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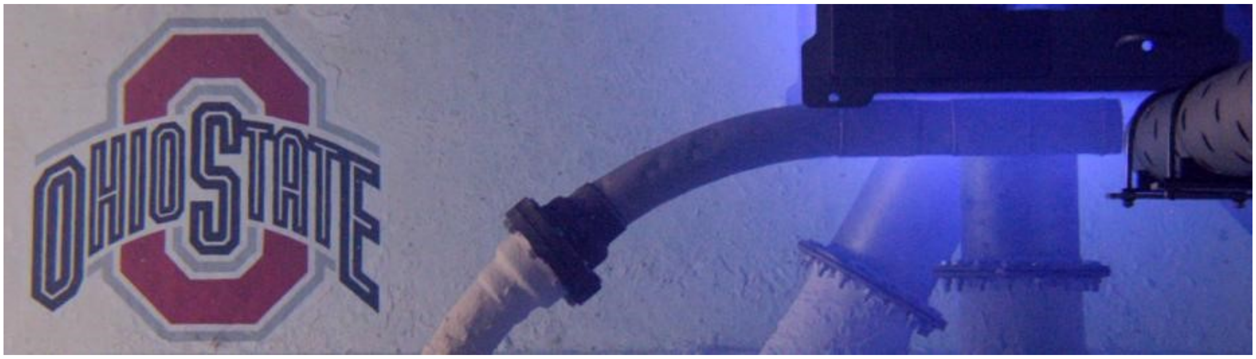

Nuclear Reactor Laboratory User Guide

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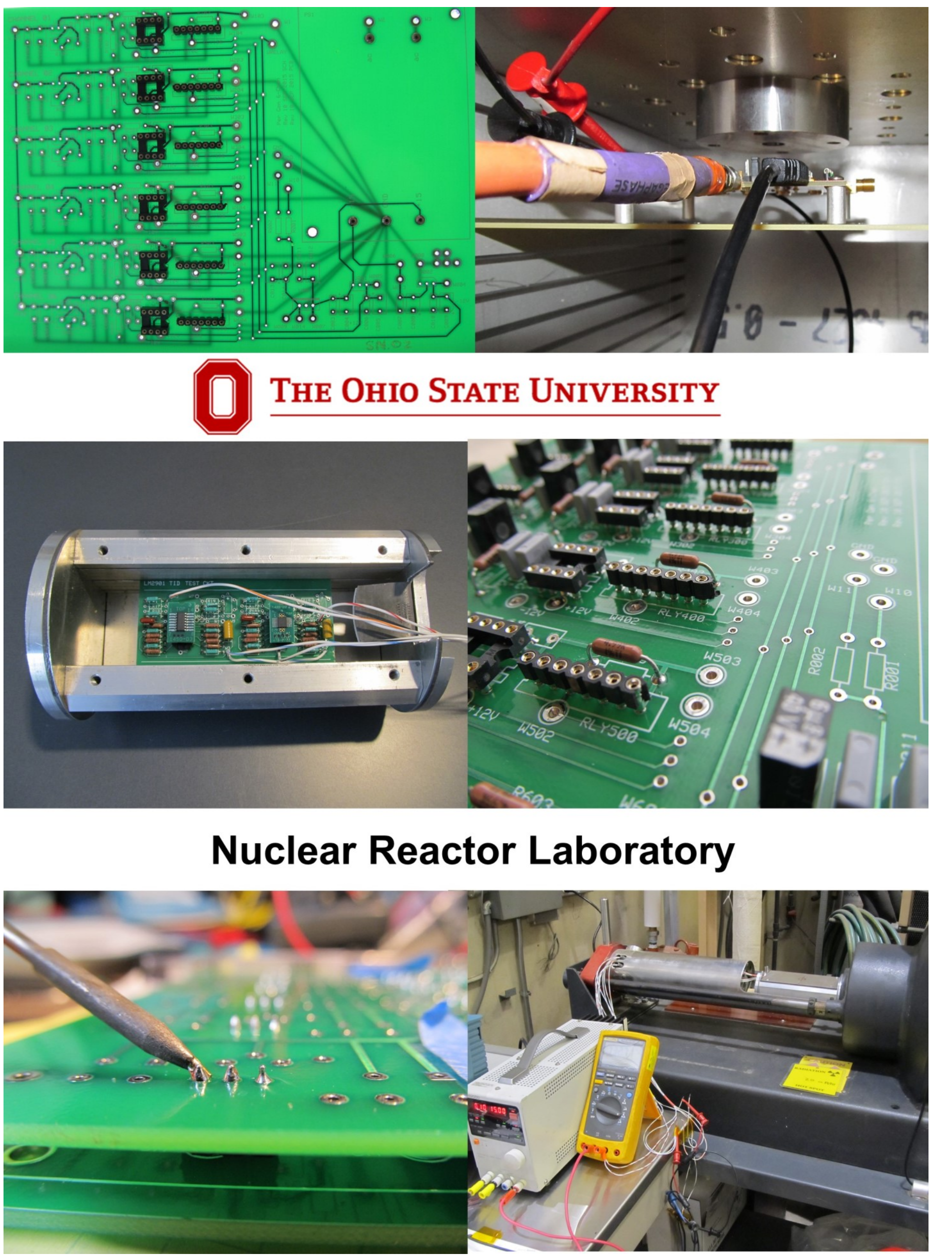
The NRL user guide serve as an introduction for prospective experimenters interested in performing irradiation research in the OSURR. These pages contain brief descriptions of the facility and its experiment capabilities, the ancillary capabilities of the NRL to support development of irradiation and post-irradiation examination (PIE) experiments, the process for users to follow to conduct an experiment, and the conditions that apply to experimenters. These resource pages do not provide all the necessary information required to perform an experiment in the OSURR, but they serve as a guide for concept development and initial experiment planning. The experienced team of NRL researchers works with users to design experiments that meet the users' research needs while ensuring that the experiments comply with all safety requirements.



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1. Nuclear Reactor Laboratory Introduction

The Ohio State University Nuclear Reactor Laboratory (NRL) is an interdisciplinary research facility within the university's College of Engineering. The NRL features The Ohio State University Research Reactor (OSURR), a professional gamma-ray spectroscopy system, multiple gamma-ray irradiators, and other irradiation facilities and radiation measurement equipment.

The NRL provides irradiation and measurement services in support of student and faculty research, student education, and as a service to industry. In addition, the laboratory provides instructional services in the form of student laboratory sessions that support the university's Nuclear Engineering Program and tours for education groups. Services are scheduled during regular business hours and are charged to users on a cost-recovery basis. For inquiries regarding costs for services, please email reactor@osu.edu.

The laboratory is centrally located within Ohio, making it very accessible to all institutions in the state. In addition, Columbus is home to an international airport, making the NRL very accessible to out-of-state users.

2. The Ohio State University – Nuclear Reactor Lab (NRL)

The Nuclear Reactor Laboratory was built in 1960 and the Research Reactor first went critical in 1961. It was originally a 10-kW training reactor that utilized high-enriched uranium (HEU) solid plate fuel.

The design of the OSURR is based on the Bulk Shielding Reactor (BSR), which was located at the Oak Ridge National Laboratory (ORNL). This reactor is in a class of reactors generally known as a Materials Testing Reactor (MTR). This class of reactors share various common features, such as light water moderation and cooling, open pools, and plate -type fuel. The reactor itself was supplied by Lockheed Nuclear Products, then a division of the Lockheed Georgia Company. Lockheed operated a reactor very similar in design to the OSURR, at a power level of 1 megawatt steady-state thermal power, in a forced convection cooling mode. When operated in the natural convection cooling mode at power levels up to 10 kilowatts, the Lockheed reactor was essentially identical in operating characteristics to the OSURR for the first 25 years of operation.

In the 1980s, analyses were performed to move from HEU to low-enriched uranium (LEU) fuel. Analyses were also done to support an increase in the reactor power. The fuel conversion from HEU to LEU was completed in 1988. The power uprate to 500 kW was approved by the NRC in 1992.

At present, the OSURR is the only operating research reactor in the State of Ohio. The OSURR is licensed to 500 kW, utilizes LEU solid plate fuel, and has multiple vertical dry-tubes in which experiments can be placed. Neutron fluxes in the various irradiation facilities are in the range of 10^{12}-10^{13} n/cm^2/s at full power. There is also a beam facility with a thermal flux ~10^6 n/cm^2/s.

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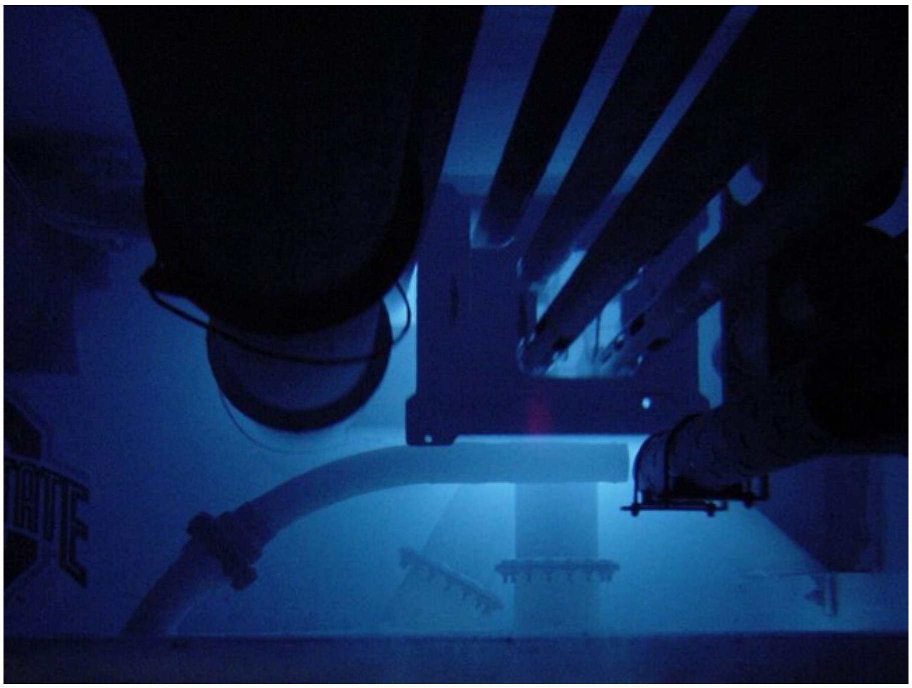
2.1 Research Capabilities

The Ohio State University Nuclear Reactor Laboratory (NRL) offers a number of irradiation capabilities, including the unique capability of reactor irradiations in external large-experiment dry tubes using The Ohio State University Research Reactor (OSURR). In the next-to-core position in which either a 6.5 inch I.D. or a 9.5 inch I.D. external dry tube can be located, irradiations can be performed in a neutron flux up to $\approx 10^{12}$ n/cm^2/s. Among the possibilities for use are experiments involving instrumented, high-temperature irradiations of prototype instrumentation for next-generation reactors, sensors and sensor materials, and optical fibers designed for up to 1600 °C. In addition to the external large-experiment dry tubes, the reactor also has two 2.5 inch I.D. in-core dry tubes that support instrumented experiments, but at ambient temperature.



Large External Dry Tube Next to Core

The NRL has a pool-top workbench and another adjacent work surface where experimenters can set up equipment to support their instrumented experiment at a convenient location without running long wires. Experimenters can design and use their own test rigs for use in the dry tubes (per a successful safety review), and they can operate their own equipment for controlling and monitoring their experiments. Finally, the NRL does not have a fixed operations cycle, which allows for great flexibility in designing experiments with different power levels and even power transients (not including pulsing). Previous experiments have involved multiple stepped reactor powers and multiple experiment temperatures, and the flexibility in operations, experiment size and design, and monitoring makes the NRL reactor a valuable resource for many types of experiments, including testing of potential instrumentation for next-generation reactors. Numerous phase-1 level experiments have successfully utilized the large external irradiation dry tubes for performing high-temperature, instrumented experiments.

To complement these reactor capabilities, the NRL has a Co-60 irradiator that presently has a dose rate in the range of 10-20 krad/hr in silicon and that is capable of being upgraded to Mrad/hr-level dose rate. The NRL is part of a nationally recognized research institution that holds a broad-scope radioactive materials license that allows for a wide range of radioactive materials in various forms. The NRL has four experienced staff members, of which three are senior reactor operators for the OSURR. The staff can assist with design of experiments that safely meet the experimenter's needs, and they also perform experiment installation and removal, safety review, and necessary radiation safety functions, including use of gamma ray spectroscopy to characterize post-irradiation activity in experiments and preparing Limited Quantity packages for shipment.

