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NUCLEAR SAFEGUARDS

NONDESTRUCTIVE INSTRUMENT DEVELOPMENT

Los Alamos NATIONAL LABORATORY


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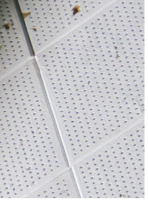
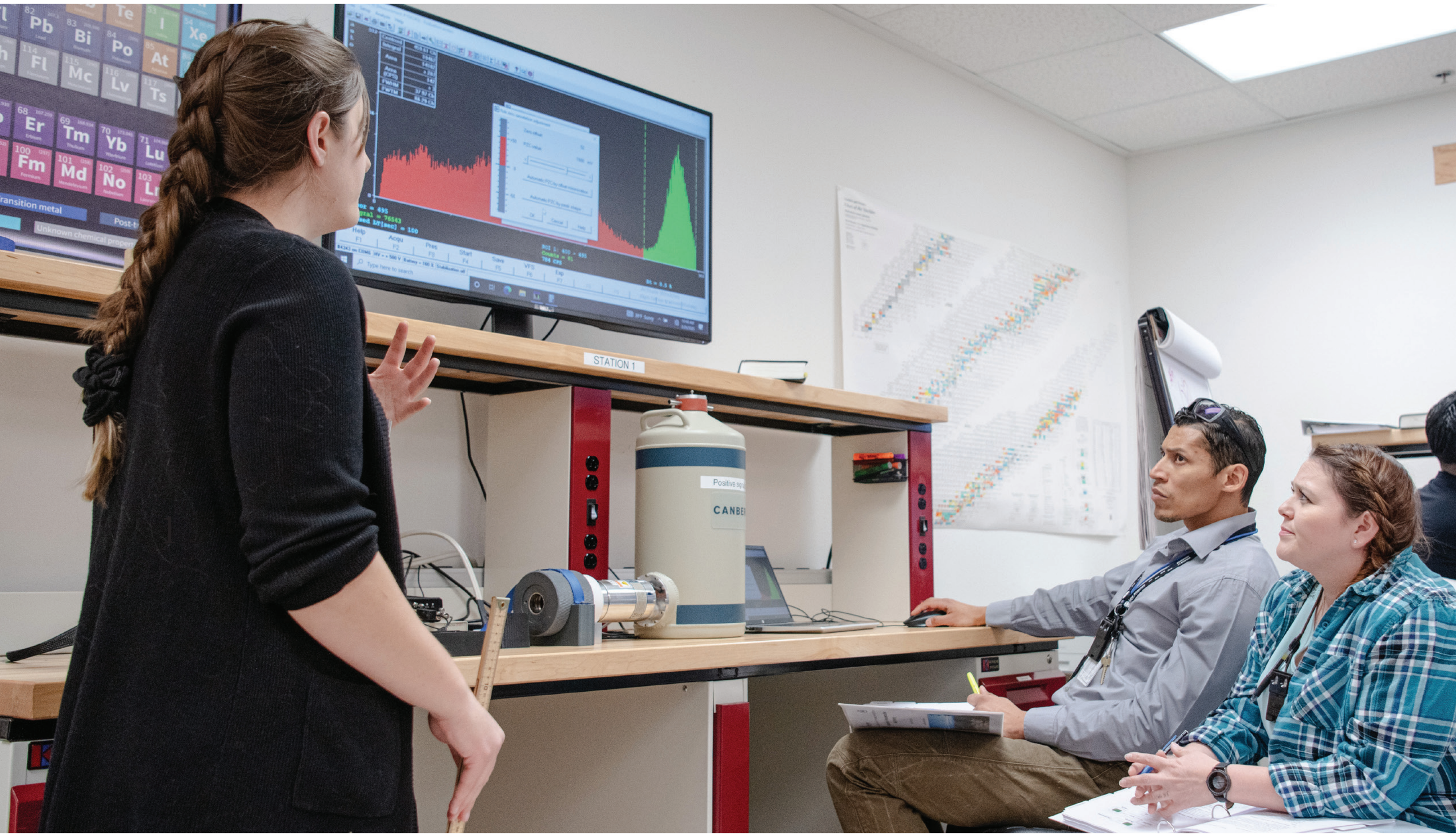


Contents



Safeguarding the Future, foreword by Alison Pugmire 2

4 50th Anniversary of the Safeguards and Security Technology Training Program

14 NDA Instruments of the Safeguards Training Program

24 Atomic Management: The DYMAC 2.0 Initiative

36 Tracking Nuclear Materials Using RFID

42 From Starlight to Safeguards: The SOFIA Gamma-Ray Spectrometer

48 ND-Alpha: The World's First Nondestructive Alpha Spectrometer

52 The Race to Nonproliferation: The Baruch Plan

Safeguarding the Future—A Legacy of Innovation at Los Alamos

Safeguards work at Los Alamos National Laboratory (LANL) has long stood at the intersection of science, technology, and global security policy. Since 1966, when physicist Robert Keepin founded the nation's first safeguards R&D program at LANL, the Laboratory has played a leading role in developing tools and techniques that underpin international nuclear nonproliferation. Anchored by the Safeguards Science and Technology group (NEN-1) in the Nuclear Engineering and Nonproliferation Division, the Lab has remained at the forefront of safeguards, delivering world-class solutions to help the International Atomic Energy Agency (IAEA) verify compliance with the Nuclear Nonproliferation Treaty, ensuring that nuclear materials are used for peaceful purposes.

Credit: IAEA

A cornerstone of this mission is the use of neutron- and gamma ray-based nondestructive assay (NDA) methods, which allow for the quick characterization of nuclear materials without altering them—a capability critical for inspections in high-radiation environments or through sealed containers. These techniques have been refined and deployed worldwide, serving as the foundation for automated, remote monitoring systems that improve both safety and accountability. LANL's approach is deeply rooted in field-based innovation, observing real-world problems in nuclear facilities and responding with tailored instrumentation and integrated solutions. Increasingly, these tools are designed for 24/7, unattended operations, a necessity as the number of nuclear facilities grows and inspector resources remain limited.

This issue of the magazine celebrates that enduring legacy by highlighting past, present, and future advances in safeguards. We begin with a retrospective on the **50th Anniversary of the Safeguards and Security Technology Training Program** (SSTTP), a globally respected LANL program that has trained over 7,000 professionals—including nearly every IAEA inspector since 1980. The SSTTP provides hands-on training with real nuclear materials and cutting-edge NDA instruments, helping set international benchmarks for safeguards competency (*p4*).

A companion article offers a **primer on NDA instrumentation,** summarizing key techniques such as gamma spectroscopy, calorimetry, and neutron counting (*p14*). These are the tools at the heart of modern safeguards, many of which originated or were perfected at LANL.

Looking ahead, we explore how international safeguards science is being adapted to the pit production mission. In **Atomic Management: The DYMAC 2.0 Initiative**, you'll read about LANL's ambitious effort to bring real-time, in-line material monitoring to the Lab's plutonium facility (PF-4), overcoming previous challenges with high background radiation through advanced data acquisition systems and distributed neutron sensors (*p24*). Complementing this is an article on **RFID tracking**, which shows how LANL is replacing manual nuclear inventory methods with smart, passive systems for more efficient and agile operations (*p36*).

This issue also showcases breakthroughs in safeguards instrumentation, such as **SOFIA, a superconducting gamma-ray spectrometer** adapted from astrophysics to deliver ultra-high-resolution isotopic analysis in nuclear facilities (*p42*), and **ND-Alpha, the world's first nondestructive alpha spectrometer** enabling point-and-shoot isotope identification in the field (*p48*).

The issue rounds out with a thoughtful reflection on the historical **Baruch Plan**, connecting the roots of modern nuclear governance with today's pressing need for international oversight—particularly as emerging technologies like AI begin to impact the safeguards landscape (*p52*).

Together, these articles not only celebrate LANL's historical leadership but also underscore its commitment to anticipating and shaping the future of global nuclear security. Next year, we will celebrate the 60th anniversary of safeguards at LANL, marking six decades of innovation and impact. The Laboratory's safeguards work continues to evolve, grounded in scientific excellence and driven by the urgent mission to keep the world safe.

— *Alison Pugmire*
Group Leader, Safeguards Science and Technology

50th Anniversary of the Safeguards and Security Technology Training Program

By Owen Summerscales

After the advent of nuclear weapons during the Manhattan Project, it became evident that international cooperation was essential to prevent the proliferation of such technology. Efforts such as the 1946 Baruch Plan, which proposed firm international control over weapons to ensure the peaceful use of nuclear energy, failed due to opposition from the Soviet Union (see p52). In time, safeguards emerged as the primary mechanism to prevent proliferation, including measures to verify that countries adhere to their commitments to avoid using nuclear materials for weapons purposes.

Nuclear materials emit distinctive radioactive signatures, making safeguards dependent on a range of detection instruments—most of which did not even exist when nonproliferation principles were first introduced. From the outset, Los Alamos National Laboratory has been at the forefront of developing nondestructive assay (NDA) instruments, particularly those designed for neutron detection, and has established a globally recognized training program dedicated to their use—the Safeguards and Security Technology Training Program (SSTTP). This program has shown impressive longevity, marking its 50th anniversary in 2023. In this article, we explore the program's history within the broader context of safeguards history and the evolution of NDA technology.

Figure 1. Since 1980, all new IAEA inspectors have been required to come to Los Alamos to complete a two-week course on nondestructive assay instruments within their first year on the job. Credit: IAEA.

History of safeguards

Formalized international safeguards began in 1957 with the establishment of the International Atomic Energy Agency (IAEA) under the United Nations, which functions as the world's nuclear inspectorate and is the international center for cooperation in the nuclear field. The aims of the IAEA are to prevent nuclear weapons proliferation, build trust among nations, balance energy and security goals, and address emerging threats. In practice, achieving these objectives requires a dedicated team of highly skilled inspectors—along with nuclear experts and political advisors—who collectively work together to promote global security.

The IAEA became the implementing body for the modern cornerstone of nuclear safeguards, the Non-Proliferation Treaty (NPT), when the treaty was established in 1968. Under the NPT, non-nuclear-weapon states agree not to develop nuclear weapons in exchange for access to peaceful nuclear technology. As of early 2025, according to the IAEA, 32 countries operate nuclear power plants, with another 30 planning to begin programs, but only nine possess nuclear weapons. The IAEA is responsible for safeguarding 230,754 significant quantities of nuclear material worldwide, encompassing 1,353 nuclear facilities (a "significant quantity" of nuclear material is defined as the minimum amount that could be used to manufacture a nuclear explosive device).

This mission requires navigating a complex geopolitical landscape and can be highly demanding, at times even requiring missions to conflict zones. For example, in 2022, IAEA inspectors undertook a critical mission to the Zaporizhzhia Nuclear Power Plant in Ukraine (now under Russian control) to assess and ensure its safety amidst the ongoing war.

Los Alamos and the establishment of international safeguards

Los Alamos has a long history of developing technology for nuclear safeguards and global security. This originated with physicist Bob Keepin, who, after returning from a two-year stint at the IAEA in 1966, established the Los Alamos Nuclear Safeguards Program, where he pioneered the development of NDA technology. Contrasting with the traditional, destructive forms of analysis that involved removing material from facilities and sending it to laboratories for analysis, these tools were better suited to performing inspections, which often have to be carried out quickly and on location.

The Laboratory at the time also faced a pressing need—establishing an internal accounting system for the nuclear materials used in its research and development (R&D) endeavors. NDA instruments were perfectly suited for this application as they allowed an inventory to be performed without affecting the integrity of the materials (see p24 for a detailed account of the DYMAC initiative). By the early 1970s, Keepin's research program had become the premier safeguards R&D program in the world and produced many instruments that are now staples in the safeguards inspector's toolkit.

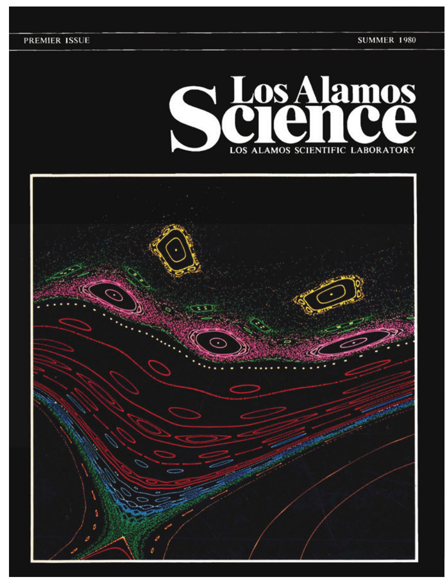


Figure 2. Cartoon of Bob Keepin taken from "Nuclear Safeguards—A Global Issue" written by Keepin for Los Alamos Science, 1980.

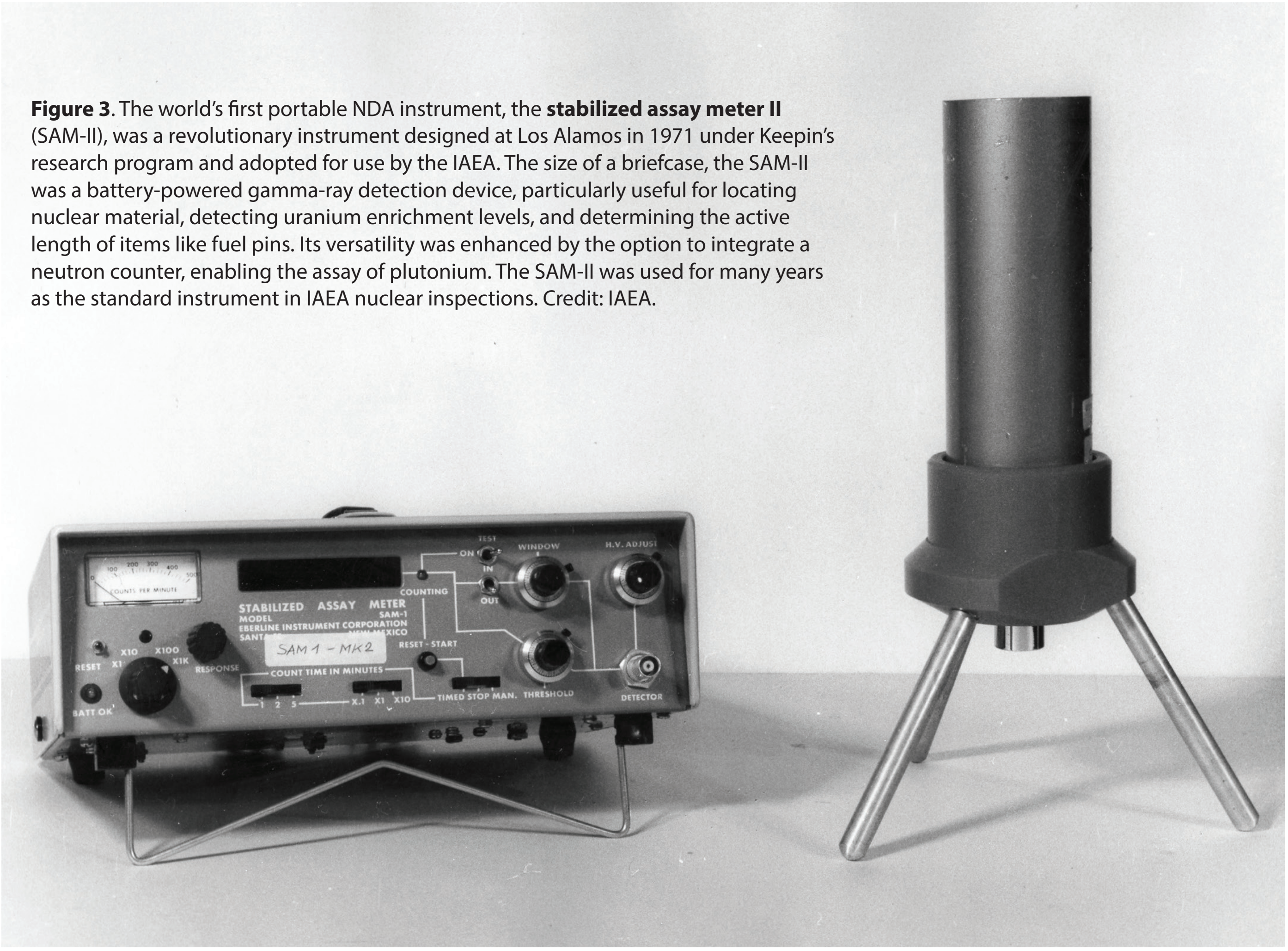


Figure 3. The world's first portable NDA instrument, the **stabilized assay meter II** (SAM-II), was a revolutionary instrument designed at Los Alamos in 1971 under Keepin's research program and adopted for use by the IAEA. The size of a briefcase, the SAM-II was a battery-powered gamma-ray detection device, particularly useful for locating nuclear material, detecting uranium enrichment levels, and determining the active length of items like fuel pins. Its versatility was enhanced by the option to integrate a neutron counter, enabling the assay of plutonium. The SAM-II was used for many years as the standard instrument in IAEA nuclear inspections. Credit: IAEA.

NDA training at Los Alamos

Early on in the safeguards research program, it became evident that IAEA inspectors and other NDA users needed supplemental training—having developed many of these NDA tools, Los Alamos assumed responsibility for training inspectors on the tools' use. In 1973, the course *Fundamentals of Nondestructive Assay with Portable Instrumentation* was offered by the Laboratory and has been presented almost every year since. From this seed, many new branches have sprouted, now composing the Safeguards and Security Technology Training Program (SSTTP), which celebrated its 50th anniversary in 2023. Over this time, more than 400 courses have been conducted as part of the SSTTP, training 7,000 participants from over 50 countries—including over 1,000 IAEA inspectors. Since 1980, all new IAEA inspectors have been required to come to Los Alamos to complete a two-week NDA course within their first year on the job.

The impressive attendance figures are testament to the unique aspects of the program, which is unparalleled anywhere else in the world. Marc Ruch, the director of the SSTTP, explains, "Inspectors come here and get to learn on the real equipment that they use, by people who are either the developers or at least the experts in the field on that equipment." With Los Alamos remaining at the forefront of NDA instrumentation, this level of expertise is rare and highly valuable in the world of safeguards.

Figure 4. The SSTTP has trained virtually every IAEA inspector since 1980 and boasts several notable alumni. In this photo (above, *right*) from the 15th NDA Inspector Training Course (1985), the current IAEA Deputy Director General and Head of the Department of Safeguards, Massimo (Max) Aparo, is pictured at front, far left. Howard Menlove, pioneer of many safeguards techniques at Los Alamos and an original member of the Lab's Safeguards group, hired by Bob Keepin in 1966, is standing second from left in the back row.

At a dedicated training laboratory at Los Alamos, trainees get to assay real nuclear materials—"representative of the kinds of stuff they would see in the field," Ruch says. "We have plutonium, uranium—everything from depleted to highly enriched—metals, oxides, all kinds of materials in an accessible facility where we can actually get started at 8:30 and wrap up at 5:00—you don't need hours of security every day."

This unique combination of technical expertise, access to a wide variety of special nuclear material, and a streamlined security process for all trainees—including foreign nationals (it is essential to accommodate the international safeguards community)—explains the success and longevity of the SSTTP. And the program has never been as popular as it is now. Ruch says that they run their keystone tuition course, Fundamentals of NDA, several times a year—available to almost anyone who can pay the registration fee—and the course is usually sold out within 24 hours of being announced.

The SSTTP brings together a wide range of nuclear scientists, inspectors, technicians, and officials from around the world and various career levels—at times, a high-ranking foreign government official may find themselves working alongside a student or trainee technician. Ruch notes that during downtime in the training lab, engaging discussions often arise while instruments are collecting data, allowing the instructors to learn about the challenges that trainees face in the field and keeping the Laboratory's Safeguards Science and Technology team informed about important issues. In addition to fostering networking and collaboration, Ruch says that some participants end up joining their group after taking courses in the SSTTP, describing it as an effective recruitment tool.

Figure 5. At a dedicated facility at TA-66, staff members of Safeguards Science and Technology (NEN-1) teach courses as part of the Safeguards and Security Technology Training Program to participants from outside of the Laboratory.

