Performing health physics and radiation safety functions under a special nuclear material license and a research and test reactor license at a major government research and development laboratory encompasses many elements not encountered by industrial, general, or broad scope licenses.

Reactor Health Physics Operations at the NIST Center for Neutron Research

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Abstract: *Performing health physics and radiation safety functions under a special nuclear material license and a research and test reactor license at a major government research and development laboratory encompasses many elements not encountered by industrial, general, or broad scope licenses. This article reviews elements of the health physics and radiation safety program at the NIST Center for Neutron Research, including the early history and discovery of the neutron, applications of neutron research, reactor overview, safety and security of radiation sources and radioactive material, and general health physics procedures. These comprise precautions and control of tritium, training program, neutron beam sample processing, laboratory audits, inventory and leak tests, meter calibration, repair and evaluation, radioactive waste management, and emergency response. In addition, the radiation monitoring systems will be reviewed including confinement building monitoring, ventilation filter radiation monitors, secondary coolant monitors, gaseous fission product monitors, gas monitors, ventilation tritium monitor, and the plant effluent monitor systems. Health Phys. 108 (Supplement 1):S19–S28; 2015*

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Key words: *operational topics; instrumentation; neutrons; reactor, nuclear*

INTRODUCTION

The National Institute of Standards and Technology (NIST) NIST Center for Neutron Research (NCNR) is part of NIST at Gaithersburg, Maryland. The efforts at NCNR focus on providing neutron measurement capabilities to the U.S. research community. The NCNR is a national research center that uses thermal neutrons and cold neutrons, offering facility instrumentation for qualified applicants. Many of the instruments rely on intense beams of cold neutrons emanating from an advanced liquid hydrogen moderator (Cappelletti et al. 2001).

Neutron beams at the NCNR have the characteristics of being small in size (cross-section typically less than 2 cm × 4 cm), high intrabeam dose rates (may be greater than 1 Sv h^{-1}), and low dose rates outside the beam. Control measures at NCNR include signage on entrance doors for areas that contain neutron beams. The neutron beam areas are High Radiation Areas as defined by U.S. Nuclear Regulatory Commission (U.S. NRC) 10 CFR 20 (U.S. NRC 2013). Every neutron beam area has similar identifying features including neutron beam "On or Off" signs, posted neutron beam warning signs, and alarming infrared proximity detectors (NCRP 1971).

Neutrons are powerful probes of the structure and dynamics of materials ranging from molecules inserted into membranes that mimic cell walls to protons that migrate through fuel cells. The unique properties of neutrons can be exploited by a variety of measurement techniques to provide information not available by other means.

At the NCNR, neutrons reveal properties not available to other probes used in scientific research. Neutrons can behave like microscopic magnets, can diffract like waves, or set particles into motion as the neutrons recoil from the particles. Wavelengths of neutrons range from ≈0.01 nm (thermal) to ≈1.5 nm (cold) (1 nm = 10 Å), allowing them to form observable ripple patterns from structures as

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large as proteins to as small as atoms (Cappelletti et al. 2001). Neutron energies are on the scale of millielectronvolts, the same as the motions of atoms in solids or liquids, waves in magnetic materials or vibrations in molecules. Exchanges of energy between neutrons and matter as small as nanoelectronvolts and as large as tenths of electronvolts can be detected. Selectivity in scattering power varies from nucleus to nucleus almost randomly. Specific isotopes can stand out from other isotopes, even of the same kind of atom. Specific light atoms, difficult to observe with x rays, are revealed by neutrons. Hydrogen, especially, can be distinguished from chemically equivalent deuterium. Magnetism makes the neutron sensitive to the magnetic spins of both nuclei and electrons, allowing the behavior of ordinary and exotic magnets to be detailed precisely. Neutrality of the uncharged neutrons allows the neutrons to penetrate deeply without destroying samples and pass through walls controlling a sample's environment allowing measurements under extreme conditions. Properties ranging from residual stresses in steel girders to the unfolding motions of proteins are amenable to measurement by neutrons. The characteristic radiation emanating from specific nuclei will capture incident neutrons and these can be used to identify and quantify minute amounts of material in pollutants or ancient pottery shards (Cappelletti et al. 2001).

Neutrons are particularly well suited to investigate all forms of magnetic materials such as computer storage and memory devices. The atomic motion of hydrogen can be measured and monitored (in your mind's eye: picture water molecules during the setting of cement). Residual stresses trapped inside stamped steel automobile parts can be mapped. Neutron-based research covers a broad spectrum of disciplines, including engineering, biology, materials science, polymers, geology, chemistry, and physics.

The NCNR's neutron source provides intense beams of neutrons required for these measurements. In addition to the thermal energy neutron beams from the heavy water moderator, the NCNR has a liquid hydrogen moderator (cold source) that supplies intense neutron beams for high resolution research at the cold neutron facility.

There are 28 experiment stations that provide high neutron flux positions for irradiation, and neutron beam facilities used mostly for neutron scattering research.

