INSIGHTS FROM THE SECURITY OF ADVANCED REACTORS WORKSHOP

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ABSTRACT

The Nuclear Security and Physical Protection Technical Division of the Institute of Nuclear Materials Management (INMM) and The Pennsylvania State University (PSU) INMM Student Chapter hosted the Security of Advanced Reactors Workshop on November 2nd-4th, 2022. The workshop gathered nuclear security experts to engage in discussions about the challenges of protecting advanced reactor designs. The workshop events were available to both in-person participants and those connecting remotely, with over 100 participants from almost 40 various institutions. Over 25 students participated in the workshop with 13 students either presenting or moderating at least one session. The workshop featured four keynote speakers: Alice Caponiti, the U.S. Deputy Assistant Secretary for Reactor Fleet and Advanced Reactor Deployment, discussed the roadmap for advanced reactors with a focus on Safety, Security, and Safeguards (3S); Dr. Jean Paul Allain from PSU and Dr. Sola Talabi from Pittsburgh Technical LLC reviewed the PSU-led advanced reactor research initiative Post-Industrial Midwest and Appalachia Nuclear Alliance (PIMA NA); and Mr. Steve Burns, a former United States Nuclear Regulatory Commission (USNRC) Chairman, addressed the harmonization of advanced reactors with a regulatory framework. Both in-person and remote participants had the opportunity to tour the PSU Breazeale Reactor, observe a live demonstration of ARES Security's Ghost Robotics Quadrupedal Unmanned Ground Vehicle (Q-UGV), and attend a special community engagement event. The sessions were focused on an array of topics such as evolving policy, regulatory guidance, modeling and simulation, insights from industry and non-government organizations (NGOs), security by design, cyber security, and security for advanced reactor fuel fabrication facilities. The purpose of this paper is to evaluate both the technical knowledge shared during the workshop and the practical insights gained from organizing and hosting the event.

1 Introduction

Nuclear security experts are placing greater importance on the topic of physical security for advanced nuclear reactors. With the development of more advanced designs and technologies, it is crucial to consider the potential security risks associated with these reactors. To address this issue, the INMM Nuclear Security and Physical Protection Technical Division and the PSU-INMM Student Chapter hosted a workshop on the Security of Advanced Reactors on November 2nd-4th, 2022. The workshop brought together nuclear security experts to discuss the challenges of protecting advanced reactors. The event included keynote speakers, sessions on a variety of topics, and opportunities for both in-person and remote attendees to tour the PSU Breazeale Reactor and observe a live demonstration of ARES Security's Ghost Robotics Q-UGV. The goal of this paper is to review the security concepts discussed in the workshop, provide insights into the execution of the event, explore the involvement of the student chapter and sponsors, and assess the impact of the workshop beyond just the technical discussions.

2 Insights about the Security of Advanced Reactors

The Security of Advanced Reactors Workshop provided a unique platform for experts in the nuclear industry to share their insights and discuss critical issues related to advanced reactor security. In this section of the conference record, we present the key takeaways from the workshop's technical discussions and keynote speakers.

2.1.1 Diversity of Reactor Designs

To provide workshop attendees with a foundation in commercially pursued advanced reactor concepts, undergraduate and graduate students from PSU gave presentations on five prominent designs: 1) Lead and Lead Bismuth Fast Reactors (LFRs and LBFRs), 2) Microreactors, 3) Molten Salt Reactors (MSRs), 4) Sodium Fast Reactors (SFRs), and 5) Pebble Bed Reactors (PBRs) [1].

