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The Institute of Nuclear Materials Management is dedicated to the safe, secure and effective stewardship of nuclear materials and related technologies through the advancement of scientific knowledge, technical skills, policy dialogue, professional capabilities, and best practices.

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President's Message

By Cary Crawford
INMM President

Hello, INMM Community!

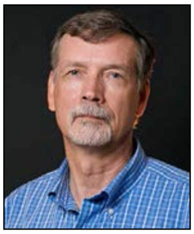
I hope your Spring is going well. At the time of writing this, we are right in the middle of the COVID-19 pandemic, with most of our colleagues in some form of quarantine. It certainly makes for some interesting times. After adjusting to modified work schedules, kids at home, dogs barking, and other challenges, it also gives us time to think about the threats and challenges to nuclear materials management and how those challenges can change due to events such as this. I trust that you will, first and foremost, take care of yourselves and your families. After that, I hope we can further develop some insights and mitigation strategies to our nuclear materials management needs in such uncommon times. While I certainly would not have wished this event on us, I do hope that we can learn and grow from it within our community. I look forward to hearing those insights from you, hopefully at the now virtual, online INMM Annual Meeting.

With that in mind, I would highlight that a positive spin on this is that it has pushed the leadership to think of alternative ways of communicating or to hold large workshops and conferences. Many good ideas have emerged, currently as contingency plans, but possibly as new venues for future collaboration.

In addition, as you might have noticed in the call for papers we are working at holding more cross-cutting sessions this year and hope to be able to bring you the most current and relevant meeting we've had in several years. We sincerely hope you can attend with this new, online format, and we anticipate great collaboration.

Stay safe, and keep working toward a safer and more secure world!

Sincerely,
Cary Crawford
President, INMM



Adding to the Knowledge in Our Field During the COVID-19 Pandemic

By Markku Koskelo
JNMM Technical Editor

Two more contributed manuscripts have made it through the peer review process and are included in this issue. Both are well thought out and extensively referenced. The overall page count of this issue is not that different from many prior issues that have had more papers.

The first article looks at the effectiveness of a multidisciplinary educational program on nuclear energy human resource development, The Gulf Nuclear Energy Infrastructure Institute (GNEII) at Khalifa University of Science and Technology (KU) in the United Arab Emirates (UAE). UAE is one of the many countries with no present nuclear power generation that are moving ahead with a nuclear energy option. Clearly the country will need local professionals to operate the reactors, provide regulatory oversight, and do everything in accordance with the international safeguards agreements. A review of the effectiveness of the education at KU clearly indicates that the nuclear energy program at KU has been successful. Overall, GNEII's activities between 2011 and 2016 illustrate significant local, regional, and global impacts. One of the INMM's objectives is to educate and train the next generation of nuclear material shepherds. I cannot help but wonder whether a similar study should be conducted elsewhere.

The second article discusses a new Passive Neutron Albedo Reactivity (PNAR) Ratio method for use in measuring the net neutron multiplication in a spent fuel assembly. Plans are being made to use this method in an integrated, non-destructive assay instrument for safeguards in connection with the Finnish encapsulation of nuclear waste before final disposition. While the PNAR method has been used before, it needs to be validated for the Finnish VVER-440 reactor fuel before it can be adopted for use. The paper describes all the work that has gone into making sure that the method and the proposed instrument fit the intended purpose.

In his column, "Taking the Long View in a Time of Great Uncertainty - Scenario Planning in the Age of COVID-19," Jack Jekowski, Industry News Editor and Chair of the INMM Strategic Planning Committee, takes us through the various articles that he and others have published on scenario planning to address unexpected situations. I was particularly struck by Jack's words related to the present pandemic: "'Why didn't we do something to prepare for this?' And, 'Why didn't we 'connect the dots?'" Scenario planning, when applied appropriately, could have the power to change the mindsets of leaders, but more importantly, can put "what ifs" into a form that stirs the interest of the public and creates the urgency for policy makers and governments to act. Jack's column is well worth reading.

Interestingly, the book review provided by our Book Review Editor, Mark Maiello, talks about scenario planning as well. The book titled, "Bargaining Over the Bomb" is about using game theory for decision making. While he admits that it is a book for those of us that are mathematically inclined or that code for a living, this book review could not be more timely. The book explores the use of the method for tradeoffs and scenarios for nuclear proliferation. While the subject of nuclear proliferation (specifically, *nonproliferation*) is close to our hearts, this book and the game theory concepts are applicable beyond nuclear nonproliferation. It is also a way to explore decision making processes and their consequences in other fields. Perhaps something like this would be applicable to all the things Jack has discussed in his past columns that we all thought "couldn't happen."

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

Markku Koskelo
JNMM Technical Editor

The Gulf Nuclear Energy Infrastructure Institute: A Multidisciplinary Educational Approach for Integrated Nuclear Energy Safety, Security, and Safeguards in the Middle East

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Abstract

The Gulf Nuclear Energy Infrastructure Institute (GNEII) at Khalifa University of Science and Technology was created as a regional institute offering education, research, and technical services that support nuclear energy safety, security, and safeguards (3S) objectives. A mixed methods approach—using the (1) *Course Evaluation*, (2) *GNEII Alumni Survey,* (3) *Capstone Project,* and (4) *GNEII-Related Literature* data sets—was used to evaluate the effect of implementing this multidisciplinary ‘3S’ educational program and the broader impact of the associated ‘3S’ multidisciplinary institute on nuclear energy human resource development. Data sets (1), (2), and (3) illustrate how well GNEII implemented this novel 3S curriculum and resulted in successful knowledge transfer. Data sets (2), (3), and (4) illustrate how well GNEII’s impact has positively influenced professional workplace behaviors and the institute’s broader reputation to support responsible nuclear energy program education. GNEII demonstrates one option for successfully providing a multidisciplinary, 3S curriculum to support broader nuclear infrastructure and human resource development aims.

Introduction

The late 2000s and early 2010s saw an increased global interest in nuclear energy, primarily driven by a desire for improved living and social standards, energy security, and climate change mitigation. Many of the regions expressing a strong interest in nuclear energy programs—such as the Gulf region—lacked the necessary human infrastructure to support such programs. Here, human infrastructure incorporates two key aspects. First, it includes having adequate numbers of individuals available to work in nuclear-energy-related government and industry positions. Second, it also includes ensuring such individuals have the appropriate level of education, training, experience, and knowledge across a range of responsibilities within nuclear power programs. In addition, the new nuclear energy program in the United Arab Emirates (UAE) demonstrated a need to address the lack of *indigenous* human infrastructure capabilities available to support growing regional interest in nuclear energy.[1]

Addressing this gap in nuclear energy human infrastructure development posed two unique challenges. The first related to the limited knowledge and experience in nuclear energy programs existing in Gulf-region states. The second related to the breadth of safety, security, and non-proliferation (or safeguards) concerns unique to nuclear energy programs. What resulted was a lack of appreciation across these varying concerns, as demonstrated when:

> students [of nuclear safety, for example] typically know little about the problems and values of other students in other disciplines [like nuclear security or safeguards, for example], which is a precursor to the lack of awareness in the real world.[2, p. 21]

Further, recent research in engineering education indicates that future engineers “need to be able to deal with complex interrelationships that include not only technical issues…but human and environmental factors as well.”[3, p. 2]

In response, a focus arose to implement a multidisciplinary education program—seeking to synchronize both technical and non-technical aspects of nuclear energy safety, security, and safeguards—that balanced the advantages of more deeply theoretical academic programs with the applied, practical knowledge of hands-on training courses. Further, by incorporating this range of topics across nuclear energy disciplines into the educational program, potential graduates were expected to have an increased “awareness of the social impact of their chosen [nuclear energy program-related] profession.”[4, p. 133] The result was the Gulf Nuclear Energy Infrastructure Institute (GNEII), housed at Khalifa University of Science and Technology (KU) located in the United Arab Emirates (UAE). From its inception, GNEII's goal was to help generate expertise among future leaders of Gulf-region nuclear power programs in global standards, norms, and best practices in safety, security, and safeguards.[5] GNEII does not provide a short course training program (e.g., like the various topic-specific courses offered by the International Atomic Energy Agency [IAEA]), nor does it provide a university-based nuclear engineering degree. Rather, it is a multidisciplinary human capacity development institute offering education, research, and technical services to support responsible nuclear energy programs.[6]

GNEII's creation emerged from a strategic partnership between Emirati implementers (KU) and stakeholders (the Emirates Nuclear Energy Corporation [ENEC], Nawah Energy Company, the Federal Authority for Nuclear Regulation [FANR], the Critical Infrastructure and Coastal Protection Authority [CICPA]), and the National Emergency Crisis and Disaster Management Authority [NCEMA]), as well as U.S. implementers (Sandia National Laboratories [SNL] and Texas A&M University's Center for Nuclear Security, Science, and Policy Initiatives [NSSPI]) and sponsors (U.S. National Nuclear Security Administration's offices of Global Material Security and Nonproliferation and Arms Control and the U.S. Department of State's Partnership for Nuclear Security). For more details, please see Williams, et. al.[7] Over its developmental history, nearly 100 regional nuclear professionals have completed this novel, multidisciplinary education program (Table 1).

Table 1. Summary of GNEII Fundamentals Course Fellows 2011-2016

Year	# UAE Fellows			# Non-UAE Fellows	Yearly Total	Countries Represented
	ENEC*	**FANR**	**CICPA**			
2011	4	5	1	0	10	UAE
2012	3	9	2	8	18 (22)**	UAE, Kuwait, Saudi Arabia, Qatar, Jordan
2013	4	6	3	7	20	UAE, Saudi Arabia, Qatar
2014	6	3	3	0	12	UAE
2015	7	4	5	2	18	UAE, Jordan
2016	2	16	3	0	21	UAE
TOTAL	**26**	**43**	**17**	**17**	**99**	**5**

*Includes Fellows from Nawah, the NPP operating company that split from ENEC in 2016.
**Due to modular structure of the course in 2012, not all international participants were able to finish all required modules due to logistical reasons.

GNEII's Educational Approach

The founding element of GNEII's human resource development objectives was its Fundamentals Course. Described in more detail in subsequent sections, this Course was based on a multidisciplinary, systems theory-based pedagogical approach consisting of two key elements. First was the multidisciplinary approach, similar to Gorman, et. al.,[8] and Rhee, et. al.,[2] to help new nuclear professionals identify where nuclear energy safety, security, and safeguards (3S) interdependencies exist. This also emphasized the need for future nuclear energy program leaders to manage across these aspects, as responsible nuclear energy decisions often require interactions between safety, security, and safeguards. Second was a systems-thinking based program structure similar to that described by Bozkurt and Helm (2013)[9] underlying their *Systems Engineering Framework* for online education development. Here, the systems engineering concepts of a *holistic view*, *life-cycle orientation*, *identification of system requirements*, and *interdisciplinary effort* helped develop our responsible nuclear energy program (RNEP) framework, which reframed the multidisciplinary aspects of nuclear energy enterprises in systems theory terms.[10,11] For the Fundamentals Course, the faculty coordinator oversaw a rotation of U.S., UAE, and other global subject matter experts as lecturers in support of the multidisciplinary curriculum. Last, the course combined lectures, hands-on activities, classroom exercises, and case studies to help meet course learning objectives. More details of this multidisciplinary curriculum can be found in Williams, et. al.,[12] and Williams, et. al.[10]

To further support this novel educational approach, GNEII identified and established three areas of institutional research emphasis: integrated 3S methodologies, nuclear infrastructure, development and Gulf/Middle East regional nuclear interactions. Research-related activities included expanding the analytical depth of Fundamentals Course and Visiting Research Scholar projects. More details on the research pillar can be found in Williams, et. al. [13] Additional efforts were undertaken to enhance the institute's capabilities (and opportunities) to provide hands-on, practical experiences—to include exercises in KU's nuclear engineering department laboratories, tours of the Barakah Nuclear Power Plant (2012), and (the state-of-the-art) radiation portal monitoring system at Khalifa Port in Abu Dhabi (2014-2016). These activities developed into both a means to provide regional stakeholders with short-term, technical, and targeted nuclear energy-program services and also create a new set of capabilities for the institute. For more details on the technical services pillar, please see Williams, et. al.[14]

Research Questions

To support the compelling accomplishments of the institute, this study aims to better identify and characterize GNEII's overall impact in two parts. First, this study evaluates the efficacy of implementing an integrated 3S curriculum in a Gulf region and new nuclear context for knowledge transfer. More specifically, it analyzes the development of GNEII's multidisciplinary 3S paradigm and curriculum via the effectiveness of GNEII's Fundamentals Course. Second, it analyzes GNEII's impact on a broader scale (e.g., beyond knowledge transfer) by assessing GNEII's influence on Emirati, regional, and international discourse on responsible nuclear energy program development. In summary, the two research questions are:

- *RQ1:* Can a multidisciplinary approach to 3S curriculum be implemented in a regional educational program?
- *RQ2:* What is the institutional impact of GNEII?

Design/Method

To answer these two research questions, we use a mixed methods approach and several data sources. Mixed method research designs are useful for addressing multiple facets of complex issues and reconciling trends and insights from different perspectives.[15] In addition, "using multiple methods to gather and analyze data is necessary to paint a more comprehensive picture of complex phenomena like student learning and development"[16, p. 323], making this research approach appropriate for the aims of this study. As such, we included quasi-experimental survey and context analysis for "triangulating multiple sources of data to establish trustworthiness and consistency in interpretation."[17, p. 9] Our data sets are summarized in Table 2. This mixed methods approach is appropriate for evaluating our wide-ranging research questions by providing a framework by which to triangulate findings across traditional and non-traditional data sources.

Data Set #1: GNEII Fundamentals Course Feedback

Each iteration of the GNEII Fundamentals Course between 2011 and 2016 asked the participants to complete evaluation forms to collect feedback on the success of the various course topics. The goal of this evaluation mechanism was to identify what could be improved in the Fundamentals Course itself—the single course taken by Fellows during that semester. The specific questions asked were adjusted from year to year and to better align with strategic institute decisions (e.g., the 2016 evaluation form being influenced by the UAE national education accreditation process). Yet, there are close enough qualitative similarities in certain items—for example, "The instructor demonstrated a thorough knowledge of the subject matter," in 2011 and, "The instructor presented material clearly and lectures were well organized," in 2016—to elicit insights regarding the success of each topic to meet GNEII's educational and knowledge transfer goals. The feedback for the evaluation was provided on a 1-to-5 Likert scale, where a '1' is the lowest possible and a '5' is the highest possible score.

This data set is composed of Fundamentals course topical feedback forms from 2011 and 2016. The 2011 data set consisted of 12 weekly topics and eight (8) evaluation questions while the 2016 data set consisted of 10 weekly topics and 13 questions. The 2011 weekly topics were collapsed to match those in the 2016 data by averaging the associated feedback scores between the combined weekly topics. Then, as summarized in Table 3, the actual feedback questions were collapsed (and the respective scores averaged) into three common categorical measures: instructor effectiveness, course structure effectiveness, and overall topic effectiveness.

The analytical goal of this data set was to measure the improvement between the first (2011) and last (2016) offerings of the GNEII Fundamentals Course to meet the professional development needs of the Fellows (and address RQ1). The unit of analysis is the individual response from each Fellow for each question evaluating a course topic. Given demographic similarity between the two groups of Fellows (Table 1), comparison between the evaluation scores registered in 2011 versus those in 2016 is appropriate for eliciting insights from this data set. More specifically, the degree to which the responses are the same or improve from 2011 to 2016 supports an affirmative response to RQ1, indicating that (near) real-time feedback from Fellows represents (at worst) consistency with and (at best) improvement in instructor, course structure, and overall topic effectiveness.

