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1 NIST CENTER FOR NEUTRON RESEARCH & NBSR

1.1 Introduction

The NIST Center for Neutron Research (NCNR) is a reactor-laboratory complex providing the National Institute of Standards and Technology (NIST) and the nation with a world-class facility for the performance of neutron-based research. The heart of this facility is the National Bureau of Standards Reactor (NBSR). The facility is located on the 575 acre NIST campus in upper Montgomery County, Maryland, approximately twenty miles northwest of the District of Columbia. NIST is a non-regulatory federal agency of the U.S. Commerce Department within the Technology Administration.

The NCNR is a national resource used by nearly 2000 engineers and scientists for some part of their research every year. In 2002, the researchers came from 30 other federal laboratories, 127 universities, 47 industrial laboratories, and 21 divisions and offices of NIST, and from all areas of the country. The major research areas include materials science, non-destructive evaluation, chemistry, biology, trace analysis, neutron standards and dosimetry, nuclear physics, and quantum metrology. A large cold neutron source and seven neutron guides provide the United States with world-class capabilities in cold-neutron research. Up to 25 cold and thermal neutron instruments provide the only internationally competitive neutron scattering capability in the country. As a result, the NCNR has served over 60% of the neutron users in the USA in the time period 2000-2003. The reactor is operated 24 hours a day, seven days a week with routine shutdowns every five-and-one-half weeks for partial refueling and as needed for maintenance. This operating schedule allows for the operation of a robust user program, which solicits proposals for experiments twice a year. Research done at the NCNR has formed the major justification for 8 major physics and chemistry prizes over the past decade. A recent study by an inter-agency working group of the Office of Science and Technology Policy (OSTP, 2002) stated "The NCNR is the highest performing and most used neutron facility in the United States at this time, and will remain in that position at least until the Spallation Neutron Source (SNS) is operational and robustly instrumented." The NBSR is the key to the success of the NCNR, which is critical to national goals, and is at the forefront internationally.

The NBSR is a heavy water moderated and cooled, enriched fuel, tank type reactor designed to operate at 20 MW of power. It is a custom designed variation of the Argonne CP-5 class reactor; it differs from the CP-5 in its power rating, core configuration and cold neutron source, but retains the proven technology. The three most notable modifications to this basic design are: a 7-inch (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 vessel to provide optimized cooling to the core; and the method for remote handling of fuel elements during refueling.

The design of the NBSR includes many inherent, passive safety features. The prompt neutron lifetime is relatively long as a result of heavy water moderation. The reactivity coefficients of void and temperature are negative. The reactor operates in a low temperature, unpressurized condition and has no large stored energy content. Two inner structures within the reactor vessel retain heavy water in the event of a loss of water from the vessel. In the event of a loss of cooling water, one of these structures immediately supplies emergency coolant flow to the elements without any operator intervention, while the other maintains water around the lower half of the core. An overhead reserve tank can supply heavy water for emergency cooling either to the top or to the bottom of the elements for extended periods of time.

1.2 Summary and Conclusions on Principal Safety Considerations

This section summarizes safety criteria, the principal safety considerations and the resulting conclusions of the Safety Analysis Report (SAR). Detailed information is given in the subsequent chapters of this report.

1.2.1 Consequences from the Operation and Use of the NBSR

The principal conclusion of the safety analysis contained in this report is that the continued operation and use of the NBSR will result in considerable benefit without any significant cost to the public health or to the environment. Specific conclusions are:

a. Continued operation and use of the NBSR will provide significant national benefits in research and education. It is a heavily utilized facility with a total of nearly 2000 researchers from more than 200 organizations and institutions, including over 200 PhD students.

b. Continued operation and use of the NBSR will be conducted without endangering the health and safety of the public. No significant environmental impact will result.

c. The purpose of the NBSR is within the scope of Section 104c, Research and Development, of the Atomic Energy Act of 1954, as amended. It will continue to be operated in conformity with this Act.

