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Abstract

Brookhaven National Laboratory (BNL) has a distinguished history of contributions to the field of international safeguards. BNL's Technical Support Organization led to the establishment of numerous projects in support of the United States government and the International Atomic Energy Agency's nonproliferation verification activities. BNL is the home of the International Safeguards Project Office which has served the international safeguards community through its management of the U.S. Support Program to IAEA Safeguards since 1977. BNL also provides technical support to the National Nuclear Security Administration's Next Generation Safeguards Initiative and the Defense Nuclear Nonproliferation program. This paper will provide a high-level overview of current programs and provide some insight into future directions for BNL.

Introduction

BNL, located on 5000 acres in Upton, Long Island, NY, is a multi-disciplinary science laboratory managed by the U.S. Department of Energy's Office of Science. It has 2700 employees and hosts 4000 users who visit the laboratory to use its scientific facilities, such as the Relativistic Heavy Ion Collider, the Center for Functional Nanomaterials, the National Synchrotron Light Source II, and the NASA Space Radiation Laboratory. Seven Nobel Prizes have been awarded for research conducted at BNL.

International safeguards programs at BNL are concentrated in the Nonproliferation and National Security Department (NN). NN has three groups that address safeguards issues: the Nonproliferation Policy and Implementation Group, the International Safeguards Project Office, and the Radiation Detector and Nonproliferation Research and Development Group.

History of Safeguards and Nonproliferation at Brookhaven National Laboratory

Safeguards and nonproliferation work at BNL began formally in 1968 with the establishment of the Technical Support Organization (TSO). There were several factors at the time that led the Atomic Energy Commission (AEC) to establish TSO at BNL. First, it became known around 1966 that a facility in Pennsylvania processing highly enriched uranium was unable to account for about 100 kilograms of HEU. Second, the Lumb Panel[i] report was completed in 1967 and recommended a central office in the AEC for nuclear materials safeguards and security policy, minimum security requirements for all licensee facilities, increased penalties for SNM diversion, a safeguards R&D program, and nine other safeguards system enhancements. Third, it was clear that the United States would ratify the Treaty on the Nonproliferation of Nuclear Weapons (NPT) in the near future and the AEC and the Department of State would benefit from technical support in international safeguards. Finally, at AEC contractor facilities, special nuclear material (SNM) was protected and accounted for largely based on classification, site security and contract requirements while at private licensee facilities, SNM accountability was largely based on regulatory security requirements and its high monetary value. It became clear that strengthened and standardized

regulations on safeguards and security were needed based on the consequences of theft of SNM and the growing concern over terrorism.

Scientists at BNL, who were concerned about safeguards on SNM, proposed to the AEC that an office be established to provide technical support to the AEC Division of Nuclear Materials Security. The AEC solicited proposals from contractors interested in establishing an organization to fill this need. The AEC selected BNL from the respondents.

TSO was directed initially to conduct research on safeguards of nuclear material and analyze safeguards data. However, over time, BNL was directed into much broader areas of work encompassing safeguards at AEC contractor sites, commercially licensed facilities and international safeguards as implemented by the International Atomic Energy Agency (IAEA). Since 1968, the work undertaken by the Nonproliferation and National Security Department, the successor to the TSO, has expanded into research and development and technical and policy support for several U.S. government agencies in arms control verification, homeland security, radiation detector development, radioactive source security, and nearly every area associated with the nonproliferation of weapons of mass destruction.

