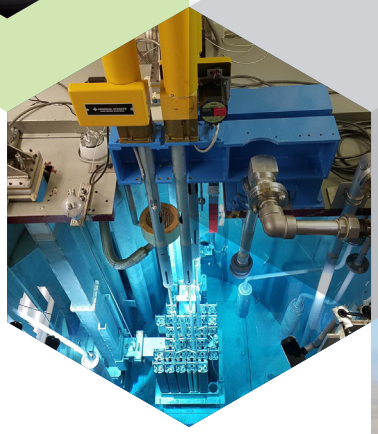

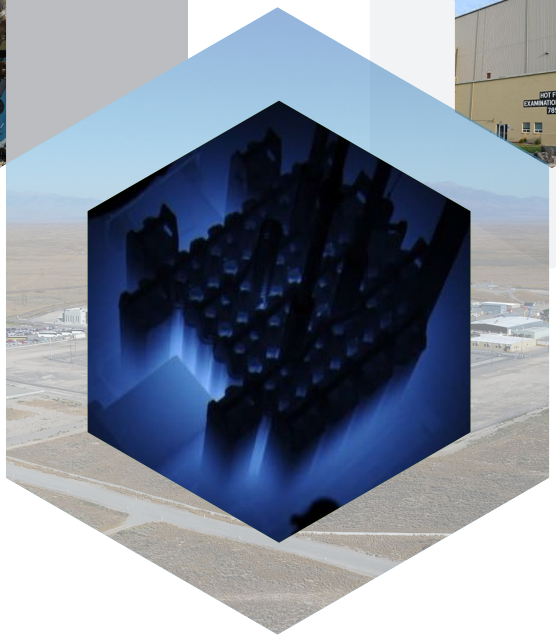

USERGUIDE

A PRACTICAL GUIDE TO THE NEUTRON RADIOGRAPHY REACTOR (NRAD)

INL Idaho National Laboratory

NRAD VISION

Accelerate scientific understanding and qualification of nuclear energy technologies and irradiated nuclear fuels and materials.

NRAD MISSION

Leverage the Neutron Radiography Reactor's proximity to the Hot Fuel Examination Facility to combine state of the art neutron-based techniques with access to highly radioactive materials, establishing a suite of material science capabilities that is unique worldwide.

VALUES

Excellence, inclusivity, ownership, safety, teamwork and integrity.

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Executive Summary

The Neutron Radiography Reactor (NRAD) located at Idaho National Laboratory's (INL) Materials and Fuels Complex (MFC) is a 250-kW pool-type research reactor with two neutron beamlines and two in-core irradiation positions.

What makes NRAD unique is its location beneath the Hot Fuel Examination Facility (HFEF) main cell in a Hazard Category-2 nuclear facility. This location provides access to infrastructure, scientific capabilities, staffing, licensing, and procedures, thereby enabling research and testing using highly radioactive materials that is not possible at other research reactors.

NRAD was originally installed specifically to provide neutron radiography capabilities for post-irradiation examination of highly radioactive nuclear fuels. One neutron beam is routed east from the NRAD core to a radiography station directly beneath the main hot cell. A sample elevator enables highly radioactive samples from the main cell to be positioned in NRAD's east neutron beam for film-based transfer method of neutron radiography, which is not sensitive to gamma radiation. A second beam routes north to another radiography station for examination of either hand-positioned samples or samples brought to the facility inside a shielded cask. Both neutron beams have direct line of sight to the NRAD core, thereby providing a higher neutron flux compared to typical tangential neutron beams, but with elevated gamma-ray and higher-energy neutron contents. At full power, NRAD produces maximum neutron fluxes of 5.9×10^{7} $cm^{-2}s^{-1}$ at the East Radiography Station (ERS) image plane and 4.5×10^{6} $cm^{-2}s^{-1}$ at the North Radiography Station (NRS) image plane.

NRAD has expanded its original capabilities beyond film-based transfer method of neutron radiography to include modern digital neutron imaging systems and in-core irradiation capabilities to address a broader range of DOE and INL mission space.

A modern digital camera-based neutron imaging system provides neutron computed tomography for hand-placed samples emitting up to 1 rem/hr, such as transient irradiated experiments from the Transient Reactor Test (TREAT) facility. The north neutron beam is also larger than typical neutron beams, so the digital neutron imaging system offers a 14-in. wide by 17-in. tall field of view.

Two in-core irradiation positions are available for experiments. At maximum power, 250 kW, NRAD produces a peak thermal neutron flux of $5.2x10^{12}$ $cm^{-2}s^{-1}$ in the in-core C4SW position and $2.1x10^{12}$ $cm^{-2}s^{-1}$ in the in-core F1 position. Irradiated samples can be transferred from either position into the hot cell relatively quickly (within one day) to enable access to short-lived fission products. This is especially useful for re-irradiating fueled samples for subsequent gamma scanning to evaluate migration of fission products.

The capabilities at NRAD continue to expand to meet the current and future mission needs of INL and Department of Energy (DOE). There are significant opportunities to further utilize this strategically located, bright neutron source by combining state-of-the-art neutron-based techniques (e.g. neutron diffraction, imaging, and prompt neutron activation analysis) with access to highly radioactive materials, establishing a suite of material science capabilities that is unique worldwide.

1. Introduction to the NRAD Reactor

The National Reactor Testing Station (NRTS), now known as the Idaho National Laboratory (INL), has been a pivotal site for nuclear research and reactor testing since it was established in 1949. INL is the proving ground for new nuclear reactor technologies, having 52 nuclear reactors in the course of its history. Currently there are four nuclear reactors operating at INL, including the Advanced Test Reactor (ATR), ATR-Critical (ATRC), TREAT facility, and NRAD.

NRAD is the newest reactor, installed at the Materials and Fuels Complex (MFC) beneath the HFEF main hot cell, going critical for the first time in March 1977. The goal of its construction was to support a variety of nuclear research, with a particular emphasis on nondestructive examination of irradiated reactor components using neutron radiography. The mission of NRAD has grown to support the broader INL mission to discover, demonstrate and secure innovative nuclear energy solutions. Today, NRAD contributes to INL nuclear research, development, and testing of nuclear fuels, materials and technologies, and conducting experiments related to nuclear reactor physics and reactor safety.

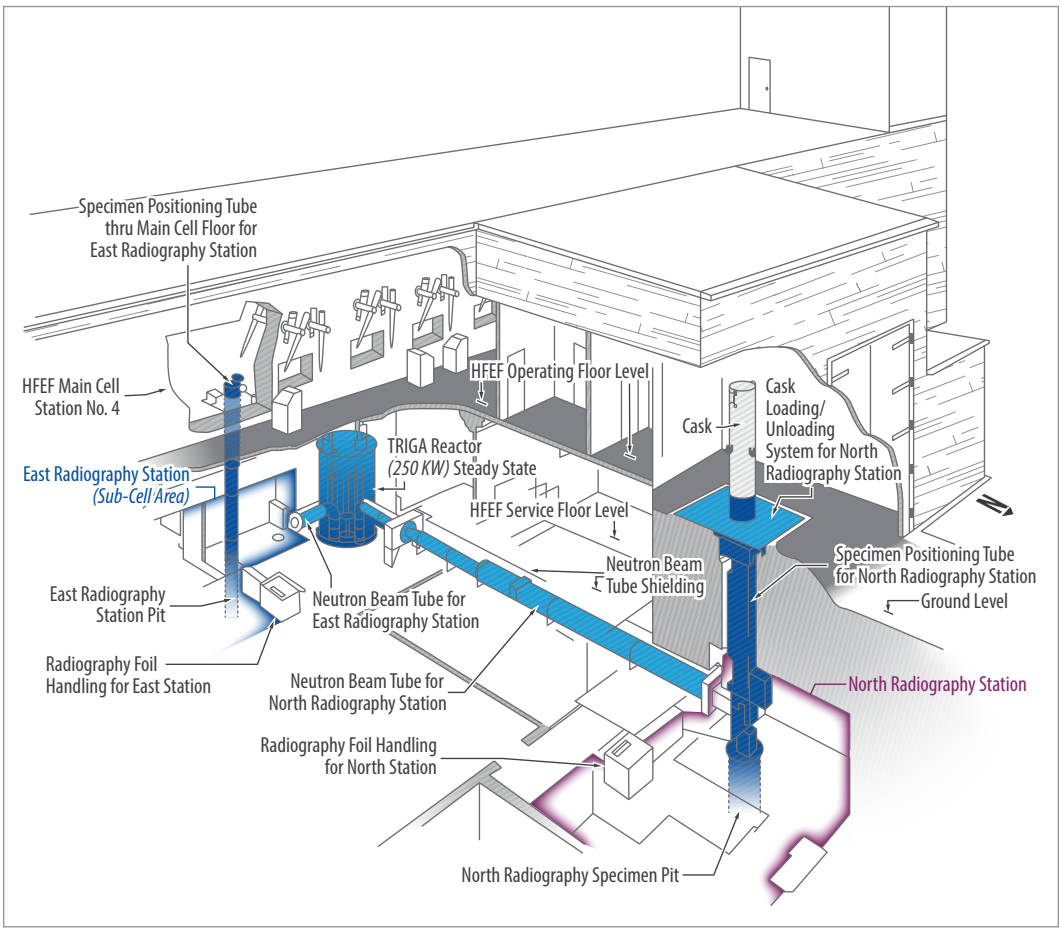
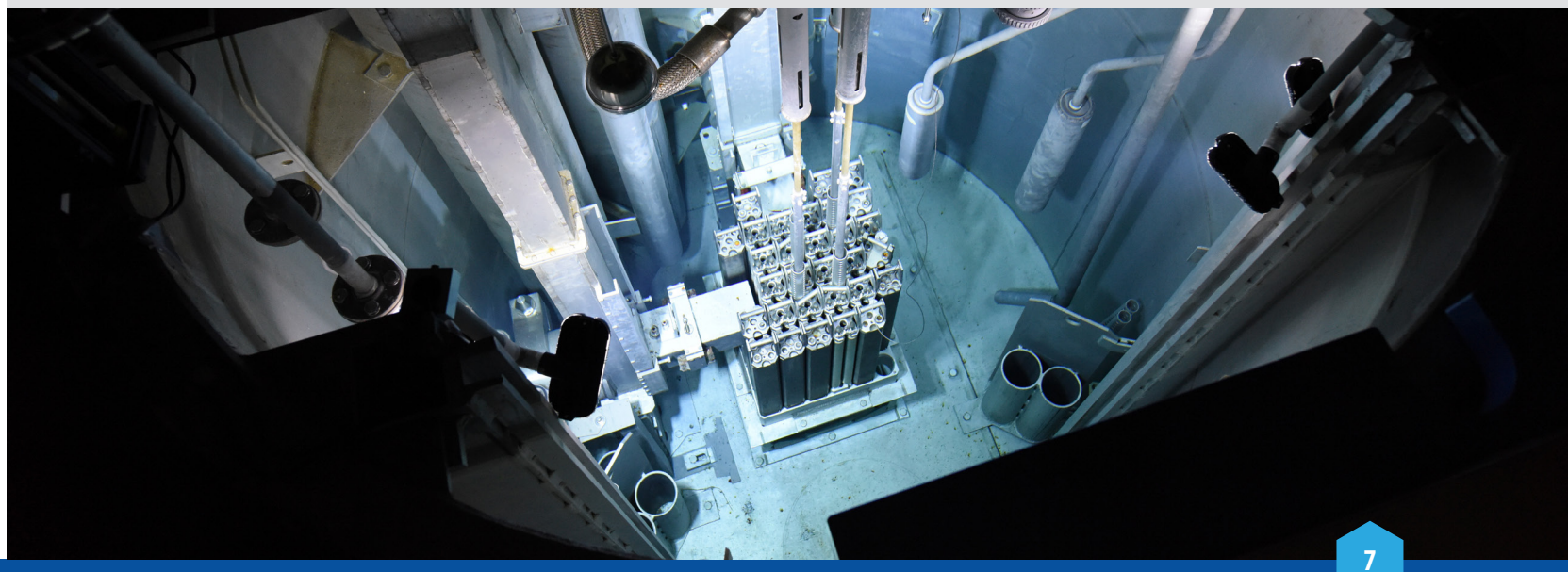


