IANCAS Bulletin

Research Reactors of India (Part I): High Flux Research Reactor

INDIAN ASSOCIATION OF NUCLEAR CHEMISTS AND ALLIED SCIENTISTS
C/o Radiochemistry Division, BARC, Mumbai - 400 085
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Research Reactors of India (Part I): High Flux Research Reactor

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IANCAS sincerely thanks BRNS, DAE, for the financial support towards publication of this Thematic Bulletin.

Research Reactors of India (Part I):
High Flux Research Reactor

Table of Contents

It is with great pleasure that I present this volume on "Research Reactors of India (Part I): High Flux Research Reactor". The part brings together basic features of the High Flux Research Reactor (HFRR) including design of major systems, core components, safety aspects and various facilities envisaged to meet diverse need of researchers, academia and the industry in the field of nuclear science.

Research reactors are crucial in the development of advanced fuels and reactor structural materials as these are exposed to a demanding combination of environments - high temperature, intense irradiation and corrosion. Research reactors provide various irradiation utilization facilities along with associated instruments. These utilities will provide neutron sources for performing neutron scattering experiments, production of radioisotopes, testing of new nuclear fuel and other materials, neutron transmutation, neutron activation analysis, neutron radiography etc. Design, development, qualification, and deployment of such facilities are possible solely by seamless integration of multidisciplinary activities. This bulletin highlights such integrated efforts through contributed papers from the scientists and engineers working across the spectrum.

These articles also cover details of engineering design of systems, structures and components of HFRR including the specific features envisaged for in-core material test device, corrosion test loop, cold neutron source facility, fuel test loop, pneumatic carrier facility, neutron transmutation doping of silicon and advanced facilities for carrying out neutron scattering experiments. Collectively, they provide the reader with a comprehensive picture of design and utilisation of the advanced research realisable with HFRR.

I compliment the Guest Editors and all the contributing authors for their sustained efforts in meticulous compiling of this volume and also the team of IANCAS, for publishing this bulletin. I am sure that this publication will serve as a valuable reference for researchers, engineers and students engaged in nuclear science and neutron beam research activities.

Joe Mohan
Director, Reactor Projects Group
BARC, Mumbai

From Editor's Desk

Nuclear Research Reactors with neutron as the probe in terms of neutron flux or neutron beam have got immense contributions towards Radioisotope Productions, Research in many frontier areas using Neutron Scattering for condensed matter research, Neutron Radiography and Imaging, Neutron Activation Analysis for major to trace element determination, Nuclear Fission and Reaction, Materials Irradiation and Testing. In addition, research reactor produced radioisotopes Co-60, Mo-99, Lu-177, I-131, I-125, Br-82, Sc-46, Au-198 are playing key role in societal and industrial applications in the areas like nuclear medicine, food irradiation and processing, agriculture, and many industries. In view of the enhanced requirements towards departmental, societal and industrial applications, a 40 MWt High Flux Research Reactor (HFRR) is being proposed to be constructed at Visakhapatnam, Andhra Pradesh. The proposed reactor with low Enriched Uranium dispersion type fuel and light water as coolant and moderator will have a maximum thermal neutron flux of 1×10^{15} n/cm^2/s. This reactor will have various facilities for advanced research, materials testing and radioisotope production catering diverse needs of our country and even useful for industrial/commercial applications.

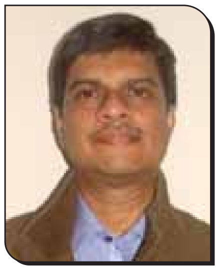
The current issue of the IANCAS bulletin on "Research Reactors of India (Part I): High Flux Research Reactor" gives a broad overview of HFRR in terms of its specifications, flux and facilities as well as various research and development activities that can be pursued. It is a well-designed bulletin which consists of nine articles.

On behalf of IANCAS, I thank all the authors of the articles for sharing their exhaustive research and development works for making this bulletin an important one. On behalf of IANCAS, I would like to sincerely thank the Guest Editors of this issue Dr. Samiran Sengupta, OS & Head, RRDPD, RPG, BARC, Dr. Tej Sigh, OS & Head, RPNES, RG, BARC, and Shri Aniruddha Ghosh, RRDPD, RPG, BARC for bringing out this important issue of IANCAS bulletin. I am also thankful to Shri Joe Mohan, DS & Director, RPG, BARC for his support & encouragement and also for his message.

Sincere thanks to President, Vice Presidents, Secretary & all other EC members of IANCAS for the continued support and time to time suggestions to bring out such type of thematic bulletins relevant for DAE, Industry and Society. I sincerely thank Dr. A. K. Mohanty, Chairman, AEC & Secretary, DAE, and Shri Vivek Bhasin, Director, BARC, for their continued support towards IANCAS activities and IANCAS publications. On behalf of IANCAS, sincere thanks and acknowledgement to Board of Research in Nuclear Sciences (BRNS), DAE, Chairman, BRNS and Scientific Secretary & Head, BRNS for their support and granting funds towards IANCAS publications of such relevant thematic bulletins.

Raghunath Acharya
Head, IRAD, BARC
Editor, IANCAS

President's Message



Dear friends,

Greetings!!

In our endeavour for popularizing Nuclear Sciences and Engineering, and Applications of Radioisotopes, IANCAS (Indian Association of Nuclear Chemists and Allied Scientist) has been bringing out Thematic Bulletins on key topics on DAE activities. As you are aware, development of reactor technology is one of the most important as well challenging mandates of DAE. This is required in view of the increasing energy demands, to meet the 'Net Zero' target set by the Indian Government and also to cater to the fast increasing demands for radioisotopes in various sectors of the society.

The present bulletin "Research Reactors of India (Part I):High Flux Research Reactor" is focussed on the proposed High Flux Research Reactor (HFRR) to be built at the upcoming BARC campus at Vishakhapatnam, in the near future. The bulletin gives a broad overview and insights into the recent developments and advanced facilities proposed for the upcoming HFRR in order to meet the current and future requirements of researchers, academia, health sector and industry. The proposed reactor will provide higher neutron flux as compared to existing Indian reactors. Due to the projected higher flux, HFRR will be a unique facility for radiation damage testing of materials, and doping of silicon wafers and advanced neutron scattering experiments for condensed matter research. A number of colleagues from the Reactor Projects Group (RPG) led by Dr. Samiran Sengupta, Head, RRDPD, BARC, have contributed to this thematic bulletin.

I would like to extend my sincere appreciation to the Guest Editors of this important issue, Dr. Samiran Sengupta and Shri Aniruddha Ghosh, both from RPG and Dr. Tej Singh Head, RPNES, Reactor Group, BARC. On behalf of IANCAS, I thank Shri Joe Mohan, Director, RPG, for his support. I also thank all contributors of this bulletin for the praiseworthy job in preparing excellent articles to make this a very valuable and informative volume. I also thank all EC members of IANCAS, especially the Vice-President (HQ), Secretary and Editor for their efforts and acknowledge the support of BRNS, DAE for funding.