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2.1.1 Instrumented Experiments

Bench Test of High-Temperature Furnace

The NRL has multiple vertical in-core dry tubes (2.4 inch and 2.5 inch I.D. tubes) as well as movable vertical ex-core dry tubes (6.5 inch and 9.5 inch I.D. tubes) available for experiments. These tubes extend from the pool top down to the reactor core such that instrumented experiments can be installed for real-time, in-situ measurements in a neutron and gamma radiation field. Instrumented experiments for evaluation of advanced sensor prototypes and sensor materials can be designed for test in these dry tubes. To complement data collected by the user, the NRL can provide an analog reactor power signal that can be integrated into the user's data acquisition. The available neutron flux varies by dry tube, but experiments with neutron fluence up to ≈$1x10^{18}$ n/cm^2 can typically be performed.

The movable vertical ex-core dry tubes can be loaded with an experiment and positioned against the east face of the reactor core, allowing for a wide range of reactor irradiation experiments. For instance, instrumented high-temperature furnaces have been used in these tubes to investigate material effects in fiber optics in a high-temperature radiation environment. Furnace rigs up to 1200 °C have been used, and a rig for a 1600 °C experiment is being developed. Instrumented ultra-cold experiments have also been run in the 9.5 inch tube using a cryostat to cool fiber optics and electronics to about 4 Kelvin while being irradiated by the reactor. With the reactor at maximum power, the neutron flux in either of these dry tubes positioned next to the core is ≈$1x10^{12}$ n/cm^2/s, and experiments with neutron fluence on the order of $1x10^{17}$ nv can typically be performed.

2.1.2 Neutron Transmission Testing

Neutron Transmission Sample in front of Aperture

Using a collimated, thermal neutron beam, the NRL provides for users the means to measure the neutron-absorbing capability of sample coupons. In addition to the beam, the NRL provides the mounting location and the neutron-measurement pulse channels necessary for measuring both the transmitted neutrons and the reactor power correction. Typically, the measurements are performed as standards-based measurements per ASTM E2971, but this can be modified as needed by the experimenter. The user must provide the standards for such tests, and coupons with neutron-absorbing capability equivalent to a boron areal density of up to 70 mg/cm^2 can be measured.

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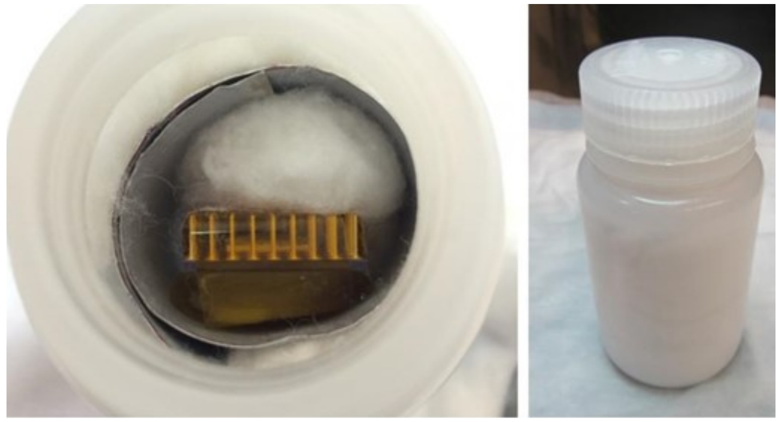
2.1.3 Electronics Damage Testing

The NRL offers two types of electronics damage testing: neutron displacement damage testing, and total ionizing dose (TID) testing.

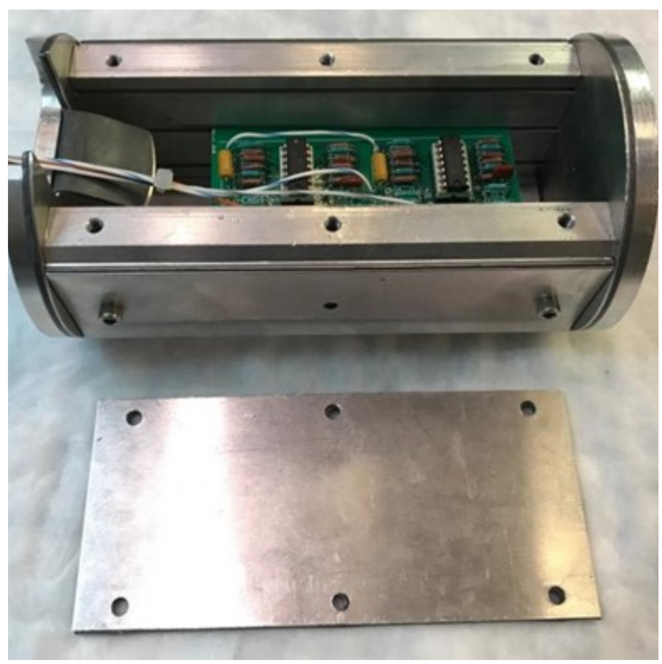
Neutron Displacement Damage Testing:



Pneumatic Transport System Tube Sample from Electronics

Multiple vertical dry tubes and a beam port are available at the NRL for displacement damage testing with neutrons. 2.4 inch and 2.5 inch I.D. vertical dry tubes are located in the core, and either a 6.5 inch or 9.5 inch I.D. vertical dry tube can be positioned against the east face of the core for testing. Experiments can be designed using these tubes such that guidelines published in ASTM F1190 and E1854, MIL-STD-750 TM 1017, and ESCC 22900 are met, and these experiments can be for 1 MeV silicon-equivalent neutron fluences up to ≈$1x10^{17}$ n/cm^2 for the in-core tubes and up to about $5x10^{15}$ n/cm^2 for the ex-core tubes. For testing requiring a higher neutron-to-gamma ratio, an experiment rig utilizing a 2 inch-thick bismuth plate is being designed for use in the 9.5 inch I.D. tube. Neutron dosimetry is performed by spectrum unfolding using induced activity in metal foils, and this dosimetry can be performed specific to the test article's location on the experimenter's test fixture.

Total Ionizing Dose (TID) Testing:



Benchtop Irradiator Filter Box

Gamma-rays from cobalt, cesium, and scandium sources may be used to evaluate electronic devices for effects caused by ionizing radiation. The cobalt and cesium sources are in fixed-geometry irradiators, but use of the scandium sources can be customized to the requirements of the experiment. The scandium sources are created by activating scandium metal using the reactor, and the sources are used in a "spot source" testing facility that can make use of an adjustable-position collimator to provide dose to the test article while minimizing dose to other ICs mounted on the evaluation board. The collimator reduces dose 1.5 inches away from the test article to less than 20% of the test article exposure.

Available dose rates in the irradiators range from less than 10 mrad(Si)/s to 8 rad(Si)/s. The lower dose rates fall in the range for Enhanced Low Dose Rate Sensitivity (ELDRS) testing, as published in MIL-STD-750 TM 1019, ESCC 22900, and ASTM F1892 guidelines. Dosimetry is performed using nanoDOTS™ placed at the test article's location inside the test fixture.

NRL can provide additional guidance and support in designing and developing radiation test fixtures and circuits, and radiation test plans. Previous customers have developed and used various dry tubes and gamma irradiators for evaluating devices from cryogenic temperatures up to 150 °C.

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2.1.4 Neutron Imaging

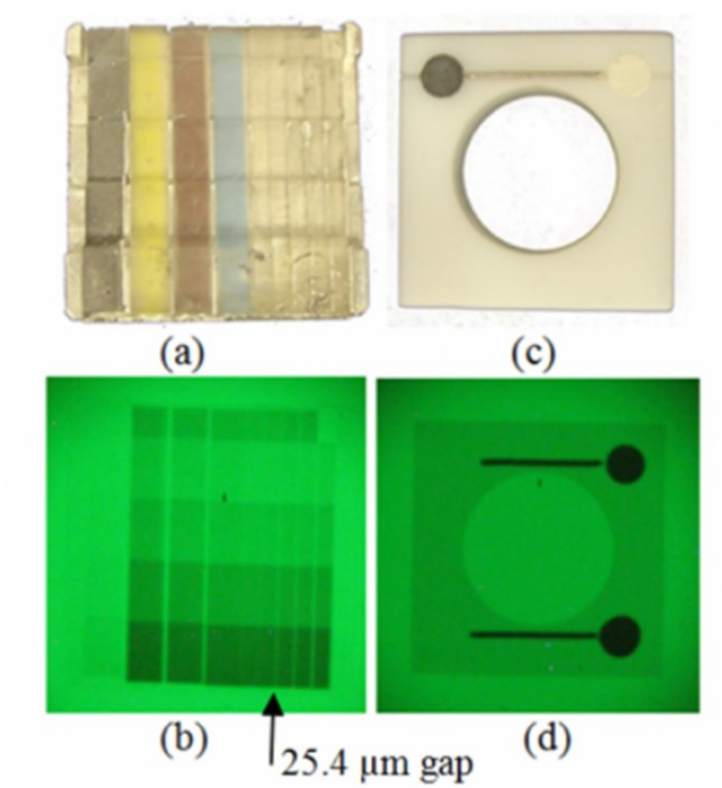
In its neutron beam facility, the OSURR is able to deliver a relatively-clean, small-sized (< 30 mm diameter) thermal neutron beam to a workbench, where neutron imaging can be performed. See the university's [Nuclear Analysis and Radiation Sensor (NARS) Laboratory] site for more information.

2.1.5 Neutron Depth Profiling (NDP)

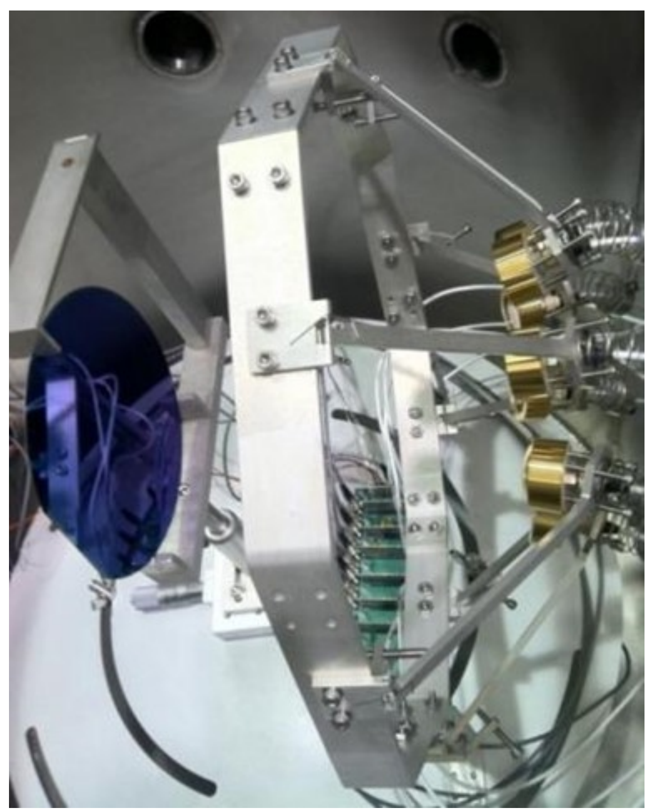
In its neutron beam facility, the OSURR is able to deliver a relatively-clean, small-sized (< 30 mm diameter) thermal neutron beam to an instrumented vacuum chamber, where neutron depth profiling can be performed. See the university's [Nuclear Analysis and Radiation Sensor (NARS) Laboratory] site for more information.

2.1.6 Instrumental Neutron Activation Analysis (INAA or NAA)

INAA is a method to determine the concentration of trace (1 to 100 ppm), minor (0.1 w/o to 1.0 w/o), and major (1.0 w/o and above) elements in a variety of matrices. Samples are exposed to neutrons, producing radioactive nuclides in the sample (neutron activation). When radioactive atoms in the sample decay, gamma rays with characteristic energies are emitted by each nuclide. Using a gamma-ray spectroscopy system (GRSS), the quantity and energy of emitted gamma rays can be measured. The energy of the measured gamma rays can be used to “fingerprint” the radioactive nuclides, and therefore the elements that were activated. In addition, the concentration of these elements can be determined quantitatively by comparison of gamma ray intensities with those emitted by standards for the various nuclides. This sensitive analytical technique is useful for a variety of purposes, including geological, environmental, industrial, and forensic.



Neutron images of the ASTM standards: (a) the Sensitivity Indicator and (b) its neutron image; (c) the Beam Purity Indicator (BPI) and (d) its neutron image.



Eight Si detectors mounted inside the NDP vacuum chamber in a ring format

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Advantages of INAA

- Many elements can be analyzed simultaneously
- Very low detection limits for many elements
- Small sample sizes (1 – 200 mg)
- No chemical preparation
- Non-destructive
- Insensitive to matrix elements such as C, N, O, H, and Si, making detection of trace elements possible
- Often complementary to other analytical techniques

NAA at the NRL

At the NRL, the neutrons are supplied by the OSURR, for which irradiations can be scheduled and tailored to meet individual researcher requirements. Samples should be supplied ready for analysis in small sealed polyethylene vials, and while the NRL has a limited selection of standards materials, the researcher may need to provide standards (samples with known concentrations of the elements of interest).