The International Safeguards Project Office

The International Safeguards Project Office (ISPO) has technically and administratively managed the daily operations of the United States Support Program (USSP) to the IAEA Department of Safeguards since the USSP was established in 1977. The USSP was the first and is one of 21 Member State Support Programs to the IAEA Department of Safeguards. The USSP assists the IAEA in its mission to provide credible assurances to the international community that member states are honoring their nuclear non-proliferation obligations. The USSP responds to official requests for assistance from the IAEA Department of Safeguards. Specifically, the USSP provides financial and technical support in response to IAEA requests for work that are targeted to resolve technical safeguards issues and improve verification tools. The assistance is provided by a number of U.S. stakeholders, including Department of Energy national laboratories, private sector businesses, individual consultants on short term assignments, and cost-free experts (CFEs) and junior professional officers (JPOs) who live in Vienna and work at the IAEA headquarters for extended periods. A CFE provides expertise that is not available in the IAEA’s professional staff and human resources that cannot be financed under the IAEA's regular budget. The IAEA accepts JPOs between the ages of 18 and 32 to assist with basic yet essential work in a number of technical and analytical tasks. Presently there are 11 CFEs and 8 JPOs on assignments in IAEA under sponsorship from the USSP.

ISPO is based at BNL and maintains a Liaison Office in Vienna, Austria, in the U.S. Mission to International Organizations in Vienna. ISPO performs this service at the behest of the Subgroup on Safeguards Technical Support (SSTS), a Washington-based interagency committee that provides policy, program oversight, and funding authorization in response to IAEA requests. The SSTS is composed of representatives of the U.S. Departments of Energy, State, and Defense, and the Nuclear Regulatory Commission.

ISPO’s technical management involves evaluating the feasibility of proposed tasks, offering sound recommendations for the interagency review process, and ensuring that tasks meet the IAEA’s

stated needs. Administrative management functions include tracking schedules and budgets for active tasks, preparing status reports, obtaining proposals from prospective contractors, recruiting CFEs and JPOs, and working with USSP contractors to coordinate the various tasks under the USSP. The Brookhaven ISPO Office includes six scientific, technical and administrative staff members. The ISPO Liaison Office in Vienna serves as a mechanism for local communication with the IAEA on USSP matters and for regular transmittal of information on USSP tasks to the ISPO Brookhaven Office and to the SSTS.

The development of the On-Line Enrichment Monitor (OLEM) is an example of a project undertaken by the USSP to improve the IAEA's non-destructive assay and remote monitoring capabilities at gas centrifuge enrichment plants (GCEPs). OLEM combines gamma-ray spectrometry with gas pressure and temperature data to calculate relative enrichment as a function of time and gives the IAEA the capability to continuously measure the relative enrichment of UF_6 gas flowing through the header pipes of GCEPs. OLEM units are mounted around existing GCEP header pipes as shown in Figure 1. The project was initially a collaboration between Oak Ridge National Laboratory, which produced prototype OLEM units, and Los Alamos National Laboratory, which provided independent reviews during all phases of OLEM development and provided their expertise in the algorithm development and field testing. Later Pacific Northwest National Laboratory performed independent reviews of the prototype OLEM designs. OLEM units are undergoing field testing.

Figure 1: On-Line Enrichment Monitor

ISPO has recruited U.S. citizens for positions in the IAEA Department of Safeguards since the 1980s. Under the USSP, BNL is responsible for increasing awareness of IAEA positions by distributing information to potential candidates, providing onboarding support to individuals selected by the IAEA for positions, and participating in career fairs and trade shows. ISPO's website, www.bnl.gov/ispo, contains information to support prospective candidates where candidates can indicate their interest in working for the IAEA in order to receive information on current vacancies. ISPO serves as a link between the IAEA Department of Safeguards and well-qualified, U.S. candidates. ISPO works closely with Argonne National Laboratory, which has similar responsibilities for the non-safeguards departments of the IAEA.

Nonproliferation Policy and Implementation

The Nonproliferation Policy and Implementation Group at BNL seeks to support the international safeguards capability of the U.S. government through training and the analysis, formulation and development of safeguards policy and technical analyses. A major objective is to support the safeguards activities of the IAEA in the face of challenges such as essentially flat budgets, increasing work load as more nuclear facilities come on-line, greater reliance on safeguards information and advanced technologies, and increased efforts to detect undeclared nuclear activities. All of these challenges require new and innovative safeguard's approaches and policy formulations in order for the IAEA to successfully meet its safeguards verification mandate. In addition, the group supports other safeguards and arms control initiatives, such as analytical and policy support for the Fissile Material Cutoff Treaty and leadership and implementation of the Technical Survey Team for review and assessment of the DOE International Nuclear Security Program.

