NUCLEAR REACTOR PROGRAM
PULSTAR REACTOR USER FACILITIES

The PULSTAR reactor and supporting laboratories currently offer the following capabilities:

- Neutron Powder Diffraction Facility (NPDF)
- Neutron Imaging Facility (NIF)
- Intense Positron Source Facility (IPS)
- Ultra-Cold Neutron Source
- PULSTAR Internet Reactor Laboratory
- Neutron Activation Analysis
- Isotope Production
- Reactor Irradiations

There are dedicated facilities for each of the above applications (See Table 1 below). The Neutron Diffraction Facility is installed in beamport #4, The Neutron Imaging Facility is installed in beamport #5, the Intense Positron Source assembly is installed in beamport #6, and the Ultra-Cold Neutron source, under development, is installed in the reactor "thermal column" region. Internet Reactor Laboratory exercises are hosted from the PULSTAR control room utilizing video-conferencing and online real-time data acquisition systems. In-pool irradiation facilities are utilized for Neutron Activation Analysis, Isotope Production, and other irradiation and instrumentation testing projects.

User Facility Descriptions:

1. Neutron Powder Diffraction Facility

The Neutron Powder Diffraction facility (NPDF) is installed at beamport #4 of the PULSTAR reactor, which provides a nominal source flux of 3 x 10^{12} n/cm^2/sec at 1 MW. The instrument uses a bent, perfect single crystal silicon, doubly focusing monochromator to extract a 1.4 Å beam. Other wavelengths, 2.3 Å, 1.17 Å, 1.76 Å, and 1.07 Å can be obtained at lower flux on sample. The beam is focused on the specimen position both vertically and horizontally. The diffractometer uses a 15-element linear position sensitive Helium-3 detector array that captures a 20 degree segment of the diffraction pattern at each position of the detector shield. The entire 5 degree to 105 degree diffraction pattern is obtained by rotating the detector assembly in steps. The NPDF is optimized for analysis of small volume specimens typically employing a 3 mm x 50 mm sample container and less than 1 g of specimen.