Figure 1. Schematic showing the layout of the NRAD reactor and beamlines within the HFEF building.

HFEF has the largest inert atmosphere hot cell in the world. What makes NRAD most unique is its location beneath the HFEF main cell (Figure 1), thereby providing convenient access to highly radioactive samples with the infrastructure and staff to handle such samples, enabling reactor-based research of highly radioactive samples that cannot be examined anywhere else. A sample elevator moves highly radioactive samples from inside the main cell to position them in NRAD's east neutron beam for remotely operated, transfer method of neutron radiography [3]. In-core irradiation at NRAD and subsequent rapid transfer to the main hot cell provides access to short-lived fission products that would have decayed during long transfer times following irradiation in a separate facility.

NRAD is a 250-kW, Mark-II Training Research Isotope General Atomics (TRIGA) reactor. NRAD is equipped with two beam tubes routing from the core to two radiography stations to the east and north. NRAD is also capable of in-core and/or in-tank experiment irradiation. An empty control rod guide tube position (C4SW) and an an empty grid location (F1) can accommodate in-core irradiation experiments. Samples can be introduced and removed from the NRAD tank using the NRAD cask, which also couples to the adjacent HFEF hot cell.

Overall, NRAD provides typical research reactor capabilities, but is configured to work with highly radioactive samples, supporting the broad nuclear energy and homeland security missions at INL.



2. NRAD Facility Description

The NRAD reactor is a pool-type, heterogeneous, solid-fuel, research reactor moderated by zirconium-hydride within the fuel and reflected by its water coolant and graphite components. The reactor is configured with a full core of low-enriched uranium (19.75 wt.%) in the form of U-$ZrH_{1.6}$ (LEU 30/20) TRIGA fuel in a cluster configuration. The fuel clusters are supported by a 5-in. thick aluminum grid plate. This configuration contains 64 fuel elements and three water-followed control rods.

NRAD operates at a maximum thermal power of 250 kW, producing a peak thermal neutron flux of 5.2×10^{12} $cm^{-2}s^{-1}$ in the in-core position C4SW, 2.1×10^{12} $cm^{-2}s^{-1}$ in the in-core F1 position, 9.6×10^{6} $cm^{-2}s^{-1}$ at the ERS image plane, and 4.5×10^{6} $cm^{-2}s^{-1}$ at the NRS image plane. The NRAD core is shown in Figure 2, and the current core configuration is shown in Figure 3, showing the position of the control rods, fuels, position of the north and east beam tube, as well as the F1 and C4SW experiment irradiation positions.

The reactor layout consists of:

- 64 TRIGA® LEU SS-clad elements
- 4 graphite reflector elements and 12 graphite block reflectors
- ERS and NRS beamlines
- 1 empty grid position (F1)
- 1 empty control rod guide tube (C4SW)
- 3 control rods
- 8 in-pool storage locations (labeled G-N in Figure 3)

2.1 Analysis of Highly Radioactive Samples

NRAD is unique because it is located beneath the HFEF main cell in a Hazard Category-2 nuclear facility. NRAD has the infrastructure, scientific instruments, staffing, licensing, and procedures facilitating access to highly radioactive materials, actinides, and highly enriched uranium that would not be possible elsewhere.

- Highly radioactive samples in the HFEF main cell can be remotely positioned into the ERS neutron beam for neutron radiography.
- Highly radioactive samples can be brought in using a shielded cask, lowered with a sample elevator into the NRS for neutron radiography and tomography, as well as re-irradiation and rapid post-irradiation examination (PIE).
- Samples irradiated in NRAD can be transferred to the adjacent HFEF main cell for examination (e.g. gamma scanning, fission gas sampling), enabling access to short-lived fission products that typically decay away before samples can be transferred to HFEF from other reactors.
- Researchers seeking to utilize NRAD's capabilities also have access to the Nuclear Fuel and Materials Library (NFML), curated by the DOE National Science User Facility (NSUF) program. [website: https://nsuf.inl.gov/Page/fuels_materials_library]

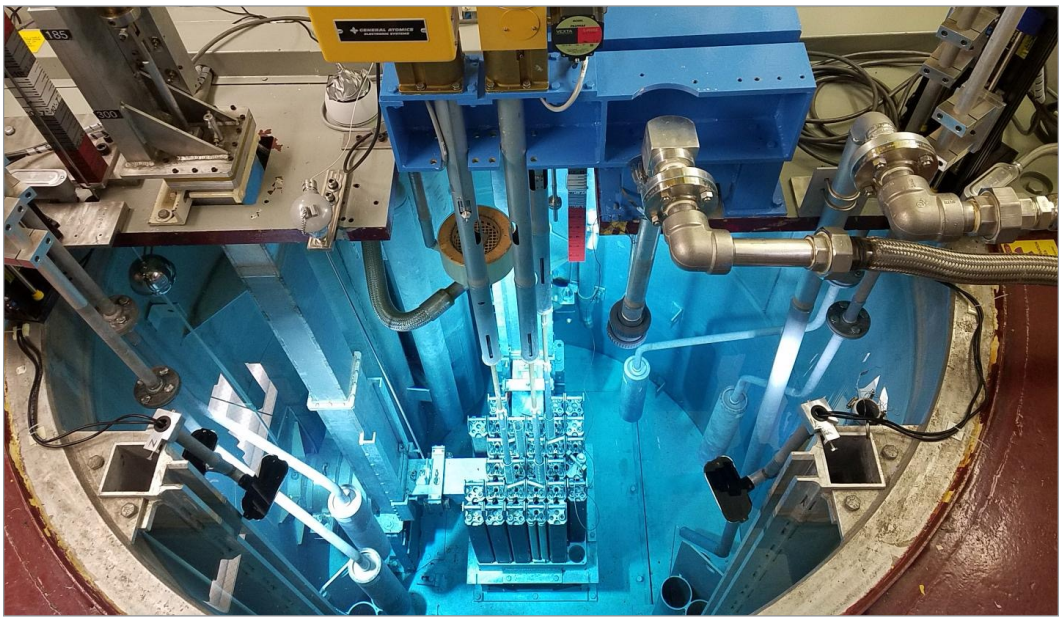


Figure 2. Picture of the NRAD from the top of the tank looking east.

