Game-based Learning in Nonproliferation at Argonne National Laboratory and Texas A&M University

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Abstract
Our international nuclear safeguards community is a dynamic one which benefits from individuals with a wide array of backgrounds. Due to our community's successful engagement into higher learning institutions, the number of university students choosing to pursue careers in nuclear nonproliferation after attaining an advanced degree in a relevant area grows each year. Many of these students, having spent years in a workforce already before they graduate with a masters or doctoral degree, can be categorized as adult learners and, hence, benefit from a more nuanced educational approach than traditional grade school education methods. A commonly understood principle of adult learning is to employ various learning styles (visual, auditory, and kinesthetic learning) to enhance the learning experience. This is especially true in the field of nuclear nonproliferation and, specifically, international safeguards, where the understanding of concepts takes place by reading relevant textbooks and/or through discussion in classrooms which can further benefit from the incorporation of an experiential component via kinesthetic learning.

Leading to this endeavor, researchers at Argonne National Laboratory have been employing game-based, simulated projects to enhance the experiential learning approach for graduate students hoping to advance their understanding of concepts relevant to the nuclear nonproliferation field of work. Since 2017, Argonne staff members have been collaborating closely with the faculty members at Texas A&M University on their graduate-level Introduction to Nuclear Nonproliferation course which is open to nuclear engineering graduate students as well as international relations and foreign policy graduate students. In this course, students learn the history and fundamentals of the nuclear nonproliferation regime ranging from the birth of the nuclear age, proliferation activities among states, the Cold War, the nuclear fuel cycle, the establishment of nonproliferation institutions, and the international safeguards regime. Complementing this conceptual understanding, students obtain from competent and knowledgeable faculty is the completion of four simulated game-based projects that serve to congeal the myriad of topics students learn throughout their semester. This presentation will discuss the evolution of this game-based approach for enhanced educational endeavors as well as the projects themselves, their learning objectives, their management campaigns, and the observed results from students completing such simulations.

Introduction
Faculty members at Texas A&M University (TAMU) and instructors from Argonne National Laboratory have been collaborating since 2017 in executing a game-based learning environment to help solidify conceptual understanding of nuclear nonproliferation topics, such as international relations theory, nuclear material transportation security, nuclear and radiological material smuggling, and international nuclear material safeguards. Begun as part of the newly formed Master of Science degree in Nuclear Engineering with a specialization in Nuclear Nonproliferation (MS-NNP) at TAMU in 2009, a culminating capstone course was designed by Professor William Charlton as a means to synthesize multiple years of advanced education for TAMU's nuclear engineering students. In concert with other TAMU faculty and staff, the culmination of the course itself consisted of a series of game-based simulation projects designed to immerse students into real-world scenarios where they were to rely on their deductive logic

and critical analysis skills to objectively study a multi-faceted problem and propose a plausible explanation leveraging a breadth of knowledge they had accumulated over their higher learning academic careers. This paper not only describes the value of this kind of kinesthetic learning for the nuclear nonproliferation community but also delves into the history of the projects, specific details of each, and what the students gained from completing it.

Game-based Learning

Game-based learning is a teaching method that uses game design and mechanics to engage and motivate students in the learning process. It involves the use of educational games, simulations, and other interactive tools to teach specific subjects, concepts, or skills. Lending itself well to the nuclear-realm, the idea behind game-based learning is that students are more likely to learn and retain information when they are actively engaged and motivated. More so, simulations employing critical assessment and logical deduction with gratifying soon-realized results emphasize conceptual teaching points for all forms of students. Overall, game-based learning provides a fun and interactive way to present information and solidify understanding. They can also be tailored to meet the specific needs of individual students and unique topics.

Game-based learning can take many forms, from simple educational games that teach basic concepts to complex simulations that immerse students in real-world scenarios. The games can be used in both formal and informal learning environments for adult and adolescent students and provide a myriad of benefits. It can help students develop problem-solving skills, improve their critical thinking abilities, deductive logic, and increase their motivation and engagement in the learning process. All these can be achieved in a safe learning environment that can be reset and modified at any moment without affecting real-world data (as is common in experimental learning where students' decisions can and do have such an impact on results).

