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J. D. Williams Student Paper Awards

Topical Paper

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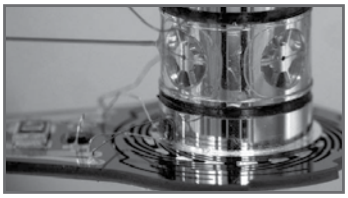

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Transitions and Challenges for INMM

By Ken Sorenson
INMM President

Well, we are in our annual period of transitions at the INMM. We have leadership position changes that I would like to highlight and then discuss some challenges that we have on our immediate horizon. They told me I have 800 words, so here goes.

Transitions

As our bylaws dictate, the President, Vice President, and Immediate Past President are on a two year cycle. Scott Vance is now our Immediate Past President, and Larry Satkowiak and myself were elected to the Vice President and President positions, respectively. As part of this transition, Steve Ortiz has moved out of the Immediate Past President position. Thanks for both Steve and Scott for their leadership and engaged management of the INMM these past two years.

The Member-at-Large positions are also part of this transition period. Mark Schanfein (INL) and Ruth Duggan (SNL) were elected to two year positions as Members-at-Large. Sara Pozzi and Teressa McKinney have rotated off the Member-at-Large positions. Thanks to Sara and Teressa for their contributions and welcome to Mark and Ruth.

These changes do cause cascade effects. Larry Satkowiak has been the chair of the Nonproliferation and Arms Control Technical Division. We are now working with Larry and Steve Mladineo, chair of the Technical Division Oversight, to identify a replacement for Larry for consideration by the Executive Committee.

Another big change we will see this year is with the Technical Program Committee. With the passing of Charlie Pietri in February, our long-standing TPC chair, we conducted a membership-wide search for a replacement for Charlie. From a pool of very well qualified candidates, the EC selected Teressa McKinney to be the chair of the TPC. Teressa has big shoes to fill but we know that she will do an outstanding leadership job with managing the TPC and the Annual Meeting. For the TPC meeting this past year, as well as the 53rd Annual Meeting, Steve Mladineo volunteered to be the interim chair of the TPC. Steve, along with a host of volunteers did an excellent job of running the TPC Paper Selection Committee meeting in March and in conducting the Annual Meeting in July. Thanks to Steve and all of the volunteers for helping make our annual meeting a success this year. And, good luck to Teressa in your new role as TPC chair.

As a volunteer technical institute, these types of changes are normal and healthy. One of the important considerations for an institute such as ours is to continually be thinking of and planning for leadership transitions. As part of our reorganization two years ago, we asked all committee chairs to make leadership transition an active part of their committee planning. We have also asked each technical division and standing committee to have a deputy chair position in place and filled to help with this transition planning.

Challenges

We do have a major challenge facing the INMM this year and for the foreseeable future. The recent U.S. Office of Management and Budget (OMB) guidance on federal employee and federal contractor attendance at conferences and workshops became a major issue for our annual meeting this year. Our meeting is large and went over the DOE guidance attendance threshold that requires an exemption letter. To add an extra level of anxiety, our meeting was the first major conference scheduled after the guidance came out. We were the guinea pigs. Different DOE program offices, DOE site offices, and DOE labs had different interpretations of the guidance and a significant amount of effort went into making sure that due diligence was exercised in meeting the intent of the guidance. Amy Whitworth, an INMM Fellow in DOE/NA-70, took the lead to shepherd an exemption letter through to the Secretary of Energy. Thank you, Amy. In the end, at the last minute, the exemption letter was signed and approval was given for a specific number of DOE employees and contractors to attend the meeting. This process resulted in about 200 professionals not being allowed to attend our annual conference. This did have an impact. Sessions had to be adjusted, some authors had to give multiple presentations, and we didn't meet our budgeted revenue projections overall. Given all of this, the conference did go well. However, we are not out of the woods yet. We have established a small team at INMM to look at all our FY13 conferences/workshops to work the attendance issue with DOE to ensure that we can still hold these important meetings in a way that continues to address the INMM mission while meeting the intent of the OMB guidance. Part of the charter for this INMM team will also be to conduct meetings at the higher levels of DOE management to inform them of the benefits to the DOE mission of the INMM Annual Conference and workshops. We need to do a better job of getting this message out. We also expect to be able to use this message outside the DOE. Stay tuned…

Another challenge that fits into the transition discussion above is key leadership positions that may turn over within the next year or two. We have been fortunate as an organization to have highly competent career individuals lead our technical divisions and standing committees. It's human nature to worry about how to replace these individuals who have demonstrated exceptional leadership. However, I believe one of the core strengths of INMM is the competency through the ranks of our membership. This provides the types of leadership transitions that result in positive outcomes for the institute. As leadership openings occur, we will continue our process of vetting and selecting the most qualified individual within our membership to carry on the duties of the specific committee, as well as the institute as a whole.

Outlook

Given the transitions and challenges that the Institute faces, I am extremely optimistic about INMM's future. Global issues regarding the management of nuclear materials are real and need the membership expertise and institute backing that the INMM provides. Our global reach through our chapters, as well as our partnerships with important sister technical organizations such as the World Institute for Nuclear Security (WINS), the European Safeguards Research and Development Association (ESARDA), and the Nuclear Infrastructure Council (NIC), provide the leverage to make INMM a leader in the field.

I thank you, the membership, for the opportunity to serve as the president of INMM. I look forward to working with you all these next two years on issues directly affecting the institute as well as on broader nuclear materials management concerns. Feel free to contact me directly at any time.

INMM President Ken Sorenson may be reached at kbsoren@sandia.gov.

Wrapping Up the 2012 Annual Meeting

By Dennis Mangan
INMM Technical Editor

As in past fall issues, this issue focuses on the Annual Meeting held this previous summer. With the passing of our Technical Program Committee Chair, Charles Pietri, this 53rd INMM Annual Meeting was chaired by interim-chair Stephen Mladineo who has provided a very informative summary of the meeting.

As Mladineo notes, the opening special session, organized by the Japan Chapter, focused on *Post-Fukushima Challenge in Safeguards and Security.* There are three papers provided that summarize this opening session: *Great East Japan Earthquake, Tsunami, and Fukushima Daiichi's Accident,* presented by Yoshinori Meguro, president of the Japan Chapter; *Overview of the Accident at Fukushima Daiichi Nuclear Power Station and the Process for Achieving Stabilization,* presented by Takeshi Ohta, from the Tokyo Electric Power Company; and *Lessons Learned from the Accident at the Fukushima Daiichi Nuclear Power Station: Nuclear Security Perspectives,* presented by Kaoru Naito of Japan's Nuclear Material Control Center in Tokyo. These three articles are very interesting and informative. Our *JNMM* Roundtable discussion, also included in this issue, involved interviewing these three gentlemen.

Also in this issue are papers by the three 2012 J. D. Williams Student Paper Awards winners: first and second place papers and one first place poster. The first place paper, *Rapid Analysis of the SNM Smuggling Threat Space for Active Interrogation Using a Green's Function Approach,* was authored by Hirotatsu Armstrong and Erich Schneider of the University of Texas at Austin, Texas, USA, and addresses the need to rapidly interrogate and detect the smuggling of special nuclear material in truck or sea containers. The second place paper, *Characterization of Special Nuclear Material Using a Time-Correlated Pulse-Height Analysis,* was authored by several investigators: E. C. Miller, S.D. Clarke, A. Enqvist, and S. Pozzi of the University of Michigan, Ann Arbor, Michigan USA, P. Marleau of Sandia National Laboratories, Livermore, California USA, and J. K. Mattingly of the University of North Carolina State, Raleigh, North Carolina USA. The paper addresses non-destructive characterization of special nuclear material for detecting diversion of such material. The first place poster paper, *Uranium Characterization by Shaped Femtosecond Laser-induced Breakdown Spectroscopy,* authored by P. Ko, K. Hartig, J. McNutt, and I. Jovanovic of the Pennsylvania State University, University Park, Pennsylvania USA, addresses nuclear forensics applications.

Assistant Book Review Editor Mark Maiello provides us an interesting review of the book, *Nuclear Jihad – A Clear and Present Danger?* by Todd M. Masse. Maiello speaks highly of this book and writes, "This amalgam of technical intelligence and policy information on potential promulgation of nuclear weapons by non-state actors contains an enormous amount of useful background information that any policy strategist would want at his or her fingertips."

Industry News Editor and chair of the INMM Strategic Planning Committee Jack Jekowski's column, *Taking the Long View in a Time of Great Uncertainty–INMM's International Role,* provides us with interesting analysis for INMM's international role. Good reading!

Finally, I would like to briefly discuss a new policy that *JNMM* has developed regarding "special issues." These issues are the ones dedicated to a particular topic and are a result of a request of the chair of one of our Technical Divisions. We endorse these special sessions as they can result in the issue being noted as a standard for the topic addressed or a learning tool for people interested in the topic. The execution of the special issues have varied from one special issue request to another. These variances have hopefully been addressed in a constructive way with the new policy which identifies roles and responsibilities and expected performances. We formulated this new policy to bring consistency to the Journal.

Should you have any comments or questions, feel free to contact me.

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

Report of the 53rd INMM Annual Meeting

Stephen V. Mladineo, Interim Chair
Technical Program Committee

The Institute of Nuclear Materials Management held a successful 53rd annual meeting at the Renaissance Orlando Resort at Sea World in Orlando, Florida, July 15-19, 2012. The meeting featured a special opening session of presentations organized by the Japan Chapter of the INMM on Post-Fukushima Challenges in Safeguards and Security. This session was particularly well-attended, reflecting widespread concerns about challenges to nuclear materials management that have arisen as a result of the devastating earthquake and tsunami that struck Japan on March 11, 2011. Japan Chapter President Yoshinori Meguro chaired the first session, and introduced the topic to the INMM attendees. Presentations included lessons learned, safeguards implications, and the road ahead for the nuclear industry in Japan.

As usual, a number of events preceeded the opening plenary session, including a meeting of the INMM Executive Committee on Saturday, at which the business of the INMM was conducted. Among other business, the EC voted to establish an early career award to recognize the contributions of some of our younger members. The meeting also included discussions about the impact to the INMM of recent policy changes that have restricted U.S. government funding for conference attendance, and their possible effect on the Annual Meeting and the budget of the Institute. The Executive Committee concluded that although there would be some attrition in meeting attendance as a result, successful workarounds ensured that the meeting would remain an outstanding experience for those in attendance. The Executive Committee's optimism was justified, as 703 attendees, including 126 students, participated in 61 concurrent sessions with 455 papers presented. Feedback from attendees was overwhelmingly positive, though as usual there were plenty of suggestions for improvement — suggestions that the INMM leadership will seriously consider.

On Sunday a full day of activities took place, starting with an early morning golf tournament with twenty-two participants, organized by Russ Johns at a nearby Marriott golf resort. Annual Meeting Registration opened, headed up by D.L. Whaley; the MC&A Technical Division held Non-Destructive Assay and Destructive Assay Users Group Meetings, led by Chris Pickett for Jeff Chapman, and Jon Schwantes respectively; Melanie May led an ASC N15/INMM 5.1 Committee meeting; the New Student Orientation was conducted by Steve Ward, who also later led the Student Reception and Mixer. Each of the six Technical Divisions held its annual meeting between 2 and 5 p.m. All were well-attended with extra chairs having to be brought in to three of the six session rooms. In the evening the annual President's Reception took place in the Exhibit Hall. This is the traditional opening event for the Annual Meeting, giving attendees an opportunity to meet up with old acquaintances and get a first chance to visit some of the exhibitors.

Monday afternoon kicked off the week's technical sessions with eleven concurrent sessions. Sessions continued throughout the week, making up the heart of the Annual Meeting. Each morning and afternoon there were ten or eleven concurrent sessions that had been organized by the Technical Program Committee during their March meeting. Each Technical Division scheduled sessions based on abstracts submitted by attendees. Some sessions were organized as joint sessions by two or more Technical Divisions, and some special sessions were held that focused on a particular topic of interest to one of the Technical Divisions. The Technical Division chairs did a great job in creating the program. To remind you of those who led all that work I have listed their names and roles below:

- Shirley Cox, Facility Operations
- James A. Larrimore, assisted by Susan Pepper, International Safeguards
- Cary Crawford, Materials Control and Accountability
- Larry Satkowiak, Nonproliferation and Arms Control
- Tom Bonner, Nuclear Security and Physical Protection
- Steve Bellamy, Packaging, Transportation, and Disposition

Taner Uckan, assisted by Grace Thompson, was responsible for organizing the Poster Session.

Tuesday morning started off with the Annual 3K Fun Run. Forty-eight hearty participants ran, walked, or slept in for the benefit of The Wellness House, Hinsdale, Illinois, USA, in honor of the late Charles Pietri, who served as chair of the Technical Program Committee for more than twenty-five years.

Between the Tuesday morning and afternoon concurrent sessions the Institute continued the practice begun at the 2010 meeting of having an extra-long lunch break to permit time for meeting attendees to attend the poster session. A total of thirty-nine posters were presented this year.

Tuesday night the Annual INMM Business Meeting was held and the results of the annual election of officers were announced. The results are Ken Sorenson, President; Larry Satkowiak, Vice President; Chris Pickett, Secretary; Bob Curl, Treasurer; Ruth Duggan, Member-at-Large; and Mark Schanfein, Member-at-Large. A reception and the Annual Awards Banquet followed the Business Meeting.

Seating at the Awards Banquet was organized by the Registration Committee and proceeded smoothly for the 690 people who attended the banquet. INMM President Scott Vance made several presentations, during which a photograph of each recipient was projected for everyone to see. Resolutions of Respect were presented to the families of Charles Pietri, Trond Bjornard, Allan Leibowitz, Jim Stewart, and Denny Weier. Five new Fellows were introduced: Shirley Cox, Shirley Johnson, Cathy Key, Kaoru Naito, and Alejandro Vidaurre-Henry. The Vincent J. DeVito Distinguished Service Award was presented to Laura Rockwood. Edway R. Johnson Meritorious Service Awards were presented to Teressa McKinney and Sara Pozzi. Yvonne Ferris and Dennis Mangan both received Charles E. Pietri Special Service Awards. And the outgoing Executive Committee Members-at-Large, Teressa McKinney and Sara Pozzi, and outgoing Past President Steve Ortiz were recognized.

Every day there were lunch meetings and additional evening professional meetings. These included a *JNMM* roundtable led by Technical Editor Dennis Mangan, a POTAS Coordinator's Meeting led by Susan Pepper, and the New Member/New Senior Member Reception led by the Membership Committee's Michelle Romano. The INMM Fellows met to discuss how the INMM could do a better job of reaching out to international members, and what new initiatives the Institute might pursue. The Chapter Committee Chair John Matter held a meeting with Chapter Presidents, and a career fair for student members was held on Wednesday night, led by Student Activities Subcommittee Chair Steve Ward for Student Career Fair Chair Cathy Key. All of the attendees had the opportunity to visit the exhibit hall each day, and to discuss opportunities and products on display with the exhibitors. And innumerable side meetings took place among the nuclear materials management professionals in attendance.

The Closing Plenary on Thursday rounded out the Annual Meeting. INMM President Scott Vance presented the following student awards:

- Robert J. Sorenson Scholarship to Jessica Feener, Texas A&M University

The J. D. Williams Student Paper Awards:

- 1st Place Oral Presentation – Hirotatsu Armstrong, University of Texas, Austin
- 2nd Place Oral Presentation – Eric Miller, University of Michigan
- 1st Place Poster Presentation – Phyllis Ko, Pennsylvania State University

The J. D. Williams Award winning papers are published in this issue of the *Journal*.

The Closing Plenary was highlighted by three presentations giving different perspectives on the future of the nuclear industry. Anthony R. Pietrangelo, senior vice president and chief nuclear officer of the Nuclear Energy Institute spoke on the U.S. Industry Response to Fukushima; Melissa Mann, manager, marketing and sales, URENCO, Inc., spoke about the Changing Face of Uranium Enrichment; and Joyce Connery, director, Nuclear Energy Policy, Office of International Economics, National Security Council, The White House, spoke about the Future of Nuclear Energy.

One unexpected complication provided a challenge for this year's Annual Meeting. On May 11, 2012, the U.S. Office of Management and Budget issued new guidelines to:

- Require agencies to decrease spending on travel by 30 percent;
- Require Deputy Secretaries to review any conference where the agency spending could exceed $100,000;
- Prohibit agencies from spending over $500,000 on a conference unless the agency's Secretary approves a waiver; and
- Require agencies to post publicly each January on the prior year's conference spending, including descriptions of agency conferences that cost more than $100,000.

These new requirements had an impact on the 53rd Annual Meeting, as the short time between the issuance of the guidelines and our meeting gave U.S. agencies little time to develop policies and procedures for complying with the new guidelines. As a result, seventy-eight papers were withdrawn from the meeting, a higher percentage of attrition than the INMM usually experiences. Additionally, as many as one-hundred individuals were forced to cancel their participation in the Annual Meeting. While disappointing, the financial condition of the Institute is good enough that it can absorb this reduction. What will be important for the INMM is to work with U.S. agencies to ensure they understand the value to these agencies of the Institute's annual meeting and workshops, and to develop procedures for managing attendance by U.S. government funded participants at future annual meetings and workshops. The Executive Committee has taken on this challenge and hopes to have a solution that supports the needs of its members, while continuing to provide an important venue for nuclear materials management professionals to meet with their colleagues to advance their technical proficiency, while supporting international and U.S. government objectives.

Finally, I would like to acknowledge Charles Pietri, who all of us greatly missed at this year's Annual Meeting. As head of the Technical Program Committee for many years, Charlie's stamp was on all of the successful aspects of the meeting. The spring 2012 issue of *JNMM* included a memorial article, so I won't attempt to repeat that, except to note that it took a lot of people to fill the leadership role that Charlie had maintained for so long. That this year's meeting was successful was a tribute to the work of the professionals of INMM's headquarters staff at the Sherwood Group, Jodi Metzgar, Lyn Maddox, Kim Santos, Anne Czeropski, Patricia Sullivan, and Jake Livsey, and especially to INMM's new President Ken Sorenson, then vice president, who calmly and courteously made everything work.

As the Interim Technical Program Committee Chair I was honored to have had the opportunity to work with all of them.

Next year we are fortunate to have a new Technical Program Committee Chair, Teressa McKinney. She has been a longtime member of the Technical Program Committee, served as a Member-at-Large of the INMM Executive Committee, and is someone who I know has the capability to get things done. I look forward to our 54th Annual meeting in Palm Desert, California USA, at the JW Marriott Desert Springs, July 14-18, 2013. I hope to see you there.

Great East Japan Earthquake, Tsunami, and Fukushima Daiichi's Accident

Yoshinori Meguro
President, INMM Japan Chapter

Good morning, Mr. Chairman and members of INMM. Mr. Chairman, I thank you very much for your kind introduction.

First of all, I wish to express my deep regret for the severe impact on the promotion of nuclear energy use over the world due to the accident at the Fukushima Daiichi Nuclear Power Station. Concerning this accident, we have received financial support and encouragement from INMM. We have also received technical and humanitarian assistance from many countries and organizations around the world including the United States.

I would like to express our sincere gratitude for this support on behalf of the INMM Japan Chapter.

Moreover, the Japan Chapter was given the opportunity to organize a special session, "Post-Fukushima Challenges in Safeguards and Security" for this important opening session of the 53rd INMM Annual Meeting today so that we can report on the current situation and exchange views.

Once again, I wish to extend our deepest gratitude for this opportunity.

Last October, Charles Pietri, former Technical Program Committee (TPC) chair, offered us the opportunity to give a report focusing on safeguards and security.

We consider it valuable for future nuclear development to report the circumstances of the accident as well as the current situation and future tasks for safeguards and security. And we also consider it is our responsibility to share this knowledge and learning broadly. Thus we proposed this idea at the TPC meeting in February and gained the approval from TPC.

However, to my regret, Mr. Pietri passed away last February. I would sincerely like to express my sadness for his death as well as my gratitude and respect to him and his family.

Overview of Great East Japan Earthquake, Tsunami, and Fukushima Daiichi's Accident

A tremendous earthquake hit northeastern Japan at 2:46 p.m. on March 11, 2011, registering a magnitude 9, which was on a scale we had never experienced before. The great tsunami followed the earthquake about an hour later. The total number of deaths or missing due to this disaster reported as of the end of June was about 19,000 people.

Although Fukushima Daiichi was also rocked by the huge earthquake, the reactors were safety shutting down via the automatic emergency shutdown function and had started the reactor cooling system. However, the plant was hit by the 15-meter tsunami about an hour later and lost its cooling functions, which caused station blackout by flooding the emergency diesel generator, the switchboard, and other equipment.

As a result, the core meltdown and the explosion of hydrogen occurred. A large amount of fission product—considered to be 770,000 TBq—was released into the environment. The Fukushima Daiichi accident is tentatively rated as Level 7 on the International Nuclear Event Scale.

The Tokyo Electric Power Company (TEPCO) has been exerting all possible efforts to settle the accident of the plant. In particular, they achieved a cold shutdown of the reactor by December 16, with technical cooperation from the United States and France. As the radiation dose rate of the reactor buildings between the unit 1 and 4 is too high to get close to, we consider safeguards and nuclear security are being maintained. In addition, the International Atomic Energy Agency (IAEA) has restarted inspections of all units of Fukushima Daiichi.

TEPCO developed medium- and long-term recovery countermeasures last December. According to that, they have started preparatory works for removing the fuels from the spent fuel pool in two years. TEPCO will report the details on Fukushima Daiichi's recovery work and the future program in this session.

Japan currently has fifty nuclear power plants, excluding the four units in which the accident occurred. Until the end of June, there were no reactors in operation in Japan since Tomari-3, which was the last working reactor after the accident, stopped operation for a periodical inspection on May 5.

Stress tests are currently being undertaken for all plants to take countermeasures against earthquakes, tsunamis, and station blackout in order to pass the government's examination for restarting the plant operation and gain understanding of the local society.

Currently, the national government of Japan has confirmed the nuclear safety of Ohi-3 and 4 units, owned by Kansai Electric Power Company (KEPCO), and decided to restart up the both units on June 16 for satisfying the electric demand in this summer. Ohi-3 has reached full power operation on July 9 and Unit 4 is to be reconnected to the grid in the end of July.

Program Outline

Today's Japan Session, "Post-Fukushima Challenge in Safeguards and Security," is composed of three sessions.

In the first session, Mr. Ohta from TEPCO will report the circumstance of the Fukushima Daiichi's accident. He will also report the medium- and long-term recovery project.

After Q&A for the TEPCO papers, Mr. Naito, the chair of Advisory Committee on Nuclear Security in Japan Atomic Energy Commission (JAEC), Nuclear Material Control Center (NMCC), and Mr. S. Abousahl of EC/JRC, will report what we should learn from the Fukushima Daiichi's accident mainly in terms of nuclear security.

In the second session, Mr. Hattori from the Ministry of Education, Culture, Sports, Science, and Technology (MEXT) of Japan/JSGO, Mr. D. Parise from IAEA/TRO, and Mr. M. V. Sickle from the U.S. Department of Energy National Nuclear Security Administration will report mainly in terms of safeguards.

In the third session, we are planning to have a wrap-up discussion focusing on the security and safeguards in today's report and discussion.

Conclusion

As a general concept, reactor cores contain a large amount of radioactive materials and the parties involved in nuclear operations have responsibilities to prevent the potential risks that the radioactive materials have an impact on the public in any circumstances. For that, we need to promote peaceful use of nuclear power, considering the interface between the so-called "3S" of Safety, Safeguards, and Security.

Although the Fukushima Daiichi's accident was an unfortunate accident, we intend to learn from it and contribute to the peaceful use of nuclear power through the knowledge we obtain. I would sincerely appreciate the continuing support and advice from those attending the INMM Annual Meeting.

I would like to conclude by thanking all of you for your generous support for this session and hope it is a valuable session for you.

Thank you very much for your kind attention.

Overview of the Accident at the Fukushima Daiichi Nuclear Power Station and the Process for Achieving Stabilization

Takeshi Ohta, Yuichiro Inoue, Masaki Kawasaki, and Naoya Hirabayashi
Tokyo Electric Power Company (TEPCO), Tokyo, Japan

Abstract

The earthquake caused the loss of all off-site electric power at the Fukushima Daiichi Nuclear Power Station, and the following series of tsunamis made all emergency diesel generators except one for Unit 6 and most of DC batteries inoperable. Thus all units resulted in the loss of cooling function and ultimate heat sink. Tokyo Electric Power Co., Inc. (TEPCO) focused on restoration of the instruments and lights in the Main Control Room (MCR), preparation of alternative water injection, and venting of the Primary Containment Vessel (PCV) in the recovery process. However, the workers faced many difficulties such as total darkness, aftershocks, high radiation, loss of communication means, etc. Massive damage from the tsunamis and the lack of necessary equipment and other resources hampered a quick recovery and eventually resulted in the severe core damage of Units 1, 2, and 3 and also the hydrogen explosions in the reactor buildings of Units 1, 3, and 4. By bringing the reactors and spent fuel pools to a stable cooling condition and mitigating the release of radioactive materials, TEPCO created the "Roadmap Toward Restoration from the Accident." Based on the roadmap, the following two steps are set as targets: "Radiation dose is in steady decline" (Step 1) and "Release of radioactive materials is under control and radiation dose is being significantly held down" (Step 2). Step 1 and 2 were achieved in July and December of 2011, respectively. Through these efforts, the reactors have reached a state of cold shutdown, and it is now possible to maintain an adequately low level of radioactive exposure at the site boundaries, even under unexpected situations in the future. This paper outlines the accident, the response made during the accident, and the effort made by all workers involved to achieve the stable state of the reactors.

Introduction

This paper first reflects what happened mainly at the Fukushima Daiichi Nuclear Power Station and how the facilities were damaged. Then it describes the main challenges and how TEPCO responded to these issues in the recovery process up to the point of achieving stable condition in December 2011. The provided event sequence of the accident agrees with the Interim Report on Fukushima Nuclear Accident compiled by the TEPCO internal Accident Investigation and Verification Committee under the Nuclear Safety and Quality Assurance Council, which was released on December 2, 2011.[1]

Overview of the Accident

On March 11, 2011, 14:46 JST, a magnitude 9.0 earthquake (the fourth largest record in the world) occurred off the coast of northern Japan. The earthquake caused huge scale of tsunamis that destroyed the coastal area of the Tohoku region. At the time of the earthquake, TEPCO was operating three of the six boiling water reactor (BWR) units at Fukushima Daiichi Nuclear Power Station (1F) and all four units at Fukushima Daini Nuclear Power Station (2F), which are located about 180 km away from the epicenter. At 14:46 JST, all seven units automatically shut down by detecting large earthquake acceleration. The maximum acceleration detected at 1F was 550 Gal at the basement of the Unit 2 reactor building. This earthquake caused loss of all off-site electric power at 1F site, and twelve on-site Emergency Diesel Generators (EDGs) were automatically started as expected. About forty minutes after the earthquake, a series of tsunamis started to reach the sites. The tsunami height was estimated to be about thirteen meters at 1F site (analysis result), which was far beyond the design basis of the site, and all the units in the site were inundated. The hydrodynamic force of the tsunami damaged most of the facilities in the field and a significant amount of sea water flowed into the buildings from their openings. As a result, all EDGs except one for Unit 6 and most DC batteries lost their functions, and ultimate heat sink

cooling water pumps also lost their functions.