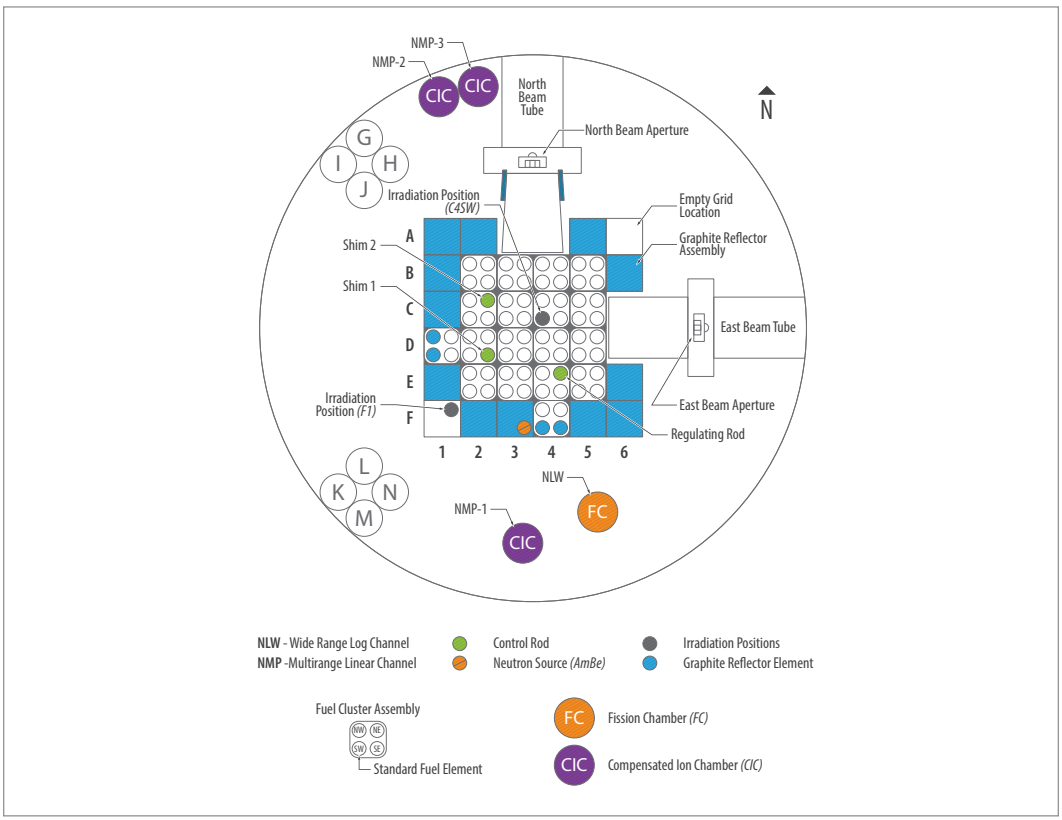


Figure 3. Current NRAD core configuration.

3. NRAD In-Core Irradiation Experiments

Apart from the two neutron radiography stations, the two in-core irradiation positions of NRAD can support laboratory programs, academia, and industry. The C4SW position has a peak thermal neutron flux of 5.2×10^{12} $cm^{-2}s^{-1}$ and an inside diameter of 1-3/16 in. The F1 position has an approximate thermal neutron flux of 2.1×10^{12} $cm^{-2}s^{-1}$ and an inside diameter of 1-5/8 in. Figure 4 shows the measured thermal neutron flux values from gold foil measurements in the F1 and C4SW positions, measured at 250 W. The data is then scaled proportionally to 250 kW to provide a reasonable estimate of the peak thermal neutron flux at full power.

Current irradiation capabilities at NRAD include:

- Routine hand-carried sample capsule drop-in experiments for fuel and materials
- Instrumented irradiation experiments for solid state fuels and molten salt fuels
- Re-irradiation of fuels to generate short lived fission products for safety testing and source term evaluation (past experiments include TRISO, molten salt, and research reactor fuels)
- Sensor and nuclear instrumentation irradiation tests with online measurements for performance evaluation
- Zero power criticality experiments
- Nuclear activation analysis
- Nuclear cross-section measurements
- Verification of uranium contents for swipes for radiological controls support
- Actinide science

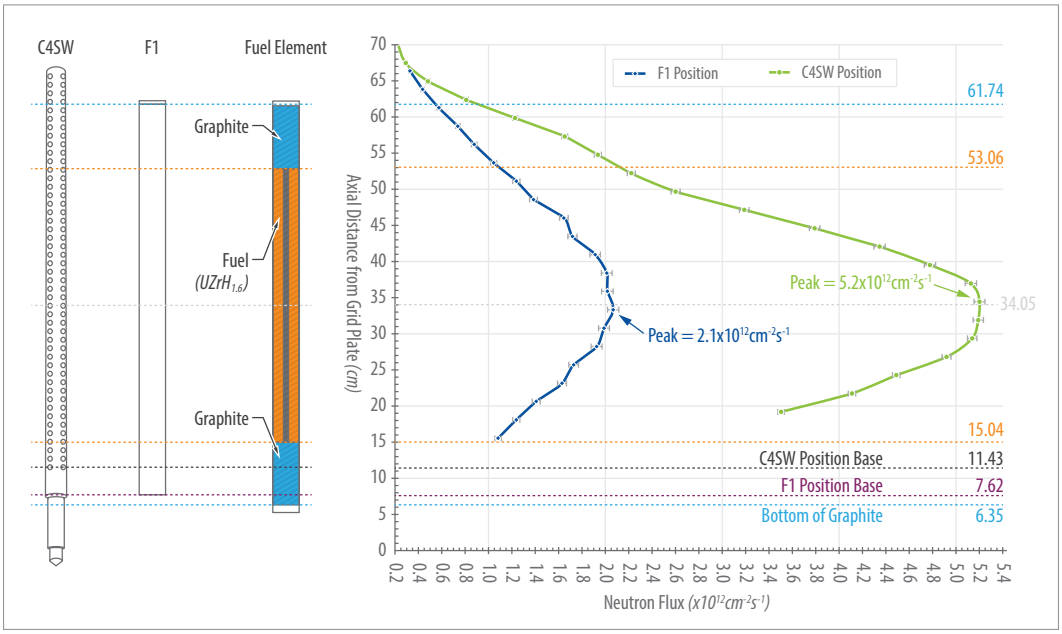


Figure 4. Measured thermal neutron flux values from gold foil measurements in the F1 and C4SW positions. These measurements were taken at 250 W, and the data presented here are scaled proportionally to 250 kW.

- Neutron flux determination
- Fusion breeder materials irradiation for tritium production
- Irradiation of KBr to generate short lived isotopes for emergency and radiological response training programs.

3.1 Standard Irradiation Capsules

Several standard irradiation capsules and configurations are available for quick irradiation tests, reducing user development time and cost. Additionally, customized experiment and capsule configurations are possible to address specific programmatic and user needs. The following subsections describe standard irradiation capsules and some specific experiments to provide prospective users with introductory information about what is possible at NRAD.

3.1.1. Sample capsules for hand-carry drop-in irradiation

Figure 5 shows a few standard sample capsules used for irradiation in TRIGA reactors, including NRAD. These standard capsules come in different sizes and materials, such as aluminum, nylon, or polyethylene. The choice of capsule sizes and materials depends on irradiation temperature, reactivity worths, and allowable radioactivity. In general, metal capsules are preferred over polymers due to higher temperature and pressure margins. Currently these capsules can only be hand carried for irradiation insertion and removal. A pneumatic sample transfer system is being considered for future installation at NRAD to improve sample transfer efficiency.

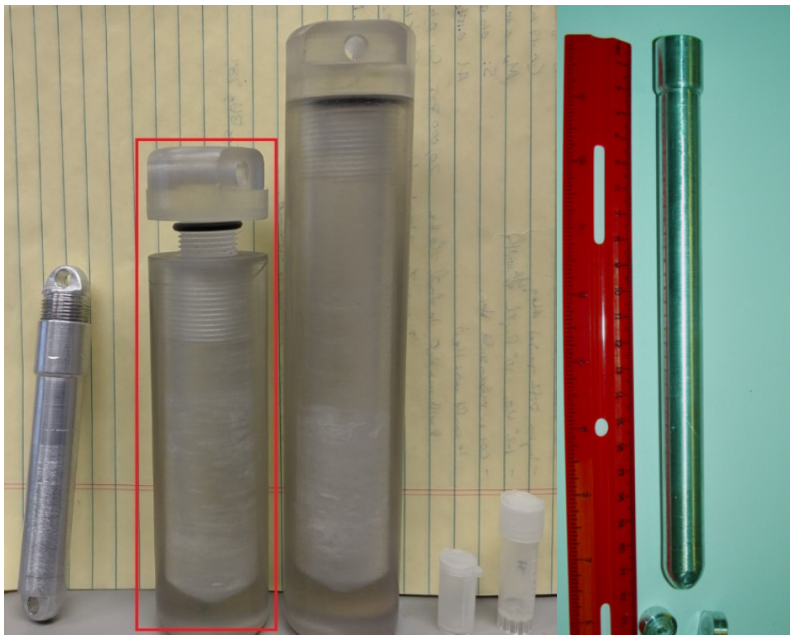


Figure 5. Available capsules for NRAD drop-in irradiation. (Left) Aluminum capsule with screw cap, also available with weld caps (right). (Middle) Nylon or polyethylene capsules of various dimensions, polyethylene vials of 0.6-in. diameter by 2-in. long and other available dimensions for containing fuel and materials, and double-capsulated in capsules shown on the left and middle.

3.1.2. Swagelok sealed capsules made of titanium or aluminum

Another available standard NRAD in-core irradiation test vehicle is the commercially available Swagelok sealed capsule made of titanium or aluminum. The material choice depends on the requirements of reactivity, pressure, strength, and temperature. Figure 6 shows an example of the Swagelok capsule used in past experiments. The Swagelok capsules can be used for both fuel and materials irradiation tests at NRAD. Only one Swagelok capsule can be irradiated at a time.