A Tool for Advanced Education

The roots of game-based learning can be traced back to the 1960s, when researchers began to explore the use of computer simulations for educational purposes. Programmers utilized the directions given to an on-screen cursor by students to execute simple lines of code in an attempt to teach those students computer programming basics. [1] This and other early simulations paved the way for more sophisticated educational video games in the decades that followed. For example, in the 1990s, as computer technology became more advanced and accessible, educational video games began to gain traction as a tool for teaching a wide range of subjects. A commonly played video game that had its origins in game-based learning for advanced education was "SimCity." Known today as a real-world based life-simulation game where players design and manage their own virtual cities, the game was initially designed as a tool for urban planning students to learn about infrastructure. Notably, another popular game during that decade, "Where in the World is Carmen Sandiego?", led millions of young students to learn about geography and history of places while acting as an investigator collecting clues to the whereabouts of the game's namesake international criminal.

Today, there are a wide variety of educational video games available for advanced education, covering subjects ranging from history and geography to economics and business. Many of these games are designed to be immersive and engaging, allowing students to explore complex concepts in an entertaining and interactive way. Some key benefits of game-based learning for advanced education include the ability to build critical thinking and problem-solving skills. Games are often designed to be challenging, requiring players to think creatively and strategically in order to successfully reach the end. [2] Game-based learning can help to prepare students for real-world challenges without the fear of affecting actual results. Furthermore, game-based learning has been proven to enhance the retention and transfer of knowledge students by providing an interactive and immersive environment beyond classroom instruction. [3] Moreover, by utilizing games in advanced education, students acquire experience in collaborative work environments, social interaction while working towards a common goal, but also strengthen the ability to segmentize an overall project into individually-pursued portions that feed back into the group work. [4, 5] Beyond educating students in mere concepts and applicable theory, the responsibility of higher education also includes teaching and enhancing these aforementioned skills prior to graduates entering the workforce.

A Case for Game-based Learning in Nuclear Nonproliferation

Educating the next generation of nonproliferation experts is a critical task, given the threat of nuclear weapons proliferation and the need to ensure global security. There are several key strategies that can be used to prepare the next generation of nonproliferation experts:

1. Academic Programs: Many universities offer academic programs focused on nonproliferation studies, providing students with a deep understanding of nuclear weapons proliferation and their impact on global security, with methods to minimize the risk. These programs often include courses in international relations, nuclear policy, and technology to achieve the objectives of nuclear nonproliferation.
2. Internships: Students can gain practical experience and build their skills through internships at government agencies, national laboratories, other non-governmental organizations, or think tank type organizations focused on nonproliferation. Internships provide students with an opportunity to work alongside experts in the field and gain real-world experience.
3. Conferences and Workshops: Attending conferences and workshops focused on nonproliferation can provide students with an opportunity to learn about the latest developments in the field, network with other experts, and gain insights from experienced professionals.
4. Mentorship: Mentoring programs can help to provide guidance and support to students interested in pursuing a career in nonproliferation. Mentors can offer advice on career paths, provide feedback on research projects, and help students navigate the complex landscape of global security.
5. Collaboration: Collaboration between academia, government agencies, and non-governmental organizations can help to ensure that the next generation of nonproliferation experts have the skills, knowledge, and experience they need to succeed. These collaborations can involve joint research projects, collaborative training programs, and other initiatives that bring together experts from different fields.

Educating this next generation of nonproliferation experts requires a multifaceted approach that involves academic programs, internships, conferences and workshops, mentorship, and collaboration between different stakeholders. As diverse the methods by which this community develops the next generation workforce are, so are the types of problems that could arise during their professional careers in the world of nuclear nonproliferation and global security.

Nuclear nonproliferation (and, generally, nuclear engineering) are fields which benefit greatly from simulations. The development and continued use of reactor modeling skills through a myriad of stochastic and deterministic modeling software packages easily conveys this importance. For the ease of confirming operability without spending copious funds in actually building reactors, reactor physicists have long used robust codes to simulate the performance of reactor designs. Students of this field are trained in these computer codes either explicitly during their studies or implicitly while conducting research to enhance their understanding. The field of nuclear nonproliferation is not dissimilar to this. If there exist easy ways to effectively convey the negative impacts of nuclear material diversion, facility misuse, export control violations, nuclear smuggling, etc., via simulations, they should be employed to the greatest extent possible. This was the mentality behind the idea of solidifying conceptual understanding through game-based learning via simulations.

Generally, in education, simulations and experiments are both valuable tools that can be used to teach students. However, within the realm of nuclear policy, science, and engineering in certain situations, and for the below reasons, simulations may be better suited than experiments.