The group is comprised of researchers with backgrounds and expertise in nonproliferation studies, safeguards methodology, cultural anthropology, international policy, economics, and affairs strategic planning and program and project management, and draws on the technical expertise of the other groups in the Department. The group's main sponsor is the National Nuclear Security Administration's Office of Nonproliferation and Arms Control (NA-24). The group has performed work for the former NA-25 (Material Protection Control and Accounting) to reduce the threat of unsecured nuclear materials and is building programs with the Department of Energy's Office of Nuclear Energy, the Department of State, the Defense Threat Reduction Agency, and the Department of Homeland Security. The group contributes to NNSA's Next Generation Safeguards Initiative (NGSI) which has programs in human capital development, safeguards policy, concept and approaches, technology, and international engagement. BNL's significant training experience is applied in support of human capital development, international engagement, and strengthening IAEA safeguards.

As an example of BNL's work for NGSI, each year since 2009, BNL has offered a course entitled, "Nuclear Nonproliferation, Safeguards and Security in the 21st Century," referred to as NNSS, for graduate students in technical and policy disciplines related to nuclear safeguards and nonproliferation. The course focuses on relevant policy issues, in additional to technical components, and is part of a larger NGSI short course initiative that includes separate courses that are delivered at three other national laboratories and NNSA headquarters.[ii,iii] The course includes lectures from esteemed nonproliferation experts, tours of various BNL facilities and laboratories, and in-field and table-top exercises on both technical and policy subjects. The students conduct a mock Design Information Verification[iv] at BNL's decommissioned Medical Research Reactor. Throughout the course instructors present scenarios to the students that make them use the concepts presented by the lecturers to consider resolutions for current nonproliferation-related situations. The course is open to domestic and foreign students, and generally caters to students in, entering, or recently having completed graduate school. The international and interdisciplinary mix of students attending the course encourages discussions of the topics presented during the course. Information about the course is available at https://www.bnl.gov/nnsscourse/.

The NGSI International Nuclear Safeguards Engagement Program (INSEP) provides outreach to IAEA member states that need assistance in understanding and fulfilling their safeguards commitments under the NPT and its Additional Protocol. A BNL staff member serves as the regional lead for countries of the Former Soviet Union, and BNL staff members contribute to training activities in all regions of the globe. BNL participates in engagements wherein member state representatives are trained in the development of and maintaining regulatory systems and state systems of accounting and control, their commitments under the Additional Protocol, and the preparation of safeguards declarations. BNL staff members have foreign language capabilities that enable them to lecture in the native languages of some of the member states.

With NGSI funding, NN staff members coordinated the development of a textbook entitled, *Deterring Nuclear Proliferation: The Importance of IAEA Safeguards*.[v] This textbook is now in wide use and is distributed cost-free electronically through the NN website, at https://www.bnl.gov/NNS/IAEAtextbook.php.

In recent years, with support from NGSI, NN has established close relationships with four specific institutions: Pennsylvania State University, the City College of New York, Stony Brook University, and University of Massachusetts-Lowell. NN has hosted a number of interns from the Pennsylvania State University (PSU), visited PSU and spoken twice at meetings of their Student Chapter of the Institute for Nuclear Materials Management (INMM), and hosted their INMM Student Chapter at BNL on three occasions. To the INMM Student Chapter, NN presented a program highlighting its work, including tours of our Radiation Detector Research and Development laboratories and the National Synchrotron Light Source (NSLS) and NSLS-II and a demonstration of the use of radiation detectors for identifying nuclear materials. NN has also hosted the City College of New York (CCNY) on three occasions including the most recent visit in April 2016. The program presented to CCNY students during these visits is similar to that presented to PSU. In addition, BNL presented lectures on nonproliferation and national security as part of a CCNY course in 2013.