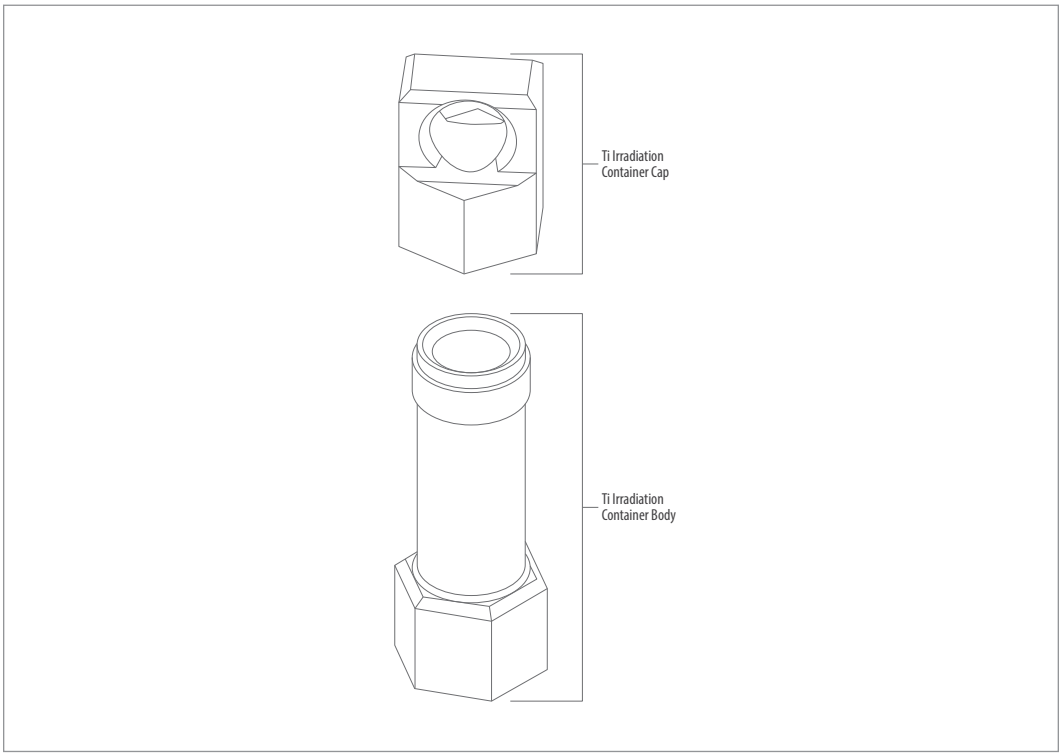


Figure 6. An example of Swagelok capsule that was used for TRISO particles, TRISO compacts, structural materials.

3.1.3. Irradiation test train with multiple sample capsules

To irradiate multiple capsules simultaneously, a multi-sample test train and sample container can be used, accommodating up to 12 sample containers. This experiment design was used for tristructural isotropic (TRISO) compact re-irradiation experiments, called Removable Assembly Providing TRISO Re-irradiations (RAPTOR), as shown in Figure 7. The fuel test train is also equipped with a thermocouple that can measure the container temperature during irradiation.

Figure 7. RAPTOR irradiation test train and capsule, used for TRISO fuel compact irradiation.

3.1.4. Instrumented molten salt irradiation capsule

NRAD also conducted an instrumented molten fuel salt (UCl_3-NaCl) irradiation in 2023-2024, called Molten-salt Research Temperature-controlled Irradiation (MRTI). The experiment design was equipped with an externally controlled heater, multiple thermocouples at different locations, and an optional self-powered neutron detector (SPND), as shown in Figure 8. Changes to this existing design can accommodate future molten salt irradiation experiments as needed.

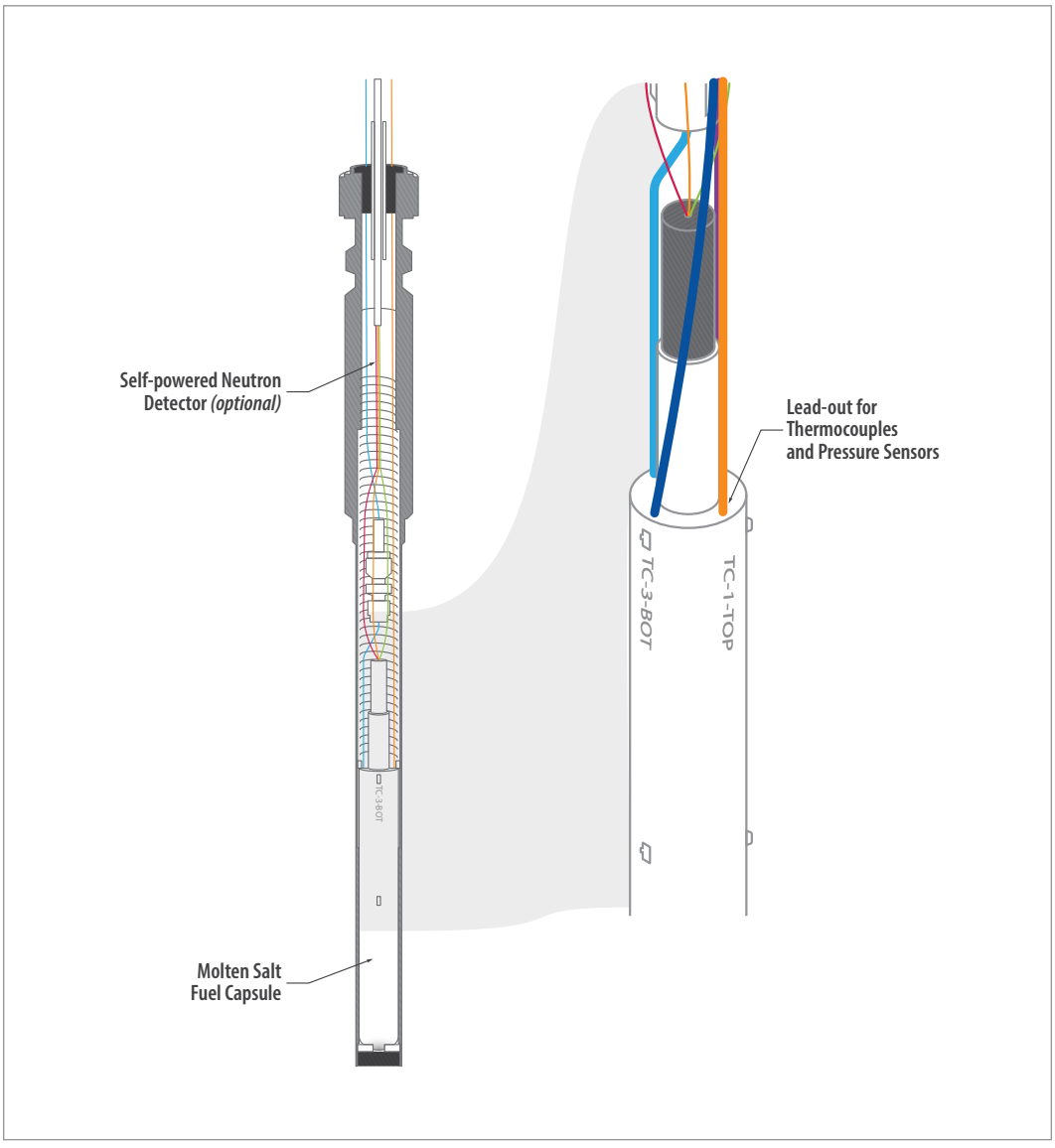


Figure 8. Existing design for instrumented molten salt irradiation, used for MRTI experiment.

3.1.5. Sensor irradiation

NRAD is also used for evaluating irradiation performance of new sensors, nuclear detectors, and instrumentation. Irradiation experiments can be conducted in various forms and locations within the core or tank, depending on user's needs. There are standard irradiation designs and devices available that can be modified to meet users' needs. One standard sensor test device used in the ATR gamma tube with a heating capability is shown below. A similar sensor irradiation vessel could be designed for use at NRAD.