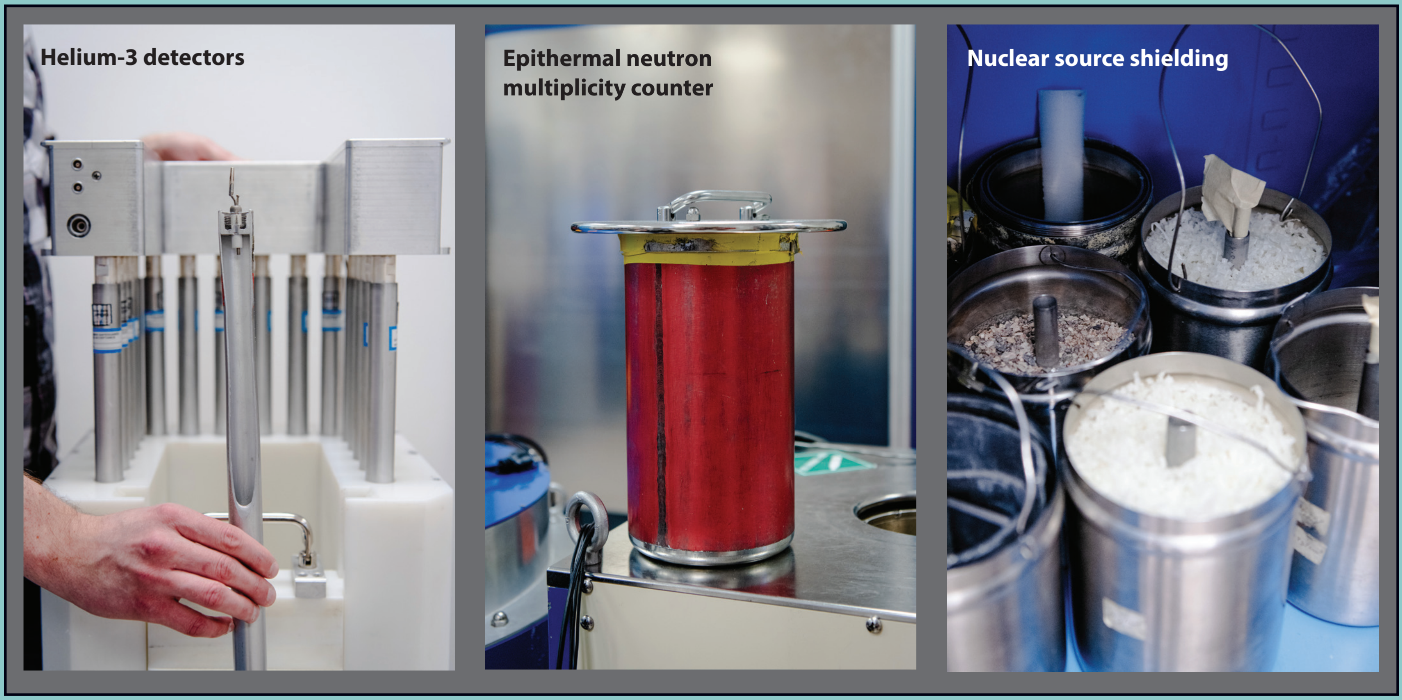
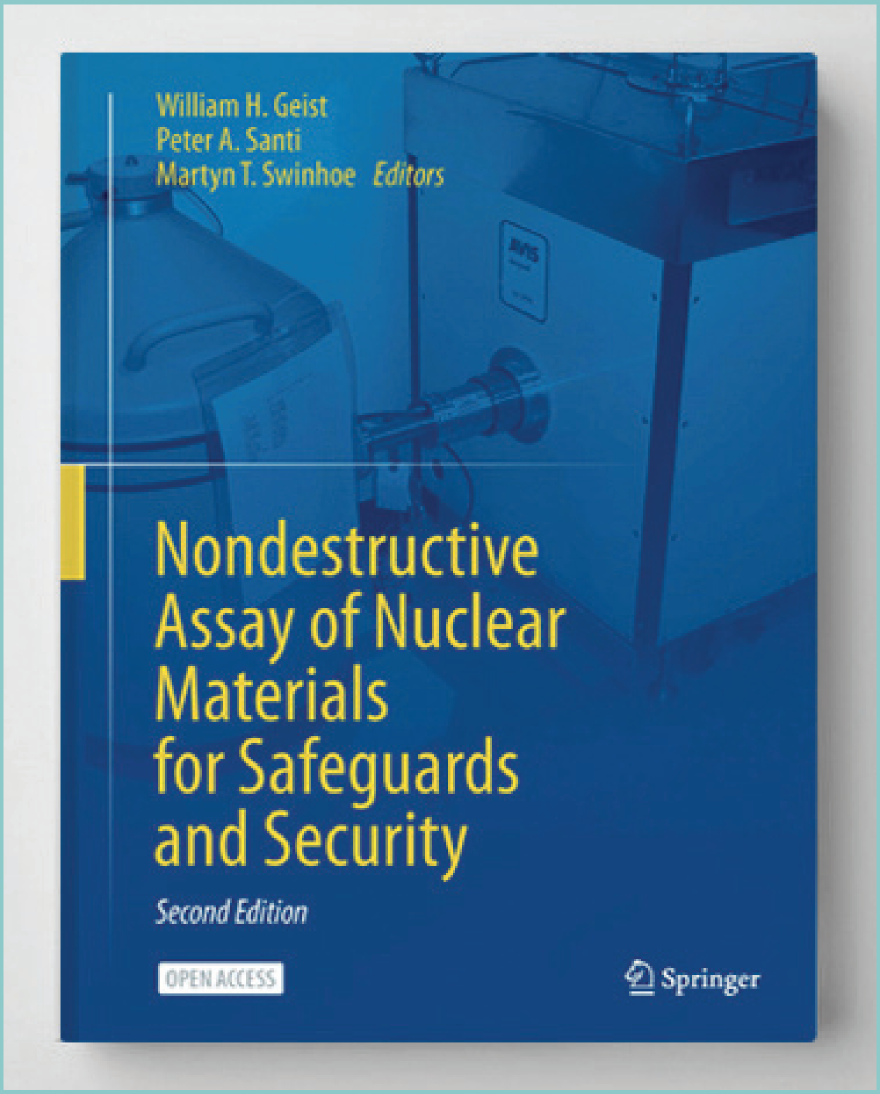


Figure 6. In the foreground is a helium-3 proportional counter that has been cut open to show participants the interior workings. Behind it is a uranium neutron coincidence collar (UNCL) with its helium tubes and electronics lifted and exposed.

The graphite top plug for an epithermal neutron multiplicity counter (ENMC). Material to be assayed is placed inside the well of the ENMC and the plug is replaced to reflect neutrons back into the system that would otherwise escape from the top.

Cans containing different matrices (e.g., polyethylene, sand, etc.) are used as teaching tools to show how these materials can impact measurements around nuclear material: a californium-252 source is placed into the central tube in one of the cans and is measured in a neutron well counter.

Figure 7. A high purity germanium (HPGe) detector with its electronic components exposed, attached to a liquid nitrogen dewar for cooling to enable it to operate and detect radiation. This cooling process is crucial to reduce leakage current and noise, which would otherwise degrade the detector's energy resolution. The crystal of high purity germanium from a separate detector is visible on tabletop below; HPGe crystals are engineered single-crystal ingots, free of dislocations and defects, with exceptional purity levels (up to 13N or 99.99999999999%).



The safeguards reference book

In 2024, following years of dedicated effort, the Safeguards Science and Technology group released a comprehensive 700-plus page book titled focusing on NDA measurements. This open-access title is the second edition of *Passive Nondestructive Assay of Nuclear Materials*—known as the PANDA manual—which has been a classic reference text since 1991. The book originated from the SSTTP training program, with most of the updates in the new edition authored by Los Alamos scientists, and was dedicated to their colleague, Howard Menlove, to recognize his pioneering contributions to numerous methods and instruments: Menlove began working in Keepin's safeguards program in 1967 and has developed NDA instruments for nearly five decades.

What do trainees learn?

At present, in addition to the Fundamentals of NDA course, there are four additional courses that compose the SSTTP, each taking around 3–5 days to complete, taught by 19 members of staff. Trainees gain skills with a variety of NDA methods, including neutron, gamma-ray, and calorimetric techniques, for measurements of uranium and plutonium in various forms, such as fuel, waste, and holdup (the material that accrues inside equipment during production processes). Other topics have also included radionuclide identification, nuclear material control and accounting (MC&A), statistics for MC&A, and physical protection.

Ties with international partners are also strengthened through this program. Specialized safeguards courses have been created for both the Japanese and Chinese nuclear authorities, in 2011 and 2023, and a workshop on nuclear materials and accounting was held in 2023 for the executive representatives and technical staff from nuclear regulatory bodies across five African countries.

There are also courses available for students at Los Alamos, including the Keepin Summer Program, an eight-week intensive program instigated in 2014 that includes safeguards training. Los Alamos also houses one of 18 analytical laboratories outside of Austria (home of the IAEA) that compose the IAEA Network of Analytical Laboratories, which evaluate samples of special nuclear material collected from facilities under the IAEA's purview.

Current and future challenges

Across the nation, government and private industry are pushing for the development and implementation of advanced nuclear reactors that can support increased energy demands and help achieve greater energy security. This push is creating new technologies along with increased global trade in nuclear materials, and, therefore, stricter oversight and inspections have been needed to prevent misuse.

Modern nuclear fuels in particular pose some unique challenges, with mixed-oxide fuels representing an increased proliferation risk. These fuels complicate neutron detection patterns with fissile sources of both plutonium and uranium isotopes. High burnup fuels—which squeeze more energy out of the fissile reactions—remain in reactors longer, resulting in greater isotopic complexity and higher levels of residual radiation, and accident-tolerant fuels introduce additional materials into the assemblies and dopants into the fuel, requiring new tools to assess these materials' behavior and properties. These problems are being addressed with Los Alamos NDA innovations such as the Active Well Coincidence Counter, FRAM software, and the handheld laser-induced breakdown spectrometer (LIBS), which apply modern computational methods to safeguards technologies (see sidebar on p13 for more details).

SSTTP courses are continuously being improved to reflect these new challenges that face inspectors in the field. One piece of technology that the IAEA has expressed interest in is the CZT (cadmium-zinc-tellurium) detector, a highly portable type of gamma detector, similar to high-purity germanium detectors (HPGe; see p14 for more information), but without the need for cryogenic cooling. Ruch wants to incorporate this tool into the program, which may offer practical improvements over current instrumentation. He is also keen to obtain any advanced nuclear fuel samples for the program, such as TRISO (TRi-structural ISOtropic) particles, a very robust form of enriched uranium slated for use in the next generation of reactors. It is essential, Ruch says, that instructors at Los Alamos get ahead of the game and start developing training programs for these materials before they start appearing in real nuclear facilities.

The SSTTP has constantly evolved over its 50-year history, keeping pace with developments in instrumentation and adapting to new challenges in the global security landscape. Today, these challenges seem greater than ever as the world shifts to embrace nuclear and the nuclear industry itself undergoes a paradigm shift with the deployment of a long-anticipated fleet of advanced reactors. It is of little surprise that one of the Laboratory's longest running programs is in greater demand than ever.

Acknowledgments

The author would like to thank Marc Ruch, Bill Geist, Nina Rosenberg, John McLeod, Jake Bartman, and Anne Jones for help with the article, and the IAEA for additional images.

G. Robert Keepin was a pioneering physicist at Los Alamos who played a key role in developing nuclear safeguards. In the 1960s, he served as head of the Physics Section at the IAEA, where he helped shape the agency's early nonproliferation efforts. He returned to Los Alamos to establish a research program that developed technology for non-destructive assay, laying the foundation for modern safeguards systems still in use today. This image is taken from the American Nuclear Society's Nuclear News, in which Keepin authored a three-part series on the IAEA in 1966. Credit: American Nuclear Society.

Los Alamos safeguards innovations

Of all the NDA instruments pioneered at Los Alamos, perhaps the notable are the sophisticated **neutron-based detection systems**, many of which are used in the SSTTP (described in detail in the article on p14). These systems are designed to tackle real-world problems, such as the complexities inherent in the contents of nuclear waste drums or the complications arising from particular nuclear fuel configurations.

Los Alamos has also advanced the use of **laser-induced breakdown spectroscopy (LIBS)** for nuclear and environmental applications, and since the 2000s has played a leading role in the development of portable LIBS systems for nuclear safeguards and homeland security, collaborating with private industry to refine the technology for field applications.

Improving computational tools for analyzing data collected from NDA instruments is another essential component of the research efforts. These tools include the **IAEA Neutron Coincidence Counting software**—an adaption of the Los Alamos Neutron Coincidence Counting code, first developed in the 1990s—and the gamma-ray isotope analysis software **FRAM (Fixed-Energy Response-Function Analysis with Multiple Efficiency)**, a code used by IAEA inspectors primarily to determine the isotopic composition of plutonium in special nuclear materials.

Above: The portable laser-induced breakdown spectrometer (LIBS), used for homeland security, emergency response, and environmental monitoring of hazardous materials, is an example of an NDA safeguards innovation developed at Los Alamos. Pictured is the Thermo Scientific Niton Apollo Handheld LIBS Analyzer. Credit: Thermo Scientific.

NDA Instruments of the Safeguards Training Program

By Owen Summerscales

Nondestructive assay (NDA) instruments are widely used in industries such as aerospace, materials science, oil and gas, and construction, where they are employed by engineers to interrogate the structure of a material without affecting its composition. These instruments also find a very important application in the nuclear industry—particularly in nuclear material accounting and control (NMAC) and inspections—as the radioactive signatures of nuclear materials makes them amenable to a range of NDA techniques. These methods preserve the integrity of the sample, minimize health and safety risks in hazardous environments, and provide rapid, often real-time results.

Types of NDA methods for determining properties of nuclear materials include neutron-based techniques, gamma ray spectroscopy, X-ray fluorescence, calorimetry, radiography, ultrasound and acoustic methods, laser-induced breakdown spectroscopy, and surface analysis. Today, the IAEA (International Atomic Energy Agency) routinely uses dozens of NDA systems, the majority of which were pioneered at Los Alamos National Laboratory. This article provides a technical overview of the primary techniques taught to inspectors in the Los Alamos Safeguards and Security Technology Training Program (SSTTP; see p4 for an overview of the course).

1. Gamma-ray spectroscopy

Gamma rays are the highest—and most damaging—energy form of electromagnetic radiation, with photon energies ranging from hundreds of keV to several GeV. They are emitted by radioactive decay at energies that are unique to specific isotopes, making the distribution of gamma ray frequencies an effective fingerprint for isotope identification. By measuring the intensities of the energies, the abundance of various isotopes in a given sample can then be further calculated.

For the measurement of gamma rays—both inside and outside of safeguards applications—there are several types of detectors:

- **Inorganic scintillators**, e.g., sodium iodide (NaI). These materials fluoresce when exposed to gamma rays, producing pulses of light that can be analyzed.
- **Semiconductor (solid-state) detectors**, e.g., high purity germanium (HPGe). Gamma rays ionize these materials, creating electron-hole pairs that convert the energy of the gamma rays into an electrical current, which is measured.

Additionally, outside of the scope of the SSTTP:

- **Gas-filled detectors**, e.g., Geiger counters. A volume of gas is ionized by gamma rays and creates an electric current between two electrodes. These detectors are not frequently used in safeguards applications because they lack the spectroscopic resolution needed in the energy range typical for uranium and plutonium (approximately 100–1,000 keV).
- **Microcalorimeter detectors**, e.g., SOFIA (see p42). Currently in the R&D phase, these highly sensitive devices are capable of generating extremely high-resolution spectra by utilizing material properties at ultra-low temperatures, below 0.1 K.

Figure 1. Left: An IAEA inspector uses an HPGe gamma detector to measure enriched uranium at URENCO in the Netherlands. Right: IAEA inspectors doing a physical inventory of nuclear fuel assemblies stored on a fresh fuel rack at Slovakia's Mochovce nuclear power plant. Credit: IAEA/Dean Calma.

1.1 Inorganic scintillators

A scintillation detector consists of a scintillator crystal, photodetector, and a circuit for measuring the pulses from the photodetector. A typical output plots energy (or "channels") versus counts. Scintillator crystals that are best suited for the detection of gamma rays contain absorbing atoms with high atomic number (high-Z materials), which are usually doped with an impurity to help release the absorbed energy. When the material absorbs a gamma ray, it excites an electron from the valence band into an excited state, creating an electron-hole pair—this pair moves around the crystal lattice until it finds an impurity center, where it can relax and release the energy as scintillation photons that can be counted.

Thallium-doped sodium iodide is by far the most commonly used scintillator material and finds wide applications in nuclear NDA (as well as in fields such as crystallography, where it has been foundational). It was first discovered in 1948, ushering in the field of inorganic scintillation X-ray and gamma spectroscopy, and remains popular due to its extremely good light yield, high stopping power (thanks to high-Z element iodine), and excellent linearity. More recently, the IAEA has switched to using more expensive cerium-doped lanthanum tribromide due to its better energy resolution.

The first ever electronic scintillation counter was built by Curran and Baker in 1944 during the Manhattan Project to detect alpha emissions from uranium. They used a zinc sulfide scintillator and the newly available photomultiplier tube to obtain a record of electrical pulses that could be subsequently analyzed, giving reliable measurements of uranium. Previously, counting these scintillations had to be laboriously performed by eye using a special type of microscope.

Figure 2. Inorganic scintillators emit light when exposed to ionizing radiation—one of the oldest known techniques for detecting radiation. Credit: CAEN SyS (caensys.com); S.E. International, Inc (seintl.com).

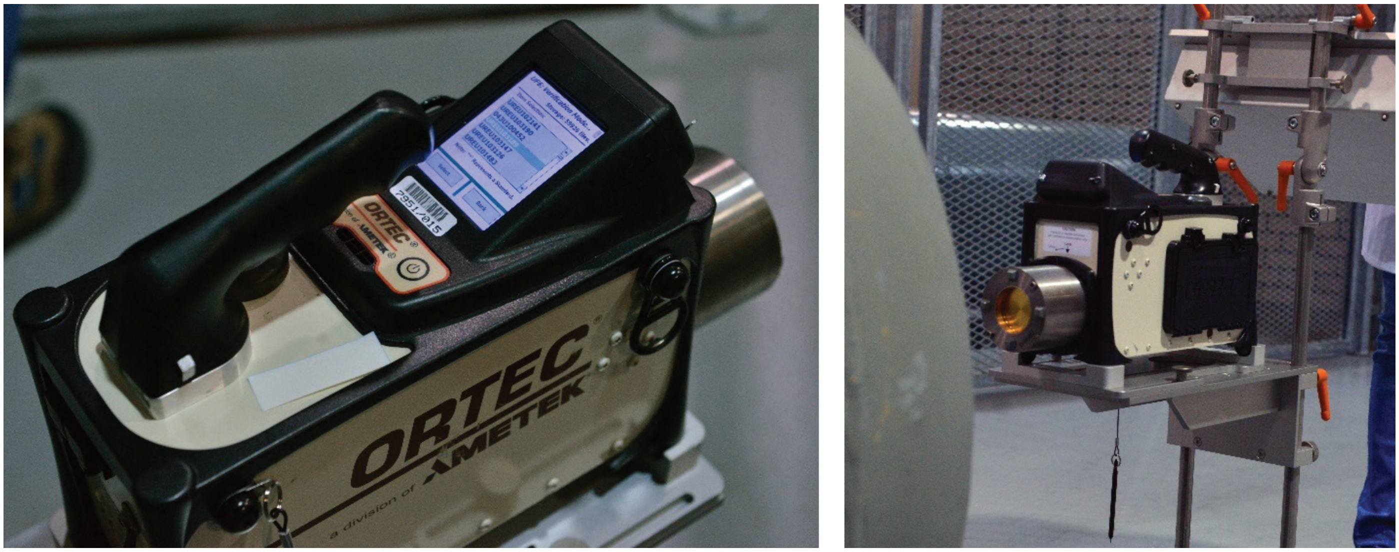


Figure 3. High purity germanium detectors are the industry-standard for gamma detection with portable NDA instruments. Credit: Dean Calma/IAEA.

1.2 Semiconductor detectors

Semiconductor detectors made from high purity germanium (HPGe) offer a significant increase in energy resolution over sodium iodide scintillators, which, despite their many advantages, give very broad gamma-ray peaks by comparison (Fig. 4). This means that closely spaced peaks cannot always be resolved with scintillator detectors, making them unsuitable for complicated mixtures of materials or with elements that have multiple isotopes and emit many gamma energies. The germanium crystal used in HPGe detectors is extremely pure—in excess of 99.999999999%. This is far beyond the purity of typical semiconductor-grade materials, as even trace impurities can dramatically degrade detector performance.

HPGe detectors comprise a semiconducting diode directly connected to a circuit: upon absorption of a gamma ray, an electron-hole pair is created in a similar manner as in a scintillator material. Under the influence of an electric field, the electron-hole pair travels to the electrodes, giving a measurable electric pulse. One disadvantage of these detectors is that they must be cooled to cryogenic temperatures—at room temperature, thermal excitation causes excessive noise and destroys energy resolution. The need for cooling therefore makes them more expensive and less portable.