P. K. Mohapatra
Former Director, RC&IG, BARC
President, IANCAS

From Secretary's Desk

Indian Association of Nuclear Chemists and Allied Scientists (IANCAS) was founded in 1981 with an objective of popularizing nuclear and radiochemistry, applications of radioisotopes, and nuclear techniques among the scientific community in India. For this purpose, IANCAS is continuously organizing seminars, workshops and publishing periodic thematic bulletins focused on fundamentals of nuclear and radiochemistry, and applications of radioisotopes in education, research, agriculture, medicine and industry. With active participations of the life-members, IANCAS has become one of the popular associations for popularizing the subject of nuclear and radiochemistry across the country.

IANCAS through its various outreach programmes motivate the young researchers and scientists to apply nuclear and radiochemistry based methods in their respective research field. In addition, IANCAS life-members through IANCAS activities motivate students to pursue a career in the field of nuclear science. For the promotion of nuclear science among the researchers, IANCAS has instituted three Awards; (i) Dr. M. V. Ramaniah Memorial Award, (ii) Dr. Tarun Datta Memorial Award and (iii) Prof. H. J. Arnikar best thesis Award. All these three Awards are conferred annually. The details of these Awards are available at the IANCAS website (www.iancas.org.in)

IANCAS conducts National Workshops and Outreach Programmes at Indian Universities and colleges. IANCAS also regularly publishes thematic bulletins on the topics directly related to the nuclear science and technology with the financial support from BRNS, DAE. These bulletins are available free to all the IANCAS life-members, and are made freely available at IANCAS website (www.iancas.org.in) for download.

In the series of IANCAS bulletins, the present bulletin titled "Research Reactors of India (Part I): High Flux Research Reactor" aims at giving details of design, developments and some applications of the proposed High Flux Research Reactor. IANCAS thanks to all contributors/authors of the articles for sparing their valuable time and in making such an important bulletin possible. I sincerely thank, Dr. R. Acharya, Editor, IANCAS, and the Guest Editors Dr. Samiran Sengupta, Head, RRDPD, RPG, BARC, Dr. Tej Singh, Head RPNES, RG, BARC and Shri Aniruddha Ghosh, RRDPD, RPG, BARC, for their efforts in bringing out this important thematic bulletin.

Sandeep Kumar Sharma
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Preface from Guest Editors

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Research reactors have been the cornerstone of progress in nuclear science and technology worldwide, offering unparalleled capabilities for fundamental research, applied sciences, and technology development. They provide advanced facilities for studies related to nuclear fuels and reactor materials, production of radioisotopes, neutron transmutation doped silicon, neutron activation analysis, and a wide spectrum of neutron-based experimental techniques. Through these multifaceted roles, research reactors contribute not only to scientific advancement but also to strategic national programmes and societal development.

India has a distinguished and sustained legacy in neutron based research. Neutron scattering research in the country commenced with the Apsara reactor and subsequently evolved through the CIRUS reactor, maturing further at the Dhruva and Apsara-U reactors. Over several decades, these facilities have nurtured a vibrant and expanding research ecosystem involving scientists from DAE units, universities, and national laboratories. This growth has been strongly supported by collaborative frameworks such as the UGC–DAE Consortium for Scientific Research and the Board of Research in Nuclear Sciences (BRNS).

Furthering this rich legacy, High Flux Research Reactor (HFRR), a state-of-the-art pool-type research reactor, is going to be constructed at the BARC campus, Visakhapatnam. Designed to deliver significantly higher neutron flux and equipped with a host of advanced neutron beam stations, HFRR will substantially elevate the nation’s neutron scattering research capabilities. A particularly noteworthy feature is the cold neutron source, first of its kind in India, which will unlock new opportunities in materials science, condensed matter physics, chemistry, soft matter, and biological research. With its world-class neutron beam instrumentation, HFRR is poised to place India firmly among the global leaders in neutron-based science and technology.

In addition to its beam research capabilities, HFRR will host a diverse range of irradiation facilities of high technological and societal relevance. These include facilities for advanced radioisotope research and production of neutron transmutation doped (NTD) silicon to meet the growing demand for high quality semiconductor materials. Furthermore, in support of India’s expanding nuclear programme, HFRR will provide specialized experimental facilities such as the Fuel Test Loop and Corrosion Test Loop, for the qualification and validation of nuclear fuels, materials, and components for future advanced reactors.

While being an advanced and highly versatile research reactor, HFRR accords the highest priority to safety in both design and implementation. The reactor incorporates a comprehensive set of inherent safety features, and engineered systems which ensure safe and trouble free operation throughout its service life. With its long-term operational vision and multifaceted experimental capabilities, HFRR will significantly strengthen India’s research reactor based capabilities for decades to come and will play a vital role in advancing scientific excellence, technological self-reliance, and the nation’s journey towards Viksit Bharat.

We express Gratitude to the EC of IANCAS for facilitating this volume and hope that this compilation will provide insights into the High Flux Research Reactor to researchers and technologists in the nuclear community as well as any seeker wishing to delve into this fascinating field.

High Flux Research Reactor – An Overview

Samiran Sengupta*, Aniruddha Ghosh, Vijaya K. Veluri, Prince K. Jain, Istiyak Khan, V. Shrivastava, A. Saha, D. Singh, N. C. Gohel, Arvind K. Singh, V. K. Kotak, P. K. Guchhait, Runner Ghosh, Joe Mohan#

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Abstract

At present, Dhruva and Apsara-U reactors provide the majority of the research reactor-based facilities to meet the diverse research needs of the vast pool of researchers from DAE and various other academic institutions of the country. In order to expand the horizon and scope of research and development in nuclear and allied sciences, a new 40 MWt High Flux Research Reactor (HFRR) is being developed by BARC. The proposed HFRR is planned to be built in the BARC Campus at Visakhapatnam in Andhra Pradesh on the eastern coast of India. This article describes some of the design features and safety aspects of this reactor.