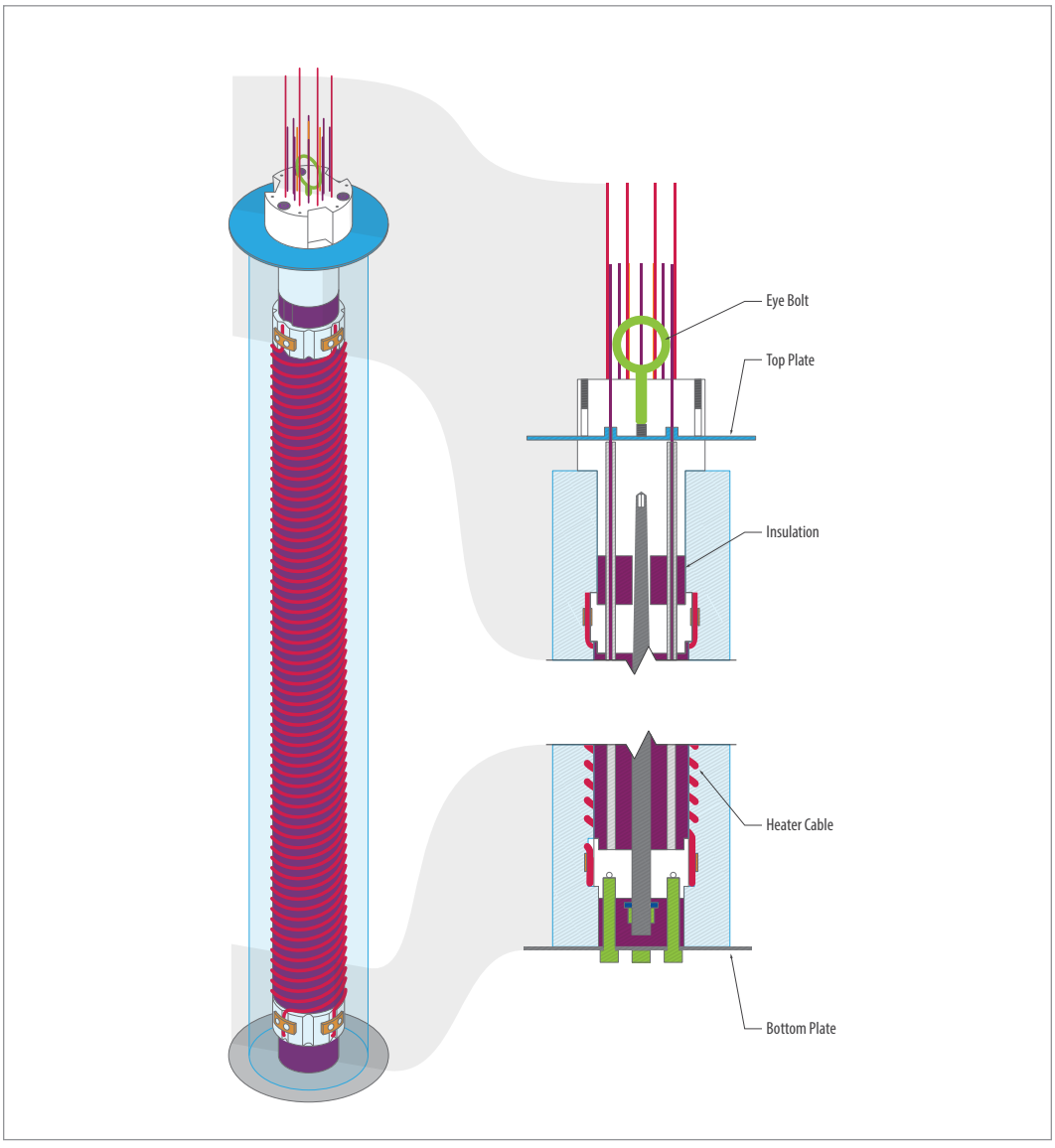


Figure 9. An example of test train for sensor irradiation used in the gamma tube at ATR, which is also suitable for NRAD irradiations with custom modifications to meet users' needs.

3.1.6. Standard irradiation test train for multiple capsules between fuel clusters

A test train was developed for NRAD to perform irradiation tests at alternative locations such as the empty space between four clusters. The test train design is shown in Figure 10. The test train was initially designed for void reactivity measurements and neutron flux measurements using gold foils attached to different axial locations of the test train. The test train can also be used for multiple irradiation capsules at different axial locations.

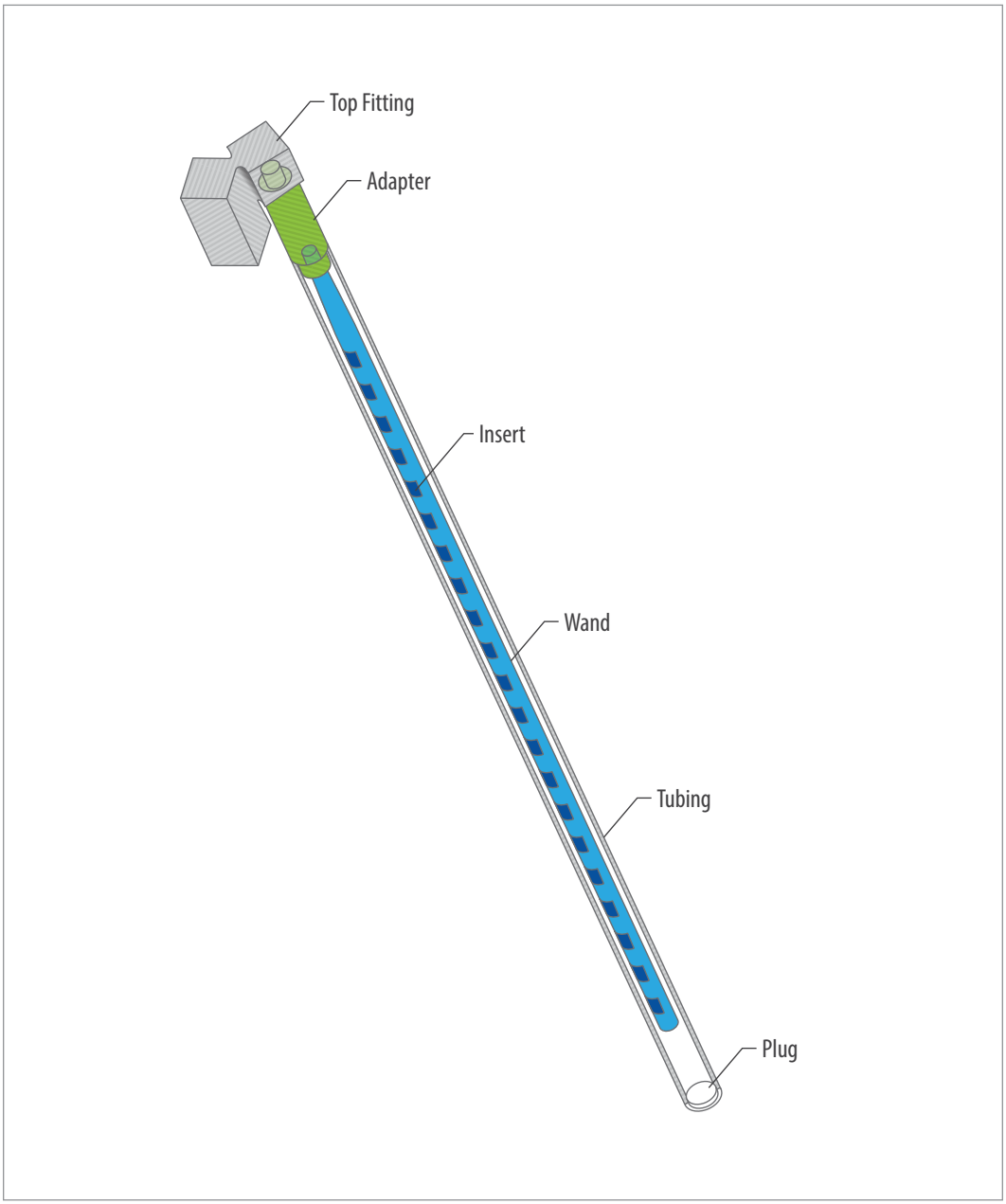


Figure 10. A standard irradiation test train for multiple samples or capsules at locations between fuel clusters; (left) illustration of the test train and (right) view of the test train mounted on a dummy fuel cluster.

3.1.7. Future irradiation capabilities

Additional irradiation experimental capabilities could be considered for the NRAD reactor to meet future user demands including:

- In-pile creep testing of pre-irradiated structural materials
- In-pile fuel tests with instrumentation
- Rapid capsule tube irradiation to support fundamental studies such as actinide sciences, radiation assisted diffusion, radiation enhanced corrosion, etc.
- Water loop or molten salt capabilities for irradiation and corrosion studies on pre-irradiated materials.

3.2 Sample Transfers

Irradiated sample transfers can be conducted by hand-carried tools or via shielded cask, depending on the radioactivity of the samples. For low radioactivity samples, irradiation capsules can be packaged in a one-gallon "paint can" sized container and shipped in a Department of Transportation (DOT) approved Type-A drum (five-gallon drum) to internal and external sites for post-irradiation examination (PIE) or designated uses.

For irradiated fuels and highly-radioactive samples, the NRAD cask, shown in Figures 11 and 12, can be used to transfer samples into and out of the HFEF hot cell. The NRAD cask is a top-loading cask sized for one fuel cluster or one control rod. The cask weighs approximately 7,000 lbs, not including the cask cap assembly. The cask is filled with lead and encased with 1/2 in. of steel. The main section of the cylindrical cask is 22 in. outside diameter and 43.75 in. long. The inner compartment is 39 in. tall with an inner diameter of 4.5 in.

3.3 Transfer System Improvement Capabilities

To improve the efficiency of sample transfer in and out of the core, reduce the time and cost, a pneumatic transfer system, or "rabbit", can be installed to connect the NRAD reactor to a glovebox and the HFEF hot cell. For more information on the rabbit system status, users are encouraged to reach out to NRAD staff at NRAD@inl.gov.