1. Safety: Simulations can be used to teach concepts that are too dangerous or impractical to be demonstrated in an actual experiment. For example, simulating a spent fuel measurement can provide students valuable insight without exposing them to radiological hazards.
2. Cost: Simulations are more cost-effective than experiments, particularly if the experiment requires expensive equipment or materials. In many cases, a simulation may be the only feasible option due to budget constraints.
3. Time: Simulations can be completed more quickly than experiments, allowing students to explore more concepts in a shorter amount of time, which can be particularly useful in courses where there is a lot of material to be taught.
4. Controlled Variables: Simulations allow for a high level of control over variables, which can be beneficial when teaching specific concepts or theories. In a simulation, variables can be easily varied and controlled to allow for a more focused learning experience.
5. Real-World Scenarios: Simulations can provide students with access to scenarios that may be difficult to replicate in real life, such as natural disasters or emergency situations. This can allow students to develop critical thinking skills and problem-solving abilities in a safe and controlled environment.

Of course, there are also situations where experiments may be better suited than simulations. For example, experiments can provide students with a more hands-on experience and may be more engaging for some students. In addition, experiments can provide students with a deeper understanding of the practical applications of scientific concepts. With this in mind, the work presented herein aims to incorporate these benefits but through simulated real-world nonproliferation-focused scenarios through the employ of a game.

Nuclear Nonproliferation Projects at TAMU

Faculty members at TAMU, as part of its MS-NNP, have taught several courses focused on various aspects of nuclear nonproliferation. Currently, the courses offered for those seeking an MS-NPP degree include:

1. Introduction to Nonproliferation and Arms Control
2. Radiation Interactions and Shielding
3. Radiation Detection and Nuclear Materials Measurements
4. Nuclear Reactor Theory
5. Nuclear Reactor Analysis and Experimentation
6. Nuclear Fuel Cycles and Nuclear Materials Safeguards
7. Design of Nuclear Reactor Systems
8. Nuclear Security System Design
9. Deterrence and Coercion
10. International Security

11. Nuclear Engineering Departmental Seminar
12. Other technical and policy electives (chosen from political science, policy, international relations, etc.)

These courses listed have been developed to synthesize a broader understanding of advanced topics that TAMU graduates have undertaken as part of their curriculum in nuclear nonproliferation in achieving professional successes in their respective organizations. Prior to its cancellation in 2014, a specifically-focused capstone course, Critical Analysis of Advanced Nuclear Security Topics (NUEN 656), was taught annually and aimed to teach students in a real-world simulation by challenging their critical assessment skills and utilizing an immersion tactic for solidifying their understanding of nuclear nonproliferation issues. As discussed above, with a heavy focus on nuclear nonproliferation, this course served as an opportunity for students to apply their conceptual understanding to a real-world scenario with controlled data and from the safety of the classroom.

The NUEN 656 course initially began as a series of six separate projects, superficially independent, focused on different aspects of nuclear nonproliferation (e.g., nuclear safeguards measurements, interdicted nuclear materials out of regulatory control, reports of illicit nuclear material use, nuclear forensics, uncertainty quantification, and more). Students would rely on previously acquired knowledge covered in existing curriculum at TAMU (such as gamma spectroscopy, Monte Carlo modeling, statistics, international relations, etc.) but also be able to request just-in-time (JIT) lectures in new topics (such as seismologic analysis, satellite imagery, program management skills, and resource allocation techniques). The projects would be assigned to groups of students (about 4 to 5 students per group) who would be responsible for submitting a project work plan with Gantt charts and resource allocations and later endeavor to prove a hypothesis on their individual projects. Each project lasted the entire semester and consisted of regular classroom instructions, weekly one-on-one meetings with the instructor, red-team members, a mid-semester debrief, and a full presentation of results and conclusions as the final exam. Student teams were graded on the assimilation of data as well as critical assessment skills, communication skills, and teamwork skills – these latter skills believed to be vital for the future success as the students entered the nonproliferation workforce.

Simulated Projects

With a change of TAMU nuclear engineering curriculum in 2014, the NUEN 656 course was cancelled to accommodate more academic rigor in fundamental nuclear engineering skills. Still able to graduate with a MS with a specialization in Nuclear Nonproliferation, students since 2014 have pursued curricula with more traditional nuclear engineering courses that have led to more inclusivity with other nuclear engineering students. That is, students who focused in nonproliferation were able to interact more frequently and more closely with students focused in other areas (i.e., nuclear materials and fuels, computational methods development in neutronics and simulations, health physics, thermal hydraulics, nuclear nonproliferation, etc.) during their academic careers and vice versa. It was a generally favorable view of a graduate curriculum from both perspectives.