The NCNR provides neutron research facilities for researchers from industry, university, and government agencies. These facilities are operated with many different modes of access. The facility has major instruments available either via a scientific proposal review program, collaborative research with a NCNR research scientist, or on a commercial basis for confidential R&D. There is no access charge for research for which results are freely available to the general public. A monetary assistance program is available to encourage first-time users to do measurements at our facility.

The NCNR supports important NIST research needs, and is also operated as a major national user facility with merit-based access made available to the entire U.S. technological community. Every year, more than 2,000 research participants from across the country, including industry, academia, and government use the facility for measurements. Access is gained through a peer-reviewed, web-based proposal system with beam time allocated twice a year by the Beam Time Allocation Committee (Cappelletti et al. 2001).

The mission at NCNR is threefold:

1. Safely operate the NCNR as a cost-effective national resource;
2. Conduct broad research programs using neutron techniques, and to develop and apply new neutron measurement techniques; and
3. Operate the NCNR as a national resource for researchers from industry, university and government agencies.

Reactor overview

The 20 MW NIST research reactor provides a source for neutron scattering techniques. The Neutron-Beam Split Core Reactor (NBSR) is located at the 1,384 hectare site purchased in 1959 for the new location of the National Bureau of Standards (NBS) in Gaithersburg, MD. In 1988, the name of the NBS was changed to NIST (Rush and Cappelletti 2011).

The NBSR is a heavy water moderated and cooled enriched fuel, tank type reactor designed to operate at 20 MW of power. The reactor is a custom designed variation of the Argonne CP-5 class reactor. The difference from the CP-5 include power rating, core configuration and cold neutron source. The major modifications to the CP-5 basic design are the 18-cm gap between the upper and lower fuel regions in each fuel element to reduce the fast neutron background in the neutron beams; a double plenum at the bottom of the reactor vessel to provide optimized cooling to the reactor core; and the method for remote handling of fuel elements during refueling operations. The maximum thermal neutron flux near mid-plane is on the order of 10^{14} neutrons cm^{-2} s^{-1} at 20 MW. The NBSR is operated, maintained and refueled by NRC licensed senior reactor operators. The typical cycle for reactor operations is 38 operational days (24 h d^{-1}) followed by 10-d shutdown for refueling and maintenance activities.

The basic nuclear reaction in heavy water is slow; that is, the prompt neutron lifetime is relatively long and reactivity coefficients of temperature and void are negative. The reactor operates in a low temperature unpressurized condition and has no large stored energy content. The maximum hypothetical accident assumes complete melting of one fuel assembly. For this scenario, the dose to a person on the site boundary 24 h a day for 30 d would be 0.07 mSv and the iodine dose to the thyroid would be negligible (1 μSv). Inherent (or passive) safety features include:

- The reactor core is designed so that the temperature coefficient of reactivity is negative;
- The reactor core is designed so that the void coefficient of reactivity is negative; and
- There is a passive gravity drain of 3,000 L of D_2O from the inner reserve tank within the reactor vessel into the core.

Neutrons generated via nuclear fission have high kinetic energies, and are slowed to thermal energies by heavy water surrounding the fuel. Some neutrons are slowed even further by a volume of liquid hydrogen (cold source) located near the fuel. The neutrons produced are called thermal neutrons and cold neutrons respectively. In addition to scattering, which is the main technique used at the NCNR, neutrons can be used to create new stable or radioactive nuclei by absorption. This property is the basis of Neutron Activation Analysis, a technique used in analytical chemistry and health physics for identification and quantitative analysis of isotopic species. Other measurements at the NCNR involve the fundamental properties of the neutron, such as neutron lifetime (free neutrons are unstable and decay with a mean lifetime of about 15 min into a proton, an electron, and an antineutrino). Typical research conducted at the NCNR involves the analysis of materials to be utilized in, for example:

1. magnetic monopoles;
2. magnetic data storage;
3. high temperature superconductivity;
4. energy storage and collection devices (batteries, fuel cells and solar cells);
5. piezoelectric materials;
6. biological applications; and
7. polycrystalline modeling.

This article will focus on the aspects of applied health physics utilized for radiation safety and security of radioactive material at the NCNR (Shleien et al. 1998).

Radiation and radioactive material: safety and security

Access to the NIST campus is controlled. Admission to the NCNR facility is controlled and right of entry to the research areas has additional access and security measures. Table 1 delineates how the entrances to research areas are posted. Each instrument experimental area has specific access controls and security and safety measures in place. Instrument areas are posted as Radiation Area or High Radiation Area as needed (U.S. NRC 2013).

During periods when the reactor is critical, daily radiation surveys are performed with a pressurized ion chamber to assess adequacy of posting and control measures. Fig. 1 shows the instrument locations where the daily radiation readings are taken and represents an overhead view of the facility and the locations of data collection points. The distance from the reactor center to the beam stop on NG-6 End Station is 150 m.

Table 1. Research area entrance postings.