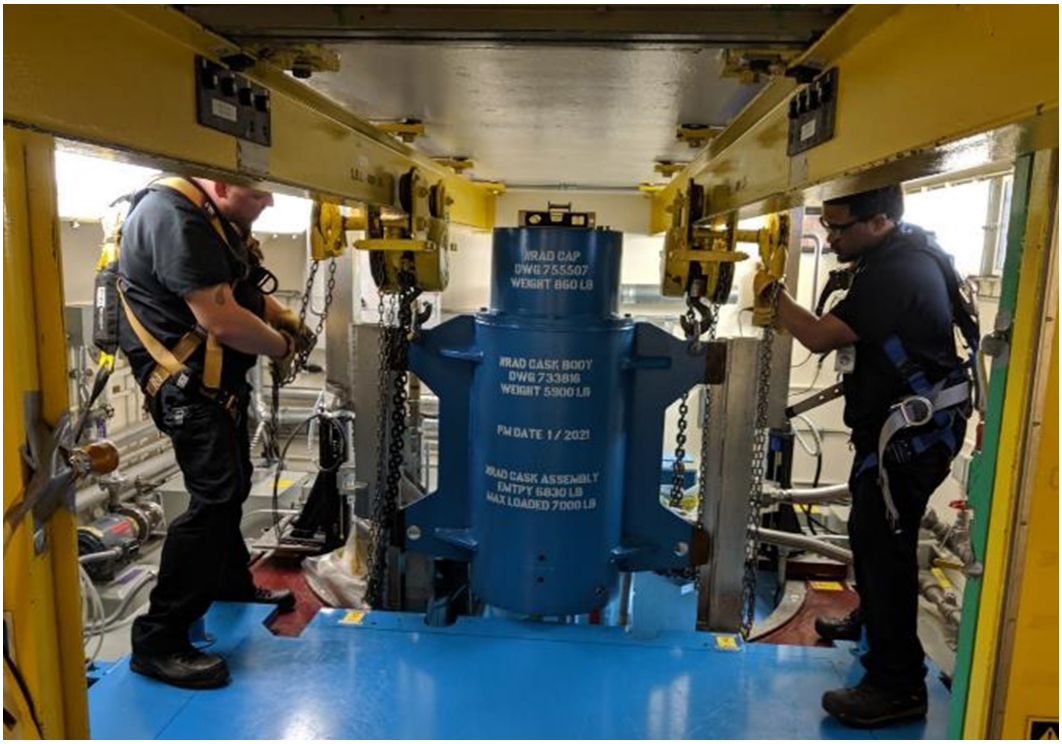


Figure 11. Picture of the NRAD cask positioned over the NRAD tank.

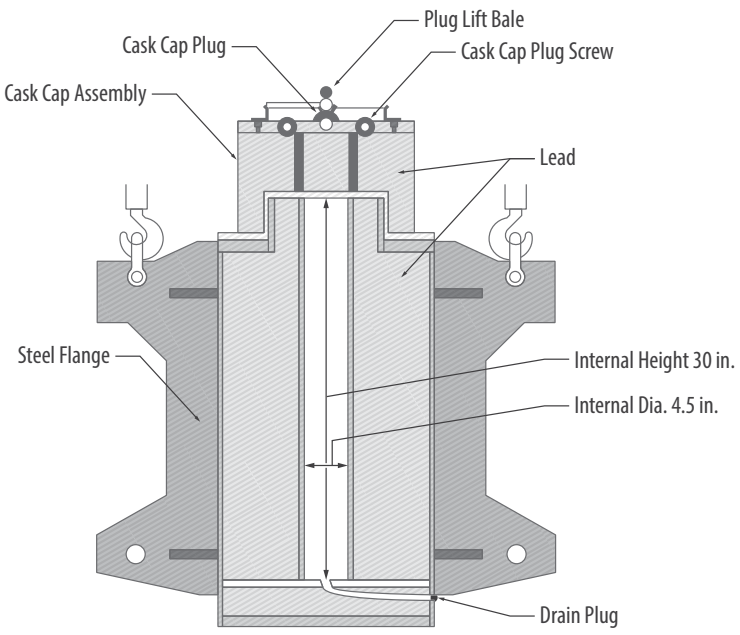


Figure 12. Schematic of the NRAD cask.

4. Neutron Beamline Radiography and Experiments

The NRAD facility has two neutron beamlines that route from the reactor into two separate shielded radiography stations, i.e. the ERS and NRS, as shown in Figure 13. Both beamlines are designed primarily for neutron radiography of irradiated nuclear fuels. Both beam tubes are radial neutron beams with direct line of sight to the NRAD core and thus have high gamma content and higher-energy (epithermal and fast) neutron content. Key parameters of the NRS and ERS are shown in Table 1. Each aperture setting represents a particular L/D ratio and corresponding neutron flux.

Table 1. Key parameters describing each of the NRAD radiography stations.

	NRS		ERS	
Access to Sample	Hand-placed (<1 rem/hr) Cask to NRS elevator		Hand-placed (<1 rem/hr) HFEF main cell to ERS elevator	
	L/D FLUX AT IMAGE PLANE		**L/D FLUX AT IMAGE PLANE**	
	185	**4.5×10^{6} $cm^{-2}s^{-1}$**	50	5.9×10^{7} $cm^{-2}s^{-1}$
	300	1.7×10^{6} $cm^{-2}s^{-1}$	**125**	**9.6×10^{6} $cm^{-2}s^{-1}$**
	700	3.1×10^{5} $cm^{-2}s^{-1}$	300	1.7×10^{6} $cm^{-2}s^{-1}$
FOV	**UP TO 14 IN. WIDE ×17 IN. TALL**		**UP TO 7 IN. WIDE ×17 IN. TALL**	
Imaging Systems	Transfer method with film or image plates Digital radiography & tomography		Transfer method with film or image plates	

Values in bold are the typical operating values.

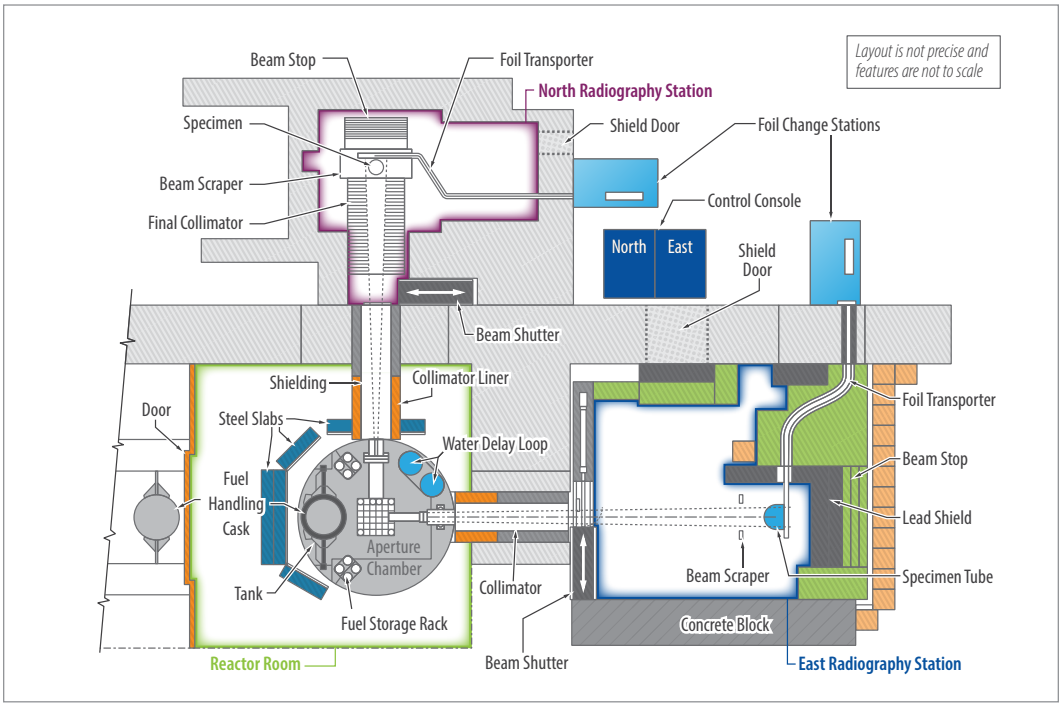


Figure 13. Plan view showing the layout of NRAD beneath the HFEF main cell and the two neutron beams routing to the north and east. [4]

Both neutron beams have a direct line of sight to the reactor core and thus are considered "radial" beams. Most neutron beamlines worldwide have a direct line of sight to a moderator region adjacent to the core, not directly to the core, and are considered "tangential" neutron beams. Because tangential neutron beamlines do not "see" the fission reaction in the core, they have lower gamma content and higher cadmium ratios (i.e. higher thermal-to-fast neutron ratios). Conversely, radial neutron beams have higher gamma content and lower cadmium ratios (i.e. higher epithermal and fast neutron content).

The radial neutron beamlines at NRAD are specifically designed for examination of strongly-attenuating and highly radioactive materials. The epithermal neutron content of the neutron beam provides deeper penetration of uranium compared to thermal neutrons. Also, the gamma content of the neutron beam is minor compared to the gamma-ray fields emitted from highly irradiated nuclear fuels and is therefore not a detriment. The beams are also large enough to illuminate a 14-in. wide by 17-in. tall area at the image plane, which is much larger than most beams worldwide. However, the field of view (FOV) is limited by the 7-in. wide by 17-in. tall foil size available for transfer method of radiography. These large neutron beams with higher-energy neutrons and significant gamma-ray content require thicker shielding walls for the beam room than most neutron beams at other neutron research centers. Accessing the ERS and NRS is therefore not as simple as accessing neutron beams at other facilities.

A key characteristic of neutron beams that describes collimation of the beam is known as the L/D ratio, which is the ratio of the length from the aperture to the sample (L) and the aperture's diameter (D). Users can calculate the anticipated blur (i.e., unsharpness) introduced because of the size of the aperture by dividing the object-to-detector distance by the L/D ratio. For example, a sample with a feature placed 20 mm from the detector imaged with L/D=185 will impose a blur of 20 mm / 185 = 0.108 mm of unsharpness. A higher L/D ratio will provide improved image sharpness at the cost of lower neutron flux and longer exposure time.

4.1 East Radiography Station

The neutron beam at the ERS travels 4.57 meters through both an open air and a helium-filled aluminum tube, beginning from the outer eastern edge of the reactor core to the ERS image plane. The beam apertures are positioned approximately midway between the reactor core's outer edge and the outer wall of the reactor tank. The three circular apertures with diameters of 8.89 cm, 3.53 cm, and 1.50 cm provide L/D ratios of 50, 125, and 300, respectively.