A new type of detector being considered by the IAEA (and slated to be included in the SSTTP training course) is the CZT (cadmium-zinc-tellurium) detector, which offers similar performance to HPGe instruments but without the need for cryogenic cooling (Fig. 5).

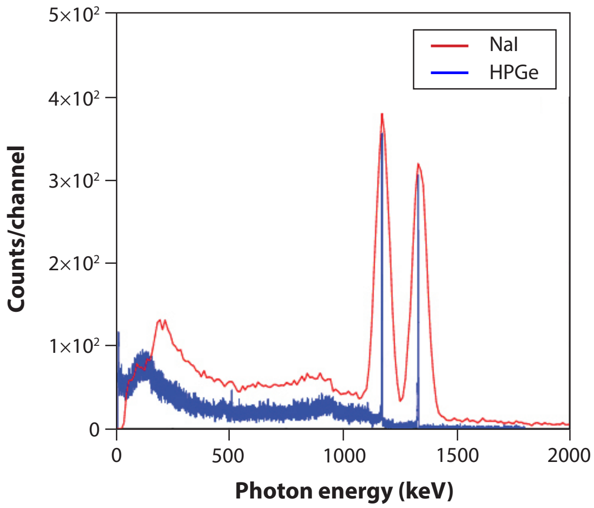


Figure 4. Demonstration of the improved resolution in gamma spectra of HPGe (blue) over NaI(Tl) (red) for a sample of cobalt-60. Credit: Radioisotopes and Radiation Methodology, Soo Hyun Byun, McMaster University, Canada.

Figure 5. The IAEA is considering the cadmium-zinc-tellurium (CZT) semiconductor detector as a more advanced alternative to traditional HPGe instruments. Credit: H3D Inc.

2. Calorimetry: Quantification through heat

Calorimetry is an alternative and complementary assay method for gamma ray detection, being simpler and more robust than spectrometry, and useful for environments where total energy output is the primary concern. Gamma radiation produces heat when it hits a sensor, and by quantifying this thermal power, an accurate mass measurement of the isotope can be obtained. The main prerequisite is that the half-life of the radioisotope must not be either too short (producing an inconsistent heat output) or too long (producing too little heat to measure on a practical timescale). For safeguards purposes, this prerequisite is met by most of the common plutonium isotopes (plutonium-238, -239, -240, and 241), tritium, and americium-241. Uranium-235 and -238 decay too slowly for quantification via standard calorimetry.

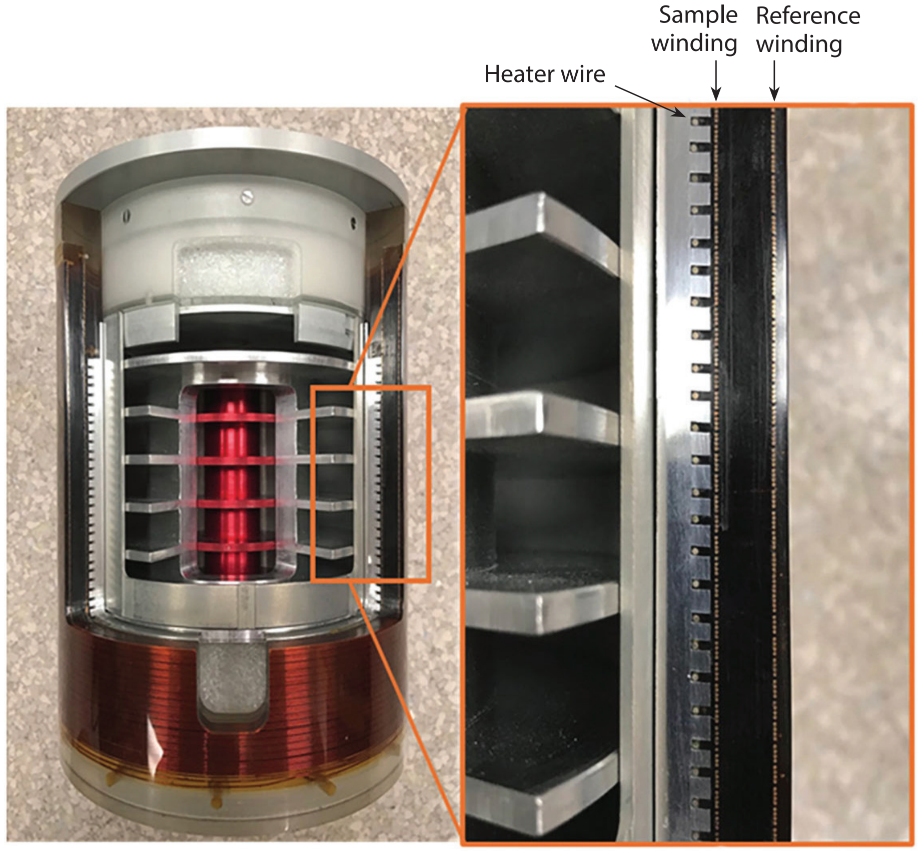


Figure 6. In calorimetric assay, thermal power is measured and combined with knowledge of isotopic composition to determine the mass of each nuclide in an item. In a gradient bridge calorimeter, pictured here in cutaway, the sample winding and reference winding are two key components that serve as sensing elements. They detect small temperature differences between a sample and a reference; the term "bridge" refers to the use of a Wheatstone bridge circuit. Credit: PANDA manual.

Calorimetry is a simple and accurate technique and is widely used in the nuclear industry to account for plutonium in fuel pellets, powders, and metals, often obtaining the highest precision and accuracy of all NDA methods. It focuses on the total energy absorption rather than resolving individual gamma-ray energies and can also be used to quantify radiation dose. Because calorimetry cannot detect isotopic signatures, it cannot be used alone for plutonium and needs to be combined with a method of determining isotope ratios—typically, gamma spectroscopy or mass spectrometry. In some situations, for instance large items where the use of gamma spectroscopy is limited, or when quicker analysis is needed (calorimetry measurements typically take 1–8 hours), neutron-based methods are used. Plutonium also often contains varying amounts of americium-241, a heat-producing decay product, that needs to be accounted for.

3. Neutron counting techniques

Neutrons, being electrically neutral, can only be detected indirectly from their interactions with matter. These interactions generate charged particles—such as alpha particles, protons, and positrons—as byproducts, which produce electrical signals that are picked up by the detection system. Due to the nature of these neutron-induced reactions, detectors generally offer limited energy information, providing the number of neutrons detected rather than their energy. As a consequence, many neutron detecting systems are referred to as counting methods. The raw count rate is referred to as “singles” neutron counting, which is used to distinguish it from more sophisticated coincidence and multiplicity measurements, discussed below.

Neutron-based detection techniques are very powerful and include a range of basic methods that count the number of neutrons emitted spontaneously, such as passive neutron counting. In addition, more complex techniques can be employed, including active neutron interrogation, which uses additional neutron sources to induce fission events. Many of these techniques rely on helium-3—an expensive material—used in neutron proportional counters, and involve bulky, specialized equipment that is often deployed alongside previously described methods such as gamma ray spectroscopy.

Three important transportable neutron counting instruments covered by the SSTTP are the high-level neutron coincidence counter (HLNC), the active well coincidence counter (AWCC), and the uranium neutron coincidence collar (UNCL), described below. In the training course, participants get a hands-on learning experience with all of these instruments, which were originally designed at Los Alamos in the 1970s and 1980s specifically for safeguards inspection.

Counting techniques for plutonium: 240 is the magic number

Spontaneous fission is the primary NDA signature and assay method for plutonium—a typical sample of plutonium metal emits approximately 100–400 neutrons per gram per second. This process occurs exclusively in the even-numbered isotopes of plutonium—238, 240, and 242—with plutonium-240 being the dominant contributor due to its high abundance in a typical sample of plutonium metal, making it the key isotope for analysis.

One of the complications of passive neutron counting is caused by (α,n) reactions, which occur when light elements absorb alpha particles. These light elements can include oxygen present in oxides or hydrocarbons found in packing material. The (α,n) neutrons that come from these reactions can be a significant source and difficult to differentiate from the primary fission neutrons, if one is only counting the total number of neutrons detected.

A solution to this problem can be arrived at by looking at the time distribution of neutron detections: spontaneous fission produces bursts of time-correlated neutrons (Fig. 7 shows the probability distribution of neutron counts in each burst for plutonium-240), whereas emission from (α,n) reactions creates individual, uncorrelated neutrons at random. With this knowledge, a method called coincidence

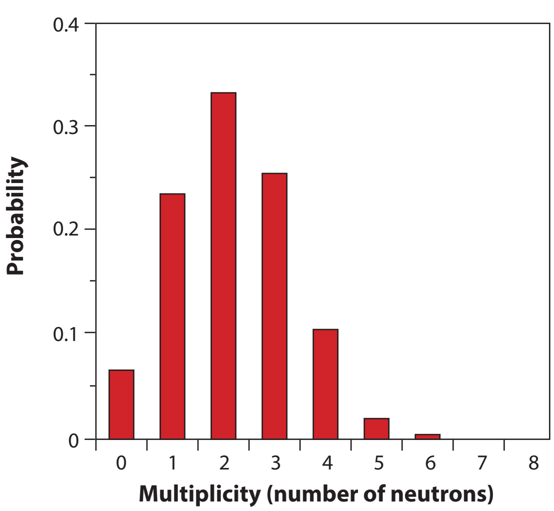


Figure 7. Passive neutron multiplicity counting requires analyzing neutron multiplicity to estimate the mass of plutonium. This figure shows the multiplicity distribution for spontaneous fission in plutonium-240 (i.e., the probability distribution of the number of neutrons released in each spontaneous fission event). Using coincidence counting statistical methods, the time-correlated bursts of neutrons can be parsed from the uncorrelated secondary neutrons. Credit: PANDA manual.

counting uses statistical methods to count the pairs of correlated neutrons which can only be produced from fission events. The "doubles" count is the number of coincidence events where two neutrons are detected within a defined time window (usually microseconds)—indicating neutrons from the same fission chain or event.

For plutonium, coincidence counting can be used to yield an effective mass of plutonium-240, which can be taken in combination with a method to determine the isotopic distribution, such as gamma ray spectroscopy, to give the total plutonium mass in the sample. Neutron coincidence counting is widely used in international safeguards inspections to certify conventional nuclear fuels. However, its application in domestic accountability measurements has been more limited due to the potential for error when the technique is improperly applied to impure materials.

Figure 8. Various sizes of gas-filled neutron detectors (top) and cut-out views of a typical helium-3 detector tube (middle and bottom). Credit: Geist, Santi, and Swinhoe, "Nondestructive Assay of Nuclear Materials for Safeguards and Security," 2024 (known as the PANDA manual).

Impure samples such as mixed-oxide (MOX) fuels that contain large amounts of neutron moderating or scattering materials cannot be accurately measured using the standard coincidence counting technique. In these cases, a method known as neutron multiplicity counting can be used to get a more accurate answer than coincidence counting can provide. In the coincidence counting method, only the correlated pairs of neutrons are measured, but in multiplicity counting, the correlated triples (i.e., three neutrons in a short timeframe) are measured. Using this added information, the multiplicity method solves a system of equations known as the "point model equations" to explicitly solve for the mass and level of impurity in the item. The neutron multiplicity counting method gives a more accurate answer than coincidence counting when unknown amounts of impurity are present.

3.1 Helium-3 proportional counters

Helium-3 proportional counters are a very popular way of detecting neutrons as they have a high absorption cross section optimized for thermal neutrons (i.e., neutrons with low energy) and negligible sensitivity to gamma rays. Thermal neutrons are generally preferable for NDA instruments over fast neutrons because of the higher likelihood of thermal neutrons to undergo nuclear reactions. In cases where the source emits fast neutrons, moderating materials such as high-density polyethylene can be used to slow them down and reduce their energy for detection.

In helium-3-gas-filled proportional counters, absorption of a thermal neutron in an (n,p) nuclear reaction creates hydrogen-1 (proton), hydrogen-3 (tritium), and a release of energy (764 keV). The proton and tritium ionize the gas, which is collected and produces a pulse. Each pulse observed is a neutron detected. The time distribution of the pulse streams is then analyzed to determine the number of neutrons, as well as the number of correlated pairs and triples.

$$He^3 + n^1 \longrightarrow H^1 + H^3 + \gamma \text{ (764 keV)}$$

thermal neutron (n¹); proton (H¹); tritium (H³)

HLNCC
passive counting

AWCC
active counting

Figure 9. *Left*: JCC-31 high level neutron coincidence counter (HLNCC); *Right*: JCC-51 active well coincidence counter (AWCC). The HLNCC is an example of a passive neutron counter and is the standard instrument for assaying plutonium content up to a few kilograms. The AWCC meanwhile uses active neutron interrogation with an americium-241/lithium source of neutrons, located immediately beneath the cavity, which is useful for assays of uranium-235. Both these instruments were developed through a technology transfer from Los Alamos National Laboratory. Credit: Mirion Technologies.

3.2 High-level neutron coincidence counter (HLNCC)

The HLNCC is the standard instrument for assaying plutonium content up to a few kilograms via passive coincidence counting of plutonium-240 spontaneous fission neutrons (Fig. 9). It uses multiple helium-3 tubes positioned around the detection assembly and was originally developed at Los Alamos for the IAEA under the US Support Program to IAEA Safeguards. Examples of the types of materials it can assay include plutonium dioxide, MOX fuels, metal carbides, fuel rods, fast critical assemblies, solutions, scrap, and waste.

3.3 Active well coincidence counter (AWCC)

While the HLNCC is useful for assaying plutonium-240, it is ineffective for uranium-235, whose rate of spontaneous fission is effectively too low to detect using passive neutron techniques. Furthermore, gamma ray spectroscopy has limited use, as it can only measure the exterior of the nuclear material. The solution is to use an active rather than passive approach—applying a neutron source to induce fission and increase neutron production, known generally as an active assay.

The AWCC uses an americium-241/lithium source of uncorrelated neutrons that have energies below the threshold for uranium-238 fission—hence they only induce fission on uranium-235. The mass of uranium-235 is then derived by coincidence counting similar to plutonium. A wide variety of HEU (highly enriched uranium)-containing materials can be assayed, including bulk uranium dioxide, highly enriched uranium metals, and uranium alloy scraps. It can also be used in passive mode, without the neutron source, to detect plutonium-240 and uranium-238 in a manner similar to the HLNCC.

3.4 Uranium neutron coincidence collar (UNCL)

It is essential that nuclear inspectors be able to independently confirm the composition of nuclear materials without relying on statements from the operator. This can be a particular concern when measuring uranium-235 content in fresh LWR fuel assemblies, especially those for pressurized water reactors (PWRs), which contain a variable number of burnable poison rods that can complicate NDA inspections. The poison rods' function in the assembly is to absorb neutron flux for higher uranium-235 enrichment levels, but they also absorb the thermal neutrons applied in an active assay (such as with the AWCC). As such, inspectors need to know how many neutron-absorbing rods are contained in the assemblies to obtain correct calculations.

Figure 10. Uranium neutron coincidence collar (UNCL-II) design. It consists of three polyethylene sides that contain helium-3 detectors and a fourth side (at front) that contains an americium-241/lithium source. This is the primary NDA system used by IAEA inspectors to verify uranium content in light-water reactor fresh fuel assemblies. Credit: PANDA manual.

To solve this puzzle, Los Alamos researchers—working in collaboration with the IAEA in the late 1970s—invented the uranium neutron coincidence collar (UNCL; see Fig. 10). This instrument uses cadmium liners around the sample cavity to filter thermal neutrons from the applied flux, leaving only fast (high energy) neutrons for the interrogation, which are not absorbed by the poison rods. Although effective, the one drawback to this solution is that because the stimulated fission rate is reduced, measurement times are increased, to around an hour.

3.5 Add-a-source method for correcting errors in waste drums

Waste drums contain complicated mixtures of materials—such as concrete, polyethylene, wood, paper, and metal—that can introduce error into verification measurements by absorbing thermal neutrons and reducing neutron flux energy. Inspectors can, however, correct for this bias using the add-a-source method. This method works by adding an additional neutron source, for example californium-252, positioned at one or more locations around the sample (californium-252 is often used because it produces fission neutrons with a similar energy to nuclear material.). By measuring the change in counting rate from this source specifically (whose stream of neutrons can be separated in analysis using neutron multiplicity counting), the absorption rate of the material can be inferred. This corrective factor can then be applied to the final verification measurements. Add-a-source also requires a calibration, which is typically performed by creating mock waste containers with matrix materials that are expected to be in the assay items.

Figure 11. The high efficiency passive neutron counter (HENC) system is a passive neutron coincidence counter designed to assay 55 gallon drums of nuclear waste. The add-a-source technique can be used with the HENC to correct for measurement uncertainty owing to additional matrix elements in the waste (e.g., concrete, steel, glass, plastic, and paper). Credit: Mirion Technologies.

Summary

The NDA instruments featured in the Los Alamos SSTTP stand out not only for their utility in nuclear safeguards but also for their historical significance and continuing innovation. Many of these instruments—like the high-level neutron coincidence counter and the active well coincidence counter—were first conceptualized and built at Los Alamos and have since become international benchmarks in nuclear measurement.

Acknowledgments

Thanks to Bill Geist and Marc Ruch for their assistance in writing this article.

Atomic Management: The DYMAC 2.0 Initiative

By Jake Bartman

Every day, workers in Los Alamos National Laboratory's plutonium facility (PF-4) handle significant quantities of nuclear material more valuable than gold. Beyond their expense, these hazardous materials pose substantial security risks, and Los Alamos has stringent legal and ethical obligations to account for all the special nuclear material under its control.

In the past five years, the Laboratory has developed its capacity to produce war reserve plutonium pits for the nation's stockpile, with the goal—established by the National Nuclear Security Administration—of producing no fewer than 30 pits per year by 2030. Increasingly, however, tracking and accounting for special nuclear material inside PF-4, which for decades was primarily a research and development (R&D) facility, has created a bottleneck: The process of assaying material involves pausing production, removing the material from the production line, transporting it to a centralized laboratory for analysis, and then returning it to production. Because such inventory reconciliations often occur twice per year and take several weeks apiece, they can potentially cause major impacts to production timelines.

In fact, PF-4 was originally designed to avoid exactly this kind of bottleneck. The Dynamic Materials Accountability (DYMAC) system, which went into operation with the facility in 1978, incorporated a suite of nondestructive assay (NDA) tools and other technologies in the glovebox line throughout the facility. The idea—highly ambitious for the time—was to provide a near-real-time account of the movement of special nuclear material through PF-4, ensuring that nuclear material accounting goals were met. However, in the decades after the facility opened, the system degraded. One unsurmountable challenge the system faced was detecting the signature of a given source against the background of a busy and constantly changing operating environment—akin to trying to hear someone speak in a hurricane. The nascent computer technology available in the 1980s was not sufficiently advanced to solve this complex problem.

Although a centralized approach to asset management was sufficient when the facility operated at a R&D scale, this approach could become a critical constraint as activity increases for pit rate production. In 2020, a team of researchers led by Rollin Lakis launched DYMAC 2.0. The initiative is designed to find new methods of dynamically monitoring the movement of material in the facility, fulfilling the promise of the original DYMAC system. As a part of DYMAC 2.0, researchers are building on decades of advances in safeguards R&D to create novel methodologies and tools to implement in PF-4.

The techniques that the DYMAC 2.0 team is developing—which range from incorporating additional radiation shielding around detectors to deploying distributed sensor networks—contribute to the goal of having an accurate, near-real-time account of the movement of material through PF-4. These developments are expected to increase production speed, lower facility downtime, and save millions of dollars, all while reducing workers' exposure to radiation.

Figure 1. Adam Phelan, scientist, working in one of the materials properties gloveboxes in RLUOB (Radiological Laboratory Utility Office Building) at TA-55 where he researches the materials physics of plutonium. This work involves careful nuclear accounting: safeguarding the significant quantities of nuclear material as well as accounting for primary and secondary sources of transuranic waste.

Road to DYMAC: International safeguards

DYMAC 2.0 continues a legacy of nuclear safeguards R&D work that began at Los Alamos nearly six decades ago. In 1966, nuclear physicist Bob Keepin returned to the Laboratory from two years at the International Atomic Energy Association (IAEA) in Vienna, Austria. At the time, IAEA inspectors—who were beginning to monitor nuclear facilities around the world to ensure against the misuse or theft of nuclear materials—relied on inspections and destructive techniques, sending samples of material to laboratories for analysis (see p4 for more on this history). Such methods were time-consuming and could disrupt operations while also using up valuable material.