Research Area Entrance Postings
Restricted Area: Dosimetry Required Area, Visitors must be escorted
Caution: Radioactive Materials work area
CAUTION: High Radiation Areas in the beams in this room are designated by NEUTRON BEAM—NO ENTRY, contact Health Physics for additional information
No eating, drinking, smoking in this area

Table 2 lists typical location sampled, maximum, mean, and minimum radiation level in units of μSv h^{-1} for the daily radiation readings collected. Table 2 represents a review of data collected during a prior year of reactor operation at the NCNR. A pressurized ion chamber was utilized to collect this data. The C100 locations represent data collected in the reactor building at the thermal neutron beam instruments. The Guide Hall locations represent data collected at the cold neutron beam instruments and experiment locations. Routine wipe tests are conducted to ensure instrument experiment areas remain free of loose radioactive material. Throughout the facility wipe tests are performed and analyzed for removable radioactive material with gas flow proportional counting system. The samples may also undergo liquid scintillation analysis and gamma spectrum analysis.

All personnel that enter Controlled Areas (Reactor confinement and Guide Hall areas) upon exiting must pass through radiation portal monitors each with six large area (27.9 cm × 48.3 cm) gamma-sensitive plastic scintillator detectors. Half-body monitors (with gas flow detectors) and Hand and Foot monitors (with sealed proportional detectors) are strategically located at exit points throughout the building adjacent to research laboratories and operational support facilities. Area radiation detectors are in the Reactor building and the Guide Hall. Alarming continuous air monitors that sample particulates and noble gasses are located throughout the facility. Routine and non-routine grab air samples are collected with evacuated ionization chambers. Personnel are monitored with self-reading pocket ion chambers (PICs)

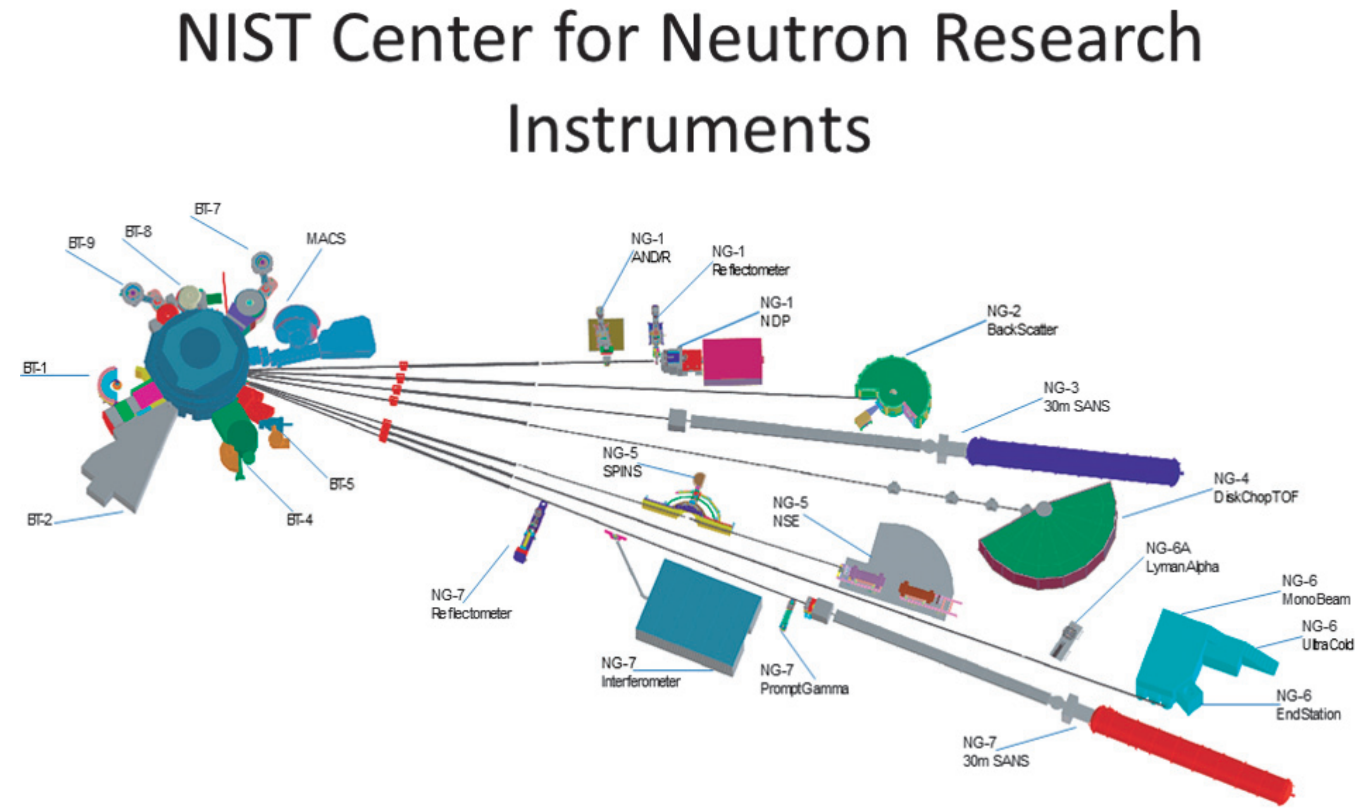

FIG. 1. Location of data collection points.