Instrument Layout

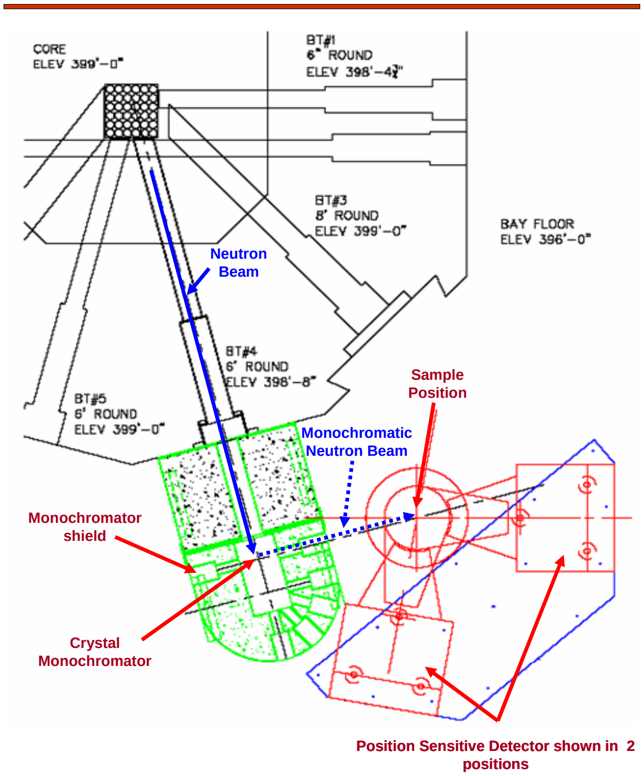


Table 1
PULSTAR Reactor Facilities / Capabilities

Facility / Capability	Description / Status	Intensity
Rotating Exposure Ports (4 in-pool, ex-core)	2.5” ID wet sample irradiation terminus.	1.0×10^{13} thermal n/cm^2/sec 1.0×10^{12} fast n/cm^2/sec
Dry Exposure Ports (2 in-pool, ex-core)	1.25” ID dry sample irradiation terminus.	4.0×10^{12} thermal n/cm^2/sec 1.0×10^{11} fast n/cm^2/sec
Pneumatic Terminus (1 in-pool, ex-core)	1.25” ID fast rabbit sample transfer system	1.0×10^{13} thermal n/cm^2/sec 1.0×10^{12} fast n/cm^2/sec
Pool Standpipes (4 in-pool, ex-core)	3.5” ID dry sample irradiation positions	1.0×10^{11} thermal n/cm^2/sec 5.0×10^{9} fast n/cm^2/sec
Beamport #1	6-in. diameter radial tube	1.0×10^{12} thermal n/cm^2/sec at core end
Beamport #2	6-in. diameter tangential ‘through’ tube	1.0×10^{12} thermal n/cm^2/sec at centerpoint
Beamport #3	8-in. diameter radial tube	1.0×10^{12} thermal n/cm^2/sec at core end
Beamport #4 - Neutron Powder Diffraction Facility (NPDF)	6-in. diameter radial tube; NDF facility installed.	~ 0.5×10^{5} 1.4 Å n/cm^2/sec on target
Beamport #5 - Neutron Imaging Facility (NIF)	6-in. diameter radial tube; NIF facility installed.	~ 5.0×10^{6} thermal n/cm^2/sec at 6.5 meter imaging plane.
Beamport #6 - Intense Positron Source (IPS)	12 in. by 12 in. sq. radial tube; IPS moderator assembly and beam transport system installed.	6×10^{8} positrons/second at target; beam spot diameter is 25 mm; e^{+} energy variable up to 30 keV
Thermal Column – Ultra-Cold Neutron Source (UCN)	5’×5’×7’ cavity in biologic shield adjacent to reactor core. Cryogenic plant installed.	Projected intensity of 6 to 16 million UCN’s per second.
PULSTAR Internet Reactor Laboratory	Video conferencing system (Polycom VS4000) located in PULSTAR control room with remote operation of cameras directed at console instruments. Online reactor experiment data acquisition system.	

Table 2. Comparison of NCSU NPDF with other major neutron diffraction facilities.

Facility	Power (MW)	Source ϕ (n/cm^2s)	Sample Size	Sample ϕ (n/cm^2s)
NIST BT-1 Cu-311/15'	20	4×10^{14}	10 cm^3	4×10^5
NIST BT-1 Cu-311/7'	20	6×10^{14}	10 cm^3	2×10^5
MURR PSD-II	10	6×10^{13}	0.35 cm^3 1 cm^3	1.35×10^5
NCSU	1	2.7×10^{12}	0.35 cm^3 1 cm^3	0.64×10^5

2. Neutron Imaging Facility

The Neutron Imaging Facility (NIF) is installed at beamport #5 of the PULSTAR reactor, which provides a nominal source flux of 2.5×10^{12} $n/cm^2/sec$ at 1 MW. The beam is collimated and filtered with 12 inches of single crystal sapphire. The current aperture is a 1.44"×1.75" (1.8" effective diameter) rectangular cross section opening in a BORAL plate, which yields an L/D ratio of ~140 at the 6.5 meter imaging plane (see Table 3). The resolution of the system is ~ 33 μm for conventional radiographic film. Measurements using ASTM standards show that the NIF achieves a beam quality classification of I^A.

Imaging techniques available include conventional film, molecular phosphor digital imaging plates, and real-time Micro-Channel Plate and Thompson Tube imaging systems. Neutron tomographic measurement may be made utilizing a motorized sample positioning system in concert with real-time imaging systems.