Keepin had the revolutionary idea that Los Alamos could develop technologies to assay nuclear material nondestructively. Soon, scientists at the Laboratory began developing gamma-ray and neutron detectors for safeguards. In addition to reducing the need to divert valuable material for assay, the NDA tools developed at Los Alamos enabled IAEA representatives to assess the materials at nuclear facilities much more quickly—in minutes or hours rather than days or weeks. Within a decade of their development, these tools were being applied in the new DYMAC initiative and slated for use in Los Alamos's PF-4, which was then being built. (See sidebar spread on p28 for more about the original DYMAC initiative.)

"We have four decades of development that we can apply here at Los Alamos." — Robert Weinmann-Smith, Safeguards Science and Technology

PF-4 today: Identifying a bottleneck

Today, however, inventorying material in PF-4 involves a logistically complex process of "bagging out" the material (loading specialized containers for transport) and then moving it to a centralized NDA laboratory for analysis. This process is time-consuming and disrupts production in just the way that the DYMAC system was designed to avoid—and these problems are expected to grow more acute as pit production efforts increase.

Robert Weinmann-Smith, a researcher with DYMAC 2.0, says that the Laboratory's decades of work in international safeguards are being brought to bear on DYMAC 2.0. "Over the last 40 years, the reason the tools have developed is because of international needs," Weinmann-Smith says. "Now, we have four decades of development that we can apply here at Los Alamos."

For example, in the past two decades, researchers at the Laboratory supported the development of safeguards at the Rokkasho Nuclear Fuel Reprocessing Facility in Japan. The Rokkasho facility is designed to separate plutonium from spent reactor fuel so that it can be recycled into mixed oxide (MOX) fuel.

Los Alamos developed an NDA system that made it possible to monitor fluctuations in the Japanese facility, maturing technologies that now underpin the deployment of DYMAC 2.0. Notably, as a part of the Rokkasho project, researchers advanced a Los Alamos computational technique called list mode, which involves recording separate streams of data from individual sensors in fine-grained detail. List mode records detailed information about each detected neutron event as a chronological list, including the timestamp and position.

"Since the original DYMAC system was deployed, electronics have improved enough to enable measurements on a nanosecond timescale," Weinmann-Smith says. "And so, for example, if an item passes by in the trolly overhead and the background goes up for a few seconds, we can then subtract a little more background for those seconds. We can now do all of this with very high fidelity."

These advances are enabling the development of new NDA techniques for PF-4. "A detector is a collection of sensors combined together," Weinmann-Smith says. "In the past, in a measurement, you'd put an item in a detector, you'd hit start, and you'd come back 30 minutes later for your reading. Now, we read the sensors' measurements independently, which allows us greater spatial and time resolution. That allows us to conduct sophisticated analyses while speeding up the measurements and reducing uncertainty."

Figure 8. The Rokkasho Nuclear Fuel Reprocessing Facility in Japan, where spent nuclear fuel is reprocessed, adjacent to the site of the forthcoming J-MOX facility. Researchers at Los Alamos have developed monitoring systems for these sites that are similar to the DBCM system.

Applying Los Alamos innovations: A dual-pronged approach

List mode may also prove a key technology in addressing the issues with background radiation that plagued the original DYMAC system. As a part of DYMAC 2.0, researchers are evaluating techniques and technologies that span the full spectrum of technology readiness levels. For example, the simplest way to reduce background radiation is to increase the amount of shielding around neutron-emitting materials. However, the fast neutrons produced from plutonium fission are highly penetrating and require large amounts of cumbersome shielding—depending on location, a foot or more of shielding can be needed to absorb stray neutrons from a given source.

Consequently, researchers are also evaluating other, more sophisticated techniques to account for background radiation, broadly divided into two approaches. The first approach involves modifying neutron detectors to include an additional array of sensors that measures the background. These sensors are arranged in the detector as concentric rings—the inner ring measures neutrons from the sample while the outer ring measures background radiation—and, using list mode, measurements of incoming neutrons can be dynamically subtracted from the measurements of a material. This approach is being incorporated into NDA tools such as the dual assay instrument with list mode (DAIL) and the XL Line detector (described later).

"Since the original DYMAC system was deployed, electronics have improved enough to enable measurements on a nanosecond timescale." — Robert Weinmann-Smith

A second approach to addressing background involves deploying a distributed sensor network to monitor neutron flux. To optimize this approach, researchers created a testbed comprising four mock gloveboxes, each with a helium-3 detector in every corner (Fig. 5). This testbed, with its dispersed sensors, allows researchers to evaluate the feasibility of monitoring nuclear material in different configurations inside the glovebox.

"Background is always a signal from somewhere," Weinmann-Smith says. "That means that if we're able to measure the plutonium everywhere in the facility, and if we know that, for example, a given glovebox has a hundred grams of plutonium in it, we can calculate how much background that hundred grams is contributing, and we can subtract that background dynamically. We can solve the background everywhere and propagate to where a given measurement instrument is."

This distributed approach is especially useful in accounting for "holdup"—the residue, dust, or powder that is left over inside gloveboxes as a part of material processing. As a part of inventory reconciliations, workers undertake the laborious task of accounting for this material using NDA tools and statistical methods. Although localized sensor networks are well suited to tracking material during individual steps in the production process, constantly monitoring gloveboxes throughout the facility would make it possible to track holdup as well.

DYMAC 1.0

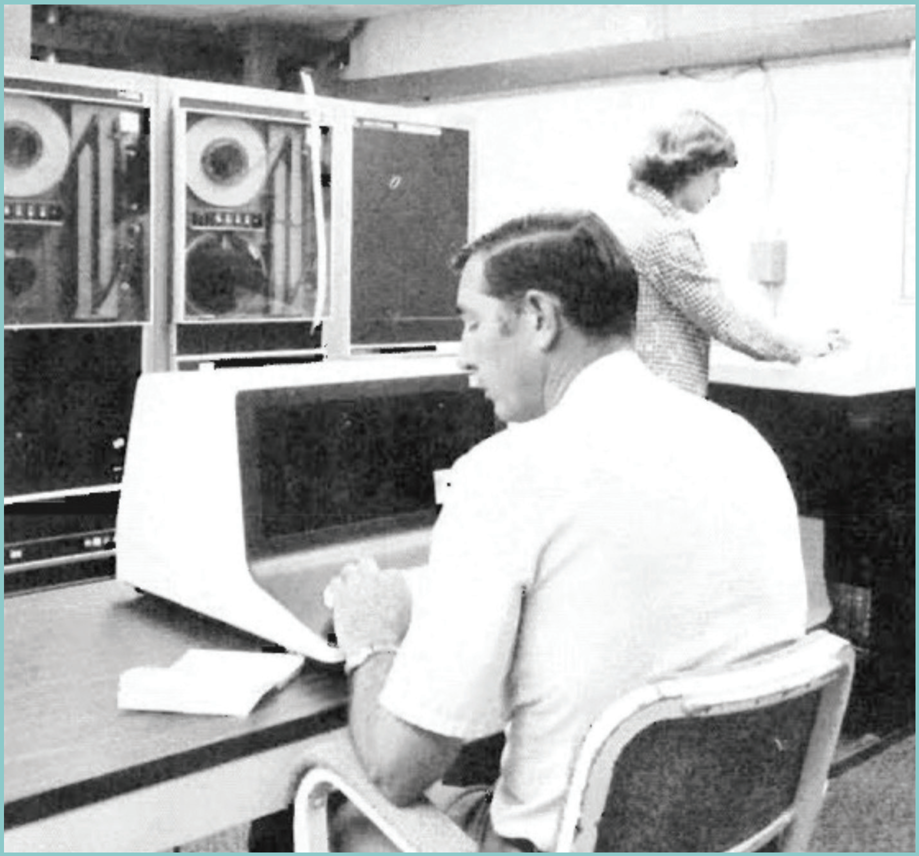
In the mid-1970s, Los Alamos Scientific Laboratory (as the Laboratory was then known) was developing plans for PF-4—a high-tech facility that would research and process plutonium. Researchers in Los Alamos' safeguards program understood the importance of accounting for special nuclear material inside the new facility, and they proposed implementing what they called the Dynamic Materials Accountability (DYMAC) system in PF-4. DYMAC would combine video cameras and NDA tools with computer technology to keep an accurate and near-real-time account of all the nuclear material inside the facility. By taking advantage of the latest computing developments and NDA techniques, it would be possible to develop a system that would measure nuclear material during processing.

DYMAC entered operation when PF-4 received its first shipment of special nuclear material in January 1978. Four years later, in 1982, a group of researchers published a report that evaluated the DYMAC system. The report noted that the

The newly constructed PF-4 building at Los Alamos in 1980.

system was a significant improvement over pre-DYMAC methodologies. Prior to DYMAC, "accountability of nuclear material lagged weeks behind the constantly changing physical inventory" because the methods involved relying on process personnel to write paper transactions on a timely basis. With its incorporation into the production line itself, DYMAC reduced the need for these post-hoc inventories. However, the report noted that DYMAC's implementation remained imperfect and that the system was accomplishing around 75% of its design goals, largely because it lacked certain key tools for analyzing the collected data.

In subsequent decades, the DYMAC system deteriorated. For one thing, the system was ill-designed to handle new workflows in PF-4, which introduced new kinds of special nuclear material—and higher volumes of material—into the facility. These changes created challenging levels of background radiation that hampered the system's accuracy, and over time, the system of dynamic material monitoring that Bob Keepin and others had envisioned went by the wayside.



The original DYMAC central computer, which kept track of the facility's inventory. Even by 1980, PF-4 had over 6,000 inventory items to safeguard.

1. Assaying waste with DAIL

When DYMAC 2.0 was created in 2020, the initiative's goals in PF-4 were threefold: improve the characterization of background radiation, determine where NDA tools could be best applied, and develop a methodology to track items. The team considered tools that were lab ready as well as longer-term approaches, including technologies as diverse as digital twins, radiofrequency identification (see p36), and sophisticated spatial absorption models. Today, researchers are developing several advanced NDA instruments that can be incorporated into PF-4's production line, including DAIL, which is intended to augment the assay process in PF-4's 400 wing.

In the 400 wing, transuranic waste is packaged for disposition. Currently, waste in the 400 wing is bagged out into a drum, assayed in PF-4's NDA laboratory, and measured with a high efficiency neutron counter (HENC; see Fig. 2). Then, it is packed and sent to the Waste Isolation Pilot Plant (WIPP) in southern New Mexico for long-term storage. This process involves moving waste three times—an inefficient arrangement that increases workers' risk of exposure to hazardous material. Moreover, the limitations of current measurement techniques are such that the waste containers aren't packed as fully as they could be.

DAIL, which is a bit larger than a washing machine, is intended to reduce the movement of material and increase efficiency by assaying material in the production line itself, right before it is loaded into 55-gallon waste drums. The instrument consists of a gamma detector and a thermal neutron detector (hence the "dual assay" in its name) in a central cavity that is large enough to accommodate a 5-gallon waste container (Fig. 3). The material could be anywhere in that space, causing measurement uncertainty and requiring the 55-gallon drum in turn to be conservatively filled to less than the legal limit. However, with list mode, the helium-3 neutron sensors can be used to triangulate, with a high degree of precision, the location and volume of material in the 5-gallon container, allowing operators to determine (for example) if the waste is evenly spread out or concentrated near the bottom of the container, where its neutron flux could be problematic.

"The location of material inside the container is the single biggest source of uncertainty for this kind of measurement," Weinmann-Smith says. "Our studies show that this design allows us to cut down on uncertainty by 75%."

Figure 2. Transuranic waste in PF-4 is currently bagged out into a 55-gallon drum, assayed in the NDA laboratory, and then measured again with a high efficiency neutron counter (an example instrument pictured). Currently, this inefficient process involves moving waste three times. Credit: Antech.

DAIL incorporates an outer ring of sensors that take background radiation into account, as described previously. This crucial innovation—which was matured at DYMAC's testbed—allows for assay to be conducted in the production line, while ensuring that sudden changes in background don't hamper the detector's measurements. To develop DAIL, researchers drew on several earlier detectors such as HENC and ENMC (epithermal neutron multiplicity counter).

In fiscal year 2023, Los Alamos sent 817 drums of transuranic waste to WIPP, each costing hundreds of thousands of dollars to process. If DAIL was incorporated into the 400 wing, the instrument could make it feasible to pack 20 to 40% more material in each drum than is possible with current methods—a significant reduction in the number of drums sent. In addition to saving millions of dollars, DAIL could speed up the characterization process by around 20%—saving some 36 days per drum—all while reducing workers' potential exposure to hazardous material. The detector is expected to enter operation by the end of 2026.

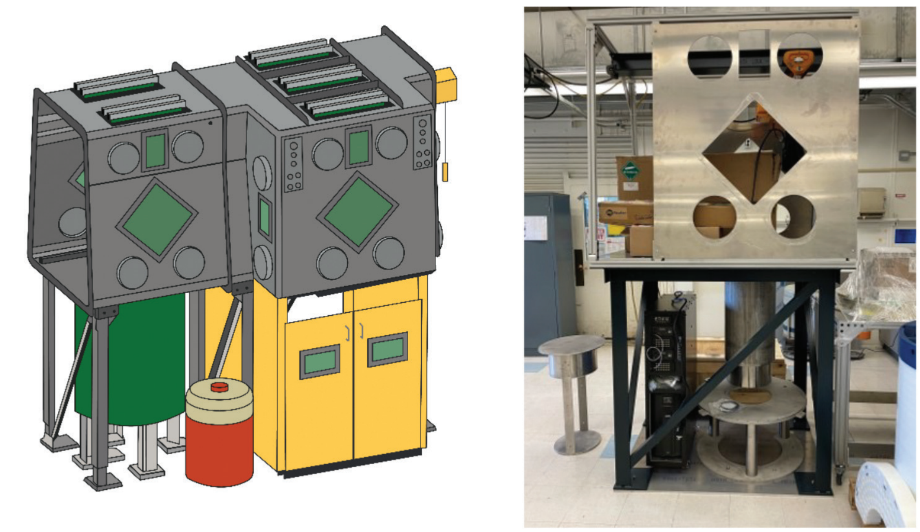


Figure 3. The dual assay instrument with list mode (DAIL) instrument (large green drum in illustration, lower left) integrated into a new-build glovebox. DAIL will speed up operations in PF-4 by assaying waste material in the production line itself, right before it is loaded into 55-gallon waste drums for disposal.

Figure 4. A cache of 55-gallon transuranic waste drums being prepared for shipment to the Waste Isolation Pilot Plant (WIPP).

2. Aqueous chloride processing: The XL Line detector

Another project inaugurated under DYMAC 2.0 is an NDA instrument for PF-4's XL Line. At this processing line, plutonium and americium are extracted from materials including legacy waste—primarily salt residues that were used decades ago in research—and the tail, or waste, from another separation process (see Actinide Research Quarterly First Quarter 2023 for more information). In effect, it is a salvaging operation for valuable radiological elements. Part of processing requires quantifying extracted plutonium to keep track of it, and like other analytical processes in PF-4, this is a tedious process that involves bagging out and transporting material to the centralized NDA laboratory.

An in-line thermal neutron counter would bolster worker safety and substantially improve the XL Line's efficiency, says Nick Smith, who leads the XL Line detector's development. "Any time you can introduce an in-line detector, you can substantially reduce the time you need to make a measurement, you reduce effort, and you increase safety," Smith says. "And, really, safety is the biggest thing here. Whenever you have to bag out material, you have the risk of an accidental release. We can eliminate that risk with an in-line detector." Lakis adds that the decrease in time and effort associated with in-line measurements will substantially increase efficiency for the pit production mission, too.

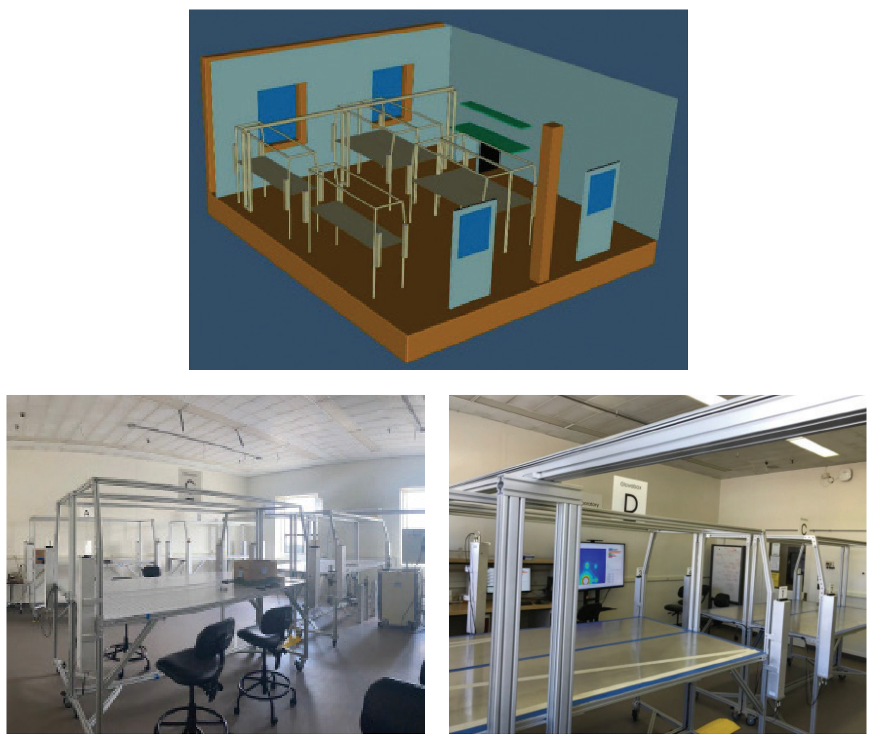


Figure 5. To optimize the distributed sensor network of the DBCM system, researchers developed a testbed consisting of four mock gloveboxes, each equipped with helium-3 detectors at all four corners. This setup enables evaluation of the network's capability to monitor nuclear material under various glovebox configurations.

The minifridge-sized instrument is based on DAIL, with a similar neutron detecting well that employs dynamic background subtraction techniques and list mode. There are, however, some unique challenges for the XL Line detector. The processed actinide salt solutions vary greatly in composition, complicating efforts to meet the required precision and accuracy standards. Moreover, unlike DAIL, which was designed to integrate with a newly constructed glovebox, the XL Line detector must be retrofitted onto an existing one.

"Like a custom car, there are aspects of these detectors that you just don't change."
— Nick Smith, Safeguards Science and Technology

Rachel Connick, who recently converted from a postdoctoral to staff position, has been working to help design the XL Line detector. Connick says that, among other difficulties, developing a detector small enough to fit beneath an existing glovebox complicates the design because a shorter detector means shorter helium-3 tubes, reducing efficiency. Connick's work has also involved implementing a custom gamma detector into the detector's design. In addition to difficulties related to space constraints, incorporating a gamma detector into the bottom of the neutron detector's well affects the behavior of neutrons inside the well, adding complexities that must be accounted for to ensure that the detector meets requirements.

Smith, who expects the detector to be deployed within the next four years, likens the development to the process of designing a custom hot-rod car. Although all cars have certain characteristics in common—four wheels, an engine, and a transmission, for example—cars vary widely depending on what kind of driving the car is intended for (a drag race or the Indy 500). Similarly, although different NDA tools have characteristics in common, each tool must be designed to suit a specific application.

"Like a custom car, there are aspects of these detectors that you just don't change," Smith says. "Different detectors may be similar in principle. But they're very different in practice." Lakis observes that this is the "art and practice of detector engineering—balancing the design and performance, within constraints, to best accommodate the mission."

3. DBCM: Continuous background monitoring for plutonium in PF-4

Connick and Weinmann-Smith are both contributing to another DYMAC 2.0 project, the DYMAC background characterization module (DBCM). This portable system comprises eight neutron detectors on flagpole stands and a cart bearing data acquisition electronics (Fig. 6). It can be positioned around a glovebox to monitor the production processes inside, allowing for tracking and accountancy of plutonium and other special nuclear materials (Fig. 7).

DBCM was designed to evaluate the signals and background that a network of sensors might pick up inside PF-4. A fully developed version of the system could resemble the glovebox unattended assay and monitoring system (GUAM), which was developed at Los Alamos for implementation in Japan Nuclear Fuel Ltd.'s J-MOX facility (slated to enter operation in 2028). GUAM uses a sensor on every glovebox, passively measuring plutonium levels overnight and providing data to operators every morning about the plutonium's quantity and location. A similar scheme, the plutonium inventory measurement system, was created for the Rokkasho facility.

(a) (b)

Figure 6. (a) DBCM packed on the cart (six neutron detectors visible as white rectangular boxes on the upper tray); (b) Components of a single neutron detector, which is positioned on a flagpole as part of the DBCM system.