Table 2. Summary Data Set Descriptions

Data Set Name	Date Set Description
Course Evaluation Data	Fellow reviews of the weekly course topics from the 2011 and 2016 GNEII Fundamentals Courses
GNEII Alumni Survey Data	Online survey responses from alumni of the GNEII Fundamentals Course that consisted of 15 questions of various types
Capstone Project Data	The total set of Capstone Projects completed by the 99 GNEII Fellows across the six years of the Fundamentals Course
GNEII-Related Literature Data	Professional reports and academic articles (not authored by institute-affiliated personnel) that mention/describe GNEII

Table 3. Summary of the Evaluation Categories for the GNEII Fundamentals Course 2011 and 2016 Weekly Topic Feedback Forms

Evaluation Category	**Specific Course Evaluation Question:** 2011	**Specific Course Evaluation Question:** 2016
Instructor Effectiveness	• The instructor was well prepared for the presentation • The instructor demonstrated a thorough knowledge of the subject matter • The instructor interacted well with the participants • The instructor clearly expressed interest in addressing all questions raised by the participants • The instructor's response to questions was clear and understandable	• The instructor's activities/exercises and slides helped me achieve the learning outcomes • The instructor kept good discipline in the classroom • The instructor showed enthusiasm for the subject matter • The instructor was available for help outside of class • Assessment and feedback was fair and prompt by the instructor • The instructor included sufficient relevant examples
Course Structure Effectiveness	• The materials (handouts, on-screen visuals, videos, job aids, etc.) provided and reviewed were easy to understand • The materials (handouts, on-screen visuals, videos, job aids, etc.) provided and reviewed offered valuable information that will help me in the future	• The instructor presented material clearly and lectures were well organized • The instructor's activities/exercises and slides helped me achieve the learning outcomes • The instructor kept good discipline in the classroom • The instructor showed enthusiasm for the subject matter • The instructor was available for help outside of class • Assessment and feedback was fair and prompt by the instructor • The instructor included sufficient relevant examples • Overall, I am fully satisfied with the module content
Overall Topic Effectiveness	• The materials (handouts, on-screen visuals, videos, job aids, etc.) provided and reviewed offered valuable information that will help me in the future • The length of the presentations was sufficient to deliver the subject matter	• The module was informative and helped me develop an interest in the subject • I believe I achieved the learning outcomes of the module • The content of this module is relevant to my needs/interests/job responsibilities • The instructor presented material clearly and lectures were well organized • The instructor's activities/exercises and slides helped me achieve the learning outcomes • The instructor kept good discipline in the classroom • The instructor showed enthusiasm for the subject matter • The instructor was available for help outside of class • Assessment and feedback was fair and prompt by the instructor • The instructor included sufficient relevant examples • Overall, I am fully satisfied with the module content • Overall, I am fully satisfied with the module delivery • Overall, I am fully satisfied with this module

Data Set #2: GNEII Alumni Survey Data

From October 23 to November 13, 2016, GNEII alumni were given the opportunity to complete an anonymous online survey regarding their experiences during, and after completing, the GNEII Fundamentals Course. The survey was administered via Survey Monkey™ and was preceded by an introductory email sent to the alumni via the last known email address they had provided to the institute. The survey consisted of multiple question types (e.g., Likert Scales, multiple choice, and open-ended) that were organized around two key themes (Note: Please contact the authors for the actual survey text). The first theme sought to elicit levels of improvement in Fellow knowledge from completing the GNEII Fundamentals Course. The second theme sought to elicit levels of improvement in Fellow capability to perform their current job tasks after completing the GNEII Fundamentals Course. In total, 29 of 99 alumni responded for a 31% response rate (Table 4).

Table 4. Summary of GNEII Alumni Respondents to 2016 Online Survey

Year	# UAE Fellows			Affiliation Not Reported	Total
	ENEC	FANR	CICPA		
2011	--	--	1	--	1
2012	1	2	--	1	4
2013	1	1	--	2	4
2014	1	1	--	--	2
2015	6	--	1	1	8
2016	1	7	--	2	10
TOTAL	**10**	**11**	**2**	**6**	**29**

The analytical goal of this data set was to assess the knowledge improvement within GNEII Fundamentals Course alumni in key topical areas (and address RQ1) and to evaluate the impacts of the course on the Fellows' professional careers (and address RQ2). Here, the unit of analysis is similarly the individual response from each Fellow for each survey question. More specifically, this manifests itself in numerical comparisons of reported Likert Scale scores (e.g., between Q4 and Q5), numerical counts (e.g., for Q6), and assessing trends across years (e.g., Q9). In addition, the affirmative evidence for RQ1 was dependent upon the extent to which:

- the level of knowledge in various topics before versus after the Fundamental Course decreases, sustains, or increases (Q4 and Q5)
- the most often selected topic is related to either the 3S, security, safety, or safeguards topics as most useful (Q6)
- Fellows select either moderate or substantial impact on knowledge regarding 3S, security, safety, or safeguards topics (Q7)
- trends increasingly agree or strongly agree on the benefit of the novel 3S approach (Q8)

Similarly, the larger institutional impact (RQ2) of GNEII was measured by the extent to which:

- Fundamentals Course topics were considered relevant to current job duties (Q9)
- the knowledge and experiences from the Fundamentals Course help in advancing professional careers (Q10)
- the knowledge and experiences from the Fundamentals Course are regularly used in the professional environment (Q11)
- the knowledge and experiences from the Fundamentals Course help in building overall professional opportunities (Q12)

Data Set #3: GNEII Fundamentals Course Capstone Project Data

For each iteration of the GNEII Fundamentals Course, Fellows were required to complete a Capstone project (Note: All GNEII Capstone projects are catalogued as 'GNEII Working Papers,' and can be accessed by contacting co-authors Dr. Philip A. Beeley or Dr. Saeed Al-Ameri at KU). Per the Fundamentals Course requirements, the Capstone was a short-term, applied research project that allowed Fellows the opportunity to focus their newly gained knowledge to address a real nuclear infrastructure development problem, need, or issue.[13] These Capstone Projects served three purposes: providing metrics by which to evaluate Fellow performance at the end of the Fundamentals Course, providing opportunities for the Fellows to demonstrate their analytical capability to professional peers, and providing tangible evidence of potential solutions to current problems with which they could return to their employer. Though a set of secondary data, the centrality of the Capstone Project to the Fundamentals Course make this data appropriate for exploring our research questions.

The analytical goal of this data set was to assess (1) the increase in topical and technical sophistication in Capstone Projects (to address RQ1) and (2) the possibility of extending Capstone Projects research ideas into more in-depth academic research projects within the institute (to address RQ2). Each Capstone Project Report was evaluated individually for sophistication in terms of research design, technical depth, topical complexity, and logical consistency. According to this content analysis, the larger the increase in sophistication of the Capstone Project reports the greater the knowledge transfer during the Fundamentals Course (addresses RQ1). It is important to note that the increased sophistication of Capstone Projects is not a measure of *absolute* knowledge transfer, particularly when considering the possibility for a steady increase in the overall baseline knowledge of subsequent classes of GNEII Fellows. That said, this data set can speak to how knowledge transferred expanded beyond the *relative* baseline level(s) of each class of Fellows completing the Fundamentals Course. Similarly, the extent to which these Capstone Projects produced follow-on research efforts is one measure of the broader (e.g., beyond knowledge transfer) impact of GNEII (addresses RQ2).

Data Set #4: GNEII-Related Literature Data

Over the course of GNEII's operations, the institute has built a strong, positive reputation and was increasingly referenced in professional fora (e.g., conferences and professional society meetings) and invited to participate in regional and technical exchanges in relevant topic areas between 2011 and 2019. As such, this data set, summarized in Table 5, consists of all references to GNEII within the academic and professional publication space. By using a range of online search capabilities (e.g., Google Scholar and SCOPUS™), the terms "GNEII" and "Gulf Nuclear Energy Infrastructure Institute" were queried to identify these data, with the final search occurring on October 16, 2019 (Note: We excluded all search returns that were authored or co-authored by institute-related professionals).

The analytical goal of this data set was to assess the topical and geographic range over which GNEII is described in the professional and academic literatures. The unit of analysis is the individual document and each was evaluated as to how and why the institute was described. As such, the larger the topical and geographic spread of references to GNEII within the professional and academic literatures—and the deeper the description or analysis of GNEII—the larger the institutional impact (to address RQ2).

Table 5. Summary Results of GNEII-Related Searches in Academic Databases

Year	Article/Chapter Title		Source
2011	A	The status of renewable energy in the GCC countries	Renewable and Sustainable Energy Reviews
	B	Models for Aspirant Civil Nuclear Energy Nations in the Middle East	Energy Security Initiative at Brookings Institute
	C	Inside a U.S. Embassy: Diplomacy at Work, The Essential Guide to the Foreign Service	Potomac Books
2012	D	Nuclear Energy in the Gulf Cooperation Council States	Security Index: A Russian Journal on International Security
	E	Going Nuclear in the GCC Countries: Rationale, Challenges, and Politics (Chapter)	The GCC Economies: Stepping up to Nuclear Challenges
	F	Energy Security: The United Arab Emirates	Asian Affairs
	G	Human Resource Development in New Nuclear Energy States: Case Studies from the Middle East	Energy Security Initiative at Brookings Institute
	H	An Assessment of the Nuclear Security Centers of Excellence	The Stanley Foundation
2013	I	The Challenge of Shale to the Post-Oil Dreams of the Arab Gulf	Energy Policy
	J	The United Arab Emirates (Chapter)	The Palgrave MacMillan Alternative Energy in the Middle East
	K	Containment Through Cooperation: A Proposal for a Nuclear Energy Agreement with Iran	James A. Baker III Institute for Public Policy
	L	Nuclear Weapons: The State of Play	Centre for Nuclear Non-Proliferation and Disarmament
2014	M	The Strategic Context of the UAE's Nuclear Project: A Model for the Region?	Middle East Policy
2015	N	Civilian Nuclear Development in the Arabian Peninsula: Prestige, Energy, and Iran	Journal of Arabian Studies
	O	The Arab Gulf States and the Knowledge Economy: Challenges and Opportunities	The Arab Gulf States Institute in Washington

2016	**P**	U.S. National Laboratory Contributions to Global Nuclear Security	Brookhaven National Laboratory
	Q	Nuclear Regulation in New Jurisdictions: The United Arab Emirates in Comparative Perspective	Presented at the Annual Meeting of the International Political Science Association
2017	**R**	A New Era for Energy: The Nightmare Gulf Scenario and Implications for Human and Environmental Security (Chapter)	Environmental Change and Human Security in Africa and the Middle East
	S	Promoting nuclear security in the Middle East	Bulletin of the Atomic Scientists
	T	On the Impact of Scientists and Engineers on Global Nuclear Security	Presented at a Federation of American Scientists event
2018	**U**	Confidence Today, Weapons of Mass Destruction Free Zone in the Middle East Tomorrow (Chapter)	Energy Transitions in the Gulf: Key Questions on Nuclear Power
2019	**V**	Mapping the Emergence of International University Research Ventures	Journal of Technology Transfer

In summary, combining the quasi-experimental *Course Evaluation Data* and *GNEII Alumni Survey Data* with the secondary *GNEII Capstone Project Data* and *GNEII-Related Literature Data* provided rich, substantial data with which to evaluate trends, findings, and insights that address our research questions.

Results

Analysis of Data Set #1: GNEII Fundamentals Course Feedback

Overall, the responses across the three evaluation categories—instructor, course material, and overall topic effectiveness—for all weekly topics in both 2011 and 2016 range from 3.8 to 4.8 and illustrate a high level of consistency in response from the Fellows. In terms of instructor effectiveness (Figure 1[A]), the data show a decrease in five topic areas (e.g., *Critical, System & 3S Thinking*), an increase in four topic areas (e.g., *Security II*) and no change in the *Nuclear Fuel Cycle History & Policy* topic area. In terms of course material effectiveness (Figure 1[B]), the data show a decrease in only three topic areas (e.g., *Nuclear Power Operations & Systems*) and an increase in seven topic areas (e.g., *Safeguards II*). Lastly, in terms of overall topic effectiveness (Figure 1[C]), the data show a decrease in the same three topic areas as the course material effectiveness, an increase in six topic areas (including the same seven topic areas as course material effectiveness except for *Security I*), and no significant change in the *Security I* topic area.

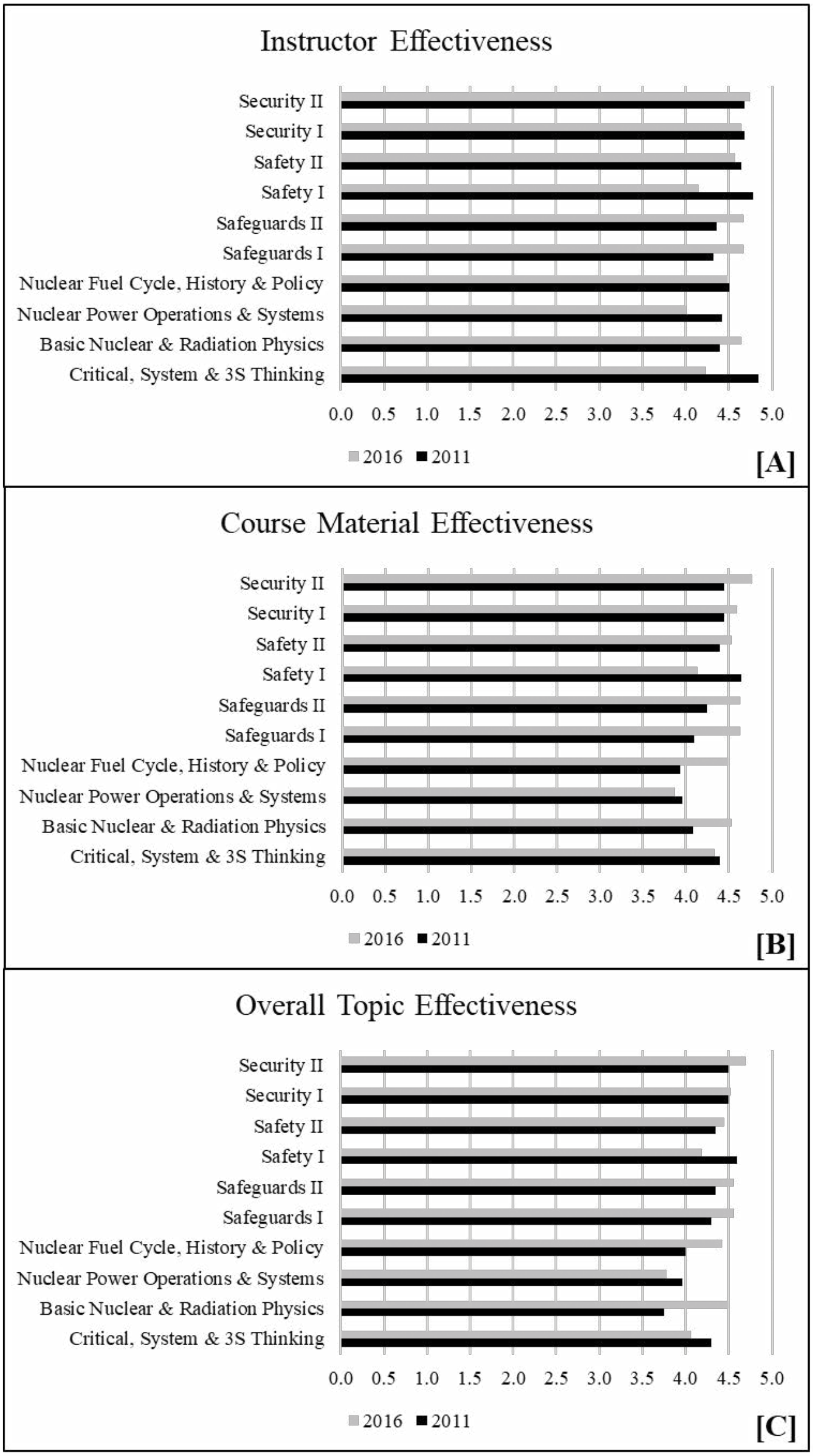
The data suggests that the Fundamentals Course instructors were able to adjust successfully to Fellow concerns despite the reported decline in five topic areas. Further, any negative influence of decreasing instructor effectiveness seemed offset by the increase in both course material and overall topic effectiveness. These trends illustrate that the multidisciplinary design of the Fundamentals Course successfully transferred knowledge across this broad set of topics and improved over time. An additional trend of note was the decrease in all three effectiveness categories for the *Critical, Systems & 3S Thinking*, *Nuclear Power Operations & Systems*, and *Safety I* weekly topics (averaging 0.35), which was inconsistent with the other trends. Though not explicitly investigated in this study, possible causes for this categorical decline in effectiveness of these topics include the increased expertise (perhaps as a result of GNEII alumni matriculating through regional nuclear energy programs) of the Fundamentals Course Fellows between 2011 and 2016.

On average, the *GNEII Fundamentals Course Feedback* data showed improvements across most of the other weekly topics for each of the three evaluation categories between 2011 and 2016. There is also an indication that course material and overall topic effectiveness can compensate for weaker instructor effectiveness—another insight suggesting success in implementing this multidisciplinary 3S curriculum to convey the wide range of complex issues facing new countries pursuing responsible nuclear energy programs. As such, these results directly address RQ1 and the improvement across all effectiveness measures from 2011 to 2016 suggests that a 3S-based curriculum can be implemented in a regional education program.

Analysis of Data Set #2: GNEII Alumni Survey Data

Comparing the responses to Q4 (level of knowledge *before* the course) and Q5 (level of knowledge *after* the course) described the increase in the level of knowledge across all topics for all years of response (Note: The response from the lone 2011 respondent was omitted because they indicated an increase from

Figure 1. Analytical Results from the Evaluation Categories for the GNEII Fundamentals Course 2011 and 2016 Weekly Topic Feedback Forms for [A] Instructor Effectiveness; [B] Course Material Effectiveness; and [C] Overall Topic Effectiveness



1 to 5 on all topics, which skewed the data representation). Figure 2 indicates the normalized change in knowledge levels for each year of the Fundamentals Course and shows that 2012, 2015, and 2016 Fellows each had at least a 50% increase across all topics. Respondents also indicated that, overall, the *Critical, System & 3S Thinking* and the *Basic Nuclear & Radiation Physics* topics both decreased in reported knowledge transfer from 2011 to 2016—which may be partially explained by an overall increase in knowledge of, or increased comfort with, these topic areas. Likewise, the *Nuclear Power Operations & Systems, Nuclear Safeguards, Nuclear Safety* and *Nuclear Security* topics all averaged an increase in reported scores between 2011 and 2016—which may be partially due to a better alignment of these topics with the GNEII stakeholder (and Fellow) needs. Lastly, the *Nuclear Fuel Cycle, History & Policy* showed the most consistent rating and the *Nuclear Safeguards* recorded the highest average.