Beam tube #5 – cutaway view of NIF collimator assembly

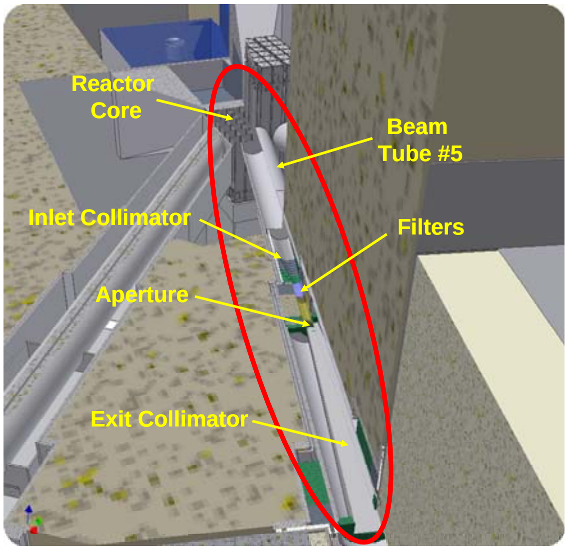


Table 3. Parameters of the Thermal Neutron Imaging Facility (NIF)

Parameter	Value
Neutron Flux	$1.8x10^6$ to $7x10^6$ $n/cm^2/sec$
TNC	~ 70%
N/G	$4.43x10^4$ to $1.34x10^6$ $cm^{-2}mR^{-1}$
L/D	100 to 150
Divergence	~2.29°
Cd Ratio	~450
Scatter Content	~1.8%

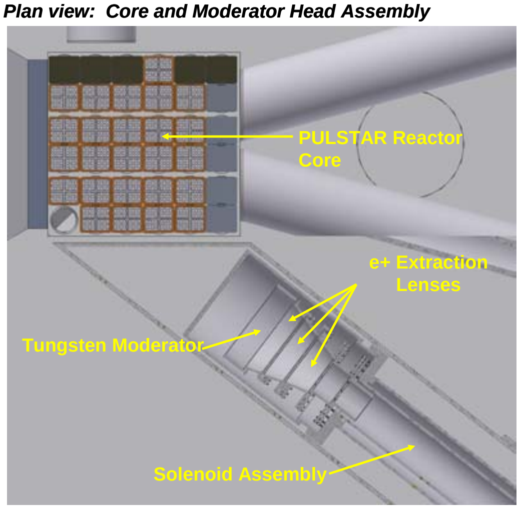
Examples of Neutron Imaging applications performed at NCSU:

- Coolant channel blockage in aircraft turbine blades
- Water transport in operating PEM Fuel cell
- Plant root growth in soil plaques (*in-situ*)
- Cracks in metal castings
- Spray pattern from fuel injector nozzle
- Tomographic imaging of defects in Ti-6-4 prototype aircraft structural component.

3. Intense Positron Source

The Intense Positron Source (IPS) is installed in beamport #6 of the PULSTAR Reactor. Positrons are produced through pair production in a tungsten converter irradiated by high energy gammas from the reactor core, and from neutron capture in a cadmium end-cap surrounding the source (*see inset plan view diagram*). Positrons emitted from the tungsten with kinetic energies of a few eV are accelerated to around 1 keV and focused electrostatically into a solenoidal magnetic field for transport out of the bio-shield. The IPS delivers a 25mm diameter beam with an intensity of **6×10^8 positrons/second**, with a positron energy variable up to 30 keV. The beam is transported through two magnetic switches and into adjacent labs that will house two positron lifetime spectrometers, now under construction.

Plan view: Core and Moderator Head Assembly



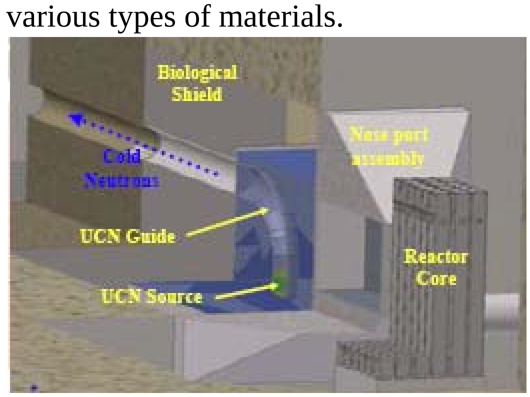
The first instrument, a Positron Annihilation Lifetime Spectrometer (PALS), uses a time varying electric fields to bunch positrons onto sub-nanosecond pulses (*rep rate of 50 MHz, time resolution of 100 ps)* for positron lifetime studies in materials such as semiconductors and metals.