Figure 1: CCNY student visit to BNL in April 2016.

NN also coordinated the development of a course on international safeguards and nonproliferation at Stony Brook University and collaborates with Kathleen Araujo, an associate professor at Stony Brook, whose research interests focus on energy policy and, in the case of nuclear power, its relationship with nonproliferation. Our newest relationship is with the University of Massachusetts (UMass)-Lowell. NN staff members visited UMass-Lowell to speak to its graduate Nuclear Engineering Seminar in 2015 and 2016, and Marco Marzo, Research Professor and Associate Director of the Integrated Nuclear Security and Safeguards Laboratory, spent June 2016 at BNL, where he conducted research, participated in NN's NNSS short course, assisted with the mentoring of NGSI interns, and discussed safeguards issues with staff members.

Radiation Detector Research and Development

The Radiation Detector R&D Group is a scientific, laboratory-based organization that performs experimental work on the materials and principles related to the measurement and detection of nuclear materials. The group is comprised of scientists and engineers with expertise in a variety of disciplines including nuclear engineering, electrical engineering, physics, and material science. The group's sponsors include the National Nuclear Security Administration's Office of Defense Nuclear Nonproliferation Research and Development (NA-22), the Defense Threat Reduction Agency, the Department of Homeland Security, and the National Institutes of Health, and the group has Cooperation Research and Development Agreements (CRADAs) with commercial entities.

Since the 1990s NN has conducted research on technologies to locate and characterize SNM by detecting ionizing radiation, including gamma ray spectroscopy, neutron imaging and gamma-neutron coincidence analysis.

In the early 1990s, BNL developed a high-resolution gamma-ray spectroscopy system called Controlled Intrusiveness Verification Technology (CIVET) that was proposed for arms control treaty verification. The system created templates using a few selected gamma-ray lines from SNM, so that a treaty-limited item could be shown to be the same as, or different from, other tested items. An essential feature of the CIVET design was that every hardware and software element of the system could be inspected and verified to ensure that it would not reveal sensitive information. The outputs of the measurement were two parameters that indicated whether two items were matched and a statistical confidence level of the measurement.

In the late 1990s, BNL carried out a measurement campaign for the DOE Office of Safeguards and Security to acquire high resolution gamma spectra of all the types of nuclear warheads in the enduring stockpile with a goal of confirming the presence and type of a weapon by means of high

resolution gamma spectra. BNL developed methods that are useful whenever weapons are transferred back from DoD deployment to DOE custody.

In the early 2000s, BNL staff transferred the CIVET technology to the All-Russian Institute of Automatics in a collaboration known as the Weapons Safety and Security Exchange (WSSX) agreement, and a Russian version of the system was built and tested.

In the decade from 1995-2005, BNL also developed a novel method of imaging one or more nuclear devices using passively emitted thermal neutrons. The instrument relies on a cadmium-coded aperture mask that casts a shadow on a position-sensitive helium-3 gas ionization chamber. The pattern formed by the neutrons can be decoded to create an image of the source configuration. This technology has been modernized in recent years and is available for treaty verification and other nonproliferation applications. For example, it should be capable of counting the number of warheads on a missile. Recent work on neutron imaging includes detailed modeling of the imager response and of possible source configurations to aid in the interpretation of experimental images.

BNL has also worked for a decade on developing an alternative material to high purity germanium that will provide medium to high resolution gamma spectra without the need for cryogenic cooling. BNL scientists lead the effort to understand the factors limiting the performance of cadmium zinc telluride (CZT) semiconductor detectors, which operate at room temperature. BNL's National Synchrotron Light Source I, which provided beams of x rays that could probe the response of the detectors and their crystalline structure on a microscopic scale, enabled the discovery and investigation of the typical defective structures in CZT that affect its performance in radiation detection. With the recent commissioning of the National Synchrotron Light Source-II, the department now has access to the most advanced light source in the world. BNL contributes to a steady improvement in the quality of commercial material by providing commercial suppliers of crystals with detailed characterization data.

