Abstract
Since 1949 Idaho National Laboratory (INL) and its predecessor organizations have served as a hub for research and development on nearly all aspects of the civilian nuclear fuel cycle for peaceful applications. Throughout this period work at INL has included the design, construction, operation, and decommissioning of nuclear facilities from bench-scale to industrial-scale operations including fuel fabrication, reactor operation, used-fuel storage, fuel reprocessing, and waste consolidation and storage. As a result of these activities INL now serves as the steward of a singularly-important resource of radiological and special nuclear materials with relevance for science-based studies relating to material protection control and accountancy, safeguards, nonproliferation, arms control, treaty verification, and nuclear forensics. Over the last decade INL has been aggressively working to provide access to these materials to the broadest possible group of practitioners in these fields. While simulations serve as an immeasurable resource for advancing technology for these areas, ultimately, working directly with special nuclear materials is a necessity. Recognizing this, in 2012, INL created the Nuclear and Radiological Activity Center (NRAC) to further improve its ability to support visiting national laboratory, academic, and commercial research teams seeking to perform work using these materials. In this paper we summarize INL’s capabilities for supporting research and development, test and evaluation, training, and education with special nuclear materials, using examples of recent activities at INL to illustrate resources and opportunities.

Keywords: uranium, plutonium, experiments, nonproliferation

Introduction
Recent special nuclear material (SNM) consolidation activities in the United States have reduced the ability of scientists and engineers to access these materials and perform realistic research and development experiments. Lack of access to SNM has similarly diminished the ability of operational groups to execute realistic training cycles using these materials and has also negatively impacted the ability of research sponsors and commercial instrument developers to test and evaluate radiation detection and measurement methods and instrumentation. A need exists to facilitate work with SNM so these groups can have access to them to perform work. In particular, new challenges and requirements are being identified in the fields of material protection control and accountancy, safeguards, nonproliferation, arms control, treaty verification, and nuclear forensics that require the development of new instruments and methods for securing the nuclear fuel cycle.

Recognizing this need, Idaho National Laboratory (INL) recently initiated the formation of the Nuclear and Radiological Activity Center (NRAC) within INL's Nuclear Nonproliferation Division. INL-NRAC consists of multiple INL research facilities, laboratories, and complexes that combine to facilitate visitor access to the INL Site and the unique radiological and SNM resources at INL (See Figure 1). INL-NRAC is intended to serve as a central gateway for researchers seeking to use these resources, to facilitate and coordinate research activities among the NRAC components, and to streamline the process for outside teams visiting INL and performing nonproliferation and nuclear security work with INL's researchers and its radiological and SNM resources. Creation of INL-NRAC was a DOE-mandated laboratory milestone in fiscal year
2012 and is intended to facilitate greater cooperative research work between INL and outside entities interested in using radiological materials and SNM at INL. As the custodian of many important SNM resources present at the INL Site, formation of NRAC illustrates INL's commitment to ensuring broad user-community access for performing meaningful research in support of national interests related to nuclear security and nonproliferation.

Figure 1 Layout of the INL Site in the State of Idaho, showing the key INL-NRAC resources.

This paper outlines several of the key assets, including both materials and facilities, at INL that contribute to INL-NRAC. The paper begins with a brief overview of INL and a discussion of key facilities and laboratories that are leveraged to allow INL to meet the goals of NRAC. The paper then presents an overview of important SNM resources that are available for visiting researchers to use. After this, the paper illustrates these capabilities by giving a few examples of collaborative activities that illustrate the use of NRAC facilities and resources by visitors to INL.

**Key INL-NRAC Facilities**

Since 1949 INL and its predecessor organizations have served as a hub for research and development on nearly all aspects of the civilian nuclear fuel cycle for peaceful applications. Throughout this period work at INL has included the design, construction, operation, and decommissioning of nuclear facilities from bench-scale to industrial-scale operations, including fuel fabrication, reactor operation, used-fuel storage, fuel reprocessing, and waste consolidation and storage. As a result of these activities INL now serves as the steward of a singularly-important resource of radiological and SNM with relevance for science-based studies relating to material protection control and accountancy, safeguards, nonproliferation, arms control, treaty verification, and nuclear forensics. Over the last decade, INL has been aggressively working to provide access to these materials to practitioners in these fields.
INL’s primary mission area is to support the development and deployment of advanced civilian nuclear energy systems. Nuclear nonproliferation is an important component of this work and research in this area serves as a key enabling activity towards this mission. INL routinely hosts visiting research teams from academia, industry, and other laboratories. Notably in this context, INL is capable of supporting visiting research teams from a diversity of backgrounds in their work using SNM, including professors, students, and industrial personnel. INL does this on a nearly weekly basis. INL is also capable of hosting foreign-national researchers performing work with SNM. INL-NRAC resources are spread across the laboratory but most notably among 10 principal locations which are illustrated in Figure 2 and described in the following sub-sections.