The survey results also indicated that the Fundamentals Course at least moderately increased their understanding of nuclear security (Figure 3[A]), safety (Figure 3[B]), safeguards (Figure 3[C]) and nuclear energy 3S (Figure 3[D])—with a lone respondent indicating a minimal increase over their current knowledge of nuclear safety. These results are consistent with Figure 2, wherein the Fellows reported higher levels of positive impacts on their understanding of safeguards, safety and security from the Fundamentals Course. The consistency in these responses (55% to 72% of moderately increased knowledge of safeguards, safety, and security independently—and for the 3S collectively) indicate the success of this multidisciplinary pedagogy based on an integrated 3S approach.

Figure 4 illustrates how respondents evaluated how much they (dis)agreed with statements about the effectiveness of the 3S approach (and in particular the responsible nuclear energy program model) in helping them better understand course topics and whether or not the GNEII curriculum taught them a new way to think about this range of nuclear energy-related issues. The near identical (neutral, agree, and strongly agree) responses regarding the utility of the *integrated 3S framework* and the *responsible nuclear energy program model* (left and center charts, respectively) illustrate close alignment of the two main teaching aids for the Fundamentals Course. Lastly, the primary elements of this multidisciplinary, integrated 3S approach to nuclear energy infrastructure education all seemed to have increased the knowledge transfer for individual topics.

Figures 2-4 represent how Fellows described their knowledge transfer for key nuclear energy infrastructure development topics from GNEII's multidisciplinary, integrated 3S curriculum and pedagogical approach and support RQ1.

The remaining survey questions evaluated the impact of the knowledge gained during the GNEII Fundamentals Course outside the classroom. Figure 5 illustrates the reported relevance of each course topic to the Fellows' current job responsibilities. The average of each Fundamentals Course class, except for

Figure 2. Normalized Percentage Improvement in Level of Knowledge for GNEII Fundamentals Course Topics (from Q4 and Q5 in the GNEII Fellow survey).

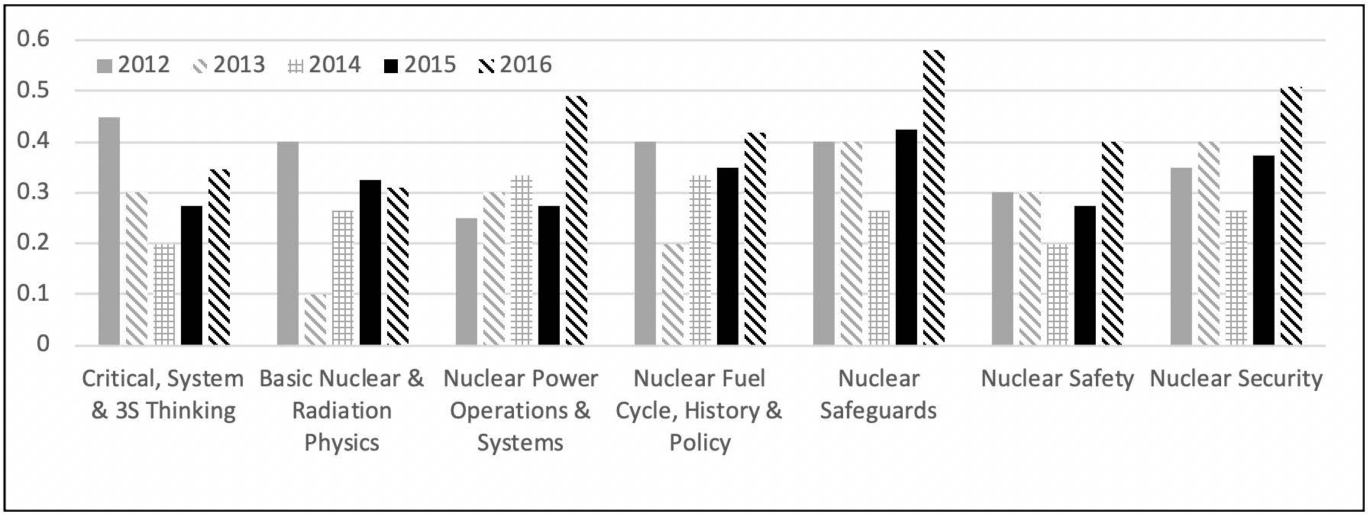


Figure 3. Description of How the GNEII Fundamentals Course Impacted the Statement 'In the GNEII Fundamentals Course, I {Minimally, Moderately, Substantially} Increased my Knowledge of Nuclear Security [A], Safety [B], Safeguards [C], and Nuclear Energy 3S' [D] (from Q7 in the GNEII Fellow Survey)

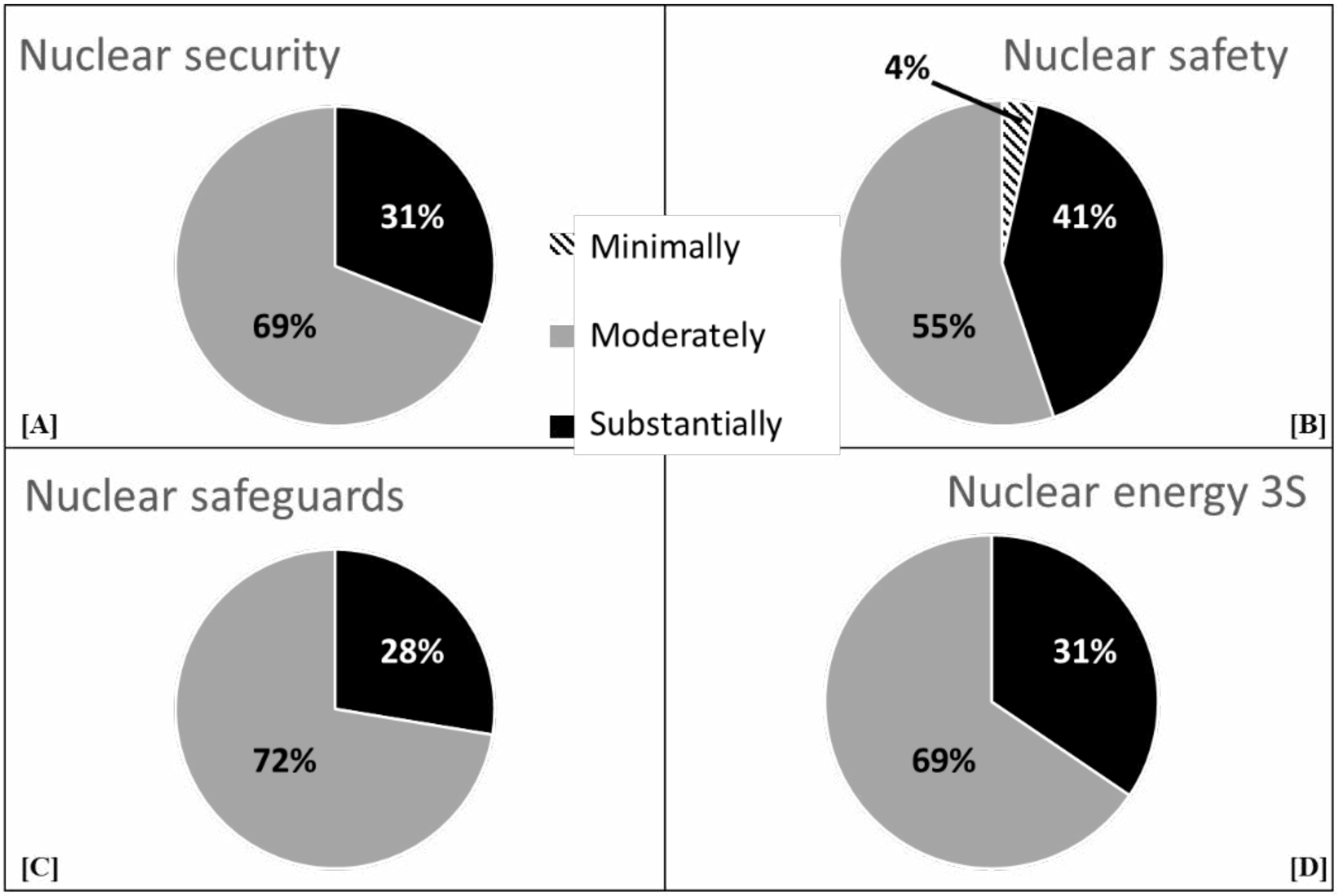


Figure 4. Description of the Relevance of the GNEII 3S Framework [A] and Responsible Nuclear Energy Program Model [B] for Understanding—and Extent to which They Provided a New Way of Thinking About [C]—Individual Fundamentals Course Topics (from Q8 in the GNEII Fellow survey)

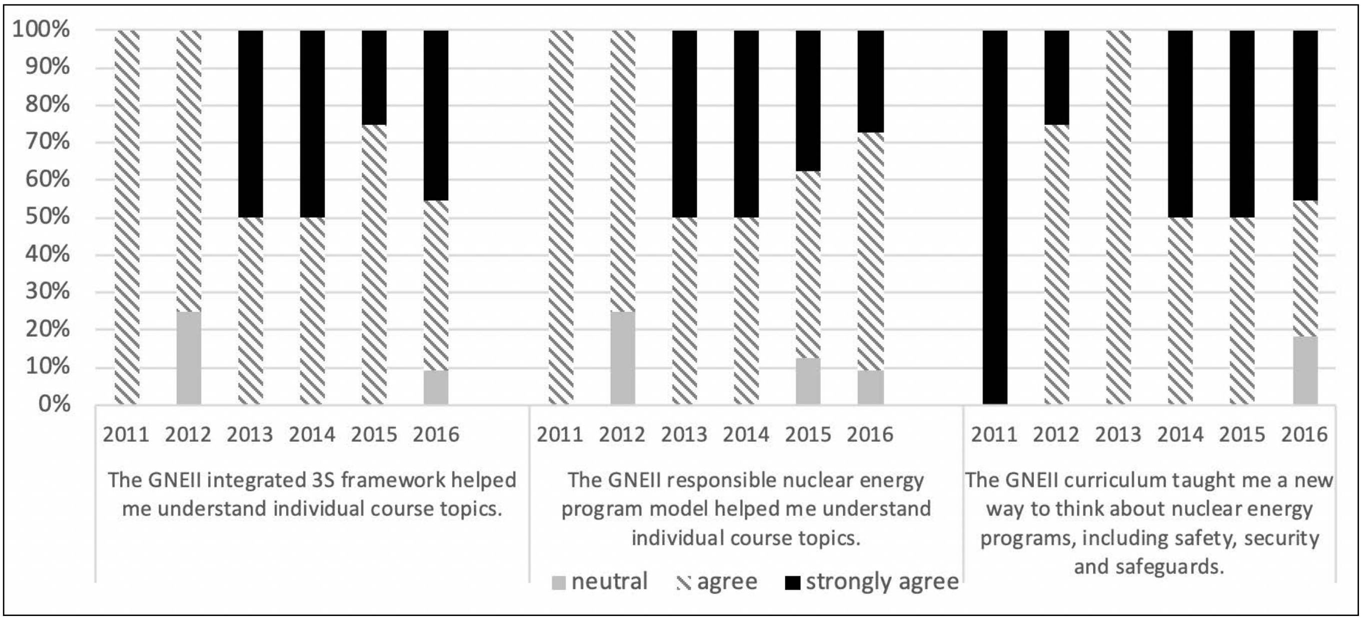
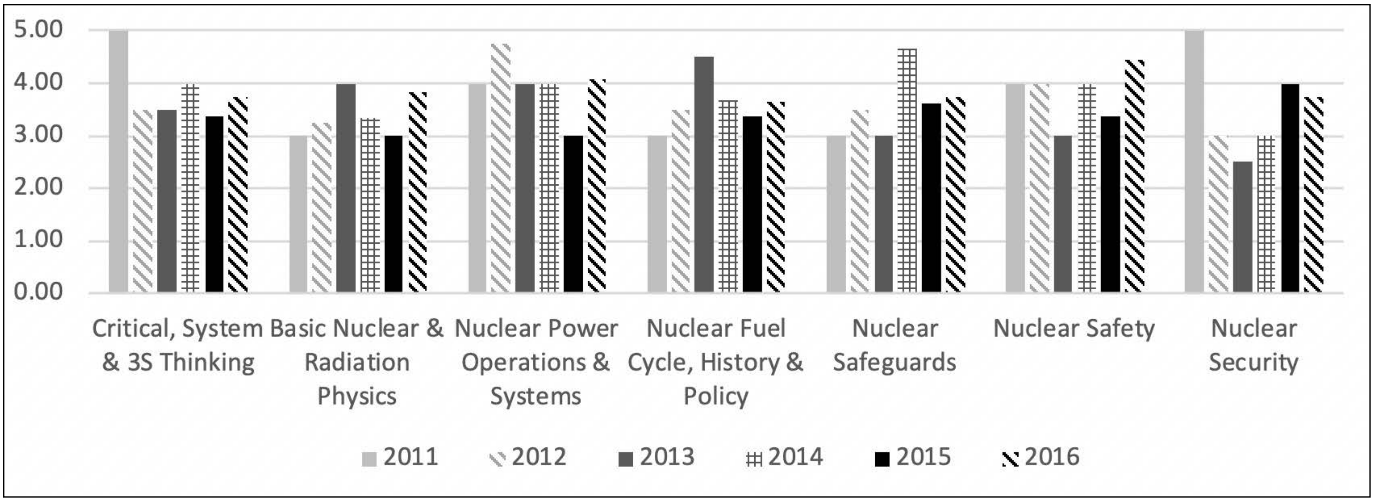


Figure 5. Description of the Relevance of the GNEII Fundamentals Course Topics to Current Job Duties of Respondents (from Q9 in the GNEII Fellow Survey)



2013, averaged at least a 3.0 for the importance of all topics. The two topics that averaged the highest reported impact were *Critical, System & 3S Thinking* and *Nuclear Power Operations & Systems*. Likewise, both the *Nuclear Fuel Cycle, History & Policy* and *Nuclear Safeguards* topics trended toward an increasing impact on job responsibilities between 2011 and 2016, while *Nuclear Security* trended toward a decreasing impact (possibly due to the separate entity for security in the UAE and the lack of interaction opportunities).

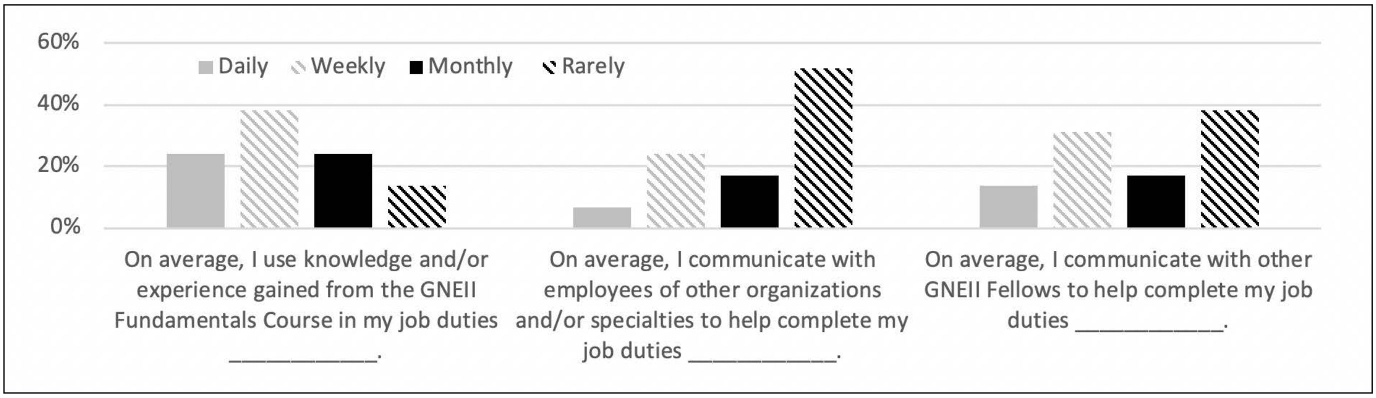
The respondents also commented on their beliefs of how the course aligned with their current professional responsibilities (Table 7) with all but one stating that the GNEII Fundamentals Course *has helped me advance in my career*—and a majority of those strongly agreeing. Similarly, and speaking to the relevance of the course topics, respondents described how the Fundamentals Course also prepared them for real nuclear energy infrastructure job responsibilities. Here, 83% at least agreed with the relevance of the Fundamentals Course to job responsibilities and 86% believed that Fundamentals Course made them better prepared.

Table 6. Description of How the Knowledge and Experiences from the GNEII Fundamentals Course Influence Current and Future Job Possibilities (from Q10 and Q12 in the GNEII Fellow Survey)

Survey Question	Degree of Agreement	Strongly Disagree	Disagree	Neutral	Agree	Strongly Agree
Q10a	HAS helped me advance in my professional career in nuclear energy	0%	3%	0%	41%	55%
Q10b	WILL help me advanced in my professional career in nuclear energy	0%	3%	3%	41%	48%
Q12a	Was relevant to my job duties	0%	0%	17%	34%	48%
Q12b	Made me better prepared to succeed at my job	0%	0%	14%	41%	45%

Lastly, respondents commented on the actual utility of the GNEII Fundamentals Course in terms of daily professional responsibilities. As summarized in Figure 6, approximately 60% of Fellows used the knowledge gained from the Fundamentals Course at least weekly (and 80% used it at least monthly). In terms of communicating across professional disciplines (and organizational stovepipes), only 50% of Fellows indicated they do so on at least a monthly basis.

Figure 6. Description of the Frequency With Which GNEII Fundamentals Course Experiences Impacts Regular Professional Duties/Tasks (from Q11 in the GNEII Fellow Survey)



Figures 5 and 6 and Table 6 illustrate the reported impact of the GNEII Fundamentals Course in the nuclear energy infrastructure professional workplace and supports RQ2 of describing GNEII's broader institutional impact.