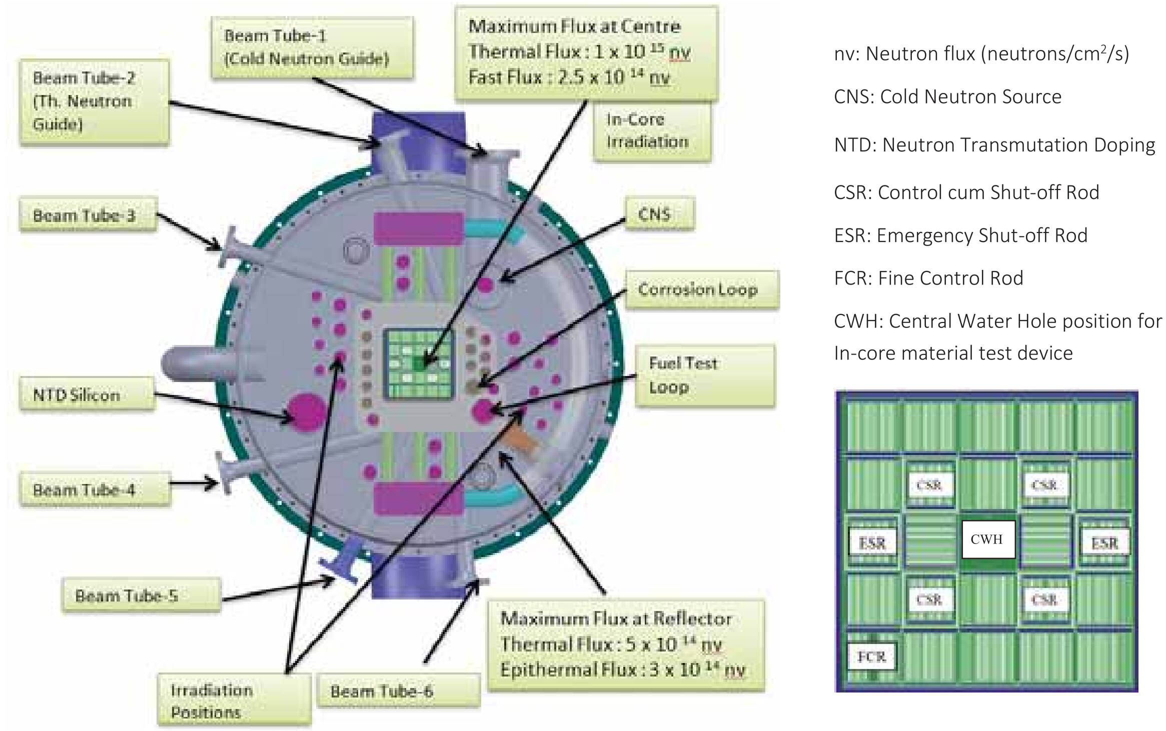
Keywords: *Pool type reactor, Reflector vessel, Fuel assembly, Irradiation studies, Reactor pool, Service pool, Delay tank.*

1. Introduction

Research reactors with high neutron flux play a crucial role in providing unique facilities for basic research in frontier areas of science and for applied research related to development and testing of nuclear fuels and other materials. These reactors also support advanced research in the field of radioisotopes for wide range of applications in agriculture & food irradiation, medicine & healthcare, industry and research. Keeping in view of the advanced requirements of the academia and the industry for neutron beam research, fuel & material irradiation studies, and production of radioisotopes for medical and industrial applications, design of a high flux research reactor (HFRR) proposed to be constructed at Vizag has been undertaken. It is a pool type nuclear research reactor with compact core using low enriched uranium fuel, light water as the coolant & moderator and heavy water as the reflector.

The HFRR with its high neutron flux and irradiation volume will provide an appropriate platform for carrying out research in reactor fuels and structural materials, condensed matter research for study of structure and dynamics of materials, stress analysis of engineering components especially reactor materials, dynamic radiography, time of flight refractometry. It will also cater to the study of opto-electric materials, protein crystals, fullerenes, porous-silicon, etc., including high pressure and milli-Kelvin range studies which will greatly help the nation to keep abreast of the developments in the field of material sciences and development of novel materials and alloys.

The proposed 40 MWt research reactor will have a maximum thermal neutron flux and fast neutron flux of 1×10^{15} n/cm^2/s and 2.5×10^{14} n/cm^2/s respectively. The reactor will be fueled with Low Enriched Uranium dispersion type fuel and will use light water as coolant and moderator. The reactor core will be surrounded by an annular heavy water tank to achieve a high neutron flux and irradiation volume to maximize the number of irradiation positions available for isotope production and material irradiation. Most of the irradiation positions will be accommodated in the heavy water reflector vessel surrounding the core.



(a) Experimental facilities

(b) Core configuration

Figure 1. Core configuration along with experimental facilities of HFRR.

2. Salient Design Features

The reactor core is constituted by 25 lattice positions laid in a square pitch of 81.7 mm. The nominal equilibrium core consists of seventeen standard fuel assemblies, six control fuel assemblies, one fine control fuel assembly and one central irradiation position. The core is surrounded by 900 mm thick heavy water reflector. The reactor has been designed with a compact core for achieving high neutron flux level and the central position with highest neutron flux of 1×10^{15} n/cm^2/s is made available for in-core material test device. Incorporation of a large heavy water reflector vessel around the reactor core helps in sustaining high thermal neutron flux over a large radial distance where most of the experimental/irradiation positions are easily accommodated. The core configuration along with experimental facilities in the reflector vessel is shown in Fig. 1.

The HFRR core will be loaded with plate type fuel assemblies. The fuel meat is loaded with Low Enriched Uranium (19.75%, w/w U^{235}) in the form of U_3Si_2 dispersed in aluminium matrix. A uniform narrow gap is maintained between the fuel plates for coolant flow through the assemblies for efficient heat transfer from the core. Fuel assemblies are of three types: (i) Standard fuel assembly (ii) Control fuel assembly and (iii) Fine control assembly. A standard fuel assembly consists of 20 fuel plates and two Al-alloy inert plates. The control fuel assembly is similar to standard assembly with 17 plates. The cross section of control fuel assembly is reduced to accommodate box type control element made of Hafnium. Out of 6 Control fuel assemblies, 4 assemblies are called control cum shut-off rods (CSRs) and 2 assemblies are called Emergency shut-off rods (ESRs). CSRs are always placed inside the active core region during normal operation of the reactor and ESRs are parked above the core region to allow them to fall by gravity on specific signal of reactor trip. The Fine control assembly is similar to standard assembly with four fuel plates removed to create space for accommodating the Hafnium control blade absorber element.

Table 1. Salient Design Features.

Reactor Type	Pool type
Nominal Fission Power	40 MWt
Maximum Thermal Neutron Flux	1.0×10^{15} n/cm^2/s (at In-Core irradiation position)
Maximum Fast Neutron Flux	2.5×10^{14} n/cm^2/s (at In-Core irradiation position)
Maximum Thermal Neutron Flux	5.0×10^{14} n/cm^2/s (in Reflector vessel)
Core Design features	Dimensions of core: 421mm x 421 mm x 600 mm Lattice Configuration: 25 positions (5 x 5)
Fuel	LEU Uranium Silicide (U_3Si_2) dispersed in aluminium.
Reflector	Heavy Water (inside annular reflector vessel)
Reactivity Control Devices	Control cum Shut-off Rods (CSRs) made of Hafnium Emergency Shutdown Rods (ESRs) made of Hafnium Reflector Heavy Water
Shutdown System Configuration	Shutdown System-1 (SDS-1): Gravity dropping of 4 CSRs Shutdown System-2 (SDS-2): Gravity dropping of 2 ESRs along with heavy water reflector dumping
Primary Coolant and Moderator	Demineralised Water
Normal Cooling	Forced convective, upward flow
Shutdown cooling	Forced convective, upward flow for 4 hours after shutdown Natural convection for long term shut down cooling
Secondary cooling	Cooling tower system
Reactor Building	Containment
No. of Beam tubes	Six
Irradiation/Experimental positions in reflector region	Irradiation positions: ~ 30 Pneumatic Carrier facility: 1 Neutron Transmutation Doping: 1 Pneumatic carrier facility for Neutron Activation Analysis: 1 Fuel Test Loop: 1 Corrosion Test Loop: 1