The basis for these conclusions is the detailed review of the NBSR design and operational safety that is documented in this SAR. Areas of review include site characteristics, design bases for facility structures, reactor core and the coolant systems, engineered safety features, instrumentation and control systems, electrical power and auxiliary support systems, and experimental facilities. Administrative elements of design and operation such as radiological safety programs, operating procedures, accident scenarios, technical specifications, and financial qualifications were also reviewed as part of the process that led to the above conclusions.

1.2.2 Safety Considerations on Choice of Site, Type of Reactor and Fuel, and Power Level

The NBSR initiated neutron research in 1969. The genesis of the project a decade earlier was the recognition that a reactor at the National Bureau of Standards (NBS) would serve the standards and measurements mission of the Bureau, and would act as a regional and national resource to serve other U.S. government agencies, universities and industry. The mission and the measurement needs of this multidisciplinary community encompassed a varied range of interests in materials, chemical analysis, radiation standards, and other areas. The development of the Cold Neutron Source and the construction of the Cold Neutron Guide Hall provided the United States with world-class capabilities in cold-neutron research. The NCNR has become the most heavily utilized neutron center in the United States (OSTP, 2002).

Since almost all of the work at NCNR involves the use of thermal neutrons, the reactor type chosen was one that generates a well-thermalized neutron spectrum. The need for thermal neutrons, combined with the requirement that the flux be competitive at a reasonable power, dictated the choice of an enriched fuel, and heavy water moderated and cooled reactor. The reactor is of the Argonne CP-5 class. It consists of an aluminum vessel filled with heavy water, which also contains the core or grid of enriched plate-type fuel elements. The core consists of an array of thirty plate-type fuel elements containing enriched uranium, clad with aluminum.

The design of the reactor core included three unique features. The first is a “split-core,” with uranium fuel placed above and below the mid-plane in the heavy-water moderator tank leaving a 7-inch (18-cm) gap in which the thermal neutron flux reaches a peak, and other radiation emanating from fission processes is reduced. The insertion of nine large 5-inch to 6-inch (13-cm to 16-cm) radial beam tubes into this gap allows high intensity beams (with low “background” from unwanted fast neutrons and gamma rays) to be extracted for thermal neutron scattering research. A second feature is the large volume in the core that provides very flexible capabilities for thermal neutron irradiation. Finally, the insertion of the “cold neutron source” provided the nation’s first internationally competitive facility for cold neutron research on materials (Cappelletti, 2001).

The Confinement Building is made of reinforced concrete and is sufficiently tight so that, when closed, the building leakage rate is limited to 24 cfm per inch of differential pressure (0.27 cubic meters per minute per cm) or less. The internal atmosphere of the confinement building is recirculated and filtered. At the same time, a portion of the atmosphere is exhausted from the building through absolute filters and the stack at such a rate as to maintain a small negative differential pressure across the building walls, thus eliminating air leakage out of the building. Even under the worst hypothetical conditions, the dose to a person on the site boundary would be negligible.

One modification from the CP-5 design is the double plenum at the bottom of the reactor vessel. By means of two independent concentric plenums, flow to the inner and the outer array of elements can be separately controlled.

Another modification is the method of handling fuel elements. For transferring elements to a different core position or for removing elements from the core, it is not necessary first to withdraw the element into a cask above the reactor top as in the CP-5 design. Pick-up and transfer tools operating through the top plug effect the movement of the fuel element under a blanket of helium.

A significant feature of the NBSR is the means for providing extensive heavy water emergency cooling. An overhead tank can supply water either to the top or to the bottom of the elements. Additionally, two inner structures within the reactor vessel retain heavy water in the event of a loss of water from the vessel. One of these structures supplies coolant flow to the elements and the other maintains water around the lower half of the core.

1.2.3 Inherent Safety Features

There are no unusual safety problems connected with the NBSR, either by virtue of its basic type or by virtue of its particular design. 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. Even for this scenario, the dose to a person on the site boundary is minor.