In some cases, the irradiations are performed using the pneumatic transport system, which uses air flow to deliver samples to a position adjacent to the core. After a pre-determined irradiation time (typically on the order of minutes), the system automatically returns the sample to a shielded holding box. In others, the samples will be placed within the CIF vertical dry tube and irradiated within the core for an hour or more.

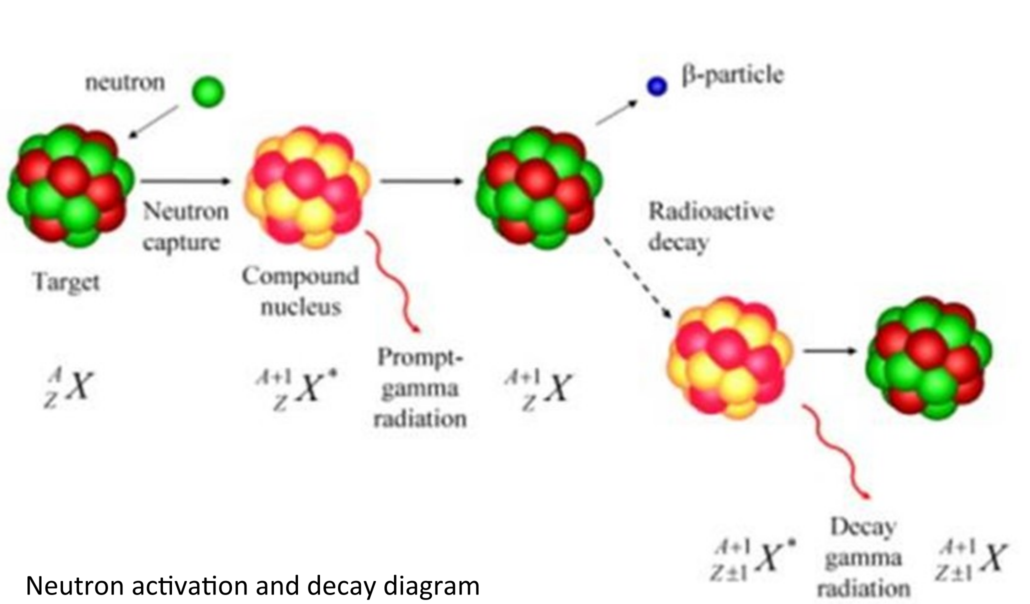
Following an appropriate decay period, the gamma-ray spectrum is measured and recorded using the NRL GRSS. The decay period depends on the element of interest and the other elements present in the material. In some cases, the spectrum is recorded as soon after irradiation as possible. In others, the sample may decay for a day, week, or month before analysis. Finally, a staff member will take the information from the sample and the standard(s) and perform the requested level of analysis. (Some customers only need raw data, while others will want a more formal report.)

Detection Limits

This table at Ortec Inc. provides approximate detection limits for several elements. Actual detection limits depend on major components of the material.

Requesting Neutron Activation Analysis

The NRL can provide NAA services in support of research and development. Researchers interested in neutron activation analysis services at the NRL should fill out this form with the requested information. We will reply by e-mail after we have reviewed your request.



Neutron activation and decay diagram

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2.1.7 Neutron Irradiations

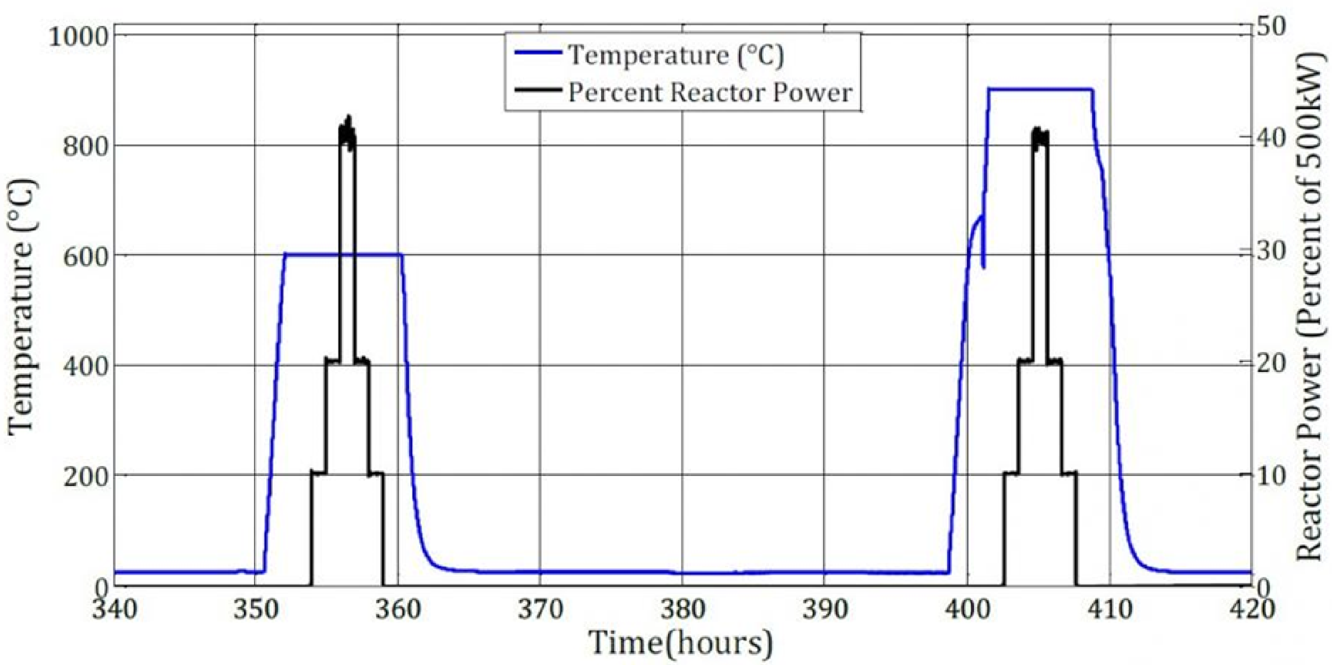
The Nuclear Reactor Laboratory neutron irradiation capabilities include:

- In-core irradiation of samples: the OSURR has three in-core dry tubes in which encapsulated samples can be irradiated. The CIF and AIF tubes each have special sample carrier baskets available that can be used to hold samples for irradiations.
- Ex-core irradiation of samples: the OSURR has multiple ex-core large-experiment dry tubes in which encapsulated samples can be irradiated.
- Timed irradiation of samples using polyethylene bottles in a pneumatic facility. The pneumatic transport system (rabbit) irradiation facility makes use of a vacuum system for insertion and extraction of samples in two-inch outer-diameter sample carriers for precisely-timed irradiations. The transfer time is less than a second.
- Irradiation of samples or experiments with thermal neutrons using a thermal column.

2.1.8 Other Research Capabilities

In addition to the specific capabilities separately listed, the Nuclear Reactor Laboratory also has other experiment and testing capabilities, including:

- Gamma-ray irradiations of experiments using a Co-60 underwater irradiator, a Cs-137 benchtop irradiator, or a Sc-46 spot irradiator.
- Experiments utilizing the alpha, beta, gamma, and neutron sources of the NRL
- Creation of other types of beta/gamma sources using the OSURR, such as the Sc-46 sources used for the spot irradiator.



Example temperature and reactor power profile for high-temperature experiment

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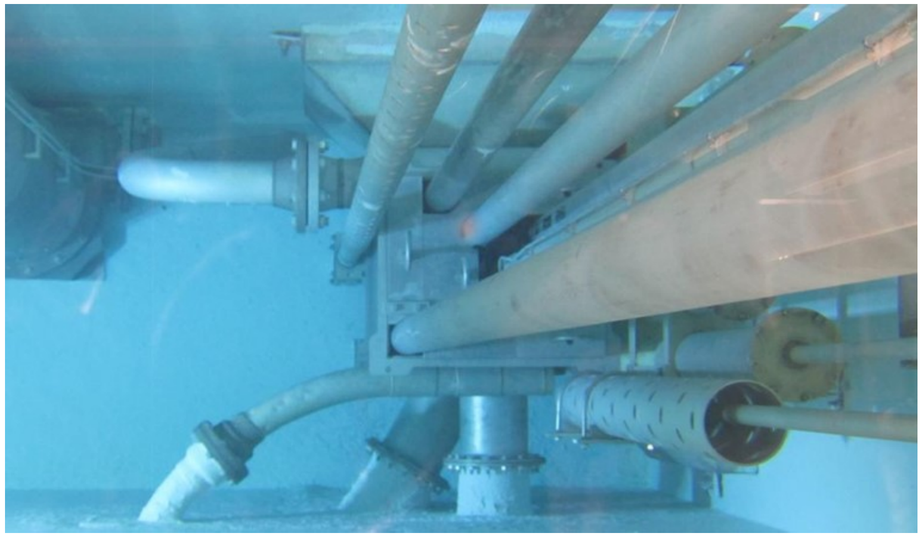
2.2 Reactor Description

The OSURR is an open pool, MTR-type research reactor that is a unique asset to nuclear engineering research and education at the university and in the State of Ohio, and it is utilized for instructional, research, and service activities. It has multiple vertical dry tubes and beam ports that serve as irradiation facilities, and the OSURR is licensed to operate at thermal powers (no electricity is produced) up to a maximum of 500 kilowatts. At the maximum power, the neutron flux in the available irradiation dry tubes are on the order of 10^{12}-10^{13} n/cm^2/s.



View of reactor pool from above

The OSURR is used for a wide range of nuclear-related research endeavors, including evaluation of material elemental constituents using neutron activation analysis (NAA) and neutron depth profiling (NDP); evaluation of radiation damage to electronic components and other materials, such as optical fibers and optical fiber-based sensors; evaluation of neutron and gamma-ray radiation sensitive detector performance; isotope production; and biomedical experiments.

The OSURR is not constrained by a fixed duty-cycle, allowing great flexibility in scheduling research and education activities. The reactor has multiple irradiation locations that allow instrumented experiments, enabling in-situ experiment measurements and real-time monitoring during irradiations. The non-fixed duty cycle enables researchers to perform experiments utilizing varying reactor power levels and even power transients.

A number of experimental facilities converge at the reactor core, which allows simultaneous performance of multiple experiments.

Table 2: NRL Irradiation Facility Dimensions

Facility	Inner Dimension
CIF	1.3'' Diameter
AIF	2.4'' Diameter
Rabbit	1.1'' Diameter *
6.5'' Movable Dry Tube	6.6'' Diameter
9.5'' Movable Dry Tube	9.5'' Diameter
Beam Port #1 (BP1) Sample Holder Position	2.0'' Diameter x 3.7'' Height
Function Test Vessel in BP1	Phenolic mounting board
Beam Port #2 (BP2) External Beam Line Facility	~30 mm Diameter
Thermal Column	4'' x 4'' Square/Stringer

* 1.10'' is the ID of the mouth of the polyethylene bottles used in the rabbit facility

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Table 1: NRL Irradiation Facility Neutron Fluxes and Neutron & Gamma Dose Rates

Facility	Total Neutron Flux (n/cm²/s)	Percent Thermal (%)	Thermal Neutron Flux (n/cm²/s)	epi-Cd Neutron Flux (n/cm²/s)	1.0 MeV Eq Neutron Flux (n/cm²/s)	Neutron Dose Rate in Si (rad-Si/hr)	Gamma Dose Rate in Si (rad-Si/hr)
			(E_n<0.5 eV)	(E_n>0.5 eV)	$F_{D,1.0\ MeV,Si}$ = 95 MeV•mb $F_{D,1.0\ MeV,GaAs}$ = 70 MeV•mb (Ref: ASTM E722-14)		
1.3" CIF	2.9E13*	62	1.7E13*	1.2E13*	5.8E12 (Si)† 6.2E12 (GaAs)†	1.7E06	8.7E07‡
2.4" AIF	1.1E13§	49	5.6E12§	5.8E12§	2.8E12 (Si)† 3.0E12 (GaAs)†	8.2E05	3.8E07‡
Rabbit	3.8E12**	73	2.8E12**	1.0E12**	5.6E11 (Si)† 6.1E11 (GaAs)†	1.6E05	
6.5" External Dry Tube	1.6E12††	73	1.2E12††	4.5E11††	2.0E11 (Si)† 2.4E11 (GaAs)†	6.6E04	7.6E06‡
9.5" External Dry Tube (Flux Box Evacuated)	1.3E12‡‡	67	8.7E11‡‡	4.2E11‡‡	2.3E11 (Si)† 2.5E11 (GaAs)†	6.8E04	4.4E06‡
Beam Port #1 (BP1) Sample Holder Position	4.2E12§§	54	2.3E12§§	1.9E12§§	1.0E12 (Si)† 1.1E12 (GaAs)†	3.1E05	
Functional Test Vessel (FTV) in BP1	1.4E11***	4	6.2E09***	1.4E11***	6.8E10 (Si)† 6.9E10 (GaAs)†	2.0E04	1.4E06‡
Beam Port #2 (BP2) External Beam Line Facility			4.4E6†††				
Thermal Column G7, core end, stringer open			2.5E11‡‡‡				