The reactor has been designed with an aim to keep sufficient reactivity margin to operate for complete fuel cycle. The shutdown systems have sufficient negative reactivity to shut down the reactor at any time. The reactor has two independent shut down system. The first shutdown system consists of 4 Control cum shut-off rods (CSRs). The

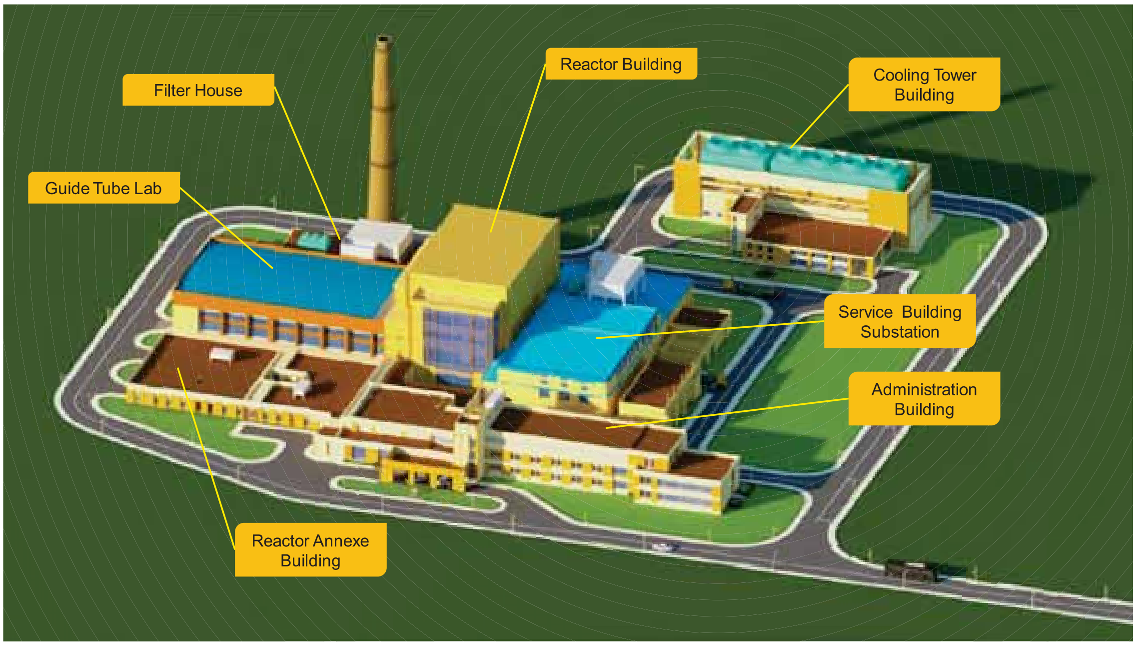


Figure 2. Overall plant layout of HFRR.

second shutdown system consists of two Emergency shut-off rods (ESRs) along with dumping of heavy water in the reflector vessel. Four CSRs and one fine control rod (FCR) control the core reactivity through the operating cycle. Salient design features of the proposed reactor are shown in Table 1.

3. HFRR plant layout

The overall plant layout of HFRR is shown in Fig. 2. The reactor building is a rectangular RCC building located at the center of the reactor complex. Entry to the reactor building is through the Personnel Air Locks (PAL) and Vehicular Air Lock (VAL). The reactor building houses the reactor pool block, primary coolant system, reflector cooling system, hot water layer system, cover gas system, pool cooling system etc. The Control building which houses the Main Control Room is also a part of the reactor building.

The Service Building located adjacent to the reactor building houses the Supplementary Control Centre, Fresh Air and Compressed Air Supply Systems, Machinery Cooling Water System, Ventilation supply fans etc. On the terrace there are Emergency Water Storage Tank (EWST), Cooling towers for Machinery Cooling water system & Decay Heat Removal System. There are adjacent HT transformer yard, Electrical Substation and Diesel Generator Rooms. The Substation building houses the HT and LT buses, battery banks for plant equipment and instrumentation and control equipment supplies.

The Filter House building houses main exhaust fans, emergency exhaust fans, filter house & guide tube lab exhaust fans and their associated dampers. An Emergency Water Storage Tank is provided on the terrace of this structure. The basement houses ion exchanger beds, main effluent collection sumps, their pumps and associated electrical panels. The exhaust air from reactor building, guide tube lab, decontamination and change rooms and filter house is released to the environment through a stack located behind the filter house.

Guide Tube Building is located adjacent to the reactor building to house two numbers of neutron guides with a number of positions for installation of instruments for physics experiments. The reactor annex building and administration building are also located adjacent to the reactor building. The cooling tower building structure is located outside the vital area boundary of the reactor complex. It houses induced draft cooling towers in the first floor. The secondary cooling water pumps which feed the cooling towers are located in the ground floor.

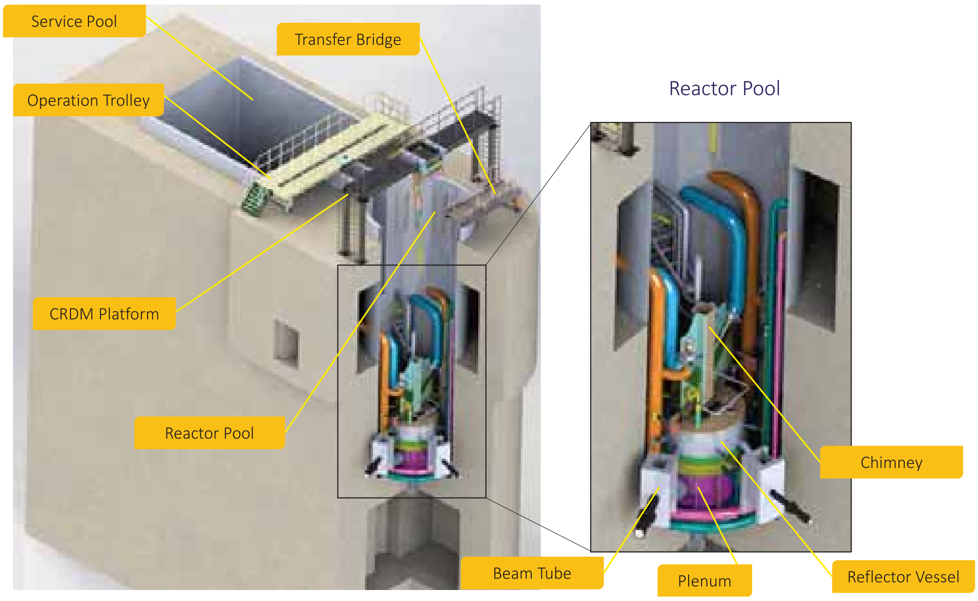


Figure 3. Reactor Pool Block of HFRR.