Analysis of Data Set #3: GNEII Fundamentals Course Capstone Project Data

Reviewing the 45 Fundamentals Course Capstone Projects produced between 2011 and 2016 provided additional evidence for exploring the impact of GNEII. As shown in Table 7, there was a good spread of the Capstone Projects across GNEII's three core competency research areas.[13] Some of the Capstone projects address more than one core competency research area and were subsequently categorized in more than one area. Consider, for example, how the 2014 Capstone Project 'Evaluation of Security and Safeguards Measures for the Transportation Security in the UAE' addresses both 3S methodologies and infrastructure development (Note: This explains why there are 52 entries in Table 7 and only 45 Capstone Projects).

Table 7. Categorization of GNEII Capstone Projects by Core Research Competencies

Core Competency Research Area	2011	2012	2013	2014	2015	2016
Integrated 3S methodologies	1	1	4	4	2	3
Nuclear infrastructure development	0	6	4	4	4	3
Gulf/Middle East regional nuclear interactions	1	4	3	1	4	3

Three criteria were developed to address the breadth, depth, sustainability, and appropriateness of the Capstone Projects. The first criterion was the *technical sophistication* of the research, where weak projects did little more than match experiences or literature-based information to Fundamentals Course concepts and strong projects illustrated a deep technical understanding of the topic by identifying gaps and suggesting solutions. The second criterion was the *methodological complexity* of the research. Here, depth of understanding ranged from basic literature reviews to conducting experiments. Lastly, the third criterion was the *analytical depth* of the research. The Capstone Projects were reviewed for the types of conclusions provided, specifically searching for simple, intuitive insights or data-supported non-intuitive (and interesting!) insights. Table 8, below, shows a representative set of the Capstone Projects based on this evaluation rubric.

Table 8. Representative Set of GNEII Capstone Projects Categorized According to Three Evaluation Criteria (with Increasing Research Quality from Left to Right)

Technical Sophistication		
Basic Concept Mapping	**Technical Summaries**	**Solutions for Identified Technical Limitations**
Integrations of Safety, Security & Safeguards (2011)[a]	*Safety, Security, and Safeguards Challenges for Building a Final Repository for Spent Fuel in the UAE (2013)*[a]	*Operational Security and Information Protection in the Areas of 3S (2015)*[a]
Effects of the Environment on Nuclear Power Plant Operations (2011)[b]	*An Initial Radiation Baseline Study of Urban Environment in Abu Dhabi (2014)*[b]	*Evaluation of Cosmic-Ray Dose in the UAE (2016)*[b]
Methodological Complexity		
Basic Literature Review & Summary	**Advanced Literature Review & Identifying Gaps**	**Real Data Collection [Experiment]**
A Qualitative Assessment of Fuel Fabrication Options in the UAE (2013)	*Survey of the Current Spent Nuclear Fuel Storage Technologies & Assessing Safety Approaches of Existing Systems for Barakah Nuclear Power Plant (BNPP) (2014)*	*Measurements of radionuclides concentration in UAE cucumber (2016) [Experiment]*
SBO Roles and Mitigation Plan (2012)	*Evaluation of Threats by Drones to a Nuclear Power Plant** (2015)*	*Neutron activation of living insects for safety and security applications (2016) [Experiment]*
Analytical Depth		
Intuitive Insights	**Non-Intuitive Insights**	**Non-Intuitive Insights Supported by Data**
Filling the Gaps Between Safety and Security (2013)	*Development of Recommendations for the Nuclear Security Culture in the UAE (2014)*[c]	*Mitigation of national cultural differences effects during safety, security emergency at an NPP site (2016)*[c]
Transparency in Nuclear Security (2012)	*Safety, Security, and Safeguards Challenges for Building a Final Repository for Spent Fuel in the UAE** (2013)*	*Investigation on the Sensitivity of UAE Domestic Agricultural Production to Radiological Contamination Following a Hypothetical Severe Nuclear Accident at Barakah NPP*,** (2015)*

[a] 3S implementation as a common research thread over the course of GNEII 2011-2016 activities
[b] Environmental effects as a common research thread over the course of GNEII 2011-2016 activities
[c] Nuclear security culture as a common research thread over the course of GNEII 2011-2016 activities
*Indicates a successfully presented at a professional conference
**Indicates a project that served as a seed for follow-on, more in-depth research

The data also illustrated a few research themes that were consistent throughout institute activities between 2011 and 2016—itself an indication of increasing depth in knowledge and insights being generated from GNEII. For example, the conclusions from 2014's 'Development of Recommendations for the Nuclear Security Culture in the UAE' were incorporated into the research design and data collection of 2016's 'Mitigation of national cultural differences effects during safety, security emergency at an NPP site.' This increase in analytical depth (bottom of Table 8) resulted in deeper insights on the importance of clear communication (e.g., selecting a single language to use during emergency operations) in developing and maintaining responsible nuclear energy programs. Similar common research threads are demonstrated in the first and second row of *Technical Sophistication* in Table 8, respectively.

Lastly, several of these GNEII Capstone Projects seeded follow-on, more in-depth research efforts. For example, the 2015 'Evaluation of Threats by Drones to a Nuclear Power Plant' resulted in expanded analysis in both a graduate-level term paper[18] and a published article.[19] In addition, the Capstone Project "Investigation on the Sensitivity of UAE Domestic Agricultural Production to Radiological Contamination Following a Hypothetical Severe Nuclear Accident at Barakah NPP' (2015) spurred a presentation at the 2015 'International Conference on Energy, Water and Environmental Sciences" and a published article on natural occurring radioactive material (NORM) in date palms.[20]

Ultimately, the content analysis of the 45 GNEII Capstone Projects completed from 2011 to 2016 indicated an increased technical sophistication, methodological complexity, and analytical depth of research conducted by the Fellows. It also illustrated a broader, more nuanced set of topics covered and a non-education impact of the GNEII Fundamentals Course. As a result, the ability for Fellows to complete higher quality Capstone Projects, serves as evidence of successfully implementing a multidisciplinary, 3S regional education program (addressing RQ1). In addition, the expanding research portfolio, experience, and reputation evidenced in the data (and the follow-on research efforts) is a measure of the broader, institutional impact of GNEII (addressing RQ2).

Analysis of Data Set #4: GNEII-Related Literature Data

Summarized in Table 9 below, the results of searches through several academic databases for references to GNEII (summarized in Table 5 and labeled with bracketed letters) yielded descriptions found in eight journal articles, six book chapters, five published reports, two conference presentations, and one set of published remarks (Note: Two of the authors participated in a 2011 meeting hosted by the Brookings Institute that contributed to the GNEII reference in [B]). In addition, these references to GNEII ranged from energy resource management (Renewable and Sustainable Energy Reviews [A]), regional and energy policy (Energy Policy [I] and Journal of Arabian Studies [N]), to human capacity building (the Brookings Institute [B]). Lastly, as illustrated below, slightly more than half of these publications were produced in the United States and the remainder were produced in other countries, including Australia and Qatar.

Table 9. Summary of Analytical Results for the GNEII-Related Literature Data Set

GNEII Reference Type	U.S.-Based	Europe-Based	Other-Based [Country]	Total
Peer-Reviewed Journal Article	M, S, V	A, D, F, I	N [Qatar]	8
Book Chapter	C, E	J, R, U	L [Australia]	6
Report	B, G, H, K, O	--	--	5
Other	P*, T	--	Q* [Canada]	3
*Conference Presentation				

These GNEII descriptions included describing GNEII as "an important step" in the UAE's development of nuclear power program [F], "the latest step in creating a nuclear nonproliferation culture in the [Gulf] region" [D], helping to "distinguish [UAE] tangibly and symbolically from its neighbors through modernization, technology, and development" [N] and "develop[ing] a responsible nuclear culture and…a regional hub for the development of human resources in direct support of their own and other regional nuclear energy programs" [U]. Similarly, 5 out of the 22 references positively described GNEII's integrated 3S educational approach, including how the institute "recognizes the importance of an integrated approach to security, safety, and safeguards in the design of these 'centres of excellence'" [L] and is a multi-institution collaboration "that has produced a successful regional institute capable of indigenizing global norms and standards in nuclear energy safety, safeguards, and security" [P]. Some additional benefits attributed to GNEII in this data include: being a good example of international cooperation between the U.S. and UAE/Gulf [G, O, P]; illustrating a positive application of scientific diplomacy [C]; serving as a strong part of UAE mission to build indigenous, highly qualified nuclear energy workforce [A, B, J, T]; increasing transparency in the UAE (and promoting transparency in regional) nuclear power programs [K, S]; and, acting as a regional resource for developing nuclear power human capacity [D, M].

Overall, these 22 references to GNEII by non-affiliated authors suggests a larger institutional impact beyond improving knowledge transfer to the Fellows. In addition, the range of publication types in which the institute was referenced and the geographic spread of the publishers further support GNEII's growing institutional impact. The analysis of this GNEII-related literature data suggests that GNEII has a reputation for producing quality Fellows equipped with a strong understanding of key nuclear energy safety, security, and safeguards concepts. Further, the positive tone of these descriptions of the institute—as well as the growing topical fields using GNEII as a positive example—further indicate a growing, positive institutional impact (addressing RQ2).

Discussion

Taken together, the results of evaluating the four data sets expand upon Williams, et. al.,[21] and provide evidence that the GNEII Fundamentals Course successfully implemented a multidisciplinary, 3S curriculum in a regional education program. The *Course Evaluation data set* illustrated improvement trends in instructor, course structure, and overall topic effectiveness over GNEII activities from 2011 to 2016. Further, this data set described (near) real-time adjustments made to ensure this multidisciplinary curriculum would adequately transfer a breadth of nuclear infrastructure related knowledge. Likewise, as demonstrated in the analysis of the *GNEII Alumni Survey data set*, Fellows' responses clearly illustrate that various aspects of the Fundamentals Course pedagogy—particularly the Responsible Nuclear Energy Program model and 3S framework—yielded high levels of knowledge transfer. Lastly, the increase in quality demonstrated in the *Capstone Project data set* provides two equally plausible—and positive—outcomes. This increased quality speaks to *either* the ability of the GNEII Fellows to apply knowledge gained from Fundamentals Course to applied research topics *or* it speaks to an increased level of baseline knowledge of incoming Fellows—both of which provide new perspectives to various nuclear infrastructure development challenges.

An additional set of interesting outcomes can be gleaned from implementing the GNEII Fundamentals Course between 2011 and 2016. First, this course represented an ability to successfully provide this broad range of nuclear infrastructure development knowledge to a regional audience (e.g., Table 3). Second, because the Fellows who responded were representative of the range of occupations necessary to support responsible nuclear energy infrastructure development (e.g., utility, regulatory, security organization, other federal entities), the GNEII Fundamentals Course model seems well positioned to assist other potential nuclear newcomers building up their own nuclear energy infrastructure. Third, this evidence that supports RQ1 also speaks to the flexibility and adaptability of GNEII's pedagogical model—as demonstrated in the ability to match changing stakeholder needs. For example, these results illustrate the beneficial work of the GNEII Steering Committee—whose members are described in the Introduction (more details are provided in Williams, et. al[7]—who met annually to review and update the Fundamentals Course curriculum. Lastly, these results support the design of the Fundamentals Course as a semester-long, post-graduate, professional development program to best provide Fellows a broad overview of key topics for responsible nuclear energy infrastructure development.

Similarly, evidence across the different data sets describe the broader impact that GNEII has had *beyond* its primary goal of knowledge transfer to young and mid-career nuclear professionals from Gulf and Middle East region energy programs. More specifically, the second set of questions in the *GNEII Alumni Survey data set* provides evidence describing how the GNEII Fundamentals Course impacts the professional workplace of the Fellows in terms of increased professional capability, enhanced preparation for occupational responsibilities, providing higher performing employees, and increasing interaction across typically siloed areas of expertise. The *Capstone Project data set* illustrates GNEII's impact as an incubator for fledgling research ideas and exhibited a growing base of regional SMEs.

As a more far-reaching example, the 2016 Capstone Project investigating linguistic challenges during emergency operations at nuclear power plants resonated with high-level stakeholder representatives and generated changes in regional outreach and engagement on nuclear safety, safeguards, and security topics. In addition, the Capstone Projects themselves increased the ability to inform decisions in regional nuclear energy infrastructure development efforts—and include the Gulf-region's voice in the broader, global nuclear energy discourse. Lastly, the mere fact that GNEII is referenced at all in the publications in the *GNEII-Related Literature data set* shows a strong and growing positive reputation of the institute. In this manner, GNEII is achieving its mission of supporting the responsible use of nuclear energy locally, regionally, and globally.

This evidence supporting RQ2 provided a supplementary set of interesting insights. Here, GNEII's institutional impact is broad and varied—ranging across local (e.g., the use of the Fundamentals Course as an official step of "on-boarding" for UAE stakeholders), regional (e.g., regular requests for participation from across the greater Middle East region), and international (e.g., requests for assistance in replicating GNEII in other geographic areas) boundaries. In a similar manner, the strategic (e.g., vision and mission) and tactical (e.g., three pillars and 3S-based pedagogy) multidisciplinary design decisions led to a larger positive institutional impact than originally envisioned. Lastly, and perhaps most clearly, GNEII's institutional impact is demonstrated best in its role in KU being named as the only *IAEA Collaborating Centre for Nuclear Energy Infrastructure and Human Resource Development* (for more, please see Alameri, et. al.[22]). According to the IAEA, such collaborating centres are "scientific institutions such as laboratories, universities, research facilities, etc., that... have been designated to collaborate with the IAEA in a variety of fields, such as food safety, environmental protection, water resources, and human health." Further, the pedagogical approach and list of topics provided in the GNEII Fundamentals Course is similar to more recent IAEA initiatives—namely the Nuclear Energy Management School (launched in 2010) and newly developed International Nuclear Management Academy (launched in 2013)—aimed at providing "managerial and technical competencies that are required to support national nuclear energy strategies" and "master's programmes with specialized focus on advanced aspects of management in nuclear technology, science and engineering," respectively. This suggests that GNEII was near the head of the curve on this holistic emphasis on nuclear infrastructure development—and its ability to implement a multidisciplinary, 3S-framework based curriculum.

Yet, these results are challenged by limitations within this study. Despite the admirable 31% survey response rate, these insights may not be truly representative across all past GNEII Fellows and this limits their applicability to future Fellows. The survey itself also could have been designed to include a larger number of questions that covered additional knowledge transfer (e.g., How has the knowledge you gained in the Fundamentals Course helped in you subsequent educational or professional development endeavors?) and institutional impact (e.g., The extent to which my employer values GNEII-related knowledge or additional opportunities I pursued based on my knowledge from my GNEII experience) related questions. Likewise, the lack of additional *Course Evaluation data* (e.g., from the 2012 to 2015 classes) limits validity of the related analytical trends. Any future work to further this study should also include either surveys or interviews with representatives from regional nuclear energy program stakeholders to assess their perspective of GNEII's impact (Note:: A preliminary version of such analysis is offered in Williams, et. al.[14 but needs to be expanded).

Despite these limitations, GNEII has provided a high-performing, well-prepared cadre of early and mid-career professional to support regional nuclear energy programs; increased the quality and sophistication of its research efforts; and grown into a Gulf and Middle East regional hub for addressing nuclear infrastructure and human capacity development needs. Sustainability and future plans are in development and will include crafting a modularized academic program accredited by federal UAE authorities; expanding collaborative research projects with institute stakeholders; and, growing the institute's ability to provide technical services to meet short term, targeted needs by regional nuclear energy stakeholders. Similarly, longer-term sustainability efforts will focus on benchmarking GNEII's new modular technical degree curriculum with IAEA best practices and supporting KU in building new research capabilities to leverage recent national Emirati interested (and financial support) in research in specific technical areas.

Conclusions

GNEII demonstrates one option for successfully providing a multidisciplinary 3S curriculum in support of broader nuclear infrastructure development aims. As such, other initiatives could leverage the key lessons learned during GNEII's activities from 2011 to 2016, including (but not limited to): (1) appropriately scope the length of the program to adequately cover the breadth of necessary multidisciplinary topics; (2) include a version of the capstone requirement (as multidiscipline capstone projects result in more useful, evidence-based solutions to complex problems[23]); (3) develop and use a systems thinking-based carry-through framework or model; (4) appreciate (and actively seek) the complexity of geopolitical and professional diversity in the course participants; (5) leverage a wide range of subject matter experts; and, (6) the fundamental utility of a faculty coordinator to provide an anchor of stability throughout—and thread of consistency across multidisciplinary topics in—such a course. The results of this study (indicating the successful implementation of a multidisciplinary education program preparing young professionals to operate responsible nuclear energy programs) also support the claim that mixed methods approaches can be used to evaluate education programs that emphasize the importance of systems thinking to create socially responsible and technically prepared graduates to meet the challenges of a complex, global society.[24]

Though just one piece of a much larger, multi-faceted, multi-national, and loosely coordinated effort to develop the needed human infrastructure for nascent nuclear energy programs throughout the world, GNEII's activities between 2011 and 2016 illustrate significant local, regional, and global impacts. Locally, GNEII has advanced the UAE's quest to become a leader in responsible nuclear infrastructure development in the region. Regionally, the institute provided an enhanced, localized understanding of responsible nuclear energy programs (including safety, safeguards, and security obligations) more conveniently located than commonly used alternatives in Europe or the United States. Globally, GNEII gives the nuclear infrastructure development community a model for an education and research-based institute that addresses the "critical role of the curriculum in promoting interdisciplinary habits of mind and action in building multidisciplinary competence"[25, p. 90] across nuclear energy safety, safeguards and security in regional contexts to improve both infrastructure and human capacity development. Finally, GNEII has proven capable of developing an internationally-knowledgeable, regional cadre of nuclear professionals who can engage with their peer groups to analyze and develop more useful solutions for complex safety, security, and safeguards challenges to global nuclear energy expansion.