and four element thermoluminescent dosimeters (TLDs). The TLDs (a high-sensitivity LiF:Mg,Cu,P thermoluminescent material, TLD-600/700; Note: TLD-600 contains 4.40% ^{7}Li and 95.60% ^{6}Li while TLD-700 contains 99.93% ^{7}Li and 0.07% ^{6}Li) monitor photon Deep Dose, Shallow Dose, Eye Dose, and albedo Neutron Dose. Albedo TLD's measure scattered thermal neutrons emitted from the body. These dosimeters also measure incident thermal neutrons since no cadmium was used in the filtration of the TLD holder to absorb thermal neutrons (Cassata et al. 2002). Visitors are monitored with pocket ion chambers that contain TLDs (TLD chips are attached to the outside of the PIC with heat-shrink tubing). Personnel that routinely enter certain areas must submit monthly urine samples for bioassay analysis. Health Physics (HP) and Reactor Operations staff is monitored with a baseline urinalysis and whole body count upon initial assignment at the NCNR. Environmental TLDs are located inside and outside the facility and along the NIST fence. Environmental radiation data are collected monthly from battery powered Geiger-Mueller (G-M) detectors located inside and outside the facility and along the NIST fence. Environmental vegetation and soil samples are collected monthly on the NIST campus and undergo gamma spectrum analysis. Environmental water samples are collected monthly from locations on and off the

Table 2. Facility radiation readings in μSv h^{-1}.

C100 locations	Max[a]	Mean[a]	Min[a]
BT-5	81.0	31.1	2.3
BT-4	350.0	74.7	1.0
BT-2	450.0	40.7	0.3
BT-1	98.0	28.5	1.5
BT-9	400.0	68.4	0.8
BT-8	192.0	27.4	3.0
BT-7	1,080.0	236.6	1.2
MACS	2,000.0	120.1	1.1
Guide Hall locations	**Max[a]**	**Mean[a]**	**Min[a]**
NG-7 Reflectometer	98.0	36.0	21.0
NG-7 Interferometer	45.0	9.8	1.0
NG-7 Prompt Gamma	181.0	31.9	1.5
NG-7 30 M SANS	124.0	32.7	0.1
NG-6 End Station	46.0	8.5	0.1
NG-6 U (Ultra Cold)	12.2	1.9	0.1
NG-6 Monochromator Beam	34.0	16.2	1.5
NG-6A (Lyman/Alpha)	68.0	20.0	12.0
NG-5 Spin Echo	280.0	75.7	1.5
NG-5 SPINs	65.0	6.5	2.0
NG-4 Disk Chopper TOF	120.0	14.3	0.2
NG-3 30 M SANS	87.0	12.8	0.5
NG-2 Backscatter	90.0	19.4	1.3
NG-1 NDP	140.0	45.6	1.5
NG-1 Reflectometer	21.0	2.4	1.0
NG-1 AND/R	16.1	6.6	0.6

[a]Readings in μSv h^{-1} taken with pressurized ion chamber.

NISTcampus and undergo liquid scintillation and gamma spectrum analysis (Cassata et al. 2002; NCRP 1971, 1976b, 1986).

General health physics procedures

The general health physics procedures provide for protection of NIST personnel and the public, to comply with applicable regulations and the NBSR reactor and radioactive material licenses and to comply with management policy and commitment to keep radiation exposures and releases as low as is reasonably achievable (ALARA). All individuals have the responsibility to protect themselves, to maintain their radiation exposures ALARA, and to actively ensure that NBSR ALARA goals are met. During normal business hours, the NBSR HP staff is available to assist in matters pertaining to the radiation protection program and for matters involving radiation or radioactive material. The Duty HP is on call 7 days a week and 24 hours per day. During off hours reactor operators are available to handle immediate needs of visitors and staff, with the Duty HP on call. The National Institute of Standards and Technology, the management of the NBSR, and the HP staff are committed to the policy to keep exposures within the limits defined by NRC 10 CFR 20, and to keep exposures as low as reasonably achievable consistent with sound operating practices (U.S. NRC 2013). All operations are planned and conducted in a manner consistent with this policy. Approval by the NCNR Director and HP is required prior to bringing radioactive materials into the NCNR. HP approval is required for transfers of radioactive material from the NBSR to other NIST areas and off site facilities in accordance with U.S. Department of Transportation (U.S. DOT) and International Air Transport Association (IATA) regulations (NCRP 1978; U.S. DOT 2012; IATA 2012).