4. Reactor Pool Block

The Reactor Pool Block is an RCC Structure made of high-density concrete. Stainless steel tanks of Reactor Pool and Service Pool are embedded in the concrete. The reactor pool is cylindrical in shape of 5 m diameter x 13.5 m deep and the service pool is cuboidal having size of 6.6 m x 8 m x 8.9 m deep. The two pools are interconnected by a transfer canal. The Reactor Pool houses the reactor core, and the Service Pool is used for storage of irradiated assemblies. Both pools are filled with demineralised light water which ensures core submergence and provides radiation shielding to the pool top areas. The service pool is designed to store the spent fuel assemblies. The transfer canal provides a path through which spent fuel is transferred from the core to the service pool. Two tracks are also laid on either side of the pool tanks for the movable platforms (Operation Trolley and the Transfer Bridge) for transferring fuel/ isotope irradiation rods from the reactor pool to the service pool. A fixed platform namely control rod drive mechanism (CRDM) platform above the core at pool top is also provided to serve as support for control rod drives. Fig. 3 shows a three-dimensional view of the Reactor Pool Block structure.

The enlarged view of the reactor pool shows the reactor core components housed inside the reactor pool. The major components of the core structure include Plenum, Reflector Vessel, Chimney and Neutron Beam Tube Assemblies. The reactor pool is 13.5 m deep with concrete wall thickness of 2.4 m, which provides requisite biological shielding in radial direction. The pool water provides shielding against radiation in axial as well as in radial direction and also acts as moderator and coolant for the reactor core. The pool water also acts as the heat sink in the event of non-availability of forced cooling. An elevation view of the rector pool shows the location of reactor core (fuel assemblies), coolant inlet/outlet lines, inlet plenum, grid plate, intermediate plenum, reflector vessel, chimney, fuel locking mechanism in Fig. 4.

The Fuel Locking Mechanism (FLM) provides safe retention of fuel assembly within the core and prevents the ejection or dislocation by the high velocity primary coolant flow. The FLM is located inside the inlet plenum and the Fuel clamping tools are guided through an embedded block to the Fuel Clamp Room situated below the reactor pool. The hydraulically operated mechanism is provided

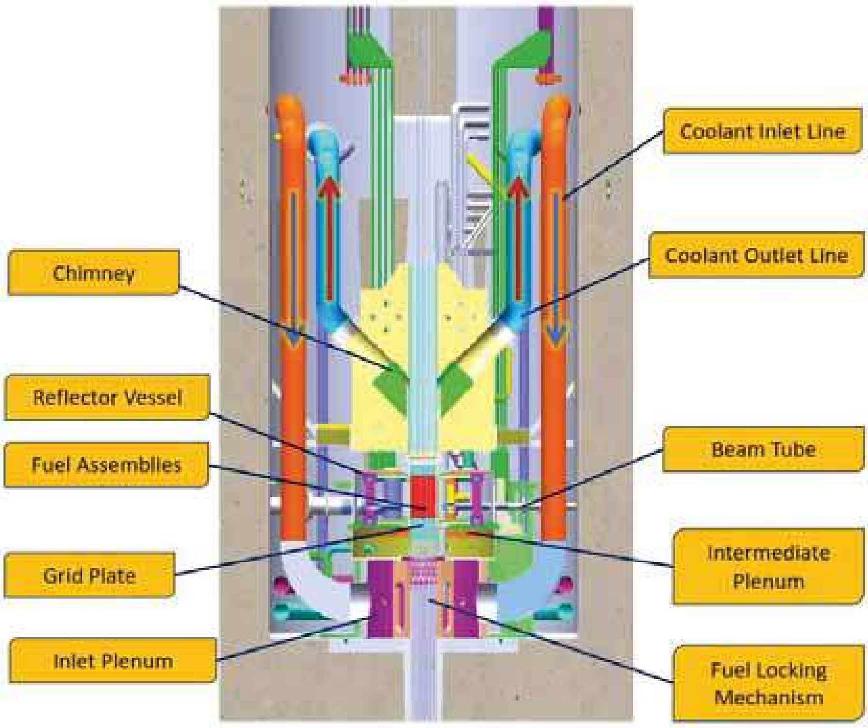


Figure 4. Elevation view of Reactor Pool with major core components of HFRR.

in the Fuel Clamp Room and this facilitates clamping each fuel at its extended toe region. Each fuel assembly is individually locked at its bottom end against the drag force in upward direction generated by coolant water flow.

Six numbers of tangential beam tubes are provided around the reactor core. These Beam Tubes guide neutrons from reflector region to the experimental devices in the reactor hall/ Guide tube laboratory. The Beam Tubes are adequately spaced to facilitate setting up of experimental set-ups in the reactor hall and Guide tube laboratory.

5. Process and Auxiliary systems

HFRR has a number of process systems which function to remove heat, maintain chemistry and radiological parameters within specified limits. There are also Auxiliary systems such as Machinery cooling water system, Compressed Air system, Effluent Management System, Service Water System, Fire Protection System related to operation of the plant.

5.1 Primary Coolant System

The reactor core is cooled by primary coolant system which consists of two independent loops, each comprising of two main coolant pumps with two plate type heat exchangers. The primary coolant system water which flows from the bottom to the top of the core through the fuel assemblies is led to the chimney. The main coolant pumps take suction from two arms of the chimney (one arm for each loop). The water is drawn by the pumps through the delay tanks for decaying the short-lived activities like ^{16}N and subsequently through the heat exchangers for transferring heat to secondary coolant system. From the pump discharge, about 90% of the total pump flow is sent to the inlet plenum for providing core cooling and the balance 10% is sent directly into the pool bypassing the core. This bypassed 10% of the pump flow is sucked downward due to flow balancing from the pool into the chimney where it mixes with the upward flow from the core. This chimney and the flow arrangement

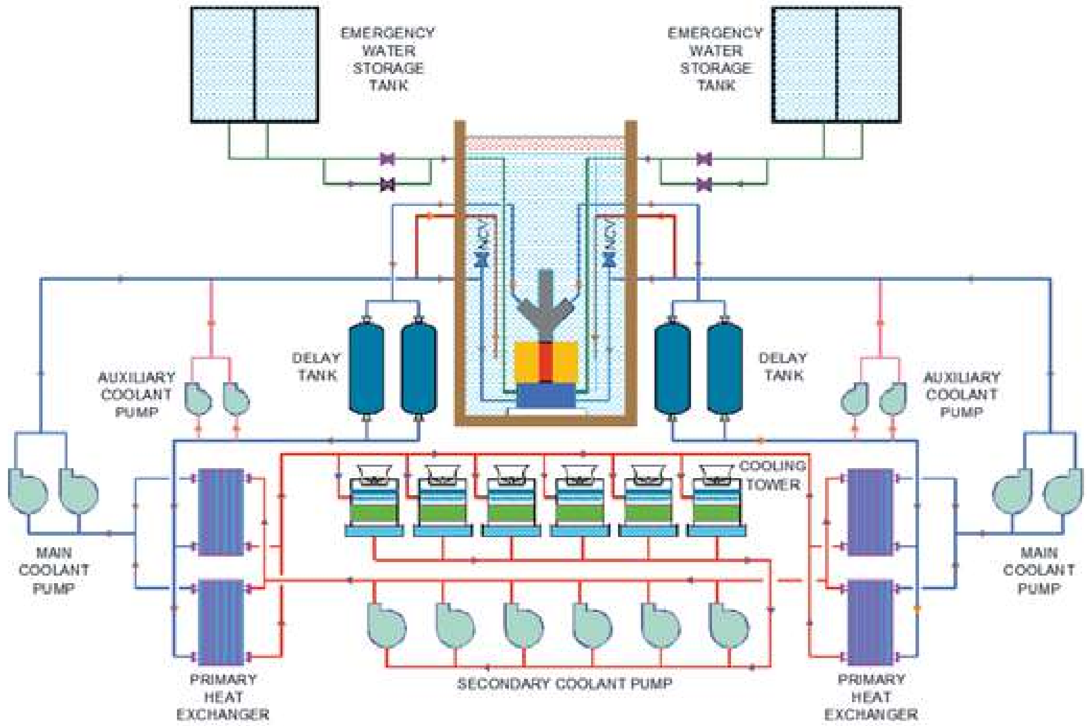


Figure 5. Schematic flow diagram of Primary and Secondary coolant systems of HFRR.