**SNM Resource Facilities**: INL maintains several nuclear facilities for fabricating items containing nuclear materials. These facilities primarily support advanced nuclear fuel research and development; however, they are also capable of producing customized materials for material protection control and accountancy, safeguards, nonproliferation, arms control, treaty verification, and nuclear forensics. Two examples of key INL SNM resource facilities are listed below. There are also other, smaller-scale prototype fuel development facilities.

- **Experimental Fuels Facility (EFF)**: This facility maintains a complete suite of equipment to support fuel fabrication for metal, oxide, nitride, carbide, silicide, and composite uranium-bearing fuels. It houses equipment such as a hot isostatic press, electrodischarge machining, other metal-working machines, and experiment specific machining.
- **Fuel Manufacturing Facility (FMF)**: This facility is focused on the fabrication of contact-handled metallic and ceramic fuels containing plutonium and minor actinides. It houses dedicated gloveboxes for this purpose with furnaces and machine tools.
**Irradiated Fuel Research Facilities:** Taking advantage of programmatic experimental research developing advanced nuclear fuels and fuel cycles, INL-NRAC also draws on multiple experimental facilities designed to allow work with irradiated nuclear material.

- **Fuel Conditioning Facility (FCF):** This is an engineering-scale hot-cell facility dedicated for electrochemical separations research and development, demonstration, and implementation. Involving irradiated fuels. It is also capable of producing fuel-cycle test samples and new fuel materials that must be fabricated in a shielded facility. As an operating fuel processing facility, FCF can also serve as a demonstration and evaluation test bed for hosting safeguards research related to electrochemical separations.

- **Hot Fuel Examination Facility (HFEF):** This is a very large research hot-cell focused on advanced fuel cycle research and development, including waste processing. The facility is designed to support non-destructive and destructive analyses of irradiated fuel, including full-sized commercial spent fuel assemblies. These experimental capabilities are of particular importance for safeguards-related nondestructive analyses, including in-cell passive gamma-ray spectrometry, and forensic analyses.

- **Analytical Laboratory (AL) and Radiochemistry Laboratory (RCL):** Destructive physical and chemical assay measurements are an important part of advanced nuclear fuel research and development. The AL and RCL facilities contain hot cells for working with irradiated nuclear materials and gloveboxes for working with transuranic-containing materials. Both facilities play important roles in INL’s nuclear nonproliferation and nuclear forensics programs and can support external research and development collaborations.

**Nondestructive Radiation Detection and Measurement:** Access to SNM in support of research, development, test and evaluation, training, and education activities is a central aspect of INL’s NRAC. The Laboratory maintains multiple facilities for this purpose, including highly-secure indoor test areas, versatile outdoor test areas, and multipurpose laboratory facilities for prototype development and calibration testing.

- **Zero-Power Physics Research (ZPPR) Facility:** This facility, formerly known as the Zero-Power Physics Reactor, is located at INL’s Materials and Fuels Complex (MFC). ZPPR is the central component of NRAC, providing research teams with access to greater-than-kg quantities of highly enriched uranium (HEU) and plutonium. ZPPR can also accommodate high-intensity radiation generating devices, including electronic neutron generators and high-energy x-ray machines, in support of active interrogation.[1] The main work space at ZPPR is the ZPPR Cell, a large 15-m-diameter shielded work room with a high ceiling and a low-neutron-return steel-plate floor. Due to a large gravel overburden, the neutron background radiation rate in the ZPPR Cell is low, approximately 1/20 the level found in regular research laboratories in Idaho Falls. With this very-low neutron background environment, highly sensitive neutron time-correlation studies may be performed there.