The second instrument, a Positronium - Positron Annihilation Lifetime Spectrometer (Ps-PALS), uses secondary electrons from the target for timing (*1 ns time resolution*) and will be used to study positronium lifetimes in porous materials such as low-k thin films.

In addition to the positron beam described above, a Na-22 based bulk PALS system is also currently operational at the PULSTAR reactor. This system can be used for the studying porosity (or void) concentration, size, connectivity etc. in various types of materials.

4. Ultra Cold Neutron Source

The PULSTAR Ultracold Neutron Source (UCN) is designed to produce neutrons with energies below about 300 nano-electron volts, or below temperatures of about 3 mK. These neutrons behave similar to light, in that they can reflect off of some material surfaces for any angle of incidence and therefore can be guided and stored in material



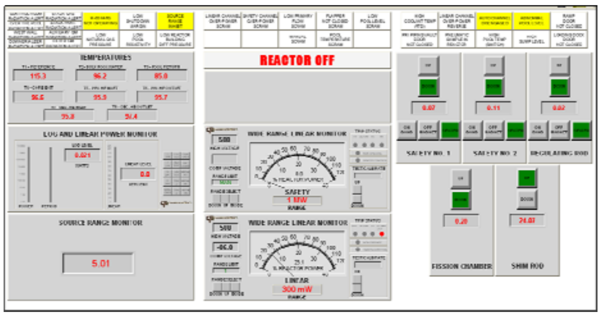
bottles. Although ultracold neutrons are used primarily for fundamental physics studies of the properties of the neutron, they also have some application for non-destructive surface studies, an active area of research for the faculty at NCSU.

A graphite-lined nose port is used to couple the reactor face to the moderator geometry in the thermal column, where the source will be located. This geometry ensures minimal heating for the cryogenic source materials due to gamma-rays and fast neutrons from the reactor core. The source itself is composed of one liter of solid deuterium, placed in an ultracold neutron guide held below 5K, inside of a nested set of thermal and cold moderators. Ultracold neutrons are produced in the deuterium and then guided to experiments.

Initial estimates for the number of ultracold neutrons produced range from about 6 million to 16 million per second, resulting in world class UCN densities comparable to those available at the strongest UCN facility in the world, at the Institut Laue Langevin in Grenoble, France.

5. PULSTAR Internet Reactor Laboratory

Distance Learning Laboratories are hosted from the PULSTAR reactor control room. Video conferencing and online reactor instrumentation and data acquisition systems are utilized to provide reactor laboratory sessions to students at other academic institutions. This capability enriches academic programs where reactors are not available, and may be used to expand the educational opportunities for nuclear engineering students throughout the United States.

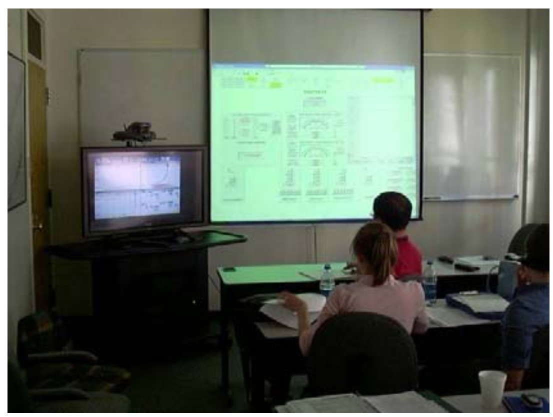


A view of the virtual reactor console used by the off-site students. The virtual console is connected through the internet to the PULSTAR console.

Distance learning laboratory participants are able to interact with reactor facility personnel through direct video and audio communication links, and have the ability to direct remote control cameras in the PULSTAR control room. An online data acquisition system is utilized to provide real time visualization of the reactor operating parameters, and for collecting experimental data.