Under the Station Black Out (SBO) condition together with severe damage to Ultimate Heat Sink (UHS), Unit 1 first lost its core cooling function and core damage started about three hours after the earthquake on an analysis basis. On Units 2 and 3, steam-driven water injection systems, Reactor Core Isolation Cooling system (RCIC), and High Pressure Coolant Injection system (HPCI), maintained their functions for the following few days, but these pumps eventually failed and thus all cooling functions were lost. Although site workers made extensive effort to restore core cooling function by using fire engines, continuous aftershocks, recurring tsunami alerts, and extensive damage to the surrounding infrastructures and facilities significantly hampered their recovery effort. Despite their continuous efforts, the core damage due to inadequate core cooling in both Units 2 and 3 progressed.

The core damage in Units 1, 2, and 3 resulted in the generation of hydrogen, which leaked out to the reactor buildings. The hydrogen then accumulated in the buildings and this led to the explosion in Unit 1 one day after the first series of tsunamis, and also in Unit 3 three days after the tsunami. On the following day, another explosion occurred in Unit 4, which is considered as a result of hydrogen backflow from the Unit 3 vent line through the Standby Gas Treatment System (SGTS) piping.

This accident was later rated as level 7 on the International Nuclear and Radiological Event Scale (INES), as a result of major release of radioactive material with widespread health and environmental effects requiring implementation of planned and extended countermeasures.

Earthquake and Tsunami

The magnitude 9.0 Great East Japan Earthquake on March 11, 2011, was caused by combination of several focal areas that ranged approximately 500km in length and 200km in width extending from the offshore of Iwate Prefecture to the offshore of Ibaraki Prefecture. The ground motion that 1F experienced was nearly equivalent to the design basis seismic ground motion on the plant design.

About forty minutes after the earthquake, the series of tsunamis reached both 1F and 2F sites. The 1F site was inundated by an approximately 13m high tsunami (analysis result) and the whole area surrounding the major buildings of Units 1 to 4 was flooded to a depth of approximately 1.5m to 5.5m. The depth of water surrounding the major buildings of Units 5 and 6 was less than 1.5m. The 2F site was also attacked by the tsunami. Although the average tsunami height of 2F was lower than that of 1F site, approximately 9m based on analysis, the height of the tsunami that ran up along the road on the southern side of Unit 1 was approximately 15-16m.

Figure 1 shows the relationship between the design basis tsunami height, site elevation, and the inundation height recorded on March 11. Both the 1F and 2F sites were originally designed to withstand the design basis tsunami height of 3.1 m, which was determined as the highest historical value of that area recorded after the Chile earthquake in 1961.

In 2002, a new design guideline "Tsunami Assessment Method for Nuclear Power Plants in Japan" was issued by the Japan Society of Civil Engineers. This document has since been referred to as the standard method for tsunami assessment at nuclear power stations in Japan. The design basis tsunami height was reevaluated based on this guideline and the new design criteria was raised to O.P.$_1$ (Onahama point) +5.4 to 5.7m for the 1F site and O.P. +5.1m to 5.2m for the 2F site. Since major building areas were constructed at the elevation of O.P. 10-13m, it was considered that even if the site were attacked by a tsunami with reevaluated height, tsunami wave would not reach the major buildings. On the other hand, facilities located in the lower elevation had modifications such as sealing of openings and relocation of pump motors to a higher elevation in order to enhance the resistance against tsunami hazard.

However, the tsunami on March 11 was still far beyond the reevaluated design basis and it severely damaged the facilities on the site. But no significant damage by the earthquake have been confirmed.

Figure 1. Tsunami arrival at 1F and 2F site

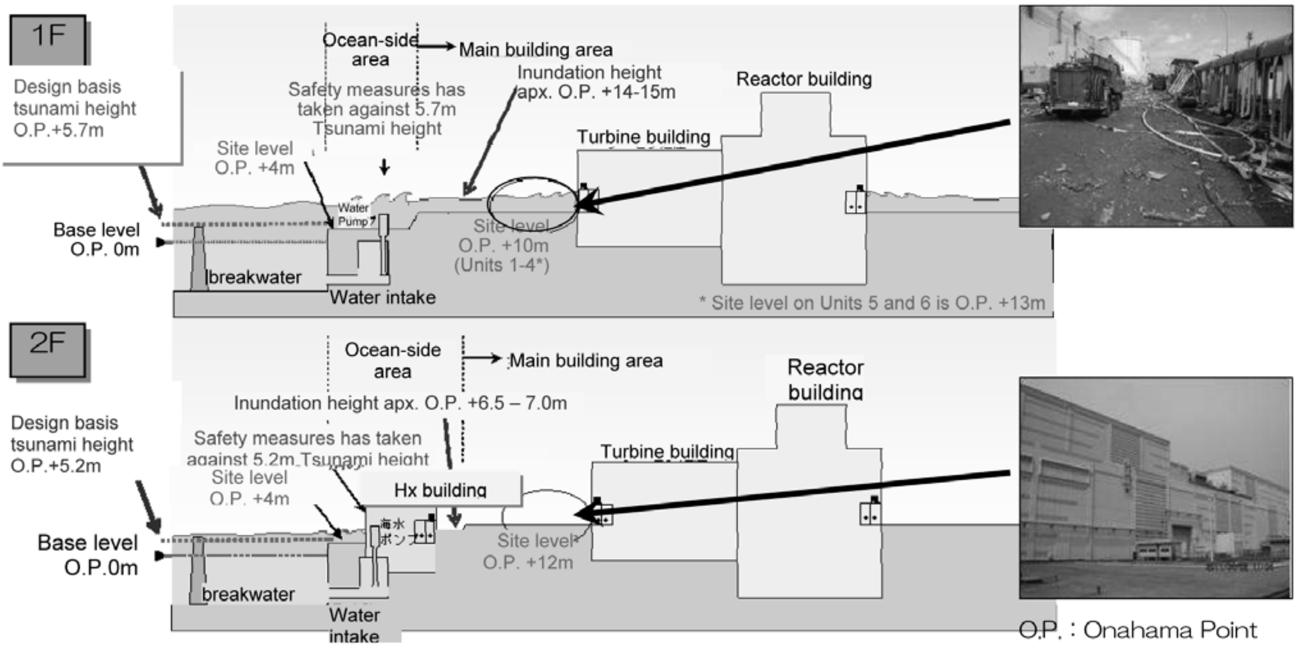
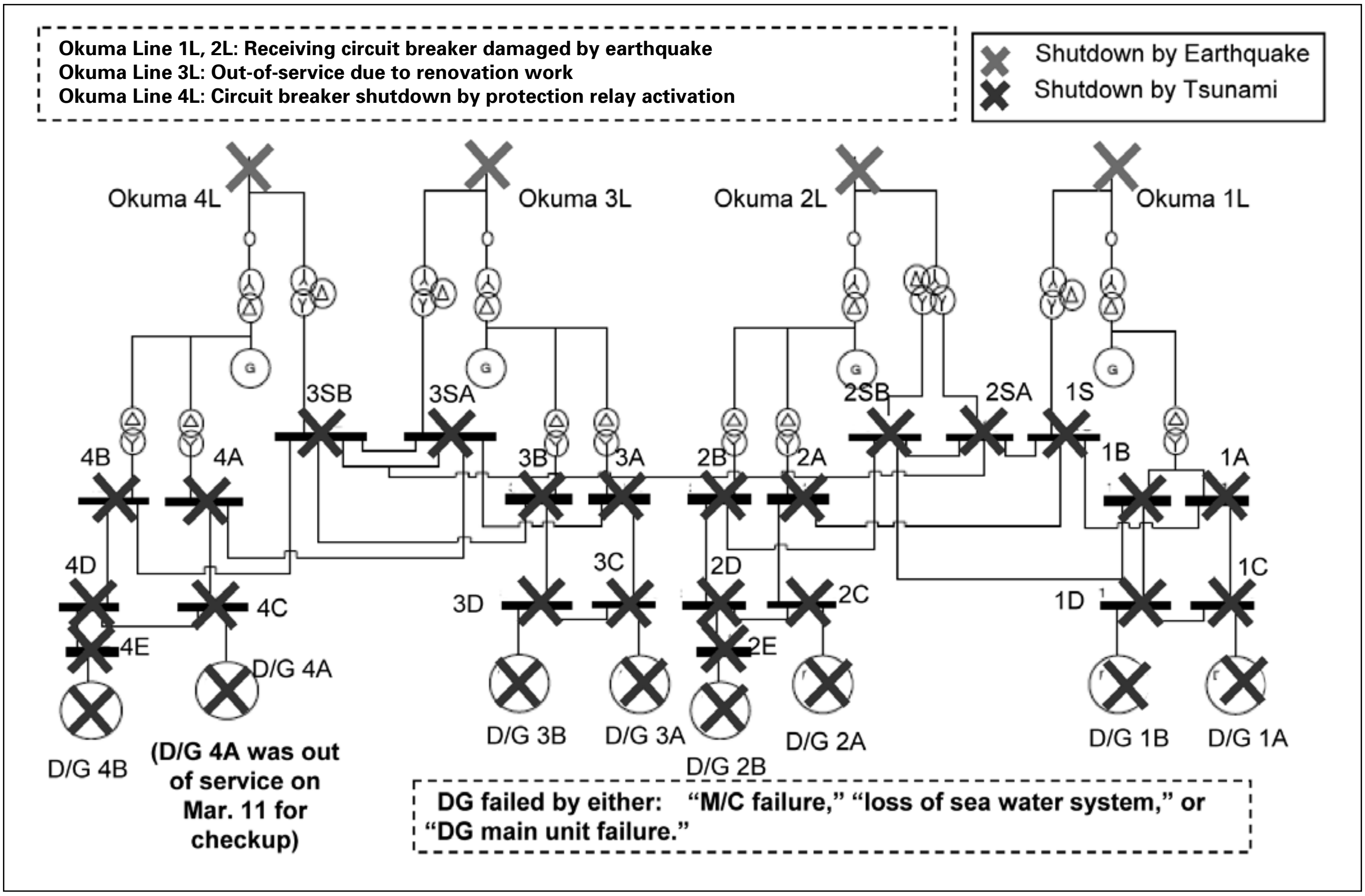


Figure 2. Damage to power supply systems for Units 1-4 at 1F



Description of Damage to the Power Source

After the earthquake, all the offsite power to 1F was lost due to the damage to circuit breakers and disconnectors, or a collapse of a transmission line tower. Soon after the loss of offsite power, all of twelve EDGs that were ready for operation started as expected and continued supplying electricity to all the six units while the reactor shutdown operation was successfully implemented.

However, the arrival of the tsunami waves changed the situation significantly. Figure 2 shows the availability of in-house power supply for Units 1 to 4 at the 1F site after the tsunami struck. All the seven operating EDGs for Units 1 to 4 lost their function due to flooding and failure of the associated Metal Clad (M/C) switchgears, the sea water pump motors, or the EDG's main unit (Table 1). The seawater intake structure was severely damaged and was rendered nonfunctional. Moreover, most batteries in these units were also flooded and damaged. As a result, Units 1-4 had lost majority of the available power source and had to face the SBO condition. This means loss of all functions that require electricity such as motor-driven pumps and valves. These were no longer usable for reactor cooling. Instruments in the Main Control Rooms (MCRs) could not show vital plant parameters.

Table 1. Location of EDG, M/C switchgear & battery and cause of failure

Unit	EDG		M/C	Battery
	Location	Cause of failure	Location	Location
1	1A:T/B B1F O.P.1900	Damaged by flooding	T/B 1F	C/B B1F
	1B:T/B B1F O.P.1900	Damaged by flooding	T/B 1F	
2	2A:T/B B1F O.P.1900	Damaged by flooding	T/B 1F	C/B B1F
	2B:SP/B 1F* O.P.10200	M/C submerged	SP/B B1F	
3	3A:T/B B1F O.P.1900	Damaged by flooding	T/B B1F	T/B MB1F
	3B:T/B B1F O.P.1900	Damaged by flooding	T/B B1F	
4	4A:T/B B1F O.P.1900	Damaged by flooding	T/B B1F	C/B B1F
	4B:SP/B 1F* O.P.10200	M/C submerged	SP/B B1F	
5	5A:T/B B1F O.P.1900	Cooling function lost	T/B B1F	T/B MB1F
	5B:T/B B1F O.P.1900	Cooling function lost	T/B B1F	
6	6A:C/S B1F O.P.1000	Cooling function lost	C/S B2F	T/B MB1F
	6B:DG/B 1F* O.P.13200	Survived	C/S B1F	
	6H:C/S B1F O.P.1000	Cooling function lost	C/S 1F	

* Air cooled Diesel Generator

SP/B: Shared Pool building, DG/B: Independent DG building, C/B: Control Building, C/S: Combination Structure surrounding R/B

At the 1F site, ten out of thirteen EDGs are water-cooled and the rest are air-cooled. Although diversity and the location of the EDGs were implemented, only one of the air-cooled EDG for Unit 6 survived the tsunami. (Remaining two air-cooled EDGs for Unit 2 and 4 lost their function due to M/C submergence.) This EDG continued to supply electricity to Unit 6, followed by Unit 5 whose important loads were connected directly using temporary cables from Unit 6 switchgears, and it was crucial for bringing these units to eventual cold shutdown. This shows that the flood protection was important not only for the EDG itself but also for the associated electric facilities such as M/Cs and batteries. Therefore, it can be summarized that the current design of safety-related electric and instrumentation and control equipment from the perspective of their layout, diversity and internal barriers for separation need to be reviewed to prevent common cause failure by severe external event.

Recovery Works

Initial Challenge of Core Cooling

On Unit 1, Isolation Condenser (IC) and steam-driven High Pressure Coolant Injection system (HPCI) are designed for cooling and injecting water in high-pressure conditions. Following the reactor shutdown after the earthquake, the IC automatically started up due to reactor pressure high signal. Operators repeatedly started and stopped the IC to control the cool down rate of the Reactor Pressure Vessel (RPV) temperature within 55 degrees C/h. After the tsunami, AC power supply to Unit 1 was lost by the DG failure. Although both IC and HPCI are designed to be operable by DC power for system control, operators could not start up these systems due to damage on the batteries and subsequent loss of DC power. Therefore, Unit 1 lost its cooling function under the SBO condition and core damage is considered to have started soon after the tsunami. In addition to the loss of cooling function, DC power supply to the instruments in the MCRs was soon unavailable and operators were unable to read necessary data to understand the plant condition. On Units 2 and 3, the RCIC and HPCI are designed for injecting water in high-pressure conditions. Following the reactor shutdown after the earthquake, operators used the RCICs to maintain the cooling function in both units. After the arrival of the tsunami, AC power supply to both units was lost by the DG failure, but the steam-driven RCICs maintained their water injection capability although the SBO condition made operators difficult to verify that the RCICs were still in operation. Consequently, it was found that the RCIC of Unit 2 worked for about three days after the tsunami. The RCIC of Unit 3 worked for about twenty-one hours after the tsunami attack and the HPCI worked for about fourteen hours after the RCIC tripped.

Plant Recovery Work during the SBO

During the first days of the accident, operators and emergency response teams concentrated mainly on the following three tasks: (1) Restoration of the instruments and lights in the MCRs, (2) Preparation for alternative core injection, and (3) Preparation for venting from the PCV.[2,3]

Figure 3. Connected temporary batteries to recover instrumentations in MCR

Figure 4. Debris hampering the site recovery

In this section, more details of the above three tasks are described for the case of Unit 1. Similar recovery work was simultaneously or sequentially on-going at other units.

Restoration of MCR Instruments and Lights

In order to recover the instruments in the MCR, batteries and cables were collected from the warehouses and cars throughout the site. Then the collected batteries were connected to the vital instruments and at about 21:30 JST on March 11, the voltage from the RPV water level gauge was successfully recovered first on Unit 1 and then on Unit 2 (Figure 3). Note that batteries for Unit 3 survived from the tsunami flooding and the reading of the vital plant parameters were maintained for about thirty hours. Temporary lighting was implemented in the MCRs using small generators after battery depletion.

Preparation for Alternative Water Injection

Priority was initially on Unit 1 since it lacked any sufficient water injection method available after the tsunami damage. At the Emergency Response Center (ERC) on the site, preparation for alternative core coolant injection using fire protection systems and fire engines started in the evening of March 11.

In the field, recovery work was hampered with many difficulties such as recurring aftershocks and large tsunami warnings. Lack of lighting and communication means made even simple activities extremely difficult. Furthermore, debris and holes on the road interfered with the traffic of people and service vehicles (Figure 4). In this situation, field workers worked hard to line up an alternative water injection line, and others surveyed the field in order to find any intact facilities. As a result of the field survey, the ERC restoration team found that electrical panels (metal-clad switchgears and power centers) for Unit 1 were all flooded and unusable, while one of the Unit 2 power centers was still usable.

A diesel-driven fire protection pump was the candidate and it was expected as an alternative water injection. It became ready to inject water after depressurizing the RPV at about 20:50 JST on March 11, but the plan was never realized due to ground fault of the starter motor when it was about to inject water.

A new plan arose to use Standby Liquid Control system (SLC) as a possible candidate for coolant injection by connecting the power supply vehicle to the only survived power center. However, this attempt eventually failed because the cables connecting the power supply vehicle and the power center were damaged by the Unit 1 hydrogen explosion at 15:36 JST on March 12.

These recovery efforts continued overnight, and fresh water injection finally commenced for Unit 1 in the early morning of March 12 by using a fire cistern and fire engines. However the amount of fresh water injected was limited and it was not adequate for cooling down the reactor.

In addition to the restoration effort for the fresh water injection, the preparation for the sea water injection was also conducted at the ERC and the field. The main condenser backwash valve pit of Unit 3, which is located closer to the dire units and at an elevation above sea level, became the next expected water source and the temporary hoses were obtained and laid down. However, this line up was also damaged beyond use by the hydrogen explosion of Unit 1. The injection line from the pit was again reestablished with three fire engines connected in series from the pit to the fire hydrant. The sea water injection was finally started at 19:04 JST on March 12.

Preparation for PCV Venting

Another critical issue was on how to reduce the containment pressure. Manual operation for PCV venting through the hardened vent line became necessary under the SBO condition, but there existed no detailed procedure for such an evolution to open and line up the vent system manually. Piping and instrumentation diagrams, Accident Management (AM) procedures, valve diagrams, and other documents were collected for developing a method to line up the hardened venting line without power source.

At 9:04 JST on March 12, after the completion of local civilian evacuation, operators started the actual field line-up work for the venting in the reactor building. In the MCR of Units 1 and 2, three teams consisting of two senior shift operators in each was planned for the vent line-up, since complete darkness and lack of communication means at the field made it extremely difficult and dangerous to execute the task by a single person. A high radiation dose was expected, and retreating due to large aftershock was anticipated. Eventually the first team entered the reactor building and successfully opened a motor-operated (MO) valve on the second floor. The second team then entered the reactor building and tried to open an air-operated (AO) valve on the basement floor inside the torus (suppression chamber) room. However, on the way to the air-operated valve, the team was forced to retreat due to high radiation dose in the torus room.

The plan for the manual operation of AO valves was then terminated. Opening the AO valves was eventually achieved by connecting a temporary air compressor to the air supply line. At 14:30 JST on March 12, the decrease in the PCV pressure for Unit 1 was observed and PCV venting was finally successful.

This section could be summarized that some countermeasures such as procedures or provision of tools against the beyond design-basis accident were not readily available to stop or mitigate the accident. Previous preparations were limited only to certain accident response systems and procedures for an accident beyond the design basis. The tsunami's impact was far beyond the previous estimation and resulted in a situation in which almost all expected equipment and power sources failed.

Stabilization of the Accident

Implementation of the Roadmap Toward Stabilization of the Accident

From the onset of the accident, presentation at the earliest possible date of a roadmap towards settling the situation at 1F was requested by people home and abroad, especially the residents around 1F.

On April 17, 2011, TEPCO has released this roadmap titled, "Roadmap Toward Restoration from the Accident at Fukushima Daiichi Nuclear Power Station," which was an important step forward that symbolized a transfer from the "emergency response phase" to the "planned and stabilizing action phase." The settlement of the situation was now the aim of this roadmap. In the roadmap, the following two steps are set as first main targets: (1) radiation dose is in steady decline (Step 1); and (2) release of radioactive materials is under control and radiation dose is being significantly held down (Step 2).

On July 19, 2011, the Nuclear Emergency Response Headquarters Government-TEPCO Integrated Response Office confirmed the achievement of the Step 1 target with the steady decline of the radiation dose based on the evaluation of exposure dose at the site boundary with approximately 1.7mSv/year at the most (Cs-134, Cs-137), which showed sufficient decrease compared to that during the initial phase of the accident.

In order to achieve Step 2, issues concerning Step 2 were broken down into ten specific categories (this includes categories added during the implementation of Step 2) and targets and countermeasures were individually set for each issue.

Issue (1): Core cooling is maintained steadily while monitoring the parameters such as the RPV bottom temperatures and injection rates, and aim for the reactors to reach "a condition equivalent to cold shutdown." A condition equivalent to cold shutdown is defined as:

- The RPV bottom temperature is below 100º Celcius.
- The release of radioactive materials from the PCV is under control and public exposure from additional releases is being significantly down (The target is to keep the doses below 1 mSv/year at the site boundaries.)
- In order to satisfy the above two conditions, the mid-term safety of the circulating water cooling system is being secured.

Issue (2): More stable cooling of Spent Fuel Pools by establishing the circulating pool cooling system for all units.

Issue (3): Reduction of accumulated radioactive water by maintaining stable operations of the water processing facilities to reduce the total amount of accumulated radioactive water within the site.

Issue (4): Preventing ocean contamination through groundwater by controlling accumulated radioactive water leakage into the groundwater.

Issue (5): Suppressing the scattering of radioactive materials from site to lower the radiation level in the surrounding area.

Issue (6): Radiation measurement, reduction and disclosure by the Government, prefecture, municipalities and TEPCO with full-fledge decontamination effort.

Issue (7): Preparation against future natural disaster (earthquakes, tsunamis, etc.).

Issue (8): Enhancement of living/working environment of people at the site to maintain workers' motivation.

Issue (9): Enhancement of workers' healthcare with strict radiation protection measures and implementation of sickness prevention measures (heat stroke, influenza, etc.).

Issue (10): Staff training/personnel allocation to meet legal dose criteria of workers and trying to ensure the availability of site workers for recovery work.

On December 16, 2011, all reactors at 1F and 2F were confirmed to be in a condition equivalent to cold shutdown, and in case an accident occurs, radiation dose at the site boundaries will be maintained at a sufficiently low level. Thus the reactors were stabilized and the accident in the station was finally settled. In addition, all other issues for controlling radioactive materials and holding down of radiation doses to significantly low level were achieved.[4] Thus the completion of Step 2 was confirmed on the same day.

Conclusion

More than a year has passed since the accident and various restoration work is still progressing at full speed in order to improve reliability and also to prepare for defueling and decommissioning the units. In parallel with these works, event investigation and analysis has also been continuously conducted. TEPCO realized through the event investigation and analysis process that it would be important to carefully consider the robustness of current design of nuclear power plants and emergency preparedness against beyond design basis events that could lead to common cause failures regardless of their assumed probability. In order to prevent the recurrence of such a severe accident anywhere else, it is very important to share this lesson among the nuclear industry in the world, to develop appropriate countermeasures and surely implement them. Lastly, TEPCO is forever indebted for the tremendous support and tireless dedication given to the recovery effort by all workers involved; they made it possible for the Fukushima Daiichi and Daini sites to achieve the progress they have today.

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Lessons Learned from the Accident at the Fukushima Daiichi Nuclear Power Station: Nuclear Security Perspectives

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Abstract

The nuclear accident at the Fukushima Daiichi Nuclear Power Station (NPS), or the Fukushima Accident, was caused by the devastating tsunami associated with the Great East Japan Earthquake. It demonstrated that total station blackout and loss of core cooling and spent fuel pool cooling should be prevented at the time of natural disasters. At the same time, it became clear that a similar extensive nuclear accident could be caused by a terrorist attack on vital equipment that is essential for maintaining NPS power supply, core cooling, and spent fuel pool cooling. Thus the Advisory Committee on Nuclear Security (ACNS), established in December 2006 under the Atomic Energy Commission of Japan (JAEC), initiated the review of Fukushima Accident to extract lessons learned from nuclear security perspectives and made a report to JAEC in November 2011, summarizing the result of its review and recommending appropriate measures to overcome nuclear security vulnerabilities that have been identified by the Fukushima Accident. This paper presents the content of the ACNS report and the response of the relevant Japanese government agencies and licensees to its recommendations.

Note: The views expressed in this paper are solely those of the author and do not represent those of the author's organization or any government agencies he is associated with.

Introduction

Japan's Policy and Measures Taken for Assuring Nuclear Security

The importance of nuclear security has been recognized globally and extensive efforts have been exerted, both domestically and internationally, to address the issue of assuring nuclear security. In the earlier days of 1980s, the protection of nuclear materials during international transport was a primary concern of the international community. Then the dissolution of the former Soviet Union (FSU) resulted in the frequent discoveries at borders of illicit trafficking of nuclear and other radioactive materials originating from ill-protected nuclear facilities in FSU countries. This, coupled with the simultaneous terrorist attacks of 9/11, made the international community highly aware of a terrorist threat of using nuclear materials or other radioactive materials in an improvised nuclear explosive devices or a radiation dispersion device (RDD or a dirty bomb).

Thus, the scope of protection has been expanded, from initially the protection against unauthorized removal of nuclear material in use, storage, or during transportation and against the sabotage of nuclear facilities or transportation, to recently the protection against the unauthorized removal of radioactive materials and against the sabotage of facilities using radioactive materials or their transportation. The IAEA guidelines in the field of nuclear security followed this trend. The IAEA published in 1975 the guidelines for the physical protection of nuclear materials, or INFCIRC/225, in its effort to assist its member states to establish and maintain an effective physical protection system. The guideline was revised several times, namely in 1977, 1989, 1993, 1999, and 2011, to accommodate the new concerns including the acts of sabotage and to cover other radioactive materials.

After 9/11, the IAEA initiated the development of the Nuclear Security Series publications to assist the member states in establishing new nuclear security regimes, or in strengthening existing ones. The Nuclear Security Series are designed in a tiered approach with 1) the fundamentals-level publication providing the Objective and Essential Elements for the entire nuclear security regime, 2) recommendations-level publications outlining what a nuclear security regime should do in specific areas of nuclear security, and 3) the implementing and technical guidance publications providing detailed guidance about how to establish specific nuclear security systems and measures. While the fundamentals document is currently in its final stage, three recommendations documents were published in January 2011, namely Nuclear Security Recommendations on 1) Physical Protection of Nuclear Material and Nuclear Facilities (or INFCIRC/225/Rev.5), 2) Radioactive Material and Associated Facilities, and 3) Nuclear and Other Radioactive Material out of Regulatory Control.