Recently, DBCM detectors were deployed at a process (or room) inside PF-4, with the goal of capturing neutron data and continuously tracking nuclear material inside the glovebox. However, during this test, the neutron detectors proved sensitive enough to pick up neutrons emitted from plutonium-238 processing in an adjacent room. This background signal overwhelmed the detectors, preventing measurement of the primary source material—not the outcome that the DYMAC 2.0 team had expected. The result highlighted the need for detectors spread out through the entire facility. But background is always a signal from somewhere, and the team directly mapped the background fluctuations to processing plutonium-238.

"We could see to the minute when different processing steps started, and on the weekend or at night, the signal was dead flat," Weinmann-Smith says. "In the future, we'd want to track everything happening in each of the room's gloveboxes on a minute-by-minute basis."

Researchers hope to put DBCM in another room of PF-4 this year, demonstrating proof of concept before deploying it facility-wide. Although there are significant engineering challenges to pioneering such a system in a busy work environment like PF-4, doing so could almost eliminate operational pauses for nuclear material control and accountability.

Figure 7. Neutron detectors on flagpole stands, part of the DBCM system deployed at a glovebox in PF-4.

Looking to the future

Today, Laboratory researchers are leveraging decades of experience in safeguards research to overcome the challenges that led to the original DYMAC system's dissolution. The tools and techniques that are in development as a part of DYMAC 2.0 represent a broad-based approach to solving enduring challenges in nuclear material accounting. Some of these developments, such as DAIL, are nearer to implementation; others, such as DBCM, need additional research to be developed into mature systems. Taken together, these methods point toward a future in which nuclear material accounting at Los Alamos is faster and more effective, supporting production and bolstering safety throughout PF-4 for decades to come.

Tracking Nuclear Materials Using RFID

By Jake Bartman

At Los Alamos National Laboratory, workers support the nation's nuclear security enterprise by producing the plutonium pits that are the cores of the United States' nuclear weapons. Although the Laboratory has produced limited quantities of pits since its founding in the 1940s, the US has lacked the capacity to manufacture pits at scale since the Rocky Flats Plant ceased pit production in 1989.

In October 2024, Los Alamos completed its first production unit—the first pit to meet the National Nuclear Security Administration's (NNSA's) requirements for acceptance into the nuclear stockpile since the Laboratory produced some 30 pits in the 2000s. This achievement was a key step toward reaching the NNSA's target of producing, by 2030, no fewer than 30 pits per year at Los Alamos—an accomplishment that required developing and deploying modern techniques that will make pit production safer, more efficient, and more sustainable than it was at Rocky Flats.

Despite these accomplishments, for decades, little has changed in how the Laboratory tracks and accounts for the special nuclear material and other assets used in pit production. Today, as in years past, workers in PF-4 (the Laboratory's Plutonium Facility) conduct inventories with a clipboard and pen in hand before manually entering counts into a database. Periodically—often twice per year—production must be paused altogether while workers perform inventory reconciliations that can take 35 to 70 days apiece. To help modernize the inventory process, as a part of the DYMAC (Dynamic Materials Accountability System) 2.0 initiative, a team of researchers began evaluating RFID (radio frequency identification) systems for implementation in PF-4—a technology that could revolutionize asset tracking in the facility. (For more on DYMAC 2.0, see p24)

"There are a lot of activities and projects in Weapons Production that are doing manual inventories," says Ray Ferry of Los Alamos' Production Analysis and Transformation group, which works to bridge current and future production techniques and practices with those that have historically been conducted in the nuclear enterprise. "It's just the way we've always done it. But we have to change." More efficient inventory operations would allow for better use of spaces and labor resources.

Overcoming security challenges

When DYMAC 2.0 was created, the program initially focused on developing nondestructive assay tools to measure nuclear materials in PF-4, reducing the need to pause production and conduct inventory reconciliations. RFID was dismissed as part of this work, however.

"As modern asset management systems were being envisioned, RFID was almost discounted because there had been almost 20 years of activity at the Laboratory with no substantive progress toward meeting security requirements," Rollin Lakis, the leader of the DYMAC 2.0 initiative says. "But technology has advanced dramatically in the RFID community. We soon recognized that these technologies would provide such an enormous benefit to the mission that we needed to invest into that R&D portfolio, to overcome security and technical barriers for implementation."

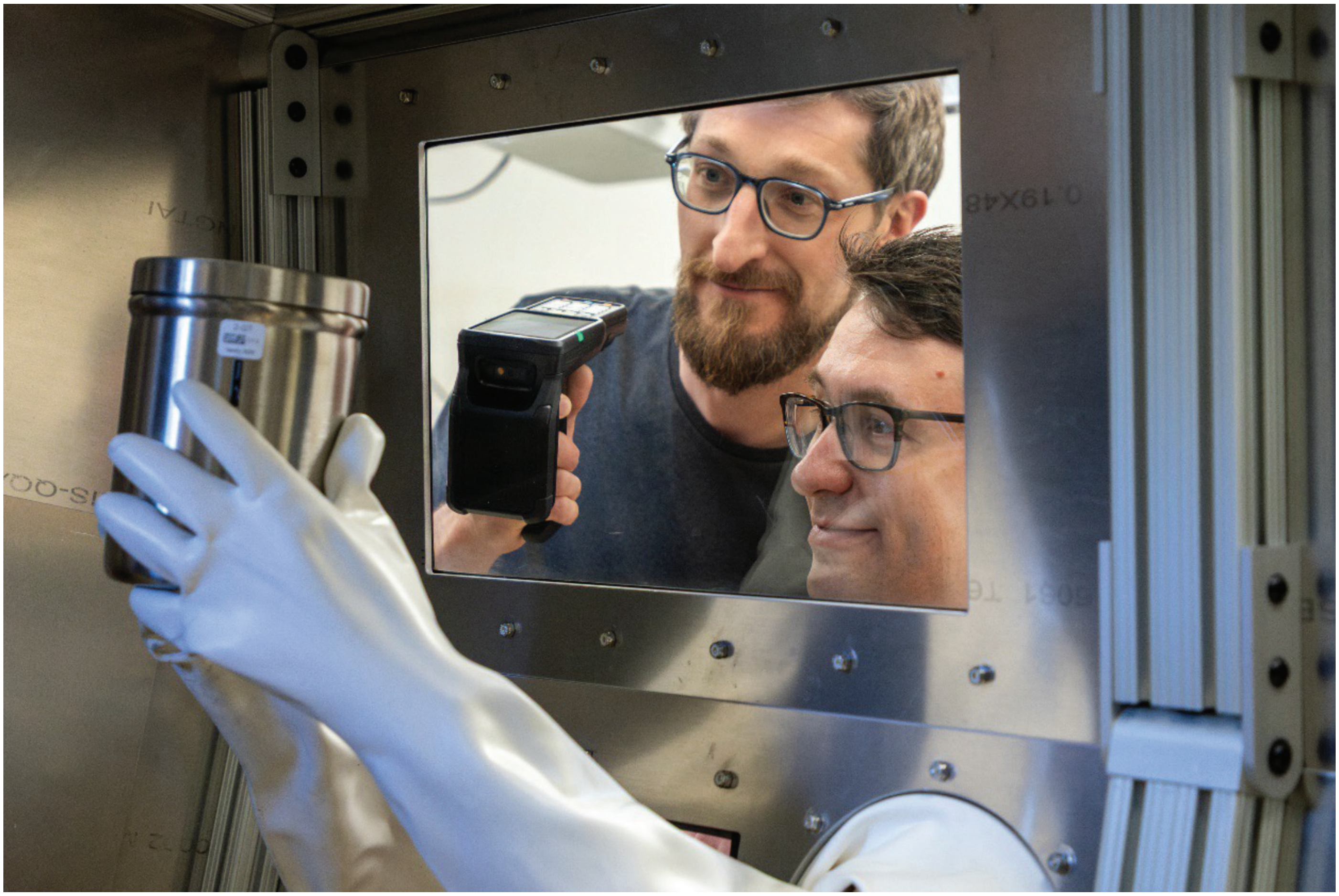


Figure 1. Deploying RFID technology in PF-4 could revolutionize asset tracking in the facility. Here, a mock-up glovebox is used in the RFID laboratory to simulate the physical environment of PF-4.

"There are a lot of activities and projects in Weapons Production that are doing manual inventories... But we have to change." — Ray Ferry, Production Analysis and Transformation

The RFID research team has had to overcome substantial challenges to bring RFID into PF-4. In addition to stringent security requirements, much of the work completed in the facility involves material that is hazardous and potentially of high consequence. Every step of the process of developing and incorporating an RFID system must be rigorously evaluated to ensure the system's accuracy and reliability—there's no room for error.

And yet, the goal of implementing RFID into PF-4, which seemed fanciful only a few years ago, is on its way to being achieved, with four RFID pilot programs slated to take place inside TA-55 (which includes PF-4) in fiscal year 2025. Beyond tracking material in the facility, the RFID team's work has opened doors to ways in which RFID could bolster many aspects of PF-4's mission beyond asset tracking. These opportunities will help make the facility safer, more secure, and more productive.

RFID 101

RFID is everywhere: in contactless credit-card readers, transportation toll collection, airplane components and operations, retail apparel, and more. Although it is possible to trace RFID's origins to the World War II–era development of radar, RFID, as we understand the technology today, wasn't developed until the 1970s. It entered the commercial marketplace in the 1980s and rolled out to multiple industries in the 1990s. Today, RFID is even more widespread with an estimated 40 billion RFID tags placed on assets just in 2024.

At its most basic, an RFID system comprises three components: tags (which are placed on or inside an object to be tracked), readers (which interact with the tags to gather their location and other information), and a backend system (which tracks and processes data). RFID technologies can be divided into three classes—active, passive, or semi-passive—based on how the tag and the reader interact.

Figure 2. Passive ultra-high frequency (UHF) RFID tags in use in the RFID laboratory.

Figure 3. A LANL SAVY container fitted with RFID tag along with commercial Zebra reader and label printer, which has UHF RFID encoding capability. The SAVY-4000 is a container system developed by LANL for the safe storage of solid nuclear materials, first deployed in TA-55 in 2011.

In active systems, battery-powered RFID tags intermittently transmit signals across distances up to hundreds of feet. By contrast, in passive RFID systems, the tags have no internal power source; the reader emits an electromagnetic field that powers an integrated circuit or microchip in the tag. Passive systems, featuring tags that are typically 10–100 times less expensive than those used in active systems, have a shorter range than active ones (passive systems' range is typically limited to just a few feet). Active systems can also operate at higher frequencies (into the microwave band).

A key first step in deploying RFID, therefore, is determining the right type of system for a given use. At Los Alamos, the RFID team is deploying a passive ultra-high frequency (UHF) system, which has promising characteristics for tracking assets in nuclear facilities (Figs. 2 and 3). Passive UHF systems enable tracking within a few feet from the assets, their readers and tags are relatively inexpensive, and the tags are durable and can withstand radiation levels typically found in most parts of the plant. UHF RFID systems' decades of use means that they are a mature technology with well-accepted and maintained standards.

"Technology has advanced dramatically in the RFID community… [and] would provide such an enormous benefit to the mission." — Rollin Lakis, Safeguards Science and Technology

Expanding RFID's capabilities

One promising idea involves deploying stationary RFID scanners at doorways to automatically track the movement of material into and out of rooms. The research team is also exploring the possibility of deploying real-time asset tracking that would allow operators to see, on a map, where materials are. "This is particularly useful if you want to locate an asset in the facility and send an operator to inspect the asset—to make sure that it is where it's supposed to be and in the condition that it's supposed to be in," says Alessandro Cattaneo (of the Mechanical and Thermal Engineering group), who leads the DYMAC RFID team.

However, radio waves can reflect off the surfaces of metallic objects, complicating the use of RFID in gloveboxes. This problem is compounded when nuclear material containers are pushed together in clusters, for instance when glovebox operators need some extra elbow room to maneuver, and also by the limits imposed on RFID power settings due to security constraints in PF-4.

To help understand these systems and their limitations, the team created an RFID laboratory as a testbed that contains several mockup gloveboxes and a collection of empty nuclear material containers. This made it possible for researchers to evaluate the variables that affect RFID performance in a controlled environment.

The research team has collaborated closely with the Laboratory's Statistical Sciences group, who have taken a rigorous statistical approach to determining the tags' performance and establishing a performance baseline—an important consideration at a time when RFID tools are evolving constantly, with different tools providing different levels of performance. Other internal collaborations have developed models to capture the propagation of RF waves and helped modify off-the-shelf software to reprogram the handheld readers and expand functionality. The goal is to design tools that can be optimized, without resorting to trial and error, for distinct environments.

To support real-time tracking of material in the facility, Allison Davis (of the Mechanical and Thermal Engineering group) has created a tool that will allow operators of the RFID system to visualize data in a photorealistic way (Fig. 5). The software, which is based off a game engine, allows users to follow the movement of assets through a room—something that has proven especially useful in helping operators to understand the relationship between assets and the environment.

Brendon Parsons, the RFID subject matter expert in the Safeguards Science and Technology group, notes that RFID is versatile enough that with careful engineering, it is possible to design systems that go beyond asset tracking. "RFID can also be used to communicate data," Parsons says. "For example, there are RFID tags that are able to measure temperature and humidity, and interface with microcontrollers." In turn, these microcontrollers could connect with precision equipment inside gloveboxes, allowing for continuous monitoring of the glovebox environment.

Figure 4. Members of the RFID team, from left to right: Rollin Lakis (NEN-1), Alessandro Cattaneo (E-1), and Brendon Parsons (NEN-1).

Tamper-indicating devices

A promising application is incorporating RFID tags into tamper-indicating devices, or TIDs. TIDs can be used to control and protect nuclear material by making it clear to operators when there has been unauthorized access to a container. Although some TIDs are available commercially, these technologies don't necessarily meet the Laboratory's requirements. For that reason, the RFID team has also evaluated the possibility of additively manufacturing RFID-enabled TIDs at scales that could support the Laboratory's production mission by helping operators follow material throughout a dynamic production environment.

"This is a very disciplined operation," says Arnold Guevara, former leader of the Safeguards division, which works to track and protect nuclear material in PF-4. "You have to know the material, its weight, its location, and so on. It would be easier if the material was static, but that's not the case."

Guevara says that current TIDs suffer certain shortcomings. For one thing, like other items in the facility's workflow, TIDs must be tracked manually. Moreover, the materials used in TIDs can degrade over time. "Developing TIDs with embedded RFID would save a lot of effort," he says.

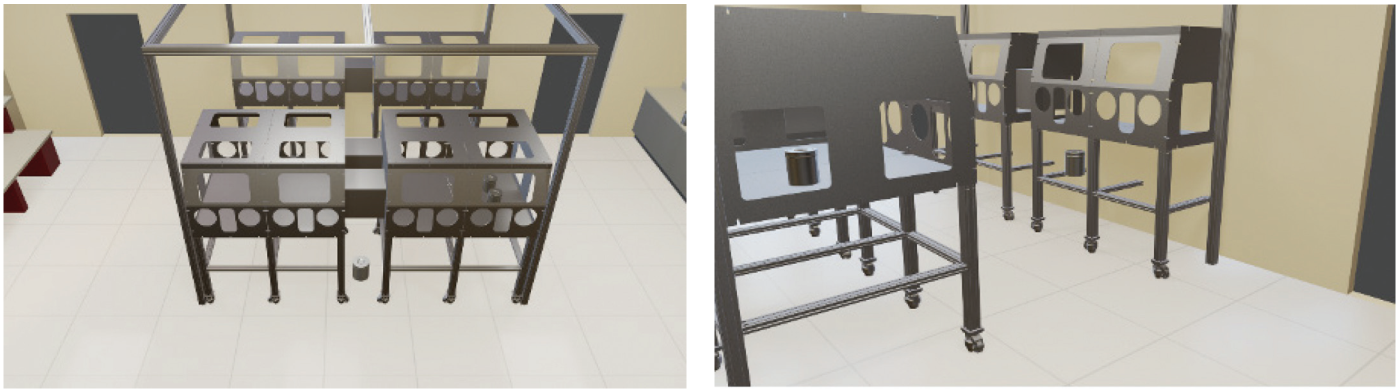


Figure 5. The 3D visualization tool supports real-time RFID tracking, allowing users to visualize asset movement through rooms. Left: Mock-up gloveboxes rendered with the 3D visualization tool for asset localization tracking. Right: The 3D visualization tool shows the position of a nuclear material container as it moves through the aisle between different mock-up gloveboxes.

The research team has been collaborating with Auburn University, which has a renowned RFID research and development program, to develop RFID technologies that meet the Laboratory's needs. "We didn't want to reinvent the RFID wheel, and we recognized their experience, so we collaborated with them," Ferry says. "We want to benefit from what private industry is doing and look at what technology would work in our environment."

Ferry says that Auburn has helped the Laboratory to establish testing requirements for its RFID technologies. The university is also helping Los Alamos to determine standards for RFID tags that then might be manufactured by industry partners. The collaboration has brought Auburn students to Los Alamos, some of whom are working to help identify tags that meet the Laboratory's standards (and some of whom Los Alamos has hired).

The budget for the RFID project has grown substantially since it was launched in the middle of 2021, and the program now receives around $3 million per year in funding (with DYMAC 2.0 garnering some $5 million). Encouragingly, the project recently received additional funding from the NNSA's Office of Information Management to help to move RFID toward implementation in PF-4: In fiscal year 2025, four pilots are planned for PF-4.

Figure 6. In the TA-55 "cold lab," from left to right: Scott Mcduffie, Brendon Parsons, Erick Alvarez Velazquez.

Summary

Recent advancements in RFID technology, previously overlooked in PF-4 due to insufficient security features, now hold the potential to transform the accountancy of nuclear materials. Furthermore, these systems could also bolster safety and production quality—they can be used, for instance, to support in-situ process monitoring, ensuring that only materials that meet quality standards are advanced through the production process. The potential for RFID continues to grow, with other novel applications on the horizon. But the fundamental goal of implementing RFID in PF-4—to support nuclear material control and accountability—remains the same. "The name of the game is to increase production while lessening the burden on operators and ensuring compliance," Guevara says. "It is a team effort."

From Starlight to Safeguards: The SOFIA Gamma-Ray Spectrometer

By Owen Summerscales

Analyzing the composition of actinide materials is particularly challenging in environments such as Los Alamos National Laboratory's nuclear production facility (PF-4) or at nuclear reactor sites. Radioactive processes can produce extremely complex mixtures of actinides and decay or fission products, each contributing gamma-ray signals, and despite decades of advancements in gamma spectroscopy, these signals remain notoriously difficult to deconvolute in situ using conventional techniques. To address this, researchers at Los Alamos have adapted ultra-sensitive superconductor technology originally developed for astrophysics. This innovation—SOFIA (spectrometer optimized for facility integrated applications)—comprises a series of prototype gamma spectrometers that overcome many of the limitations inherent in traditional systems, representing a major leap forward in gamma-ray nondestructive assay (NDA) capabilities.

At the heart of SOFIA lies a microcalorimeter array that dramatically reduces measurement uncertainty by delivering spectral resolution an order of magnitude beyond industry-standard high-purity germanium (HPGe) detectors. This level of precision eliminates problems caused by closely spaced or overlapping energy peaks, combined with a high Compton scattering background—challenges that are particularly problematic when measuring large items such as those found in PF-4. Advances such as these could reduce the cost and time required for nuclear material accounting measurements and also offer advanced solutions for safeguarding the next generation of reactors. Furthermore, SOFIA's advances are being integrated into a new generation of NDA tools, forming part of an ongoing series of microcalorimeter spectrometers based on transition-edge sensor (TES) technology.

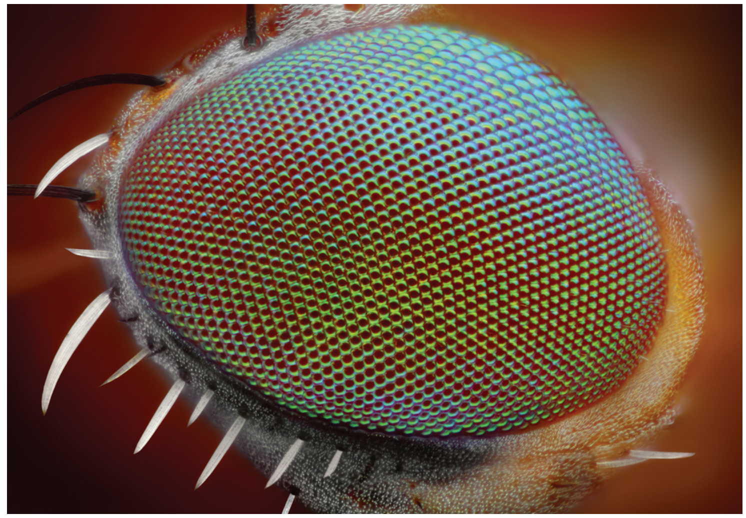
Ultra-high resolution: Detecting more isotopes

While earlier TES microcalorimeters served primarily as research tools, SOFIA—winner of an R&D 100 award in 2022—is specifically optimized for routine deployment in nuclear facilities. Its leap in precision is especially critical in high-throughput environments, where high fission product activity or strong background signals typically degrade performance in other types of detectors. Unlike previous experimental microcalorimeters, which were relatively bulky and relied on liquid cryogens for cooling, SOFIA's remarkably compact, cryogen-free design allows it to be integrated into operational workflows, including use alongside gloveboxes and hot cells. It can also analyze materials in various forms (solid, liquid, or powder) and under diverse environmental conditions. SOFIA is easy to use, allowing robust, non-destructive testing with no need to open the sample container. The technology's ultra-high resolution also allows hard-to-detect isotopes to be characterized by differentiating closely spaced gamma-ray peaks and detecting weak emission signals (e.g., the neptunium-237 86.5 keV peak, the uranium-238 113.5 keV peak, and the plutonium-240 104.2 keV peak).