1) LFRs/LBFRs use Pb or PbBi eutectic respectively as the moderator and coolant, which have significantly higher melting and boiling points than Na, another material being considered for use in other advanced reactor designs. This also provides LFRs/LBFRs an advantage over Light Water Reactors (LWRs) in that LFRs/LBFRs can operate at significantly higher temperatures to perform much more energy-intensive work such as industrial process heat. In addition, LFRs/LBFRs can be simplified to reduce system complexity, and thus construction and maintenance costs, relative to LWRs.
2) Microreactors are being designed for use in remote communities, military bases, industrial process heat, desalination facilities, and emergency power solutions. These reactors will produce <10 MWe sitting with a ~1-acre footprint and will have limited on-site staff. The use of High-Assay Low-Enriched Uranium (HALEU) fuel, whether as Tri-Structural Isotropic (TRISO) fuel particles or another design, is a common feature of these microreactor designs.
3) MSRs can utilize fuel dissolved in a molten salt eutectic or use the molten salt as the coolant. When operated in the fast neutron spectrum, MSRs can operate as a U-235 burner or as a breeder using thorium, while also eliminating most fission product waste in the fuel. The use of liquid fuel provides unique capabilities for fuel reprocessing and fission product removal but also poses security and proliferation risks due to potential Material Accounting and Safeguards (MA&S) issues and complex reprocessing methods.
4) SFRs operate in the fast neutron spectrum with molten Na as both the coolant and moderator and can process transuranic waste. Compared to modern LWRs, SFRs operate at higher temperatures due to the boiling point of Na and can operate at atmospheric pressures. Furthermore, Na does not result in significant corrosion for stainless steel reactor components [1]; however, the Na must be separated from any water as the reaction is exothermic and yields extremely flammable hydrogen.

5) PBRs are high-temperature reactors that use fuel pebbles comprised of thousands of TRISO fuel particles. These pebbles will continuously pass through the reactor, but due to their inhomogeneous burnups, which are rigorously assessed upon leaving the core, each pebble is expected to pass through the core 5-15 times before being discharged.

2.1.2 Protection of HALEU

Joe Rivers of Rivers Security Services LLC. highlighted the importance of protecting HALEU, which is a critical component for several advanced reactor concepts [2] [1]. He also underscored the challenges associated with this effort, particularly considering the non-existent HALEU supply chain. Current U.S. Nuclear Regulatory Commission (USNRC) regulations were published in 1979 and do not appropriately address HALEU; however, the USNRC is developing options for the resumption of rulemaking to update regulations. Mr. Rivers described existing performance objectives for securing Special Nuclear Material (SNM) and important variables for licensing a facility, defining the threat, target material quantity, and system performance objectives. He also discussed assumptions needed when defining a security scenario, such as the need to containerize material and move material by vehicle and defense-in-depth considerations for HALEU facilities that are independent of each other. Security and delay features discussed include appropriately located cameras, sufficient site boundary barriers, cages or lock bars for SNM, use of Vault-Type-Rooms (VTRs) for attractive feed materials, safeguarding of onsite cargo transports, and disabling adversary vehicle tires when possible. Adversary scenario analysis requires knowing the following: number of adversaries, a combination of items to yield quantity goal, number of adversary trips into a facility, and total delay time for material acquisition. Mr. Rivers suggested that an armed, on-site, response may not be necessary if sufficient delay and a reliable response from a local law enforcement agency (LLEA) can be assured.

2.1.3 Reliance on Offsite Response

Mr. Fletcher Boone, from PSU World Campus/Naval Reactors, conducted offsite response simulations using AVERT software to assess security effectiveness [3]. The simulations were based on a generic SMR model shown in Figure 1, with a baseline physical protection system consisting of detection and delay features and on-site security that could be enhanced. The design basis threat consisted of two teams of four adversaries attempting to sabotage different areas of the site. Two