When the Japan Atomic Energy Commission (JAEC) established the Advisory Committee on Physical Protection (ACPP) in April 1976, there was no specific legal provision in place in Japan for physical protection of nuclear materials, but relevant *de facto* measures in line with INFCIRC/225 had been taken by the licensees based on administrative guidance of regulatory agencies. The committee was tasked to consider what measures were necessary to strengthen the physical protection system in Japan. It made a preliminary report to the Commission in September 1977 with the following findings and recommendations:

- Various physical protection measures have been in place in Japan that can meet most of the physical protection requirements laid down by INFCIRC/225;
- The Japanese government should clearly define the measures required for physical protection of nuclear materials in a nuclear facility or during transportation according to INFCIRC/225, make them legally binding, and check their implementation regularly;
- The Japanese government should review the criminal code system to make such unlawful acts as theft of nuclear materials punishable offenses in light of international trends;
- The response regime in the event of a physical protection emergency should be established so that comprehensive measures are taken promptly such as mobilization of response forces, recovery of illegally removed nuclear materials, and mitigation of radiological disasters that might occur after an act of sabotage;
- The responsive forces should be equipped with necessary resources so that they can be mobilized promptly and suppress adversaries in time while licensees delay the accomplishment of their attack through physical protection measures;
- The effective mechanism of close communication and coordination should be established among the relevant government agencies including the regulatory and the security agencies;
- Relevant R&D activities should be promoted in order to develop necessary equipment for physical protection and the methodology for evaluating the effectiveness of a physical protection system employed by licensees;
- International cooperation should be promoted in order to assure physical protection of international transfer of nuclear materials.

The ACPP continued its deliberations and elaborated further on the points listed above as the measures the Japanese government should take in order to further enhance the physical protection regime of Japan. In June 1980, its final report was presented to JAEC, describing inter alia the following points:

- The necessity of establishing an effective physical protection regime/system;
- The objectives and the elements of a physical protection regime/system;
- The physical protection requirements for the licensees in use, storage and transportation of nuclear materials corresponding to those specified by INFCIRC/225/Rev. 1;
- The need to establish an effective response regime in the event of a physical protection emergency, the respective specific measures to be taken by the licensees, the response forces and the regulatory agencies in such an emergency, as well as those to be taken by them in advance in preparation for such an emergency;
- The need of related R&Ds, the framework of conducting them, the areas of R&Ds;
- The need to establish a legal framework to impose on licensees to comply with the physical protection requirements based on regulatory rules and regulations and the need for ratifying the Convention of Physical Protection of Nuclear Material (CPPNM) that had opened for signatures in March 1980.

Based on the report, in May 1988 the government revised the Nuclear Regulation Act to include the physical protection of nuclear materials as one of the specific objectives of the Act, and to add physical protection provisions in line with the requirements of INFCIRC/225/Rev. 1, as well as revising the criminal law to make punishable the offences specified in the CPPNM. Thus, Japan ratified CPPNM in November 1988.

In December 2005, the Nuclear Regulation Act was further revised to accommodate the requirements of INFCIRC/225/Rev. 4, including the need for the licensees to make appropriate measures of physical protection based on DBT (design-basis-threat) that is to be determined by the government in view of prevailing security conditions, the need for them to undergo annual physical protection inspections to evaluate the effectiveness of their physical protection system, and the need for them to protect the physical protection secrets.

Activities of ACNS

In view of the growing international concern about expanding the scope of protection from nuclear materials to that of radioactive materials, in December 2006 the JAEC established the Advisory Committee on Nuclear Security (ACNS) to advise the commission how to accommodate the requirements of assuring nuclear security in Japan in view of international trends including the publication of Nuclear Security Series documents by the IAEA.[1] After extensive deliberations, the committee, chaired by the author, made a report to the commission in September 2011, "the Fundamental Approach to Ensuring Nuclear Security" (ACNS September 2011 Report),[2] describing the basic policy to ensure nuclear security in Japan, with a view to Fundamentals Document that was in the final stage of development as the top tier document in the IAEA Nuclear Security Series. As for its future activities, ACNS identified two remaining tasks, namely 1) to consider what additional measures should be taken in order to accommodate the requirements of IAEA's three Recommendation documents and 2) to hasten its deliberations on what specific measures should be taken in response to lessons learned from Fukushima Accident from the nuclear security perspectives. JAEC authorized the report and requested the licensees, and the regulatory and security agencies to promptly take responsive measures in accordance with the report and make progress reports to the Commission as appropriate.[3]

On the other hand, in June 2011, ACNS set up a working group (WG) to review the Fukushima issues and in October 2011 approved the findings of the WG report of September 30, 2011, "The Responses to Nuclear Security Issues in view of Fukushima Daiichi Nuclear Power Plant Accident." In November 2011, ACNS provided the report to JAEC as its progress report (ACNS November 2011 Report). When approving it, JAEC again requested the licensees, the regulatory, and the security agencies to promptly take necessary measures in accordance with the report and make progress reports to the Commission as appropriate.[4]

After additional deliberations, in March 2012 ACNS produced its final report on the remaining two tasks, "Strengthening of Japan's Nuclear Security" (ACNS March 2012 Report),[5] reflecting its previous progress report in November 2011 and the responsive measures already taken by the licensees and the regulatory and security agencies with respect to the November 2011 report. JAEC approved the report and made its decision to request the relevant government agencies, such as the regulatory and security agencies, and the licensees give serious consideration of the report in order to steadily enhance the nuclear security measures, while fully paying respect to the importance of enhancing mutual coordination and obtaining the understanding and the cooperation of the general public.[6]

ACNS Report on Lessons Learned from the Fukushima Accident

The ACNS March 2012 report states the following as its basic recognition of the Fukushima Accident:

- A nuclear disaster can tremendously impact the economy and society, widely contaminating people's living environment and causing social disorder;
- The accident revealed the possibility that a similar incident with serious impact on our society can be initiated by an act of terrorism against nuclear facilities. It is Japan's duty to extract lessons learned from the accident from the viewpoints of not only safety but also security and share them with the international community in order to duly reflect them in the international efforts to strengthen nuclear security;
- It is appropriate for the licensees and the regulatory and the security agencies to take relevant measures of nuclear security, assuming that a sabotage act against NPSs is a plausible threat. In their practice, they should enhance their measures in accordance with the ACNS September 2011 Report and establish an effective system through mutual coordination and cooperation.

Further, the report describes the terrorist threat to NPSs as follows:

- In view of the accident and associated damages, people's interest in NPSs have increased, as well as terrorists' interest in NPSs as their potential and effective targets;
- It is crucial to prevent total station blackout (SBO) and functional loss of cooling reactor cores and spent fuel pools and thus it is necessary to further strengthen measures to protect these facilities/equipment;
- It is necessary to take into account the potential risk of a terrorist attack on the facilities/equipment installed outside a protected area or an act of sabotage by an employee who has been granted access to key facilities/equipment;
- In view of the above points, nuclear security functions should be maintained or enhanced in the event of emergency situations, such as high radiation level or SBOs, caused by an accident.

Then the report proposes the following measures against additional threats identified by the Fukushima Accident:

1) Early Detection of Intrusion

For the sake of detecting earlier the intrusion of an adversary to assure enough time for notification and response, the licensees are required to shift the intrusion detection line from the present position toward a site boundary. The regulatory authorities should make relevant regulations to ensure that necessary measures are put in place. Further, in view of the fact that NPS sites in Japan are normally very confined, the consideration of additional measures should be made in order to enhance the capabilities of detecting suspicious persons at the areas surrounding an NPS site, on land, or at sea.

2) Delay of Terrorists' Action

Similarly, relevant regulations should be set up by the regulatory agencies to ensure that the licensees should take appropriate measures to prevent and delay the terrorist's action near the point of intrusion detection, for example, by placing additional obstacles or reinforcing existing ones at a site boundary, in addition to placing fences as obstacles surrounding a protected area. In view of particular conditions of NPSs in Japan such as their confined sites, the licensees and the regulatory agencies should review the specific measures of such prevention and delay and the division of their respective roles by taking into account of specific conditions at an individual NPS site, and in good consultations with the security agencies.

3) Enhancing Robustness of Protected Facility/Equipment

In order to increase the robustness of the facilities/equipment to be protected against a terrorist attack with explosives, relevant regulations should be set up by the regulatory agencies to ensure that the licensees should take appropriate measures by, for example, encasing them with strong materials. Further, these facilities/equipment should be installed at the place closest to protected areas in order to facilitate more strict measures for them.

4) Establishment and Sustenance of an Adequate Nuclear Security Regime

The licensees and the security agencies are required to respectively establish and sustain an adequate nuclear security regime so that notification and response actions can be done promptly and nuclear security functions can be maintained even in the event of emergencies. For this purpose, the licensees should be equipped with sufficient resources of personnel, material, and equipment necessary to detecting an unauthorized access and notifying the security forces in such an event and the same applies to those of the security forces that are to respond to intruders when receiving such a notification. The licensees and the regulatory agencies should review specific measures and the division of their respective roles by taking into account the specific conditions at an individual NPS site, and good consultations with the security agencies. In this context, the licensees may be requested to provide the security forces stationed at NPSs with a stronghold or other facilities/equipment for their effective response actions.

5) Preparation of Mitigation Measures

In order to prepare for an event when protected equipment is destroyed, measures for mitigating the damages by a terrorist attack should be taken, in advance, in accordance with the concept of defense-in-depth. It is important to carefully examine if the measures concerned willfully function as designed at the time of such act of terrorism. Contingency plans among the licensees, the regulatory agencies, and the security agencies should be prepared for the mobilization of additional personnel and equipment as well as the effective plan for safe evacuation of the staff members, the casualties and neighboring residents in the event that an act of terrorism is conducted that is beyond the scope of the existing nuclear security regime. Further, it is desirable to make prearrangements for smooth communication among the organizations involved in such mobilizations and evacuations.

6) Exercises and Evaluations

The licensees and the regulatory and security agencies should more closely collaborate in conducting more practical exercises and feeding back the evaluation results of these exercises in order to make the security measures more effective. In addition, the integrated exercise should be conducted at a nuclear facility, involving as many organizations as possible including those involved in mobilization and evacuation as mentioned above.

7) Measures Against Insider Threats

More thorough checking of ID passes and scrutinized searches of personnel and accompanying items at the time of access control should be ensured by the licensee. The system for establishing trustworthiness should be introduced in Japan with due consideration of international practices. Pending its establishment, such measures as the two-person rule should be strictly adhered to as an interim alternative in order to enhance the effectiveness of measures against insider threat.

Actions Taken

As stated earlier, JAEC approved each of the ACSN reports and requested the licensees and the regulatory and security agencies to take prompt responsive measures in accordance with the report and make progress reports to the commission as appropriate.

In December 2011, NISA (Nuclear and Industrial Safety Agency), which is currently the competent regulatory authority in charge of NPSs, revised relevant regulations in order to accommodate the additional measures proposed by the reports as well as some of the new requirements identified in the INFCIRC/225/Rev. 5 as follows:

- A limited access area should be established outside a protected area in order to create an additional layer of protection for detection, access control, and delay against unauthorized removal of nuclear material or act of sabotage;
- Protective measures such as enclosing with robust barriers should be applied to the equipment related to an AC power supply or cooling of a nuclear reactor or a spent fuel storage pond that, being located outside an inner area, could be easily susceptible to acts of sabotage causing the loss of cooling of a nuclear reactor or a spent fuel storage pool and resulting in the release of radioactivity into the environment;
- Cyber security measures should be applied to the information system related to operation and control of an NPS as well as that of nuclear security equipment.

Another revision of relevant regulations was made effective in the end of March 2012 in order to reflect the final report of ACNS on the basic policy on incorporating the requirements of INFCIRC/225/Rev. 5 into the Japanese nuclear security regime.

As of the end of January 2012, in order to enhance their guard/alert regime, the security agencies are increasing the number of police officers stationed onsite at nuclear facilities and providing with necessary equipment and instruments required for improving the response capabilities against terrorism using explosives. In addition, other measures such as required expansion of personnel and equipment, review of guidelines for an alert, and reinforcement of inter-organizational collaboration through conducting field exercises are currently being implemented or are under contemplation.

The licensees are now taking respective measures in consultations with NISA and the security force. For example, they are preparing for stricter access control at the boundary of limited access areas (e.g., security check of vehicles, personnel, and accompanying equipment) in response to the above mentioned revision of relevant regulations as well as installing the required equipment and instruments. They are also considering measures for improving nuclear security capability in the event of natural disasters, and providing the security forces stationed at NPSs with a stronghold or other facilities/equipment for their effective response actions.

Conclusion

ACNS has been tasked by JAEC to establish Japan's basic policies on nuclear security with due considerations of "Fundamentals" and the three "Recommendation" documents that are in the top two tiers of IAEA Nuclear Security Series. Its report reflecting the former was presented to JAEC in September 2011 and the latter was made in March 2012, just before the 2012 Seoul Nuclear Security Summit. The relevant regulations have been revised to reflect these basic nuclear security policies.

ACNS was also asked to review the Fukushima Accident to extract lessons learned from nuclear security perspectives. The Committee approved its WG's report of September 2011 in October 2011 and presented it to JAEC in November 2011, summarizing the result of its review and recommending appropriate measures to overcome the nuclear security vulnerabilities that have been identified by the Fukushima Accident. Receiving the report, JAEC made a statement requesting the licensees, the competent regulatory agencies and response forces to take relevant measures in accordance with the report as soon as possible and make progress reports to JAEC. All the parties concerned are now taking their respective measures.

In January 2012, the Japanese government laid before the Diet the bill for creating the new regulatory body, Nuclear Safety and Security Agency (NSSA), in order to overcome the shortcomings of the Japan's previous safety regulation regime that have been recognized through the Fukushima Accident. The new body was originally planned to start its operation on April 1, 2012, as an affiliated organization under the Minister of Environment with the centralized authority in nuclear safety and security.[7] At the time of drafting this paper, the bill has not been passed and NSSA has not been established. It is hoped that Japan's nuclear security regime become more effective with the revision of her regulatory system and the related specific regulations incorporating ACNS's final report.

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JNMM Roundtable

July 16, 2012

Opening Session Speakers:

Yoshinori Meguro
President, INMM Japan Chapter

Kaoru Naito
Nuclear Material Control Center, Japan

Takeshi Ohta
Tokyo Electric Power Company, Japan

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Dennis Mangan: I think you gentlemen did an outstanding job this morning. It was one of the better and more interesting plenary sessions and I learned a lot more than I have in most plenaries. I just learned that daiichi means "number one."

Kaoru Naito: I think some American GIs picked up the frequently used Japanese phrase ichiban. Ichiban is "number one." Ichi is one. Dai is a prefix to make an ordinal number. So, Daiichi also means number one.

Mangan: Thank you. First, I want to thank you all for participating in this Roundtable. My question is a little more personal because one of the jobs that I had supported John Matter and the U.S. Department of Energy (DOE) in the revision of the International Atomic Energy Agency (IAEA) document, the Physical Protection of Nuclear Materials and Nuclear Facilities (INFCIRC/225), which is recognized as a worldwide standard. The end result was the issuance in January 2011 of Revision Five of that document. I found the presentation interesting by Naito-san with regard to the work they're doing to improve the nuclear security of Japan. When he went through the presentations, almost every slide seemed to be coming out of Revision Five. Right now Japan is like all countries really; it's under Revision Four. I've always wondered as we were doing this Revision Five, how long it would take for a country to implement and say they are Revision Five because there are a lot of good revisions in Five. His presentation reflected a lot of those things.

So Naito-san I'd like to ask you, do you have any thoughts regarding to how long it will take Japan to be able to say, "We are under Revision Five now"?

Naito: Thank you for the question. I may not have made clear to the audience the position of Japan now related to Revision Five. What I presented is the work of ACNS, otherwise known as the Advisory Committee on Nuclear Security under Japan's Atomic Energy Commission (JAEC). The report gives the general guideline or direction on what should be done for accommodating Revision Five, i.e., what's lacking basically, and what additional measures need to be taken.

Revision Five is related to nuclear material and the nuclear facilities including transportation. For nuclear power plants, NISA (Nuclear and Industrial Safety Agency) has already taken almost all necessary revisions into the regulatory system. The same goes for research reactors. The corresponding competent authority, MEXT (Ministry of Education, Culture, Sports, Science, and Technology) has already incorporated almost all necessary revisions into the regulatory system. As for nuclear material transportation, it's still under development. It's very difficult to say what is the target date or my expectation when Revision Five will be implemented fully in Japan. But I think, especially after the creation of this new regulatory commission, I believe they will make every effort to hasten to incorporate what is lacking in Japan from the viewpoint of Revision Five into the regulatory system.

It is my hope that it will be done as soon as possible, but it may take one year, two years, or three years. It's up to the regulatory body to finally complete the action. So I hope I answered your question.

Mangan: For other people's information, the U.S. government in agreements that we have with other countries where we provide U.S. origin nuclear material, those agreements require that the country secure the material per the INFCIRC/225, the latest revision of it. It's going to obviously take some time for the government to adopt Revision Five's recommended requirements.

John Matter: I have a follow-up question for Mr. Naito. Regarding the ACNS report, will it be made available and shared with the IAEA and member states so that other countries can benefit from it and learn from your lessons learned and your recommendations for going forward?

Naito: Fortunately our report is on the website and my paper gives the specific website address. The Japanese version is there and for the English version we have made an attempt to translate both last year's November report and this year's March report. They are now on JAEC website as tentative translations.

Gotthard Stein: My question relates to the management of this important and impressive decommissioning project, which will range far into the future. In this context I missed any mention of the term "safeguards-by-design" and how the IAEA, the Japanese government, and operators will interact to implement international safeguards as easily as possible and save costs. The other question is, how far can future-level safeguards help to improve efficiency and effectiveness of safeguards?

Naito: I didn't fully understand your question. Is it to the decommissioning process or just in general?

Stein: Let me explain one problem in the example of final disposal of spent fuel in Finland, which is now under construction. Non-destructive assay (NDA) measurement of the spent fuel is a central element of the safeguards approach, since this is the last possibility to have access to the spent fuel and gain quantitative information about the nuclear material. These discussions have to start as early as possible between the stakeholders of the project to get optimal solutions.

Naito: Safeguards-by-design itself is a new concept but we have been implementing it already for the Rokkasho Reprocessing Plant, taking into account the outcome of LASCAR (Large Scale Reprocessing Plant Safeguard Forum) and also for the plutonium MOX (mixed oxide) fuel fabrication plant, JMOX we call it, in Rokkasho. And this is all reflected by our experience with the JAEA (Japan Atomic Energy Agency) MOX fuel production plant. So this is already in place. But your first question is on the decommissioning, but I don't think we are designing this project, rather it happened and so there have been close contacts among the IAEA and the JSGO, TEPCO, NMCC, and also JAEA. Mr. Parise of the IAEA mentioned the official task force created for this. So we are doing our best efforts through this collaboration and the coordination. So I hope this answers your question.

Stein: My budget is delicate. The question is, where's the say, is it the operator or is it our safeguards people who know? Who is the dominating factor?

Naito: I don't think there is a dominating factor. I think it's a collaboration. TEPCO may have some operational limitations and also the IAEA may want something else. So it's a kind of a joint venture to be materialized after a consensus.

Bernd Richter: I realized in your presentations that you went from installed cameras to portable cameras. I wonder whether they are still indoors or if some of them were put outdoors and whether there are plans in the nuclear power stations that are heavily damaged to have outdoor surveillance.

Naito: I repeat the question for Mr. Ohta. Referring to the Fukushima, the question is what is the practice of the installation of cameras. Is it the stationary or portable or remote monitoring type?

Richter: And whether there are plans to put them outdoors for those buildings that are not accessible right now.

Takeshi Ohta: I'd like to answer your question. We are now having discussions about the next stage of safeguards and the IAEA wants a gate monitor in front of our main gate. So if there is a gate monitor, they will be able to check that we don't transfer any spent fuel from the gate. So that is their next plan. And we are now discussing whether or not we will be able to check the transfer of spent fuel. As I said before, we are now keeping dry casks in the cask custody building. So they have planned for checking the possibility of NDA detection from outside the cask. So that is under discussion.

Richter: So the onsite plan shows there is a plan to place it outside.

Chris Pickett: You discussed the triage activities that you went through in the aftermath of the great tragedy with safety systems at Fukushima to get things under control. Can you share any lessons learned on what might be some good triage activities for re-establishing safeguards and security after an event of this type?

Naito: In the long-term or at the time of emergency situation?

Pickett: About the time you got things safe and under control.

Ohta: It is difficult to answer that question. After the earthquake and the tsunami, we had heavy damage to the security system. However we did our best to restore the physical protection system. I think the first priority is, of course, human life, and we need to keep the plant safe. The point raised is related to the security of nuclear material. I can't answer your question in detail. It's a very delicate question.

Ken Sorenson: I have a little different question, maybe for Meguro-san. In your opening statement you mentioned, I believe, that Ohi-3 came online on June 9 and Ohi-4 will be coming online the end of July. So, two of your reactors are online. That still leaves dozens of healthy reactors not producing power. Is there a plan to sequentially startup these nuclear reactors or is this still a matter of debate within the country, if and when more of these reactors will be brought online?

Yoshinori Meguro: Our utilities strongly hope to restart other nuclear power plants. Currently Japan has fifty nuclear power plants (NPPs) excluding the four stricken units at Fukushima Daiichi that are deemed to be decommissioned. Stress tests are now being undertaken for all the plants to take countermeasures against earthquake, tsunami, and station blackout as prerequisites for restarting the plant operation with the understanding of the local society.

The bill has been passed to reorganize Japan's nuclear regulation regime and a new Nuclear Regulation Commission of Japan (JNRC) is expected to start its work in September. As for Ohi 3 and 4, the Cabinet made the decision to restart their operation in view of the results of their stress tests and the extremely tight balance of electricity demand and supply for this summer in the Kanasai area that covers Kyoto and Osaka. After the creation of the JNRC, however, the results of stress tests will be carefully examined by the new commission. For this reason it might take more time to examine the results of stress tests for other nuclear power plants. But all utilities are strongly hoping they restart at earliest dates.

Sorenson: So everything is stopped until the new organization.

Meguro: Probably that is correct.

Naito: There is no concrete plan yet to restart other nuclear power plants. The conditions for the restart are very complicated, involving local politics and the public's attitude toward nuclear power—and also strong government decision. And also the complication is that the Nuclear Safety Commission will cease to exist. The regulatory power will be shifted to the newly created JNRC. As Mr. Meguro said, the stress test check will be performed by this new organization. So it takes time. And there's lots of speculation about which is next. And one possibility is Sikoku Electric Power Company's Ikata NPP. The other one is Sendai NPP owned by Kyushu Electric Power Company. And also Tomari NPP of Hokkaido Electric Power Company. But again, all depend on the difficult politics. So, it's not easy to speculate.

Jack Jekowski: This question builds a little bit on that response. The events at Fukushima and the actions that you're taking now in recovery and decommissioning are all going to modify everybody's risk assessment process in building, running, and operating nuclear power plants. Those costs that you're incurring now are going to have to be taken into account and designs adjusted as a result of that. The work that you're doing right now to carefully look at the plants as you bring them online are what would be expected. But as you do that, what is the public opinion in Japan in terms of what they're giving up right now in electricity versus what they view as being safe? Are you doing anything in the area of public opinion to sway public opinion in terms of convincing them that you now have a process that's going to assure their safety?

Ohta: For my company, TEPCO, we are now doing our best to achieve the roadmap for decommissioning. We are having press conferences every day. We are giving much information to the press members. However, we don't think it's a time for our company to convince the people of the safety of the nuclear power plant. We are now keeping them informed about the condition of the Fukushima Daiichi plant. I think all the Japanese nuclear industry should reassure the public about nuclear energy—not only TEPCO but all the members belonging to the nuclear industry.

Jekowski: Is there anything that the INMM as an international institute can do to help you with that? Because it impacts all of us as well. You don't have to answer that question today, but it's a good thing to be thinking about.

Meguro: Thank you very much. There are a lot of challenges that we have to face in the area of nuclear materials management, namely safeguards and nuclear security in the medium- and long-term recovery work at the Fukushima site. We would like to have the strong support from the INMM.

Leslie Fishbone: A week or two ago the Japanese Diet issued a report of its own investigation of the accident, and it basically accused the industry and trade organizations of capturing the regulatory framework in Japan and being unwilling to invest money to strengthen the nuclear power plants. Is it correct that this new regulatory organization is a response to that accusation and, in effect, an attempt to reform the industry?

Naito: The investigation committee made that report and then shed light on these points. Then who is going to be the chairman of JNRC? I think it's very, very difficult to select someone for that position. But there's also an expectation that the new organization will handle the matter correctly. Lots of expectations but can we find the right person? That is the real question. Because the basic argument is that the person should be less affiliated with so-called nuclear circle, or the nuclear industries, power companies, and R&D institutes, but on the other hand should have a very excellent expertise in the technical details of operating nuclear power plants. So it's kind of a dilemma. But on the other hand, lots of expectations fall on the new organization.

Sam Savani: I want to briefly echo what Dennis Mangan said earlier. I thought the session was very interesting, very informative, and you put a lot of time and effort into making the presentation and I really enjoyed it. It was a very excellent summary. I don't think I heard anything this morning in the presentation about this. There are six reactors on Fukushima 1 and four on Fukushima 2, so roughly 10 reactors were impacted. How are you making up for the loss of that electricity, because I assume that they were producing power and that energy was needed or there was a demand for it. And all of a sudden you're missing all that energy. How are you handling this and what are the consequences for not having that power available?

Naito: I repeat the question. There were no nuclear power plants running until the end of May. How could you substitute the loss, by what means?

Savani: How have you made up for that loss?

Ohta: First, the demand has been decreasing in the Tokyo area and also we are operating the fossil power plants that were under shut down. So there is a possibility of the trouble on the old fossil power plants. We have to keep the operation of that kind of fossil power plant.

Naito: Some of the electricity has been replaced by natural gas-fired power plants. That means the electricity bill will be much higher and in fact all the power companies are requesting price hikes on the consumer bills. Currently the typical consumer is going to have a price hike of about eight percent. Regardless of the price of natural gas, they have to buy to replace nuclear. And we are also competing with China and other countries. So inevitably the economic cost is the major impact. But as for ordinary people, they consider that they are now living without nuclear power, and therefore they can do it for good. That is the kind of mentality. They don't know what the real impact will be in the end and it's coming.

Steve Ortiz: Following up on Denny Mangan's comments on INFCIRC/ 225, Rev. 5 potential background. I was just wondering, do you see any value in having, once you are operating, an external advisory group come in and search, to see how well you're doing against the recommendations?

Naito: I see the value of the peer review mission. It's the decision of the government whether Japan invites such a mission. It's the decision of the new regime.

Robert Curl: I have a question that goes back to operations and lessons learned from the disaster. It touches a little bit on what Chris Pickett asked as well. Clearly, during the disaster there was loss of electrical power. I am sure there were problems with pumps and cooling systems, and many other things as well. What happened could not have been predicted, but as lessons learned because of it, can you speak to any thoughts or plans on future hardening of those systems against possible natural disasters like this great tsunami? This would apply to reconstituting the existing plants if that happens, and application to the plants that were not necessarily affected, but still could face the same thing? Again, I am asking about power systems, pumps, cooling systems, security systems, and things of that nature. Is there anything that came out of the disaster that you might consider lessons learned for future application?