The ALARA program required by 10CFR20.1101(b) is integrated into these procedures (U.S. NRC 2013). Elements of the program include: strong supervisory oversight of operations involving potential significant exposures; explicit, reviewed procedures via Radiation Work Permits (RWP) for major activities; review of work experiences and exposure histories; individual involvement and responsibility for meeting ALARA goals; and, review of environmental sampling and dosimetry system results. HP conducts an annual review of HP procedures and the implementation of 10 CFR Parts 19 and 20 (U.S. NRC 2012, 2013). The review emphasizes a continuing application of ALARA principles, current protection practices, and application of experience gained at the NBSR and other facilities (Emery et al. 1995). The greatest contributor to reduction in worker exposures during maintenance activities is directly related to HP oversight. HP direct oversight results in reduced personnel exposures especially during activities dictated by RWP.

Precautions and control of tritium

Precautions to prevent or minimize exposure to tritium include monitoring the air with tritium monitors, with cold trap samples of water vapor evaluated in a liquid scintillation counter, and with air samples collected in an evacuated ionization chamber and evaluated with an electrometer; monitoring surfaces with smears or wipes counted in a liquid scintillatio counter; restricting exposure time for work in elevated tritium concentrations; using a local exhaust system for ventilation around maintenance operations on the D_2O and helium systems; and requiring waterproof clothing be used to avoid direct skin contact with water containing high levels of tritium. Tritium uptake is determined by urinalysis, using a liquid scintillation counter. Routine and timely samples are required from persons working with tritium or tritium-contaminated materials. Personnel designated by HP regularly submit a urine sample each month. A special sample is submitted no sooner than one hour after a known or suspected uptake of tritium or when requested by HP. A special sample is submitted in any week that work is performed involving primary system water, e.g., leaking primary system seals, heat exchanger work, etc. (NCRP 1976a; Liu et al. 1999; Kase et al. 2003; Turner 2007). During refueling operations, reactor operators must submit pre-job and post-job samples.

Training

Before arriving at the NCNR, visitors must register and complete a sign-in process. Radiation safety training must be requested. The training may be completed in advance at the user's facility, office, or home computer. The visitor must obtain a letter of identification from their organization (referred to as the "trustworthy" letter). If the visitor is a returning user already on the NCNR access list, personal dosimetry can be requested in advance. Upon arrival at the NCNR, a visitor must undergo HP Radiation Safety training, complete a "Facility User Safety Awareness Checklist," complete a signed Facility User Agreement, and be assigned and issued personal dosimetry (see Appendix for experimenter and beam user controls).

The HP staff participates in the training of new Reactor Operators and the biannual training and requalification of Reactor Operators. Additionally, Emergency Service staff members consist of Emergency Medical Technicians, fire fighters, and federal police officers and receive biannual training from HP staff. HP staff prepares and delivers additional training at the request of scientific staff. Examples of training topics include glove box operations for neutron beam samples, summer student introduction to radiation safety, and science teacher introduction to radiation safety.

Neutron beam sample processing

Samples or materials that have been subject to a neutron beam are delivered to the HP lab for processing, clearance or disposition. The beam user must complete the Materials Transfer Request form for each sample. HP staff performs sample screening. Sample screening consists of appropriate surveys with pancake G-M, wipe test and analysis by gas flow proportional counter, neutron activation analysis using computer modeling, and gamma spectrum analysis with high purity germanium detector. Sample disposition categories (U.S. DOT 2012; IATA 2012):

1. Release for unrestricted use (no further action needed);
2. Exempt quantity;
3. Radioactive material license transfer (verify receiver's license);
4. Not radioactive per DOT or IATA (no transportation restrictions);
5. Radioactive material per DOT or IATA; and
6. Radioactive waste.

Laboratory audits, inventory and leak tests

The HP staff performs quarterly audits in labs characterized, commissioned, and posted to possess and utilize radioactive material. Audits consist of radiation and contamination surveys, hood flow checks, and spot checks of radiation source inventory. The focal points of the Audit include:

1. General neatness and cleanliness;
2. Posting and labeling (room, area, cabinets, pygs);
3. Radioactive material security;
4. Food, drink, smoking, control;
5. Radioactive waste management;
6. Dosimetry usage and storage;
7. Survey instrument availability and appropriateness;
8. Contamination control (area, personal);
9. Access control;
10. Hood status;
11. Spill containment (benchtop, transport or movement); and
12. Radioactive material usage locations.

Leak test are conducted in accordance with license requirements for radioactive material. Sample analysis is performed using gas flow proportional counter or liquid scintillation counter. Results of detected activity of less than 185 Bq are considered acceptable. Prior to receipt of non-exempt radiation sources, a Hazard Review must be completed. These sources are assigned a Radiation Safety number and entered into the database.

Meter calibration, repair and evaluation

All portable instruments used for the detection of radiation and contamination in use at the NCNR are calibrated at NIST. Calibration is performed with pulser or appropriate gamma, neutron, or alpha sources. HP staff will troubleshoot and repair meters that malfunction, become damaged or fail calibration. Pulsers and flow meters are sent to the vendor for calibration. A small portion of meters must be sent to the vendor for repair. Upon receipt of new meters, a calibration is performed prior to placing into service. HP staff has an added position responsibility to keep abreast of developments in the portable meter industry. This duty entails review of trade literature and obtaining meters for testing and evaluation at the NCNR.