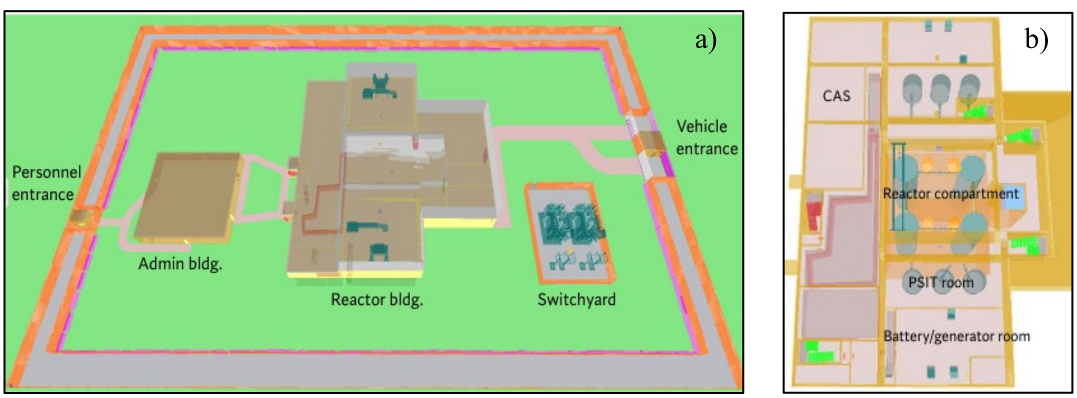

Figure 1: a) Generic SMR model for AVERT simulations of offsite response, b) schematic of the below-grade portion of the reactor building.

teams of five responders were deployed with combat skill levels equal to those of the adversaries. The simulations showed that an enhanced on-site security posture improved overall performance and reduced damage even with fewer responders. The number of responders had a significant impact on the physical protection system (PPS) performance, whereas altering the combat skill level had surprisingly little impact. The takeaways from these simulations include the importance of an on-site response and the need for an enhanced on-site security posture to improve the effectiveness of a sub-optimal response force.

The discussion surrounding on-site versus off-site response was contested among all attendees, with several attendees arguing that an on-site response is still unnecessary while others agreed with this presentation's conclusion emphasizing the need for an on-site response.

2.1.4 Modeling and Simulation

Dr. Vibhav Yadav of Idaho National Laboratory (INL) spoke on the various PPS modeling and simulation efforts at INL, focusing on the use of the Event Model Risk Assessment Using the Linked Diagrams (EMRALD) framework [4]. Dr. Yadav first discussed the basic security model used, then evaluated potential cost savings by implementing various PPS strategies via EMRALD. A case study using EMRALD to model a reaction to a power plant attack and mitigate damage was presented. The model involved the use of FLEX equipment which consists of portable generators, pumps, and other safety equipment. It was concluded that the current physical protection evaluation method is quite static and conservative, but the dynamic modeling method via EMRALD may reduce PPS design costs and conservatism. In addition, existing measures at a nuclear power plant (NPP), such as FLEX or design basis actions, could be credited toward PPS compliance and provide NPPs with more flexibility to optimize PPS design.

Mr. Jordan Parks of Sandia National Laboratory (SNL) presented on the Scribe3D© and PathTrace© tools, focusing on their high model fidelity and quantitative analysis of security designs across a wide range of scenarios [4]. Scribe3D© is a high-fidelity "tabletop" training exercise simulation suite that allows users to create PPS and visualize attacks/responses to the PPS in real-time. PathTrace© is the quantitative analysis tool used to test PPS for vulnerabilities and gaps using different adversary capabilities as well as different PPS delay and detection components, such as fencing and sensors.

Representing the commercial space were representatives of RhinoCorps Ltd. and ARES Security Corp. Mr. Dan McCorquodale of RhinoCorps Ltd. began with a discussion on Simajin/Vanguard software and its use in automating combat simulations as part of PPS evaluations [5]. He also discussed the use of Jasmin, Pioneer, and Troupe codes, which are coupled with Simajin/Vanguard to provide comprehensive simulation fidelity and security analysis. Mr. Jim Raines of ARES Security Corp. also presented the AVERT software suite, which was used in the work previously presented by Mr. Boone. AVERT tries to incorporate "physical security by design" using 3D digital-twin tools to recreate a facility and its supporting infrastructure, which is then followed by various engineering, modeling and simulation solutions. In a case study presented by Mr. Raines, assessments of NPPs using AVERT resulted in a minimum of $1-5 million in annual savings and in one case, even saving $17 million in capital costs through the efficient allocation of security resources and infrastructure. Between commercial and national laboratory efforts, it appears that advanced reactor designers will have the necessary tools to not only model their security strategies but also test them rigorously before a single reactor is built.