In 2016, TAMU faculty members in the nonproliferation research area (affiliated with the Center for Nuclear Security Science and Policy Initiatives) shared the belief that the capstone project concept of the old NUEN 656 course was beneficial for their graduate students. It served as a way to assimilate conceptual understanding of theories and provide a simulated experience some students would experience when employed. As a way to help prepare these students, TAMU faculty members adapted a subset of the original NUEN 656 projects and incorporated them into the Introduction to Nonproliferation and Arms Control course (NUEN 650) within the TAMU Nuclear Engineering

Department. Despite previously having the projects completed by advanced nuclear engineering graduate students near the end of their academic tenure, the projects had to be adapted in two ways:

1. The projects were modified so that nuclear engineering graduate students at the beginning of their studies would be able to complete the projects. This required shortening the timeline of the projects from an entire semester to 6-8 weeks, simplifying some of the project data when provided to the student teams, and providing more opportunities for JIT lecturing, which served as a stopgap measure to supplement deficient knowledge in areas like open-source research, seismological analysis, and gamma spectroscopy.
2. The NUEN 650 course was advertised as an introduction to nuclear nonproliferation and was open to students outside of TAMU's nuclear engineering program including students receiving graduate degrees in chemistry, physics, international relations, political science, and government policy. The inclusion of technical students from other disciplines and non-technical students led to the need of modifying the number of projects so as to allow multiple students in a group where the technical and non-technical students could assist each other in understanding various nuances of the projects. This added an ancillary benefit of forcing technical and non-technical students to collaborate, which was seen as a necessary skill for success in the professional world of nonproliferation.

Accommodating multi-disciplinary student groups meant offering support throughout the available resources in TAMU nuclear engineering department and the Bush School of Government and Public Service. If a group needed to better understand such elements as the fission yield curve or the calculation of separative work units for uranium enrichment or the history of bilateral relations, they were advised to use any available resources other than students who had completed the projects previously. The projects which were adapted from the original six were modified into the following four themes: nuclear forensics, safeguards data, satellite imagery, and seismic analysis.

The structure for data requests and their analysis was made rigid to allow for timeliness of data injects from the gamemaster – a member of the TAMU research staff, later a staff member from Argonne. Approximately halfway through the fall semester (around week 7 of 15 week-courses), the four projects would be introduced with an initial inject (included in the subsequent subsection). Student groups could act as advisors or representatives of an organization depending on the project. Once provided with the initial inject, student groups would have to submit a request to the gamemaster who would begin play in character. It was emphasized that all correspondences should be in character and that students must address the gamemaster not as himself but as their main conduit to their simulation. This insistence forced students to learn how best to address messages and requests and acclimatize them to a professional world which involved government officials, agency representatives, and foreign dignitaries.

With each request made, the gamemaster was given three full days to reply in character with generated data and the student group had four days to analyze it before their subsequent request. Despite the experience of performing these simulations for multiple years, the gamemaster would sometimes receive requests that fell outside the anticipated trajectory of data compelling him to generate new data that must follow the ultimate conclusion of each individual project. For eight weeks, this structure was followed except for a mid-term debrief at around week 5, where student groups would present their hypothesis, supporting data, and assessment plan to the instructors of the course, the gamemaster, and the rest of the students. This was envisioned as a red-team exercise where all audience members can challenge the presenting students on their assumptions, plans, and preliminary results. At the end of the course, all students had to compose a long-form debrief with a final report per group and present it together. This served as the final exam for the course itself and grades depended on the ability to critically assess data and the evaluations of a student's other group members. Achieving the final "answer" for each project was not incorporated into the final grade. In this sense, rabbit holes and red herrings were not made to penalize but to convey the uncertainty of data analysis.

By the end of the course, students' learning objectives included the ability to analyze diverse sets of data using their existing and newly developing technical skills as well as to present in a clear and concise manner their findings to a mixed audience both orally and in writing. Furthermore, with student groups presenting to each other, all would be exposed to varying degrees of satellite imagery analysis, gamma-ray spectroscopy, mass spectrometry, open-source research, seismic data analysis, export control data, and safeguards monitoring data. Following is a brief description of each project for discussion. Admittedly, there is a slight suspension of disbelief required to achieve the final designed conclusion of each project but the value in these exercises is conveyed as the opportunity to assess provided data within the confines of the simulations themselves. Despite the use of actual company and organization names as well as referencing country politics, the students are reminded frequently of the *gamified* nature of their projects through the extensive use of popular culture icons for individuals throughout their simulations (e.g., James Logan Howlett, Ororo Munroe, Wade Wilson, Mario Savale).