- **Critical Infrastructure Test Range Complex (CITRC):** INL is situated on an expansive 2,300-km² (890 mi²) high-desert range in southeast Idaho – the INL Site. CITRC is located near the center of the INL Site and is comprised of a series of stand-alone buildings and open-air test ranges. These multi-purpose facilities can support multiple nuclear security activities including nuclear search and emergency response training, and equipment evaluation. CITRC facilities can accommodate research activities with up to 0.7 kg of HEU; a comprehensive inventory of industrial and medical radioisotope sources is maintained to support this work. In addition to the CITRC buildings, additional INL resources exist to support activities involving aerial systems, road-based detection systems, and large-scale personnel exercises.

- **Health Physics Instrumentation Laboratory (HPIL):** This is a 1,480-m² laboratory located on the INL Site dedicated to testing and calibrating radiation detection instrumentation used for health physics measurements. To support this mission, HPIL possesses a useful inventory of well-calibrated radioisotope sources, including high-strength neutron sources. INL nuclear nonproliferation research activities frequently take advantage of HPIL resources for characterizing
the stability and calibration of radiation measurement instrumentation intended for use in safeguards and other applications.

- **Active Interrogation Laboratory (AIL):** This is a 550-m² laboratory dedicated to research and development activities related to active neutron interrogation.[2] The laboratory includes two shielded test cells and maintains a working inventory of $^{252}\text{Cf}$ spontaneous-fission neutron sources as well as deuterium-deuterium and deuterium-tritium electronic neutron generators producing monoenergetic 2.5-MeV and 14.1-MeV neutron fields, respectively.

- **International Safeguards Laboratory (ISL):** This is a multi-purpose teaching laboratory dedicated for educational programs designed to introduce INL staff, visiting laboratory personnel, and university undergraduates and graduate students to instrumentation and equipment used by the International Atomic Energy Agency. The ISL facility holds working IAEA instrumentation representing a large fraction of the tools used by IAEA inspectors during inspections performed in support of the Nuclear Nonproliferation Treaty. Class participants are taught the operating principles of the equipment and then encouraged to learn how they work through hands-on exercises at ISL, other NRAC facilities, and at INL’s Advanced Test Reactor.

### Key INL-NRAC Nuclear Material Resources

Drawing on nuclear fuel cycle research and development history at INL, INL-NRAC has access to a singularly-unique inventory of SNM, including SNM stock materials, unirradiated fuels, irradiated fuels including research fuel and commercial nuclear power plant spent fuel, intermediate reprocessing products, and waste materials. The special materials most frequently used at INL in support of material protection control and accountancy, safeguards, nonproliferation, arms control, treaty verification, and nuclear forensics purposes are highly enriched uranium (HEU) and plutonium. Raw material stocks of HEU and Pu may be used to produce custom test and inspection items at EFF and FMF. Irradiated fuels containing U, HEU, and Pu that require remote handling may be used at FCF, HFEF, AL, and RCL. Unirradiated SNM may be used at ZPPR and CITRC. Depleted uranium and natural-enrichment uranium are available for use at CITRC and AIL.

A summary of bulk uranium materials available at INL to support nondestructive measurements is presented in Table 1. User access exists for uranium of a variety of enrichment levels. Much of this material is in the form of plates (for metallic uranium) with typical dimensions on the order of 5 cm x 10 cm x 0.1 cm and pins (for oxides) with typical dimensions 1 cm (diameter) x 15 cm. Small quantities of materials in other forms and enrichments are also available. One particularly interesting test item available at ZPPR is the MARVEL inspection item, a modular cylindrical assembly of 93% enriched uranium having a total mass of approximately 20 kg.[3]