2.1.5 Waste Challenges for Advanced Reactors

Dr. Allison Macfarlane of the University of British Columbia, and former USNRC Chairman, discussed the considerations, issues, and challenges advanced reactors will confront when considering waste [6]. Dr. Macfarlane explained that the back end of the fuel cycle can play a direct and significant role in cost, public acceptance, security, and safeguards. While all reactors have back-end issues, advanced reactors have some key differences including fuels, coolants, moderators, reflectors, shields, and waste streams. These can result in some challenging questions, such as the extent of radionuclide mobility in the geosphere, how radiation damage impacts spent fuel/nearfield barriers, and the local concentration of fissile isotopes that could result in criticality. Neutron leakage for SMRs is especially problematic as leakage can result in increased levels of spent fuel and more Low and Intermediate Level Waste (LILW) compared to larger, energy equivalent LWRs [7, 8]. Other questions arise with respect to waste, such as how contaminated materials should be disposed of, how to develop viable waste forms for materials, and build the necessary processing before disposal. According to Dr. Macfarlane, advanced reactors may not reduce the waste problem, but rather make it more costly and complex. As a result, designers, operators, and regulators need to ensure that safety, security, and safeguards (3S) are properly accounted for by incorporating “back-end by design”.

2.1.6 Cyber Security

The workshop brought together government, regulatory, industry, and academic experts to discuss the cybersecurity challenges associated with advanced reactors [9]. The US Department of Energy (DOE) highlighted the need for increased integration with the cyber program due to the challenges presented by autonomous operation and remote monitoring. The National Nuclear Security Administration (NNSA) discussed the performance-based security evaluation and design validation assistance they offer to support cost-effective security systems, which include detection, delay, and response features for physical security, insider threat mitigation, and cybersecurity [10]. The USNRC and the Canadian Nuclear Safety Commission (CNSC) highlighted the importance of a graded, risk-informed approach to cyber security regulation, with a defense-in-depth concept and protection of integrity, availability, and confidentiality. Challenges discussed included offsite operation, limited interaction during force-on-force scenarios, and balancing the economics and functionality of cybersecurity. The goal of this dialogue was to inform the development of effective cyber security measures for advanced reactors, which will be crucial in ensuring the safety and security of nuclear facilities and preventing malicious cyber-attacks.

2.1.7 Evolving Policy

Ms. Beth Reed from the USNRC discussed the differences between the current licensing framework, 10 CFR Part 50 and 52, and the updated framework for advanced reactors security considerations, Part 53. She explained how the Nuclear Energy Innovation and Modernization Act of 2018 prompted the modernization of the licensing process, which reduces the licensing timeline and relies on performance-based considerations instead of conservative assumptions [11].

Ms. Becca Richardson of the USNRC discussed how new security considerations must be applied to the broad range of advanced reactors to enhance their safety. She addressed how security must be updated to consider passive safety features that could lead to an exemption of the Design Basis Threat (DBT) analysis through the Limited Scope Rule (LSR) [11]. The LSR provides alternative regulations and guidance for the physical security of SMRs and non-LWRs, such as decreasing the number of armed guards and integrating delay features other than physical barriers. Ms. Richardson also explained how Part 53 can increase flexibility for physical security and potentially relieve the requirement of protecting the site against the DBT of radiological sabotage.

Mr. Horvath from the International Atomic Energy Agency (IAEA) provided an international perspective and discussed regulation updates being explored by the IAEA [11]. He explained how the IAEA is exploring a 3S-by-design framework to advance the deployment of SMRs. Mr. Horvath also discussed how SMRs security considerations fall within the Nuclear Security Series (NSS) technical guidance, which ranges from the physical protection of sites to the evaluation of the security culture and its safety-security interface. These considerations will be used as guidance in the Document Preparation Profile (DPP) for the licensing of facilities. Mr. Horvath emphasized the IAEA's efforts in global harmonization and standardization that could lead to a more robust regulatory framework through regulatory consensus and communication between vendors on security protection plans.