establishes that the core coolant which flows upwards is always restricted well within the chimney region [1]. Thus, coolant from reactor core is prevented from reaching the reactor pool top and the pool top radiation field is well within the acceptable limit.

In case of class IV power supply failure, the reactor will trip and all the main coolant pumps (MCPs) will provide adequate coast down flow to ensure that the maximum fuel and clad temperatures are well within the acceptable limits. On non-availability of MCPs, the auxiliary pumps (XCPs) will start automatically to take care of transporting the decay heat from the core. The decay heat of the reactor is deposited in the reactor pool. After 4 hours of forced cooling by the XCPs, the reactor decay heat is low enough to be cooled by natural convection of the pool water. Two natural circulation valves (NCV) [2], one in each loop will open automatically to ensure long term shutdown cooling of the reactor.

In the unlikely event of breakage of piping or breakage of beam tubes, the pool will start to lose inventory of water. In this case, the Emergency core cooling system (ECCS) can be used to introduce water directly to the inlet plenum from two Emergency Water Storage Tanks (EWST). These tanks will supply water to the inlet plenum through gravity flow.

5.2 Secondary Coolant System

Secondary Coolant system removes heat from the primary coolant system and transfers to the atmosphere through cooling towers. The system consists of Six centrifugal pumps (four operating, two standby) and induced draft counter current cooling towers having six cells (four operating and two standby).

5.3 Heavy Water Reflector System

Heavy water of high isotopic purity is filled in an annular reflector vessel surrounding the core to act as the neutron reflector. The Reflector vessel along with the vertical thimble positions and beam tubes provided to facilitate irradiation experiments and beam tube research is shown in Fig. 6. The reflector vessel is made from Aluminium 5052 alloy to

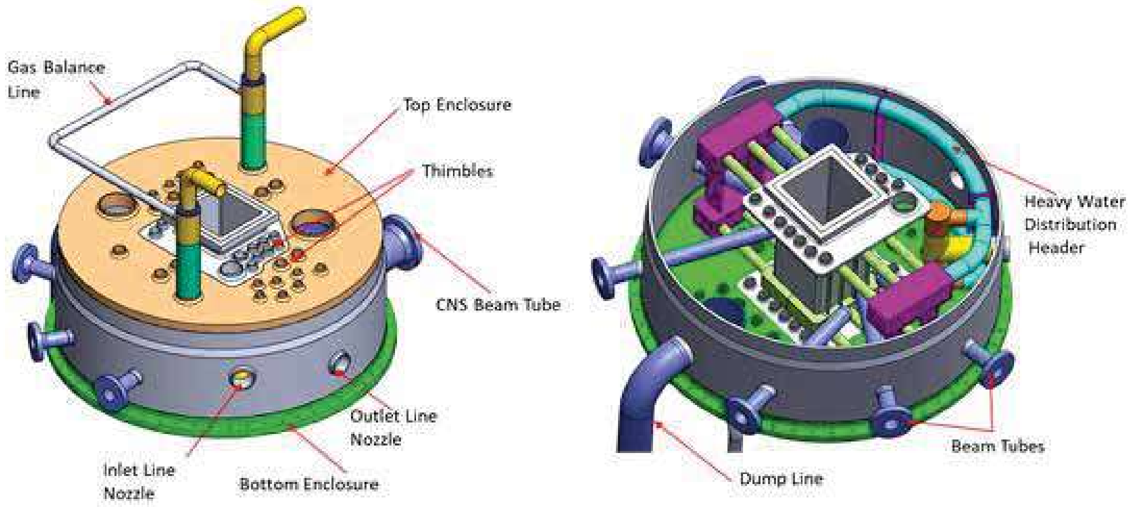


Figure 6. Reflector vessel thimble positions and internal structures.

provide adequate strength as well as neutron economy point of view. Heavy water is recirculated continuously through the reflector vessel to transport the heat generated in the heavy water reflector and its associated metallic structures [3]. Reflector vessel thimble positions and internal structures to facilitate flow distribution for cooling is shown in Fig. 6.

The heavy water recirculation system consists of two pumps (one operating), two heat exchangers (one in service), a delay tank and an expansion tank with associated piping and valves. Heat is ultimately discharged to atmosphere through cooling tower of decay heat removal system. The delay tank is provided at the reflector tank outlet to provide about 1 min delay [4] to reduce the radiation field due to ^{16}N activity on system piping and equipment in accessible areas. The expansion tank is riding on the system and helps to maintain heavy water system at the desired pressure and absorbs the volumetric changes due to temperature variations. It also provides continuous inventory status of heavy water in the system.

When power supply is not available to drive the main heavy water pump, the reactor will trip and one shutdown heavy water pump will start automatically to cater to the reflector vessel cooling requirements. On an emergency trip, the heavy water is dumped from the reflector vessel into a dump tank. This dumping is affected through four numbers of dump valves which fly open on emergency trip conditions.

5.4 Helium Cover Gas System

Helium is used as cover gas for heavy water system. Cover gas is used to maintain the heavy water pressure in the reflector vessel, expansion tank, dump tank, storage tank and drain tank in order to avoid the ingress of atmospheric air and moisture into the system. The helium system also is utilized to facilitate filling, draining and drying of all the system/equipment of heavy water system including heat exchangers, filters, ion exchangers, etc. The cover gas system consists of helium tank, recombination unit, pre-cooler, after-cooler, heater, flame arrester, gas holder, adsorber bed, freezer drier and blowers for recirculation of helium. During drying of equipment of heavy water system, helium is sent through each equipment to be drained and dried through freezer drier and/or absorber bed depending on the specific requirements.

