foot-dragging by the DPRK. Though recent hints of progress in the 6PT offer some hope, the Bush administration is boxed in by its “axis of evil” rhetoric. Backing away from the administration’s entrenched position may lead to potshots from Democrats and stiff opposition from Republicans fearing appeasement.[23] Many of these concerns are related to any reactor deal and are not specific to the LMFR. Nonetheless, the LMFR project is consistent with the vision of the Global Nuclear Energy Partnership recently announced by the Bush administration to promote the development of proliferation resistant nuclear technologies, small-scale reactors and an international fuel cycle.[24]

6PT Members

Broad support for this reactor project is required to demonstrate that all 6PT members are committed to the program and to present a unified front to compel the North Koreans to comply with the terms of the deal. Existing U.S., South Korean, and Japanese participation in compact LMFR design and fuel cycle technology can be extended to include all members of the 6PT. The Russians are ideal partners from their experience with the liquid metal cooled Alfa submarine reactors.[25] China can be engaged given its strong interest in nuclear energy and advanced nuclear power systems.[26] China’s influence in North Korean affairs is essential in compelling DPRK compliance. All of these countries are also likely hosts for fuel cycle services.

Conclusion

Should U.S. negotiating strategy call for a new reactor deal in exchange for denuclearization by the DPRK, an experimental compact LMFRs such as the ENHS offers a proliferation-resistant nuclear energy system with a unique set of carrots and sticks that engages all members of the 6PT. By locking down existing nuclear materials in this reactor and discouraging the DPRK from retaining or producing nuclear material, this deal prevents the situation from deteriorating and offers an opportunity for progress via multilateral engagement. Implementation requires careful consideration for timing the elements of the deal to reach an agreement as the DPRK’s stockpile of nuclear material represents one of their few sources of leverage.[27] Strong backing by all other members of the 6PT is critical to overcome the political liability of the inevitable delays in reactor development, counter DPRK attempts to cheat, and assure the supply of nuclear material and fuel cycle services. Even if this project ultimately fails due to DPRK intransigence, this concerted effort to provide the DPRK with at least one of their stated objectives will tease out their true ambitions and help build international support for further action.

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simulations relevant to the National Ignition Facility to advanced reactor technologies and their application to current United States policy. Fahlen received M.S. and B.S. degrees from UCLA in 2005 and 2001, respectively.

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U.S., Russia Sign Plan for Russian Plutonium Disposition

Russian and U.S. officials in November signed a joint statement outlining a plan to dispose of thirty-four metric tons of surplus plutonium from Russia's weapons program.

Under the new plan, the United States will cooperate with Russia to convert Russian weapon-grade plutonium into mixed oxide fuel (MOX) and irradiate the MOX fuel in the BN-600 fast reactor currently operating at the Beloyarsk nuclear power plant, and in the BN-800 fast reactor currently under construction at the same site. The United States and Russia also intend to continue cooperation on the development of an advanced gas-cooled, high-temperature reactor, which may create additional possibilities for disposition of Russia's plutonium.

The United States and Russia agreed that the BN-600 and BN-800 fast reactors will dispose of Russia's surplus weapons plutonium without creating new stocks of separated weapon-grade plutonium. Under the new plan, Russia would begin disposition in the BN-600 reactor in 2012. Disposition in the BN-800 would follow soon thereafter. Once disposition begins, the two reactors could dispose of approximately 1.5 metric tons of Russian weapons plutonium per year.

Russia intends to implement this program, with the United States contributing $400 million, as previously pledged for cooperation under the 2000 Plutonium Management and Disposition Agreement and subject to appropriations by the U.S. Congress. The agreement commits the United States and Russia to dispose each of thirty-four metric tons of surplus weapon-grade plutonium.

DOE Cites Battelle Energy Alliance for Price-Anderson Violations

The U.S. Department of Energy (DOE) today notified Battelle Energy Alliance, LLC (BEA) that it will fine the company $123,750 for violations of the DOE nuclear safety requirements. BEA is the DOE Idaho Operations Office prime contractor for the operation of the Neutron Radiography (NRAD) reactor. The NRAD is used to non-destructively examine irradiated materials; the imaging technique utilizes thermal neutrons and is used for quality control purposes in industries that require precision machining.

The Preliminary Notice of Violation (PNOV) issued in late November cited a series of violations that occurred on August 20, 2006, during the restart and subsequent automatic unplanned shutdown of the NRAD reactor. Violations include failures to adhere to technical safety requirements and reactor operating instructions, inadequacies in the reactor operating instructions, failure to correct known problems with a reactor component, and failure to adequately conduct management assessments in reactor operations.