The ERS sits directly beneath the HFEF main cell, with an elevator system that remotely positions specimens into the ERS neutron beam for transfer method of neutron radiography [3]. The ERS beam tube originates at the NRAD core with an aluminum section filled with helium, a beam filter position, a selectable aperture mechanism, and a helium-filled collimator encased in the reactor shielding wall. The active field of view measures 7-in. wide by 17-in. tall (17.8-cm wide by 43.2-cm tall). The ERS predominantly operates with an L/D of 125, providing a thermal neutron flux at the image plane of 9.6×10^{6} $cm^{-2}s^{-1}$ and a cadmium ratio of 2.1. By changing the aperture setting, the neutron fluxes at the image plane can also be set to 5.9×10^{7} $cm^{-2}s^{-1}$ for L/D=50, and 1.7×10^{6} $cm^{-2}s^{-1}$ for L/D=300.

Typical neutron radiography exposure time is 22 minutes for the transfer method of neutron radiography with film (i.e., activation of foils with subsequent transfer and exposure to film), simultaneously acquiring thermal and epithermal neutron radiographs in a single exposure [3]. The neutron radiography capabilities at NRAD are American Society for Testing & Materials (ASTM) category-I quality, the highest possible quality using ASTM standards [7].

The energy spectrum of the ERS is a thermalized fission spectrum, as shown in Figure 14. Being a radial neutron beam, the epithermal and fast neutron content are higher than tangential beams, leading to a relatively low cadmium ratio of 2.1 compared to tangential beams with cadmium ratio >100.

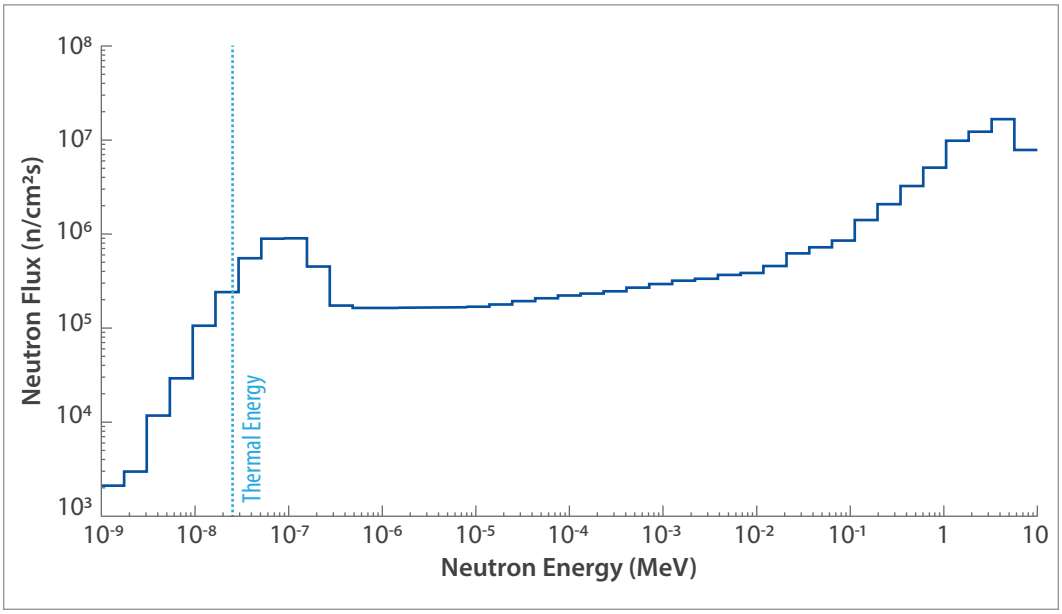


Figure 14. Neutron energy spectrum of the NRAD neutron beam in the ERS. [4]

Neutron radiographs of representative irradiated nuclear fuel rods taken using thermal (left) and epithermal (right) neutrons are shown in Figure 15. Dual-energy radiography allows experimenters to visualize a wide range of features in a single image acquisition. Together, the images provide insights into the object that are otherwise unavailable. In the example radiographs shown in Figure 15, cracking of reflector material (feature A in the radiographs) is sharper with higher contrast in the thermal image, while the central void (feature B) is visible only in the epithermal image that offers deeper penetration.

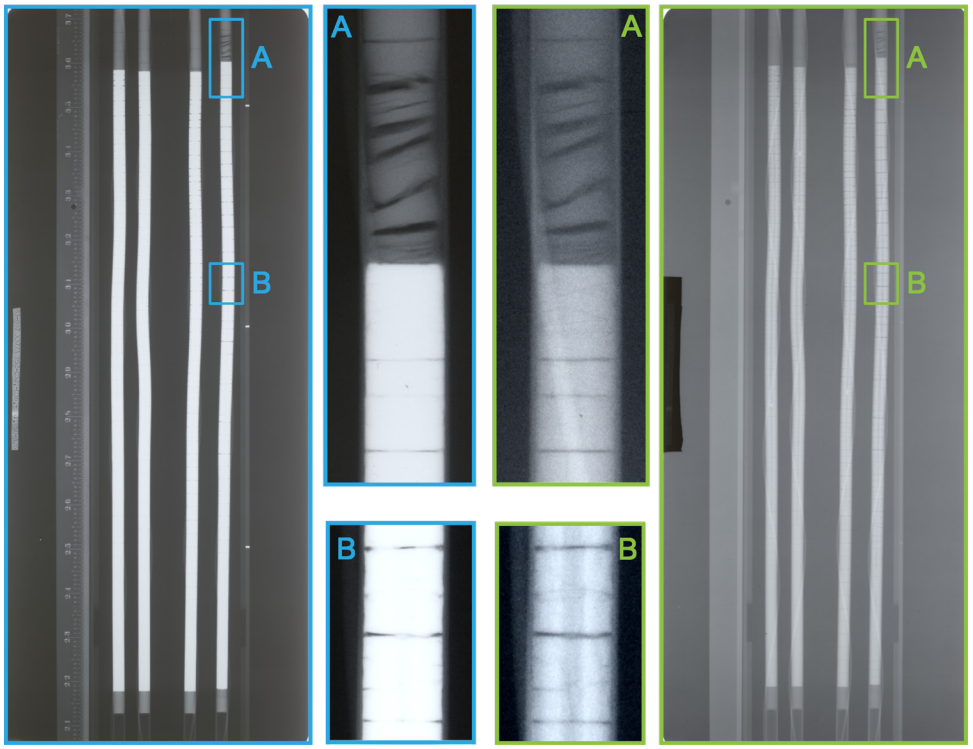


Figure 15. Neutron radiographs of representative nuclear fuel are taken using the transfer method of neutron radiography with thermal (left) and epithermal (right) neutrons. [3]

4.2 North Radiography Station

The NRS is not located beneath the main cell like the ERS. To introduce highly radioactive samples to the NRS, a cask system is used to transport fuel to the NRS high bay and an elevator is used to remotely position the sample into the NRS neutron beam for neutron radiography. The NRS is generally more accessible than the ERS and is often used to examine hand-placed samples up to 1 rem/hr on contact. Specimens to be radiographed can be lowered into the specimen tube from the cask-handling room or manually placed in the plane of radiography when the reactor is shut down and the gamma shield is closed.

The north beam tube is much longer than the east beam tube, thereby offering higher beam collimation, i.e. L/D ratios. The neutron beam's L/D ratio is adjustable to 185, 300, or 700 by selecting one of the correspondent three aperture sizes, 3.5, 2.105 and 0.92 in., respectively. A 55-ft helium-filled beam tube extends from the NRAD reactor core to the NRS. The neutron beam in the NRS is around 22 in. diameter at the image plane. The relative ease of access makes the NRS an optimal neutron beamline for developing and testing imaging systems and beamline experiments. The fluxes at the NRS image plane are 4.5×10^{6} $cm^{-2}s^{-1}$ for L/D=185 (the predominant L/D for NRS), 1.7×10^{6} for L/D=300 and 3.1×10^{5} $cm^{-2}s^{-1}$ for L/D=700. The cadmium ratio is 2.7, which indicates very high epithermal and fast neutron content.

Like the ERS, the NRS possesses the capability of performing transfer method of neutron radiography with film and image plates. The NRS also provides digital radiography and 3D neutron computed tomography (nCT). The standard exposure time for transfer method of neutron radiography in the NRS using film is approximately 45 minutes. The digital nCT system in the NRS offers multiple fields of view, depending on the sample size, including 3 cm diameter or high-resolution scanning and 10, 20, or 60 cm fields of view for larger samples. Exposure times for the digital nCT system are around 60 seconds. Figure 15 shows examples of nCT scans of transient irradiated fuel acquired in the NRS.