Keywords

Multidisciplinary education, Nuclear infrastructure development, Nuclear human resource development, Nuclear safety, Nuclear security, Nuclear safeguards, 3S education

Note: This paper is a revised and expanded version of a paper entitled *Evaluating the Educational Impact of the Gulf Nuclear Energy Infrastructure Institute (GNEII)'s Novel 3S Approach* presented at the 58th Annual Meeting of the Institute for Nuclear Materials Management in Indian Wells, CA, USA on July 16-20, 2017.

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Effect of Water Gap and Fuel Assembly Positioning in Passive Neutron Albedo Reactivity Measurements for Spent Fuel Encapsulation Safeguards

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Abstract

The Passive Neutron Albedo Reactivity (PNAR) Ratio is proportional to the net neutron multiplication of a spent fuel assembly. In the planned integrated non-destructive assay instrument for Finnish encapsulation safeguards, a PNAR instrument is used to confirm the presence of fissile material. In this study, the sensitivity of fuel-type-specific PNAR Ratio measurements to the size of the water channel of the instrument is determined using MCNP5 Monte Carlo simulations. Based on the study results, use of the smallest possible water channel is recommended to maximize the dynamic range of the instrument. In the Finnish fuel encapsulation context, this means using water gap sizes of 5 mm and 3 mm for measurements of boiling water reactor (BWR) and water-water energetic reactor (VVER-440) fuel, respectively. Based on the neutron emission rates of the Finnish spent fuel inventory, we recommend maximizing count rates by having detectors all around the fuel assembly, i.e., 4 detectors for BWR fuel and 6 detectors for VVER-440 fuel. With these water gap sizes, and neutron detectors all around the fuel assembly, the variation of the PNAR Ratio measurement caused by the uncertainty on the position of the fuel in the instrument is estimated to be 0.06% for BWR fuel and 0.13% for VVER-440 fuel.

Introduction

The Passive Neutron Albedo Reactivity (PNAR) concept has been developed to measure the neutron multiplication of nuclear fissile materials.[1-4, 7-9, 11, 14, 15] To meet the recommendations given to the International Atomic Energy Agency (IAEA) in the “Application of Safeguards to Geological Repositories (ASTOR) Report on Technologies Potentially Useful for Safeguarding Geological Repositories,” the integrated non-destructive assay (NDA) instrument designed for repository-related safeguards measurements in Finland is expected to incorporate a PNAR system.[5] The purpose of the NDA instrument is to determine, by a set of measurements, whether a fuel assembly is compliant with its declaration. The primary metric measured by a PNAR instrument is the PNAR Ratio, which is proportional to the multiplication of the measured fuel assembly.[11] The PNAR Ratio is calculated in the context of spent fuel by taking the ratio of the neutron count rate measured when the assembly is in a high-multiplying setup to the count rate when the assembly is in a low-multiplying setup. In the high-multiplying configuration, the nuclear fuel is surrounded by hydrogen-rich material (such as polyethylene or water). This maximizes the flux of thermal neutrons back-scattered to the assembly. The measured PNAR Ratio will be compared to a simulated value. A difference between expected (i.e., simulated) and measured PNAR Ratio values can be caused by two main factors:

- deviation of the actual fissile material content from declared values due to uncertainties in the initial assembly characterization and details of reactor exploitation or due to diversion of fissile material;
- uncertainties associated with the PNAR instrument.

In the Finnish instrument design, the high-multiplying configuration is achieved by measuring the fuel while underwater in a cooling pool. In the low-multiplying configuration, the back-scattered flux of thermal neutrons is suppressed by using a material that is an efficient thermal neutron absorber. In the Finnish conceptual PNAR design, a liner made out of cadmium is positioned underwater, close to the fuel, to create the low-multiplying configuration. The fuel is in a fixed position for the measurements, while the Cd-liner moves up and down along the assembly to create the high- and low-multiplying configurations. In the absence of fissile material, the PNAR Ratio is close to 1; a PNAR Ratio above 1 is due to neutrons created by fission induced by thermal neutrons present in the high-multiplying configuration that are absorbed by the Cd-liner in the low-multiplying configuration. Thus, the PNAR concept can be thought of as interrogating the spent nuclear fuel assembly with thermal neutrons emitted at the location of the Cd-liner. In studying the design parameters of the PNAR instrument, provided the intrinsic detection efficiency is the same for both PNAR configurations, the higher the PNAR Ratio value obtained for a chosen reference assembly, the wider the dynamic range of the instrument. This in turn means that the instrument can better resolve deviations of the fissile material content from the declared content.

As the PNAR Ratio is proportional to the multiplication of a given assembly, it is necessary to calibrate the instrument. In the encapsulation/repository context, the context of interest of this publication, it is anticipated that approximately 100 assemblies will be measured as part of the instrument characterization process. The PNAR instrument will provide a comparison of the multiplication among all these assemblies. Furthermore, because the initial conditions of each assembly as well as the reactor history are known, the multiplication can be calculated for each assembly. In this manner, a connection between the measured PNAR Ratio and the calculated multiplication of each assembly is obtained.

Because the goal of reactor operators is to optimally extract the inherent nuclear potential energy in each assembly, most assemblies being measured at an encapsulation facility will have nearly the same multiplication; a multiplication value that indicates that the fissile material is still present in the assembly. For this reason, another useful application for the PNAR Ratio to regulators may be in a "threshold mode" by which the following logic is applied: if a PNAR Ratio is measured below a given value (selected based upon the measurement performed as part of the characterization process), then a notice/alarm is given the regulator.

PNAR Instrument Design

For the PNAR Ratio, the water gap between the Cd-liner and the fuel impacts how much the Cd-liner can alter the multiplication of the fuel. The position of the fuel assembly within the central measurement channel of the PNAR device is a source of uncertainty in the determination of the PNAR Ratio because this position affects the water gap. The present study characterizes these two effects via Monte Carlo simulations with MCNP5.[10]

The geometry of the PNAR instrument should be adapted to the geometry of each fuel type. Reactors currently active in Finland use either square boiling water reactor (BWR) fuel or hexagonal water-water energetic reactor (VVER-440) fuel (pressurized water reactor fuel will be used in the Olkiluoto 3 reactor). The PNAR instruments to be developed for Finland are expected to operate underwater, but spent BWR fuel is stored in fresh water while spent VVER-440 fuel is stored in boron-doped water at a concentration of 14±1 g of boric acid per kg of water.

The geometry of the conceptual BWR-specific PNAR instrument is shown in Figure 1. The key features of the geometry are introduced below.

- ^{3}He tubes: 17.4 mm in diameter and a fill pressure of 6 atm. The tubes are placed in the horizontal plane perpendicular to the fuel assembly. The maximum active length of 200 mm is divided into five segments in order to study the effect of detector length.
- Lead shielding, needed to reduce the gamma dose to the ^{3}He tubes, which is 52 mm thick at its thickest.
- Cadmium is located around the detectors and in the Cd-liner surrounding the fuel; Cd was included in the detector in order to preferentially detect high energy neutrons from the fuel as this was shown by Lee, et. al.[1] to more uniformly sample neutrons spatially from the fuel. All Cd layers are 1 mm thick; the Cd-liner is 0.74 m long.
- Four detector units, each housing one detector (D1-D4) on each side of the assembly to reduce the sensitivity to anisotropy in the assembly burnup. To accommodate the size of the detector units, the detectors are placed at two closely located vertical levels, with a 100 mm vertical offset (D1and D2 form the bottom layer while D3 and D4 form the top layer).

The VVER-440-specific PNAR instrument, shown in Figure 2, has the same features as the BWR-specific one, except that it has six ^{3}He tubes, reflecting the hexagonal geometry of the fuel. The active length of each tube is 100 mm. Detectors D2, D4, D6 form the top detector layer while detectors D1, D3, D5 make up the bottom detector layer. An additional large volume of polyethylene, 0.74 m long, surrounds the fuel assembly. This polyethylene displaces the borated water, ensuring sufficient multiplication power in the high-multiplying configuration of the PNAR instrument.

The Radiation and Nuclear Safety Authority of Finland decided that the NDA system to be used for encapsulation safeguards should have a measurement time of, at most, 5 minutes.[6]

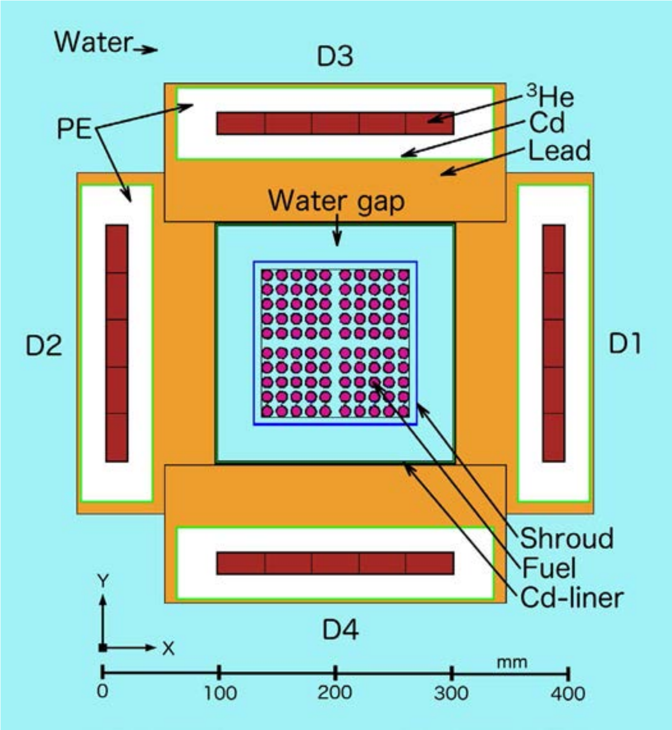

Figure 1. Top View of the BWR-Specific PNAR Instrument with a 10x10 BWR Fuel Assembly in the Measurement Channel

A water gap of 30 mm, the largest water gap used in this study, is present around the fuel. The drawing is to scale. The ^{3}He tubes surround the fuel assembly on all four sides and are located in two horizontal (X,Y) planes with a 100 mm vertical (Z) offset (D3 and D4 above D1 and D2 in this top view). The ^{3}He tubes are divided into five segments in order to study the effect of detector length.

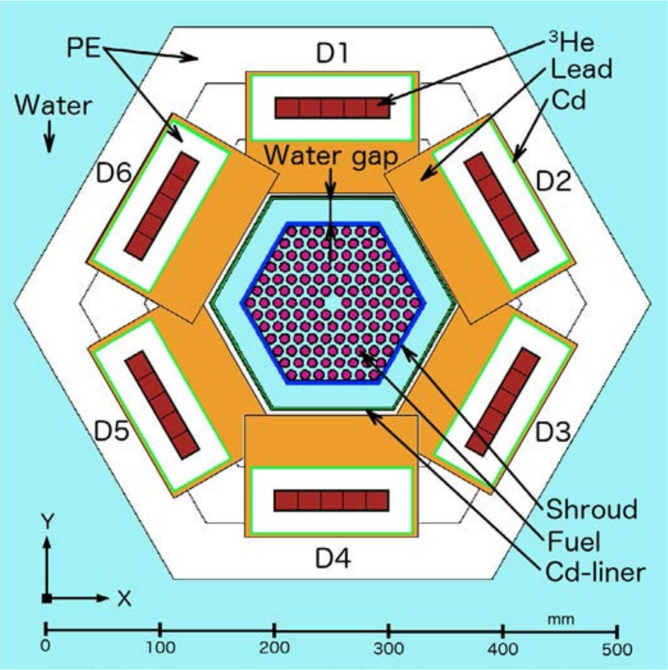

Figure 2. The Horizontal (XY Plane) Cross-Sectional View of the VVER-440-Specific PNAR Instrument with a VVER-440 Assembly in the Measurement Channel

A water gap of 20 mm, the largest water gap used in this study, is present around the fuel. The drawing is to scale. The ^{3}He tubes surround the fuel assembly on all six sides and are located at two different vertical levels with a 100 mm Z-axis offset.

Subsequently, the PNAR measurement process is planned to consist of two 2-minute measurements (with/without Cd-liner) with a 1-minute intermission to move the Cd-liner in or out of the active instrument region. The count rates for the fuel expected to be measured at the Finnish encapsulation facility with the PNAR instrument are expected to vary roughly between 800 counts/s and 200,000 counts/s for the combined count rate of the four detectors. This range was estimated between a 17 GWd/tU, 60 year cooled assembly and a 55 GWD/tU, 20 years cooled assembly, respectively.[11] For the particularly low neutron emitting assemblies, the counting duration is expected to be increased.

Monte Carlo Simulations

Measurements of the PNAR Ratio were simulated using the Monte Carlo N-Particle Code Version 5 (MCNP5 V1.40) with 0.60c cross sections libraries.[10] The isotopic mixture of the spent fuel assemblies was produced by the Monteburns code as part of the Next Generation Safeguards Initiative (NGSI).[12-14] For the same burnup, initial enrichment and cooling time, the isotopic mix will vary between PWR fuel considered in the NGSI and BWR and VVER fuel considered here. However, these differences are not expected to have a significant impact on the PNAR design characteristics of interest in this publication. Two typical isotopic compositions, available from the NGSI, were used:

- initial enrichment 3 wt.%, burnup 30 GWd/tU, cooling time 20 years (IE=3, BU=30, CT=20)
- initial enrichment 4 wt.%, burnup 45 GWd/tU, cooling time 20 years (IE=4, BU=45, CT=20)

Within the isotopic mixtures available from the NSGI, these are equivalent to near fully burnt assemblies with parameters that most closely match the typical Finnish fuel. Note that the PNAR Ratio is not very sensitive to variation in the cooling time within the range of interest for this study (20-60 years).[11] Considering neutron attenuation and scattering in the setups under study, only a 1.2 m long section of the fuel assembly is simulated, as neutrons generated outside of this section do not contribute to the PNAR signal.

As VVER-440 fuel has only a 3% greater mass per unit length compared to 10×10 BWR fuel, both fuel types are expected to have a very similar neutron emission rate.

For each PNAR Ratio, two independently-seeded simulation runs of 1×10^9 initial neutrons are performed, one with and one without the Cd-liner. Any additional neutrons produced in the simulation, such as those resulting from induced fission, are followed through until they are absorbed or leave the simulated volume. The output of a simulation run is the probability per source neutron of a neutron being absorbed in a given detector, with its associated statistical uncertainty (MCNP tally F4). The count rate is calculated by the product of the detection probability per source neutron times the number of source neutrons emitted per second by the fuel section simulated.

Simulation parameters for water gap and assembly position

To estimate the effect of the size of the water gap, the PNAR Ratio was simulated with increasing water gap size, while keeping the assembly in the center of the instrument's measurement channel. For BWR fuel, the water gap size varied from 5 mm to 30 mm while for VVER-440 fuel, the water gap size varied from 3 mm to 20 mm.

The uncertainty due to fuel positioning will depend on how well the crane positions the assembly inside the PNAR instrument's measurement channel as well as on how bent the assembly is. For a deployed system, the PNAR operator will likely want to remeasure several assemblies several times to quantify the PNAR uncertainty due to positioning. In the current study, we investigate this uncertainty by simulating the following displacement scenarios:

- center - the assembly is in the center of the instrument's measurement channel with an equal water gap on all sides
- side - the assembly is centered against one of the walls of the measurement channel
- corner - the assembly is positioned in a corner of the measurement channel

Figures 3 and 4 show how these scenarios are simulated for BWR and VVER-440 fuel, respectively.