The proposed civil penalty of $123,750 is based on the significance of the violations and reflects substantial mitigation granted by DOE for BEA's identification of the issues and corrective actions they have taken to prevent recurrence of the identified deficiencies. While the deficiencies in NRAD reactor operations did not compromise reactor safety systems, they did represent a significant departure from what the Department expects in the operation of its reactors. BEA will have thirty days to respond with any objections to the notice.

Canada to Join Global Nuclear Energy Partnership

Canadian officials announced in late November that Canada has accepted an invitation to join the Global Nuclear Energy Partnership (GNEP). GNEP is an international partnership that promotes a safer, more secure and cleaner world through the responsible development of nuclear energy for peaceful purposes. GNEP will focus on enhanced safeguards, and cooperative research in developing advanced technologies.

The U.S. Department of Energy officials commended Canada's announcement that it will join the voluntary partnership that seeks to expand the use of clean and affordable nuclear energy for peaceful purposes worldwide in a safe and secure manner through a closed nuclear fuel cycle that increases energy security, while promoting non-proliferation. Canada's announcement will bring the total number of GNEP partners to eighteen.

Retired Major General Sworn in as Head of NNSA Defense Programs

Retired Major General Robert L. Smolen was sworn in as deputy administrator for defense programs at the U.S. Department of Energy's National Nuclear Security Administration (NNSA). Smolen will oversee the nuclear weapons program for NNSA.

Previously, Smolen served as commander for the Air Force District of Washington until his retirement from the U.S. Air Force in August 2007. Prior to that, Smolen served as the director for Strategic Policy and Arms Control at the National Security Council. From 1998-2004, Smolen held various positions at the Pentagon, including director of Nuclear and Counterproliferation for the United States Air Force headquarters and director for Manpower and Personnel for the Office of the Joint Chiefs of Staff. Smolen served as commander of the 72nd Air Base Wing at Tinker Air Force Base in Oklahoma from 1996-1998.

U.S., Latvia to Cooperate on Preventing Smuggling of Nuclear and Radioactive Material

The U.S. and Latvian governments will coordinate efforts to thwart nuclear smuggling by installing radiation detection equipment at multiple border crossings in Latvia. The agreement signed today means the two countries will work together to detect illicit shipments of nuclear and other radioactive material.

The agreement, signed by the U.S. Department of Energy's National Nuclear Security Administration (NNSA) and the Ministry of the Interior of the Republic of Latvia, will allow NNSA to install radiation detection and integrated communications equipment, and provide related training at multiple border crossings, airports and seaports in Latvia. U.S. technical experts have begun working with the State Border Guard Service of Latvia by surveying sites for future equipment installations.

NNSA's Second Line of Defense (SLD) program is performing the work with Latvia and provides detection systems around the world to help combat nuclear proliferation and terrorism. SLD installs radiation detection equipment at strategic locations and provides training in detection, identification, and interdiction of nuclear and radiological materials, as well as training in the operations and maintenance of the equipment.

Security Upgrades Completed at 25 Russian Nuclear Warhead Sites

With the completion of U.S.-funded security upgrades at a Russian Strategic Rocket Forces base in Siberia in October, all of the security work at twenty-five Russian nuclear missile sites outlined in a 2005 agreement between Presidents Bush and Putin has been finished. The final base completed, known as GSM-5BR, is part of Russia's network of bases with intercontinental ballistic missile nuclear forces and personnel.

The agreement covers twenty-five rocket sites at eleven Russian missile bases, and calls for NNSA to do this work as a part of its overall, annual $1.7 billion global nuclear nonproliferation and threat reduction mission.

Since 2003, NNSA has spent about $150 million to improve security at the twenty-five Russian Strategic Rocket Forces sites. Upgrades include state-of-the-art intrusion detection and monitoring systems, metal and explosives detectors, new entry control portals, and nuclear material detectors. In addition, security guard forces at the sites received strengthened fighting positions, a centralized response facility and look-out towers. The work was carried out through NNSA's Material Protection, Control and Accounting program by experts from Sandia and Oak Ridge National Laboratories.

NNSA has secured enough Russian nuclear material for thousands of warheads and has completed upgrades at more than 85 percent of the Russian nuclear warhead, material and missile storage sites of concern with work underway at the balance of sites to be completed by 2008. NNSA has also secured numerous nuclear material buildings outside of Russia.

U.S. and Mongolia Sign MOU to Increase Cooperation in Preventing Nuclear Smuggling

The governments of the United States and Mongolia signed a Memorandum of Understanding, which will kick off cooperation between the two countries to prevent illicit trafficking of nuclear and other radioactive material.