### Table 1  INL bulk uranium holdings.

<table>
<thead>
<tr>
<th>Description</th>
<th>$^{235}\text{U Enrichment (wt%)}$</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>Metal</td>
<td>0.22</td>
<td>Kel-F coated metal plates</td>
</tr>
<tr>
<td>Ceramic Oxide</td>
<td>0.20</td>
<td>Stainless-steel clad pins</td>
</tr>
<tr>
<td>Ceramic Oxide ($\text{U}_3\text{O}_8$)</td>
<td>0.21 – 0.22</td>
<td>Kel-F coated metal plates</td>
</tr>
<tr>
<td>Metal</td>
<td>0.70</td>
<td>Kel-F coated metal plates</td>
</tr>
<tr>
<td>Ceramic Oxide ($\text{UO}_2$)</td>
<td>0.70</td>
<td>Stainless-steel clad pins</td>
</tr>
<tr>
<td>Powder Oxide ($\text{U}_3\text{O}_8$)</td>
<td>0.70</td>
<td>Loose powder</td>
</tr>
<tr>
<td>Ceramic Oxide ($\text{UO}_2$)</td>
<td>16.37</td>
<td>Stainless-steel clad pins</td>
</tr>
<tr>
<td>Ceramic Oxide ($\text{UO}_2$)</td>
<td>46.42</td>
<td>Stainless-steel clad pins</td>
</tr>
<tr>
<td>Metal Feedstock</td>
<td>33, 66, and 93</td>
<td>Pins and scrap pieces</td>
</tr>
<tr>
<td>Metal</td>
<td>93.24</td>
<td>Kel-F coated metal plates</td>
</tr>
<tr>
<td>Metal</td>
<td>93.08 – 93.27</td>
<td>Stainless-steel clad plates</td>
</tr>
</tbody>
</table>

*Kel-F composition: 48.4% F, 30.5% Cl, 20.6% C, and 0.5% H.*
Plutonium is a key material of interest for material protection control and accountancy, safeguards, nonproliferation, arms control, treaty verification, and nuclear forensics; numerous nondestructive assay techniques have been developed to detect and measure the radiation emitted from Pu. Historically, these measurements have dealt with gamma-ray spectrometry (to assess isotopic composition) and neutron correlation counting (to determine mass and the relative abundance of $^{239}$Pu/$^{240,242}$Pu_{effective}).[4] Neutron related measurements are of particular value when dealing with Pu because of the large spontaneous fission rates of $^{238,240,242}$Pu and the production of neutrons from $(\alpha,n)$ reactions when Pu is in oxide form. (An estimation of the neutron emission rate from metallic plutonium is provided in Table 1.[5]) Access to diverse Pu materials is also important for research related to safeguards calorimetry; INL is well equipped to support advanced calorimetry research, including allowing access to very high $^{241}$Am content materials and access to small quantities of commercial spent fuel for this purpose.

A summary of bulk plutonium materials available at INL to support nondestructive measurements is presented in Table 2. Plutonium is available as pure metal (not listed below), in a variety of alloys, as pure oxides (not listed below), and as mixed oxide with uranium. Other forms are available; for unique requests special products may be manufactured.

**Table 2 INL bulk plutonium holdings.**

<table>
<thead>
<tr>
<th>Description</th>
<th>Pu isotopic composition (wt%)</th>
<th>Percentage Compared to Pu (wt %)</th>
<th>Ratio of uranium to plutonium by weight</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>Plutonium-Aluminum</td>
<td>0.04 75.83 22.79 0.69</td>
<td>0.64 3.99</td>
<td>&lt;0.01</td>
<td>Stainless-steel clad metal plates</td>
</tr>
<tr>
<td>Pu-U-Mo</td>
<td>0.07 70.50 27.12 0.82</td>
<td>1.49 4.86</td>
<td>1.92</td>
<td>Stainless-steel clad metal-alloy plates (with molybdenum)</td>
</tr>
<tr>
<td></td>
<td>0.03 87.93 11.65 0.23</td>
<td>0.16 1.34</td>
<td>2.45</td>
<td></td>
</tr>
<tr>
<td></td>
<td>NR 91.18 8.67 0.12</td>
<td>0.04 0.80</td>
<td>4.02</td>
<td></td>
</tr>
<tr>
<td></td>
<td>NR 95.43 4.53 0.04</td>
<td>NR 0.77</td>
<td>&lt;0.01</td>
<td></td>
</tr>
<tr>
<td>MOX</td>
<td>0.06 72.07 26.84 0.89</td>
<td>0.15 3.95</td>
<td>5.77</td>
<td>Ceramic oxide (with depleted uranium) in stainless-steel pins</td>
</tr>
<tr>
<td></td>
<td>0.06 87.74 11.72 0.31</td>
<td>0.17 1.45</td>
<td>4.75</td>
<td></td>
</tr>
</tbody>
</table>

**Collaborative Activities at INL by Visiting Teams**

For the past several years, INL's Nuclear Nonproliferation Division (now through the INL-NRAC organization) has hosted visitors to the INL Site seeking to use one or more of the NRAC resources. The typical frequency of these activities has been, on average, about two events per month, year round. The longest events have been approximately one month in duration while one day activities have also occurred. Typically activities are scheduled to last one week. Visiting team sizes vary from one person to over 100 personnel, the typical team size is from 5–10 people. While activities occur year round, the majority of outdoor activities take place in the late spring and early-autumn.