Note: All values are for 450 kW operation, except for the FTV in BP1 which is limited to 25 kW

* NRL memo 2019-13, "CIF Neutron Spectrum Measurement"
† NRL memo 2013-12 Rev. 06, "1.0 MeV Equivalent Flux Calculations in Si and GaAs"
‡ NRL memo 2016-17 Rev. 03, "Gamma Dose Rates of Reactor Facilities"
§ NRL memo 2019-14, "AIF Neutron Spectrum Measurement"
** NRL memo 2019-18, "Rabbit Neutron Spectrum Measurement"
†† NRL memo 2019-19, "6.5-inch External DryTube Neutron Spectrum Measurement"
‡‡ NRL memo 2019-25, "9.5-Inch External Dry Tube (Flux Box Evacuated) Neutron Spectrum Measurement"
§§ NRL memo 2015-07 Rev. 1, "BP1 Sample Holder Neutron Spectrum Measurement"
*** NRL memo 2018-15, "Functional Test Vessel Neutron Spectrum Measurement"
††† NRL memo 2015-05 Rev. 1, "BP2 Facility Flux Measurements"
‡‡‡ NRL memo 2015-08 Rev. 2, "TC Thermal Flux Measurements"

A summary table listing the neutron fluxes and dose rates in the various OSURR facilities. Referenced memos are available upon request.

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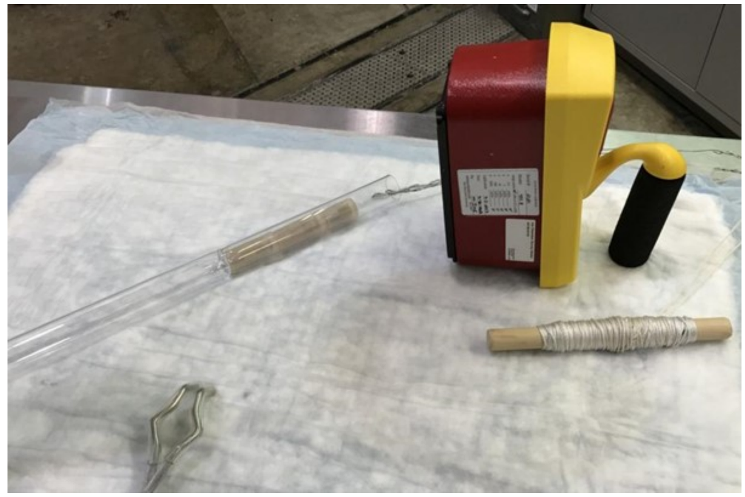
3. User Facility Descriptions

3.1 CIF Vertical Dry Tube

The central irradiation facility (CIF) vertical dry tube consists of a 1.3-inch inner-diameter dry tube that extends from above the reactor pool down into the central grid position of the core, in which the dry tube is surrounded by a water-filled flux trap that boosts thermal flux. This facility has the highest available flux at the OSURR, with a maximum total flux of ~2×10^{13} n/cm^2/s, and a maximum thermal flux of ~1×10^{13} n/cm^2/s.

The CIF is often used for irradiating small samples using pure quartz irradiation baskets, although other experiments can be performed using the CIF, such as in-situ testing of fiber-optic based detectors.



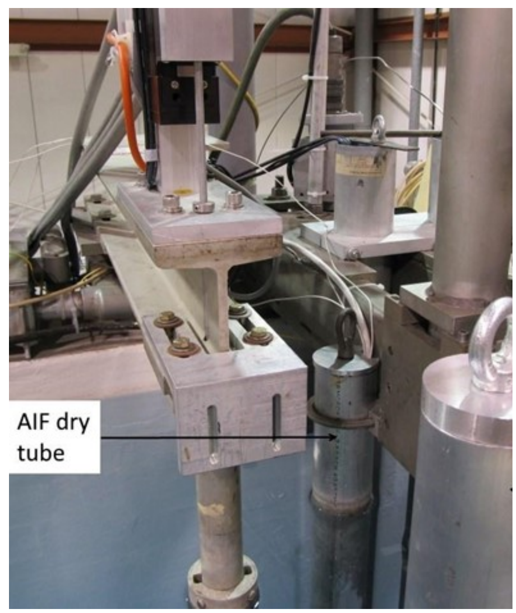
CIF Sample Basket

Notes for experimenters:
The CIF has high reactivity worth, so strong neutron absorbers cannot be put there. The CIF is used for regular testing, so it cannot be tied up with an experiment for long periods of time ≈ 1 week.

3.2 AIF Vertical Dry Tube

The auxiliary irradiation facility (AIF) vertical dry tube is a 2.4-inch inner-diameter tube that extends from above the reactor pool down into a position in the core grid along the south edge of the core. It has a ~1×10^{13} n/cm^2/s maximum total flux and ~5×10^{12} n/cm^2/s maximum thermal flux.

The shielding plug for each tube has a cableway that allows cabling out of the dry tube to enable in-situ measurements from instrumented experiments, and for irradiating samples there is an aluminum sample basket available.



AIF dry tube

An aluminum irradiation basket is available for irradiating samples in the AIF, and it can accommodate samples with a diameter up to 2 inches. Another irradiation basket is available for irradiation with a hard neutron spectrum. The basket has a cadmium liner to screen out neutrons with energies less than ~0.5 eV, which is useful for neutron displacement damage experiments in which minimal activation from thermal neutrons is desired. The cadmium liner allows for samples with a cross section up to 1.25 inches x1.25 inches.

Aluminum Irradiation Basket

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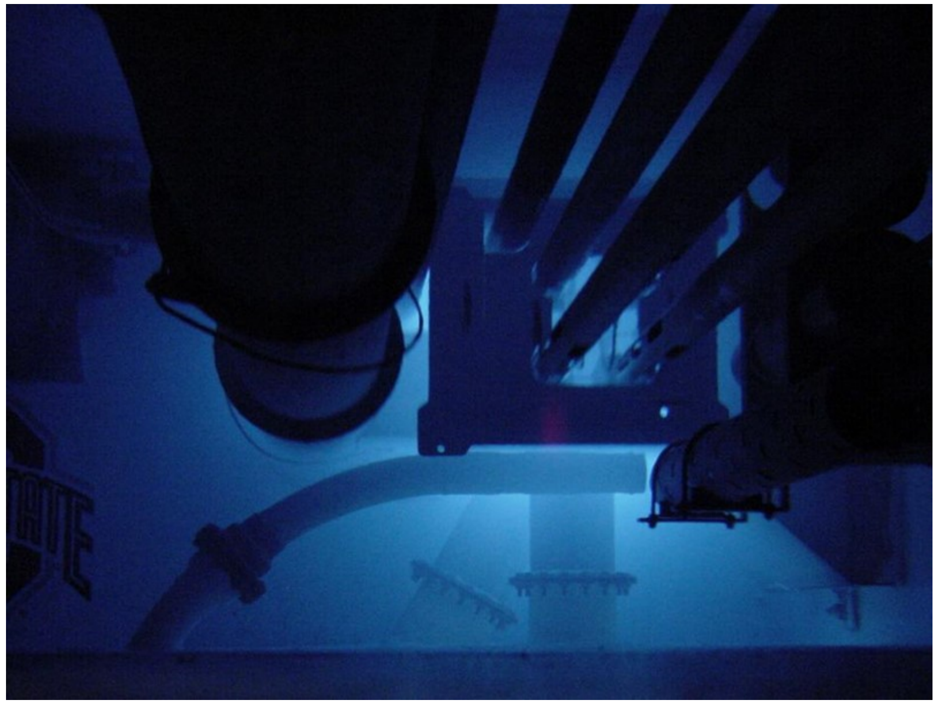
3.3 Moveable Vertical Dry Tubes

The Ohio State University Nuclear Reactor Laboratory (NRL) offers the unique capability of reactor irradiations in external large-experiment dry tubes using the Research Reactor (OSURR). In the next-to-core position in which either a 6.5-in I.D. or a 9.5-in I.D. external dry tube can be located, irradiations can be performed in a neutron flux up to ~10^{12} n/cm^2/s. The shielding plug for each tube has a cableway that allows cabling out of the dry tube to enable in-situ measurements from instrumented experiments. Among the possibilities for use are experiments involving instrumented, high-temperature irradiations of prototype instrumentation for next-generation reactors, sensors and sensor materials, and optical fibers designed for up to 1600 °C.

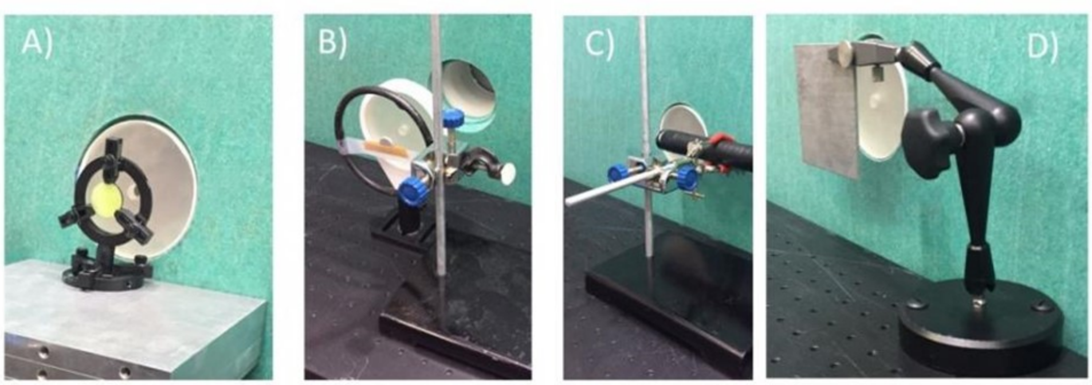


9.5 inch dry tube next to the reactor core

3.4 Beam Facility

The external neutron beam line at OSURR is able to deliver a relatively-clean, small-sized (< 30 mm diameter) thermal neutron beam to a workbench, where various instruments can be set up for detector evaluation and in-situ materials characterization. The neutron collimator consists of single-crystal sapphire and polycrystalline bismuth filters (providing fast neutron and gamma-ray filtration, respectively) followed by a parallel series of 3-cm apertures for collimation. The thermal-equivalent neutron flux is ~$4x10^6$ n/cm^2/s at the sample position, which is an optical table upon which instrumentation may be set up for in-situ testing of radiation detectors or coupons may be set up for characterizing materials, and ~$2x10^6$ n/cm^2/s in the high-vacuum chamber. The cadmium ratio, which is defined as the ratio of the activities of bare and cadmium-covered gold foils detectors and which characterizes the epithermal and fast neutron contributions in the neutron spectrum, was measured to be 92.

See the university's [Nuclear Analysis and Radiation Sensor (NARS) Laboratory] site for more information.



Various experimental set-ups for neutron beam work. A) Shows an optical mounting system with an aluminum stand and a lithium-glass collimator in place. B) Shows another mounting system with the collimator's distance adjusted. C) Demonstates a claw mounting system while D) Depicts an adjustable arm mounting system.