Under the agreement, the U.S. Department of Energy's National Nuclear Security Administration (NNSA) will install radiation detection equipment at several of Mongolia's border crossings and at the Chinggis Khan International Airport in Ulaanbaatar. NNSA plans to install radiation portal monitors on Mongolia's main border crossings to detect nuclear and radiological radiation coming from vehicles, pedestrians, and railroad cars.

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 physical protection, material control and accounting, waste management, transportation, nuclear nonproliferation/international safeguards, and arms control and verification. *JNMM* also publishes book reviews, letters to the editor, and editorials.

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  2. Jones, F. T. 1976. *Title of Book*, New York: McMillan Publishing.
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Nuclear Safeguards Pioneer G. Robert Keepin

Photo courtesy of Los Alamos National Laboratory

Former INMM Chairman and Los Alamos National Laboratory Fellow G. Robert Keepin, honored many times over the years for his groundbreaking efforts in developing nuclear safeguards at Los Alamos, passed away at Los Alamos Medical Center on New Year's Eve, December 31, 2007.

The "Father of Los Alamos Safeguards," Keepin founded the LANL Nuclear Safeguards Research and Development Program in 1966 and became a leader in international safeguards.

Keepin was elected chairman (now president) of INMM in 1979-1980. He was a Fellow of the Institute and was honored with the Distinguished Service Award in 1982. During his many years of service on the Executive Committee (1975-1982), he initiated or sponsored a number of activities that are central to INMM including the idea of chapters, which culminated with the acceptance of the Japan Chapter in 1976; the establishment of the Awards Program; the formation of Technical Working Groups that evolved into today's Technical Divisions; and the exploration of the need for an executive director of INMM that was established in 1982.

In mid-November 2006, Keepin was honored at the American Nuclear Society's 2006 Winter Meeting and Nuclear Technology Expo with a special award in recognition of more than forty years of work in the areas of safeguards and nonproliferation. The award was presented at the General Chair's Special Session on Nonproliferation and Security.

"Bob Keepin not only was the father of nuclear safeguards at Los Alamos, his intelligence and leadership inspired generations of Los Alamos staff in N Division and elsewhere," said INMM president and LANL Nuclear Nonproliferation (N) Division leader Nancy Jo Nicholas. "We will miss him, and we will dedicate ourselves to continuing his vision of a safer world."

Born in 1923, the son of a minister in the upper Midwest, Keepin received his undergraduate education as a V-12 Naval Cadet and a doctoral degree at Northwestern University. He then served as a post-doc at the University of Minnesota and an Atomic Energy Agency Postdoctoral Fellow at the University of California, Berkeley.

In 1952, Keepin joined Los Alamos in the Critical Assemblies Group at Pajarito Site, where he did pioneering work on delayed neutron yields and half-lives culminating in the publication of his much used textbook, Physics of Nuclear Kinetics.

Keepin was a U.S. delegate to the First United Nations Atoms for Peace Conference in Geneva in 1955 and headed the Physics Department at the International Atomic Energy Agency (IAEA) in Vienna from 1963-1965. In 1966, he founded the Nuclear Analysis Research and Development Group, N-6, at Los Alamos to develop methods and instruments to measure nuclear materials in whatever form they are found throughout the world. He named this technology nondestructive assay or NDA. This technology is now in active use at every nuclear facility in the world and by every nuclear regulatory agency. Keepin was instrumental in the formation of the nuclear safeguards program at the United States Atomic Energy Commission and is recognized worldwide for his tireless leadership in developing approaches and technologies in support of nuclear safeguards and nonproliferation.

Keepin returned to the IAEA in 1983-85 as a special adviser to the deputy director general for safeguards. He was appointed a Los Alamos National Laboratory Fellow in 1985. In addition to his work at Los Alamos, and with the INMM, Keepin was a Fellow of the American Physical Society, and the American Nuclear Society.

Keepin retired from Los Alamos in 1990. He is survived by his wife, Madge; children G. Robert Keepin III, William, Mavis, Ardis, and Denise; several grandchildren; and his brother William.

For those wishing to do so, Madge Keepin has requested that donations be made to the American Parkinson's Disease Association, New Mexico chapter (www.nmapda.org). Donations can be mailed directly to NM Chapter ADPA, 10817 Griffith Park Dr. NE, Albuquerque, NM 87123 USA.

Calendar

March 30 – April 4, 2008
INMM – ANS 8th International Conference on Facility Operations – Safeguards Interface
Benson Hotel
Portland Oregon USA
Sponsor: INMM and the American Nuclear Society
Web site: http://nnp.ornl.gov/ans2008/

July 13–17, 2008
49th INMM Annual Meeting Celebrating 50 Years in Nuclear Materials Management
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October 6–9, 2008
6th Joint INMM/ESARDA Workshop: Meeting Safeguards Challenges in an Expanding Nuclear World
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