For fiscal year (FY) 2013, utilization of the ZPPR facility by visiting research teams has accounted for approximately one-quarter of the year, which equates to approximately one-half of the facility’s availability for research use. Approximately one-quarter of FY 2013 has been used in support of Department of Energy work activities; the remaining half of a typical ZPPR year is dedicated to maintenance work, facility upgrades, and other sustaining activities.

Typical scheduling for work at all of the NRAC-related is performed approximately six-months in advance. Events requiring more than one week of continuous utilization of a facility typically require longer lead time notification while activities requiring less than a full week can occasionally be accommodated with less advanced notice. All INL Site facilities operate four days per week, Monday through Thursday, with 10-hour shifts per day. With sufficient advanced planning, special accommodations can often be made to extended or alter this schedule.
The University of Michigan: One example of a successful collaborative engagement by an outside team using SNM resources at INL was a safeguards research project at ZPPR to study advanced methods for characterizing plutonium MOX fuel.[6] This project involved the specialty-packaging of three cans of MOX fuel: one can of 90 pins with 1.056-kg of low-\(^{240}\)Pu content plutonium; one can with 90 pins of 1.260-kg of high-\(^{240}\)Pu content plutonium, and one can of 45 pins with 0.528-kg of low-\(^{240}\)Pu content plutonium. The research activity lasted a week in duration and involved a visiting professor, a visiting research scientist, a visiting graduate student, and two INL research staff. Two of the participants were foreign nationals. Photographs from the experiments are presented in Figure 3.

Figure 3  Photographs from a joint University of Michigan-INL experiment campaign at ZPPR.

Preparation of one can of MOX fuel pins.

Oak Ridge National Laboratory: A second example of a visiting research team working at INL and using INL SNM resources occurred in 2011, when three visiting research scientist from Oak Ridge National Laboratory (ORNL) came to INL’s ZPPR facility to test a fast-neutron imaging system.[7,8] In this case the research team requested a square array of MOX fuel pins. Four canisters were prepared: one full, one with a MOX pin removed and replaced with a depleted uranium (DU) pin, and two cans with three MOX pins removed and one replaced with a stainless steel pin, one replaced with a DU pin, and one left as a void (different removal patterns). All of the pins in this case were high-\(^{240}\)Pu content pins (~26% \(^{240}\)Pu). The project also used a set of pre-existing Pu and HEU containing inspection objects in the ZPPR inventory and available for visitor use.[9] The research activity lasted two weeks.
This experimental campaign was noteworthy because of its use of an INL-supplied electronic neutron generator (ENG) to facilitate active neutron interrogation measurements for a part of the campaign. The ORNL team requested access to a deuterium-tritium ENG; prior to the exercise a suitable instrument was temporarily checked-out from the AIL facility and shipped to ZPPR to support the exercise. INL has a strong research base in both active neutron interrogation and active bremsstrahlung interrogation and maintains an inventory of multiple sources for use by INL staff and visiting research teams. Due to other ongoing research activities at INL it is straightforward to use these sources at multiple INL-NRAC locations.

**Summary**

As the Department of Energy’s lead laboratory for civilian nuclear energy research and development, INL possesses a unique and diverse inventory of SNM resources. Nuclear nonproliferation research and development activities play a key role in advancing the laboratory’s mission and hands-on work with radiological and nuclear materials at the INL-NRAC facilities are a key aspect of this. With the goal of expanding user-access to INL’s facilities and materials for visiting research teams working in this area INL has created the Nuclear and Radiological Activity Center, a central resource serving as the entry point for outside groups in academia, industry, other laboratories, and other government agencies. Across the INL’s expansive research site many different facilities are available to support a wide-range of research and development, test and evaluation, training, and education needs. This paper has highlighted 10 key components of the NRAC framework. INL’s ZPPR facility serves as the hub of this concept, providing a secure research area for many different visiting research teams. Many other specialty resources exist as well. Due to its open-campus concept and research focus on civilian nuclear energy research, INL can accommodate both small and large research teams, including teams with diverse backgrounds most often found at universities and small businesses.
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