2.1.8 Integration of 3S-by-Design

While safety is understandably the foremost concern for every reactor designer, and part of the nuclear community has realized the benefits of considering safeguards early in the reactor design, this session aimed to stress the importance of nuclear security in the reactor design process. Representing Great Britain's National Nuclear Laboratory, Dr. Jeremy Edwards pointed out the security challenges advanced reactors might face and how consideration of those challenges from the onset of reactor design could enable reactor certification and economically viable operation [12]. Failure to integrate 3S could compromise the reactor's ability to receive regulatory approval. Very often, when security concerns are examined late in the reactor design, it creates a need for costly design changes and retrofits that hurt the reactor's economic viability. Since advanced reactors are often smaller than currently operating conventional reactors, there is a need for security solutions to be more creative to avoid high operating costs associated with extensive reactor security details. This point is underscored by the numerous advanced reactor designs proposed, each of which presents distinct security challenges. It is crucial to customize the security strategy for each reactor concept because a one-size-fits-all approach is not suitable for all types of reactors.

2.1.9 Vendor Perspective

Many professionals from across the nuclear industry attended the workshop and shared their insights throughout the other technical discussions. In the workshop's dedicated vendor perspective session, speakers from Westinghouse Electric Company (WEC) and Kairos Power shared some insights from their eVinci™ microreactor and Fluoride Salt-Cooled High-Temperature Reactor (FHR) projects [13]. Representing Westinghouse, Stephen Reed shared his perspective on the importance of having security and physical protection experts at the table from day one in the design of new reactors. By ensuring that security is a concern from the inception of these projects, the number of design iterations required to meet the project goals, while ensuring plant security, can be reduced significantly. Mr. Reed also emphasized the importance of establishing the threat basis that these reactors face before specific solutions to these threats can be crafted. He reinforced this statement by discussing the rapidly evolving cyber security threat posed to these facilities and how difficult it is to accurately predict these threats. Following Stephen's talk, Margaret Ellenson from Kairos Power spoke on the new and unique security challenges that advanced reactor designs present from construction to decommissioning. She spoke on the difficulties presented by new fuel types, fuel loadings, transportation, siting, refueling, and spent fuel management. With each of these new reactor concepts utilizing different and innovative fuel cycles as well as modular or even factory construction, the 3S challenges presented are far more complex than traditional reactors. Considering 3S throughout the entire design phase through construction, deployment, and decommissioning will be crucial with these new first-of-a-kind designs.

2.2 Keynote Addresses

2.2.1 Ms. Alice Caponiti (DOE Deputy Asst. Secretary for Reactor Fleet & Advanced Reactor Deployment)

Ms. Alice Caponiti spoke on the decarbonization potential of advanced reactors and on the security and safeguards challenges facing these reactors [14]. Regarding safeguards, Ms. Caponiti spoke about how the DOE, USNRC, and NNSA have worked with vendors to develop more robust physical security measures by evaluating various threat vectors. This has been done through the Advanced Reactor Safeguards (ARS) program to address domestic requirements for material control and accounting (MC&A) and PPS. Regarding security, Ms. Caponiti spoke on PPS research and development efforts, focusing on evaluating a combination of new technologies (e.g., Remote Operated Weapons Systems) and approaches (e.g., Deliberate Motion Algorithms) to reduce upfront and operational costs and providing vendors with several PPS options for microreactors and SMRs. In addition, Ms. Caponiti spoke about the importance of licensing for security and MC&A to include international safeguards, robust security information sharing among vendors, and implementing security by design concepts.

2.2.2 Dr. JP Allain (Penn State University, PIMA-NA) & Dr. Sola Tolabi (Pittsburgh Technical, PIMA-NA)

Dr. Jean Paul Allain and Dr. Sola Tolabi began the second day of the workshop by discussing the Post-Industrial Midwest and Appalachia (PIMA) Nuclear Alliance [15]. The talk went into the importance of advanced reactor development and deployment for the economic and environmental impacts on the Midwest and Appalachia regions. A key takeaway of the talk is the necessity of advanced reactor designs to be economically viable and scalable with production. Ideally, advanced reactors would be built modularly in factories all over the Midwest and Appalachian regions and employed in these states to provide power and process heat for towns and manufacturing hubs that currently rely on fossil fuels. In addition to discussing the overall goals of the PIMA initiative, Dr. Allain and Dr. Tolabi discussed the partnership between PSU and WEC to build an eVinci™ microreactor research platform at the University Park campus. This partnership offers Westinghouse an opportunity to build a demonstration reactor while giving PSU a research reactor, making a total of two research reactors on campus, capable of contributing to projects across several research initiatives across the university.