Radioactive waste management

The radioactive waste program encompasses a broad range of processes and materials. Low volume and low activity samples originate from neutron beam-related experiments and research. Reactor operations and reactor maintenance events including retooling contribute significant high activity volumes of waste. Liquid waste is collected in onsite radioactive waste tanks and disposed to the sanitary sewer after appropriate sampling and review to ensure the radionuclide and activity meet the waste effluent concentration limits in compliance with Federal, State, and Local regulations. A commercial waste contractor handles disposal of solid waste and liquid waste not suitable for sanitary sewer disposal (NCRP 1996). Waste for shipment consists of routine laboratory waste, waste samples from neutron beam experiments, material and equipment from retooling neutron beam lines and neutron beam instruments. Other high activity waste consists of:

1. Reactor primary resins;
2. Reactor primary filters;
3. Filters and resins from other systems;
4. Shielding plugs and related neutron beam shields;
5. Experiments, or experimental components removed from high neutron flux locations;
6. Reactor components; and
7. Miscellaneous contaminated materials, such as laboratory waste.

Site emergency response

The NIST Fire Protection Group (FPG) provides around the clock support and protection for the NIST Gaithersburg facility. The FPG provides fire prevention inspections, fire suppression, emergency medical service, hazardous materials (HAZMAT), and miscellaneous services for the Gaithersburg campus. All firefighters are certified emergency medical technicians and hazardous materials technicians. National Fire Protection Association (NFPA) codes are accepted as the standard level of protection for the NIST Gaithersburg facility (NFPA 1993, 2014a and b).

The NIST Police Services Group (PSG) provides Federal Police Officers and security staff for police services at the NIST Gaithersburg campus. The PSG is responsible for the protection of the site.

Radiation monitoring systems

Confinement building monitoring. The reactor confinement building monitoring system consists of ten beta-gamma area monitors. The detectors are halogen quenched G-M tubes and each detector assembly is equipped with an alarm light and an alarm buzzer. The detectors have local dose rate indicators with ranges from 0.01 μSv h^{-1} to 1 Sv h^{-1} (Knoll 1979; Shleien et al. 1998).

Ventilation filter radiation monitors. There are three filter monitors associated with the ventilation system: irradiated air exhaust from the reactor; normal air exhaust (non-irradiated room air taken from the face of the reactor); and basement air exhaust. The activity in these three ducts is indicated on log ratemeters with independently set alarm points. The ratemeters have a range of 20 cpm to 200,000 cpm (cpm, counts per minute) and time constants that vary from 60 s at 20 cpm to 0.05 s at 200,000 cpm. Visual and audible alarms in the Control Room are energized by activity conditions that exceed preset levels on the meter relays. Additional G-M detectors are located adjacent to the high efficiency filters in ductwork that serves the laboratory areas. Radiation levels at the filters are indicated on a computer screen in the HP lab. These levels are also recorded in the HP lab. Count rates that exceed levels preset on the meter relays actuate visible and audible alarms on a computer screen in the HP lab (Knoll 1979; Shleien et al. 1998).

Secondary coolant monitors. The secondary coolant downstream from the main D_2O heat exchangers is monitored for radioactivity to indicate a primary to secondary leak. The system has two shielded detectors, two pumps, and associated valves and instrumentation. Normal line-up will have two pumps and both detectors in service. Each detector consists of a G-M tube inside a shielded liquid sampler located in an equipment room. The output of these detectors is indicated locally on log ratemeters. Both detector outputs are also indicated and recorded in the Reactor Control Room. The ratemeter has a range of 10^1 cpm to 10^6 cpm, and activity that exceeds preset levels on the meter relay actuates an annunciator in the Reactor Control Room. Each pump has the capacity to draw secondary water through either detector from the heat exchanger return line. Water then passes through flow meters, a pH instrument and a test heat exchanger before joining the return flow to the cooling towers (NCRP 1978, 1986; Knoll 1979).

Gaseous fission product monitors. The helium sweep gas is continuously monitored for radioactivity to provide an indication of a fuel element cladding failure. A sample of helium is pumped through a shielded gas sampler that contains a G-M tube. A log ratemeter, located with the detector in the monitor room indicates the radioactivity of the helium gas. This level is also indicated and recorded in the Reactor Control Room. The ratemeter has a range of 10^1 to 10^6 cpm. Activity that exceeds a preset level on the ratemeter activates a Reactor Control Room annunciator. During normal reactor operations at power, on-scale meter readings indicate the presence of activated argon, the source of which is in-leakage of air during reactor shutdown operations, which include maintenance and refueling operations (Knoll 1979).

Gas monitors. The system consists of a gas pump, two shielded gas samplers and detectors, and two log ratemeters in a single housing on the reactor basement mezzanine. Each detector is a thin-walled sensitive G-M tube with the irradiated air detector being smaller than the normal air detector. Gas samples are continuously pumped from the irradiated air and normal air ventilation system exhaust ducts. When the activity in either duct exceeds a preset value, a major scram is initiated and audible and visual alarms are energized in the Reactor Control Room (NCRP 1986).