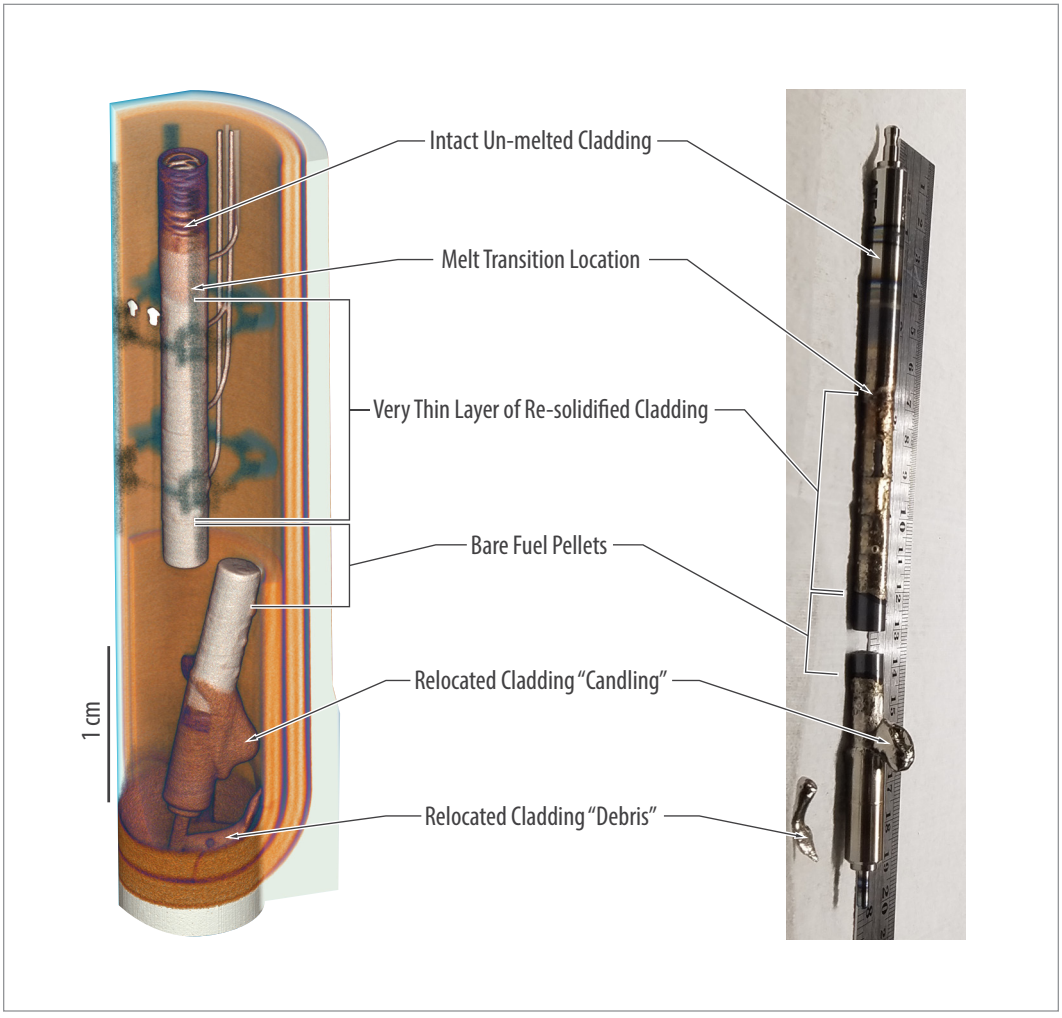


Figure 16. Neutron radiograph (left), tomographic reconstruction (middle), and a photo of the internal contents (right) of a, Accident Tolerant Fuel sample following a transient test at TREAT (SETH-E). [5]

5. Additional Equipment and Specialized Facilities

Following irradiation or radiographic examination at NRAD, samples can be taken to post-irradiation examination (PIE) instruments and facilities for further analysis. These experiments can be sent to one or more PIE facilities at MFC, including HFEF, the Irradiated Materials Characterization Laboratory (IMCL), the Electron Microscopy Laboratory (EML), and the Sample Preparation Laboratory (SPL). The PIE capabilities at HFEF generally focus on engineering scale measurements for evaluation and qualification of nuclear fuels and materials. The PIE capabilities at IMCL and EML generally include microstructural examinations to better understand the scientific underpinnings of fuels and materials behavior. Overall, the PIE capabilities at MFC enable the characterization of irradiated nuclear fuels and materials across the full range of length scales, from the engineering scale (centimeters) down to the atomic scale. Below are detailed descriptions of the PIE facilities at INL.

HFEF enables remote handling and detailed examination (both nondestructive and destructive) of highly irradiated fuel and material samples. The facility's argon-atmosphere hot cell, specialized laboratories, and equipment support work on a variety of fuel types, ranging from small particles to full-sized commercial fuel rods. Routine PIE activities at HFEF include visual inspections, neutron radiography using the NRAD reactor, fission gas analysis (GASR), dimensional measurements, precision gamma scanning (PGS), optical microscopy, radiochemical analysis, profilometry, and mechanical testing of nuclear materials, including tensile, creep, and fatigue testing at prototypical temperatures. Additionally, HFEF assembles experiments requiring the handling of irradiated fuel and materials, such as experiments for transient testing at the TREAT facility. Samples can be prepared for metallurgical examinations and microstructural analysis at nearby facilities. HFEF also supports the fabrication and refabrication of irradiated experimental fuel pins and assemblies, facilitating research on new fuel designs and materials.

IMCL specializes in microstructural analysis, micromechanical analysis, microchemical analysis, and thermophysical characterization of irradiated nuclear fuels and materials. The facility is designed to accommodate advanced characterization instruments that require vibration control, temperature stability, and protection from electromagnetic interference. Its shielded instrumentation allows for detailed analysis of highly radioactive fuels and materials at the micro, nano, and atomic scales, which is ideal to investigate induced damage in samples.

EML is equipped for chemical, thermal, and microstructural analysis, primarily utilizing electron and optical microscopy techniques. EML can accommodate classified work. The facility includes a shielded glovebox and several fume hoods for disassembling TREAT experiments and preparing samples for electron microscopy.

SPL is a non-alpha facility, meaning that it is not for examination of nuclear fuels, but rather for irradiated structural materials and components. SPL provides mechanical and thermal testing capabilities, including under extreme thermal or corrosive conditions.

6. Future Capabilities

Long-term plans and proposals for NRAD include new capabilities to expand utilization of NRAD for INL and DOE mission space. The following subsections briefly describe some of these prospective future capabilities.

Pneumatic Sample Transfer System

A pneumatic sample transfer system (PSTS, sometimes called a "rabbit" system) will enable more efficient sample transfers between the reactor core and the hot cell as well as reduce personnel dose exposure. The PSTS rabbit capsule will be transported through a cylindrical tube using a system driven by differences in air pressure. It will move through the transfer tube as a vacuum pulls it forward while atmospheric pressure pushes it from behind. Samples would be placed inside the rabbit for transit within the system. After the sample has been irradiated, the rabbit will be moved back through the system to a glovebox, where it will be unloaded. The sample could then be transferred to the HFEF main cell for additional analysis.

Irradiation Capability
NRAD staff are developing standardized capsules and Experiment Safety Analyses to perform routine instrumented, heated experiment irradiation. In addition, NRAD core reconfiguration to accommodate larger experiments and higher radiation fluxes could be possible.

Imaging Systems
NRAD staff are developing capabilities that would enable direct digital imaging of highly radioactive samples in the ERS. A single-event mode detector allows researchers to distinguish between gamma-ray and neutron events, which could enable direct examination of highly radioactive samples. This system is currently being tested for feasibility and, if successful, would enable 3D digital nCT of highly radioactive samples in the ERS as routine PIE.

Neutron Diffractometer
The NRAD North Beam Hall was recently repurposed from its prior use and is now available as a low-background space for a new suite of scientific instrumentation. Neutron diffraction has been demonstrated at NRAD using the north beam, but the radiation background in the NRS is far too high. A proposed neutron diffractometer instrument would be located further up-beam in the old diesel generator room to significantly reduce the radiation background compared to the NRS. A neutron diffractometer at NRAD would be unique because it could examine highly radioactive samples that existing facilities elsewhere are not willing or able to handle.

Reactor Power Increase
Increasing the maximum reactor power would increase the neutron fluxes for in-core irradiation positions and in the neutron beamlines, improving these capabilities for all instruments and users. There are a series of modifications and actions at NRAD that would enable an increase in the reactor's maximum power from 250 kW to as high as 1 MW.

A Suite of Neutron Instruments
Researchers are leveraging NRAD's unique proximity to HFEF, ATR and TREAT to combine state-of-the-art neutron-based techniques (e.g. neutron diffraction, imaging, and prompt neutron activation analysis) with access to highly radioactive materials, establishing a suite of material science capabilities that is unique worldwide.

7. How to Start

Prospective users are encouraged to reach out to NRAD staff at NRAD@inl.gov for additional information on technical questions, feasibility, and access for the NRAD reactor. The experimental process is similar to that used for ATR and TREAT at INL in concept, but with more opportunity for a cost-saving graded approach. Users can refer to the ATR and TREAT user guides [8, 9] as a model for a proposal and experimental process for access to NRAD.

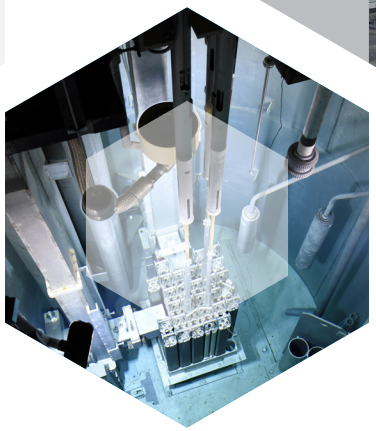
For general questions about nuclear materials irradiation tests, contact the Nuclear Fuels and Materials division at irradiationtesting@inl.gov.

DOE programs such as the Nuclear Science User Facility (NSUF) program and Gateway for Accelerated Innovation in Nuclear (GAIN) program offer users access to NRAD at no cost via a competitive proposal process.

For university researchers using NRAD through the NSUF program, visit nsuf.inl.gov or email nsuf@inl.gov for the latest information.

For industry developers of advanced reactors seeking NRAD access through a Nuclear Energy voucher, contact the Gateway for Accelerated Innovation in Nuclear at gain@inl.gov or visit gain.inl.gov.

The National Reactor Innovation Center (NRIC) is a national DOE program charged with aiding developers committed to demonstrating advanced reactors. Questions about assistance through NRIC can be sent to nric@inl.gov or visit nric.inl.gov for more information.

8. References

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