Abstract

The capability to perform neutron radiography and computed tomography is being developed at Oak Ridge National Laboratory. The facility will be located at the High Flux Isotope Reactor (HFIR), which has one of the highest steady state neutron fluxes of any reactor in the world. Neutrons are quite penetrating in most engineering materials and can be useful to detect internal flaws and features. Hydrogen atoms, such as in a hydrocarbon fuel, lubricant or a metal hydride, are relatively opaque to neutron transmission. Thus, neutron based tomography or radiography is ideal to image the presence of hydrogenous materials within engineering structures. The Monte Carlo N-Particle transport code (MCNP), versions 4A and 4B, has been used extensively in the design phase of the facility to predict and optimize the operating characteristics, and to ensure the safety of personnel working in and around the blockhouse. The HFIR source flux provides unparalleled opportunity for future upgrades, including real-time radiography for analysis of dynamic processes. A novel tomography detector has been designed using optical fibers and digital technology to provide a large dynamic range for tomographic reconstructions. Film radiography is also available for high resolution imaging applications. This paper summarizes the results of the design phase of this facility and the potential benefits to science and industry.
This document was presented at the Denver X-ray Conference (DXC) on Applications of X-ray Analysis.

Sponsored by the International Centre for Diffraction Data (ICDD).

This document is provided by ICDD in cooperation with the authors and presenters of the DXC for the express purpose of educating the scientific community.

*All copyrights for the document are retained by ICDD.*

Usage is restricted for the purposes of education and scientific research.

**DXC Website**  
– [www.dxcicdd.com](http://www.dxcicdd.com)

**ICDD Website**  
- [www.icdd.com](http://www.icdd.com)
Introduction

The nuclear interactions of neutrons with materials are different from the electromagnetic and photoelectric x-ray interactions, and as such can be used in complementary or unique ways for the nondestructive examination of materials. While x-ray interactions are dominated by the photoelectric effect, and thus dependent on the atomic number of the element, neutron interactions with matter are dependent on the nuclear state of the target nuclei. The result is that while the interaction probability for x-rays generally increases steadily with the atomic number of the target atom, there is no proportionality to atomic number which governs the interaction probability for a neutron. Neighboring elements and even different isotopes of the same element can have very different neutron attenuation coefficients. One application of the uniqueness of neutron interactions is in the detection of hydrogenous material within engineering materials and structures. Most metals typically used for manufacturing purposes are readily penetrated by neutrons, surpassing even the maximum depth of high energy x-rays, while hydrogen atoms have a high probability of scattering neutrons out of the incident beam.

The concept for the Neutron Computed Tomography and Radiography Facility (NCTRF) was proposed as one part of a Laboratory Directed Research and Development project aimed at adding new capabilities to the neutron scattering and diffraction programs already in place at ORNL. Film radiography would be available for high resolution applications, while a novel computed tomography system would be developed for characterizing the internal structure of objects. The applications for such a facility include void and inclusion detection in castings and weldments, hydrocarbon location, water migration in materials (percolation, absorption, etc.), and nondestructive detection of corrosion and manufacturing defects.

Design Goals

The key issues in the design of any facility for neutron imaging include the neutron flux, the L/D ratio, the thermal-to-fast neutron flux ratio (also called the cadmium ratio), the thermal neutron-to-gamma ratio, the flux uniformity, and the imaging method. The parameters most important to the quality of the image data are the L/D ratio, the ratio of the length of the collimator to the diameter of the aperture, a measure of the divergence of the beam, and an indicator of the amount of blurring that will be present in the resulting images, and the thermal neutron-to-gamma ratio, an indicator of
Figure 2. Drawings showing the layout of the HFIR core and the four HB and EF facilities, plan view (left), vertical section (right).

the relative contribution of the gammas to the image data. The layout of a typical neutron radiography facility is shown in Figure 1. Optimization is usually constrained by the source type, as well as by the means available to bring the neutrons from the source to the desired location. The goal of this work was to optimize the beam parameters and provide the maximum possible flux to permit high resolution imaging with exceptional dynamic range. Due to the large amount of beryllium present around the core and the indirect path that neutrons must follow to enter the experiment room at the end of EF-1, the neutron flux is expected to be highly thermalized and should produce a beam with a very high cadmium ratio and a thermal neutron-to-gamma ratio greater than $1 \times 10^6 \text{ n/cm}^2\text{-mR}$. Based on the geometry of the system, it is expected that the beam will have an I/D ratio greater than 100 and, due to the flux distribution shaping which can be done with the lead/bismuth filter, provide a reasonably flat flux profile. Helium will also be used as a fill gas to limit the beam attenuation from air scattering and cleanup plates made with cadmium and borated aluminum have been designed to remove any scattered neutrons or neutrons that are not well collimated from the source.