The NBSR design includes a number of inherent (or passive) safety features. They are:

a. The reactor core is designed so that the temperature coefficient of reactivity is negative. This mitigates the consequence of any reactivity excursion and also promotes self-regulation of the reactor.

b. The reactor core is designed so that the void coefficient of reactivity is negative. This also mitigates the consequence of any reactivity excursion.

c. There is a passive gravity drain of approximately 800 gallons (3,000 liters) of D_2O from the holdup volume of the Inner Reserve Tank (IRT) within the Reactor Vessel into the reactor core.

1.2.4 Design Features for Safe Operation and Shutdown

The NBSR license and the technical specifications define the limits of safe reactor operation and, where applicable, the limits of facility operation. There are a number of design features and design bases of the systems and components associated with the NBSR that promote safe operation and shutdown. They are:

a. Reactor Control System: Four shim safety arms and one regulating rod control the reactor. The shim safety arms are of the semaphore type. They are located just below the upper grid plate. Their poison segment is 0.040-inch (1-mm) thick cadmium, clad with aluminum. The regulating rod consists of a solid aluminum cylinder, 2.5-inches (6.35-cm) in diameter. It is mounted on a vertical rod and located in a thimble. The shim arms are held in place by electromagnetic clutches. Upon de-energizing the magnets the spring-assisted, gravity insertion of the shim safety arms makes the reactor subcritical.

b. Reactor Protection System (RPS): The reactor protection system consists of the nuclear instrumentation and the process instrumentation. The RPS monitors parameters that are important to safety including reactor power and period, coolant flow and vessel level. Actuation of the RPS generates a reactor scram, de-energizing the shim arm clutches to make the reactor subcritical. In extreme emergencies, actuation of the system generates a major scram, initiating closure of the Confinement Building in addition to generating a reactor scram signal.

c. Emergency Shutdown: There are two emergency shutdown mechanisms. The primary one is the shim safety arm system. This is backed up by the second mechanism, which dumps the moderator from the top reflector to a level 1 inch (2.5 cm) above the core.

d. Emergency Cooling: This system provides cooling for the reactor core and experiments in the event of a loss of normal coolant through a pipe rupture. The system consists of a D_2O emergency cooling tank located external to the reactor vessel and a passive inner emergency cooling tank. Upon a rupture, cooling water drains into the core to remove decay heat. Domestic light water can be added to the emergency cooling system in extreme emergencies.

e. Confinement Building: The Confinement Building houses the reactor and its primary systems and components. It is not considered credible that any accident would lead to significant overpressure within the building. Thus, the building is designed to meet the more normal structural requirements of wind and snow loading. Under normal operating conditions, the building operates at a pressure slightly below atmospheric. Although no overpressure is expected, and the underpressure during normal operation is nominal, it is possible under emergency conditions, when the building is sealed, for rapidly rising atmospheric pressure to create an abnormal external pressure. The structural design has included this effect. In addition, a pressure relief valve has been incorporated which will prevent any detrimental pressure differential from developing across the building walls or roof.

f. Ventilation System: The Confinement Building is air conditioned with air that is partially recirculated except for the process equipment area of the reactor basement that is separately heated and ventilated. All effluent air that is exhausted from the containment building is monitored for radioactivity. In the event that high radiation levels are detected, the normal ventilation system is shutdown, all building closure devices operate to seal the building and the emergency ventilation system is activated. The emergency exhaust system is designed to draw air at such a rate from the building that a pressure differential is established across the building structure to assure that any leakage of air is into the building rather than out of it regardless of the outside pressure. All air exhausted is filtered to remove particulate and gaseous effluent such as iodine. All recirculated air is also filtered to remove particulate and gaseous activity such as iodine with an approximate 2-hour time constant for once through cleaning.

g. No Mixing of Secondary Coolant (H_2O) with Primary Coolant (D_2O): There should be no mixing of the light water (H_2O) of the secondary cooling system with the heavy water (D_2O) of the primary cooling system. In the unlikely event that this should happen, the addition of any amount of light water into the primary coolant represents a negative reactivity insertion.