Ohta: One example is the Kashiwazaki-Kariwa Nuclear Power Station. We are now making a new tide embankment for rejecting the massive tsunami power.

We also made the tight door on the reactor building and turbine building that keeps out the water. We prepared many fire trucks, power supply vehicles and the cars with gas-turbine generators on high ground in the facility. So we have taken many countermeasures.

Naito: And also for the nuclear security aspects, I have explained that NISA has already changed regulations to accommodate the requirement to avoid any attack on this vital equipment whose function may affect the safety of NPPs and also causing similar accident or the release of huge amounts of radioactivity. So this has been already in place.

Meguro: Mr. Ohta gave the example of the Kashiwazaki-Kariwa nuclear power station. We have fifty nuclear power plants in Japan. And overall, the plants are providing comparable measures. Namely, they are reinforcing measures for huge earthquakes, building a very high tide embankment for tsunamis and securing outside electrical power sources.

Naito: Not typically reported in the media is that the same earthquake and the tsunami affected none of our other power stations. They survived. Why? Because they had been taking precautions against tsunami and earthquakes. This has not been reported by the media. But when a dog bites a man that's not news. If a man bites a dog, that is bigger news. It's a similar thing. Many local residents in or near the Onagawa NPP fled into the nuclear power station for safety reasons after the quake and the tsunami. The operator of the Onagawa NPP, Tohoku Electric Power Company, accepted these so-called refugees and then they soon ran out of food because there were so many extra people. So they transported food in by helicopters to support these evacuees in the nuclear power plants.

Markku Koskelo: Let me switch gears a little bit on you. I enjoyed the talks this morning very much. What struck me was that they emphasized the regulatory framework that is being done in Japan in response to this, the cooperation with the IAEA, and possible cooperation with the United States R&D organizations. What I didn't see in there was what role does the very substantial Japanese nuclear industry play in all of this, such as Hitachi, Toshiba, and any number of the very capable companies that are based in Japan. I would assume they have a role in all these activities that will now follow. Could you comment on what they are doing and how their work is being coordinated?

Ohta: Toshiba and Hitachi are big companies who constructed nuclear power plants in Fukushima Daiichi. After the accident Toshiba and Hitachi joined with us in coping with the accident. Also after the accident, Toshiba and Hitachi and also Mitsubishi have provided great support for us in restoring the plant. For example they made a new water treatment system in Fukushima for reducing the radioactivity of contaminated water.

Brian Boyer: Mr. Naito I believe you mentioned there would be a forty-year limit on nuclear reactors, and I know in the U.S. there are reactors that are in that age group and they're trying to extend their lives. I think the Gen 3/Gen 4 are planned to be sixty years and I think with Gen 4 they're talking trying to go eighty years. I'm wondering how the nuclear industry might feel about that, the limit of forty years—if you see that for old reactors or see that limit also for next generation reactors?

Naito: Unfortunately this new regulation is put forth by political considerations, not technical considerations. So many people in nuclear industry and also nuclear experts are doubtful about the validity of this uniform forty years. The new regulation provides that there may be extensions, but only once. I don't know is it fifty years or sixty years altogether? It's a kind of an argument based on the popular reasons. It's the basic thinking of the general public. They are not so assured of the safety of older plants. The argument is that the Fukushima Daiichi, it was the old BWR (boiling water reactor), the first generation of GE type. And there have been many arguments to abolish it, but the operator extended it by putting some technical fix that does not necessarily give confidence to the general public. So it's more or less political position.

Meguro: My company, JAPC, also has the oldest BWR (Tsuruga-1) in Japan. This plant commenced operation in 1970, now in more than forty years of operation. We have checked the nuclear and plant safety as an annual inspection every year and, in addition, periodical plant life management evaluation is conducted every ten years. We obtain the confirmation on safety operation from NISA. We believe that we can maintain the plant safety more than forty years of operation. Therefore, our company is not considering stopping its operation. JAPC has no concrete program for shutting it down.

Matter: Going back to the report and recommendations from the Japanese independent investigation committee, what impact and what changes do you anticipate they might have in the future, whether it has to do with your mid- and long-term roadmap or more generally your operations and business practices? What impact do you think those recommendations will have in Japan and the commissioning of nuclear power plants in the near-term and beyond?

Naito: In a talk I gave yesterday at the (INMM) International Safeguards Technical Division Meeting, I reported that by the end of August the long-term energy needs and long-term energy strategy will be formulated by the Energy and Environment Council (EEC), which has proposed three options to be considered for the year 2030. They are zero nuclear, 15 percent nuclear, and 20-25 percent nuclear options. They also suggest an increase in alternative energy sources, and a reduction in fossil fuel to meet the government's commitment made some years earlier to reduce the greenhouse gas effect by 25 percent relative to the 1990 level by 2020. According to their schedule they're going to have public hearings starting this month through the end of August and then finalize the long-term strategy. It's really too early to speculate which option will be adopted. But in principle, zero nuclear, 15 percent nuclear, 20-25 percent nuclear options are on the table. So the government will chose one of these taking into account various factors, including economic impact and the support of the public, and so forth.

Richter: Is there any cooperation with the European Union or any individual European state with Japan on Fukushima?

Naito: Yes, AREVA has been cooperating in the waste water processing. Before the technical development for decommissioning R&D program, every country and every entity is welcome to participate with a concrete program or the technology to tackle with this restoration, removing and accounting molten core debris, decommissioning the plants and so forth. I don't think there's a bid already but we are waiting for specific proposals and then will consider if it is really feasible or not.

Jekowski: You're taking some extraordinary efforts at Fukushima to move the spent fuel to a common storage area and also to dry cask storage. Is there any thought to use that concept at your other power plants in the future to provide perhaps a better located or a safer and more secure storage onsite rather than in the immediate vicinity of each of the reactors?

Ohta: In my company we don't have any plans to use dry casks for storing spent fuel at an NPP. So this is limited to the case of Fukushima Daiichi because, as I said, we have to make a clearance in the common pool for retrieving the spent fuels from the Unit 1 to 4 spent fuel pools, so this is limited to this case.

This is the case for the Fukushima power plant. We are now preparing for the off-site interim spent fuel storage facility to accommodate spent fuels in dry casks. It has a concept of keeping many dry casks for about forty years. It is a joint undertaking between my company, TEPCO and Meguro-san's company, JAPC. It is now in construction stage at Mutsu, Aomori Prefecture.

Naito: Concerning what I explained as the three options and the EEC, the zero option means direct disposal of spent fuel. So inevitably it needs dry storage. The 15 percent option and the 20-25 percent option, either reprocessing only or direct disposal only or a combination of both. If the direct disposal is involved, the dry storage is also inevitable.

Fishbone: Does TEPCO have enough funds to finance the cleanup and decommissioning, and if not, what happens?

Ohta: It's a difficult question because our company has been owned by the Japanese government so the fund is a critical problem for our company. We have to do our best for achieving the goal of decommissioning. The funding approval is critical for us.

Sorenson: Just a follow up on the dry storage in the Mutsu facility in Aomori Prefecture. Is that part of the plan when you decommission the Fukushima site to move dry cask storage from the temporary cask custody area? Is part of the plan to move those casks to Mutsu or what is the plan?

Ohta: If we start the operation of the Mutsu interim storage facility we are going to transfer the casks that are stored at temporary cask custody area to Mutsu facility. But we have not decided the concrete plan for the transfer to the Mutsu facility.

Mangan: We normally end this session on one of two things. Either we run out of questions or we run out of time. In this particular situation, we've run out of time.

I want to thank you ever so much. You've been very kind. Your answers have been very, very good. So, thank you again for taking your time to be with us.

Rapid Analysis of the SNM Smuggling Threat Space for Active Interrogation Using a Green's Function Approach

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Abstract

Detection of smuggled special nuclear material (SNM) in truck or sea containers is essential for ensuring the security of the United States from radiological threats. Radiation transport simulation is a widely used tool for evaluating the probability of detection given some SNM, smuggler strategy, detector system, and alarm algorithm. Inherent in these calculations is the tradeoff between the speed and the fidelity of the computation. Full Monte Carlo (MC) radiation transport captures the true physics and geometric richness of the system; however, doing this in a reasonable amount of time for a spanning set of threats requires vast computing resources. Simplifications such as 1-D deterministic approximations can reduce the computation time drastically, but may miss important physical and geometric phenomena. We present a method that uses Green's Functions, which are computed once up front and are then stored for future use, to rapidly analyze many possible scenarios with the fidelity approaching that of full 3-D MC transport but with a computational time on the order of seconds. Using this technique, we model an active interrogation (AI) photon source incident on a cargo container containing some SNM and analyze the time dependent flux of neutrons at the detector. We present an illustrative application of our technique on the neutron background from cosmic radiation. First, we model cosmic interactions in the atmosphere to obtain the neutron flux as a function of both energy and direction at 150m above the ground. We break the subsequent transport of the neutrons into several distinct regions: neutrons incident on the ground per neutron at 150m, neutrons reflecting back and exiting the ground per neutron incident on the ground, neutrons in the detector per neutron leaving the ground, as well as the direct path of neutrons into the detector per neutron at 150m. We are able to vary parameters such as ground composition, air composition and humidity, detector height above ground, and detector type. With this method we have achieved a 7.3 percent root mean square difference between our spectral neutron flux and that obtained from a full MCNPX calculation.

Introduction

Recently there has been an increase in attention to the problem of detecting SNM being smuggled into the United States for use as either a weapon or radiological dispersal device (RDD). Development of systems that can reliably detect these threats requires computational benchmarks of many possible threat scenarios to ensure the system will perform reliably before the expensive step of building and testing of the physical system is done. Due to the complexity of the threat scenario as a whole, full computational benchmarks of all permutations are typically not done. Rather, a small subset of the full threat space is computed and often with many simplifying assumptions. The major drawback to this approach is that since only a small subset of the entire threat space is sampled, the system can only be said to work reliably under those conditions that have been analyzed. The system may not perform reliably once more realistic scenarios are considered.

To illustrate the complexity of the full threat space, consider the interrogation of a shielded sphere of SNM in a truck cargo container. If we take only a very rough sampling of all possible permutations of the threat scenario (number of samples in parenthesis): isotopic composition of SNM (2), size of SNM (5), shielding type (2), shielding thickness (10), location of SNM within cargo (15x5x15), average Z of cargo (3), distance of truck from detector (3); we easily can come up with several million possible combinations of threat scenarios. If we consider other variables such as detector type, AI source energy, vehicle type, and vehicle velocity, or if we take a finer sample of these variables, it is easy to see how the scope of the entire threat space can rapidly become unmanageable. A detailed analysis of even a relatively small but representative subset of the threat space is also infeasible as each scenario requires large amounts of computational resources and/or time. Even if the computational resources are available to compute a spanning set of threats, any new scenario that needs to be specifically analyzed would require the computation of that scenario, which will lead to a delay in the time it takes to analyze the results. In this paper, we outline a methodology for rapid analysis of the entire threat space by breaking the problem into various sub-regions and developing response functions for each of the sub-regions. A source is then introduced and the appropriate response functions are applied to the source to ultimately obtain the response in the detector due to that source. This methodology can lead to computational times on the order of seconds for any given scenario with only a very modest machine (personal laptop) as compared to hours, days, or weeks on large clusters.

Methodology

The methodology proposed requires breaking the problem into various sub-regions and for each sub-region computing the Green's function (response function) for each of the sub-regions from monoenergetic sources entering the sub-region. The response functions *(R)* are stored as matrices and describe the contribution to all energy bins from a source in a single energy bin as it traverses the sub-region. This data can be created in MCNPX by starting sources of monoenergetic particles entering the sub-region and tallying the current of particles exiting the sub-region. An MCNPX run is needed for sources in each of the energy bins used in the energy group structure. In general, direction would also need to be tracked, but this leads to much larger data storage requirements. Where possible, the angular distribution of the particles is either fit to an analytic function or is assumed to be a cosine distribution, depending on which is most appropriate. These angular distributions must be fed into MCNPX when starting the monoenergetic sources into each of the sub-regions to obtain the correct coupling of boundary conditions between the sub-regions.

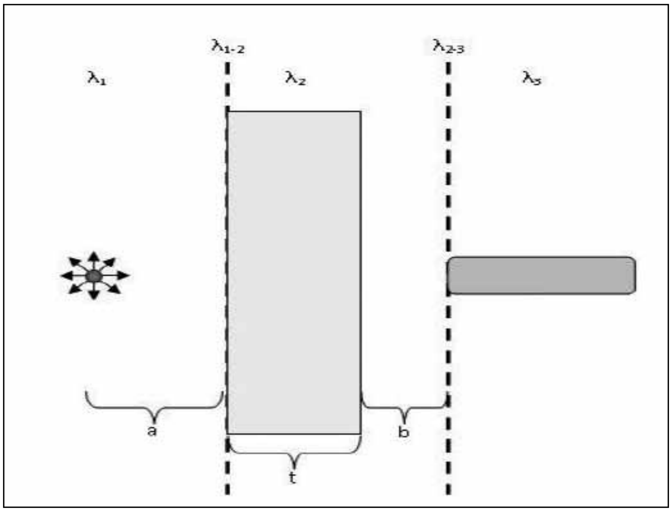
To illustrate the methodology with a simple example, consider a spherical source of strength emitting particles in a vacuum with some arbitrary angular and energy distribution. An infinite slab of thickness t and total absorption and scattering cross-sections of Σa and Σs is located a distance a from the center of the source. A detector is placed at a distance b on the other side of the shield and we want to know the flux in the detector. The solution to this problem can be obtained by breaking up and solving for the response functions in three separate regions. The entire phase space λ can be divided into regions λ_1, λ_2, and λ_3 with each region having an associated response function R_1, R_2, and R_3. The phase space corresponding to the interfaces of these regions are designated by $\lambda_{1\text{-}2}$ and $\lambda_{2\text{-}3}$.

$\lambda_{1\text{-}2}$ describes the points in phase space corresponding to particles of all energies, directed into region 2, located on the plane at the interface of regions 1 and 2; $\lambda_{2\text{-}3}$ is defined similarly for the interface between regions 2 and 3.

To get the response function for region 1 *(R_1)*, we start a monoenergetic volumetric spherical source of energy *e0* with the given angular distribution in MCNPX and tally the particle current on the plane at the interface between regions 1 and 2. This will give us a single column in the response function matrix that describes the energy distribution at the interface of regions 1 and 2 from a unit source of energy *e0* in region 1. This is repeated for monoenergetic sources of all energies in the group structure to completely fill the response function matrix for region 1. This same process is repeated for regions 2 and 3, where the tally in region 3 will be the value of interest in the detector (either flux or counts).

Once the response function data is created and stored, obtaining the solution to the problem requires simple matrix multiplication of the response functions with the source term. Since the response functions describe the response to unit sources in each of the energy bins, we can use superposition to obtain the result of interest in the detector for a source of any arbitrary energy distribution. If a source of arbitrary energy distribution (but with the same angular distribution as was used to compute *R1*) is given, then the current of particles in energy bin e that are entering region 2 from this source is given by

Figure 1. Geometry of the example problem with a source in region 1, a shield in region 2, and a detector in region 3



$$\psi_e^{1-2} = \sum_{g=1}^{G} R^{e,g} q_g, \tag{1}$$

where q is our neutron source and G is the total number of bins in the energy group structure. The total energy dependent current vector at the interface of regions 1 and 2 is then given by the matrix multiplication of R1 and q,

$$\boldsymbol{\psi}^{1-2} = \boldsymbol{R_1 q}. \tag{2}$$

If we treat this current, $\boldsymbol{\psi}^{1-2}$, as a source of particles entering region 2, then we can apply *R2* to this current to obtain the current of particles entering region 3. Given the current entering region 2, the energy dependent current of particles entering region 3 is given by

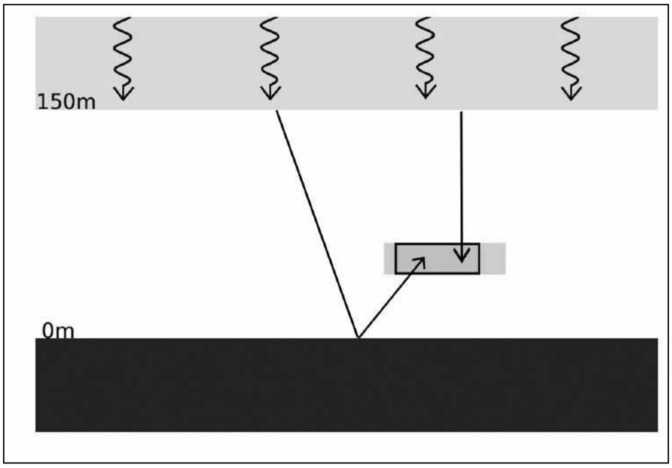
$$\boldsymbol{\psi}^{2-3} = \boldsymbol{R_2 \psi}^{1-2} = \boldsymbol{R_2 R_1 q}. \tag{3}$$

And again applying this same reasoning to region 3, we can obtain either the flux or counts in the detector (whichever quantity was tallied when *R3* was computed) by applying *R3* to $\boldsymbol{\psi}^{2-3}$.

$$\boldsymbol{\psi^{det} = R_3\psi^{2-3} = R_3R_2R_1q}. \tag{4}$$

Using the response function methodology reduces the computation of the final result to simple matrix multiplication as compared to a full computation of the entire problem. With this methodology the result from sources of any arbitrary energy distribution can easily be calculated allowing for rapid parametric study of any arbitrary source strength and energy distribution. If any other parameter in the system would like to be changed, all that would be required is that the appropriate response function be interchanged. For instance, if the thickness of the shielding material is to be changed, a different *R2* should be used that is calculated with the new thickness. Or if the shielding material is to be changed, then *R2* should be calculated with the new material and used. Generating these response functions requires large upfront computational costs as the response functions need to be created for many geometries and sets of materials. However, interpolation between response functions can be used to reduce the total number of response functions that need to be computed for things such as shielding thickness or detector position. The benefit of this methodology is that once the response functions are calculated, any permutation only requires the changing of that particular response function and does not require the expensive recomputation of all other parts of the problem that do not change. For example, if we decided to design a new detector and wanted to test it out over many threat scenarios, all that we would need to do is calculate a new *R3* for this detector. With this new response function we will now be able to rapidly analyze all possible threat scenarios with the new detector very quickly. Using a brute force MCNPX computation, we would need to remodel every scenario, in full, with this new detector. Transporting the particles through the shielding in region 2 can be an expensive calculation, and the distribution of particles making it through should be independent of the type of detector used. Therefore, we would spend a lot of time recalculating things that have not changed due to using a different detector. With our method, since we have already precomputed that data and it is stored in the response functions *R1* and *R2* that do not change, we can use those same response functions and waste no additional time recomputing quantities that have already been computed.

Figure 2. Diagram showing the two major components to the cosmic neutron background signal in a detector

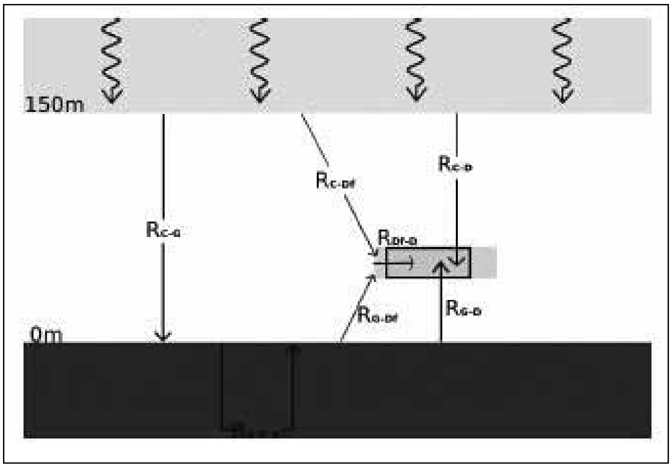


Implementation: Cosmic Background

The implementation of this response function methodology has been applied to the flux in a detector due to the cosmic neutron background. We start with a source of neutrons q at some arbitrary distance above the ground; for our purposes we choose 150m since that is higher than most buildings and other objects that we may want to place in our geometry at a future time. To obtain the source of neutrons at 150m, we model high energy cosmic protons and alpha particles impinging on the earth at an altitude of 65km. These particles are then transported through many layers of atmosphere down to 150m where the energy and angular distribution of neutrons is tallied. This distribution is then used as our source term q. We then create a semi-infinite geometry by making a cylinder, with the axis along the vertical direction, which has reflecting walls. We place a thick disk of ground material at the bottom of the cylinder and fill the rest of the cylinder with 150m of air. The neutron source is placed at the top of this cylinder and a detector is placed 1m above the ground. The flux in the detector is the quantity we would like to compute.

In our scenario we use an He-3 detector that is modeled as a single 1m long He-3 tube of radius 2.54cm that is surrounded by 1 cm of moderator along the back face and sides, and 1cm of moderator on the front face as well. The He-3 tube is also shielded by 1.7mm of cadmium on all sides except the face. To obtain the flux in the detector from cosmic neutrons, there are two major components that we need to consider: direct contributions to the detector and contributions that come from neutrons scattering back from the ground (Figure 2). But breaking the problem into these two components and creating response functions for these would only allow for limited flexibility in changing parameters of the system. With just these two response functions, we would only be able to easily vary ground composition. This would be done by generating response functions for the flux contribution in the detector from neutrons scattering back from the ground, for many different ground compositions. However, due to the coupling of the ground with the detector in the response function, if one wanted to change the detector type or the parameters of the same type of detector (such as moderator thickness), it would not be a simple task. To accomplish this, all response functions that had been previously created would need to be recalculated using the new detector. To overcome this issue, we break the problem into many more components such that the detector is almost completely decoupled from the geometry. Doing it this way allows the properties of the detector, or the detector as a

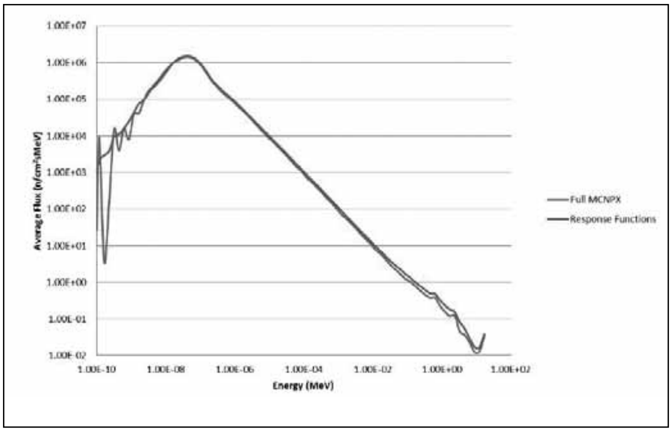
Figure 3. Diagram showing the response functions needed for decoupling of the detector from the geometry and allowing for easy changing of detector parameters



whole, to be swapped out easily without needing to recompute all of the other response functions for the new detector.

Figure 3 shows how the problem is broken up to allow for many parameters to be easily changed. Calculation of the background cosmic neutron flux in the He-3 detector is broken into eight components: 1) direct contributions to the flux in the detector from all sides other than the face per neutron at 150m *(RC-D), 2)* current on the face of the detector per neutron at 150m *(RC-Df), 3)* contribution to the flux in the detector per neutron incident on the face *(RDf-D), 4)* current of neutrons entering the ground per neutron at 150m *(RC-G), 5)* current of neutrons leaving the ground per neutron entering the ground *(RG-S-G)*, 6) contributions to the flux in the detector from all sides other than the face per neutron exiting the ground *(RG-D), 7)* current of neutrons on the face of the detector per neutron exiting the ground *(RG-Df)*, and 8) contribution to the flux in the detector per neutron incident on the face from the ground *(RDf-D).* Each of these components requires the computation of its own response function except for components 3 and 8, which can be the same if the angular distribution of neutrons hitting the face of the detector directly and from the ground are similar (i.e., relatively isotropic). Having each of these response functions calculated independently allows us to change many of the parameters in our problem easily. If we would like to vary the ground composition we just create many *RG-S-G* response functions for the different ground compositions; if we want to vary the thickness of the moderator on the face of the detector we simply create many *RDf-D* response functions spanning the range of thicknesses of interest; if we want to change any of the geometry of the detector such as size or moderator thickness around the sides, we simply generate new *RC-D* and *RG-D* response functions with the new detector geometry.

Figure 4. Comparison of the response function calculation with the full MCNPX solution for a shielded He-3 detector with 1cm of moderator on all sides

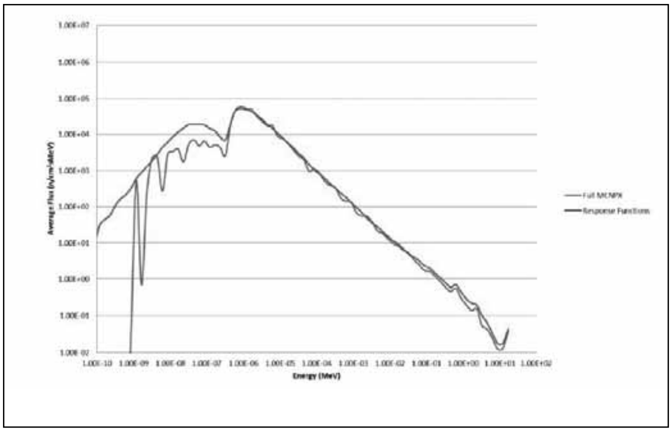


The calculation of each of the response functions should be done as independently as possible to avoid double counting contributions in the various response functions. For example, the calculation of *RG-S-G* should be done with a vacuum above the ground so that neutrons that scatter back into the ground from the air and then scatter back out of the ground into the air are not included in the calculation. This scattering between the air and ground is captured in *RG-D* and so including it in *RG-S-G* would increase the effective number of neutrons leaving the ground and lead to an increased signal in the detector.

Results

The average neutron flux in the detector calculated with response functions is compared to a direct calculation with MCNPX. Figure 4 shows the results of the two methods plotted together. Using 80 logarithmically spaced energy bins from 10-^{10}MeV to 20MeV, the results match well over nearly the entire energy range. The increase in the flux at 20MeV is due to all of the neutrons above 20MeV being lumped together and placed in the 20MeV energy bin. The RMS value of the data is calculated for each of the data sets and compared. The flux given by the response function calculation has an RMS value 7.3 percent higher than the true solution given by MCNPX. The difference in the low energy region can be attributed to poorer statistics in the MCNPX run as compared to the response function data. Since the calculation of any single response function is simpler than the full calculation, the response functions can be created with many more particle histories than are used in the full calculation while still being calculated relatively quickly. This leads to the ability to create response functions with low relative errors. The difference in the higher energy regions (10^{-2}MeV to 20MeV) can be attributed to not having perfectly matching boundary conditions, especially for the angular distribution of neutrons, at the interfaces of the various sub-regions.