2.2.3 Steve Burns (Former USNRC Chairman and Third Way Senior Visiting Fellow)

On the final day of the workshop, the Former Commissioner of the USNRC, Steve Burns, presented on improving harmonization of regulations with evolving nuclear technologies [16]. Mr. Burns began with an overview of the Convention on Nuclear Safety (CNS) enacted in 1996, an international obligation that the safety of nuclear plants is assessed and verified throughout a licensing procedure, providing general safety considerations for contracting parties to ensure safety installations during the entire lifetime of the plant. The framework follows a top-down approach with the national constitution, international treaties, legislation, and obligations at play. The regulatory regime is the statutory basis for implementing the license terms and conditions such as operating procedures, industry codes, and international consensus standards. Mr. Burns reiterated points from the evolving policy panel, such as the importance of harmonization with advancing nuclear regulatory frameworks while maintaining regulatory independence, with national legislation paving the regulations of each country. Mr. Burns then spoke on the challenge of achieving consensus among regulators regarding technical classifications of structures, systems, components, fuel qualification, and quality assurance. To move toward harmonization, the frequency of reviews of advanced reactors needs to increase in order to develop the next generation of regulatory talent.

3 Insights about the Execution of the Workshop

The workshop brought together a diverse group of stakeholders from various communities to discuss challenges and identify solutions related to physical and cyber security. In addition to technical sessions, the workshop also featured less-formal events, including a tour of Penn State's Radiation Science and Engineering Center (RSEC) and a community engagement event. The involvement of students in various aspects of the workshop was also notable, including their contributions to technical discussions and logistical tasks. Overall, the workshop demonstrated the importance of fostering community collaboration through multi-stakeholder dialogue. The following subsections provide insights about the student chapter's involvement in the workshop, the value of the less formal events, and the benefits that came from community collaboration.

3.1 Student Chapter Involvement

The workshop was notable for the significant involvement of students in various aspects. Students collaborated with professionals beforehand to prepare for technical discussions and met with Joe Rivers to gain deeper insights into advanced reactor concepts. During the workshop, students gave presentations and participated as panelists in discussions related to reactor design and security considerations (see Figure 2). Each session had a student and professional moderator. The students also helped with logistical tasks such as communications, check-in, online technical support, and Q&A facilitation. Additionally, Amanda Gray, an Administrative Support Coordinator and assistant for INMM Faculty Advisor Matthew Zerphy, played a crucial role in organizing the venue, catering, and hotel arrangements. The student chapter outsourced audio-visual and IT support to a technician from the College of Engineering which greatly reduced logistical complications for the presenters and online (Zoom) participants. Overall, the student-to-professional interactions and engagements were a highlight of the workshop.

3.2 Beyond Technical Discussions

In addition to the technical sessions offered at the workshop, there were additional less-formal events available to the participants. Among these were a tour at Penn State's RSEC, sponsor engagement events including a demonstration of the Q-UGV platform by ARES Security Corp., and a community engagement session offering a panel on advocating for nuclear science over dinner. The tours of RSEC were carried out over the lunch breaks of the conference. Participants were shown the university's 1 MW TRIGA research reactor and operators' room, the new addition to the facility which will soon include a small angle neutron scattering source, as well as some of the office and lab spaces of the facility. Lunch breaks featured Q-UGV demonstrations from ARES Security Corp. These demonstrations showcased the promise the Q-UGV platform has in assisting on-site security and monitoring without relying on human personnel while fitted with an array of cameras, detectors, and deterrence devices.

A panel discussion was held during an evening dinner on nuclear communication and engagement. Nuclear experts explained how the history of accidents and misinformation has led to a lack of trust from the public in the nuclear industry [17]. To combat this, the communication experts emphasized the importance for scientists and engineers to understand where each stakeholder or public member's knowledge and background affect their frame of reference and view on nuclear science. To help rebuild and gain back the public's trust, nuclear engineers must be able to communicate at various levels to help others understand the benefits that can be provided and how previous incidents can be prevented. Workshop participants valued the change of pace beyond technical discussions to critical societal conversations.