In parallel with performing the essential task of characterizing and understanding the limitations of commercially produced material, BNL has launched an effort to grow crystals of other related semiconductors that may one day prove superior in performance and lower in cost than CZT. These include cadmium telluride with additions of magnesium, manganese or selenium instead of, or in addition to, zinc. Some of these home-grown crystals have shown very encouraging properties. An example of a crystal grown at BNL by the Traveling Heater Method is show in Figure 2.

The Radiation Detector R&D Group developed new designs of CZT detectors known as virtual Frisch-grids (VFG), which achieved significantly better energy resolution than the previous approach of coplanar grids. Further advances were made by applying energy-loss corrections on a pulse-by-pulse basis using the signals from several independent electrodes attached to different sides of the crystal. This strategy of compensating for crystal defects allows the use of cheaper second-grade material to make detectors that perform almost as well as the most expensive selected cuts. Figure 3 shows a 2x2 array VFG detector and Figure 4 depicts the improvements in spectral response that BNL has achieved with VFG detectors.

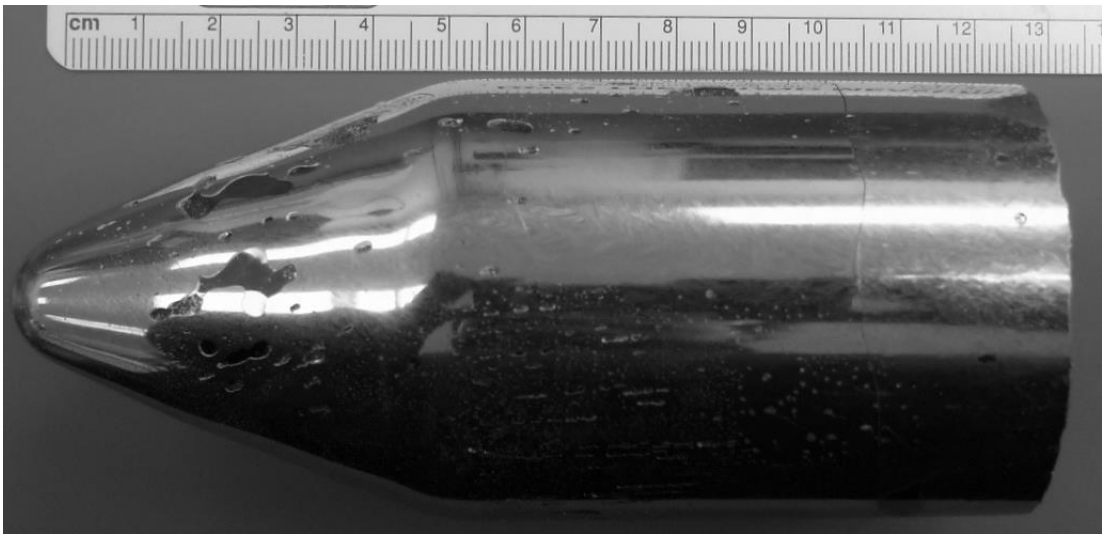

Figure 2: Traveling Heater Method-grown 5.2-cm diameter In-doped $Cd_{0.9}Zn_{0.1}Te_{0.93}Se_{0.07}$ ingot

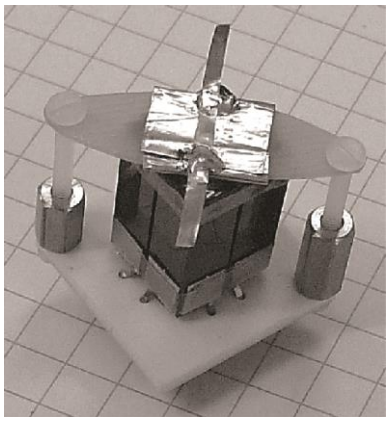

Figure 3: 2x2 array prototype of position-sensitive virtual Frisch-grid detectors developed in collaboration with FLIR Systems.