Figure 5. Comparison of the response function calculation with the full MCNPX solution for a shielded He-3 detector with 1cm of moderator on the face and no moderator on any other side



As an example of how we can quickly calculate some other scenario, we want to see what the flux in a shielded He-3 detector would be if the detector has no moderator around the sides and 1 cm of moderator on the front face. The comparison between the full MCNPX calculation and the response function calculation is given in Figure 5. The flux in the detector looks significantly different in this case due to the lack of moderator around the sides of the detector. The large drop at around 10-6MeV is due to the cadmium shielding killing nearly all neutrons below this energy; if there was no shielding material the flux would continue to increase as the energy decreases as in Figure 4. The neutron flux below the cadmium cutoff is due to neutrons that enter the detector through the face where no shielding is present. When there is moderator present around all sides of the detector (as in Figure 4) the high-energy neutrons that pass through the shielding are then moderated to low energies by the moderator on the sides of the detector. This leads to a significantly increased flux in the low energy region even though the cadmium is present to remove low energy neutrons. The difference between the MNPX calculation and our response function calculation for neutrons below the cadmium cutoff is due to poor matching of the true angular distribution of the neutrons incident on the face. However, this case where there is no moderator around the sides of the detector is the most difficult scenario to match correctly. If even a small amount of moderator is placed around the detector, the moderator tends to “fill out” the low energy region and this mismatch is nearly non-existent other than the differences in the statistics.

Conclusion

The main advantage of using response functions is the flexibility and time savings when large numbers of possible threat scenarios are to be analyzed. This method has been shown to be able to accurately reproduce the results of a full MCNPX run in a matter of seconds. While this method does not completely remove the need for large amounts of computation, it moves all of the heavy computation up front for the calculation of the response functions. Calculation of most of the response functions can be done relatively quickly as they are generally much simpler than the full problem. There is also a large time savings in not having to recompute parts of the problem that have previously been computed. Once the response functions are generated, applying the matrix multiplications to obtain the solution for any scenario to be analyzed is relatively trivial in terms of computational resources and time required.

Several considerations must be taken when generating the response functions. The assumption that the response functions can be calculated independently of each other is usually only valid for regions where there is not much scattering back and forth at the interfaces of the sub-regions. If there are regions that are strongly coupled, steps must be taken to quantify this coupling and add it into the solution such that the correct results are obtained. A physical understanding of the various outcomes of neutron interactions must also be used to understand how to correctly break up the problem and which response functions certain contributions should be applied to so nothing is double counted or missed. Keeping the correct angular distribution of neutrons at the interface of the various sub-regions is non-trivial and leads to the greatest difficulties and errors. In theory, the angular distribution of neutrons can simply be tallied and then used when building the source for the next sub-region. In practice this tends to complicate the tallies and the post processing of the tally results. However, the major drawback of explicitly tracking directionality is the large increase in the amount of data that must be stored in the response functions. Where possible, the angular distribution of the neutron flux should be fit to some analytic function such as a power of the cosine of the particle direction.

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J. D. Williams Student Paper Award—2nd Place Paper

Characterization of Special Nuclear Material Using a Time-Correlated Pulse-Height Analysis

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Abstract

The ability to perform non-destructive characterization of special nuclear materials (SNM) is extremely important to ensuring that nuclear material is not diverted. Cross-correlation measurements detect multiple neutrons in nanosecond time windows, which can be useful in distinguishing SNM from other neutron sources. Additionally, individual correlated particle pairings can be identified when the cross-correlation measurement is performed with liquid scintillation detectors with good pulse shape discrimination capability. Past efforts have shown that measurements utilizing the time difference between *(n, n)* events can be used to identify fission sources from other neutron sources. However, other correlated particle pairings can offer additional information about the source. The analysis presented here takes advantage of the timing and energy deposition of *(γ, n)* particle pairings to further characterize the source by creating a time-correlated pulse-height (TCPH) distribution. TCPH uses the height of the detected neutron pulse along with the time difference between the correlated neutron and gamma to create a surface of the pulse height at a given time delay. For sources that do not have multiplication, the maximum possible time delay at a given pulse height can be predicted by simple kinetics. With multiplication present in the system it becomes possible to have high energy events arriving at times later than the predicted maximum. This provides a means of identifying a multiplying source from a non-multiplying source. This work presents the initial development of this technique and preliminary measurement results from a ^{252}Cf source compared to results simulated with MCNPX-PoliMi.

Introduction

For many years the nuclear community has relied heavily on ^{3}He-based systems to detect and characterize nuclear material. Recently, the demand for ^{3}He has dramatically increased, and production has halted, resulting in a wide-scale shortage.[1] This situation has prompted the development of alternative detector solutions for detection, identification, and characterization of nuclear material.

Liquid scintillators, such as EJ-309, could be used to replace ^{3}He in some applications. EJ-309 is a good alternative because it is readily available, inexpensive, and non-hazardous. In addition, liquid scintillation detectors have the ability to distinguish between fast neutrons and gamma rays. Liquid scintillators are capable of detecting fast neutrons preserving the energy and timing information of neutrons. These properties allow for a much wider range of available data for analysis compared to a ^{3}He system.

One method that can take advantage of the timing information to identify fission sources is a correlation measurement.[2] Both spontaneous and induced fission events release neutrons and gamma rays that are correlated in time. A correlation measurement can be used to look for these events arriving in multiple detectors within very short time windows (approx. 100 ns). These correlated events can be further subdivided by the types of radiation involved, (γ, γ), *(n, n), (n, γ), or (γ, n)*. These subsets of the correlation contain additional information about the source. This technique has been shown capable of identifying fission sources from other neutron sources such as *(α, n)*.[3] Past efforts have focused primarily on the information that is available in the *(n, n)* distributions;[3] this work will focus on extracting information from the *(γ, n)* distribution.

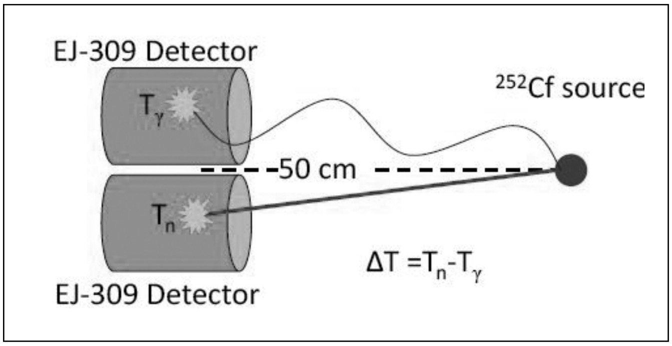
Time-Correlated Pulse-Height Technique (TCPH)

The arrival time of a neutron from a fission event is a function of the neutron energy and the source-detector distance:

$$t = \frac{d}{\sqrt{\frac{2E_n}{M_n}}} \qquad (1)$$

where d is the source-detector distance, E_n is the energy of the neutron and M_n is the neutron mass. Equation 1 allows us to determine the uncollided arrival travel time of a neutron if the time of the fission event is known. The use of a fission chamber would give nearly exact timing; however this is impractical for real-world applications. Another approach is placing the source directly next to a detector. However, by measuring the time-correlated (γ, n) distribution the arrival time of the gamma-ray can be used as the initial time trigger for the arriving neutron. This technique can be used at a stand-off distance as shown in Figure 1.

Figure 1. Example setup for a TCPH measurement setup



Using this approach the travel-time equation needs to be modified to account for the travel time of the gamma ray:

$$t = \frac{d}{\sqrt{\frac{2E_n}{M_n}}} - \frac{d}{c} \qquad (2)$$

The objective of TCPH is to show the pulse height information of the neutrons arriving in a specific time interval. This information is best presented on a surface plot with one axis representing the time difference between the arriving coincident gamma-ray and neutrons events, the other axis represents the light deposited by the neutron.

The pulse height and arrival time of the neutron are both a function of the energy of the neutron. Equation 2 acts as a theoretical time limit below which all neutrons from a single fission event should lie. The maximum possible light that can be deposited for a given neutron energy can be determined by:

$$L = V\left(WE_n - X\left(1 - e^{-YE_n^Z}\right)\right) \qquad (3)$$

where V, W, X, Y, and Z are experimentally fit detector specific parameters.[4] Using Equation 2 and Equation 3, a theoretical discrimination line can be created, below which the time travel time and pulse height for all neutrons from a single fission event must lie.

If there is any multiplication, then it becomes possible to observe counts beyond the theoretical cutoff line. This is due to the correlated neutrons from a fission chain, a gamma-ray from a earlier generation fission is still correlated in time with a neutron from a later generation event, but this neutron would arrive at a time greater than would be predicted by its energy.

By taking the ratio of the number of events below the discrimination line to those above the discrimination line, an estimation of the level of subcritical multiplication in the source can be made. Subcritical multiplication is defined as:[5]

$$M = \frac{1}{(1-k_{eff})} \qquad (4)$$

The following analysis will quantify the effectiveness of this approach.

Simulation

To evaluate the effectiveness of this technique, several experimental setups were simulated using the Monte Carlo code MCNPX-PoliMi and the MCNPX-PoliMi post processing code, MPPost.

MCNPX PoliMi

MCNPX-PoliMi is an enhanced MCNP-PoliMi code. MCNP-PoliMi was created to simulate neutron and gamma-ray correlation measurements.[6] This was done by adding improvements to the order of physics sampling, ensuring that each history resulted in realistic particle creation. In addition, the full neutron and photon energy and multiplicity distributions have been implemented for several sources. Additionally, several common neutron sources have built-in source specifications. The neutrons and gamma-rays created in fission events are also correlated, which is essential for the type of analysis presented in this work and cannot be simulated using MCNPX.[7]

MCNPX-PoliMi is also useful for the simulation of detector response. The code produces a detailed list of all of the interactions in a specified detector volume. These events can be used to reconstruct the light output in scintillation detectors.

MPPost: A MCNPX-PoliMi Post Processor

The results from MCNPX-PoliMi need to be processed to predict the physical response of a detector system. MPPost was developed to accurately simulate the response of a variety of detectors.[8]

Events in each simulated history are read into the algorithm, and each event is then converted into light output in the case of a scintillation detector. This light conversion is done based on the particle type and the energy deposited. The conversion from energy to light for photons is linear; however, the conversion to light for neutrons is nonlinear. An empirical response function for neutron light production is used to determine the light produced from each neutron collision. A pulse is determined by the events that occur in the same detector within 10 ns. The individual light contributions are summed and compared to a detection threshold. If the total light output is greater than the threshold, the pulse is counted as a detected event. Pulses are then classified by the type of particle that created them. If multiple particle types contribute to the light production the pulse is classified by the event with the most dominating effect on the tail portion of the pulse (for example, if a neutron and photon contribute light to a pulse, the pulse will be classified as a neutron). After the detected pulses have been created the cross-correlation distributions can be created.

All events in detector pairings that arrive within a short time window are considered a coincidence. One detector is designated as a start detector and all others as stop detectors. The timing between events is determined as the time difference between the stop and start detector events. These coincidences can be limited to events within the same history, or it is possible to combine events based solely on their arrival time, thus accounting for accidental counts. These simulated coincidences are used to obtain cross-correlation curves. The pulse height of the neutron is recorded and used to create a TCPH surface plot as shown in Figure 2.

Setup

In order to test the effectiveness of TCPH, several sources were simulated. The simulated geometry consists of two side-by-side 12.7 ×12.7-cm cylindrical EJ-309 detectors placed 50 cm from a source. A 30-cm concrete floor was included in the model at 1 meter below the centerline of the detectors. A ^{252}Cf source, a 4.5-kg plutonium metal sphere moderated with up to 15.24 cm of polyethylene, and a 25-kg highly enriched uranium sphere were modeled.

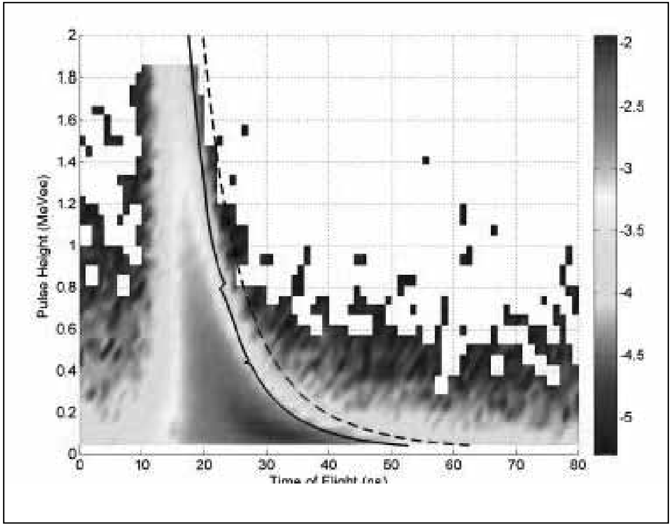
Simulated Results

The results shown here have a solid discrimination line placed at a distance of 50 cm plus the mean free path of a neutron inside of the detector. The mean free path was incorporated into the distance to improve the accuracy of the position of the discrimination line by accounting for the fact that a majority of the events interact within the first few cm of the detector volume. A dashed line is added at the distance of the back edge of the detector. The correlation window for accepted events ranged from 0 ns to 80 ns. The gray scale for all TCPH plots represents the log of counts per second.

^{252}Cf

A simulated TCPH distribution for a point source ^{252}Cf source at 50 cm from two 12.70 ×12.70-cm EJ-309 detectors is shown in Figure 2. This source has a subcritical multiplication of 1 and so correlated neutrons and gamma rays from fission events will only be measured in the area below and to the left of the discrimination line. This is clearly observed as a vast majority of the events lie below the back-face discrimination lines, as expected. The small concentrations of events near low energies and high times that are past the discrimination line are the result of multiple interactions in the detector.

Figure 2. Simulated TCPH for two EJ-309 detectors 50 cm from the a ^{252}Cf source[5]



Highly Enriched Uranium (HEU)

To examine the effect of multiplication on TCPH a 25-kg sphere of HEU was modeled as 90 percent ^{235}U with a density of 19.43 g/cm3. The k_{eff} for this source was 0.8039 with a subcritical multiplication of 5.0981. Figure 3 clearly shows a large concentration of events falling past the theoretical discrimination lines, correctly indicating the presence of multiplication.

Plutonium Sphere with Polyethylene Shells

A 4.5-kg sphere of α-phase plutonium metal with an isotopic composition of 94 percent ^{239}Pu by weight and has a density of 19.6 g/cm3. This source was chosen because this sphere has been extensively modeled with MCNPX-PoliMi with good agreement.[9]

The sphere was modeled in several different configurations with various levels of moderation. Table 1 shows a summary of the moderation, k_{eff}, and subcritical multiplication of the source. The TCPH plots for all of the cases are shown in Figure 4.

Figure 3. TCPH for a 25-kg HEU sphere

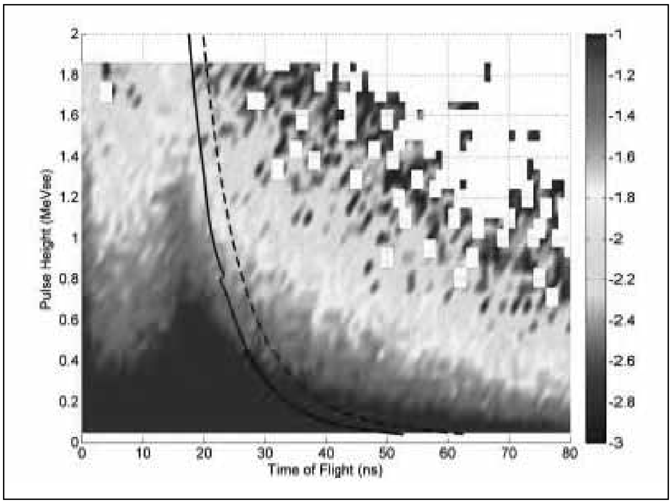


Table 1. Summary of key parameters for the plutonium sphere and polyethylene shell models

Polyethylene Thickness (cm)	k_{eff}	Multiplication
Bare	0.7768	4.48
1.27	0.8298	5.87
2.54	0.8715	7.78
3.81	0.9049	10.52
7.62	0.9390	16.40
15.24	0.9437	17.77

Visual inspection shows a dramatic difference between any of the subfigures in Figure 4 and the ^{252}Cf result shown in Figure 2: the number of counts to the right of the discrimination line is considerably higher for these distributions. Figure 5 shows the ratio of events to the right of the discrimination line to those on the left plotted against the multiplication of the source. The discrimination ratio increases as the multiplication of the source increases. However, at higher thicknesses of polyethylene the ratio begins to level off. This effect can be explained by the fact that at the higher thicknesses, the polyethylene is acting more as a shield than as a reflector.

To investigate the effect of multiplication without polyethylene, the density of the plutonium sphere was arbitrarily changed. This exercise changed the multiplication of the system without added low-Z shielding, as was the case with the polyethylene. As is shown in Figure 6, there is a linear increase in the discrimination ratio with multiplication.

Figure 4. Simulated results: a) TCPH for the bare plutonium sphere b) TCPH for the 1.27-cm polyethylene moderated sphere c) TCPH for the 2.54-cm polyethylene moderated sphere d) TCPH for the 3.81-cm polyethylene moderated sphere e) TCPH for the 7.62-cm polyethylene moderated sphere f) TCPH for the 15.24-cm polyethylene moderated sphere

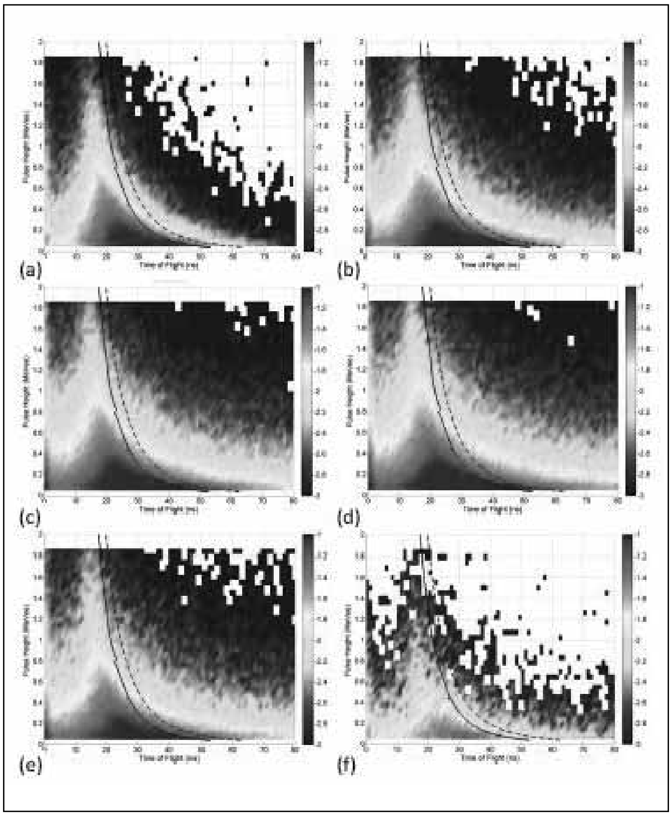
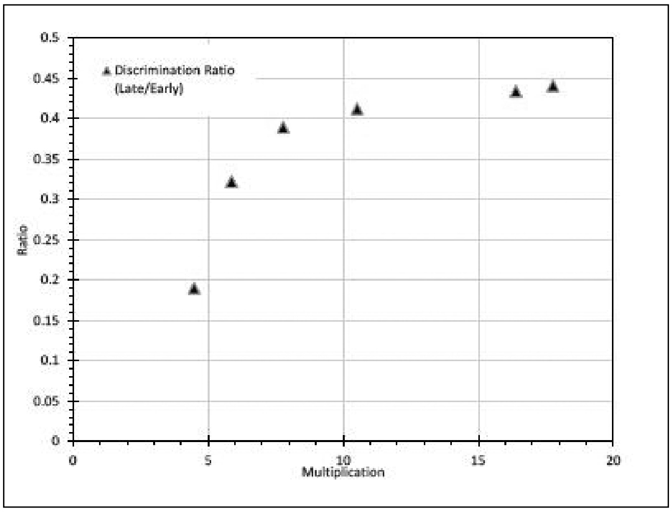


Figure 5. Multiplication vs. TCPH ratio for the moderated plutonium sphere



Validation with Measurement

In order to validate the simulations, a preliminary measurement was performed. The measurement had an identical setup to the simulation presented earlier in this paper. The source was a 41,680-n/s ^{252}Cf point source.

The measured TCPH is shown in Figure 7 and has the same behavior that was predicted by our simulations. The solid line is our discrimination line drawn at the travel time to the front face of the detector plus the mean free path of the neutron in the EJ-309. A vast majority of detected events are falling on the left side, as expected.

To further validate the simulated TCPH, the total time distribution and pulse height were directly compared to measurement. Figure 8 shows the comparison to the total time-of-flight (TOF) distribution. Excellent agreement is observed between the measured and simulated distributions with a percent difference of -0.79 percent.

Figure 6. The ratio of the number of counts to the right of the discrimination line to those on the left as a function of multiplication

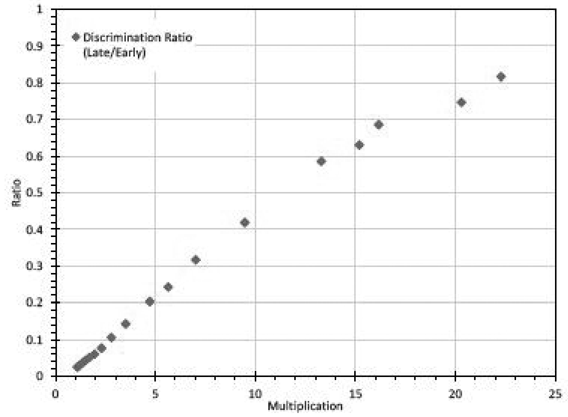


Figure 7. Measured TCPH log distribution in counts per second for a ^{252}Cf source at 50-cm

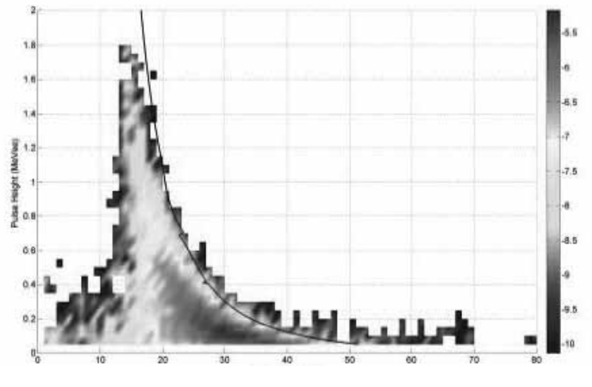


Figure 8. Comparison of the simulated and measured TOF

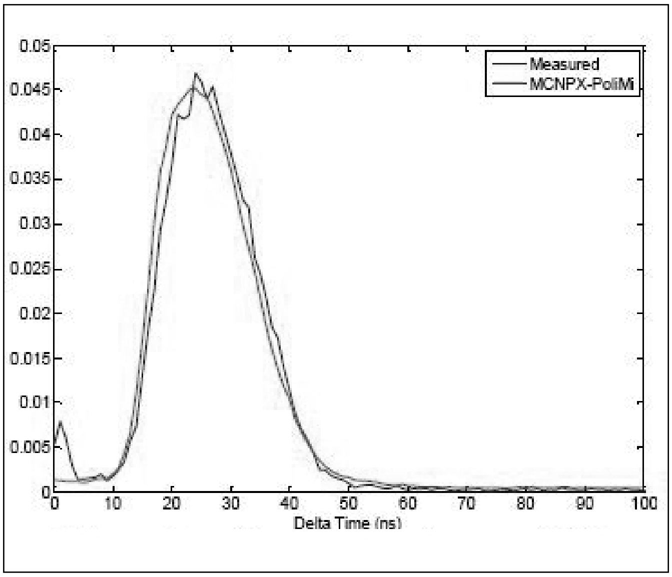


Figure 9. Comparison of the simulated and measured pulse height slice of the TCPH at 35 ns

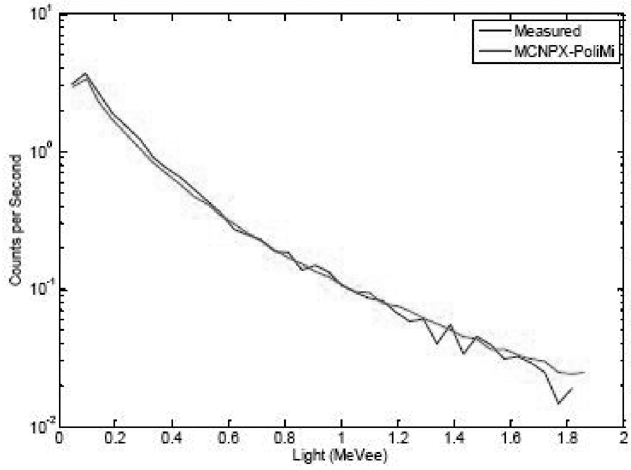


Figure 9 shows a comparison for the pulse height. Excellent agreement is observed for the correlated pulse height distribution with a percent error between the simulation and measured data of -3.42 percent.

From these results it can be concluded that the MCNPX-PoliMi and MPPost simulations will accurately predict the behavior of measured TCPH distributions.

Conclusions

This work has introduced the TCPH technique as a means of extracting additional source information out of cross-correlation measurements. By taking the time difference between arriving gamma-rays and neutrons in two EJ-309 detectors, it is possible to create time-correlated pulse-height distribution. TCPH can identify non-multiplying source such as ^{252}Cf appear from multiplying sources such as plutonium or HEU due to the dependence of the neutron energy and arrival time. This is done by looking for large pulse heights at times larger than expected linear travel time for that energy. High energy events that arrive at times greater than their expected travel time were likely created in a fission chain. An estimation of the source multiplication can be made using the ratio of events above and below the discrimination line. The number of events arriving at late times increases with increasing multiplication for a bare source, resulting in a linear increase in the ratio. This work also benchmarked the ability of MCNPX-PoliMi and MPPost to accurately simulate measured TCPH results. Future work on this project will involve improving the quality of the ratio metric. This ratio is very simplified and there are several modifications that could improve its effectiveness. Validation against measurement is also essential, measurements of source with multiplication will be necessary to validate this technique in real-world applications.

Acknowledgements

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Uranium Characterization by Shaped Femtosecond Laser-induced Breakdown Spectroscopy

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Abstract

Laser-induced breakdown spectroscopy (LIBS) is a well-established technique for elemental analysis of materials. There is growing interest in using LIBS for nuclear forensics applications because of its fast *in situ* capability and minimum or no requirements for sample preparation. Hence, new methods to improve the LIBS sensitivity continue to be explored. Controlling the shape of ultrafast laser pulses that produce and interact with the plasma can be used to improve LIBS signals, and can be accomplished by the use of Fourier-domain pulse shapers. We present the result of our initial studies of natural uranium metal using LIBS with shaped femtosecond pulses. The acquired spectra are analyzed to determine the systematic effects of various pulse shapes on uranium spectral lines. The objective of our study is to determine the strategies for feedback-driven optimization of pulse shape for improvement of LIBS sensitivity in studying uranium for nuclear forensics applications.