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3.5 Pneumatic Transport System (PTS) / Rabbit Facility

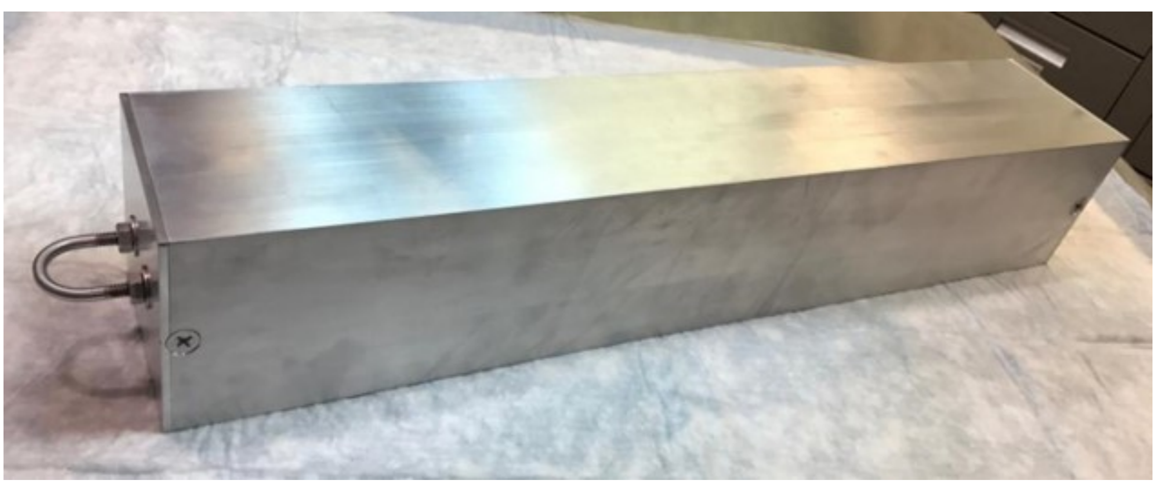
The pneumatic transport system, or rabbit, makes use of a vacuum system for insertion and extraction of samples in sample carriers with a 1.1-inch opening for precisely-timed irradiations. Nalgene wide-mouth polyethylene 125 mL bottles are used to hold the samples during irradiations, and the pneumatic facility offers a ~3×10^{12} n/cm^2/s maximum total flux and ~2×10^{12} n/cm^2/s maximum thermal flux. Following a timed irradiation, the sample bottle is automatically returned to a shielded holding box.

Sample Bottle

3.6 Thermal Column

The thermal column irradiation facility, which is situated behind the thermal column extension in the west wall of the reactor pool, consists of a large volume of graphite to thermalize neutrons and offers a very thermalized neutron field in a four-inch by four-inch area for experimentation. At the core end of the thermal column, there is a maximum thermal flux of ~2×10^{11} n/cm^2/s. At other locations in the thermal column, the thermal neutron flux is on the order of 10^9-10^{10} n/cm^2/s.

An aluminum sample holder box is available for irradiation of samples in the thermal column, and an acrylic "sled" is available for irradiation of neutron-sensitive detectors.



TC Sample Holder Box

3.7 Gamma Irradiators

The NRL can provide gamma-only irradiations using multiple different irradiators:

- The highest dose rate is achievable using a Co-60 underwater irradiator that provides gamma rays of 1173 keV and 1332 keV for in-situ irradiation of devices.
- A benchtop irradiator is also available for low dose-rate testing.
- A spot irradiator makes use of a source collimator to enable in-situ radiation-damage testing of an electronic device while minimizing the dose received by other devices nearby on the test board.

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3.7.1 Co-60 Underwater Irradiator

The Cobalt-60 Underwater Irradiator is used for research and development and educational activities, including:

- Observation of radiation effects on materials and devices.
- Inducement of radiation effects in materials and devices, with subsequent investigation and/or utilization of the effects.
- Demonstration of operation of radiation detectors, and their behavior in high-dose gamma radiation fields.

No irradiation of explosive, flammable, or corrosive materials or of food destined for human consumption is allowed.

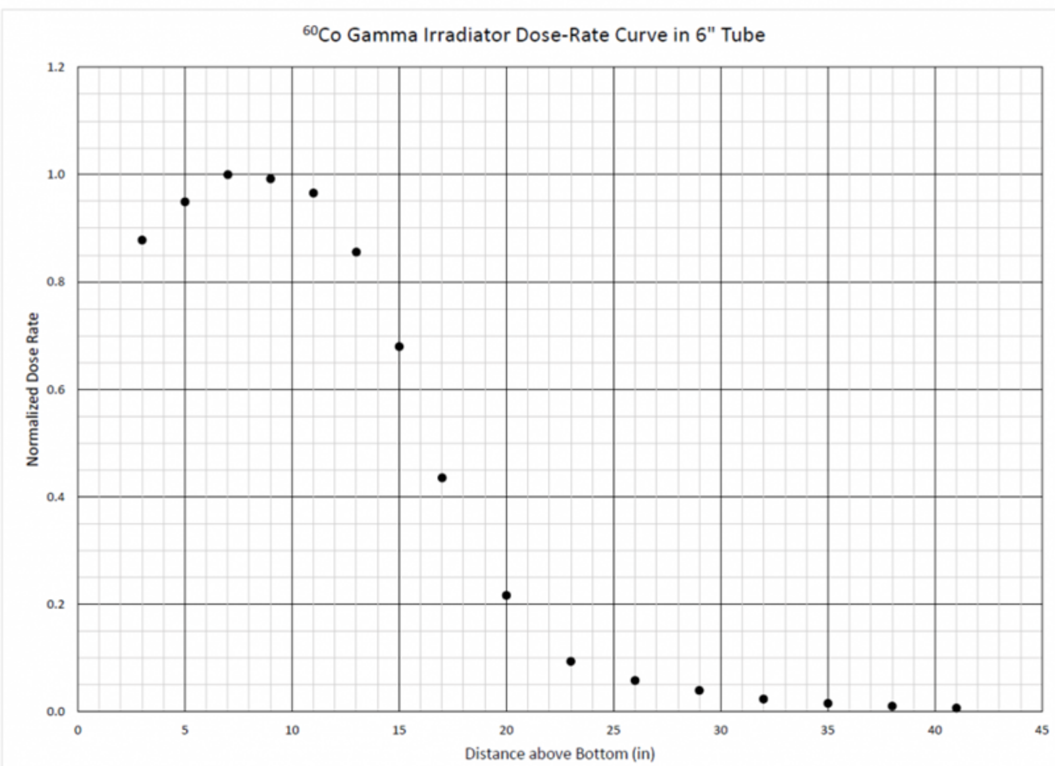
The irradiation chamber is a dry, air-filled, 6-in I.D. tube that is open to atmosphere. For irradiations, a shielded elevator assembly moves within the dry tube to lower experiments or samples into the irradiation position. The shielding in the elevator allows cables to be run out of the irradiator to enable in-situ measurements during the irradiation. The available space for experiments or samples to be irradiated is ~3.5-in diameter by the usable height seen in the flux profile below. (The usable height for irradiations is limited by the falloff of radiation. For experimenters wanting to keep the dose rate across the height of the experiment within 10%, the maximum experiment height is 6 in. For experimenters wanting to keep the dose rate across the height of the experiment within 20%, the maximum experiment height is ~11 in.) A cross-section of the experiment elevator is also shown below.

Note - the hoist that raises and lowers the shielded elevator has a 10% duty cycle, which limits its use to three up/ down cycles per hour.

Because a common use for the irradiator has been irradiation of electronics parts for radiation damage testing, a filter box has been designed and built using the guidance in ASTM E1249-10, 'Standard Practice for Minimizing Dosimetry Errors in Radiation Hardness Testing of Silicon Electronic Devices Using Co-60 Sources', in order to minimize low energy photon absorbed-dose enhancement effects.

Per nucleide.org, the decay of Co-60 results in the emission of 1173 keV and 1332 keV gammas 99.9% of the time. (Co-60 decays by beta minus emission to excited levels of Ni-60, which emits the gammas.)

The approximate dose rate in silicon at the peak location can be seen at the NRL website.



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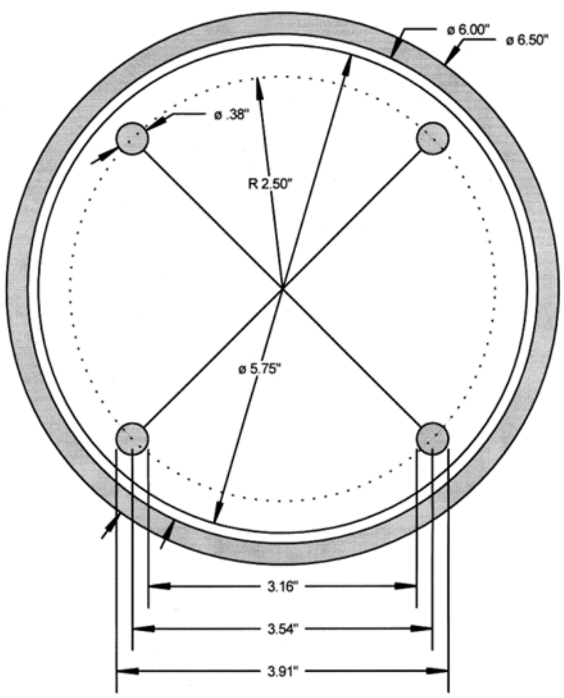
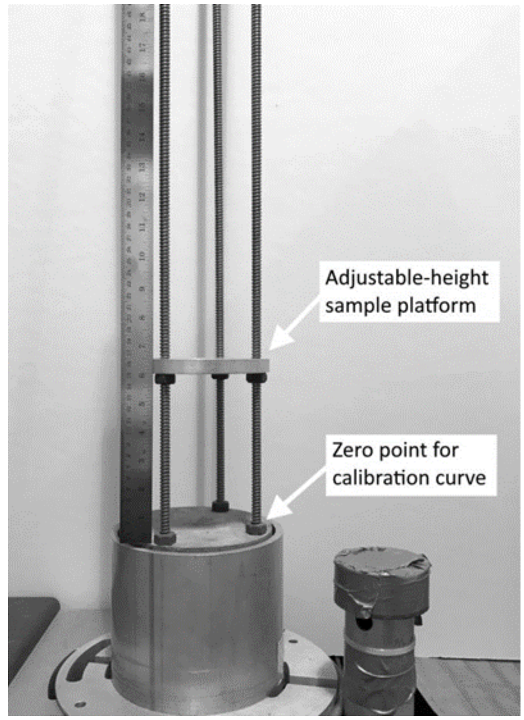


Cross-section of the elevator

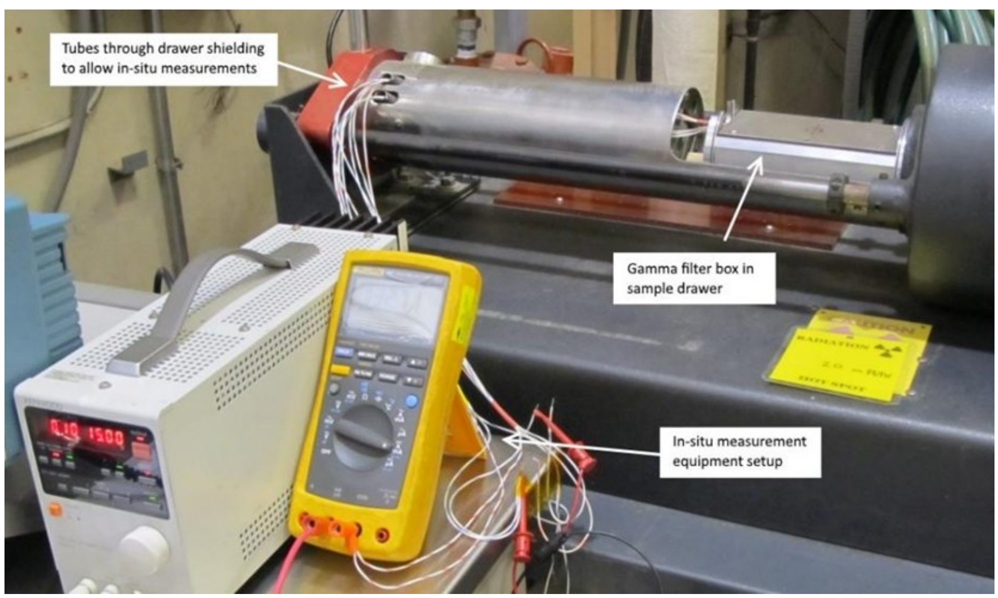


Sample Plate and Shielding

3.7.2 Cs-137 Benchtop Irradiator

The NRL benchtop irradiator is used for research and development and for educational activities. These activities may include:

- Observation of radiation effects on materials and devices.
- Inducement of radiation effects in materials and devices, with subsequent investigation and/or utilization of the effects.
- Demonstration of operation of radiation detectors, and their behavior in high-dose gamma radiation fields.



Instrumented experiment in the Cs-137 benchtop irradiator

No irradiation of explosive, flammable, or corrosive materials, or of food destined for human consumption is allowed.

Experiments or samples are put in a shielded drawer for insertion into the irradiation area, and the drawer has through-tubes that allow wires to be run out of the irradiator for in-situ measurements during the irradiation. The space for sample irradiations is 7.75 inch in length by 3.75 inch in diameter.