An essential enabling technology that is being used not only in the BNL CZT detectors, but also in those developed at the University of Michigan and its spin-off company H3D and in the modern designs of neutron imagers, is the Application Specific Integrated Circuit (ASIC). This marvel of modern microelectronics consists of millions of transistors, resistors and capacitors on a slice of silicon smaller than a fingernail. The BNL Instrumentation Division designs these circuits to read tiny pulses of current from as many as 64 independent contacts and to amplify and digitize these signals before sending them to a computer. The Detector R&D Group works closely with BNL's Instrumentation Division in defining specifications for the next generation of ASICs and incorporates them into practical instrument prototypes.

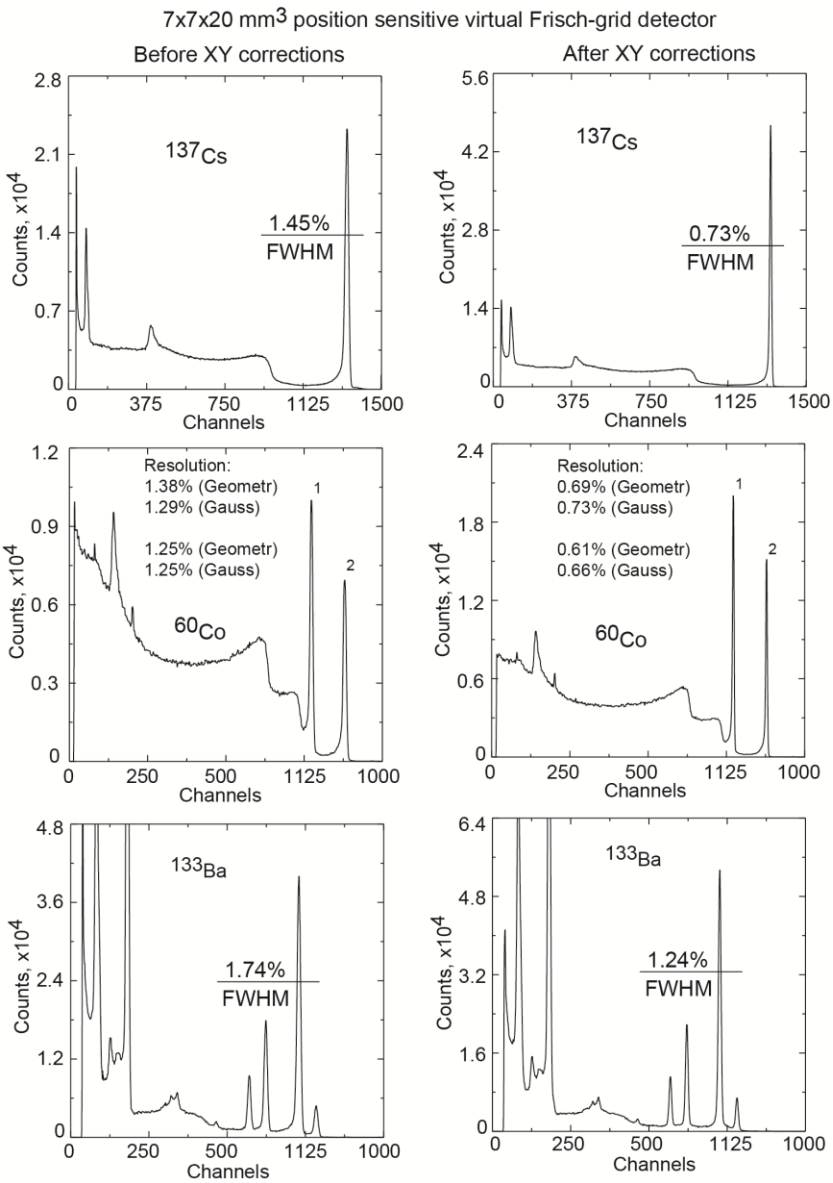

Figure 4: Improvement of spectral responses of the position sensitive virtual Frisch-grid detector before (left) and after (right) applying the 3D corrections.