h. Neutron Lifetime: The D_2O moderated NBSR reactor has a relatively long neutron lifetime. This provides a distinct advantage from the point of view of reactor control and safety. A long lifetime not only simplifies reactor control but leads to greater reactor periods for specific reactivity insertions. For a given reactivity insertion that is greater than the delayed neutron fraction, more time is available for heat transfer from the fuel elements and for bubble formation within the moderator.

i. Fuel Handling System: The NBSR fuel handling system provides for on-loading, off-loading and rearranging the fuel within the shielded area around the reactor. There is space above the core within the reactor vessel to raise a fuel element where it may be transferred to another position within the core or to a transfer chute where it can be transferred to the storage pool.

1.2.5 Potential Accidents

The maximum hypothetical accident (MHA) for the NBSR is one in which some type of object blocks all of the flow through a single fuel element while the reactor is operating at full power. This is highly unlikely because the NBSR is a closed system with upward flow. Nevertheless, if the flow in an element is blocked during full power operation, it is possible that some melting of the cladding would occur with a resultant release of some fission products into the primary water. To be conservative, however, it is assumed that the entire blocked element's cladding melts and releases fission products into the primary water. Analysis of this accident is given in Chapter 13 of this report. The calculated total whole body gamma ray dose to a person standing at the site boundary 24 hours a day for 30 days would only be 7 mrem and the iodine dose to the thyroid would be negligible.

Other reactor accidents that are evaluated in Chapter 13 of this SAR include start-up, maximum reactivity insertion, loss of flow, fuel handling, and loss of coolant accidents. The evaluations demonstrate that none of these accidents will result in a safety concern to the public or to the environment.

1.3 General Description

The NCNR reactor-laboratory complex, located on the National Institute of Standards and Technology's campus approximately 20 miles (32 km) northwest of Washington, DC, provides NIST and the nation with an extensive facility for neutron-based research in biology, chemistry, engineering, materials science, and physics.

The NBSR is a highly-enriched uranium, heavy water cooled and moderated, and vessel type reactor. This type of reactor was chosen because of its well-degraded or thermalized neutron spectrum, its high flux, its flexibility for research, and its inherent safety. The high fluxes generated by the NBSR reactor are used in five principal ways:

a. To characterize the structure and dynamics of materials critical to the US economy

b. To image large structures, and to study nuclear and neutron physics

c. To develop material and radiation standards

d. To generate radioisotopes for activation analysis and tracer production

e. To study the effects of radiation on materials through in-pile irradiation

The NCNR has a wide range of research capabilities. The liquid hydrogen cold source provides cold neutrons (neutrons slowed to speeds of 1000 m/s or less) directly to experiments in the Confinement Building, and through a network of seven neutron guides to experiments located in the Cold Neutron Guide Hall. Beam tubes provide thermal neutrons for experiments located within the confinement area immediately adjacent to the reactor. A pneumatic rabbit system provides researchers with the ability to automatically inject samples into the core region of the reactor, while vertical thimbles provide for their manual loading.

The fuel is U_3O_8 aluminum dispersion fuel enriched to 93%, which is clad in aluminum. The core is immersed in heavy water to thermalize fast moving neutrons to sustain the nuclear chain reaction, to remove heat created by the reaction, and finally to serve as the first stage of shielding.

The primary coolant system is closed, recirculating heavy water in an aluminum and stainless steel system. The heavy water is pumped through plate-type heat exchangers where it transfers its heat to light water (H_2O) before entering the core and then returning to the pumps. The secondary cooling system of light water transfers its heat to the atmosphere by means of evaporation from a cooling tower located outside of the Confinement Building.

The reactor operates at 20 MWt for 24 hours a day, 7 days a week with a routine shutdown every five-and-one-half weeks. This routine shutdown, which lasts approximately 10 days, is to refuel the reactor and perform maintenance.