How it works: SOFIA's compound eye

The TES technology on which SOFIA is based has been in development for several decades. It was originally designed for astrophysical applications—such as the detection of cosmic X-rays and gamma-rays from black holes, neutron stars, and supernovae—where exceptional energy resolution and low noise performance were achieved. These sensors measure minute gamma-ray emissions by converting their energy into heat pulses at cryogenic temperatures (~90 millikelvins), with each TES pixel in the array effectively acting as an independent microcalorimeter. The "eye" of SOFIA is therefore not a single sensor but an agglomeration of 256 spectrometers, all working in unison—somewhat analogous to the compound eye of an insect.

Each TES microcalorimeter in the array consists of three major components: a metallic detector, which absorbs gamma rays; the main TES (made from layers of normal and superconducting metals); and an amplifier. When cooled to cryogenic temperatures, the TES becomes superconducting but is poised on the limit of reverting to its normal (resistive) state—teetering on a sharp cliff edge. The smallest shove, in the form of a tiny wave of heat from the gamma ray photon (on the order of microkelvins), is enough to send it tumbling down the cliff, creating a change in its output of current. Because the gamma-ray signal is extremely weak, it must be boosted using a superconducting quantum interference device (SQUID)—a microchip-integrated amplifier capable of detecting current variations as small as a few femtoamperes.



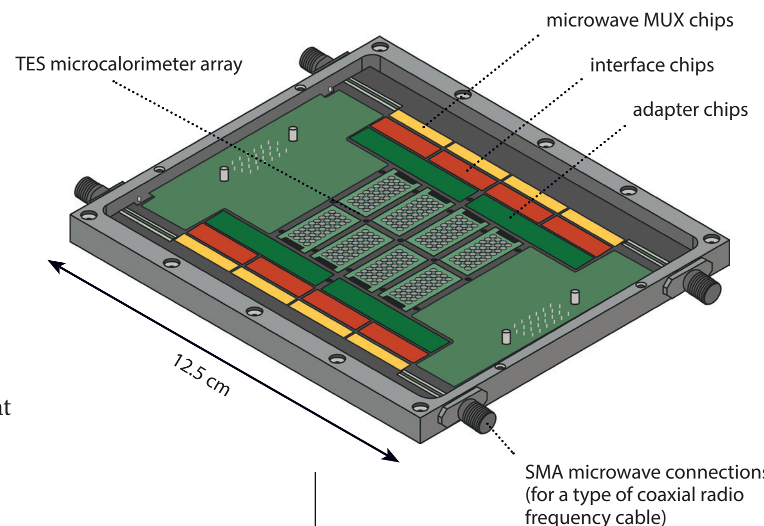


Figure 1. *Top*: An insect's compound eye works by combining the concurrent input from many individual optical units. SOFIA works in a similar manner, albeit using an array of 256 gamma-ray TES microcalorimeters. *Bottom*: Illustration of the sample box and chip layout for the SLEDGEHAMMER core of SOFIA. The 8 µMUX (microwave SQUID multiplexer) chips complete the transmission line path (yellow rectangles). The eight chip arrangement is used to simplify fabrication.

Multiplexing: SOFIA's FM radio

The next step of transmitting the detector signal to the readout electronics may seem like a small piece of the puzzle to a non-specialist. In reality, it poses a significant engineering challenge—critical to the system's performance—because hundreds of individual detectors must be read out with ultra-low noise, minimal wiring, and at millikelvin temperatures. This is achieved using a technique called multiplexing, which combines many detector signals into a smaller number of readout channels. Minimizing the number of wires connected to room-temperature electronics is crucial because each wire to the cryogenic component carries heat, and there is a physical limit on how many coaxial lines one can fit into a cryogenic refrigerator.

SOFIA evolved from an earlier prototype detector assembly, SLEDGEHAMMER (spectrometer to leverage extensive development of gamma-ray TESs for huge arrays using microwave multiplexed enabled readout), which provided a proof of concept for using microcalorimeters in nuclear material characterization (Fig. 1). SLEDGEHAMMER introduced key innovations in readout electronics and noise suppression, laying the foundation for SOFIA, which refined and optimized these advancements for deployment in facility environments.

According to SOFIA's principal investigator Mark Croce, the innovations behind SLEDGEHAMMER and SOFIA stem from an improved multiplexing scheme: "One major advance that SLEDGEHAMMER introduced was time division multiplexing. This is like turning a selector switch to, say, I want channel 2 now and then it switches over to channel 2, channel 3, etc. and cycles through." This implementation required all custom electronics, which were expensive and less advanced compared with field programmable gate arrays (FPGAs)—integrated circuits sold off-the-shelf. Croce continues: "The current version of SOFIA is essentially like FM radio. So, every channel, every sensor in the detector array has its own unique carrier frequency that it modulates. The firmware in our FPGAs is recording all of those signals simultaneously and separating them by the known resonator frequency."

This innovation was essential to achieve high count rates (up to 5,000 counts/sec), enabling measurement times comparable to those of HPGe detectors, while also allowing for a more compact instrument than previous TES-based microcalorimeters. Using SOFIA, the uranium-235/plutonium-239 ratio (an important yardstick in mixed-oxide nuclear fuels) can be determined with a 1-sigma precision of below 1.0% in hours (compared to several percent for an HPGe detector running for the same time).

Croce's team plans to incorporate the latest generation of readout electronics into SOFIA's next iteration. "These electronics were developed as part of the huge commercial investment in the digital electronics for gigahertz communications," Croce says. "This has allowed us to move most of the complexity of the previous custom superconducting SQUID chips into firmware. This is on a commercially purchased hardware platform, so the custom part is the firmware for the readout and the software to run it."

SOFIA does not serve as a blanket replacement for HPGe detectors—it is optimized for facility applications, and despite being compact for this type of TES microcalorimeter, it remains a much larger instrument than a germanium detector. Croce admits, "It does have unique capabilities, but you know, not everybody needs a race car—there's a lot that you can do with conventional germanium detector."

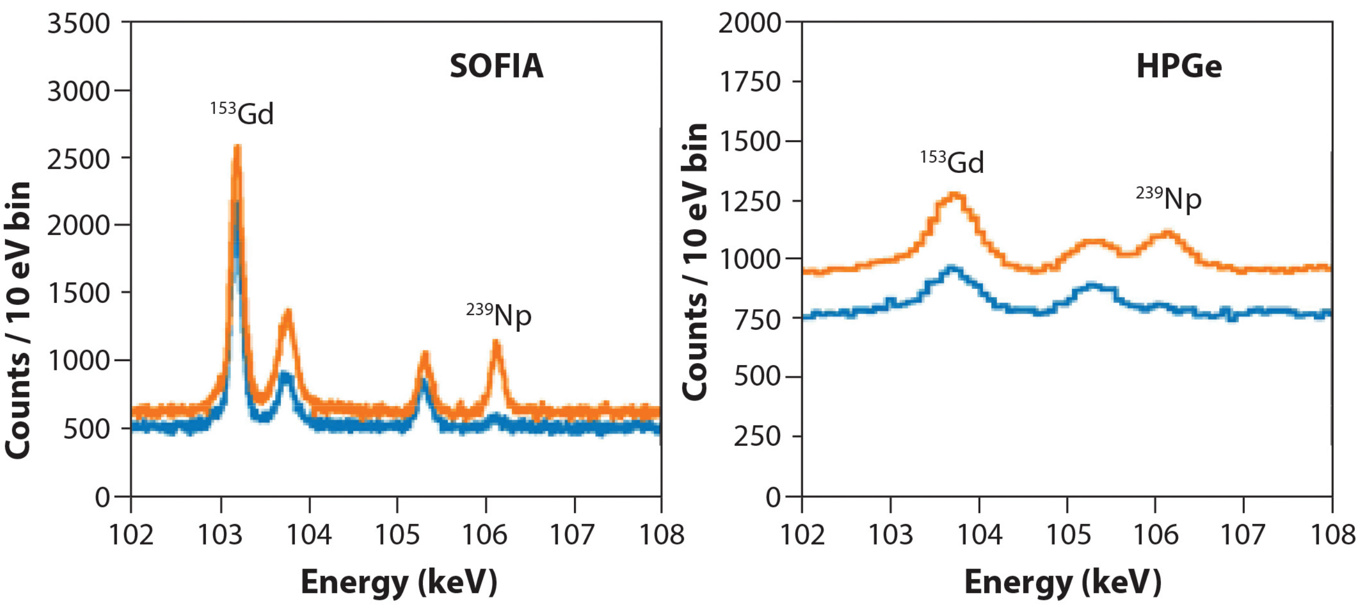


Figure 2. Demonstration of the improvement in resolution in gamma spectra with the SOFIA microcalorimeter (*left*) over HPGe (*right*) for two different electrorefiner salt samples (blue and orange lines). The 106.1 keV peak from neptunium-239 is much better resolved above the background with the SOFIA instrument. Credit: *Electrochemical Safeguards Measurement Technology Development at LANL* in the Journal of Nuclear Materials Management, 2021.

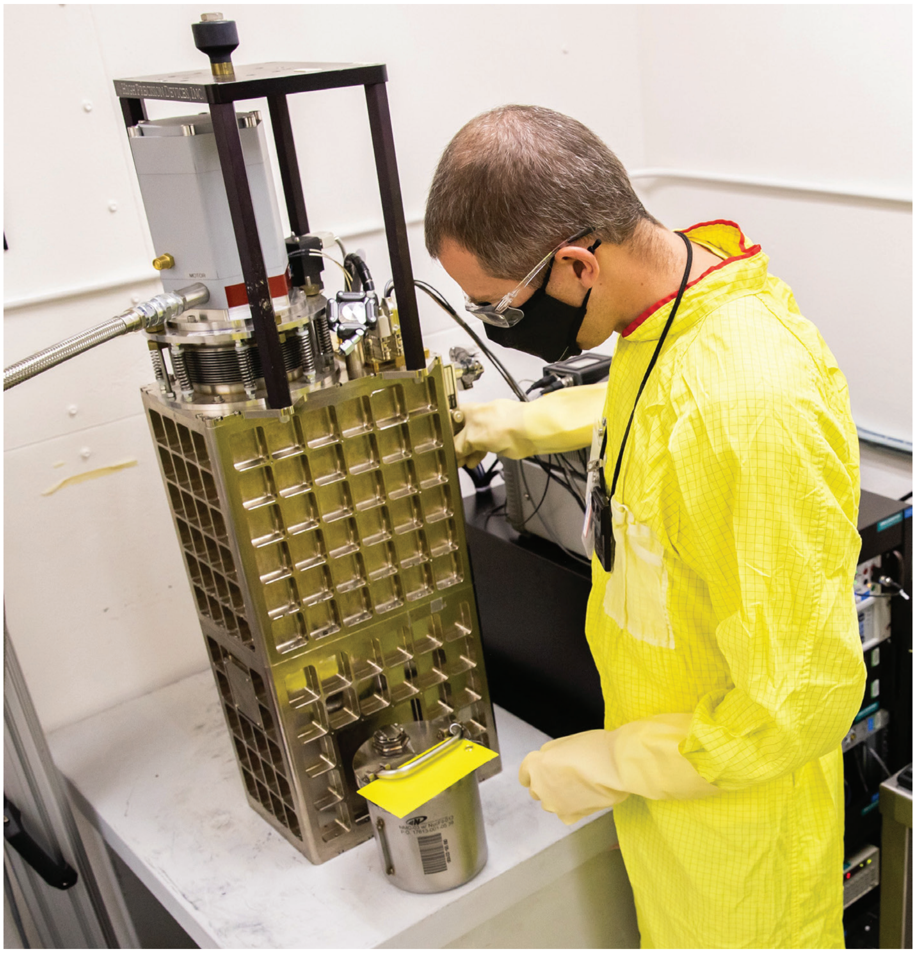


Figure 3. Mark Croce operates the SOFIA instrument, with tabletop cryostat.

Cooling

Typically, reaching ultralow superconducting temperatures requires either liquid helium or a large pulse tube refrigerator, which in turn requires three-phase power and a cooling water supply. One of SOFIA's key innovations is its use of a compact, tabletop cryostat that operates from a standard 220 V outlet, making it relatively easy to deploy in a nuclear facility (Fig. 3). However, Croce acknowledges that despite this progress, further refinement is needed to close the performance gap between SOFIA and conventional HPGe detector systems. A promising development in this area comes from recent cryogenic technology advances, particularly a new pulse tube cryo-cooler on the market that uses about half the power. This improvement could eventually allow SOFIA to run on a regular 120 V power source, much like HPGe detectors.

A 400 pixel eye: HERMES flies to other national labs

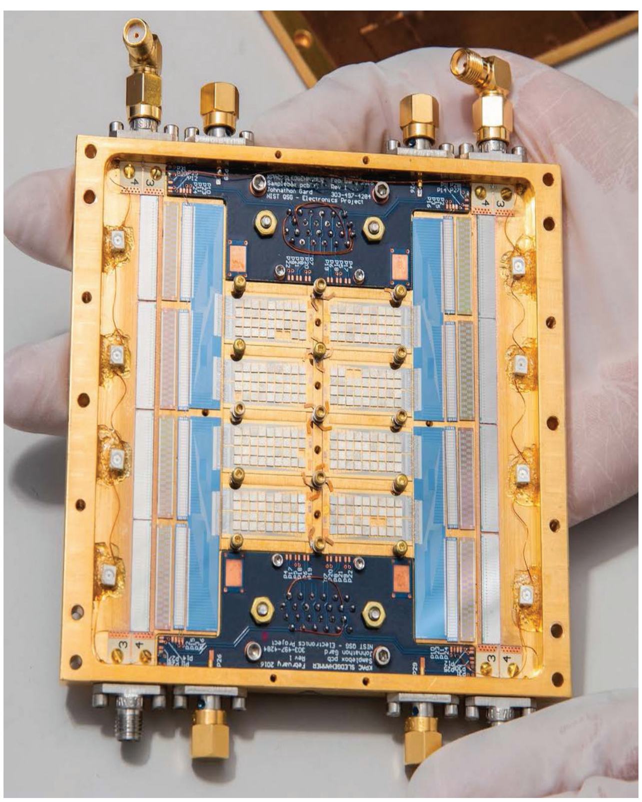
After the first iterations of SOFIA were developed, attention turned to expanding the TES array—in principle, increasing the number of detector pixels could yield further performance gains. In 2022, HERMES (high efficiency and resolution microcalorimeter emission spectrometer) was developed, featuring a 400 pixel detector that employs the same multiplexed architecture as SOFIA. It has already been deployed in nuclear facilities at the Idaho and Pacific Northwest national laboratories (Fig. 4).

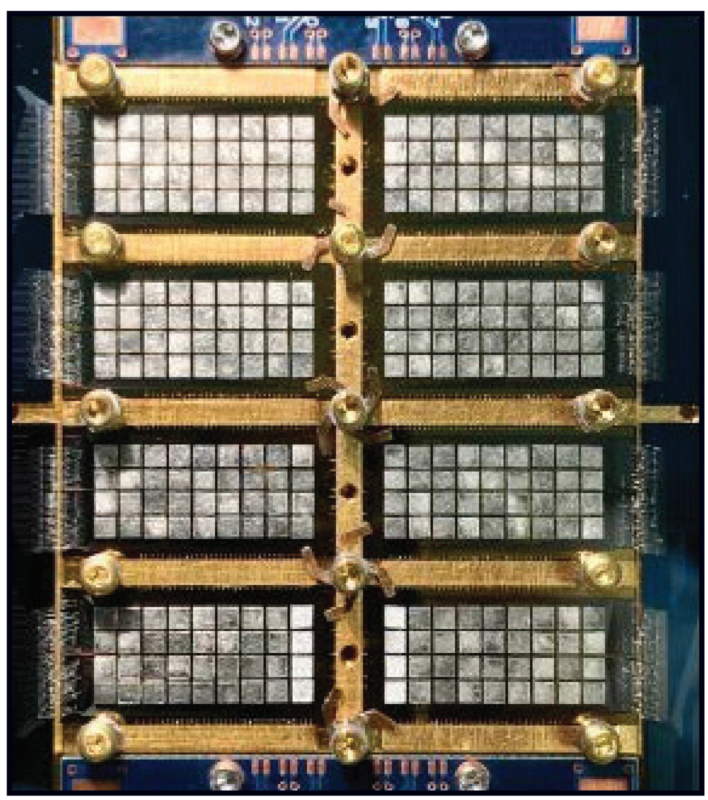
True to its namesake, the swift-footed Greek god, HERMES transmits its data rapidly, with the expanded pixel array enabling high-quality results in less time. Croce says, "If we can reduce the measurement time and still get this excellent precision and accuracy on the isotopic composition, that has huge practical benefits. For instance, in the plutonium facility, they have a lot of material accounting measurements to run through, which is often a bottleneck in facility operations." (see p24 for a full description of how a new dynamic accounting system is being designed to tackle this problem).

A less practical aspect of HERMES is its large cryostat, which is intended for permanent use in an analytical laboratory. However, Croce says, "We are actually looking at the next generation of SOFIA to use the same detector arrays and we think we can get close to 400 pixels in a SOFIA-type instrument with the small cryostat that can be used in multiple facilities."

Getting SAPPY

Advances in pulse processing and computational isotope analysis have also benefitted SOFIA and HERMES. These instruments use SAPPY (spectral analysis program in Python) as its primary software tool for analyzing gamma-ray spectra and determining isotopic ratios, which is seamlessly integrated into the operation of the instrument. It can perform isotopic analysis for both microcalorimeter data and traditional detectors like HPGe, allowing direct comparisons between instruments. Along with cross-detector compatibility, SAPPY's enhanced uncertainty modeling, improved peak fitting, and handling of high-resolution data make it very effective for interpreting complex spectra with overlapping peaks, a common real-world challenge in noisy radiation environments. This has allowed SAPPY to deliver results more quickly by automating the spectrum processing.





TES microcalorimeter array in SOFIA with 256 pixels.

Figure 4. HERMES, a higher resolution instrument intended for high-throughput operations, has been recently installed in the Analytical Laboratory at Idaho National Laboratory (INL). Left to right: Mark Croce and Kate Schreiber from LANL, Paige Abel and Brian Bucher from INL.

Outlook

Development of SOFIA and other prototypes began in the late 2010s, led by a team at Los Alamos in the Safeguards Science and Technology group. They were joined by researchers from the National Institute of Standards and Technology (NIST), who provided expertise in microcalorimeter technology and spectrometer design, and by collaborators from the University of Colorado Boulder, who contributed to the design and testing phases. Key to this work was the support of the DOE Office of Nuclear Energy's Material Protection, Accounting, and Control Technologies (MPACT) program and University Program (NEUP), which has prioritized enhancing the performance of microcalorimeters for gamma-ray spectroscopy. The team has since drawn interest from several commercial nuclear reactor developers, who view this next-generation NDA technology as a critical enabler for their advanced nuclear systems. SOFIA offers the potential for lower-cost material accounting measurements, helping to meet licensing and process-monitoring requirements for emerging nuclear reactor designs.

The Low Temperature Detectors Team consists of Mark Croce, Matt Carpenter, Kate Schreiber, Daniel McNeel, Rico Schoenemann, Emily Stark, Shannon Kossmann, Hyrum Hansen, Sophie Weidenbenner, Katrina Koehler, Tim Ockrin, Stefania Dede, Christine Mathew, and Cameron Wojtowicz.

Sideways-facing microsnouts with 400 pixels shown as installed in the cryostat of HERMES.