<u>Project 1: Nuclear Interdiction</u>
Evidence is found of material outside of regulatory control. Trace quantities of special fissionable material and surrounding activities support an initial hypothesis of illicit transformation of material into a malicious form. The student group is requested by the team who found the evidence to assess the situation and advise on what to do next. Initially, the students typically request photographs and a drafted list of items found in the vicinity. Therein, the gamemaster, as a field team member, provides a haphazardly shot photograph of some shiny metallic material and a laptop computer screen exhibiting a gamma spectrum as well as a list of items which include heavy machining equipment and various other clues outlining potential activities of the previous inhabitants. The gamemaster also provides the student group with a list of available equipment which can be used by the field team. That initial image sets the student group down the path to understanding how to read gamma spectra and learning what data to request the following week (with a keen eye to what the field team's available equipment list is). The student group then interacts with the gamemaster for multiple weeks of the semester (but in game time, only transpires over a few days) attempting to determine a) what activities occurred in that location, b) if these activities are of concern to the community, c) the material those activities were with, d) who was involved, e) where they may be, f) what support, if any, they may be receiving in the area, g) what the field team should do, and h) does this relate to other activities happening in the world. The useful skills students of this group gain usually consist of gamma spectroscopy, mass spectrometry, historical international relations issues, satellite imagery, understanding nuclear smuggling counter measures, and open-source research. Furthermore, the students learn about the incident and trafficking database (ITDB) managed by the Division of Nuclear Security within the International Atomic Energy Agency (IAEA).

<u>Project 2: Safeguards Data</u>
A shipper/receiver difference (SRD) has been reported between two respected nuclear fuel cycle facilities in different countries and the student group serving as analysts engage with the claimant to investigate and ultimately resolve the issue. Using basic statistical analysis, the student group assesses the masses of over 200 48Y UF_6 cylinders to confirm the SRD. Furthermore, they consider diversion scenarios which may include state actors after calculating potential material unaccounted for and other supporting evidence. Beyond learning about material definitions (e.g., significant quantities, direct/indirect use materials, etc.), the students of this project learn how and when seals are applied to

shipped items and the respective roles of IAEA inspectors, safeguards managers, and material custodians at large scale facilities. The gamemaster assumes the roles of various personnel in the IAEA who respond to the students' requests in character with insight into the processes at the given facilities (a uranium enrichment plant and a fuel fabrication facility) as well as familiarity with the inspection regime of both countries. The students learn commonly used measurements for safeguards purposes including non-radiological measurement systems and what uncertainties are defined in the International Target Values (ITV) resource. Over the course of the project, the student group aims to a) support or deny the claimed SRD, b) the magnitude of such SRD, c) the importance of the SRD, and, as stepping outside a conventional safeguards analyst role, d) follow leads on how this SRD could have occurred unbeknownst to both facilities. Lastly, as the material must traverse over a large swath of land, the students on this project learn about transportation security, the World Nuclear Transport Institute, and the IAEA's Implementing Guides (specifically, NSS26-G) for non-safeguards related activities. The simulated time frame of this project is months despite the 8-week long project duration.

Project 3: Satellite Imagery Analysis

A report of an unauthorized facility in a responsible country is received and the student group only has an overhead satellite image and other open-source information to determine the nature of the facility. The students analyze satellite imagery using basic skills and software like Google Earth to assess the facility is a uranium enrichment facility. Exploring the footprint of the facility, the students estimate throughput and separative work units (SWU) which should lead to a minimal understanding of activities. By incorporating known real-world actions of the state where the facility is discovered in, legitimacy of the facility is typically immediately questioned. The intent of this initial stage of the project is for students to gain an understanding of a state's safeguards obligations like declaring any new nuclear fuel cycle facility construction before breaking ground or declaring imports of equipment relevant to uranium enrichment. Utilizing images and available resources from the gamemaster during the semester, the student group learns the various steps of uranium enrichment including receipt from transported 48Y cylinders, autoclave feed/withdrawal stations, the cascade hall(s), cascade shape, SWU calculations, cold traps, and storage until shipment. Depending on how far the students get into the project, they can end up interacting with the IAEA's Division of Nuclear Security for accessing the ITDB just as in Project 1. This project helps students gain experience in a) basic satellite image analysis, b) the uranium enrichment process, c) facility throughput and SWU capacities dependent on the enrichment technology used, d) international safeguards measures for uranium enrichment, and e) open-source information analysis. The time frame of this project is weeks – most closely mimicking the real-world duration of the project.