Ventilation tritium monitor. Air within the Confinement Building is continuously sampled for tritium. A flow through ion chamber located on the basement level is supplied with air drawn by an associated blower from ten points on the ventilation system. Valved sample points are available for each of the individual sample locations. Tritium concentration is monitored and recorded in the Reactor Control Room, with an annunciator set to alarm at preselected levels on the tritium recorder. A loss of flow through the monitor will also alarm the annunciator (NCRP 1976a).

Plant effluent monitors

Stack gas monitor, RD4-1. The stack gas monitor consists of one thin-walled sensitive G-M tube located inside the stack about two-thirds of the way up the stack. The radiation level is indicated on a log ratemeter in the monitor room and is indicated and recorded in the Reactor Control Room. The ratemeter has a range of 10^1 to 10^6 cpm. Activity that exceeds a preset level will initiate a major scram and actuate the Reactor Control Room annunciator (NCRP 1996).

Stack gas monitor, RD4-2

This monitor consists of one thin-walled sensitive G-M tube located in the stack immediately below the RD4-1 detector tube. The RD4-2 detector tube is smaller than the RD4-1 detector tube. The result is that the RD4-1 detector is more sensitive at the low end of the scale, but the RD4-2 detector tube is less likely to saturate at the high end of the scale. The radiation level is indicated in the Reactor Control Room, with meter face and scale different from the RD4-1 meter. The RD4-2 meter indicates in counts per minute at the low end of the scale and general levels for the rest of the scale. The purpose of this instrument is to supply the reactor operations staff with information to assist in the determination of emergency conditions, as defined in the NBSR emergency procedures.

CONCLUSION

Neutron beams at the NCNR research reactor, a major government research and development laboratory, present a sufficient variety of applied and operational health physics applications that requires continuous oversight to maintain safety, control, and security of radioactive material and radiation sources. An introduction as to why neutrons are used in research and development was presented. Many aspects, including general health physics procedures; training; precaution and control of tritium; neutron beam sample processing; lab audits, inventory and leak tests; meter calibration, repair, and evaluation; waste management; emergency response; and the radiation monitoring systems must be incorporated into the health physics program.

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APPENDIX

General HP experimenter controls at the NCNR

1. All individuals have the responsibility to protect themselves, to maintain their radiation exposures ALARA, and to actively ensure that NBSR ALARA goals are met. Always consult HP (or the Reactor Supervisor in their absence) whenever there are questions concerning radiation exposure, contamination or other radiation protection problems;
2. Eating, drinking, and the storage of food are not permitted in the confinement building (except the reactor control room and operator office areas), in the Guide Hall, or in any laboratory used for unsealed radionuclide work. Smoking is prohibited;

3. Notify HP or the Reactor Supervisor immediately of any accident or injury involving radiation or radioactive material;
4. All experiments shall be shielded so that in any accessible area, the radiation level is less than 1 mSv h^{-1} at 30 cm from any surface. HP shall be contacted prior to conducting any experiment that might create a High Radiation Area. High Radiation Area posting and control requirements shall be implemented and a Radiation Work Permit may be required;
5. A radiation sign, rope or barrier shall not be removed without consulting HP. If it is necessary to move a radiation rope or barrier temporarily for equipment movement, then that area shall be attended. The radiation rope or barrier shall be replaced in its original position when finished;
6. Portable radiation survey instruments located on each floor should be used for short duration surveys and promptly returned to their station. Additional survey instruments may be obtained from HP for longer use;
7. A personal contamination check shall be performed each time upon leaving B-wing (warm lab or hot cell area), C-wing, or G-wing;
8. Radiation dosimeters shall be worn at all times in areas posted as requiring personal dosimetry;
9. Direct-reading pocket dosimeters shall be worn when working with radioactive samples or inside a posted Personnel Monitor Required Area or High Radiation Areas. Dosimeters shall be checked periodically by the wearer to ensure that exposure limits are not exceeded;
10. Return radiation badges and dosimeters to the racks upon leaving the building. Pocket dosimeter readings are periodically checked by HP to determine the accumulated dose;
11. Personnel working with high radiation level components or samples shall contact HP for supplementary dosimetry, e.g., finger dosimeters;
12. All radioactive material being removed from Building 235 shall be properly packaged and surveyed by HP, Reactor Operations, or other authorized personnel and all required forms completed. (See license SNM–362 and implementing procedures for transfers within NIST;†)
13. All radioactive items or containers of licensed radioactive material shall bear a durable, clearly visible label identifying the radioactive contents. The label shall bear the radiation caution symbol and the words "Caution, Radioactive Material" or "Danger, Radioactive Material". It should also provide sufficient information to permit individuals handling or using the containers, or working in the vicinity thereof, to take precautions to avoid or minimize exposure;
14. In the event of a local radiation alarm, leave immediate area, and notify HP or Control;
15. Response to fire and evacuation alarms shall be the same as the rest of Building 235. Leave by the nearest exit and assemble in front of the building;
16. If it is necessary to open outside access doors to the Guide Hall (G-wing) for any duration, the open door shall be monitored by a person on the access list. That person is responsible for any person entering the building. Outside access doors to the Confinement Building (C-wing) shall not be opened without prior approval from the Reactor Supervisor. The North and South access doors to the Confinement Building shall not be blocked;
17. All new experiments will initially be surveyed by HP if required after review by the SEC and approval by the Director, NCNR. Changes in procedures or shielding may be recommended at this time. After changes are made, the experiment will be resurveyed until satisfactory; and
18. HP shall be notified of any significant change made to the experiments so that they may be resurveyed if necessary.