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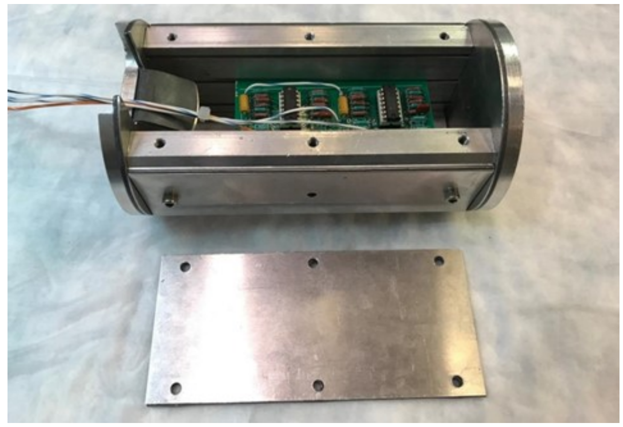
Because a common use for the benchtop irradiator has been irradiation of electronics parts for radiation damage testing, a filter box has been designed and built using the guidance in ASTM E1249-10, 'Standard Practice for Minimizing Dosimetry Errors in Radiation Hardness Testing of Silicon Electronic Devices Using Co-60 Sources', in order to minimize low energy photon absorbed-dose enhancement effects. The board size to fit in the filter box is 2 inch wide by up to 5.5 inch long, and parts should not be mounted within 1/8 inch of any of the board edges.



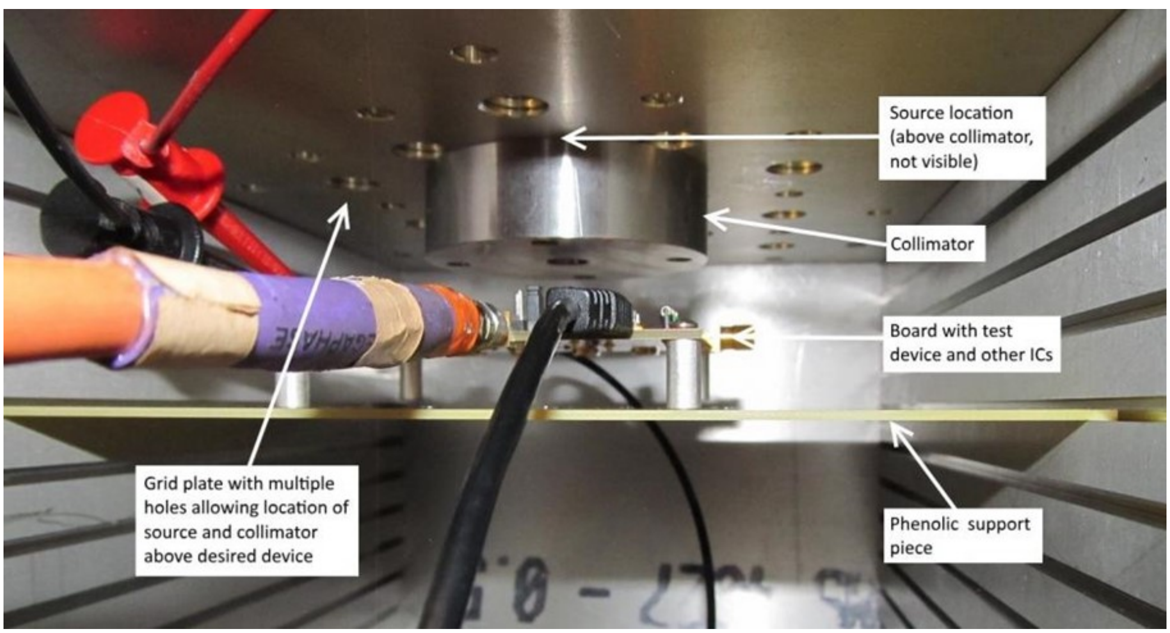
Benchtop irradiator filter box

Per nucleide.org, cesium-137 has a half-life of 30.1 years, and its decay results in the emission of a 662-keV gamma 85.0% of the time. (Cs-137 decays by beta minus emission to the ground state of Ba-137 [5.6%] and to the 662-keV isomeric level of Ba-137 [94.4%], which has a half-life of 2.55 min. Isomeric Ba-137 emits a 662 keV gamma 90.0% of the time.)

The approximate dose rate in water at the peak location can be found on the NRL website.

3.7.3 Sc-46 Spot Irradiator

Sc-46 Irradiator Setup



The spot irradiator makes use of a source collimator to enable in-situ radiation-damage testing of an electronic device while minimizing the dose received by other devices nearby on the test board. The irradiator uses scandium-46 created in the reactor from irradiation of Sc-45. Sc-46 decays with an 84-day half-life, emitting 1120 keV and 889 keV gammas. These gamma are hard enough for useful electronics damage testing such that they can act as a surrogate gamma emitter for Co-60 that can be tailored for use in enhanced-low-dose-rate-sensitivity (ELDRS) testing. The Sc-46 sources can be activated for dose rates in the range of 1 -10 mrad (Si)/s, which is the typical desired range for ELDRS radiation damage testing of electronics.

Note that the test cavity is 7 inch wide by 9 inch deep. The slots that hold the phenolic support piece are 1/8 inch high and 1/4 inch wide. Therefore, the support piece should be 7.4 inch wide by no more than 8.9 inch deep and less than 1/8 inch high. The circuit board on which the parts are mounted can have dimensions up to 6.9 inch wide by 8.9 inch deep, but the area of the board on which parts are mounted should be kept to 6 inch wide by 8 inch deep.

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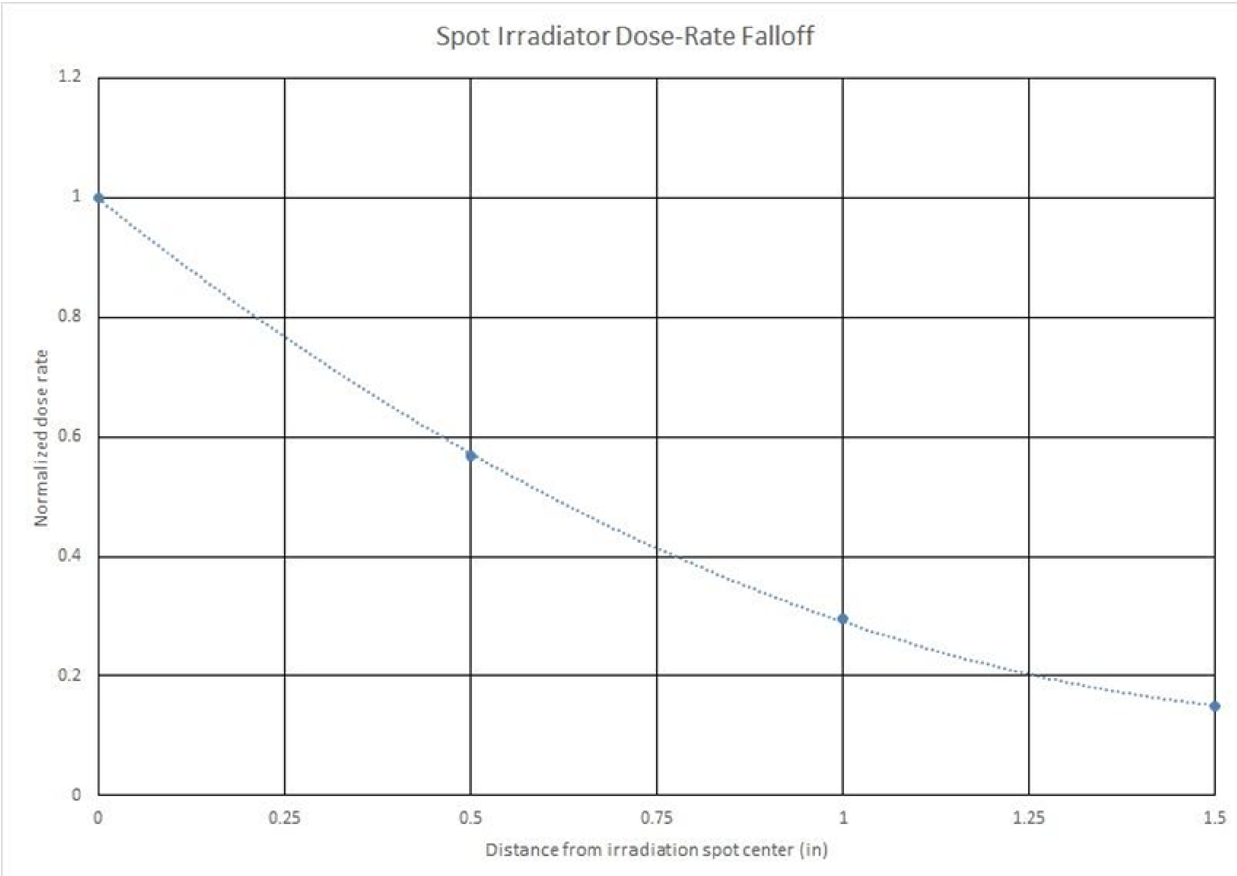
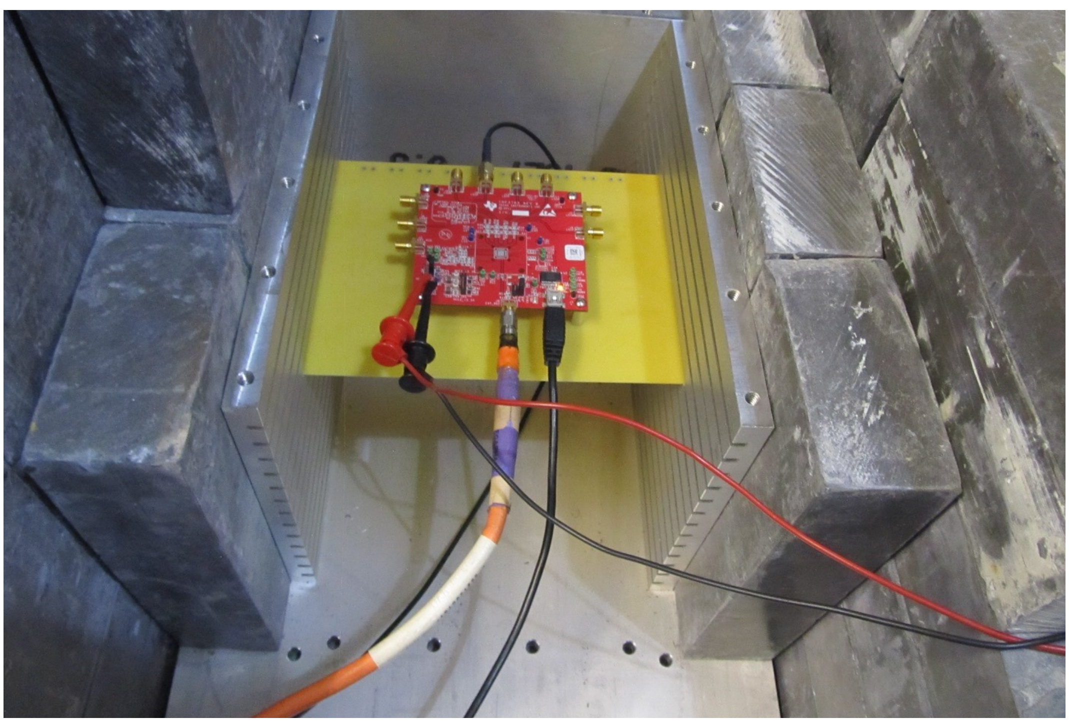
The figure below shows the approximate falloff of dose rate with distance from the center spot.





Sc-46 irradiator pictured with the top open.

The dimensions of the circuit board are 7.4 inch wide by 5.5inch deep.