Introduction

During the laser ablation process, a high-powered laser pulse is focused onto a sample surface to vaporize the material and generate a microplasma. The characteristic emission lines from de-exciting atoms, molecules, and ions can be spectrally resolved to identify the makeup of material. This method, laser-induced breakdown spectroscopy (LIBS), has advantages over conventional chemical analysis, which can involve the use of harmful chemicals and complex sample preparation. LIBS is an extensively studied technique and has many applications including materials analysis and processing.[1] Desire for improving LIBS sensitivity for nuclear forensics and safeguards applications has increased in recent years.[2,3]

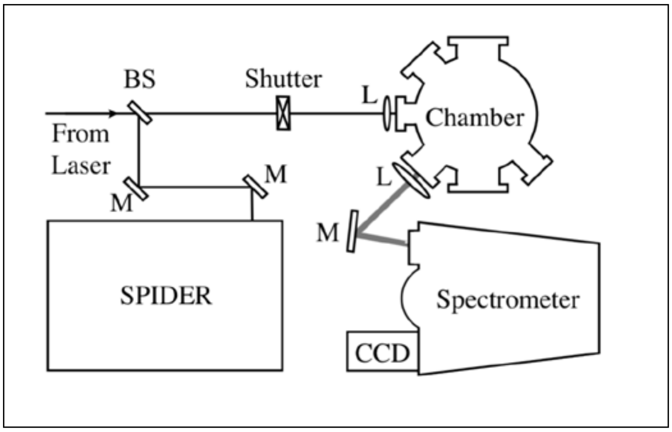
A considerable interest in femtosecond LIBS exists due to the unique properties of laser-matter interactions for ultra-short pulses, which can result in favorable properties of the LIBS signal. One approach for femtosecond LIBS signal optimization is through the use of the manipulation of the shape of an ultrafast laser pulse. For example, femtosecond pulses shaped using evolutionary algorithms have been shown to control molecular reactions[4] and laser-induced breakdown.[5] Laser temporal control has been investigated for its potential to modulate the properties of the LIBS plasma and demonstrate the enhancement of emission lines.[6,7] This paper describes experiments in which the programmable phase of the laser pulse is systematically altered to control the properties of laser-induced plasma in order to optimize the LIBS signal. The phase of an ultrafast pulse is associated with the spectral or frequency variation of the pulse in time. The only pulse shaping parameter altered in our studies is the spectral phase, while the spectral amplitude is kept unchanged and determined by the output of the laser system. One of the challenges faced in the optimization problem are the random fluctuations in measurements that arise primarily from energy and beam pointing instabilities. Our objective is to determine the variation in acquired spectral signals in the searchable parameter space available from our pulse shaper to better understand and predict the challenges of pulse shaping optimization of LIBS to be performed on natural uranium.

Experimental Setup

The diagram of our experimental setup is shown in Figure 1. We use an ultrafast Ti:sapphire chirped-pulse amplification laser system (Amplitude Technologies Trident). The central wavelength of the laser is 800 nm, and the system outputs ~40-fs pulses with good beam quality and up to approximately 14 mJ per pulse, at a repetition rate of 10 Hz. Integrated in the laser system is an acousto-optic programmable dispersive filter (Fastlite Dazzler), which acts as a pulse shaping module. The beam is directed normal to the sample surface and is focused onto the target using a 2"- diameter lens (f = 300 mm).

The light emitted from the plasma is focused onto the entrance slit of a 55-cm focal length imaging spectrometer (Horiba Jobin Yvon iHR550). Spectrum can be analyzed using interchangeable gratings of 1,200, 1,800, and 3,600 grooves/mm, which allows for the spectrometer to operate in different wavelength ranges and at different resolutions. Light emitted from the plasma is detected using an open-electrode charge-coupled device (Horiba Jobin Yvon Synapse CCD). Our spectrometer and CCD system is capable of up to 0.01 nm spectral resolution when used with 3600 grooves/mm grating. Laser pulse shape characterization is performed using spectral phase interferometry for direct electric-field reconstruction (SPIDER).[8]

Figure 1. Experimental setup for LIBS diagnostics. L – lens, M – mirror, BS – beam-splitter



Experimental Results

Natural uranium metal was characterized with a range of spectral phase settings. The programmable pulse shaper was used to test the effect of 241 different optical signals in which the spectral phase of each pulse was altered by inducing group delay dispersion (GDD). For the following experiments, each collected spectrum integrated more than ten laser shots in a 1-s integration time window of the CCD. The GDD setting was varied linearly between -82,155 fs2 and 77,845 fs2 and centered about the transform-limited pulse, which occurs near GDD = 0 fs2.

The GDD was changed in increments of 1,000 fs2 across the entire range. This process was repeated over the phase range for five consecutive trials in order to take into account random variability that may arise due to laser instability, sample inhomogeneity, and matrix effects. The phase terms may be varied for higher order dispersion (fs3, fs4) for more complex pulse shapes, but we limit our initial studies to control of the GDD.

Typical results are shown in Figure 2. Variations in the continuum background, line intensity, and ratios of different spectral line intensities are taken into consideration. The results are reported for the mean and standard deviation of the continuum background, spectral line intensity, and the ratio of two chosen spectral line intensities based on five spectra acquired for each spectral phase setting.

1. Baseline shift of signal from background: The level of signal attributed to background noise, or the baseline, was calculated using an established technique that fits the background using an asymmetric truncated quadratic (ATQ) function.[9] Results of the spectral analysis conducted in this fashion are shown in Figure 3. The ATQ method relies on the relatively slow variation of background compared to spectral lines. The background varied within a range of 581.64 counts with a median percent Relative Standard Deviation (RSD) of 5.20 and a maximum percent RSD of 16.92 over 241 phase settings.

2. Intensities of the 409.013 nm and 406.254 nm uranium spectral lines: The background determined in part 1 for each spectral phase setting was subtracted from the peak intensity measurements. Results are shown in Figure 4 for the 409.013 nm line, which, averaged over five spectra, ranged within 2509.16 counts and varied with a median percent RSD of 20.95 and a maximum percent RSD of 52.5. The 406.254 nm uranium line (plot not shown) peak height ranged within 1187.0 counts with a median percent RSD of 33.58 and a maximum percent RSD of over 97.5.

3. Signal to noise ratio (SNR) of 409.013 nm and 406.254 nm uranium spectral lines: The ratio of peak intensity to background level determined in part 1 for each spectral phase is calculated. Results are shown in Figure 5. The 409.013 nm signal to noise ratio varied in a range 1.538 with a median percent RSD of 19.91, and a maximum percent RSD of 70.16. The 406.254 nm uranium line SNR (plot not shown) ranged within 0.799 with a median percent RSD of 18.48 and a maximum percent RSD of more than 84.9.

4. Ratio of 409.013 nm to 406.254 nm uranium spectral line: Results are shown in Figure 5. The range of spectral line intensity ratio corrected for baseline shifts is 0.709 and varied with a median percent RSD of 13.03 and a maximum percent RSD of 66.34.

Comparison of baseline, peak intensities (corrected for background), SNR, and peak intensity ratios for uranium spectra at various GDD settings is shown in Table 1. Fluctuation trends observed are common to all figures. Since the spectrum was acquired across a GDD setting range for five separate but consecutive trials, it can be inferred that the trends observed for different GDD values are not random and may be optimized. Analysis of our data indicates that peak intensities have the largest range for optimization, but have high variability. SNR have a much smaller range in which to optimize compared to its percent RSD. Peak ratios have the lowest percent RSD and a modest range. Hence, in an adaptive optimization scenario, setting the figure-of-merit as the peak ratio may yield the most rapid result.

Pulse Shaping for Enhancement of LIBS

Our goal is to use optimal pulse shapes to optimize laser-plasma interactions to improve the quality of LIBS spectral signals, thereby enhancing the detection capability. A genetic algorithm is chosen as the optimization technique that will be implemented to iteratively update our pulse shapes in order to optimize the dynamics of ionization and recombination processes in the plasma. Genetic algorithms differ from other optimization approaches such as gradient methods since genetic algorithms maintain a collection of potential solutions instead of retaining a single point in the search space. Evolution toward an improved solution is driven

Figure 2. Typical LIBS spectra of natural uranium demonstrating variation of spectral line intensities for different pulse settings: (a) group delay dispersion = 2700 fs2; (b) group delay dispersion = -355 fs2

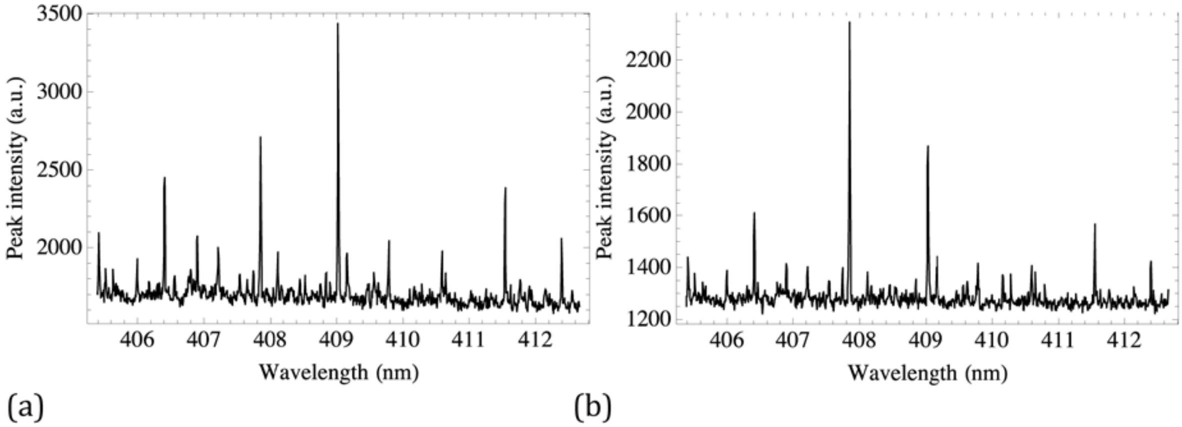


Figure 3. Baseline levels for spectra taken over various phase inputs on pulse shaper. The pulse parameter is equal to the GDD imparted on the pulse. In this example the GDD was varied in the range of -8255 fs2 and 77845 fs2 centered about the transform-limited pulse.

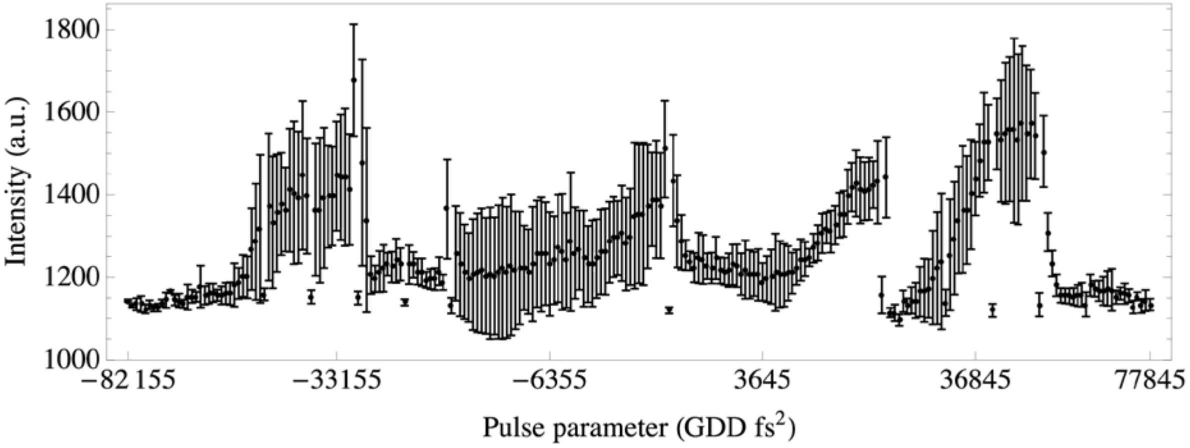


Figure 4. Intensity of 409.013 nm uranium spectral line for various GDD settings

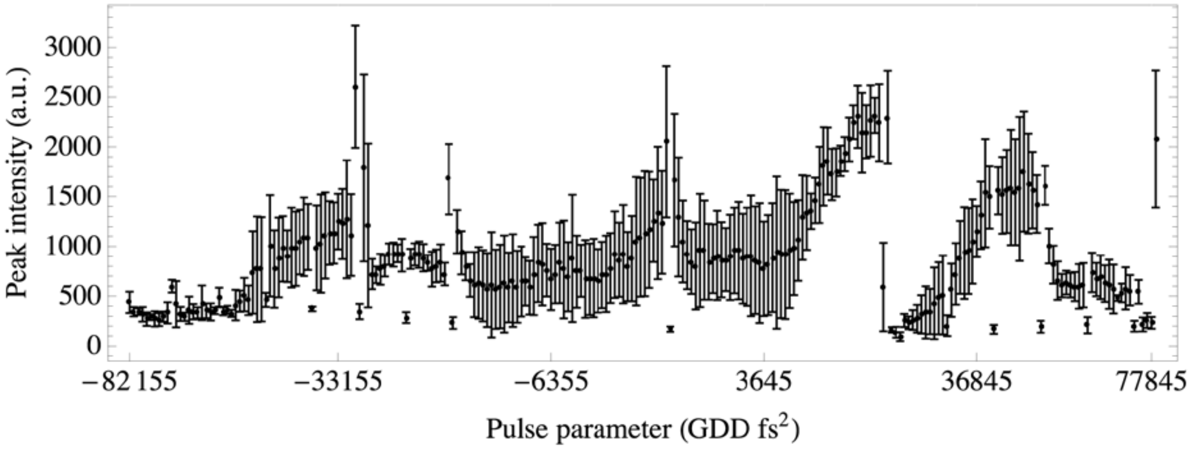


Figure 5. Signal to background ratio for 409.013 nm uranium spectral line for various GDD settings

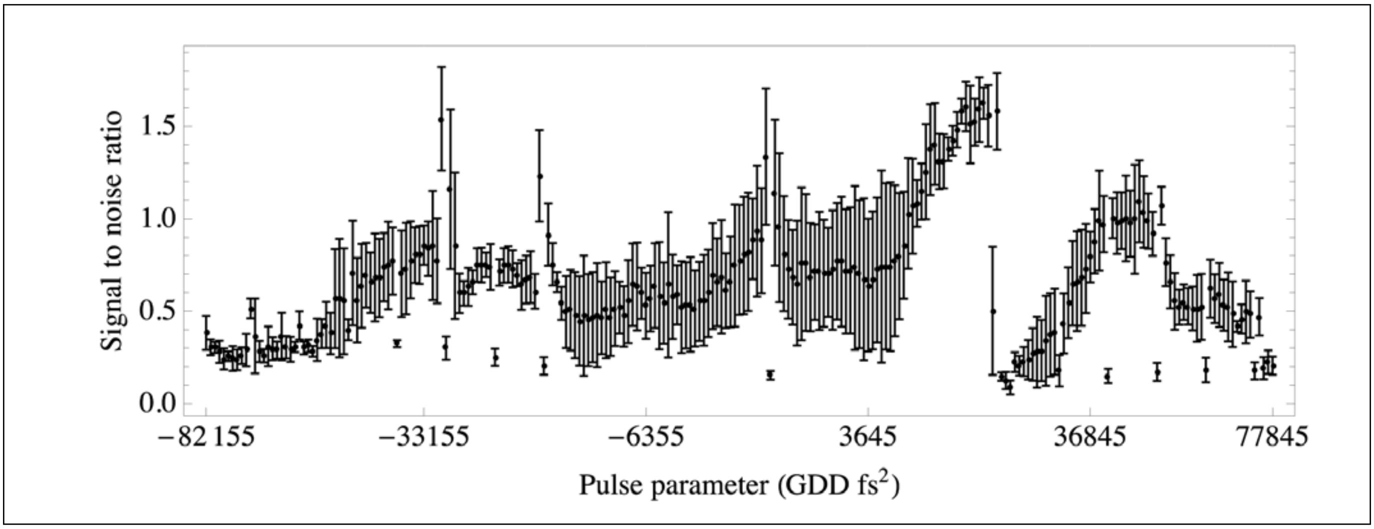
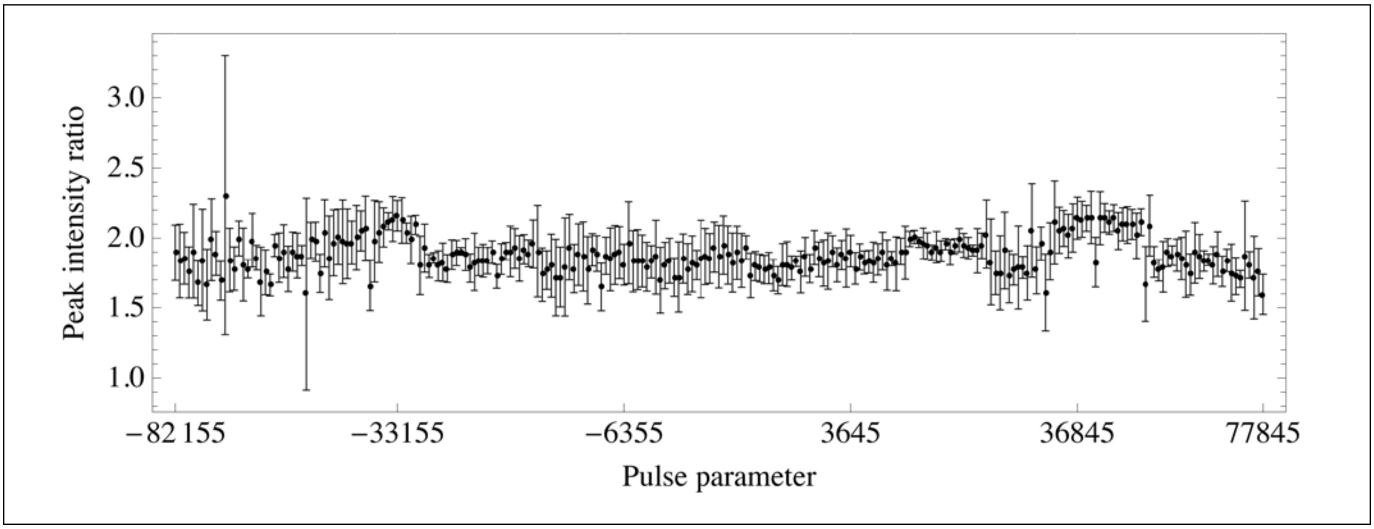


Figure 5. Ratio of 409.013 nm to 406.254 nm uranium lines at various for various GDD settings



by a predefined fitness parameter, where several possible solutions are tested and assigned a fitness value based on its performance. In each successive generation, only the fitter individuals propagate their values. The solutions for each generation should be an improvement from their predecessors.[10]

Possible fitness values in LIBS are the peak intensity of a chosen spectral line, signal-to-noise ratio, or the ratio of two spectral lines. In our experiment, the optimal pulse shape is found experimentally and is a function of the imparted spectral phase. The initial results from our uranium studies indicate that the optimization for the peak ratio fitness parameter may converge the fastest, compared to the fitness parameters associated with the peak intensity or signal-to-noise since it has the smallest percent RSD. Importantly, there is evidence that LIBS signal enhancement is achievable through adaptive pulse shaping.

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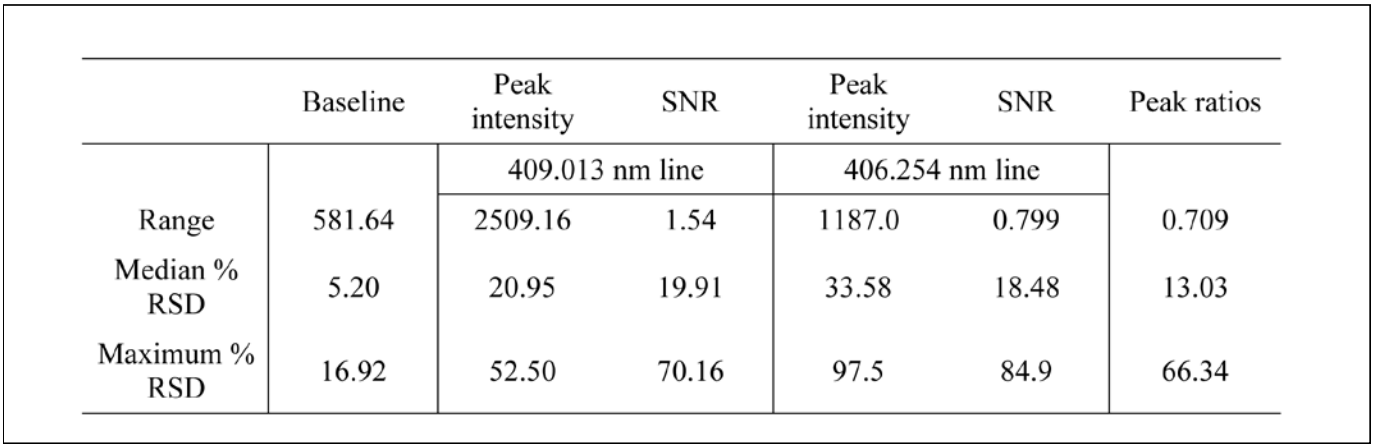
Table 1. Summary of spectral analysis for uranium lines



	Baseline	Peak intensity	SNR	Peak intensity	SNR	Peak ratios
		409.013 nm line		406.254 nm line		
Range	581.64	2509.16	1.54	1187.0	0.799	0.709
Median % RSD	5.20	20.95	19.91	33.58	18.48	13.03
Maximum % RSD	16.92	52.50	70.16	97.5	84.9	66.34

and the U.S. Department of Defense, Defense Threat Reduction Agency. Finally, the authors would like to thank to Randy Schur and Timothy Jacomb-Hood for their assistance with setting up the measurements.

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Safeguards-by-Design (SBD) Concepts for Thorium-based Fuel Fabrication Facilities

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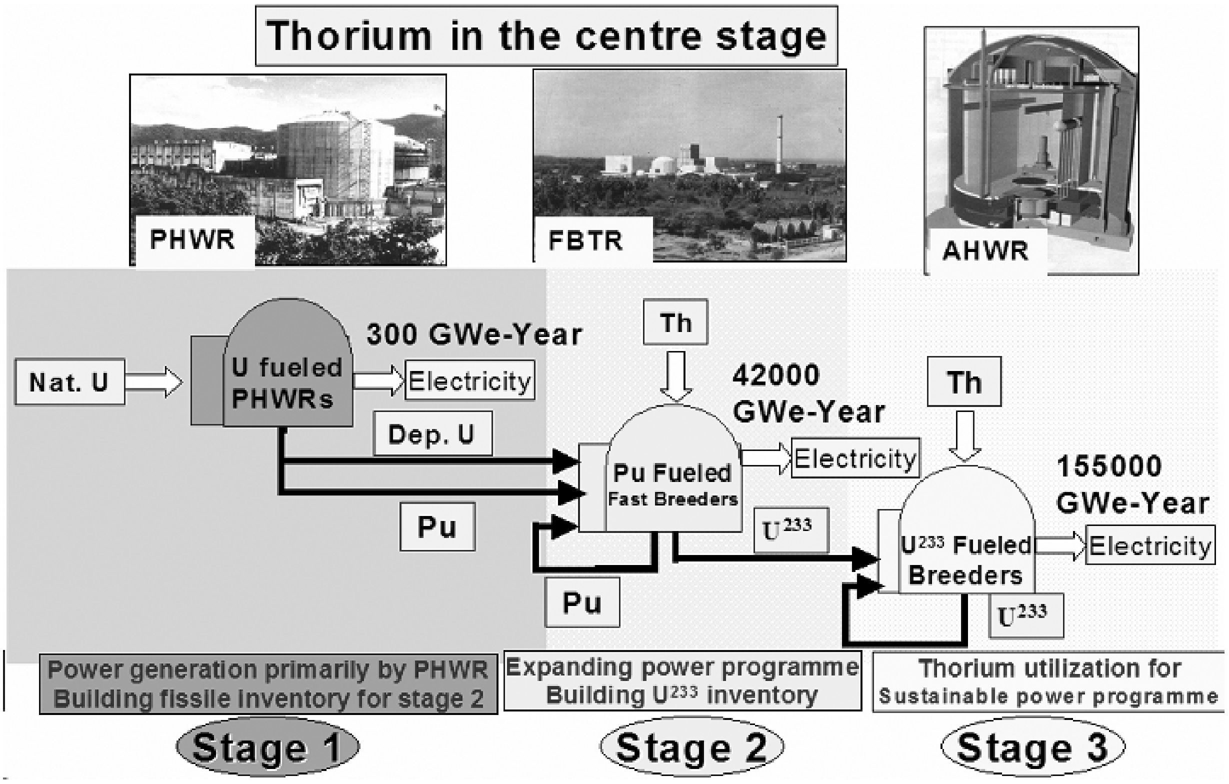
Introduction

India is a nation with a large population and is undergoing rapid economic growth. A large section of rural poor do not have access to modern energy services and rely on non-commercial sources such as firewood, crop residue, and animal waste. Rapid economic growth and a desire to have access to modern energy services are fuelling a strong demand for electricity. The present share of electricity from nuclear energy to the national grid is about 3 percent; the policy framework of the Indian government envisages a many-fold increase in nuclear installed capacity in the near future. The present installed nuclear generation capacity is about 5 GW, which is projected to grow to 63 GW by the year 2032.[1] India started working on a nuclear power program more than sixty years ago. Considering its nuclear fuel resource profile, which consists of modest reserves of uranium and large deposits of thorium, India has unwaveringly followed a closed fuel cycle approach from the inception of nuclear power program. Since the objective is to eventually use thorium for power generation, this translates into a three-stage nuclear program (Figure1). In the first stage of the program, power generation is by natural uranium in pressurized heavy water reactors (PHWRs). PHWRs are natural uranium fuelled, heavy-water moderated and cooled reactors. The reactors have a horizontal configuration and are fuelled online, and the fuel is charged and discharged every day. The fuel in the Indian PHWRs is in the form of sintered natural uranium pellets encapsulated in zircaloy clad tubes. Currently there are two variants of Indian PHWRs, viz. 220 MWe and 540 MWe. India is also building 700 MWe PHWRs. The 220 MWe type of PHWRs use nineteen-pin fuel bundles and the 540 MWe PHWRs use thirty-seven-pin fuel bundles. The PHWRs offer an excellent neutron economy, which is important for efficient fuel utilization and also for conversion of uranium to plutonium. The spent fuel from the PHWRs is reprocessed and the plutonium is separated. The plutonium recovered by reprocessing of spent fuel from PHWRs is refabricated as U-Pu MOX and used in the second stage consisting of the fast breeder reactors. The use of Pu MOX in the second stage would ensure growth of nuclear installed capacity. The fast reactors also irradiate depleted uranium or thorium in the blankets. The depleted uranium converts to plutonium while the thorium converts to fissile U^{233}. The U^{233} generated in the fast reactors would be refabricated as Th-U^{233} MOX. This U^{233}-based MOX will be the driver fuel of the thorium-fuelled breeder reactors, in the third stage of the nuclear program. The thorium in such breeder reactors will get converted to U^{233}. The reactors for the third stage will be designed to ensure generation of U^{233} in a sustained manner.[2] The thorium and U^{233}-based MOX fuel to be used in the breeder reactors of the third stage is envisaged to be fabricated by the powder-pellet route in the glove boxes and/or alpha tight hot cells facilities, to contain the airborne activity.