Project 4: Seismic Analysis

A byline from a respected periodical highlighting a suspected nuclear detonation is presented to the student group who must serve as analysts to confirm or dispute the report. In a commonly requested JIT lecture, the students receive a rudimentary presentation from the gamemaster on basic seismic analysis using waves through the earth's core and triangulation of signals. They further learn of the role and responsibilities of the Comprehensive Test Ban Treaty Office (CTBTO) and the four streams of data from the International Monitoring System (IMS). The main objectives of this project are to deduce a) if the seismic anomaly was of a nuclear nature, b) if it occurred where the report says it did, c) who could be involved with such an event, and d) the size of said anomaly. In determining size using IMS seismic data (the JIT lecture provides manners in which to translate seismic events registering on the Richter scale to nuclear yields), the group should lean towards a nuclear nature of the event and request any supporting radiological data that can be provided through the IMS' radiological sampling system. Applying knowledge of the fission yield curve to trade-wind data typically leads the student group to estimate details beyond what was initially reported. Furthermore, it behooves the group to understand historical interstate relations of the region where this was reported so as to best know how to interact with representatives of the countries where the stations reside. The students engage with the gamemaster who, while taking on two different characters (having a dedicated email address for a second character), provides them data and assistance with their analysis. As in Project 1, the timeframe (simulated time) of this project is days.

Benefits to Students

Evaluations provided by students of the course and who have graduated from TAMU have reflected on the joy they had received discovering hidden secrets which fully immersed them into the world of nuclear nonproliferation while still learning as a group. Beyond solidifying the theoretical concepts via these simulations, students have also remarked on the value in learning how to collaborate with other students (some from entirely different disciplines) towards a common goal. Intra-disciplinary education is vital to the nonproliferation community and as TAMU's introduction course, in which these projects are utilized, supports technical and non-technical registrants, students from international relations, chemistry, physics, and nuclear engineering must collaborate effectively to reach the end of the game – it is carefully noted that games are not to win so as not to promote competition but instead, to reach an agreed upon endpoint satisfying each member of the group. Collaboration and group decisions are absolutely vital to the successful execution of these simulation projects. Furthermore, aspects of the project structure have provided students with the opportunities to work within a short timeline with short turnarounds for data requests (which includes critical analysis of data); the formulation of respectful correspondences and requests from simulated characters in different groups, facilities, organizations, countries, and age groups; and the practice of being challenged in hypotheses and conclusion from results in a non-threatening and supportive environment. In every iteration of the course, the simulation projects have been shown to impact the students' critical analysis skills by the eventual realization that all four projects are connected – they all represent different stages of material diversion, transfer, development, and malicious use. If the realization of this interconnectivity is not achieved before the student groups' final presentation stemming from inter-group collaborations (which is not discouraged yet not advertised either), all students realize this while they watch each other's group presentations – many characters appear in multiple projects at different stages of the overall simulation to emphasize the complexity and diversity of the data that was provided during the 8-week time period.

Students have also expressed an appreciation for the projects in strengthening their understanding of roles and responsibilities of organizations within the nuclear nonproliferation community as well as what a career in such an organization may entail. Though an ancillary benefit to the simulated projects, game-based learning certainly provides this type of insight that may prove difficult to effectively convey without immersing the students into such a role during the tenure of the project. TAMU faculty members and Argonne researchers have engaged with both technical and non-technical graduates who participated in the projects and have shown appreciation for these projects to better understanding why they decided to continue their careers in this particular area. These graduates have since been employed throughout the U.S. Department of Energy (DOE) national laboratory complex, the DOE, the U.S. National Nuclear Security Administration, military, intelligence agencies, educational institutions around the world, industry, and the IAEA itself.

Conclusions

Game-based learning can certainly play a role in educating the next generation of nuclear nonproliferation specialists. It has been employed by TAMU faculty members and Argonne researchers in some version since 2009 and continues to be used today. The primary and ancillary benefits of this educational technique have been discussed and could possibly include more not introduced within this paper. The authors of this paper (including the gamemaster) hope this publication can work as a resource for developing more game-based learning techniques and deploy them as part of an effective educational effort in more academic and research institutions but openly admit the investment is not a trivial one. The amount of time needed to plan and execute such an endeavor is large – however, this magnitude is matched by the benefit such a teaching style provides to the students who are fortunate enough to participate in an experience like this.

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