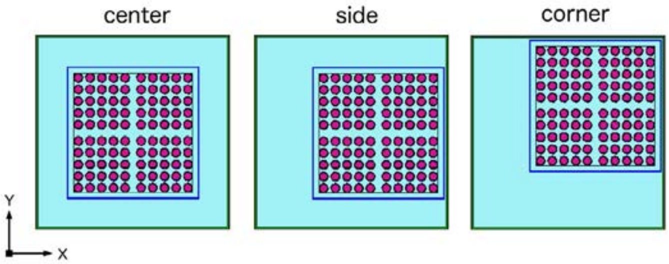

Figure 3. Horizontal (XY Plane) Cross-Sectional View of the Three Simulated Positions of the 10×10 BWR Fuel Assembly Inside the PNAR Instrument's Measurement Channel for a 30 mm Water Gap

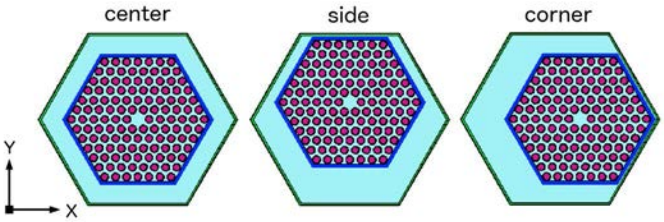

Figure 4. Horizontal (XY Plane) Cross-Sectional View of the Three Simulated Positions of the VVER-440 Fuel Assembly Inside the PNAR Instrument's Measurement Channel for a 20 mm Water Gap

BWR Fuel Results

Figure 5 shows the PNAR Ratio as a function of the water gap for BWR fuel in the center of the PNAR instrument. The water gap size affects the multiplication conditions for both the high- and low-multiplying configuration, and thus the neutron count rates. With a thicker water gap, the neutrons emitted by the fuel have a higher probability to thermalize, back-scatter, and induce fission in the assembly, enhancing multiplication and increasing the neutron flux from the assembly towards the detectors. A thicker water gap reduces the ability of the Cd-liner to affect the thermal neutron flux reflecting back into the fuel in the low-multiplying configuration as more neutrons leaving the fuel reflect back into the fuel before they reach the Cd-liner. On the other hand, with a thicker water gap, the neutron flux reaching the detectors contains a larger fraction of thermalized neutrons, reducing the fraction of neutrons detected (thermal neutrons are absorbed by the Cd surrounding the detectors). Our simulations show that the combination of the above factors results in a neutron count rate which decreases with increasing water gap for both the high- and low-multiplying configurations, as illustrated in Figure 6, but the neutron count rate decreases faster in the high-multiplying configuration. As a result, the PNAR Ratio decreases with increasing water gap. The difference between the PNAR Ratio measurement with a 5 mm water gap and 1.0, the PNAR Ratio value for an idealized non-multiplying assembly, will be used as the reference value for the dynamic range of the instrument in discussing the BWR simulation results. This dynamic range will vary depending on the assembly selected. The assembly selected for the comparative analysis in this paper is approximately a fully irradiated assembly, which is similar to the vast majority of fuel being measured at an encapsulation facility.

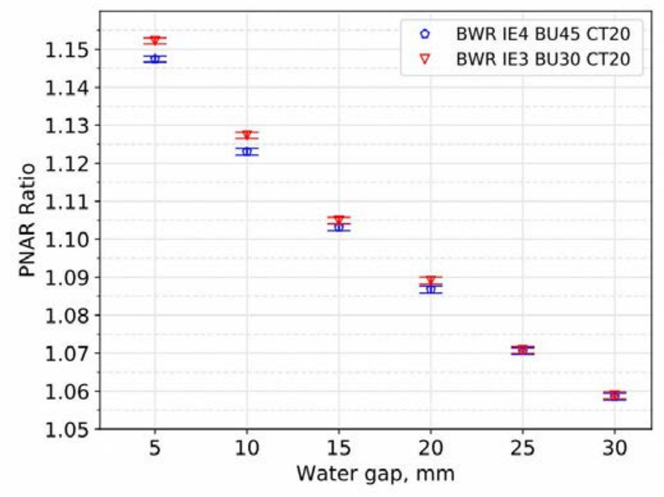

Figure 5. The PNAR Ratio for the BWR Fuel-Specific PNAR Instrument in Fresh Water as a Function of the Size of the Water Gap Around Fuel Assemblies with IE=4, BU=45, CT=20, and IE=3, BU=30, CT=20

The error bars indicate the standard deviation due to statistics in the simulations.

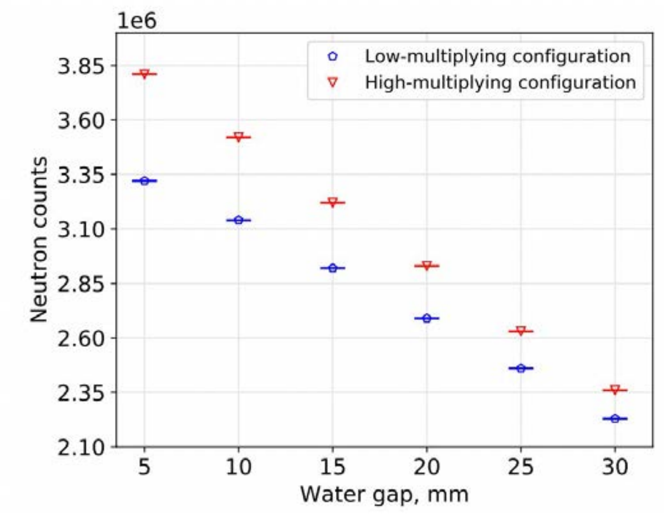

Figure 6. Simulated Neutron Counts as a Function of the Size of the Water Gap for the High- and Low-Multiplying Configurations

The simulations were done for a fuel assembly with IE=4, BU=45, CT=20. The neutron sample size is 1x10^{9}.

The PNAR Ratio with a 5-mm water gap is 1.1475±0.0008 for fuel with 4 wt.% initial enrichment and 1.1522±0.0008 for fuel with 3 wt.% initial enrichment. The uncertainties given are for MCNP statistics only. When the water gap is increased to 20 mm, the PNAR Ratio values become 1.0868±0.0009 and 1.0892±0.0009 for fuel with 4 wt.% and 3 wt.% initial enrichment, respectively. The dynamic range of the PNAR instrument decreases by ~40% in the case of a 20-mm water gap relative to the case of a 5-mm water gap. Further increase of the water gap size up to 30mm leads to a ~60% reduction of the dynamic range.

As the simulated PNAR Ratios for the two fuel assemblies are very close, and closely follow the same trend, we chose to simulate only the fuel with parameters IE=4, BU=45, CT=20 for the rest of the study. These parameters match most closely the characteristics of typical Finnish spent nuclear fuel.

Figure 7 shows the PNAR Ratio for fuel with IE=4, BU=45, CT=20 located at the three different positions shown in Figure 3. The water gap size is 5 mm. The PNAR Ratios labeled "T" are obtained by summing the signals from all four detectors into a "total" PNAR Ratio, while the values associated with the D1-D4 labels represent PNAR Ratios obtained for each individual detector. For each situation, three active detector lengths were simulated: 40, 120, and the full length of 200 mm. The active length is centered on each side of the instrument. As expected, a longer active detector length improves the statistics of the simulation. Shorter active detector lengths do not affect the PNAR Ratio value when the fuel is in the center or side position. However, in the corner position, the PNAR Ratio shows a small decreasing trend with decreasing active detector length.

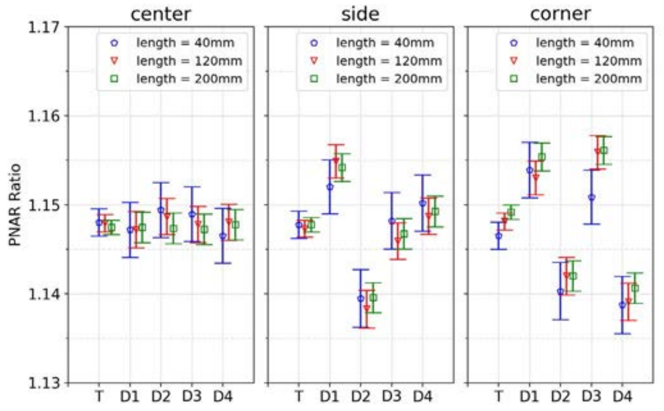

Figure 7. The BWR PNAR Ratio for a 5-mm Water Gap as a Function of the Active Detector Length and Fuel Assembly Positioning Inside the PNAR Instrument's Measurement Channel

D1-D4 refer to the individual detectors and T to the sum of all detectors. The error bars indicate the standard deviation due to statistics in the simulations.

With fuel in the center position, the PNAR Ratio values from individual detectors are within 1-sigma deviation (relative deviation of ±0.07%) of the total value. The statistical uncertainty for 120 mm and 40 mm detector sections increases up to ±0.09% and ±0.13%, respectively.

In the other two positions, individual detector measurements show large differences, consistent with the geometry of the measurement. In the side position, the detector closest to the assembly (D1) measures the largest PNAR Ratio. Detectors D3 and D4 are located in symmetric positions relative to the fuel and have comparable PNAR Ratio values. Detector D2 measures the lowest PNAR Ratio because the water gap between the fuel and the Cd-liner is widest on its side. The same logic explains the pattern of PNAR Ratio values when the fuel is in the corner position. In the central and side positions, the total PNAR Ratio values are very close (1.1475 and 1.1478, respectively, with equal absolute uncertainty of ±0.0008). In the corner fuel position, the total PNAR Ratio value is slightly higher (1.1492±0.0008). The PNAR Ratio variation due to the fuel assembly position becomes more pronounced as the water gap size increases, as can be seen in Figure 8. The difference in total PNAR Ratio values between the center and corner fuel positions for the 15-mm water gap case is 0.0206±0.0013.

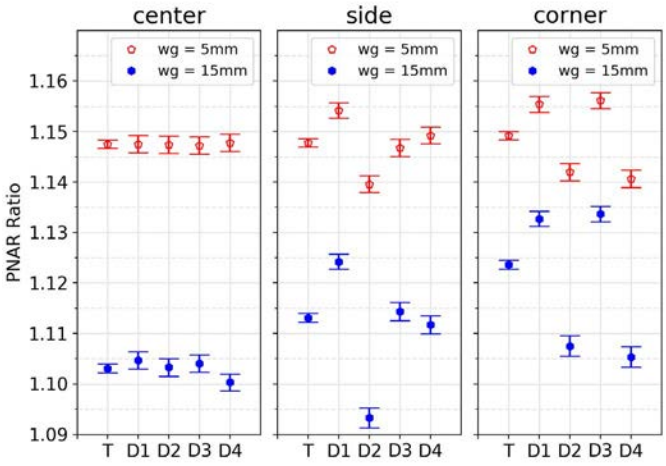

Figure 8. The BWR PNAR Ratio for 5- and 15-mm Water Gaps as a Function of Fuel Assembly Position Inside the PNAR Instrument's Measurement Channel

D1-D4 refer to the individual detectors and T to the sum of all detectors. A 200mm active detector length is used. The error bars indicate the standard deviation due to statistics in the simulations.

A summary of the PNAR Ratios obtained for the BWR fuel assembly with IE=4, BU=45, CT=20 as a function of water gap size and fuel position is shown in Table 1. The PNAR Ratios are given for full length detectors (200mm). The systematic uncertainty on the PNAR Ratio caused by the uncertainty on the fuel assembly position in the water channel is estimated as the average deviation of the PNAR Ratios of the three positions. Note that this estimation is very approximate and a conservative value as the side and corner positions are extreme situations. An accurate quantification of the uncertainty will need to be done experimentally by repeatedly remeasuring assemblies. For the 5-mm water gap case, the average PNAR Ratio is 1.1481 with an average deviation of 0.0007. For the 15-mm thick water gap case, the average PNAR Ratio is 1.1133 with a standard deviation of 0.0069. For the 5-mm water gap, the size of the systematic uncertainty estimate is approximately equal to the Monte Carlo statistical uncertainty on each simulated PNAR Ratio. For the 15-mm water gap case, the estimate of the systematic uncertainty due to fuel positioning is eight times larger than the Monte Carlo statistical uncertainty, making the estimate insensitive to our simulation statistics.

VVER fuel results

Figure 9 shows the PNAR Ratio as a function of water gap size for VVER-440 fuel with 3 wt.% and 4 wt.% initial enrichment in the center of the VVER-440-specific PNAR instrument. A water gap size from 3 mm to 20 mm is considered. The strong impact of boron-enriched water on the PNAR Ratio results in a substantial dynamic range reduction for the VVER-440-specific instrument.[15] The difference between the PNAR Ratio measurement with a 3-mm water gap and PNAR Ratio value 1.0 is used as the reference value for the dynamic range of the VVER-440-specific instrument. This dynamic range will vary depending on the assembly selected. The assembly selected for the comparative analysis in this paper is approximately a fully irradiated assembly, which is similar to the vast majority of fuel being measured at an encapsulation facility. The dynamic range is reduced by 77% for the VVER-440-specific instrument when the water gap increases from 3 mm to 20 mm. For a 5-mm water gap, the VVER PNAR Ratio shows a reduction of the dynamic range of 0.053 or 36% relative to the BWR case. As the PNAR Ratios observed for the two simulated fuel types match closely at all water gap sizes, all further results are shown only for fuel with IE=4, BU=45, and CT=20.

Table 1. The PNAR Ratios for BWR Fuel (IE=4, BU=45, CT=20) with Statistical Uncertainties for 5- and 15-mm Water Gaps as a Function of Fuel Assembly Position Inside the PNAR Instrument and Detector Selection

D1-D4 refer to the individual detectors and Total to the sum of all detectors.

Water gap (mm)	Detector	Center		Side		Corner	
		PNAR Ratio	Uncertainty absolute/relative(%)	PNAR Ratio	Uncertainty absolute/relative(%)	PNAR Ratio	Uncertainty absolute/ relative(%)
5	**Total**	**1.1475**	**0.0008/0.07**	**1.1478**	**0.0008/0.07**	**1.1492**	**0.0008/0.07**
	D1	1.1475	0.0017/0.15	1.1542	0.0016/0.13	1.1554	0.0016/0.13
	D2	1.1474	0.0017/0.15	1.1396	0.0017/0.15	1.1420	0.0017/0.15
	D3	1.1472	0.0017/0.15	1.1467	0.0017/0.15	1.1561	0.0016/0.13
	D4	1.1478	0.0017/0.15	1.1492	0.0017/0.15	1.1407	0.0017/0.15
15	**Total**	**1.1031**	**0.0009/0.08**	**1.1131**	**0.0009/0.08**	**1.1237**	**0.0009/0.08**
	D1	1.1047	0.0017/0.16	1.1242	0.0015/0.13	1.1327	0.0015/0.13
	D2	1.1033	0.0017/0.16	1.0933	0.0020/0.18	1.1075	0.0020/0.18
	D3	1.1040	0.0017/0.16	1.1143	0.0018/0.16	1.1337	0.0015/0.13
	D4	1.1003	0.0017/0.16	1.11178	0.0018/0.16	1.1053	0.0020/0.18

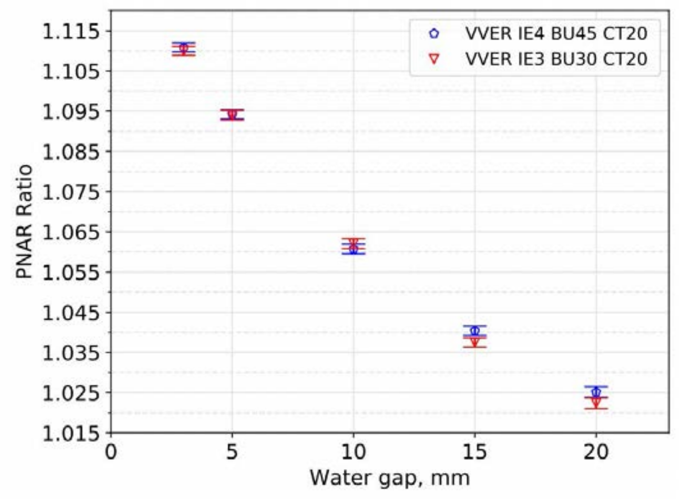

Figure 9. The PNAR Ratio for the VVER-440 Fuel-Specific Instrument in Borated Water as a Function of Water Gap Size Around Fuel Assemblies with IE=4, BU=45, CT=20 and IE=3, BU=30, CT=20

The error bars indicate the standard deviation due to statistics in the simulations.

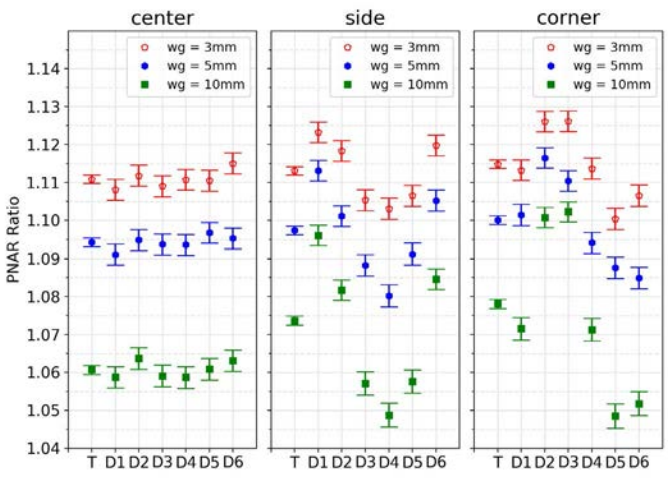

Figure 10. The VVER-440 PNAR Ratio for Water Gap sizes of 3 mm, 5 mm, and 10 mm for the Three Fuel Assembly Positions Inside the PNAR Instrument's Measurement Channel

D1-D6 refer to the individual detectors and T to the sum of all detectors. The error bars indicate the standard deviation due to statistics in the simulations.

Figure 10 shows the VVER-440 PNAR Ratio for water gap sizes of 3 mm, 5 mm, and 10 mm for the three fuel assembly positions. The PNAR Ratio from individual detectors follows the geometry of the fuel displacement scenarios as expected. The detectors closest to the fuel (D1 for the side position, D2 and D3 for the corner position) measure the highest PNAR Ratio values while the detectors farthest from the fuel (D4 for the side position, D5 and D6 for the corner position) measure the lowest PNAR Ratio values. With the fuel in the center position, the PNAR Ratios for individual detectors are identical within statistical uncertainty. The presence of borated water increases the statistical uncertainty on the PNAR Ratio determinations. The spread (difference between maximum and minimum values) of the PNAR Ratio values between detectors reaches 0.047 and 0.054 for side and corner positions, respectively, when the water gap is 10 mm.