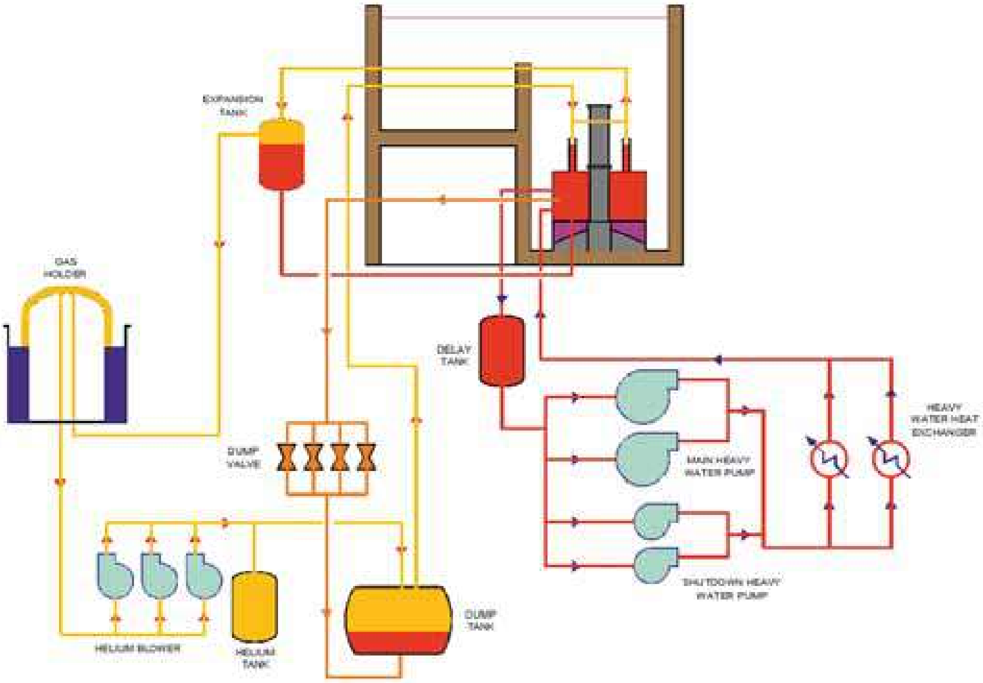


Figure 7. Schematic flow diagram of reflector system and cover gas system of HFRR.

5.5 Pool Cooling System

Pool cooling system provides cooling to all the irradiation assemblies located in the reflector vessel and the spent fuel stored in the service pool. The system mainly consists of one delay tank, three pool cooling pumps (PCPs), two plate type heat exchangers, two shutdown pool cooling pumps (SPCPs). Under normal operation, two PCPs and one Heat Exchanger are in operation. The pool water drawn downward through the irradiation assemblies is sent through a delay tank that provides a delay of about 1 min due to which the short-lived radio-nuclides decay. After the delay tank, the water enters the heat exchanger where the heat is exchanged with a light water system called Decay Heat Removal System (DHRS). The outlet of the heat exchangers joins the suction of the PCP which then circulates the water back to the pool, thus completing the circuit. The service pool water is also circulated through the heat exchangers and returned to the pool by the PCP.

5.6 Decay Heat Removal System

The Decay heat removal system (DHRS) is a light water system. It forms the secondary side of the Heat Exchangers of Pool cooling system and Heavy water reflector system. Circulation of the DHRS is carried out by pumps and the heat is finally rejected to the atmosphere by the use of DHRS Cooling towers.

5.7 Hot Water Layer System

A hot water layer system is provided in HFRR to maintain a layer of hot water (5 °C more than the temperature of pool bulk water) at the pool top. This layer of water (~ 2 m) always remains at the top of the pool owing to its lesser density resulting from the temperature difference. This layer of water maintains a barrier between the radioactive pool water and the pool top. The water in this layer is continuously circulated by the use of pumps (one operating and one standby). The temperature is maintained by the use of heaters and radiation-free clean barrier is maintained by the use of a purification circuit consisting of filters and ion exchangers (one operating and one standby). This clean layer of water thus provides shielding for the workers at the pool top.

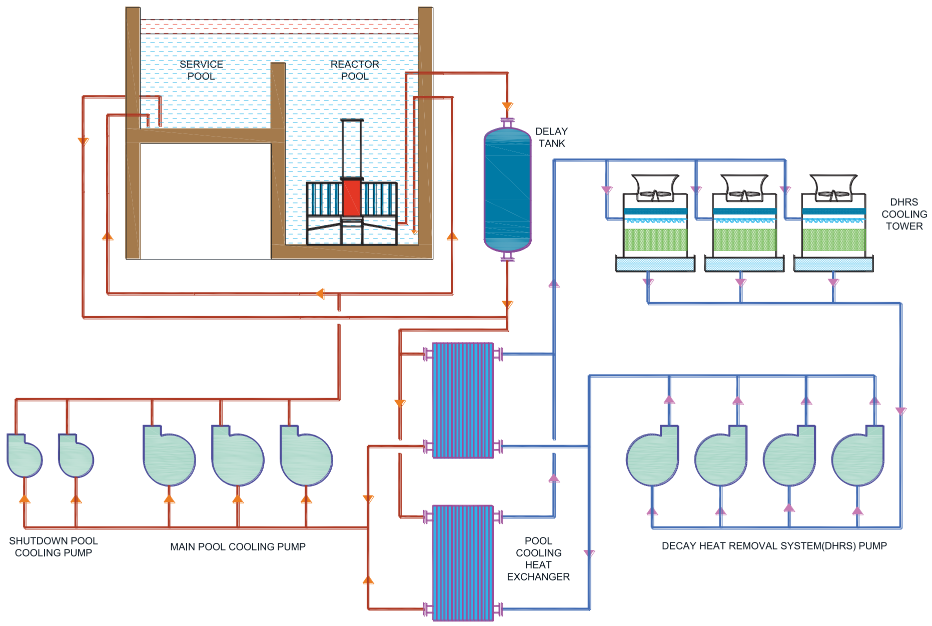


Figure 8. Schematic flow diagram of Pool cooling and Decay heat removal systems of HFRR.

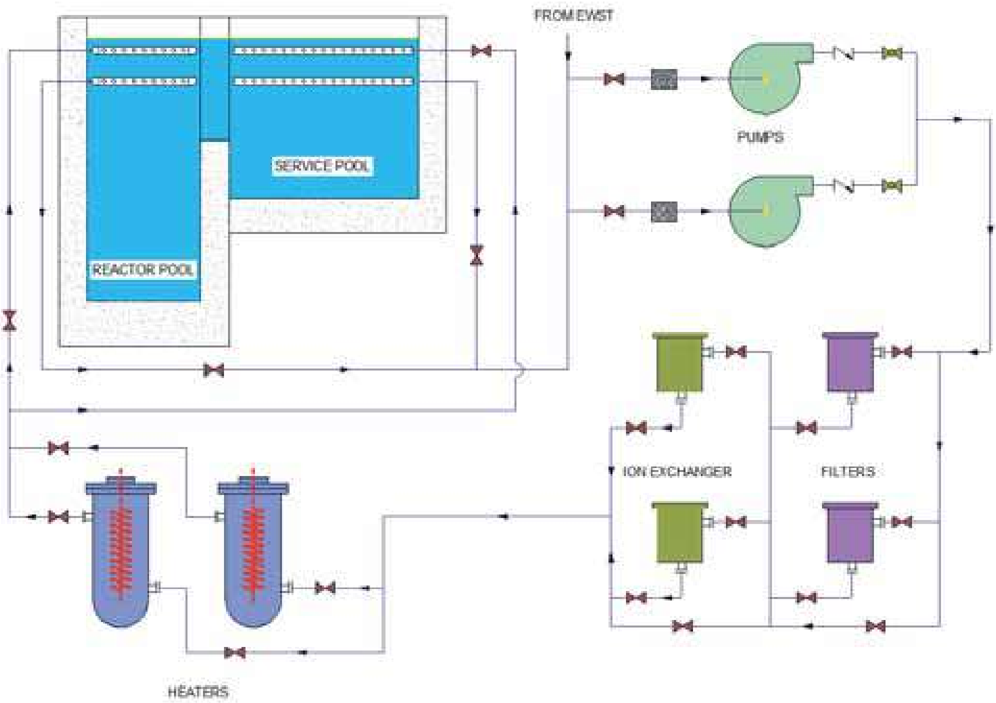


Figure 9. Schematic flow diagram of Hot water layer system of HFRR.