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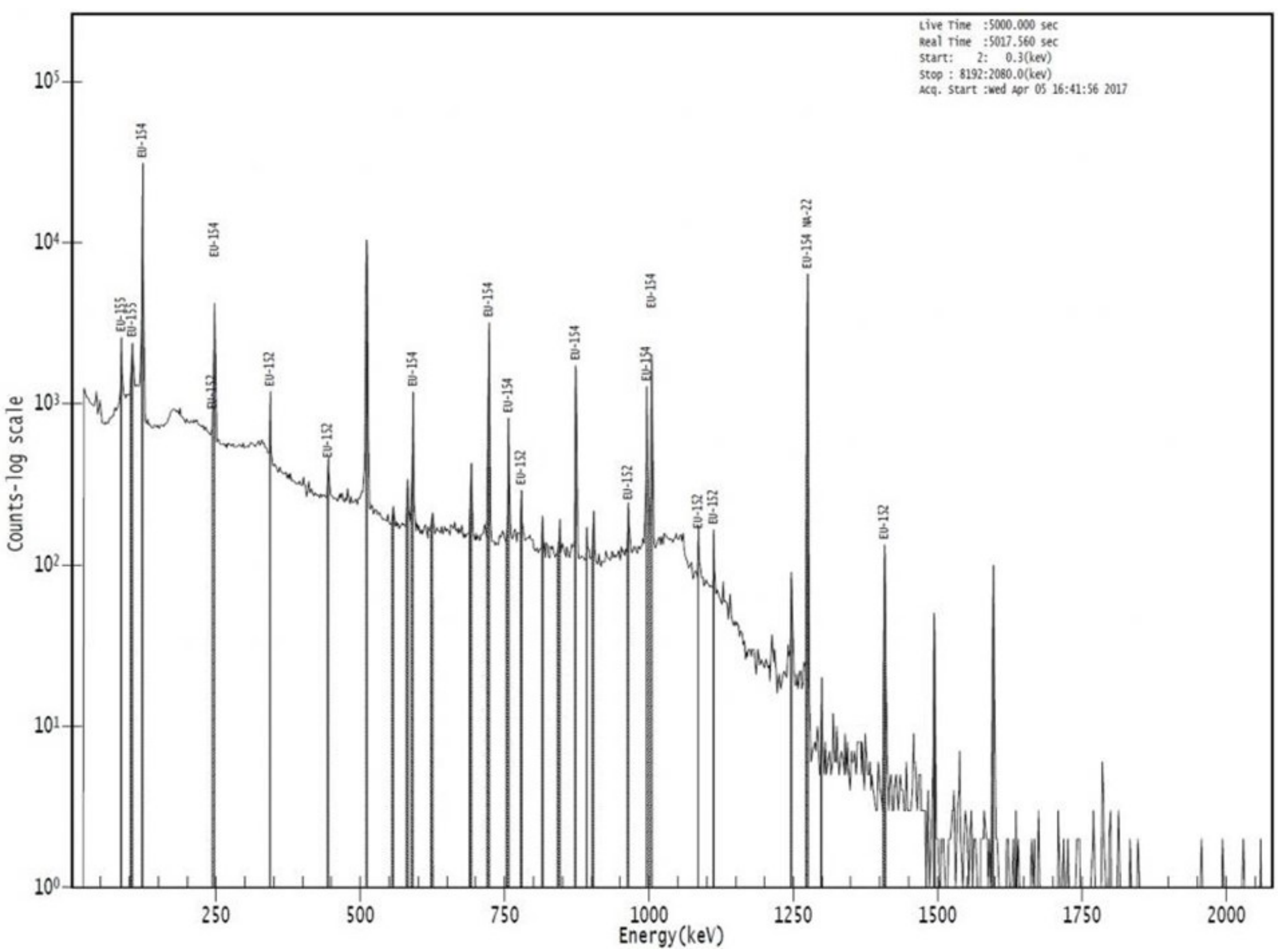
3.8 Gamma-Ray Spectroscopy

The NRL has a gamma-ray spectroscopy system with three high-purity germanium (HPGe) detectors, which is used to identify and quantify radioisotopes in samples. A typical GRSS detector channel consists of a high-purity germanium (HPGe) semiconductor detector, a pre-amplifier, an amplifier, a high-voltage power supply, a multi-channel analyzer (MCA), and a computer-based acquisition and analysis system. In modern systems, many of these components are combined into integrated units. At the NRL, the Canberra Lynx system is employed, which integrates the power supply, digital amplifier, and MCA into a single box. The Lynx units are networked, allowing one computer to control multiple Lynxes.

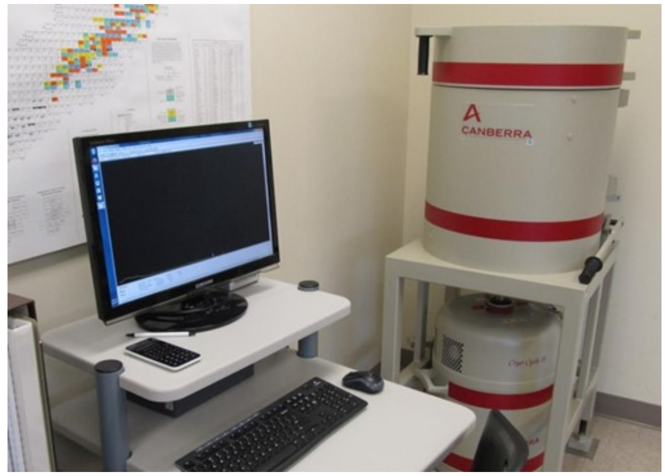
Gamma rays emitted from a radioactive source that are absorbed in the HPGe detector produce electrical pulses, and the pulse amplitude is proportional to the energy deposited in the detector, which allows for measurement of gamma ray energies. The MCA sorts these pulses by amplitude, and computer software displays a plot of the number of pulses received at each pulse amplitude. Such a plot is called a spectrum because it shows the spectrum of energies emitted by the source. Comparison of the peaks found in a spectrum against a library of known radionuclide energies and abundances allows identification of the radioactive components of a sample. If the system efficiency is calibrated using a source with traceable activity, the activity of those radionuclides can be quantified.

Data acquisition and control, as well as quantitative analysis of identified radionuclide activity, is performed by the software package Genie 2000 from Canberra Industries. The software provides for spectrum acquisition, storage, isotope identification, and activity quantification, as well as detector system energy and efficiency calibration.



Example Spectrum Plot

The figure to the right shows a picture of a GRSS system at the NRL. On the desk are the computer used for analysis and display as well as the Lynx MCA (seen behind the keyboard), and to the right is the detector shield that minimizes counts from background radiation and a vacuum dewar filled with liquid nitrogen for keeping the HPGe detector at its operating temperature.

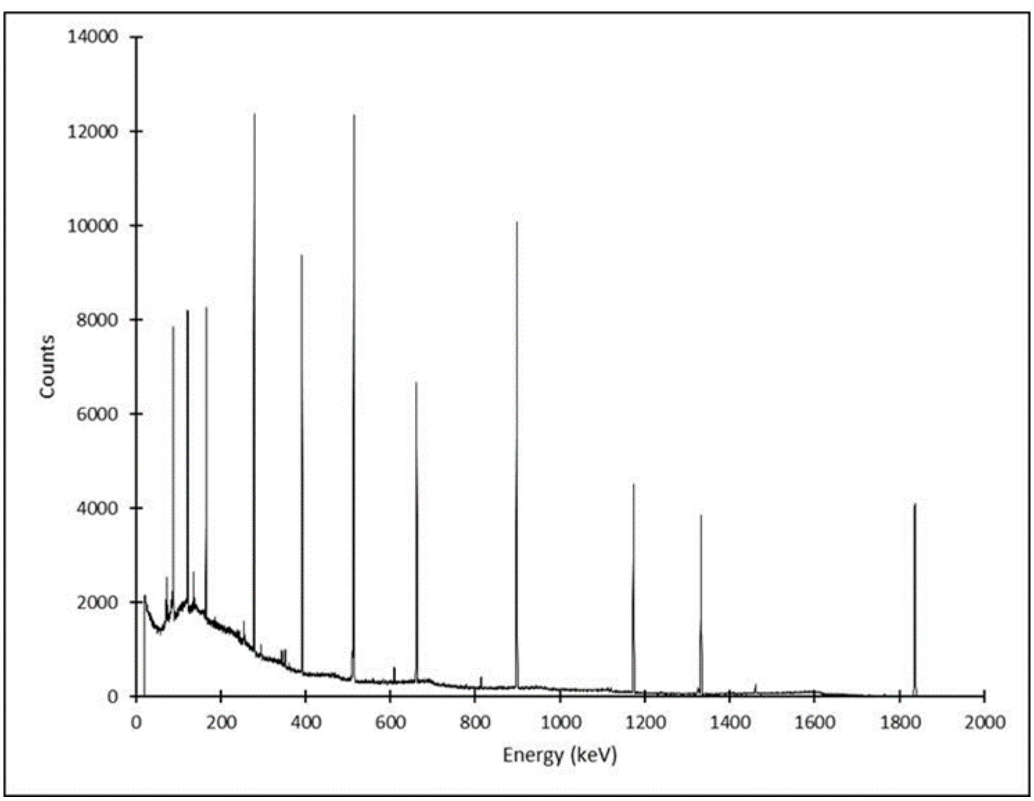


Gamma-ray spectroscopy system setup

GRSS Calibration

Calibration of a gamma-ray spectrometer involves placing a traceable source, often with emissions at multiple gamma-ray energies, in a repeatable position relative to the detector and acquiring a spectrum. Using the measured spectrum in conjunction with the source activity and date from the source calibration certificate, the analysis software computes the efficiency of the detector at each of the source energies for the source in that position. A polynomial curve fit provides an efficiency curve as a function of energy.

The HPGe detectors of the GRSS at the NRL are calibrated using a NIST-traceable mixed-nuclide point source. The first detector is a Canberra GC5019 HPGe, which has an efficiency of 50% relative to a standard 3 inch x 3 inch NaI detector at 1332 keV, and has full width at half max (FWHM) of 1.9 keV for peaks measured at 1332 keV. The second detector is a Canberra GC1419 HPGe, which has an efficiency of 14% relative to a standard 3 inch x 3 inch NaI detector at 1332 keV, and has full width at half max (FWHM) of 1.9 keV for peaks measured at 1332 keV. The third detector is a Canberra GC1420 HPGe, which has an efficiency of 14% relative to a standard 3 inch x 3 inch NaI detector at 1332 keV, and has full width at half max (FWHM) of 2.0 keV for peaks measured at 1332 keV. The calibration source contains nine radionuclides, with gamma emissions ranging from 88 keV to 1836 keV. This provides a calibration curve that covers all the major emissions from 22Na and 154Eu (123 keV - 1596 keV). For each peak in the source, the stated 3-sigma uncertainty (99% confidence) in the emission rate is 3%.



Calculations of sample activity take into account the efficiency of the detector system as a function of energy, the gamma-ray emission probability for the nuclide/energy, and correction for radioactive decay during the count. The figure to the left shows a sample spectrum from the calibration measurement. The nine nuclides result in eleven full-energy peaks.

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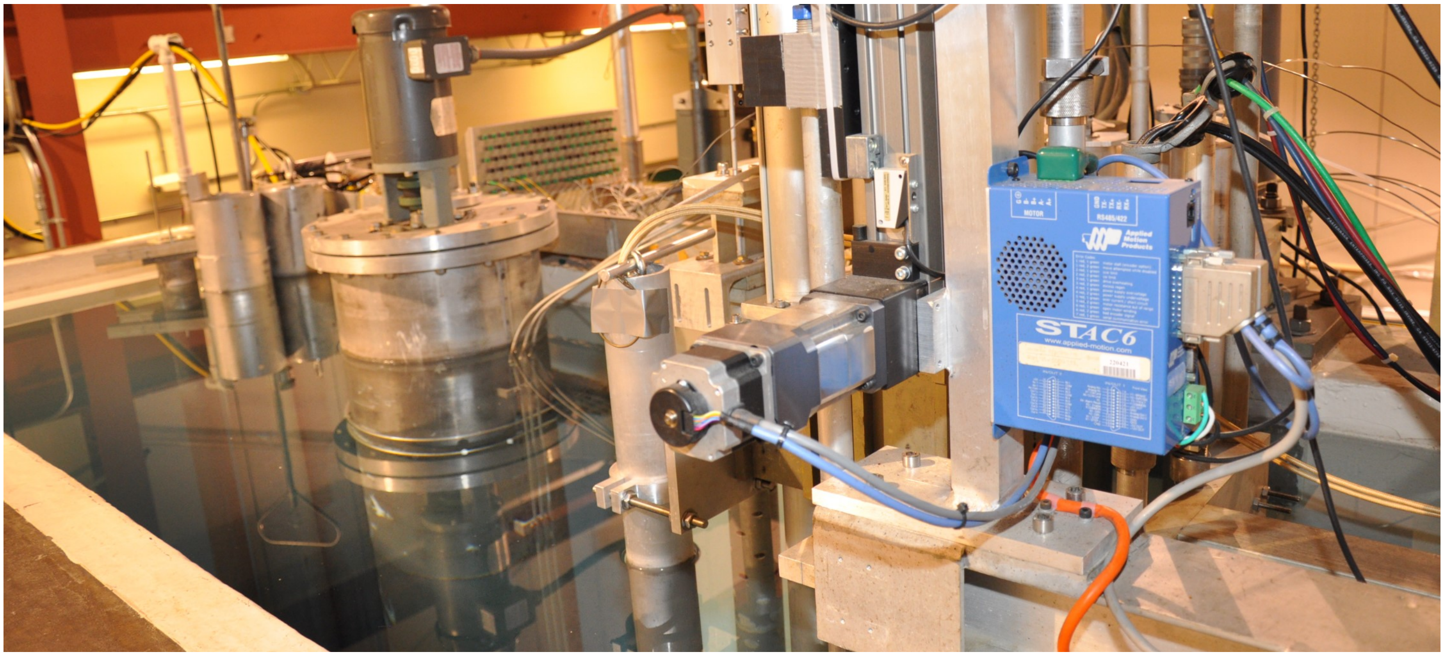
3.9 Other Research Facilities

In addition to the reactor and gamma irradiators, the NRL also has alpha, beta, gamma, and neutron sources available for use in student labs and research; and using the reactor, other types of beta/gamma sources can be created (such as the Sc-46 sources used for the spot irradiator). A range of alpha, beta, gamma, and neutron sensitive detectors are also available for use in in student labs and research.