ND-Alpha: The World’s First Nondestructive Alpha Spectrometer

By Owen Summerscales

In the critical hours after a nuclear accident, first responders face high-stakes decisions—and without fast, accurate radiation detection tools, rapidly identifying the nature of radiation hazards remains a serious challenge. Whereas many non-actinide isotopes can be best identified using portable gamma and beta spectrometers (e.g., fission products such as iodine-131 and cesium-137), there is no comparable method available for detecting the alpha signatures of actinides in the field. Actinides such as uranium, plutonium, americium, and curium are primarily alpha emitters, and their alpha emission signatures are fingerprints of each actinide isotope.

Although alpha spectroscopy is a very sensitive technique—capable of detecting sources at the nanogram scale—it has traditionally been confined to a laboratory environment due to its sample preparation requirements. Los Alamos National Laboratory scientists decided to reevaluate this approach—with the aim of producing a compact, lightweight instrument and eliminating sample preparation, they recently developed the Nondestructive Alpha (ND-Alpha) spectrometer, the world’s first alpha spectrometer for “point and shoot” use (Fig. 1).

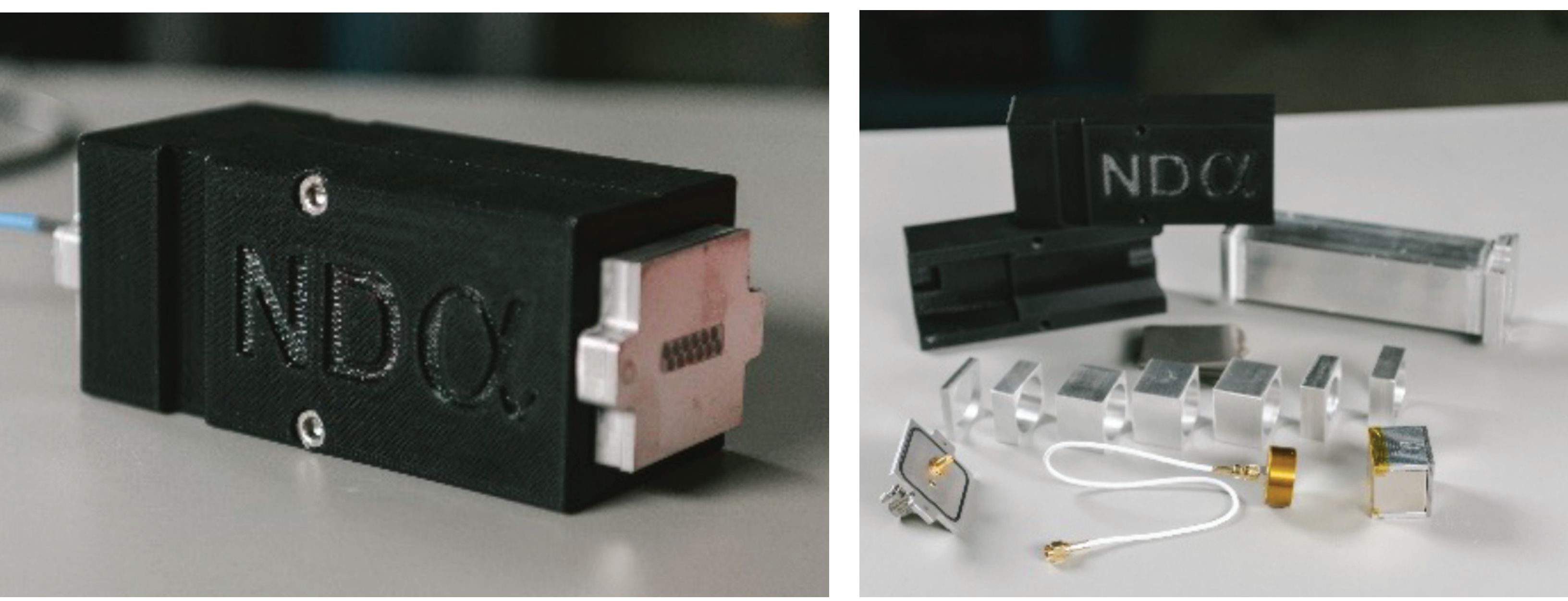


Figure 1. The portable ND-Alpha instrument, designed to use as a point-and-shoot detector with no sample preparation needed.

The ND-Alpha team consists of Mark Croce (PI), Katherine Schreiber, Daniel McNeel, Rico Schoenemann, Emily Stark, Jacob Ward, Matthew Carpenter, Istvan Robel, and Hye Young Lee. Croce explains how they developed the instrument: "I think the breakthrough came when we considered the problem of alpha spectroscopy from a different angle. So, the scientific question we had was: How do we make the most of an alpha spectroscopy signature from unprepared materials?"

"I think the breakthrough came when we considered the problem of alpha spectroscopy from a different angle." – Mark Croce, Safeguards Science and Technology

These "unprepared materials" could include complex mixtures of in situ nuclear waste or fallout debris from a nuclear accident. Croce continues, "A lot of the work in alpha spectroscopy has been about making really nice samples. Essentially, to make a field-deployable instrument, folks have tried to make a laboratory in a box where you can do some of the same techniques and make high quality samples, which is hard to do in real-world conditions."

Because alpha particles have a short penetration range, samples often need to be prepared as a thin layer to minimize energy loss and allow precise measurements. Croce says, "We considered the problem the other way, where you just accept that you have terrible alpha samples: they're dirty, they're thick. So, they attenuate the alpha radiation—but what can you do with that?"

Figure 2. Example of a traditional benchtop alpha spectrometer, which works by measuring the alpha emission spectrum from a prepared sample placed in a vacuum chamber. Credit: Mirion Technologies, Inc.; physicsopenlab.org.

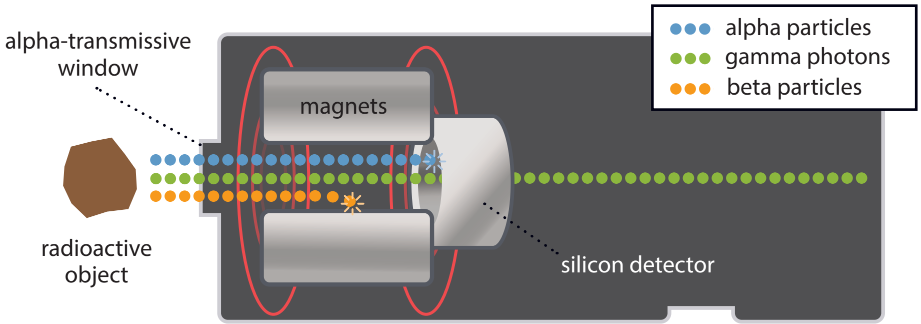


Figure 3. Schematic showing how the three types of radiation are separated in ND-Alpha. Beta particles are charged and therefore captured by the magnets. Although alpha particles are also affected by the magnetic field, they have approximately 7,300 times the mass of beta particles and so are not as strongly deflected. Gamma rays meanwhile pass through the thin silicon detector without interacting.

What the team did was build an instrument with three key components:

(i) **A thin alpha-transmissive window** that allowed them to keep the sample outside of the vacuum detection chamber, making contactless detection possible, essential for contaminated or hazardous samples (the sample still needs to be within 2 mm, however). The window is approximately 2.5 µm thick (about 1/20th the thickness of a single human hair), enough to maintain vacuum around the sensitive detector while also permitting alpha particles to pass through with minimal energy loss—only about 300 keV for a 5 MeV alpha particle, preserving most of the particle's original energy.

(ii) **A magnetic filter** which enables the instrument to be pointed directly at something as intensely radioactive as spent nuclear fuel, containing mixtures of fission products that emit beta radiation. The magnetic field traps beta radiation, which could otherwise swamp the detector. Filtering of gamma radiation meanwhile occurs naturally because of the inherent insensitivity of the thin silicon detector to gamma rays.

(iii) Algorithms, known as **alpha endpoint analysis**, which allow calculation of characteristic alpha energy maxima ("endpoints") and filtering of background noise. This innovation is essential for handling low-quality alpha samples—such as those that are thick, uneven, or affected by variable attenuation from air, dust, or protective films—which can broaden spectral features or obscure alpha peaks.

With this pragmatic design, Croce says that "We're not trying to get nice peaks. We're just trying to determine the maximum energy associated with an alpha particle." This works because accurately measured maxima give enough vital information to identify actinides uranium, plutonium, americium, and curium.

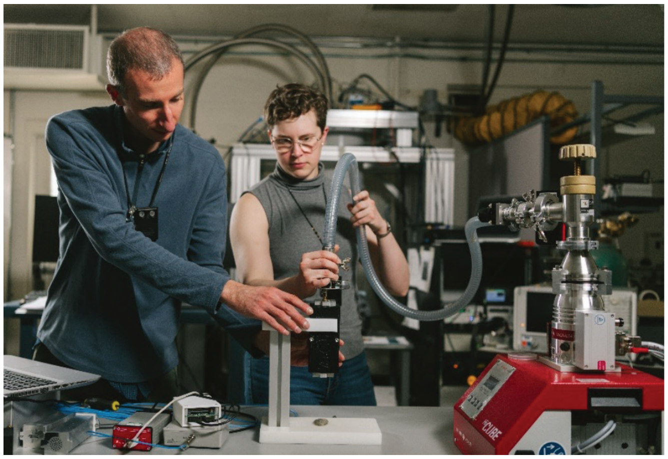


Figure 4. Mark Croce and Emily Stark demonstrate the ND-Alpha instrument.

Most current field instruments for actinides are based on gamma-ray spectroscopy, which has significantly lower sensitivity to alpha-emitting radionuclides. For example, with plutonium-239, 100% of decays emit alpha particles but only 0.006% emit the 129 keV gamma ray. As a result, gamma spectrometers are much less effective for detecting actinides unless gamma emissions are abundant (e.g., with large volumes of radioactive material or in select gamma-emitting isotopes such as americium-241). Although portable alpha-beta contamination monitors are available commercially, they are designed to give a general measurement of radiation levels but are not spectroscopic and do not distinguish uranium from plutonium. The handheld ND-Alpha instrument—a 2024 R&D 100 winner—meanwhile operates in a "point-and-shoot" mode, ideal for rapid surveys in field operations such as in nuclear emergency-response scenarios. All of the components are either commercially available or inexpensive and simple to produce, and the team currently has a provisional patent in progress.

Croce says that they are now looking to extend ND-Alpha to other applications: "We've considered molten salt reactor safeguards, and this could actually be used as an inspection tool. A sample of a fuel salt could be extracted and put in front of the detector to verify the fissile material content of the fuel." Actinides present in these salts could include thorium, uranium, and plutonium along with minor species neptunium, americium, and curium. Croce adds, "I don't know of any other passive nondestructive technique that would be so easily implemented and give you that sensitivity to the fissile content—which is really the safeguards concern."

Preliminary testing has demonstrated ND-Alpha's capability to detect and analyze alpha emissions from spent nuclear fuel and other actinide-containing materials, even with high beta-gamma radiation backgrounds. The instrument's design also allows for remote operation, for instance attached to a robot, an essential feature for use in highly contaminated radiation zones (Fig. 6). With its pragmatic approach to identifying actinide signatures, ND-Alpha fills a long-standing gap in field-ready instrumentation for alpha-emitting materials, marking a shift from lab-bound techniques to practical tools without the need for pristine samples or controlled environments.

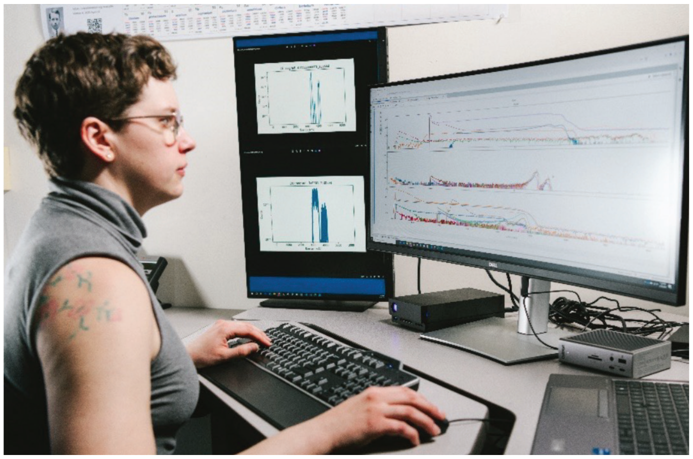
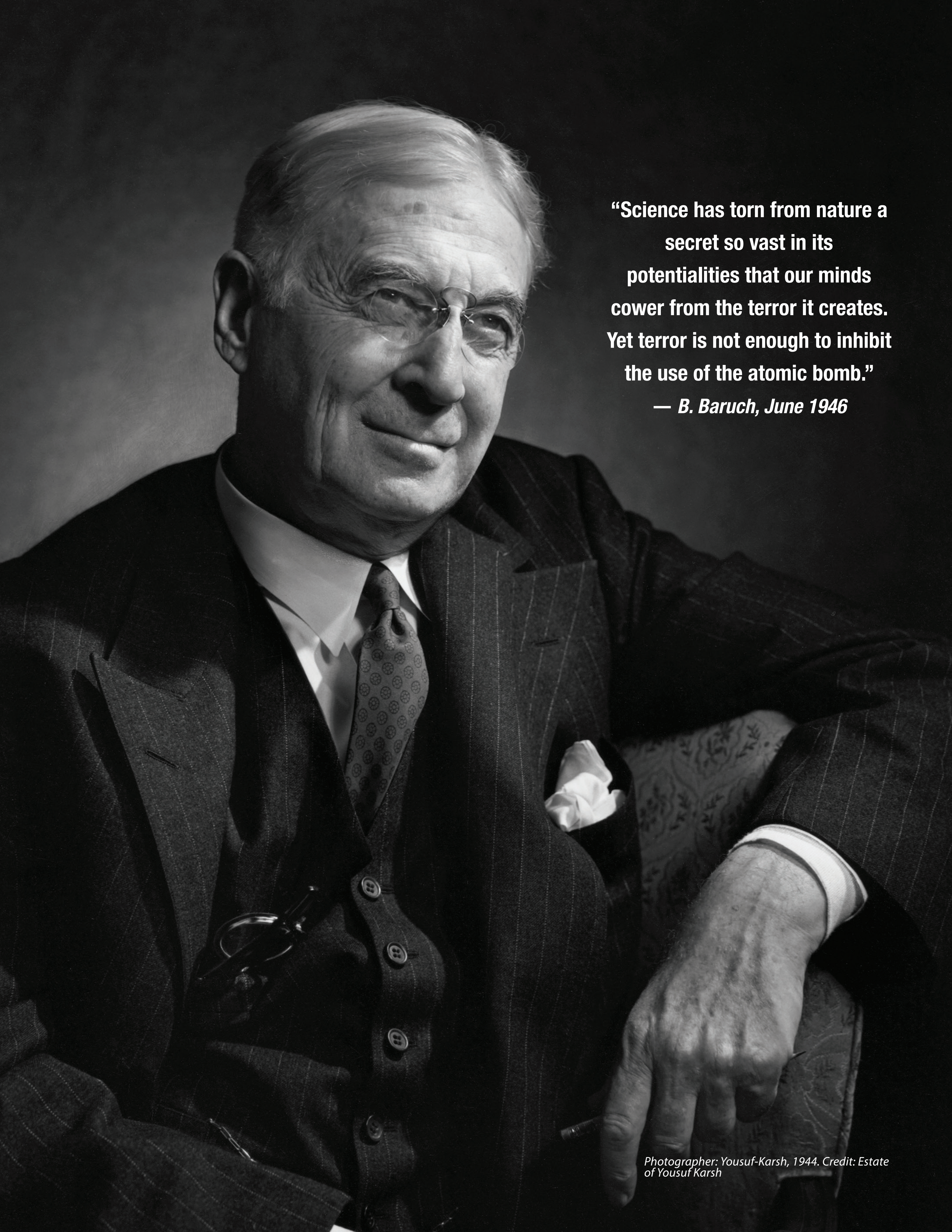


Figure 5. Alpha endpoint analysis is a key aspect of ND-Alpha. This allows the calculation of characteristic alpha energy maxima and filtering of background noise, essential for handling low-quality alpha samples which can broaden spectral features or obscure alpha peaks.

Figure 6. Using ND-Alpha remotely inside a hot cell.



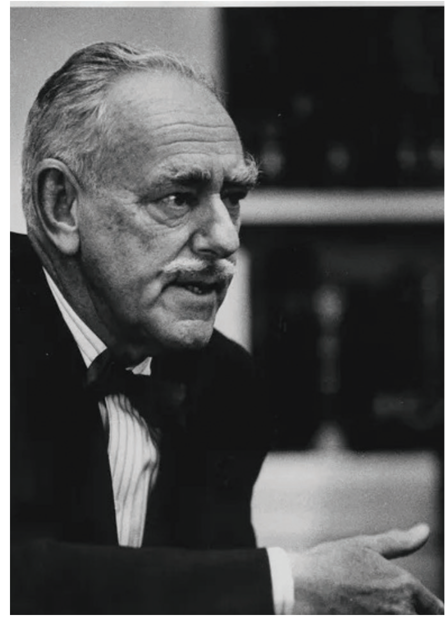
"Science has torn from nature a secret so vast in its potentialities that our minds cower from the terror it creates. Yet terror is not enough to inhibit the use of the atomic bomb."

— B. Baruch, June 1946

Photographer: Yousuf-Karsh, 1944. Credit: Estate of Yousuf Karsh

The Race to Nonproliferation: The Baruch Plan

By Owen Summerscales



Dean Acheson, July 8, 1965. Credit: Yoichi Robert Okamoto, White House Photo Office Collection, Lyndon Baines Johnson Library.

Two bombs marked the end of the deadliest war in history. As the dust settled from the Hiroshima and Nagasaki bombings, the world found itself weary of warfare and weaponry, but it faced a frantic effort to avoid a nuclear arms race between the United States and the Soviet Union—uneasy allies at best during World War II. The Baruch Plan, presented to the newly formed United Nations in 1946, was the first formal proposal from the United States for international control of nuclear energy. It sought to prevent nuclear proliferation through an unprecedented framework of safeguards, verification measures, and international oversight. Although it ultimately failed to achieve support and was followed by an international arms race,* it is still relevant today both in terms of its legacy in nuclear safeguards and as a valuable source of historical lessons.

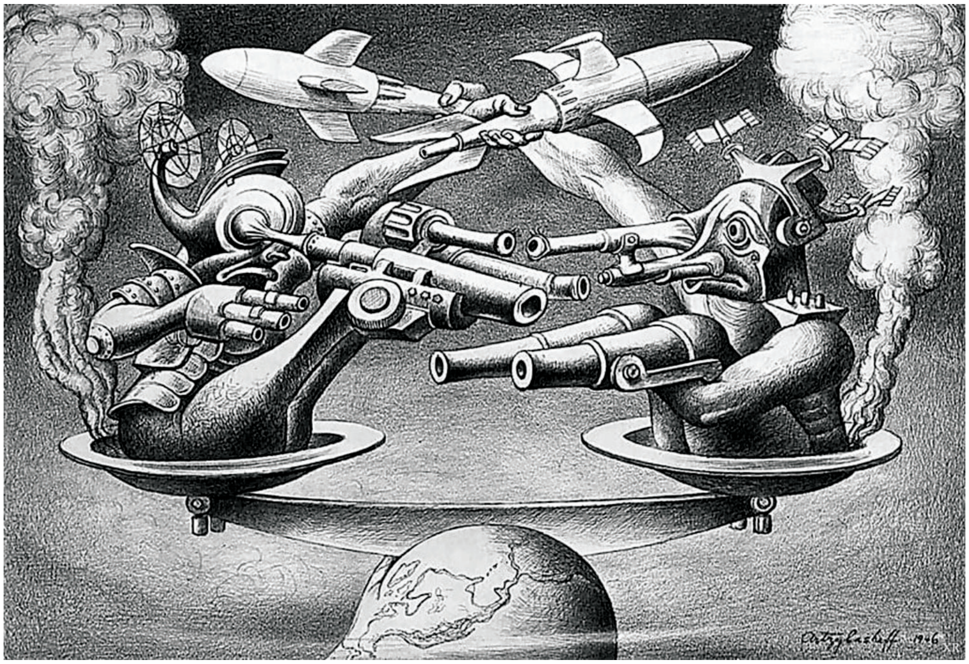
Precursor to Baruch: The Acheson-Lilienthal Report

At the end of World War II, the United States was the sole possessor of nuclear weapons. Henry Stimson, Secretary of War under President Harry Truman, had warned Truman during the war that without an effective international system to regulate nuclear energy, a "disaster of civilization" would likely ensue as a consequence of an uncontrolled global arms race. After the war, in December 1945, the United States, the Soviet Union, and the United Kingdom agreed to establish the United Nations Atomic Energy Commission (UNAEC) to explore mechanisms for controlling nuclear weapons and energy. Through this commission, both the United States and the Soviet Union sought to establish a system of nuclear regulations to prevent another major conflict—meanwhile, the Soviet Union was secretly developing its own atomic bomb using covert information gained from Los Alamos via espionage.