Safeguards implementation in bulk handling facilities like fuel fabrication facilities is a challenging task, as compared to item counting type of facilities. Moreover, fabrication of fuel in glove box or alpha tight hot cells type of facilities requires extensive measures for safeguards due to complexity in remote handling, material holdup in ventilation systems, process holdups, manipulation, and constraints of access. Effective implementation of safeguards in such fuel fabrication facilities, calls for novel measures, both intrinsic and extrinsic. It is best to incorporate all such measures at the design stage itself and this has led to the concept of Safeguards-by-Design (SBD). The SBD concept involves incorporation of safeguards measures from the stage of conceptual planning of the facility leading their integration with the plant processes on the drawing board stage itself. This reduces the cost of safeguards implementation by avoiding retrofitting at a later stage. Improvised methods using dedicated instruments for nuclear material accounting and material balance can be engineered to provide data required for safeguards. SBD can also be designed to obtain safeguards data in near-real-time monitoring mode. Early investment in SBD helps reduce holdup inventories and material unaccounted for (MUF). The added advantage of such measures is close control of inventories and avoidance of criticality due to built up of fissile material in ducting, blind areas of the fabrication lines, and equipment. Safety, security, and safeguards are an essential part of any nuclear facility. SBD can help integrate these three aspects, resulting in reduction of total equipment inventory and overall cost. Authors propose in this paper SBD methods and concepts which can be applied to glove box and hot cells based powder-pellet type of MOX fuel fabrication facilities for the thorium fuel cycle at the design stage itself so as to help achieve the goals of safeguards implementation efficiently and in a cost-effective manner.

Figure 1. India's three-stage nuclear power program



MOX Fuel Fabrication Flow Sheet

A typical MOX fuel fabrication flow sheet by the powder-pellet route is shown in Figure 2. The process starts by the blending of two or more powders. Blending is also an essential step to control the percentage of fissile isotopes and to obtain specified composition in the finished fuel. Often Clean Reject Oxide (CRO) is added at the beginning. The CRO is generated at various stages of fabrication and has the chemical composition similar to the finished pellets. The CRO does not contain waste or impurity elements. CRO recycle helps in reduction of material holdup and also efficient recovery of fissile material during the entire fabrication process. After blending, the powders are mixed and milled in attritors. The next step is precompaction and granulation. This makes the powder free-flowing. The mixed powder is then subjected to final compaction in a press. Green pellets are formed in the stage of final compaction. These green pellets are then subject to sintering at high temperatures in reducing atmospheres. Until the stage of sintering, there is a lot of powder generation and these are the process areas responsible for higher material holdup and MUF. Such areas need special attention at the design stage underpinning the relevance of SBD. The sintered pellets are measured for diameter and oversized pellets are ground to final dimensions by the centerless grinding. Centerless grinding is another area where attention is to be paid for implementing SBD measures, since a lot of dust and slurry is generated. The right sized sintered pellets are degassed and sent for stack formation and loading. They are loaded into bottom end plug welded zircaloy tubes. After the loading of sintered pellets, along with the blanket pellets and other hardware, the top plug is welded under helium pressure. The welded and sealed pins are decontaminated and sent for appendage welding and assembly. It may be noted that at a number of stages, quality control (QC) checks are carried out. When the powders are taken for blending, the samples are drawn and subjected to chemical and powder characterization. This step also involves enrichment assessment. For the hardware like fuel tubes, springs, plenum tubes, weld plugs, appendages, etc., the QC carried out include visual examination, helium leak testing, metrology, and X-radiography. At the intermediate stages of fabrication, the tests carried out on sintered pellets are dissolution test, dimensional measurement, linear mass, O/M (oxygen to metal ratio) assessment, total gas content, metallic and non-metallic impurities, and autoradiography. For the finished pin, the QC checks are visual examination, helium leak testing, gamma scanning, cover gas analysis, metrology, and X-radiography. The finished fuel pins are also checked for surface and fixed contamination after the step of decontamination.

Figure 2. Typical MOX fuel fabrication flow sheet by powder-pellet route

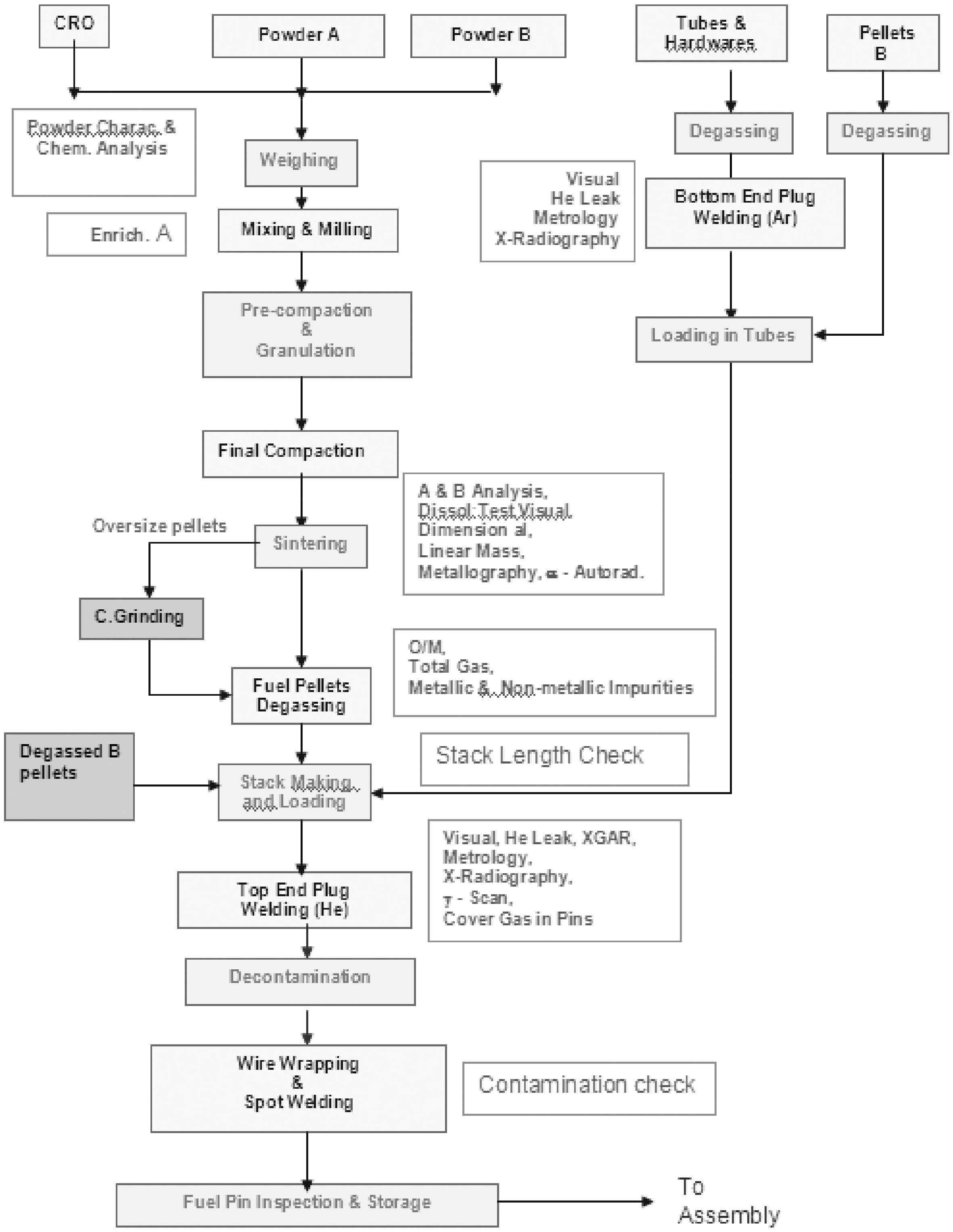


Figure 3a. Linear layout

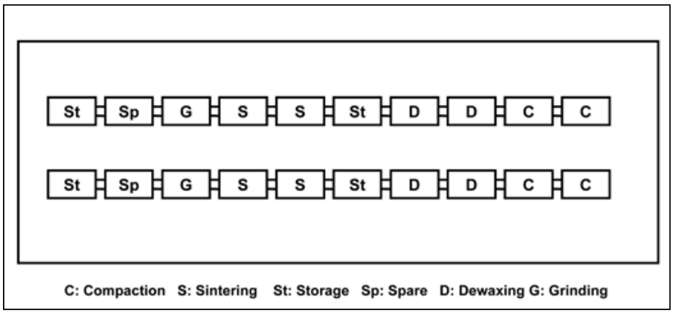
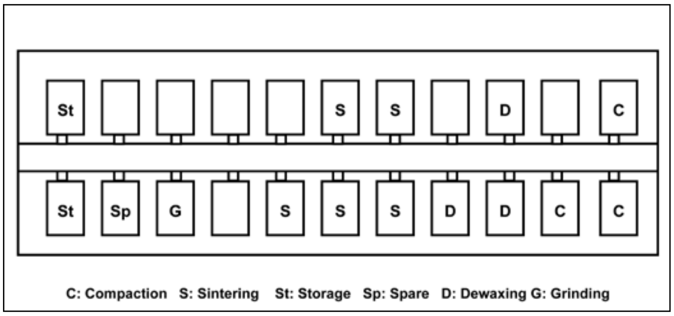


Figure 3b. Hybrid layout



Hybrid Layout for Fuel Fabrication

The conventional powder-pellet MOX fuel fabrication facilities are arranged in a linear layout, which house the equipment according to the process steps (Figure 3a). Figure 3a shows two lines in a linear layout. The two lines are meant for movement of two different batches. Such types of production lines have inherent limitations. They are not amenable to flexibility for modification. The glove boxes in these lines are difficult to isolate, in case of the breakdown of equipment or the installation of new process equipment for modification. The linear layout is not easy to automate, due to limited space in each box for a conveyor system to be installed. Similarly any mechanization is difficult to incorporate. In a linear type of layout, breakdown of any equipment down the line impairs the entire production. It is so because the process steps are sequentially laid out and bypassing of any individual box is difficult. Isolation and termination of any glove box housing the broken down equipment is difficult, if not impossible. A new layout that is hybrid in nature is proposed in this paper. The new layout overcomes the shortcomings of a conventional linear layout. The hybrid layout (Figure 3b) is a layout with a common material transfer line in the central tunnel, having bifurcations connecting it with individual glove boxes/cells.

This layout also has two lines for different batches, but due to interconnectivity, the layout offers the movement of material of any batch to any of the boxes. The central tunnel is about 300 mm x 300 mm, having service ports at various intervals.

The process material moves in the entire production lines in standardized stainless steel containers. These containers move on electromagnetic channels, such that inside of the tunnel has minimum of motorized or electrical installations. The hybrid layout offers a number of advantages over the linear layout. The central tunnel provides free movement of material in a manner that the material in the containers can be moved between any two boxes, without affecting the movement and operations in other boxes. This offers great flexibility in rerouting of material, and as a result, the total number of process equipment can be reduced. This is made possible due to sharing of equipment between the two batches moving in two lines. The hybrid layout is more adaptable to automation. The central tunnel is automated using electromagnetic mechanisms for container movement. The individual boxes can be isolated, if required either for maintenance or introduction of new equipment in the line. It can be done without stoppage of production since movement and operation in other boxes is independent and is not affected. Due to sharing of equipment by the two lines amalgamated in one hybrid layout, the overall redundancy for manufacturing can be achieved by less equipment. This also reduces the overall footprint of the fabrication line, in addition to reducing the total length of exhaust ventilation ducting. These have implications in reduction of material holdup and total MUF in the plant.[3] The hybrid layout is also more amenable for implementation of any fabrication flow design modification and introduction of new equipment for improvement.

Enhanced Features of Safeguards in Hybrid Layout

The hybrid layout for powder-pellet type of MOX fuel fabrication facility has inherent features that improve the safeguardability. As described above, the hybrid layout has a central tunnel that is helpful in the automated movement of nuclear material in standard stainless steel containers. Higher level of automation limits manual intervention, thus improving physical security of the nuclear material by increasing challenge to theft of the nuclear material. The overall manpower requirement of the fabrication plant having hybrid layout with higher level of automation and lesser number of total process stations can be optimized such that the safeguardability is enhanced. To maximize safeguardability, level of manpower deployed in a nuclear facility needs to be optimized. A very low deployment would mean that there are areas in the plant which are deserted making theft easier. Conversely a large deployment of manpower could also reduce safeguardability due to exposure of nuclear material to a larger number of personnel.

To improve plant availability, it is necessary to incorporate adequate redundancy for critical processing equipment like attritors, pre-compactors, sintering furnaces, welding machines, decontamination set ups etc. In case of hybrid layout, where two batches are laid out with interconnectivity, the redundancy can be maintained with overall lesser number of equipment as equipment across the two lines can be easily shared. As a result, the linear layout requires a greater number of process stations compared to the hybrid layout. Its overall impact is that in a hybrid plant the number of equipment comes down, the footprint of the plant is reduced and the total length of the ventilation system is shortened. A lesser number of overall fabrication stations would provide fewer areas for presence of nuclear material, thus lesser chance of theft. If the CCTV cameras are installed for surveillance monitoring, the smaller foot print would need fewer cameras for overall coverage.

The reduced length of the exhaust ventilation ducting is beneficial for reducing the in-process material holdup and MUF. In-process material holdup and MUF is also reduced due to overall reduction in number of process stations, since the powder has a tendency to deposit at the walls of the glove boxes/hot cells and also to get lodged in the inaccessible and blind areas.

Novel Safeguards-by-Design Features for Fuel Fabrication Plant in Hybrid Layout

Safeguards-by-Design helps in enhancing the safeguardability of a nuclear facility.[4,5,6,7] This section elaborates features to enhance safeguardability as developed and implemented by the authors in the design of fuel fabrication facilities in India.

Isolation of Services in a Fuel Fabrication Facility

The isolation of services enhances safeguardability by restricting access of personnel maintaining services to the nuclear material. If the number of plant personnel who may have access to the nuclear material is reduced, the chance of theft is reduced, thereby, increasing safeguardability of nuclear material.

Any powder-pellet type of fuel fabrication facility needs a number of services including electrical supply, helium and argon supply, ventilation, compressed air, water, and waste management. Due to the leak tightness requirements of and incorporation of remote handling operations in glove box type or hot cells type of facilities, the services needed are much more. Generally the services are provided in the fabrication areas from the service panels located in the ceiling. The service panels are provided at regular intervals, and all the service panels have fixtures for tapping services.

The electrical utilities include regular class I, II, III, and IV types of power supply. Class IV is the power received direct from the substation. Class III is the diesel back up. Class II is uninterrupted power supply and the Class I supply is the battery bank. The provision for diesel generator and battery banks has to be made for electrical supply. Acid storage has to be a ventilated area. Compressed air is needed for equipment and also as moisture free for breathing lines. Though large compressors are installed, additionally storage reservoir tanks are provided near the areas where the services are needed. Although the major processes in a powder-pellet fabrication facility are dry, water is needed for centerless grinders, decontamination, and furnace cooling. Moreover, water is needed for the fire services. Welding equipment uses helium and argon gas, which are provided through pipes with gas banks kept out of the plant. Ventilation systems include ducts for both supply and exhaust. The exhaust ventilation is connected to exhaust pumps and finally vented from the stack. A three stage HEPA filter system is generally used for exhaust ventilation. The low-level liquid waste is collected in the floor drains and is connected to liquid waste sump. Intermediate-level liquid waste and high-level liquid waste have separate provisions for collections. Solid waste is generally collected and compacted for near surface waste disposal.

Traditionally various services are provided by wired and piped conduits with diesel generator sets, battery banks, compressors, ventilation blowers, breathing air reservoirs, fire water reservoirs, sump tanks, etc., located in the near vicinity to reduce length of wiring, piping, and ducting.

For enhanced safeguardability, a concept of isolation of plant from services is proposed. In this configuration, the main plant is islanded in a double fenced enclosure, while the services are out of this island, in a nearby services area. This restricts access by maintenance and auxiliary staff to the main plant containing the nuclear material, thereby enhancing the safeguardability. A similar concept, involving isolation of services for a plutonium-based fuel fabrication is being designed for a fast reactor fuel fabrication in India.

Integration of Quality Control Equipment

Integration of quality control equipment with the main fabrication equipment eliminates the need to withdraw the nuclear material as samples from the main line. If this can be effectively designed and built in the fabrication plant, safeguardability can be enhanced due to reduced risk of theft.

An important part of a fuel fabrication process is quality control of feed material, intermediate material, and finished product. The QC begins with the chemical analysis and powder characterization of the starting feed. The samples have to be drawn and taken to powder characterization boxes. After the blending of the various powders is over, the blended mix needs to be checked for enrichment. This needs powder samples. Subsequent to sintering, the sintered pellets are visually checked, dimensional measurements are carried out, linear mass is estimated, and metallography and autoradiography are done. Some of the tests are carried out on samples and 100 percent metrology and visual QC is carried out. The sintered pellets for sample analysis are drawn from the sintered lots and sent for testing. They are also checked for oxygen to metal O/M ratio, total gas content and also estimates of metallic and non-metallic impurities. The encapsulated and welded pins are checked visually, and helium leak test, X-gamma autoradiography, gamma scanning, and cover gas analysis are done. In addition weld qualification of the end plug welding is carried out for both machine and welder qualification. This also needs welded samples to be sent for destructive testing by metallography. The fabricated and QC cleared pins are subject to decontamination by wet or laser decontamination. Subsequent to cleaning, all pins are checked for surface and fixed contamination. Samples, intermediate products as well as finished products are drawn at various stages of fabrication for chemical analysis, spectrometric analysis, microstructural analysis, non-destructive testing, leak testing, radiography, ultrasonic testing, metrology, etc. In many cases, the samples or the intermediate products like powder, green pellets, sintered pellets, welded pins, etc., have to be withdrawn from the main fabrication line and taken in separate boxes/cells for analysis. This involves bag-in and bag-out operations in glove boxes and material transfer in hot cells, which needs manual intervention.

The SBD concept proposed by the authors for hybrid layout consists of integrating all QC equipment and boxes/cells within the main fabrication line. Boxes/cells housing the QC equipment would be placed at locations closer to their stage of fabrication. This would ensure no removal of nuclear material in any form from the fabrication line for the purpose of QC. Though the amount of total material withdrawn for QC on a sampling basis is very small, complete elimination of this operation would greatly enhance the safeguardability of the plant. Moreover, for QC checks that need to be carried out on a 100 percent basis, like pellet visual examination, metrology, pin metrology, etc., having the equipment within the main fabrication line would eliminate their withdrawal at intermediate stages. There would be only two points of material transfer in the hybrid lines, one for entry and the second for exit of the finished product.

Process Powder Recovery Measures

A bulk handling type of facility like fuel fabrication plant has many operations where a lot of powder is generated during processing. This increases material holdup and uncertainty in estimation of MUF. The measures designed to increase in-process powder recovery contribute towards increasing the safeguardability of nuclear material in the fuel fabrication facility.

Issues for safeguards implementation in a powder-pellet type of fuel fabrication facility include estimation of material holdup and MUF.[8] All efforts must be employed to reduce these two. The very nature of many operations makes the facility prone to powder generation. The powder generated has a tendency of settling on the walls of the glove boxes and of the hot cells. It also can easily get lodged into the crevices and blind corners of the equipment and process areas. The process stages having higher powder generation and airborne activity are blenders, attritors, pre-compactors, final compactors, centerless grinders, and crushers for recycling of CRO. As an SBD measure, the concept and design put forward by the authors make provisions for reduction of powder generation and high recovery of process powders. This is achieved by having closed re-circulatory systems consisting of suction devices, powder filters and collectors and pumps, which help in efficient recovery of process powder. As discussed later, if more than one equipment can be integrated into one module, the overall powder generation and loss reduces. By having additional HEPA filters in exhaust ventilation of such areas, the airborne powders can be arrested long before they can travel far. These provisions are designed and fabricated both for glove box type and hot cell type of facilities. Early involvement by virtue of SBD greatly reduces the holdup and MUF thereby improving safeguardability. It may be noted that the reduction in powder generation and enhanced powder recovery also helps in reducing the risk of criticality hazard.

Dynamic Nuclear Material/Near-Real-Time Monitoring Systems

Dynamic nuclear material accounting and near-real-time monitoring systems have a direct bearing on safeguardability in a fabrication facility, since such measures help in immediately noticing the theft of nuclear material. Many methods have been offered for fuel fabrication plants handling powders, where incorporation of these SBD measures greatly enhance safeguardability.

In a powder-pellet type of fuel fabrication facility, the nuclear material is present in various forms. This is as powder, clinkers (CRO), green pellets, sintered pellets, fabricated fuel pins, and assemblies. Some material is also present as solid waste, normally collected and stored in waste drums. The nuclear material is also present as holdup and MUF. The glove box type of facilities are little different than alpha tight hot cells type of facilities. Such constraints pose great difficulties in measurement of nuclear material. It is possible to develop Dynamic Nuclear Material Accounting/Near-Real-Time Monitoring (DNM/NRTM) systems that can greatly reduce the safeguards efforts during annual and periodic inspections.[3] An online nuclear material accounting system consists of measuring equipment, their placement in specific locations, data acquisition and analysis systems, and data storage and transfer systems. One such system designed by the authors is in operation in one of the bulk handling facilities in India. Unattended non-destructive analysis (NDA) has been developed by some designers, which can collect and transmit data of nuclear material movement independently. Other systems developed for nuclear material accounting are for glove box assay, fuel pin assay, and waste drum monitoring system. As a part of SBD measures, such monitoring systems based on neutron and/or gamma measurements have been studied and are recommended for inclusion in the plant layout at the design stage. This would include collimators, provision of liquid nitrogen for detector systems, supply system for electronics at locations in the cells/glove boxes where monitoring needs to be done, data acquisition, and analysis systems and their integrations. Since some of these systems need collimators, which are bulky and specialized in design, incorporating them later after the facility is built could be difficult. Adequate number of such systems, placed at designated locations enhances safeguardability.

Inventory Measurement at Every Cell/Glove Box

In addition to the dynamic nuclear material accounting and near-real-time monitoring, measurement of inventory at almost all places, where nuclear material is handled in a plant, greatly enhances the safeguardability. This is accomplished as more measurements are made at various locations and a tighter control on MUF and material holdup is implemented.

The nuclear material in a powder-pellet facility starts from the powder and ends up as a finished fuel pin or assembly. It undergoes changes in shape, size, and form at different fabrication stations. In addition to the assay methods, the measurement of inventory at all the possible locations in the fabrication facility is achieved by weighing. A simple concept is to make provision for weighing as a starting and ending point in each single cell/box. The movement of the nuclear material as powder, green pellets, or sintered pellets is done in standard containers. The first activity in any box/cell, upon their receipt is weighing for which the provision is made in the form of load cell based systems. The measurements are directly coupled to the computerized material tracking system. Similarly the last step in any unit box/cell is weighing. By treating every single box/unit as an inventory monitoring station as well, the material can be tracked in real time, and a better estimate of material holdup and MUF can be made. After the pellet loading and pin encapsulation and welding, the material is handled as an item counting unit. The weight of the encapsulated and sealed pin/assemblies is also measured using similar weighing systems, at all subsequent processing stations. Though it is not impossible to retrofit such load cell based weighing systems in a built fabrication facility, it is easier to incorporate them early in the concept and design stage itself. Such systems need space in every box/cell at the start and end point, electrical and electronics with associated wiring for measurements and data transfer, and computer interface for integration with main material handling system. The load cells also need to be designed to be radiation resistant since high gamma radiation is expected to be present in the material. As an initial involvement by way of SBD, it is strongly recommended to incorporate such measures at an early stage of design itself.

RFID, Bar Codes, Readers, Transmitters, and Receivers

Radio-frequency indentification (RFID) and bar codes are finding greater use in many applications both in industry and consumer products. This concept has been extended by the authors to be incorporated in the fuel fabrication plant for enhancing the safeguardability. The challenge, however, is to deploy tags which are resistant to gamma radiation and also the harsh environment of powder processing plant.

It has been described above that the nuclear material is present in different forms at various locations in a fuel fabrication facility. As a measure to avoid any instance of criticality hazard, the nuclear material is segregated in small quantities. Thus the batch sizes for in-process fabrication are designed in a manner such that there is a storage and movement of nuclear material in smaller containers or units. For the storage and transfer as powder, clinker, green pellets, and sintered pellets, standard SS containers are designed to be used. These containers holding the nuclear material are scattered all over the process areas of the fabrication facility. It is recommended to use RFID-based container monitoring and tracking system. All containers shall have RFID tags. These are radiation tolerant since the process nuclear material is expected to radiate higher-energy gamma radiation. The tracking of such RFID tags needs detectors, amplifiers, receivers, and retransmitters. The process areas of the fabrication facility are spread over different halls and assembly areas. Thus the signals may have to be transmitted across walls and ceilings. For encapsulated and sealed fuel pins and fuel assemblies, the tracking is done by bar codes, which are engraved on the plugs using laser etching. This requires laser etching machines and their associated electrical, electronics, and mechanical systems, placed at encapsulation stations and also assembly areas. Bar code readers are installed, and provisions are made for their protection from high gamma doses. Both the RFID systems and bar code systems are integrated with the master computerized system for material tracking and nuclear material accounting. Other systems include transmitters, amplifiers, retransmitters, and receivers for RFID, electrical cabling, fixtures, and central consoles. It is prudent to design such systems making relevant provisions from the stage of conceptualization as SBD design. These SBD measures help track the nuclear material and reduce the probability of theft and thus increase safeguardability.

Plant Imagery

The authors have extended the concept of satellite imagery to the plant imagery, to enhance safeguardability of nuclear material by offering larger and real-time coverage of the plant using overlapping cameras. Such imagery systems greatly reduce the risk of nuclear material theft in a fabrication facility.

Satellite imagery has been used as a means of obtaining information on the nuclear facilities. Whereas the satellite imagery relies on the images captured by the satellites, the concept of plant imagery is akin to the surveillance measures used for safeguards by the IAEA. The major areas in a powder-pellet type of fuel fabrication facility, where nuclear material is present are powder handling area, pellet fabrication area, pin fabrication area, pin assembly area, and the pin and assembly stores. There are other small areas where nuclear material is present in smaller quantities. These are the solid waste handling areas. Various cameras, installed in areas containing nuclear material can help in tracking of material movement and also detection of theft. Different type of cameras, like continuous recording, still cameras, motion detection cameras, night vision cameras can be used in combination in a manner that complete coverage is assured during unattended periods or durations when the areas are not occupied. As compared to a linear type of layout for fabrication, a hybrid layout needs a lesser number of cameras because of its smaller footprint. SBD measures for plant imagery would entail provisions for assessing the total number and type of cameras, their locations, fixtures, cabling, interfacing, and image capture, storage, and analysis systems. Plant imagery systems for hybrid layout, by their judicial deployment, can greatly enhance the proliferation resistance in a fuel fabrication facility.

Dedicated Equipment for Material Holdup/MUF Measurement

It has been emphasized earlier that a better estimation of material holdup and MUF in a powder handling facility greatly increases safeguardability. Authors propose measures to introduce dedicated equipment located at stations where more accurate and realistic nuclear material accounting can be carried out.