The High Flux Isotope Reactor has numerous beam facilities available for research. There are four horizontal beam (HB) tubes, primarily used for neutron scattering experiments, and four engineering facility (EF) tubes, which are slant tubes passing by the core at the periphery of the beryllium reflector (Figure 2). These EF tubes are inclined at a forty-nine degree angle from the horizontal plane and enter one floor above the reactor and HB experiment hall. The angle of the EF tubes has limited these beams to certain specialized experiments and activation analysis work. In October, 1995, a Laboratory Directed Research and Development proposal was submitted with one part devoted to installing a neutron computed tomography and radiography facility at HFIR. Since
all of the HB tubes were already in use, the decision was made to use one of the available EF slant tubes (Figure 3). The choice provided the maximum flexibility for optimizing the key features listed above without interfering with the operation of any of the established facilities.

**Monte Carlo Models**

Monte Carlo models were used to optimize the parameters important to the NCTRF. An existing model of the High Flux Isotope Reactor was modified to include transport through the EF tube that was selected for the NCTRF. Initial runs were performed with MCNP to benchmark the measured flux levels recorded in the EF tube against various other known values in other regions of the core. These results were compared with prior models and experimental data to verify their accuracy. The initial runs were then used to generate surface source files which could be used in subsequent calculations. This greatly reduced the time required to generate adequate statistics for the tallies at the end of the beam tube.

The first simulations run constituted a sensitivity study to determine the optimum position and shape of the beryllium scattering block in the EF-1 thimble which would maximize the delivered flux at the exit point of the collimator. The ideal position for the beryllium block was found to be with the top of the block slightly above or right at the centerline of the core while the effect of shaping the end of the beryllium was found to be negligible. These simulations showed that this configuration would deliver an unfiltered beam flux at the exit plane of the collimator of approximately $4 \times 10^9$ n/cm$^2$-s with a neutron-to-gamma ratio of $2 \times 10^6$ n/cm$^2$-mR. A bismuth "lens" was then added to shape and filter the beam, and it was shown that the collimator design could produce a ten inch diameter beam with a flux around $2 \times 10^9$ n/cm$^2$-s with a variation of less than five percent in intensity from the center to the edge of the beam, and a neutron-to-gamma ratio of $4 \times 10^6$ n/cm$^2$-mR. However, further simulations in the experiment room indicated that the required shield
Figure 4. A diagram of the MCNP4B model of the collimator and details of the scattering block, the lead/bismuth filter and pressure boundary, and the cleanup plates.

for such a beam would exceed the floor loading limit.

Modifications were made to the collimator design based on the allowable floor loading (without reinforcement) and the available resources for shielding. The filter was changed to a lead/bismuth combination with the lead part of the filter closest to the core. Shielding and beam strength were balanced with a filter thickness that gave a flux at the collimator exit of approximately $1 \times 10^7$ n/cm$^2$-s, as it was determined that the floor would support an adequate amount of shielding to contain a beam of this strength. The beam flux distribution was shaped by placing a small hemisphere of bismuth at the top of the filter to provide uniformity. This had the added benefit of increasing the neutron-to-gamma ratio at the exit point of the collimator to $1 \times 10^7$ n/cm$^2$-mR. A diagram of the collimator model is shown in Figure 4.

Prototype Facility

The NCTRF is expected to be available for testing and users in early 1998. Two different imaging methods will be available for research applications in the prototype facility. Film radiography will be performed for high resolution applications using a gadolinium conversion screen and aluminum film cassette. The tomography detector is nearing completion and will have 96 pixel elements, each a one by one millimeter square Li$^6$F/ZnS scintillator cube coupled to an optic fiber, which will carry the

Figure 5. The layout of the Neutron Computed Tomography and Radiography Facility.
signal from the detection array to a diode array detector outside the blockhouse. Each element will have its own 32-bit counter to provide superior dynamic range.

The design of the facility provides for a fast shutter for accurate exposure control, as well as a slow shutter and shielded turntable to permit personnel access without the necessity of filling the collimator with water (Figure 5). The sample positioning device is a large 4-axis unit designed to hold and maneuver an object weighing up to 100 kg at the required 49 degree tilt of the beam with a movement range of twelve inches along each axis and a full 360 degree rotation capability (Figure 6) The table was designed with the specific requirement that none of its components would extend above the plane of the sample mounting table.

**Conclusions**

A new Neutron Computed Tomography and Radiography Facility is under construction at the High Flux Isotope Reactor at Oak Ridge National Laboratory. The facility will provide routine film radiography for high resolution applications and will utilize a novel fiber-based detector system for neutron computed tomography. The design of the collimator also provides a straightforward avenue for increasing the beam flux once shielding issues are resolved by reinforcing the floor.

The Monte Carlo N-Particle transport code (MCNP) has been an invaluable tool in the analysis of the beam characteristics and instrument performance. This experience will provide significant insights for the design and construction of future facilities and instruments.

**References**