In January 1946, the US government formed a special advisory committee, led by Dean Acheson and David Lilienthal (former Assistant Secretary of State and director of the Tennessee Valley Authority, respectively), to develop a plan to control the use of nuclear energy. This work resulted in the Acheson-Lilienthal Report, published in March 1946, which proposed international control over the production and use of nuclear energy to prevent nuclear weapons proliferation. The report suggested creating a global authority to manage all weapons aspects of the nuclear fuel cycle, leaving only peaceful applications under sovereign control.

Robert Oppenheimer was the lead technical advisor to the committee and the primary author of the final report. Oppenheimer believed that a nuclear arms race should be avoided at all costs and, furthermore, hoped that the very existence of the bomb would eliminate warfare—period—saying, "If the atomic bomb was to have meaning in the contemporary world, it would have to be in showing that not modern man, not navies, not ground forces, but war itself was obsolete." Needless to say, this

* Bernard Baruch is credited for popularizing the term "Cold War" in a 1947 speech. However, the phrase was first coined by the writer George Orwell in his 1945 essay "You and the Atom Bomb," published just two months after the Japanese bombings.



'The Balance of Power' by Ukraine-born American artist, Boris Artzybasheff, 1946.

was an ambitious goal. However, the idea of outlawing weaponry had precedent—the 1925 Geneva Protocol prohibited the use of chemical and biological weapons in warfare following World War I.

The Geneva Protocol lacked enforcement mechanisms but established a legal precedent and a strong stigma against the use of these weapons. Prior to this, the 1899 Hague Convention had sought to ban the use of poisonous gas projectiles but was largely disregarded. However, after the devastating effects of chlorine gas in trench warfare, the Geneva Protocol gained significant traction, leading major powers to largely refrain from using such weapons during World War II.

Oppenheimer hoped that after witnessing the effects of the atomic bomb, the world could be persuaded to follow a similar path for nuclear weapons. But whereas the Geneva Protocol only prohibited the use of chemical weapons, not their ownership, Oppenheimer sought the outright abandonment of nuclear weapons.

As such, the Acheson-Lilienthal report proposed the creation of an international authority—the Atomic Development Authority (ADA)—to physically control and regulate all nuclear industries. The ADA would

- Own and control all uranium and thorium mining worldwide
- Oversee all nuclear research and production facilities to ensure they were used for peaceful purposes
- Conduct international inspections to prevent covert nuclear weapons programs
- Provide licenses to countries wishing to pursue nuclear energy for peaceful applications.

The report explicitly stated that the ADA must remain at the cutting edge of nuclear technology: "It [is] absolutely essential that any international agency seeking to safeguard the security of the world against warlike uses of atomic energy should be in the very forefront of technical competence in this field." The report made it clear that if the ADA simply focused on enforcement, it would not be well-enough informed to recognize threats as they arose.

Next, the report suggested a path toward ultimately eliminating nuclear weapons through international cooperation. Much like the Geneva Protocol, enforcement would rely on transparency and cooperative security measures rather than immediate punitive actions, and thus, the Acheson-Lilienthal report hinged on US-Soviet cooperation.

Last minute change: The Baruch Plan

President Harry S. Truman (left) gets a report on bombing of Japan from Secretary of War Henry Stimson (right) upon his return from the Potsdam Conference. From the scrapbooks of Matt Connelly, Vol. 1. August 8, 1945. Credit: International News Photos, Harry S. Truman Library & Museum.

Alex Wellerstein, historian of nuclear science at the Stevens Institute of Technology, notes in his book Restricted Data that the philosophy of the Acheson-Lilienthal report "was largely rooted in Oppenheimer's belief that international control had to be based on something other than secrecy." This was why there was a focus on controlling uranium: "Without sources of raw uranium, no amount of knowledge could possibly make an atomic bomb," says Wellerstein.

Commenting on this proposed bottleneck for creating weaponry, Los Alamos historian Nic Lewis says that controlling uranium wasn't too controversial, at least in the United States—and at the time, uranium ore was thought to be a rare and therefore potentially controllable resource. However, he continues: "What became controversial was the included idea that the US would relinquish its nuclear stockpile and would share its secrets with Soviet Union, entering into a pact with the Soviets not to develop more atomic weapons. Well—Truman wasn't really on board with that last part."

With US-Soviet tensions rising, Truman refused any agreement that would eliminate US nuclear weapons without guarantees that the Soviet Union could not develop its own. The day before submitting the Acheson-Lilienthal report to the UN, Truman appointed Bernard Baruch, a senior statesman who had been an advisor to Roosevelt and Woodrow Wilson, as the US delegate to the UNAEC, trusting him to defend American interests.

Baruch modified the plan, adding the mandatory inspection of nuclear sites with the threat of sanctions against countries that weren't adhering to the stipulations. Most importantly, he added an onerous clause that there would be no veto power in the UN Security Council over these sanctions or inspections. This was significant—the Security Council was established on the basis that the five permanent members (i.e., the main Allied Powers US, UK, USSR, China, and France) all maintained a right to veto any substantive resolution. Also—significantly—the plan stipulated that the US would only begin the process of destroying its nuclear arsenal after the plan was implemented.

The Acheson-Lilienthal report had advocated for trust-based regulation, while the Baruch Plan emphasized sterner, enforcement-driven control and failed to provide the Soviets with security assurances. Nevertheless, in Baruch's speech to the UN, he passionately implored the Soviets to cooperate: "Behind the black portent of the new atomic age lies a hope which, seized upon with faith, can work our salvation. If we fail, then we have damned every man to be the slave of Fear. Let us not deceive ourselves: We must elect World Peace or World Destruction." In closing, Baruch said that the plan was "the last, best hope of earth."

Lewis says, however, that this hope was a "long shot." "It was pretty well accepted that the Soviets would not go along with those provisions because they were a bit touchy about Western inspectors coming into Soviet territory, along with sanctions that could not be overruled by veto—at that point, they believed the US had an unfair advantage in the Security Council."

Although the Soviets were cautiously interested in the Acheson-Lilienthal report, they rejected the Baruch Plan immediately, seeing it as a US attempt to maintain nuclear dominance.

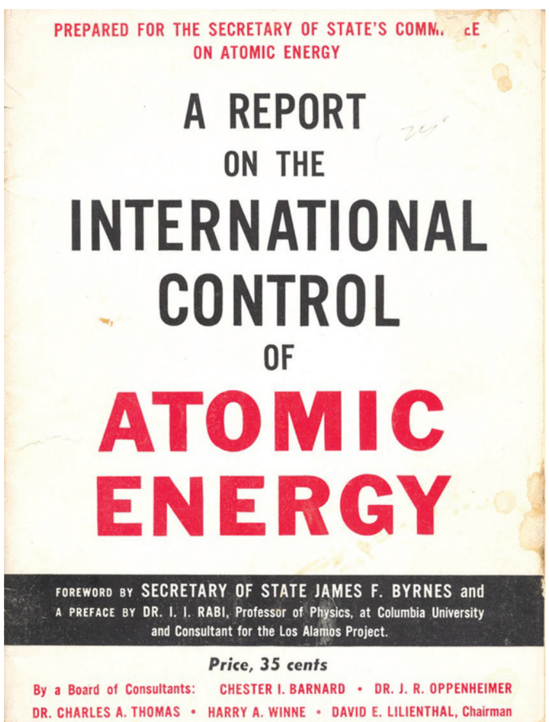
Whispers and handshakes

Many people have pointed to the covert nature of the Manhattan Project as sowing seeds of mistrust between the United States and the Soviet Union. This included an ambitious system of classifying fundamental scientific knowledge as secret—even keeping hidden the discovery of new elements plutonium, curium, and americium.

Lewis explains that "Henry Stimson argued that nuclear knowledge is a matter of nature, and you can't just hide it—and that trying to hide it would just encourage the Soviets to develop their own bomb secretly. This would just create the very situation you wanted to avoid by trying to keep everything tightly wrapped."

An unraveling of the secrecy protocols that sprang up around the Manhattan Project was planned in the Acheson-Lilienthal report, which stated: "When the plan is in full operation there will no longer be secrets about atomic energy." The Baruch Plan largely preserved this focus on restriction of nuclear materials over information, and all subsequent nonproliferation schemes have followed this principle.

The Soviet counterproposal, the Gromyko Plan, called for a complete and immediate nuclear disarmament before establishing international control over nuclear materials—a reversal in order from the Baruch Plan. The US could not accept this as without a robust verification system, and they feared that the Soviet Union (or any other country) could continue developing nuclear weapons in secret. As such, stalemate was reached and no further attempts were made to attain disarmament through the UNAEC, which dissolved in 1949.



The Baruch Plan was based on The Report on the International Control of Atomic Energy—generally known as the Acheson–Lilienthal report—written by a committee chaired by Dean Acheson and David Lilienthal with Robert Oppenheimer as the lead technical advisor in early 1946.

Oppenheimer's reaction

Oppenheimer saw the failure of the Baruch Plan as predictable based on pre-existing tensions because it was "a negotiating position, not a basis for agreement." He deeply lamented this turn of events, however, given its utmost importance: "To answer simply that we have failed because of non-cooperation on the part of the Soviet government is certainly to give a most essential part of a true answer. Yet we must ask ourselves why in a matter so overwhelmingly important to our interest we have not been successful; and we must be prepared to try to understand what lessons this has for our future conduct."

Oppenheimer critiqued the US failure to engage the Soviet Union directly at the highest levels, instead of relying on UN forums that lacked real diplomatic power and accused US politicians of maintaining a contradictory stance, advocating for openness while simultaneously guarding nuclear secrets.

Robert Oppenheimer (*left*) and David Lilienthal (*right*), circa 1950. Credit: by Popperfoto via Getty Images/Getty Images.

In the following years, Oppenheimer remained engaged in nonproliferation discussions, chairing the General Advisory Committee (GAC) of the Atomic Energy Commission, but became more realistic about global disarmament. In 1949, he and the GAC opposed the development of the hydrogen bomb, arguing that it was unnecessary and morally problematic, but the bomb program continued in spite of these objections. After this defeat, he moved away from advocating for disarmament and instead supported arms control and managing nuclear risks, before his security clearance was notoriously stripped from him in 1954, effectively ending his influence on US nuclear policy. At the end of his career, he became director of the Institute for Advanced Study in Princeton, where he focused on the broader ethical implications of science and technology, often speaking about the responsibilities of scientists and the moral implications of nuclear weapons.

"To answer simply that we have failed because of non-cooperation on the part of the Soviet government is certainly to give a most essential part of a true answer. Yet we must ask ourselves why in a matter so overwhelmingly important to our interest we have not been successful; and we must be prepared to try to understand what lessons this has for our future conduct."

– Robert J. Oppenheimer, Foreign Affairs, January 1948

The Shinkolobwe Mine in the Belgian Congo, seen here in operation during the 1940s when it was kept secret and even removed from maps, produced the world's highest-grade uranium ore (typically yielding 65% uranium) and played a pivotal role in the Manhattan Project. After World War II, it remained strategically important as a Cold War asset; although improved enrichment techniques reduced Western dependence on its ore, the United States maintained control to deny access to the Soviet Union. The Baruch Plan, proposed in 1946, called for international ownership and control of all nuclear materials, including uranium ore—a concept considered realistic at the time, given that only a few sources, such as Shinkolobwe and Jáchymov in the Czechoslovak Republic, were known to yield uranium of sufficient quality suitable for weapons production.

Atoms for Peace and the International Atomic Energy Agency (IAEA)

Reactor technology remained under tight control in the US after the war—if you could build a reactor to generate power, you could build one to produce plutonium for weapons. But this changed in 1953 when President Dwight D. Eisenhower introduced the Atoms for Peace program, a modified successor to the Baruch Plan, in which selective sharing of US nuclear know-how would be exchanged with countries in a promise to not develop nuclear weapons. Disarmament was, however, pushed to the background, remaining a distant objective at best.

"Releasing knowledge of fission for peaceful purposes would have been a big concession for the US and a major carrot for countries to join the international agreement," says Lewis. "It was a pretty remarkable idea."

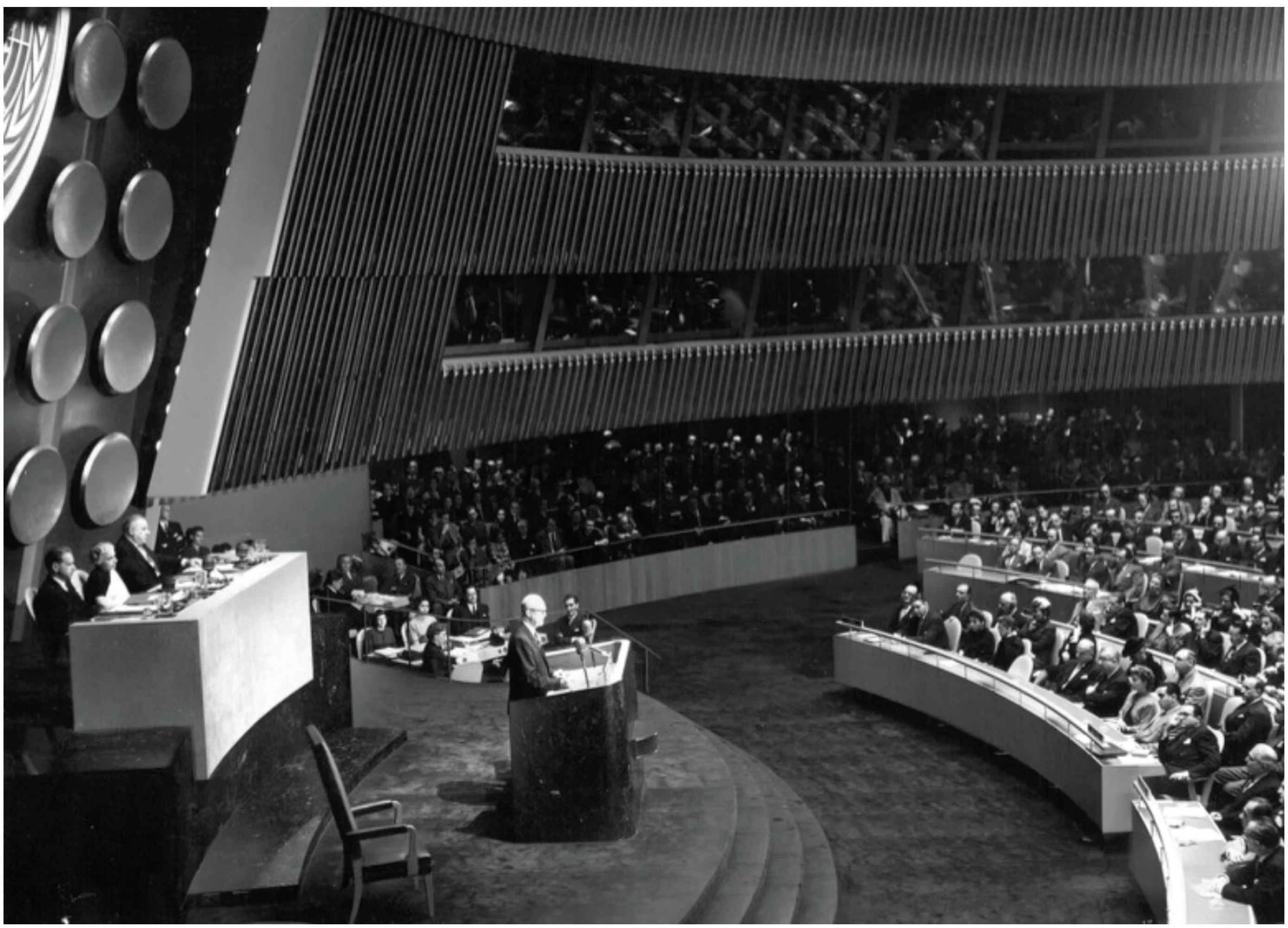
Eisenhower proposed an international agency to regulate and distribute nuclear materials for peaceful purposes, which led to the establishment of the IAEA in 1957—a weaker version of the ADA proposed in the Baruch Plan—which still oversees nuclear safety and nonproliferation today (the program's name lives on today in IAEA's motto—"Atoms for Peace and Development"). While the ADA was intended to own and distribute nuclear materials, the IAEA was assigned a more limited role, focusing primarily on regulation and oversight. This was more realistic on several levels—by the 1950s, uranium ore was found to be more abundant than previously believed, making the idea of controlling uranium mines no longer workable.

The establishment of the IAEA led to the need for technological solutions to safeguarding and verification, in particular instruments that can be used in nondestructive assays (NDAs) of nuclear material and remote measurements. In the mid-1960s, after working at the IAEA, Los Alamos physicist Bob Keepin established the Los Alamos Nuclear Safeguards Program to address this challenge, and the Laboratory has been at the forefront of these efforts ever since. Today, all IAEA inspectors must undergo training at Los Alamos National Laboratory on the use of NDA instruments, many of which were originally developed there (see p4).

Although successful in some regards, Atoms for Peace led to the rise of independent nuclear weapons programs (e.g., France, India, Pakistan) as countries that initially received peaceful nuclear assistance and later weaponized their programs—the opposite result from the scheme's intent. These weapons programs became legitimized under the subsequent Non-Proliferation of Nuclear Weapons (NPT) treaty of 1968.

The Soviet Union officially rejected Atoms for Peace, viewing it as a US propaganda tool designed to maintain Western nuclear dominance while restricting Soviet influence. Stalin and his successors were extremely resistant to intrusive onsite inspections from Western countries, a situation that hampered safeguarding efforts, persisting for decades. However, this deadlock was broken over time as technological advancements—such as satellites, seismic monitoring, and air sampling—made it possible to monitor nuclear activities remotely.

Atoms for Peace ultimately did little to temper the US-Soviet arms race, which ballooned between the early 1950s and the mid-1980s, resulting in the production of well over 50,000 nuclear weapons worldwide. Peace in some sense may have been brokered, but it rested on a fragile pact of mutual vulnerability. The Cold War ended because of the dissolution of the Soviet Union in 1991.



President Dwight D. Eisenhower delivers his historic "Atoms for Peace" speech to the United Nations General Assembly on December 8, 1953, advocating for the peaceful use of nuclear energy. Atoms for Peace, a revised successor to the Baruch Plan, offered selective sharing of US nuclear knowledge with other nations in exchange for a commitment not to pursue nuclear weapons development.

The headquarters of the IAEA Secretariat at the Grand Hotel in Vienna from 1958 to 1979. In Atoms for Peace, Eisenhower proposed the creation of an international agency to manage and share nuclear materials for peaceful purposes, leading to the establishment of the IAEA in 1957—a less powerful successor to the Atomic Development Authority envisioned in the Baruch Plan—which continues to oversee nuclear safety and nonproliferation efforts today. Credit: IAEA.

Lessons from the Baruch Plan: Safeguarding AI?

What insights can we learn from the Baruch Plan? And are they relevant today?

Many argue that these lessons are more important than ever, especially with the rise of advanced computing technologies like AI, which may require international safeguards similar to those once proposed for nuclear materials. “Are we in September 1945, for AI?” Lewis asks. “We now know these are a threat, but we don’t what the implications are. Are we going to just keep ambling towards the point of no return?”

In 2021, Oxford University’s Future of Humanity Institute published a paper entitled International Control of Powerful Technology: Lessons from the Baruch Plan for Nuclear Weapons. The authors conclude that nations prioritize national security over cooperation and that secrecy can be counterproductive as it increases mistrust and reduces opportunities for collaboration (related to the security dilemma in international relations), undermining the very things necessary to safeguard dangerous weapons. Lewis agrees, saying that history “affirms that you need a good faith, large-scale, international coalition to prevent runaway arms races that have the potential to impact the lives of everyone, whether that’s a thermonuclear weapon or a gen AI. Let’s apply those hard-learned lessons into the way we integrate technologies into society.”

Summary

The 1946 Baruch Plan was a bold attempt to nip nuclear weaponry in the bud when only a handful of warheads existed. Vested state interests and national sovereignty triumphed over the desire to avoid an arms race, however, and the genie refused to be put back in its bottle. Nevertheless, the Baruch Plan remains a pivotal moment in the history of nuclear governance, and its emphasis on safeguards and international oversight has significantly shaped the modern nonproliferation regime, in particular the IAEA, NPT, and other ongoing arms control initiatives. The technical challenges of nonproliferation continue to drive much of today’s nuclear research, with Los Alamos National Laboratory remaining a key player in advancing safeguards. Today, lessons from the failed plan remain relevant as nations continue to navigate the complex balance of national security and international cooperation, with powerful new technologies such as AI looming on the horizon.

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