Safeguards Internships at BNL

Internships at BNL in the Nonproliferation and National Security Department provide opportunities for students and recent graduates to gain valuable work experience, to learn more about career opportunities and the national laboratories, contribute to publications, and earn money that can be used for tuition or living expenses during their studies. As the host, BNL can introduce students to

its areas of research, develop lasting professional relationships, assess an individual's capabilities and work ethic, benefit from contributions to ongoing projects and research, and learn about new ideas and techniques being developed in universities. Some funding for internships is provided by the NGSI HCD sub-element, but undergraduate interns are encouraged to apply through the DOE Science Undergraduate Laboratory Internship (SULI) program, which provides funding to cover their stipend, travel, and housing allowance. Graduate students are eligible for the Graduate Research Internship Program (GRIP), a BNL managed internship program for which NGSI provides funding to cover student stipends, travel, and housing. BNL hosts undergraduate and graduate students studying political science and international affairs as well as science, engineering and math. In 2014, one of our interns won second place in the INMM's JD Williams Student Paper competition, and in 2015 he won third place in the GEM Symposium with papers on his BNL research.[vi] In 2016, another intern, who since his internship went on to receive his master's degree from Georgetown University, was selected for a Nonproliferation Graduate Fellowship in the State Department's Bureau of Verification and Compliance. BNL recruits candidates between October and December for the following summer and typically selects and notifies candidates in January and February. BNL primarily hosts interns for a ten-week period in the summer, but internships in the spring and fall are also possible. BNL interns are required to conduct a research project and document it in a poster that is presented at a symposium at the end of the internship.

Summary

BNL has a nearly 50-year history of professional and scientific work in international safeguards and nonproliferation. Our work includes policy analysis, technical research and development, and project management. The International Safeguards Project Office has assisted the U.S. government in strengthening the IAEA Department of Safeguards through technical support for 40 years. Our Radiation Detector Research and Development Group performs research and develops detectors for gamma and neutron measurements and researches semiconductor and scintillator materials to improve the safeguards and nonproliferation community's ability to detect and measure nuclear materials. Students can learn about international safeguards and nonproliferation and the work that BNL performs in these fields through the two-week NGSI short course, "Nuclear Nonproliferation, Safeguards and Security in the 21st Century," or through an internship.

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[i] The Lumb Panel was a group of industry, academic, laboratory and government nuclear experts named for the Chairman of the Panel, Ralph Lumb, and established by the Atomic Energy Commission in July 1966, to review the U.S. domestic safeguards system, and their report was completed March 10, 1967. The report commented on the IAEA and Euratom safeguards programs as well.

[ii] M. Scholz, S. Dewji, S. Poe and L. Finklea 2013, "2013 Snapshot of NGSI Human Capital Development and Future Roadmap," Institute of Nuclear Materials Management (2013).

[iii] M. Rosenthal, L. Fishbone, C. Kessler, B. Ward, "Nuclear Nonproliferation, Safeguards, and Security in the 21st Century – A Brookhaven National Laboratory Course," draft.

[iv] Design Information Verification is an inspection activity carried out by IAEA inspectors to verify that a nuclear facility's design is consistent with its declared purpose.

[v] M. Rosenthal, "Deterring Nuclear Proliferation: The Importance of IAEA Safeguards – A Textbook" (2013).

[vi] GEM stands for National Consortium for Graduate Degrees for Minorities in Engineering and Science, Inc. Founded in 1976, GEM has graduated more than 3,000 researchers, professors, entrepreneurs, inventors, and business leaders, with doctorates in the physical sciences, life sciences, and engineering.