In any bulk handling type of facility, nuclear material holdup and material unaccounted for (MUF), is of great concern. Powder-pellet type of fuel fabrication facilities have higher material holdup and MUF. This is due to the nature of the various process steps, like blending, attrition, pre-compaction, final compaction, green pellet handling, centerless grinding, CRO recycling, etc. Nuclear material that is lodged in inaccessible areas of ventilation, filter banks, and process equipments also poses a safety hazard due to criticality. Hence it is very important to reduce the total material holdup and the MUF in any plant. As a part of SBD measure, various dedicated systems can be engineered for estimation and detection of both the material holdup as well as MUF. These dedicated systems are recommended to be provided for such boxes/cells that can measure the build up of powder in the exhaust ducts, blind corners, and inaccessible areas of the cells and boxes. The provision is in the form of TLD (Thermo Luminescent Dosimeter) type monitors or collimated gamma and neutron measurement systems. SBD is useful for identification of such areas, identification of type of monitors and provision of such measurement systems, and their integration with nuclear material accounting and tracking system. Better estimation of both nuclear material holdup and MUF helps in devising methodologies for recovery of process powder and nuclear material and also prevent segregation in areas leading to safety hazards.

Provision for Material Storage During Physical Inventory Verification (PIV)

National safeguards authorities and the IAEA are the major agencies responsible for implementing safeguards in nuclear facilities in almost all the nations. There are various methods and procedures that are being followed by the safeguards inspectors for safeguards implementation. One such method is the annual physical inventory verification (PIV) that is carried out normally, once in a year at a facility. A day prior to PIV, physical inventory taking (PIT) is performed. PIT involves moving the nuclear material at various stages of fabrication to their respective areas of key measurement points (KMPs). It is easier to carry out such an exercise at item counting facilities like nuclear reactors, due to the very nature of the form in which nuclear material is present and accounted for. However, in a bulk handling type of facility, performing a PIT/PIV is much more tedious due to the nature of form of nuclear material. Nuclear material is in the form of powders, green pellets, sintered pellets, finished pins, or CRO clinkers. If during the design of such facilities, designated places, and storage wells are provided, the exercise of carrying out PIT/PIV will be easier and faster to perform. SBD methods recommended for such measures include provision of extra boxes, storage wells, or vaults, located at specified locations nearer to KMPs in the plant. While implementing SBD, these provisions can be planned and incorporated in advance rather than retrofitting, in the fabrication plant, since building wells or vaults takes up large space and also needs proper shielding and safety provisions. Such measures reduce the time for PIT and also give the plant operator designated storages for moving the nuclear material when production is halted for any reason. This greatly enhances the overall safeguardability of the facility.

Portal Monitors for Personnel Scanning

A simple concept of providing portal monitors at locations in a fabrication plant can greatly reduce the risk of theft of nuclear material thereby increasing the safeguardability of the facility.

Generally all nuclear facilities have portal monitors at various locations in a plant. A powder-pellet type of fuel fabrication facility can have multiple routes from where the nuclear material could be lost due to theft. The major points of entry and exit in such plant include personnel entry gates, material handling gates and emergency exit routes. Portal monitors are placed in most of these areas for monitoring personnel and also as part of health physics (HP) activities. HP activities are restricted to personnel and clothing monitoring and contamination checks. However, such monitors are recommended to be designed and installed for prevention of theft of nuclear material. As an SBD measure, all entry and exit points are identified. Even areas where nuclear material could be removed, like ventilation ducts, waste effluent ducts, service lines entry points, etc., are evaluated from the view point of material theft. Different and dedicated, even adequately camouflaged portal monitors could be designed to be installed at such locations so that any attempt of theft can be detected and prevented. An optimum number of portal monitors with computerized data acquisition, analysis, and transmission can be designed and installed to detect any unauthorized transit. SBD measure would thus include, identification of strategic locations, choosing right size of monitor for a specific location, making provision for installation of portal monitors, cabling and data acquisition, and transmission systems and their integration. These measures would help in increasing the safeguardability of the facility.

Integration of Safety, Security, and Safeguards Systems

Any nuclear facility has systems for safety, security, and safeguards. Safety systems comprise systems for criticality safety, fire safety, and industrial safety. Criticality safety systems have criticality monitor installations at various locations. Fire safety systems have smoke and fire detectors along with fire fighting measures. Industrial safety systems have systems for camera surveillance, portal monitors, personnel access, and security systems, interlocked vehicle air locks, emergency doors and exits with integration with security systems, etc. Safeguards systems comprise containment and surveillance measures including cameras for plant imagery. Quite often all such systems are installed in a plant independent of each other. However, such systems can be designed so that safety, security and safeguards systems are integrated. An ideal system would have a judicious integration of all three systems.[9,10] When the systems are integrated, the total number of cameras, portal monitors, safety interlocks, cabling, wiring, computers, networking, database, etc., can be reduced, with all systems taking primary feed from common systems. In a fuel fabrication facility, integration of the three systems can begin at the design stage itself.

Discussion and Conclusions

Th and U^{233} based MOX fuels need glove box or alpha tight hot cells type of facilities. Though different methods have been tried out for MOX fuel fabrication, powder-pellet type is the preferred route. A conventional powder-pellet type of MOX fuel fabrication facility is laid out in a linear fashion. The authors propose a modified hybrid layout that has a number of advantages over the typical linear layout. The hybrid layout has enhanced potential for safeguardability. In addition, in such layouts, the following SBD measures are recommended to be:

- Isolation of services from the plant;
- Integration of quality control equipment with main processing equipment;
- Incorporation of process powder recovery systems;
- Systems for dynamic nuclear material accounting/near-real-time monitoring;
- Provision of inventory measurement at every cell/glove box;
- RFID and bar code-based systems for material tracking;
- Incorporating systems for plant imagery;
- Provision of dedicated equipment for measurement of material holdup and MUF;
- Provision of systems for material storage during physical inventory verification;
- Installation of portal monitors for personnel scanning; and
- Integration of safety, security and safeguards systems.

All these measures would not only improve safeguardability, they would also otherwise benefit the operator by reducing MUF, optimizing manpower, and reducing man-rem expenditure.

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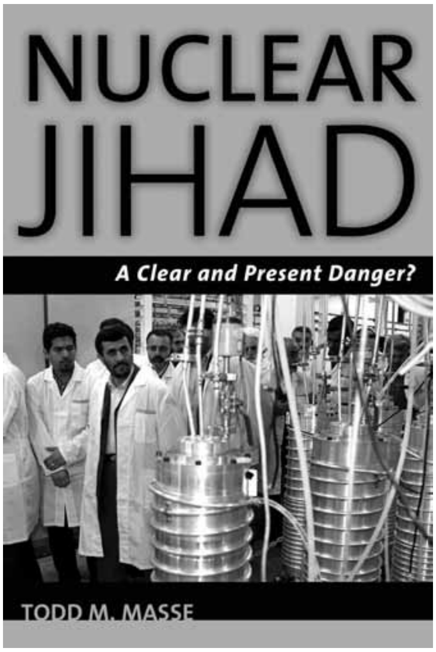
Nuclear Jihad — A Clear and Present Danger?

Todd M. Masse

ISBN 978-1-59797-528-5

Reviewed by: Mark L. Maiello, PhD
Assistant Book Review Editor



Todd Masse, a national security analyst currently working at the U.S. Nuclear Regulatory Commission, has produced a book worthy of textbook status. This amalgam of technical, intelligence, and policy information on potential promulgation of nuclear weapons to non-state actors contains an enormous amount of useful background information that any policy strategist would want at his or her fingertips. Masse's analysis of this potential threat indicates a danger but not necessarily an imminent one. If one looks at the demand side of nuclear terrorism where acquisition of fissile material or weapons is a stated but low probability terrorist goal and one looks at the supply side where much progress has been made to secure both fissile materials and weapons, the result indicates that undue public fear of a nuclear detonation on U.S. soil is unwarranted and the large expenditures of money to defend that possibility are not necessarily targeted efficiently. But, neither should the threat be ignored. Instead, steady progress to secure weapons and materials must continue and the shortcomings of that effort overcome. The low probability event is ignored at the peril of those with the responsibility to defend against them.

Masse explains that the argument for increased probability of a detonation on U.S. soil comes from those who focus on the consequences of such an event and on the intent of terrorists while down-playing the supply side mechanics of fissile material acquisition or weapon construction. His term for this group is *conventionalists. Skeptics* on the other hand, espouse that the obstacles thwarting nuclear terrorism are already very difficult and that spread of nuclear technology to non-state actors is not inevitable. There is, of course, a spectrum of opinion between these two extremes. Masse uses the two schools of thought as tools to analyze the assumptions made by both groups and to further the discussion about the most efficient means to allocate resources to defend against the threat. Masse has rigorously stated, explained, and analyzed the problem while not taking either of the sides he discusses in the book. That is what makes this a policy-maker reference and, I dare say, a good text for a one or two semester course on nuclear security analysis.

The value of the book as a reference and teaching instrument is evident from its construction. Before chapters 4 and 5, which cover the probability of nuclear terrorism and the supply side/demand side analysis, are introductory chapters 1, 2, and 3. Here, the author defines what nuclear terrorism is, the trail terrorists would take to a successful detonation, and the defense of fissile materials. Chapters 6, 7, and 8 discuss deterrence by nuclear forensics (a powerful tool if it can be fully implemented), by the domestic and international framework to foil nuclear terrorism, and through recommendations to deal with the current status of nuclear security. Three appendices explaining U.S. policy options and programs to prevent terrorism complete the analysis. Extensive notes (fifty-six pages), indicate the author's relentless attention to detail. An appendix of abbreviations rounds out this work. There are seven figures, a few of which are oddly simplistic for an effort at this level but some noteworthy ones are mentioned below. Of the nine tables, several are very useful as summaries of the multifarious issues. A more detailed table of contents would be a minor but useful improvement.

This is not the easiest of reads given the complexity of the subject matter and the author's desire to frame the issue from stem to stern as described above. The author is exceptionally erudite and occasionally packages material densely into a few sentences. Throughout the book, he quotes a plethora of security, terrorist, and nuclear nonproliferation experts such as Matthew Bunn of Harvard, Joseph Cirincione, most recently of the Ploughshares Fund, Brian Michael Jenkins of Rand and Daniel Byman of Georgetown University and the Brookings Institute. The result, given close attention by the reader, is a convincing factual presentation, deeply analytical and most importantly, dispassionate. If an effort to embrace Masse's scholarly approach is needed at all, it is well worth it.

A personally pleasing chapter was number 7, where Masse provides an overview from aloft of the domestic and international strategy to prevent nuclear weapons proliferation with concise explanations of the Nuclear Nonproliferation Treaty, UN Security Council Resolution 1540, and other devices such as the Nuclear Suppliers Group and the Zangger Committee. One of the significant highlights of this work is chapter 4 wherein the demand side of the nuclear terrorism is discussed. Here, the author clearly explains that a *plausible* threat exists only if terrorists possess the intent *and the capability* to carry it through. Although intent, especially from logistically well-run and financed organizations is a danger, the imminent threat is greatly reduced if capability does not exist. Unfortunately, capability is difficult to estimate. When this is not recognized, the conclusion may be "worst-case scenario planning" in which the threat alone spurs a defensive response that may be out of proportion to reality. In other words, even if the chance of a nuclear detonation is only 1 percent, the potential devastation warrants a response without much consideration of the ramifications for the nation's resource allocation or its world standing e.g., the U.S. reputation after war in Iraq and Afghanistan. Policy makers are instead advised to use a multi-faceted approach to prevent terrorists from developing a nuclear capability including intelligence-gathering into the areas of the terrorist's military, economic and financial assets, and diplomacy in nations where terrorists are known to harbor (Pakistan for instance) so that terrorism can be constrained at its roots.

Masse goes further in his analysis. He discusses the probability of a nuclear detonation given that terrorists already possess a working bomb. The pressures to both use the weapon immediately or to wait are discussed in detail. An analysis follows of the motivations of terrorists to use nuclear weapons, the capability to build one, and which terrorist organizations could conceivably carry out an attack. A table of skeptic vs. conventionalist thought on the demand side issues nicely summarizes salient points of this discussion. Considering that the demand side of the issue (the abilities of terrorists) is not as well understood as is the supply side (the security and inventory of nuclear material), the level of detail in the chapter is not only ambitious but very satisfying.

The supply side chapter (number 5) is dominated by an assessment of Masse's greatest concern—Pakistan. With terrorists lodging within its borders, poor political efforts to improve its economic conditions, and a tense security relationship with the United States and India, Pakistan is a weak link in the international nuclear security chain. The emphasis on this nation results in a few nice bonuses for the reader: a detailed description of Pakistan's command and control system (also provided in a figure) and a discussion of its undeclared nuclear doctrine. The chapter does not ignore the threats posed by the regimes in North Korea and Iran nor Russian nuclear security going beyond the period (coming soon) when United States funding is curtailed. Security and conversion of highly enriched uranium research reactors and even the impact of a worldwide nuclear power renaissance are issues included in this chapter. A supply side analysis must include an assessment of the threat reduction the United States has invested in across the globe but particularly in Pakistan and Russia. Masse concludes that security upgrades and conversion of HEU reactors to LEU fuel-burners should continue but with the certain knowledge that nuclear material security has thus far been improved. This is the conclusion that policy makers need to realize to properly allocate budgets, technical expertise, intelligence, and security assets amongst other forces going forward.

Masse concludes his work with an overview of defensive U.S. strategic protocols targeting nuclear terrorism. He is not without subtle criticism of the U.S. approach, indicating that the many agencies presently involved fail to coordinate. The result has often embarrassed the participants who discover the redundant effort not via interagency communication, but from the very foreign governments they are assisting. Masse covers the details and the debate over the need for a Coordinator for the Prevention of Weapons of Mass Destruction and the coordinator's link to the Office of Management and Budget for proper allocation of resources. Appendix A presents recommendations to improve U.S. counter-terrorist efforts from both the supply and demand side elements of the equation. Appendices B and C summarize the current U.S. government efforts.

This is a book that policy makers and nuclear nonproliferation analysts need to read and keep at the ready. For the rest of us, the book provides a start to finish overview that provides, in my opinion, a cool, unbiased analysis of the facts concerning the probability and consequences of nuclear terrorism. In so doing, Masse (unintentionally or intentionally) allays fears of imminent danger. The facts seem simply to result in that conclusion. However, Masse does not allow one to be complacent. It is repeated throughout that to confront the efforts of terrorists to gain access to nuclear materials, an effort that can morph with the temporal nature of the threat must continue on many fronts. You will not find a recipe for the exact mix of assets nor the budget analysis needed to currently and adequately thwart nuclear terrorism – that is left for the policy makers. You will however find a calm, composed analysis of the subject that will illuminate and inform. It is just what we needed.

Mark L. Maiello, PhD is assistant book review editor for JNMM *and a contributing editor for* Health Physics News. *In 2010 he co-edited the book* Radioactive Air Sampling Methods *(CRC Press) with Dr. Mark Hoover of NIOSH. He is a former employee of the U.S. Department of Energy and is currently employed as a health physicist with a private corporation.*

Taking the Long View in a Time of Great Uncertainty INMM's International Role

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

The INMM's 53rd Annual Meeting, held in Orlando, Florida USA, was a remarkable experience that demonstrated how interconnected we all are in the world of nuclear materials management. Setting the stage, the opening session featured presentations with extraordinary detail of the Fukushima nuclear accident and the subsequent cleanup and recovery activities.[1] Attendees also heard firsthand, in the discussion of lessons learned, the impact this event has had on almost every technical area of expertise that defines the INMM. The Fukushima accident was the subject of this column a year ago, when it was speculated that the event may represent a strategic inflection point for the emerging nuclear renaissance at the time.[2] Although a year later it is still too early to assign that level of impact, all of the indicators point to long-lasting disruptions to the renaissance on a global scale.

The international response to this event has been extraordinary, and stabilization of the situation has been successful to date. But it was difficult to walk away from the morning session without wondering what further long-term changes the accident will have on security and safety planning for nuclear plants worldwide, and how new models of risk management might already be in development for new facilities to address the experience being gained, with the estimate of decades of cleanup work that lie ahead at Fukushima.

Some of those concerns were eased during the week, as we also heard of the remarkable speed at which Middle Eastern countries are undertaking their efforts to develop nuclear power technology, driven by national needs for energy, including desalination requirements to meet the increasing clean water requirements of their advancing populations. On a very positive note, as mentioned in a previous column,[3] these nations have embraced international standards for ensuring safety, security, and adherence to nonproliferation doctrines, and are planning to more fully engage in international forums, such as the INMM Annual Meeting, to not only take advantage of technical and policy exchanges, but also provide a level of transparency that will enable future collaborations.

These two perspectives, as well as many discussions in the hallways during breaks, and during the numerous meetings all week with leadership, brought to a focus how *international* the INMM has become. When you peruse the early issues of the *JNMM*, it is obvious that the original focus of the Institute was U.S.-centric, however, more and more over the years, the Institute has become increasingly involved in international programs as the impact of events worldwide have dictated a need for greater global collaborations. In fact, today, more than 40 percent of INMM's members are non-U.S. citizens, and we have more international chapters than U.S. chapters, not counting student chapters; although this year it was announced at the annual meeting that our first international student chapter, the Jordan University of Science and Technology Student Chapter, was approved for membership. A current listing of our chapters, which is where the "rubber hits the road" in the implementation of the Institute's mission is shown in the accompanying table.

The International Role of INMM

The discussions that were stirred at this year's INMM Annual Meeting also raised a question on how effectively the Institute is engaging our international members and chapters in its activities and planning. Looking inwardly, the Strategic Planning Committee recognized that there are no non-U.S. passport holding members, something that we hope to rectify this coming year. The Strategic Planning Committee did add three additional members this year with international experience, James W. (J. R.) Russell, who is the International Nonproliferation Program Manager for NSTec at the Nevada National Security Site (formerly known as NTS); Therese Renis, who is the Vienna

U.S. Chapters	**International Chapters**	**Student Chapters**
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Northeast	Moroccan	Triangle-areas Universities
Pacific Northwest	Nigeria	Pennsylvania State University
Southeast	Obninsk	Texas A&M University
Southwest	Russian Federation	University of Michigan
	United Kingdom	University of Missouri
	Ukraine	University of New Mexico
	Urals	University of Tennessee
	Vienna	University of Washington
		Jordan University of Science and Technology

Chapter president and stationed with the IAEA in Vienna as Section Head of *Concepts and Approaches* in the Safeguards Department; and Christian (Chris) Kessler, retired director from the U.S. Department of State (having worked in nonproliferation), who has recently rejoined the INMM after many years of absence. We have asked these individuals to not only bring their international experience and perspectives to bear on our deliberations, but to also seek out potential members from the international community to become active in our committee.

Another question that was asked is how can the INMM, and the incredible expertise and experience of its membership, be leveraged to have a positive impact worldwide on events such as Fukushima? We have spoken of the INMM mission in previous columns and the importance of addressing all aspects of that mission.[4] As an element of an INMM Executive Committee (EC) strategy to accomplish its mission on a global scale, the Institute has established a number of formal partnerships with organizations that have similar interests worldwide, including the European Safeguards and Research and Development Association (ESARDA), the Nuclear Infrastructure Council (NIC), and the World Institute for Nuclear Security (WINS). The Strategic Planning Committee this year, as part of their charge from the EC, will examine current and potential future relationships with other like-missioned organizations to determine how the Institute can be more effective and efficient in its operations, and broaden its reach and positive influence. A survey of institute leadership will be performed to capture this important information with the hope that it can be utilized to strengthen the Institute and its role in addressing events such as Fukushima, and assisting nations with a desire to improve their quality of life through nuclear power with the safe and secure implementation of that technology.

The Strategic Connection to World Events

The last *Taking the Long View* column in the Summer 2012 *JNMM* issue raised the question of how do we sustain the Institute, given the global economic crisis, the loss of critical expertise, and the difficulty of attracting the younger generation to the disciplines critical for our nuclear future. All of these issues must be addressed while dealing with increasing nuclear technology proliferation; the potential for nuclear incidents, either manmade or caused by nature; and the continuing escalation of instability and hostilities in several areas of the world where nuclear weapons exist.

As we see the growing connectedness of these drivers, and the difficulties that any one organization might have to positively influence outcomes, our discussions at the INMM 53rd Annual Meeting took on a sharper focus with respect to building collaborations internationally to address some of the more important actions necessary:

- **Developing a collaborative public education program that assists countries struggling with a decline in public trust for nuclear power.** The United States saw this with Three Mile Island more than three decades ago, an event that stalled not only the promise of nuclear power as a clean and virtually unlimited source of energy, but also slowed the fundamental research necessary to advance our knowledge in critical areas such as reprocessing. This phenomena resurfaced recently with the presidential decision to halt the Yucca Mountain repository work, driven in this case not by a tragic event, but simply a lack of education of the public and policy makers on the benefits of a geologic repository to the safety and security of millions of U.S. citizens. And once again, with the tragic events of Fukushima, we are seeing the mistrust of a nation influencing the very promising future of nuclear power in Japan as that country struggles to bring assurance to its prefectures of a renewed vigilance in safety and security. Likewise, that event has dissuaded others, including the United States, causing them to slow or even halt new startup programs. Even in the Middle East, where nuclear power is so desperately needed to provide critical infrastructure, concerns about the future safety of the population dominate many discussions.
- **Providing policy makers with the information necessary to convince them of the strategic need for nuclear power, and the confidence that such energy sources will not become the nightmare so often promulgated in the media and among the uninformed.** This also speaks to the need for our scientists and engineers to consider the challenge of public office, and work within the system to convince peers and colleagues of the benefits of nuclear energy. In particular, a national and international wave of support is needed for solving the political and public-acceptance issues of spent fuel disposition. The technological issues for long-term storage are resolved, but the political ones have become almost insurmountable.
- **Capturing more than five decades of global nuclear knowledge and expertise and transferring it to a new generation.** The INMM and many other organizations have been focused on this issue for more than two decades, and despite our efforts, we continue to see the loss of significant expertise and knowledge, and are learning how difficult it is to attract and retain the new generation of knowledge necessary to sustain and advance nuclear technology. This new generation is needed not only to make new technical and policy breakthroughs, but also to safely and securely maintain the legacy of more than six decades of nuclear operations. Of all of the issues we face, this one could become the most frightening for future generations.

These are the challenges that lie ahead for the Institute.

We encourage JNMM *readers to actively participate in these strategic discussions, and to provide your thoughts and ideas to the INMM's leadership. With your feedback we hope to explore these and other issues in future columns, addressing the critical uncertainties that lie ahead for the world and the possible paths to the future based on those uncertainties. Jack Jekowski can be contacted at jpjekowski@aol.com.*

End Notes

1. Members are encouraged to read the plenary talks by searching the Annual Meeting archives, http://www.inmm.org/Annual_Meeting_Proceedings/2448.htm, after logging in, for the Plenary Session talks presented by Takeshi Ohta (2 presentations), and Kaoru Naito.
2. Jekowski, J. 2011. A Strategic Inflection Point? – The Nuclear Crisis in Japan, *Journal of Nuclear Materials Management,* Volume 39, No. 4, pp. 23-24.
3. Jekowski, J. 2011. Focusing on the Nuclear Fuel Cycle, *Journal of Nuclear Materials Management,* Volume 39, No. 2, pp. 29-31.
4. Jekowski, J. 2012. *Looking Back at a Decade of Tumult – and Looking Forward to an Uncertain Future, Journal of Nuclear Materials Management,* Volume 40, No. 3, pp. 99-101.

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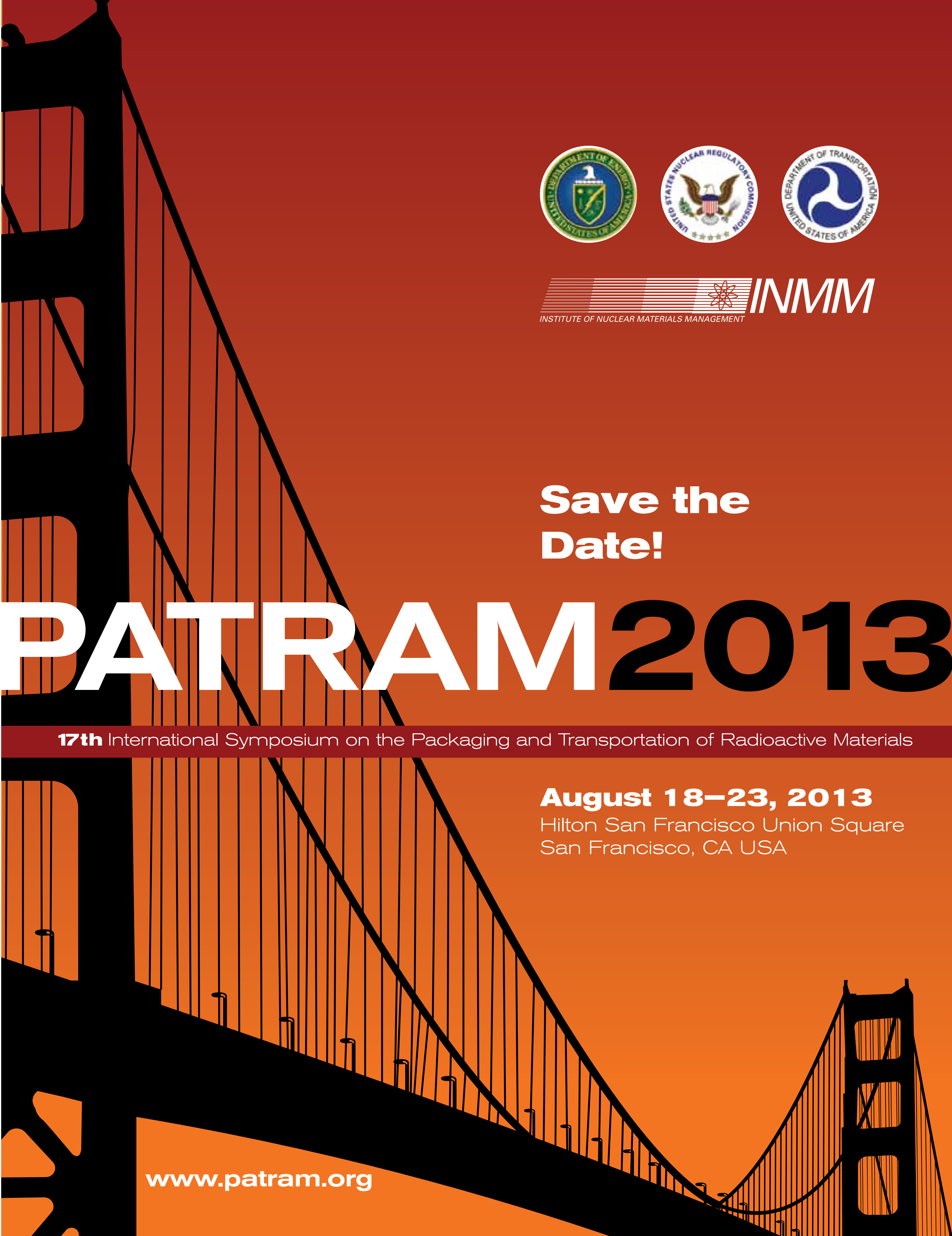

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