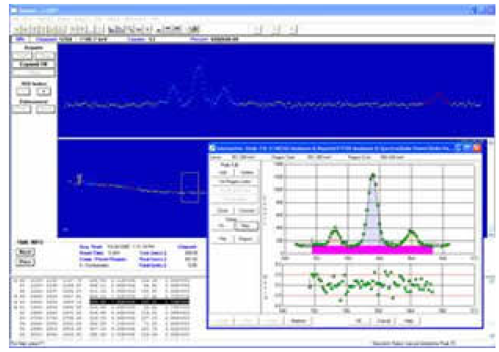
Examples of distance laboratory sessions available include;

- 1/M Reactor Startup
- Control Rod Calibration
- Moderator Temperature Reactivity Coefficient
- Axial Flux Mapping of a fuel channel
- Doppler Reactivity Coefficient



Students collecting and analyzing PULSTAR data during a lab session at Georgia Institute of Technology.

6. Neutron Activation Analysis:



The NAA laboratory utilizes the PULSTAR Reactor as an intense neutron source for the irradiation of client samples. During neutron irradiation, certain stable isotopes of elements that constitute the samples are transformed into radioactive isotopes by neutron capture. Activated trace 'radioisotopes' (e.g. As-76, Hg-197, Se-75, etc…) contained in the samples are analyzed and quantified by utilizing gamma spectrometry systems to measure gamma ray decay signatures. Certified elemental standards, traceable standard reference material (SRM) controls, method blanks, and sample duplicates are processed along with client samples to maintain a high degree of quality assurance.

<u>Advantages of using INAA for trace element analysis</u>:

- It is a multi-element technique **c**apable of determining approximately 65 elements in many types of materials;
- It is non-destructive and therefore, does not suffer from the errors associated with yield determinations;
- It has very high sensitivities for most of the elements that can be determined by INAA - most detection limits range from ~0.05 to ~50 ppm (≤ 1 ppb for some high-purity materials)

- It is highly precise and accurate;
- It permits the analysis of samples ranging in volume from 0.1 ml to 20 ml, and in mass from ~0.001 gram to 10 grams depending on sample density.
- Samples for INAA can be solids, liquids, gases, mixtures, and suspensions.

Examples of sample matrices previously analyzed at NCSU include:

- biological organs and tissues from laboratory research animals and fish
- coal, crude oil, diesel fuel
- fertilizer
- forensic investigation samples (e.g. fibers, tissue, hair, bullets)
- graphite
- geologic specimens
- human nails, urine and hair
- industrial process samples (e.g. hydrocarbons, silicon based materials)
- river and tailing pond sediment
- silicon wafers
- textile fibers

7. Isotope Production:

Radioisotopes have various research and industrial applications. The PULSTAR reactor is available to produce millicurie quantities of many radioisotopes for approved, licensed use. Examples of isotopes that have been produced at NCSU include: Au-198, Br-82, Co-60, K-42, Mn-56, Na-24, and Sb-124.

Typical uses of radioisotopes include research in medicine, life sciences, and industrial processes. As an alternative to the direct use of radioactive materials in some applications, stable tracers that incorporate elements such as gold, samarium, indium, and gadolinium can be formulated, introduced into processes, and concentrations subsequently determined via neutron activation analysis.

8. Reactor Irradiations:

The irradiation of materials, samples, and nuclear instrumentation may be carried out in any one of the numerous penetrations adjacent to the PULSTAR reactor core *(see listed in Table I above)*. Existing penetrations range in inner diameter from 1.25 inches to 8 inches, and have varying neutron and gamma energy spectra and intensities.

In addition to those irradiation facilities already available, custom experimental facilities can be developed to accommodate different experiment geometries and spectral requirements.

Examples of irradiation projects include:

- Measuring radiation damage in fiber optic stress sensors.
- Transmutation doping of Silicon wafers.
- Accelerated lifetime testing of ex-core neutron compensated ion chambers.
- Calibration of in-core neutron fission chambers.
- Radiation hardness testing of electronic nuclear instrumentation modules.