Beam user controls at the NCNR

1. All required safety systems for a specific experiment shall be present and operational unless a specific waiver is obtained from HP. HP shall be immediately notified of any failure or malfunction of such a system, e.g., interlocks, warning devices, etc.;
2. All external beams from the Reactor shall be properly barricaded to prohibit personnel from entering the beam accidentally. Beams with an accessible length greater than 30 cm are High Radiation Areas. Designed access controls (e.g., beam status indicators, barriers, local signs indicating beam status, intrusion detectors, or experiment

†NIST establishes and maintains an ionizing radiation safety program at the NIST-Gaithersburg site in accordance with Nuclear Regulatory Commission (NRC) License Numbers SNM-362, 19-23545-01E, and TR-5 (Test Reactor) and applicable Federal, State, and local regulations. The program has two functional areas: Radiation Facilities (e.g., laboratories containing radioactive materials, gamma irradiators, accelerators, electron microscopes, and x-ray devices) and the Reactor Facility at the NCNR. NIST Radioactive Material Licenses, 19-23545-01E, SNM-362. NIST Reactor License, TR-5.

features minimizing accessibility) must be functional. Exposure to these radiation beams shall be avoided at all times. Any suspected exposure shall be reported to HP or the Control Room immediately;
3. HP or Reactor Operations shall be contacted prior to any work to be done inside the biological shield with the beam shutter open. A Radiation Work Permit may also be required;
4. Any components removed from an experiment shall be checked for activation or contamination. All such radioactive items shall be appropriately labeled and shall not be transferred to an unrestricted area without HP approval. Any components removed from the biological shield or a direct neutron beam shall be surveyed by HP, Reactor Operations, or other authorized personnel;
5. For experiments requiring cooling where the coolant could become radioactive, the integrity of the cooling system shall be maintained to prevent spillage and minimize radioactive gases vented to the irradiated air system;
6. Systems or controls labeled with the "NBSR - DANGER - DO NOT OPERATE" red tag shall not be operated or disturbed without specific authorization from the Reactor Supervisor; and
7. All users of reactor beams shall receive training on the safety and operation of the specific beam tube and experimental facility used.

In-core irradiation user controls at the NCNR

1. Radiation hazards from irradiation facilities primarily consist of whole body exposure and possible contamination from activated products during irradiation, handling and use. Irradiated rabbits and samples shall be handled as Contaminated or Unsealed Radioactive Material;
2. Every effort shall be made to contain activation products in their containers or in the radioactive fume hoods. Notify HP in the event of a suspected spill, even if it is contained within the hood;
3. One of the important ways of reducing radiation exposure from activation products is by allowing short-lived products to decay before handling. This may be accomplished by allowing the short-lived products to decay in the pneumatic receiver or the rabbit storage facility. A radiation survey of the area should be performed and the area appropriately posted and controlled. In the case of the vertical thimbles, the sample may be moved above the flux area and allowed to decay in the thimble before removing;
4. When working with high-level beta emitters, goggles, protective lenses or the hood window may be used to reduce the dose to the lens of the eye. Similarly, the hood window or plastic beta shield may be used to reduce exposure to the skin, and appropriate handling devices may be used to reduce exposure to the hands;
5. Containers are provided for solid and liquid radioactive waste. When disposing of activation products, the radioactive amount and the isotope should be noted on the disposal form. HP should be informed when waste containers are full so they can be collected;
6. Volatile samples should be filtered or enclosed to prevent excessive radioactive products from escaping the hood or being deposited on the hood filter;
7. Protective lab coats and gloves should be worn when working on radioactive samples in a Restricted Area. These same articles of protective clothing should not be worn or carried into a clean area;
8. Each person utilizing the irradiation facilities is responsible for maintaining records adequate to account for all radioactive materials produced by the NBSR;
9. Air flow is maintained at the face of the radioactive fume hoods at an average flow rate of not less than 0.51 m s^{-1} and not less than 0.38 m s^{-1} in any segment of the hood face. Experiments or shielding shall not be set up to interfere with this flow rate. Periodic air flow measurements are taken; and
10. All users of the reactor irradiation facilities shall receive training on the safety and operation of the specific facility used.