4. Information for Experimenters

4.1 Laboratory Rules

- All experimenters entering the NRL must sign in at the Visitor's Logbook.
- No security clearance is necessary for experimenters, but persons who have not been granted unescorted access (which includes nearly all experimenters) will be monitored by the laboratory staff. In addition, only laboratory staff may allow persons into the Reactor Building bay.
- Some training (usually a small amount) may be necessary, depending on the experiment.
- Experimenters must follow the NRL Dosimetry Policy and the NRL Personnel Protective Equipment (PPE) Guidelines when working with radioactive samples.
- Experimenters shall not attempt to operate equipment with which they are unfamiliar.
- Eating, drinking, or applying cosmetics or contact lenses is not permitted in the reactor bay. Smoking is not permitted anywhere on campus.
- Per 10 CFR 160, visitors may not bring weapons or explosive materials into the NRL.
- Experimenters should be careful to avoid dropping anything into the pool and should not place items on the pool wall.
- All materials must be monitored for radiation when being removed from the reactor. While the reactor is operating, sample removal or insertion shall be performed only with permission from the reactor operator.
- No damaging materials are allowed near the core.
- Experimenters needing to take pictures of their experimental setup(s) need to have an NRL staff member assist them.
- Bags and packages not left in the lobby will be searched before being brought into the Reactor Building bay.

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4.2 Reactor Based Experiments

Samples

The research reactor provides a mixed-field environment composed of neutrons and photons. We have several facilities that can be used for testing. The size of your samples and the desired fluence will be used to determine which facility would best meet your needs.

When samples are irradiated in the reactor (as opposed to the cobalt facility), they have the potential to become radioactive. It may be necessary to leave the sample at the Reactor Laboratory for some period following the irradiation before it can be returned to you. If you have a license to possess radioactive materials, we would be able to return the sample to you earlier than if you do not.

Lead Time

Lead time will depend heavily upon the requested neutron fluence. If it turns out to be a one-hour test, the lead time would be a couple of weeks. We would have to do a safety analysis where we consider the makeup of the sample and what activity we expect to produce. If it turns out to be a much longer test, the lead time could be a few weeks longer. It would of course depend upon what we already had on our calendar.

Cost

The cost of the experiment will depend upon the desired total fluence, the amount of staff involvement, and the disposition of the samples following the experiment. There are hourly usage rates for the reactor and for staff time, and charges for rad waste. Staff time is used for completing the safety analysis, reactor pre-start and post-shutdown check-outs, experiment installation and removal, rad waste disposal, etc.

The reactor is operated on demand during normal business hours. The maximum operation time is seven hours in a day.

Short irradiations

We are unable to perform short exposures (i.e. a few minutes) in any of the facilities other than the pneumatic tube. The reactor takes ~25 minutes to start up from zero power and it takes ~4 minutes to shut down. We try to keep irradiations to at least 20 minutes so this ramp up and ramp down time doesn't become a significant portion of the fluence delivered. Short irradiations could consider using the pneumatic tube where a vacuum system inserts and extracts samples in sample carriers that have a 1.1-inch opening for precisely-timed irradiations.

As an alternative, we can reduce reactor power. The fluxes that are posted on the website are for a reactor power of 450 kW. The lowest reactor power at which we can operate is 20 W, and the flux scales linearly with power.

Multiple irradiations in any facility other than the pneumatic tube would need to be done on a separate days. There are short-lived nuclides that are created in the samples and in the baskets that need to be allowed to decay before the basket and sample could be removed from the reactor.

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4.3 Experiment Process

The first step in utilizing the reactor is to file a request for reactor operation. That form must be reviewed and approved by another member of our staff prior to performing the experiment. The request form details what is to be done and explains why it will be safe. Answering the following list of questions will go a long way toward creating the request form.

(1) What do you plan to irradiate, and why (damage, doping, etc.)? Which experimental facility do you plan to use? Do you want fast neutrons, thermal neutrons, or both? To what fluence do you expect to irradiate the samples? What power level(s) do you want? How will the samples be encapsulated? Will anything need to be monitored or powered during the test (e.g. sensors)? If so, the devices will need to be fused in case there were to be an electrical short that could impact the reactor.

(2) Will all of the samples be irradiated together? If so, some of the samples with higher cross sections may shield the others. Reactivity effects are generally small for small samples, but some may be an issue if the central irradiation facility (CIF) is used.

(3) A primary consideration will be radiation safety. What is the mass of each sample irradiated and its elemental composition? How pure are the samples? Are there significant trace elements present? Which isotopes will be produced, and in what quantities? The online WISE uranium project has a handy activity calculator for thermal activation. Don't forget about (n,p) and (n,alpha) reactions, if fast neutrons are present. NIST has a calculator that can be used to estimate fast neutron activation.

(4) What dose rates do you expect at the end of irradiation? A common method is to use specific gamma ray constants to estimate dose, but this misses the beta dose. As a general rule, you can expect beta emitters to produce 5 rem/hr per mCi at 10 cm (4 inches). This can add up quickly. Of course, it may also decrease quickly, depending on the half-lives involved. It is a good idea to calculate the dose rate at some times after the end of the irradiation (1 day, 1 week, etc.).

(5) What do you plan to do with the samples after irradiation? If you plan to make measurements on them here, when will they be safe to handle? If you plan to take them back to your facility, how long will you need to wait before they can be shipped? We can ship excepted packages (UN2910) if your facility has a license to possess radioactive materials. Otherwise, the samples will have to decay until they are exempt from that requirement. When shipping a UN2910 package, there are activity limits, but the limiting factor is usually dose rate on contact with the package, which cannot exceed 0.5 mrem/hr.

Once we have enough information to write the request form, it will take at least one week to write the request and have someone else review and approve it. Please allow two weeks for the approval process.

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Miscellaneous Notes

- The depth of the pool is 20' and it is about 16' to the center of the core from the top of the pool. Any cabling that is run from the experiment to the equipment should be ~25-30' in length. Equipment may be set up on the work-bench to the north of the reactor pool. The workbench is 2'x6', but more space can be allocated if needed and arranged with NRL staff.
- Irradiation baskets are available for use in the CIF and the AIF. The ID of the CIF basket is 0.9 inch and the ID of the AIF basket is 2.2 inches. If your sample(s) will not fit within one of these baskets, a rig will have to be machined to hold them. Use aluminum whenever possible for the experiment rig. Steel cannot be used in the reactor as it activates easily. PTFE also cannot be used, as it releases fluorine gas from radiation exposure. Avoid PVC, as it degrades and activates significantly, and avoid anything with chlorine.
- Samples irradiated within the pneumatic transport system facility must fit within a polyethylene bottle with a 1.1 inch ID mouth and a 3.0 inch body.
- Cadmium buttons are also available for use in reducing the thermal neutron component of the flux. The cadmium buttons are made to hold activation foils measuring one-half of an inch in diameter. Larger pieces of cadmium are available and may be used when prearranged with NRL staff.
- The core is 2 feet tall, but there will be some radiation damage to experiments above the core. When possible, leave the lowest five feet of fiber bare.
- Typically, if there is an active heating element, an independent safety mechanism will be necessary to prevent overheating, such as use of a thermocouple near the outer wall of the test rig that is connected to a controller that is independent of the main experiment controller that can cut heater current. In addition, fuses or breakers in line with heater leads are needed to ensure that there cannot be an electric short that could impact the reactor.
- Dosimetry is not typically performed during an experiment. The neutron flux has been measured in the various irradiation facilities; this can be used to calculate the dose rate to which the experiment will be exposed.
- With RG 58 coax cable, a maximum of two cables would fit through the cableway in the shielding plug for the AIF or 7 inch tube. However, if RG 316 coax cable were used, there would be room for quite a few of those in the ca-bleway (6 - 8?).
- The CIF has high reactivity worth, so strong neutron absorbers cannot be put there.
- The CIF is used for regular testing, so it cannot be tied up with an experiment for long periods of time ≈ 1 week.

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4.4 Experiment Design Tips

Below are some miscellaneous tips that should be useful for experimenters.

Materials for reactor-based experiments:

- Materials made from C, O, N, H have minimal activation.
- Use aluminum when possible due to its low cross section, short half-life, strength, and light weight. Alloy 6061 is the best widely-available alloy of aluminum to use for reactor experiments.
- If a high-temperature material is needed, titanium is a better choice than other metals. It will activate significantly more than aluminum, but less than metals such as iron, nickel and chrome.
- Use insulators made from alumina and silica.
- If tape is needed for an experiment, we have found Kapton (polyimide) tape to be the best choice.
- Avoid Fe, Ni, Cr, steel.

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4.5 Co-60 Irradiator Experiments

The cost of the experiment will depend upon the desired total dose and on the amount of staff involvement. There are hourly usage rates for the irradiator and for staff time. Staff time is used for completing any necessary safety analysis, experiment installation(s) and removal(s), etc.

Cobalt irradiators vary widely in design. Not every irradiation can be performed at our facility. Please note the following considerations:

(1) What total dose do you need? Our current max dose rate is around 20 krad/hr in silicon. If your project requires megarads, our facility may not be a good fit.

(2) Will the samples physically fit in our irradiation space? We have a 6 inch access tube. The max diameter is ~4 inches, and the peak dose rate is only a couple inches in height. If you are looking to irradiate gallons of milk, they will not fit. Tall samples that do fit will get more dose in the middle than on the ends. If you have a large number of samples, you may need to plan for multiple irradiations, given the size of the sample space.

(3) Are these samples hazardous in any way? Our lab has a campus permit for radioactive materials (obviously), but we are not trained to handle biological hazards.

(4) Do your samples require any environmental control? Our irradiator is located in the reactor bay, which has minimal heat in the winter and no A/C in the summer.

Miscellaneous Notes

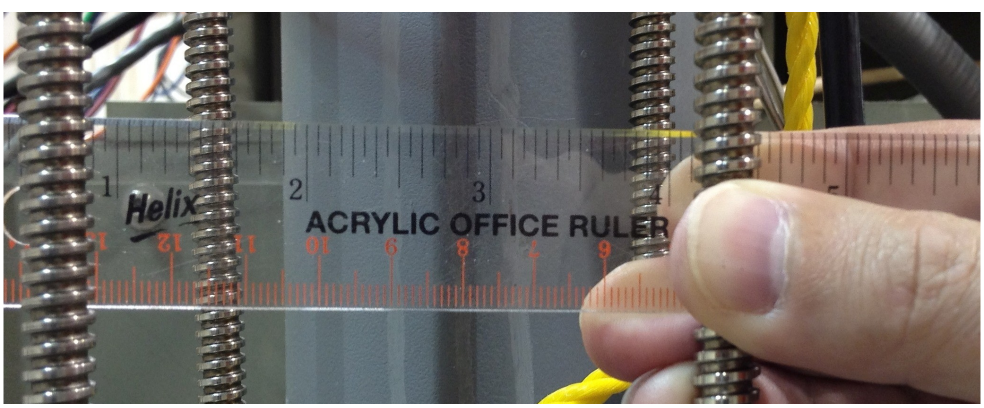
The depth of the pool is 15'8" and it is about 16' from the top of the irradiation facility to the bottom. Any cabling that is run from the experiment to the equipment should be ~20-25' in length. Equipment will be set up on the west side of the BSF pool. There is a board on the pool grates that can be used for experiment equipment. The board is 4'x6', but more space can be allocated if needed and arranged with NRL staff.

Irradiating with gamma rays does not make a sample radioactive, so the sample will be returned to you following the experiment.

Dosimetry can be added to the experiment for an additional charge.

With RG 58 coax cable, a maximum of three cables would fit through the cableways in the shielding plug. However, if RG 316 coax cable were used, there would be room for quite a few of those in the cableways (6 - 8?).

If tape is needed for an experiment, we have found Kapton (polyimide) tape to be the best choice.



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4.6 Publication Acknowledgements

The Ohio State University Nuclear Reactor Laboratory staff is pleased to participate in meaningful research in the nuclear field. Should researchers publish any of results based on experiments or otherwise make publicly available the results of the work conducted at NRL, we respectfully request the following acknowledgment is included:

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