1.4 Shared Facilities and Equipment

The Confinement Building, which is constructed of reinforced concrete and situated partially below grade, is attached to a laboratory complex dedicated primarily to nuclear-science-related research and other reactor support functions. Utilities such as municipal water and sewage, natural gas, and electricity are provided to the complex by the local utilities.

The Confinement Building has its own ventilation control system, capable of isolation mode of operation or dilution mode of operation to exhaust air to the atmosphere through an elevated stack located adjacent to the building.

1.5 Comparison with Similar Facilities

The NBSR has a large number of experimental beam lines. This type of reactor (using materials-testing-reactor (MTR) type plate fuel and heavy water cooled) is also being used at the Massachusetts Institute of Technology (MIT), and was used at Brookhaven National Laboratory, and at the Savannah River Plant before they ceased operation. Heavy water (D_2O) is used to obtain high flux values not otherwise achievable with that physical size of reactor. The design is a variation of the Argonne CP-5 class reactor.

1.6 Summary of Operations

Through 2001 NBSR has accumulated in excess of 2 million MW-hours of operation. The highly automated experimental facilities associated with the reactor allow it to be operated and utilized 24 hours a day, 7 days a week. Routine shutdowns are scheduled about every five-and-one-half weeks for partial refueling with an additional shutdown at the end of each calendar year. The reactor is normally on line approximately 250 days per year, and is fully utilized for experiments during that time.

1.7 Compliance with the Nuclear Waste Policy Act of 1982

The NBSR is a federally owned and operated facility that is part of the NIST. The U.S. Atomic Energy Commission (AEC) originally provided fuel for the operation of the NBSR. The U.S. Department of Energy (DoE) is the successor agency to the AEC. The DoE retains title to the uranium fuel used by NBSR. In a letter dated May 3, 1983, the DoE (R. L. Morgan) informed the NRC (H. Denton) of the title arrangement for the fuel. Specifically, the NBSR and the DoE have a contractual arrangement whereby DoE retains title to the fuel and is obligated to take the spent fuel and/or high-level waste for storage or reprocessing. All of the spent NBSR fuel has been returned to the DoE pursuant to this arrangement. A copy of the contract between NBSR and the DoE for fuel assistance is available.

1.8 Facility Modifications and History

The initial planning for the facility began in March 1958 when an application for a construction permit (CP) was submitted. Construction began in 1963 when the Atomic Energy Commission (AEC) issued the CP. This permit was converted to Operating License TR-5. The reactor achieved initial criticality on December 7, 1967 and began full-power operation at 10 MWt on February 9, 1969. On December 2, 1980, the NBSR requested a power increase from 10 MWt to 20 MWt and a 20-year extension of the existing operating license due to expire on June 30, 1985. This license was issued on May 16, 1984 and expires on May 16, 2004.

Except for the cooling tower, the principal nuclear and process systems were originally designed and installed for eventual 20 MWt operations. The only significant modifications to the facility not described in the previous (NBSR 9) Final Safety Analysis Report have been:

a. Replacement of the original aluminum heat exchanger with two stainless steel heat exchangers. These two heat exchangers were subsequently replaced with three plate-type heat exchangers (the third being an installed spare).

b. Replacement of the original cooling tower designed for 10 MWt with a more efficient one designed for 20 MWt and the associated modification of the secondary system piping. This more efficient cooling tower was subsequently replaced with a cooling tower of the plume abatement type.

c. Construction of the Guide Hall immediately to the north of the reactor confinement building and the installation of the neutron guides to support experiments located in it. Additional space was added to the Guide Hall by the construction of the auxiliary support building.

d. Upgrade of the original Cold Source that used heavy water (D_2O) with one designed to use liquid hydrogen to improve the energy spectrum of the cold neutrons and to increase their intensity.

1.9 References

Cappelletti, R.L., *et al*, "Materials Research With Neutrons at NIST," J. Res. Natl. Inst. Stand. Technol. **106** (2001) 127-230.

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