Table 2 summarizes the PNAR Ratio values for the VVER-440-specific PNAR instrument, for a fuel assembly with IE=4, BU=45, CT=20 for varying water gap size and fuel position. The average total PNAR Ratio for the center, side and corner positions when the water gap is 3 mm, 5 mm, and 10 mm is, respectively, 1.1129, 1.0972 and 1.0708. The average deviations are, respectively, 0.0014, 0.0020 and 0.0068. Note that, as the side and corner positions are extreme situations, these average deviations are an approximate and conservative estimate of the systematic uncertainty due to the fuel assembly position. An accurate quantification of the uncertainty will need to be done experimentally by repeatedly remeasuring assemblies. As in the case of BWR, the fuel displacement effect is well-pronounced; it exceeds the 1-sigma simulation statistical uncertainty for the 10-mm water gap by a factor of 6.

Table 2. The PNAR Ratios for VVER-440 Fuel (IE=4, BU=45, CT=20) with Statistical Uncertainties for 3 mm, 5 mm, and 10 mm Water Gaps as a Function of Fuel Assembly Positioning Inside the PNAR Instrument and Detector Selection

D1-D6 refer to the individual detectors and Total to the sum of all detectors.

Water gap (mm)	Detector	Center		Side		Corner	
		PNAR Ratio	Uncertainty absolute/relative(%)	PNAR Ratio	Uncertainty absolute/relative(%)	PNAR Ratio	Uncertainty absolute/relative(%)
3	**Total**	**1.1109**	**0.0011/0.10**	**1.1131**	**0.0011/0.10**	**1.1148**	**0.0011/0.10**
	D1	1.1080	0.0027/0.25	1.1232	0.0027/0.24	1.1132	0.0028/0.25
	D2	1.1118	0.0027/0.25	1.1184	0.0027/0.24	1.1261	0.0027/0.24
	D3	1.1090	0.0027/0.25	1.1054	0.0027/0.25	1.1262	0.0027/0.24
	D4	1.1107	0.0027/0.25	1.1031	0.0028/0.25	1.1137	0.0028/0.25
	D5	1.1105	0.0027/0.25	1.1065	0.0027/0.25	1.1004	0.0028/0.26
	D6	1.1150	0.0028/0.25	1.1198	0.0027/0.24	1.1066	0.0028/0.25
5	**Total**	**1.0942**	**0.0012/0.11**	**1.0974**	**0.0012/0.11**	**1.1001**	**0.0012/0.11**
	D1	1.0911	0.0027/0.25	1.1131	0.0027/0.24	1.1014	0.0028/0.26
	D2	1.0948	0.0027/0.25	1.1012	0.0027/0.25	1.1165	0.0027/0.24
	D3	1.0937	0.0027/0.25	1.0883	0.0028/0.26	1.1104	0.0027/0.24
	D4	1.0936	0.0027/0.25	1.0803	0.0029/0.27	1.0941	0.0027/0.25
	D5	1.0967	0.0027/0.25	1.0912	0.0029/0.26	1.0877	0.0028/0.26
	D6	1.0953	0.0027/0.25	1.1052	0.0027/0.25	1.0849	0.0028/0.26
10	**Total**	**1.0607**	**0.0012/0.11**	**1.0737**	**0.0012/0.11**	**1.0781**	**0.0012/0.11**
	D1	1.0588	0.0028/0.27	1.0961	0.0026/0.24	1.0715	0.0030/0.28
	D2	1.0637	0.0029/0.27	1.0817	0.0027/0.25	1.1007	0.0026/0.24
	D3	1.0591	0.0028/0.27	1.0571	0.0031/0.29	1.1023	0.0026/0.24
	D4	1.0587	0.0028/0.27	1.0487	0.0032/0.30	1.0713	0.0030/0.28
	D5	1.0609	0.0028/0.27	1.0576	0.0031/0.29	1.0485	0.0032/0.30
	D6	1.0631	0.0029/0.27	1.0847	0.0027/0.25	1.0518	0.0032/0.30

Tobin, et al. investigate the uncertainty in the PNAR Ratio due to a variation in boron content of 14±1 g per kg of water.[15] For a fuel assembly with 4 wt% initial enrichment, 45 GWd/tU burnup and 20 years cooling time in the center of the PNAR instrument with a water gap of 3.4 mm, the 1-sigma uncertainty on the PNAR Ratio is 0.4%. This is three times larger than the 0.13% uncertainty derived from the results in Table 2 for the same fuel assembly parameters but for a water gap of 3 mm. Therefore, in the case of VVER-440 fuel in borated water, the boron content will need to be constant to better than about 0.2 g per kg of water for the uncertainty on the PNAR Ratio due to variations in boron content to be negligible in comparison with the uncertainty due to variations in positioning. An accurate measurement of the boron content will thus be needed.

Discussion and Some Practical Considerations

The purpose of this simulation study is to support design choices concerning the water gap between the spent fuel and the Cd-liner of a PNAR instrument. Increasing the water gap decreases the PNAR Ratio measured for a given assembly (Figures 5 and 9), thus reducing the dynamic range and the sensitivity to detect an anomaly in the amount of fissile material. Additionally, a larger gap leaves more room for fuel positioning variation, increasing the uncertainty related to this variation (Figures 8 and 10 and Tables 1 and 2). The safety of fuel manipulation operations for safeguards measurements determines the minimum water gap that is practically possible. The smallest water gap sizes simulated in this work (5mm for BWR fuel and 3 mm for VVER-440 fuel) correspond to the size of the spent fuel racks used in Finland. As these water gap sizes have thus proven to be practical from an operational point of view, we recommend using the same values for the PNAR instrument.

Most simulations were performed for BWR and VVER-440 fuel assemblies with 4 wt.% initial enrichment, 45 GWd/tU burnup and 20-year cooling time. The VVER and BWR had an estimated neutron emission rate of 7.9×10^6 n/s for the 1.2 m long fuel assembly simulated, and 2×10^7 n/s for a full-length assembly. As this source strength is in the numerator and denominator of the PNAR Ratio, it does not impact the PNAR Ratio magnitude but it does impact the counting statistics.[12] This neutron emission rate is at the high end of what is expected in the Finnish encapsulation scenario, with a ratio of neutron emission rate of 255 for the strongest to weakest fuel assemblies to be encapsulated.[11]

Having neutron detectors symmetrically all around the fuel assembly mitigates the uncertainty due to position variation, as is demonstrated by the results shown in Figures 8 and 10 and Tables 1 and 2. Having detectors all around the fuel assembly increases in importance when the water gap size increases. For the small water gap size recommended based on the present results, having detectors all around the fuel assembly may not be necessary to mitigate the variation due to fuel positioning, as this variation will not dominate the total uncertainty of the measurement.

To reduce cost and complexity, one can design PNAR instrument variants with fewer detectors. To preserve robustness against fuel positioning uncertainty, we consider that half of the detectors are symmetrically removed for both fuel-type-specific instruments. In this few-detector design, for BWR fuel, the PNAR Ratio changes by 0.0001 for fuel in the central and corner positions and 0.0003 for the side position. For VVER-440 fuel, the PNAR Ratio changes by 0.001 for the side and corner positions and 0.002 for the center position. The absolute statistical uncertainty on the total PNAR Ratio increases from 0.0008 to 0.0012 for BWR and from 0.0011 to 0.0016 for VVER-440 cases, which is consistent with the factor 2 reduction in statistics due to the removal of half of the detectors. The effect on the PNAR Ratios is smaller than the simulated sample size statistical uncertainty for BWR fuel and similar to the simulated sample size statistical uncertainty for VVER-440 fuel.

A PNAR instrument that does not have detectors on all sides is less costly and complex. However, while the performance of the few-detector PNAR instrument variants is comparable to that of the instrument designs with detectors on all sides considered in this work, they cannot be recommended for two practical reasons: they are vulnerable to detector failures and unfavorable for long-cooled fuel. If a single detector malfunctions in the few-detector design, the PNAR Ratio measurement becomes unreliable, whereas with detectors on all sides the remaining detectors provide a reliable PNAR Ratio measurement. With a factor 255 difference between the highest and lowest expected neutron count rates within the Finnish spent fuel inventory, the use of the full set of 4, resp. 6, detectors for the BWR, resp. VVER-440, in the PNAR instrument is also recommended to best maintain good measurement statistics. The statistical uncertainty on the PNAR Ratio can also be reduced by longer measurement times. However, a discussion of this is beyond the scope of the present work. Nonetheless, expected neutron count rates will need to be considered when establishing detailed measurement protocols for the range of fuel characteristics that will be encountered in practice.

Conclusions

The PNAR technique is planned to be part of the integrated NDA system for encapsulation safeguards in Finland. With it the neutron multiplication of a spent fuel assembly can be measured, and the declared fissile material content of spent nuclear fuel verified. A PNAR instrument prototype is under development. Certain design choices are made based on the results of Monte Carlo simulations. In this work, MCNP5 simulations were used to study the effect on the PNAR Ratio of the size of the water gap between the spent fuel and the Cd-liner of the PNAR instrument. They also provided an estimate of the effect of the uncertainty associated with the positioning of the fuel inside the instrument's measurement channel. BWR fuel in fresh water and VVER-440 fuel in borated water were investigated. A small water gap is recommended as it provides a larger PNAR Ratio dynamic range and a smaller uncertainty due to fuel positioning variations. We recommend using the same water gap sizes as present in the spent fuel racks used in Finland: 5 mm for BWR fuel and 3 mm for VVER-440 fuel. With these water gap sizes, and detectors all around the fuel assembly, the variation of the PNAR Ratio measurement caused by the uncertainty on the position of the fuel in the instrument is estimated to be 0.06% and 0.13%.

The statistical uncertainty of our simulations is better than will typically be the case in the Finnish context.[11, 15] It is thus recommended to maximize count rates by having detectors all around the fuel assembly as in the simulated conceptual design: 4 detectors for BWR fuel and 6 detectors for VVER-440 fuel. Such a detector configuration also minimizes the sensitivity of the PNAR Ratio to the fuel position.

Acknowledgments

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Keywords: non-destructive assay, PNAR, nuclear fuel, MCNP simulation

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Taking the Long View in a Time of Great Uncertainty

Scenario Planning in the Age of COVID-19

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

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"*It was a surreal feeling. There were almost no other cars on the road, and it was rush hour. I would be home in 15 minutes instead of the 45 minutes, or longer, that it usually takes. My mind wandered to the eerie settings in some of the science-fiction movies I remember about life after an Armageddon event. But this was real. As an 'essential worker' I am allowed to be out on the road because of my work in national security programs. I never thought that I would crave for more people to be around me and for traffic to be much heavier. But given the 'Stay-at-Home' order by the government, those are 'luxuries' that no longer exist. This is not a world that I was prepared for.*"

This is not a story plucked out of a future nightmare scenario development, but one that I live with every day as I write this column in the new age of COVID-19. Analogies in the media have been made to 9/11, Pearl Harbor, and nuclear incidents (Three Mile Island, Chernobyl, and Fukushima). But this is different–it is a global, rapid change in societal norms, a frightening lesson in how economies and supply chains operate, and such a long-lived, significant event that it may forever change the mindsets of world leaders and the general public.

The potential impact on INMM is significant–will recovery occur quickly enough that our 2020 Annual Meeting, originally schedued to take place in Baltimore, Maryland in July, still be well-attended in its new online, digital form? Will an effective vaccine be developed in time that our long-planned, first International Annual Meeting in Vienna in August of 2021 will still be possible and well-attended? Even more importantly, how will nuclear facilities and their supporting contractors, both here in the United States and abroad, weather this storm successfully without another catastrophic "event"? What will be the changes necessary to emergency plans for those facilities, and will the public express more concern about what happens to those facilities when such an event occurs? Will the global community recover economically to continue new scientific and engineering discoveries? Will this event reinvigorate investment in the "inherently safe" new generation of nuclear power technologies? Will the new "Zoom generation" change the standard for face-to-face meetings?

There are a lot of unanswered questions.

Scenario Planning in the Age of COVID-19

In previous Taking the Long View columns, I have talked about the power of scenario planning to stretch the mindsets of management and policy makers, enabling them to visualize the "unthinkable" and have discussions about those futures so that they are better prepared.[1] One of the most striking examples of how scenario planning can change the world is the story told by Peter Schwartz, former CEO of Global Business Network, about how his company helped create a set of scenario stories for South Africa that facilitated the demise of apartheid.[2]

As we look at the impact of the COVID-19 pandemic on our future, it is instructive to recall several of the *Taking the Long View* columns over the past decade as they addressed future world scenarios in the context of "things nuclear," and extrapolate from these examples how scenario planning can be used to help in the new age of COVID-19. These include:

- *Jekowski J. 2010. Taking the Long View in a Time of Great Uncertainty. JNMM, 39(1), 39-41.* In this first *Taking the Long View* column, scenario planning is identified as a "strategic planning tool that has been more widely used in the [United States] federal government since the tragic events of September 11, 2001….developing the insight and perspectives to take a long view of the future even when faced with great uncertainties by 'connecting the dots.'" Recognition is given to Peter Schwartz, the author of the seminal work "The Art of the Long View" and former CEO of the Global Business Network, for bringing scenario planning into perspective as a tool to examine paths to the future for both private sector organizations and government.
- *Jekowski J. 2011. Taking the Long View in a Time of Great Uncertainty: Preparing for Social Chain*

Reactions. JNMM, 39(3), 28-29. In this column, I introduced the idea of "wildcards," events that change the game, such as the events in Tunisia and Egypt that led to the "Arab Spring." In a reference in that article on anticipating strategic surprises, Peter Schwartz and others were quoted as saying, "We live in a world of surprises…Why is the inevitable so often surprising? Many people blame a failure of imagination…but it does not get us closer to a solution…The point is that imagining things is the easy part. What is hard is imagining future scenarios that are sufficiently believable to spur one to act in advance and find ways to persuade others to act…Strategic surprises, therefore, are those patterns of events that, if they were to occur, would make a big difference to the future, force decisionmakers to challenge their own assumptions of how the world works, and require hard choices today." I also introduced a series of questions on "things nuclear" to stimulate strategic discussions among the Institute's membership on "critical uncertainties"–a term or art used in scenario planning. Some of those questions were subsequently reshaped to engage the INMM membership's technical expertise directly, based on input from Jim Larrimore.

- *Jekowski J. 2011. Taking the Long View in a Time of Great Uncertainty: A Strategic Inflection Point?–The Nuclear Crisis in Japan. JNMM, Vol. 39, No. 4, pp. 23-24.* On the heels of the Fukushima Daiichi nuclear incident as a result of a magnitude 9.0 earthquake and tsunami, this column speculated on the influence that a strategic inflection point, or wild card, would have on what was being called the "nuclear renaissance."[3]
- *Jekowski J. 2013. Taking the Long View in a Time of Great Uncertainty: Working Toward Solutions. JNMM, Vol. 42, No. 1, pp. 61-63.* This column discussed the significant world events occurring at the time (social turmoil in the Middle East, and the Iran and North Korea nuclear programs), and reflected on the power of scenario planning to help prepare organizations for any eventuality. The column also reflected on discussions with Jim Larrimore and the INMM's International Safeguards Division about how to construct the challenges being posed internationally in these columns to better engage the knowledge and experience of our members to resolve these issues.
- *Jekowski J. 2014. Taking the Long View in a Time of Great Uncertainty: Bumps in the Road. JNMM, Vol. 42, No. 2, pp. 35-37.* In this column, we explore the relationship of the term "bumps in the road" (as they pertained to the drop in Annual Meeting attendees due to the U.S. OPM decision on government travel) to the more commonly used terms in scenario planning of "critical uncertainties" and "wild cards."
- *Jekowski J. 2014. Taking the Long View in a Time of Great Uncertainty: Reflecting on the Health of the INMM. JNMM, Vol. 42, No. 3, pp. 71-74.* In this column, we update the "externalities" or critical uncertainties in the world impacting the mission of the INMM. This list has subsequently been updated and included in the tri-annual Executive Committee reports from the Strategic Planning Committee (SPC) to stimulate those discussions among the INMM leadership team.
- *Jekowski J. 2015. Taking the Long View in a Time of Great Uncertainty: A World Full of Critical Uncertainties. JNMM, Vol. 44, No. 1, pp. 37-39.* In this column, I discuss the real-time events that occurred during the 56th Annual Meeting associated with the Iran Joint Comprehensive Plan of Action (JCPOA) that was signed on the Tuesday morning of our meeting. The outcome of those historic diplomatic discussions was a critical uncertainty in our Institute's strategic discussions, and it was proposed in the column that the actual implementation and viability of the agreement was a critical uncertainty going forward, particularly with respect to the impending United States presidential election in 2016. In this column, I also introduce the concept developed by Peter Schwartz of constructing an orthogonal set of axes using the two most distinctly different and impactful critical uncertainties to create a landscape for four distinct and challenging worlds (stories of the future) that could be developed to engage management in strategic discussions.
- *Jekowski J. 2016. Taking the Long View in a Time of Great Uncertainty: Sometimes Life Seems Too Complicated. JNMM, Vol. 44, No. 2, pp. 86-88.* In this column, I use current events and critical uncertainties developed in small group discussions I had with members of the SPC and the EC to begin to develop a set of scenario axes that might be useful to the INMM: The

Advancement of Nuclear Technologies and Global Nuclear Security Threats. These axes would then be used to create four "future world" quadrants that would form the basis for a set of scenarios for the Institute. This four-quadrant scenario model, originally proposed by Peter Schwartz, is particularly attractive to scientists and engineers (the orthogonal construct) and provides a simplified framework for discussions that enables leadership to equate current events as they happen to the future world stories.