3.3 Fostering Community Collaboration

The workshop brought stakeholders together from various communities to discuss challenges and identify solutions related to physical and cyber security. The workshop facilitated discussions that might not have otherwise occurred, such as the difficulty of specifying a design basis threat (DBT) for cyber-attacks, the challenge of finding a balance between reducing onsite responders and maintaining physical protection, and discussions on how different international perspectives impact security measures.

The workshop also revealed new perspectives on the reality of advanced reactor security, including discussions on the legal hurdles and international regulations, the expected increase in waste due to neutron leakage, and the potential negative impact on public safety if security measures are reduced. The multi-disciplinary group that attended the workshop allowed for a better understanding of how different processes work and the inputs and outputs of security models.

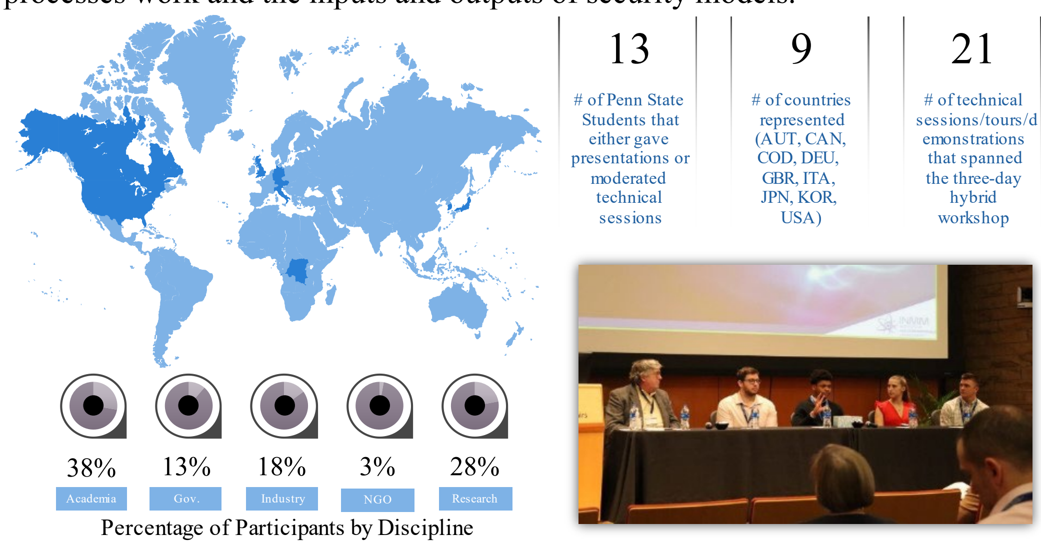

Figure 2: The INMM Security of Advanced Reactors Workshop successfully integrated students with professionals from a diverse set of backgrounds and disciplines.

The importance of these types of events is clear in how they bring people together from all of the various stakeholder communities to help uncover challenges and find solutions. By engaging in dialogues with folks that may be working on the same problem but from a different perspective, valuable insights and solutions were discovered that might not have been found otherwise. The workshop provided an ideal forum for such discussions, and its outcomes demonstrate the value of fostering community collaboration through multi-stakeholder dialogue.

4 Conclusion

The Security of Advanced Reactors Workshop hosted by the INMM Nuclear Security and Physical Protection Technical Division and the PSU-INMM Student Chapter successfully brought together a diverse group of stakeholders to discuss the challenges and potential solutions related to advanced reactor security. The workshop provided a platform for experts in the nuclear industry to share their insights and discuss critical issues related to advanced reactor security, including reactor design, cyber security, and waste challenges. The involvement of students in various aspects of the workshop was notable, including their contributions to technical discussions and logistical tasks. The workshop also demonstrated the importance of fostering community collaboration through multi-stakeholder dialogue. The event showcased the value of holding hybrid workshops hosted by student chapters and the importance of bringing a diverse group of stakeholders together to help uncover challenges and find solutions. Overall, the 2022 INMM Security of Advanced Reactors Workshop provided an ideal forum for such discussions, and its outcomes demonstrate the importance of continued dialogue and collaboration in progressing the security of advanced reactors.

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