- *Jekowski J. 2016. Taking the Long View in a Time of Great Uncertainty: Rehearsing Possible Futures. JNMM, Vol. 44, No. 3, pp. 58-61.* This column further develops the scenario axes created in the previous issue and discusses the process from which these would lead to the creation of future world stories.
- *Jekowski J. 2016. Taking the Long View in a Time of Great Uncertainty: Preparing for the Future. JNMM, Vol. 45, No. 1, pp. 51-53.* This column presented the new INMM Strategic Plan that was revealed at the 57th Annual Meeting and discussed current events that had occurred under each of the axes defined in a previous JNMM issue.
- *Jekowski J. 2017. Taking the Long View in a Time of Great Uncertainty: "That Will Never Happen"–The Power of Scenario Planning. JNMM, Vol. 45, No. 2, pp. 36-40.* This lengthy column explored the power of scenario planning in the context of two discontinuity events–the approval of the Brexit vote in Great Britain, and the election of Donald Trump as President. Both events were generally considered "unthinkable," triggering a flag that is used in scenario planning of "that will never happen"–an indicator of a future path that will stretch the imagination of leaders. In that column, I also speculate on a few "that will never happen" topics, many of which have come about.
- *Jekowski J. 2017. Taking the Long View in a Time of Great Uncertainty: Winds of Change. JNMM, Vol. 45, No. 3, pp. 35-37.* In this column, I use the example of early actions taken by the new U.S. Administration to "connect the dots" in expectation of major changes in the U.S. Nuclear Security Enterprise (NSE), including the possibility of a stronger role for the Department of Defense in the NSE. Although this path to the future has not materialized yet, we have seen similar, seemingly "improbable actions" taken by the current United States administration with the creation of the new Space Force, the sixth branch of the U.S. Military.[4]

Scenario Implications for the COVID-19 Pandemic

The human race has been dealt a wild card with the COVID-19 pandemic. If one had speculated in a scenario story the events of just the first four months of 2020, the response would have been, "That will never happen." The long-term impact of the global shut down has far reaching consequences on many issues that the INMM is engaged in–not the least of which include:

- maintaining the continuity of verification of the peaceful use of nuclear energy by the IAEA under safeguards agreements with states, and of IAEA verification under the UN Security Council mandate of how Iran is meeting its obligations under the JCPOA.[5] Will the pandemic cause an increased investment in remote monitoring technologies and systems to better cope with potential future interruptions?
- the modernization of nuclear stockpiles, particularly those in the Unites States where the nation relies on very large national laboratories and production facilities to accomplish those requirements, as well as activities associated with other national security programs such as those in the Defense Nuclear Nonproliferation program that rely so extensively on international travel. Will there be an increased investment in secure teleconferencing systems?
- the cleanup work conducted by the U.S. Department of Energy (DOE) and other international organizations–work that requires physical on-site presence and interactions. Will contractors be expected to take on greater risks for potential shutdowns or will insurance companies change the definition (and costs of insurance) for "work interruptions?"
- the response of the U.S. DOE and other nuclear facilities to "beyond design basis" threats as identified by the Defense Nuclear Facilities Safety Board (DNFSB), and the response to a similar rule issued to U.S. Nuclear Power Plants (NPPs) by the Nuclear Regulatory Commission (NRC) in August of 2019.[6] Globally, the impact of COVID-19 will cause a re-examination of operational processes and procedures under catastrophic event scenarios.

Other Cataclysmic Events to Challenge the Mindset of Leaders

With the shock of the COVID-19 still reverberating worldwide, many have asked the question–what about all the other socio-economic cataclysmic events that people have been talking about? How are we preparing for those? Some of these include:

- A global cybersecurity attack that brings down computer systems worldwide for a significant period of time.
- A cataclysmic lower earth orbit (LEO) event (either intentional or unintentional) that takes out a large portion of orbiting satellites, disabling global communications and national security systems.[7]
- An incident at a nuclear fuel rod storage pond, particularly one in the densely-populated Eastern United States.
- A nuclear war, or even a small nuclear exchange, creating a global climatic change.
- A large asteroid strike on earth.
- A coronal mass ejection impacting worldwide electrical systems.
- Global climate change–whether man-made or natural.

Let's select just one of these–a personal nightmare scenario of mine: the issue of the safety/security of nuclear spent fuel storage ponds, and the (unlikely?) possibility of a breach of one of those ponds, whether accidental or intentional, at an NPP on the East Coast of the United States. One can only imagine the socio-economic disruption that might occur with the resultant release of radioactivity that could impact millions of lives for many years. One can assume that after such an event the question would be asked, "Why didn't we do something to address this issue before the incident?" One answer might be that leadership did not create a plausible enough scenario story of the events that could lead to such a disaster in order to muster the public and policy support necessary to address it. People said, "That will never happen." Some fingers will be pointed at the political decisions impacting the Yucca Mountain project while hundreds of billions of dollars could be spent in the cleanup, as we have seen in the response to the Fukushima event.

A similar story could be told for each of these events–however, as a country (and a world) we seem to be more willing to invest tens or hundreds of times more resources after a cataclysmic event to fix everything rather than invest a much smaller amount that might have been needed to avoid it…such is the nature of our world today.

Where Do We Go from Here?

The ripple effects of the COVID-19 pandemic will be significant across the world. As researchers and scholars unpack events leading up to the spread of the virus, including the many studies and warnings that were developed over at least a decade prior to the outbreak, questions that will be asked are, "Why didn't we do something to prepare for this?" And, "Why didn't we 'connect the dots?'"

The stories created by scenario planning have the power to change the mindsets of leaders, but more importantly must be put into a form that stirs the interest of the public and creates the urgency for policy makers and governments to act.

Such is the world that we are facing in the second decade of the new millennium, with a new realization of how fragile the environment is that we live in, and how interdependent we all are on one another.

This column is intended to serve as a forum to present and discuss current strategic issues impacting the Institute of Nuclear Materials Management in the furtherance of its mission. The views expressed by the author are not necessarily endorsed by the Institute but are intended to stimulate and encourage JNMM readers to actively participate in strategic discussions. Please provide your thoughts and ideas to the Institute's leadership on these and other issues of importance. With your feedback, we hope to create an environment of open dialogue, addressing the critical uncertainties that lie ahead for the world and to identify the possible paths to the future based on those uncertainties that can be influenced by the Institute. Jack Jekowski can be contacted at jpjekowski@aol.com.

Endnotes

1. In materials developed by the author based on studies with Peter Schwartz, former CEO of the Global Business Network, some descriptions of "What Scenarios Are" include: "A modern day hearth for people to gather around and talk about what might be;" "A way for managers to say 'I am prepared for whatever happens;'" "A tool to make better decisions about the future;" "A way to suspend disbelief in possible futures;" "Stories that are filed by the mind as a memory that can be drawn upon later;" and "Ways to cause managers to ask, 'In this world what should we do, what could we do, what will we do?'"
2. See https://www.foresightfordevelopment.org/sobipro/55/768-the-mont-fleur-scenarios, or https://reospartners.com/publications/the-mont-fleur-scenarios/ (14-4-2020) for a discussion of the Mount Fleur scenarios that were developed to help facilitate the move from apartheid to democracy in South Africa in 1991-1992.

3. Jekowski J. 2011. "Taking the Long View in a Time of Great Uncertainty, *Focusing on the Nuclear Fuel Cycle*," JNMM, Vol. 39, No. 2, pp. 29-31.
4. See https://www.npr.org/2019/12/21/790492010/trump-created-the-space-force-heres-what-it-will-do (4-14-2020)
5. See https://www.iaea.org/newscenter/multimedia/videos/safeguarding-nuclear-material-during-corona-crisis (4-14-2020). The IAEA Director General Rafael Grossi has recently stated: "Safeguarding nuclear material all over the world will not stop for a single minute. IAEA nuclear inspectors are still hard at work despite the partial closure of their headquarters in Austria and other countries. Despite some travel disruptions, the inspectors continue to visit sites while complying with all local health regulations. And the nuclear watchdog has ways of monitoring nuclear material and activities remotely. This includes obtaining images from satellites and hundreds of special cameras in nuclear facilities the world over. Nuclear material is also locked with a unique Agency seal. Some of these are electronic and can be monitored long distance. So, the IAEA can continue its vital mission to ensure that nuclear material is not diverted from peaceful use."
6. The DNFSB in 2014 urged DOE to improve its ability to respond to natural and human-made emergencies at its national network of nuclear sites, resulting in the issuance of a new Emergency Management Directive, DOE O 151.1D, *Emergency Management* in August of 2018. Subsequently, the U.S. Nuclear Regulatory Commission in August of 2019 issued a new rule on the Mitigation of Beyond-Design-Basis Events, see https://www.federalregister.gov/documents/2019/08/09/2019-16600/mitigation-of-beyond-design-basis-events
7. See https://www.c4isrnet.com/battlefield-tech/space/2020/03/29/countries-keep-investing-in-weapons-to-take-out-satellites/ (4-16-2020)

Book Review

By Mark L. Maiello, PhD
Book Review Editor

Bargaining Over the Bomb

By William Spaniel
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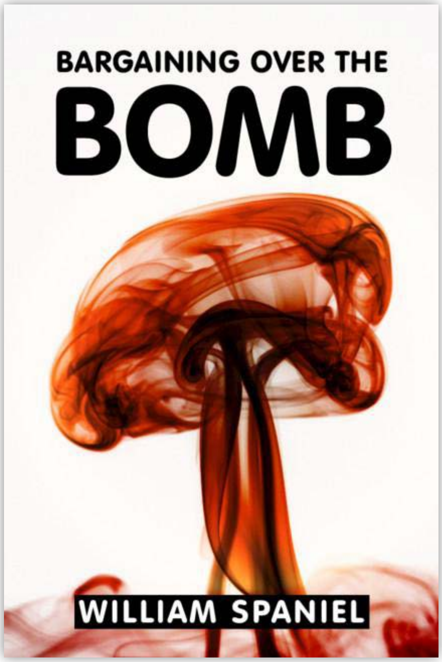

This is a read for the mathematically inclined amongst us. Those who code for a living or do so for fun will be wading into somewhat familiar territory. The balance of the book will be exploring a new horizon. Because it was derived from the author's doctoral thesis, many efforts were made to make this book more accessible. However, in some sections, the text still reads much like a dissertation with blunt statements, with an assumption that the reader has some precursor knowledge and familiarity with the terminology specific to game theory. That said, one can punch through it, and not without some gain for the sweat involved.

The question of this research is, Can diplomacy forestall potential proliferators from attempting to build a nuclear weapon? Game theory, as applied to nuclear proliferation, is the tool of the book: Where and what are the tipping points of nuclear war? What are the triggers for this decision? How can they be analyzed? One way is to computer-model the outcome (proliferation, war, or resignation to the non-proliferation regime) by assigning values to the variables that lead to the decisions of potential adversaries. These variables include the high cost of warfare weighed against the high cost of a nuclear weapons development program. The reader is taken through many such modeled scenarios, beginning with the simplest: Can the potential proliferator be bought off with inducements? What is "enough butter" to offset the bombs from being built?

The author moves on to the concept of nuclear proficiency–the ability to build bombs. The unrealized capability to proliferate (the intimidation factor) is shown to be as important for acquiring "concessions for weapons" as is possessing the bomb. The chapter that follows on successful diplomacy is a review of recent events, such as the denuclearization of the Soviet successor states (Belarus, Kazakhstan, and Ukraine). A section on Egypt and the Camp David Accords is included, as is a look at the United States' Cold War allies Japan, Australia, and South Korea. In all cases, these nations were persuaded to cease proliferation. The cost to the United States–troop deployments and security guarantees–was minimal. However, states without a big brother to protect them must bargain with rivals, a less palatable situation that makes negotiations less likely to succeed (the United States falls into this category).

As the chapters progress other variables are introduced, such as the concept of "war exhaustion," a factor that indicates the lack of will of an adversary to stop proliferation via military action after it has emerged from a war-time footing. This applied to the post-World War II period when proliferation was a concern of a war-weary United States. Will a war-tired nation make a concerted effort to stop a potential proliferator by force of arms? That did not happen with the Soviet Union because preventative war against Stalin was out of the question for the Allies, at least in the short term. United States intelligence concerning the location of Soviet "atomgrads" was literally non-existent, forcing an unpalatable and unwinnable full-scale invasion if the program was to be stopped militarily. Although the material and personnel cost of a weapons building program was very high for the Soviet Union, it took advantage of the situation and sped to the bomb as rapidly as it could. War exhaustion is a dynamic variable; it wears off with time. Witness the willingness of the United States to go to war with the Soviet Union over the 1962 Cuban Missile Crisis. The author concludes that once the cost of intervention decreases through intelligence gathering and/or military superiority, war exhaustion declines and military action becomes more feasible. The potential proliferator proliferates before this can occur so that it can induce future geopolitical concessions. Amazingly, all this can be modeled.

A subsequent chapter treats the issue of "divestment," where nations on the path to a weapon halt their projects due to the high cost of proceeding, the existential threat of war if they continue, and by sufficient inducements from other nations to cease and desist. Another factor, working with poor or non-existent inspection data of the potential proliferator's development program, is coupled to the divestment discussion. The author's conclusion is that decisions to reverse weapons development are not as incredible as they may seem. Negotiators should never discount them, especially in the face of generous concessions.

Following this the author delves into the art of the bluff, whereby the potential proliferator must determine, with imperfect data, whether the rival state is faking a preventative attack. The consequences of a poor choice can, of course, be devastating for both sides. When the rival state is weak and bluffs preventative war, the potential proliferator may purposefully build a weapon. When the rival is truly strong, proliferation could lead to war. The author translates these scenarios into equations that can then be coded.

I've been very simplistic in my descriptions of the author's scenarios. The level of detail in the book is necessarily high. Considering that challenge, the author does a very credible job of explaining the complexity of the scenarios. However, there is a set of terminology and phrasing that readers must master if they are to follow along. War, for example is an "inefficient" outcome. "Rising" states are potential proliferators, while those that seek to buy them off are "declining" states. "Power shifts" are the acquisition of weapons by proliferators. "War exhaustion" and "divestment," both mentioned above, also fall into the category of game theory jargon. You have to catch on quickly.

Four of the chapters include appendices of proofs. These are mathematical proofs of the author's propositions, theorems, or lemmas (subsidiary propositions introduced to prove other propositions). They can be skipped without loss of continuity and are not prerequisites for reading the following chapter. They do, however, illustrate the author's mathematical and logical acumen and the level of detail required to do this work. Of note, the author goes beyond what other researchers have done in the field by exploring scenarios in ways not considered before. An example is his chapter on "Bluffing Preventative War," where he investigates bargaining strategies when incomplete intelligence is available to both the rising and declining states. He overlays the complexity of bluffing by a weak declining state who may threaten preventative war without much credibility (unknown to its adversary) to estimate the outcome.

Unfortunately, it is difficult to determine if the model is informing reality, or reality is informing the model. Thankfully, the author provides substantial amounts of interesting history in his discussions of modelling as a means of coupling model outcomes to real events. This is most apparent in the chapter on modeling the bluff. Here, Spaniel recapitulates the events and rationale on both sides that led to the Israeli air strike on the Iraqi Osirak reactor in 1980.

These informative sections are, by themselves, an education. But it never feels definitively that the model is predictive of nuclear negotiations and the outcomes. It should be plain that the historical reality is the data for the model. To this reviewer, (and I take the blame here if I missed it), that connection is never laid bare as I would like it. Instead, I came away with the conclusion that there are many options inherent to the potential power shift of acquiring the bomb and that these options are meant to be explored by negotiators. They all have some credibility. In other words, the model is informing reality…or is it?

The book is supported by 13 black and white figures and six tables that assist understanding to some degree. A few, such as Figure 3.1 and Tables 4.1 and 4.2, are not as obviously helpful and need deeper study. Thirteen-and-a-half pages of references and a five-page index bring up the rear of the effort. The code for the model is appropriately not included in this concise discourse.

There is no doubt that this scholarly work makes a serious contribution to the field of nuclear proliferation. It lays out many possible proliferation scenarios and their conclusions. Because it is a mathematical treatment, it reads a bit clinically but that is not a terrible fault. Proliferation is inherently messy and can stand some sanitizing. After all, unpredictable human behavior is often involved when working with imperfect data about rival states that may or may not be bluffing about nuclear development, current capability, or intent to make war. This book runs through these twists and turns, explaining the factors upon which decisions pivot such as the costs of bomb development and the heavier price of prohibitive war, and points us to the possible conclusions. There is much educational value in painting that nuanced landscape.

Perhaps it's the paucity of real-life histories and the complexity of the scenarios and their outcomes that make it appear that modeling them is ultimately inaccurate. But the drive to predict the future–to remove some of the uncertainty veiling all catastrophes (the author's model is applicable beyond nuclear proliferation) and the frightening specter of nuclear war–is too strong not to model it with the computational tools now at our disposal. Spaniel shows us that it can be done and that the modeling points towards actions that the United States may not find palatable, such as generously delivering on concessions. How accurate is the model? How much can it be depended on? Perhaps those are questions we don't want to test. Perhaps the real value in Spaniel's thesis is his illumination of the many options that can inform the diplomatic solutions to potential proliferation.

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