6. Instrumentation and Control System

The Instrumentation and Control (I&C) System is designed for three major functions (i) to monitor parameters and take automatic control actions to maintain the reactor in a safe state (ii) to provide timely and accurate operator information regarding plant parameters so as to allow operator to take prompt and correct actions (iii) to automatically archive parameters so that post event analysis is made possible. In order to achieve these functions, I&C System is designed with Field Instruments for measurement of nuclear, process and radiation parameters and to transmit the data to automatic control systems or to operator information systems in the Main and Supplementary Control Centres in order to facilitate automatic and manual control actions. These systems are classified into four safety classes in decreasing order of importance to safety i.e., IA, IB, IC and NINS systems.

As a centralized facility for control and monitoring of the reactor, a Main Control Centre is provided. This Main Control Centre comprises of the Main Control Room, (MCR) Instrumentation Rack Area, and Cable Room. The MCR has equipment to indicate & display various plant parameters. There are controls in the MCR to be used by the operator as inputs to control the functioning of systems and equipment. In case of un-inhabitability of the MCR, reactor safety is ensured through the Supplementary Control Room.

Nuclear Instrumentation is provided to measure the neutron flux from a very low range to the maximum power level of 40 MW. In the source range, Fission Chambers are provided to monitor the low levels of neutron flux. In the intermediate and power ranges, ^{10}B Lined Ion Chambers are provided. Field instruments for measuring process parameters are pressure transmitters, pressure gauges, differential pressure transmitters, RTDs, thermocouples, level switches etc. Radiation monitors are provided to monitor plant areas and process systems to detect the presence of radioactive releases.

HFRR has been designed with two independent shutdown systems, Shutdown System-1 (SDS-1) and Shutdown System-2 (SDS-2). The SDS's are safety systems which trip the reactor whenever certain parameters exceed the trip settings. SDS-1 actuates the dropping of 4 numbers of CSRs. SDS-2 actuates the dropping of two ESRs and opening of 4 Dump valves leading to reflector dumping.

Four nos. of computer based systems are employed in HFRR. They are Reactor Protection System (RPS), Reactor Regulating System (RRS), Alarm Annunciation System (AAS), Computerised Operator Information System (COIS). The reactor protection system monitors key nuclear and process parameters important to reactor safety and automatically initiates tripping of the reactor in order to maintain the reactor parameters within safe limits. Reactor Regulation System carries out functions required for automatic/manual start-up, shutdown and regulation of reactor power. RRS controls the movement of Fine Control Rod (FCR) and Control cum Shut-off Rods (CSRs). Alarm Annunciation System (AAS) is used to alert the operator of any abnormal behaviour of various nuclear & process system parameters, subsystems, components and instrumentation. Computerized Operator Information System (COIS) is a data acquisition, data logging and data display system. This system provides displays of current and historic information regarding various plant parameters, alarm messages, status displays of equipment etc.

7. Ventilation and Air Conditioning System

Ventilation and Air-conditioning system of HFRR caters to all the requirements of the reactor building, service building, annexe building, guid-tube lab and filter house. Reactor building is provided with once through ventilation system. Containment isolation dampers are provided in the system to isolate the reactor building as and when required. Air treatment plant (ATP) is provided for supplying fresh filtered and conditioned air to the reactor building.

The ventilation system is designed to remove all the equipment heat load while maintaining temperatures within specified limits so as to ensure smooth functioning of equipment and a comfortable working environment for personnel. The ventilation system also ensures that airborne activity does not build up in any area. Active areas, such as beam tubes and associated gate chases, shielded rooms housing equipment of various process systems are maintained at lower pressure compared to adjoining areas. The exhaust air from the reactor building is passed through a bank of HEPA filters before it is released to the atmosphere through a stack.

8. Electrical Power Supply System

The electrical power supply system of HFRR is designed to provide a reliable and robust supply of power to various plant loads under both normal and off-normal operating conditions. Based on the nature of the power supply (AC or DC) and the permissible interruption duration, the electrical power supply system is classified into Class IV, Class III, Class II and Class I power supplies, consistent with the classification adopted for nuclear power plants. For each class of power supply, two independent divisions of electrical equipment with 100% redundancy are provided. Each division is independently capable of operating the reactor and ensuring its safe shutdown.

The Class IV power supply is derived from the Utility Centre-3 substation of BARC, Visakhapatnam. The incoming feeders are routed through physically separate routes to ensure independence. The Class III power supply comprising three buses, three Diesel Generator (DG) sets and associated switchgear. Two bulk diesel oil storage tanks are provided with sufficient capacity to support all safety-related loads of HFRR for a duration of seven days.

The Class II system derives its input from the Class III buses and provides regulated, filtered, and uninterrupted power to the Class II buses through dual-redundant Uninterruptible Power Supply (UPS) units. The Class I power supply is a two-wire ungrounded system that derives its input from the Class III buses through rectifiers and ensures uninterrupted DC power.

In addition to the power supply systems, the electrical system of HFRR includes lighting system, earthing system, lightning protection system, and power distribution system to various auxiliary loads of the HFRR complex. These systems are designed in accordance with applicable IS/IEC standards and AERB guidelines.

9. Safety features and Safety analyses

Some of the major safety features of HFRR provided are described below.

i) Being an open pool type research reactor, the reactor core is submerged and in direct communication with pool water without any intermediate pressure boundary.

ii) Large inventory of pool water allows that the reactor core can be at safe state in case of prolonged station black out scenario even up to 7 days from shutdown [5].

iii) Handling of all spent fuel and irradiation assemblies can be carried out under water and necessary shielding is provided by the depth of pool water.

iv) Long term shut down cooling is by natural circulation mode with pool water passing through a passive Natural Circulation Valve placed inside the reactor pool.

v) Reactor core cooling is ensured by forced flow provided by auxiliary pumps using DG sets or Class-II battery banks, when main coolant pumps are not available.

vi) Main control room and Supplementary

control room both are available and they are independently located to carry out safety functions.

vii) Negative Reactivity feedback coefficient for the reactor makes it inherently safer.

viii) Independent Shutdown Systems to take care of the trip/shut down of the reactor.

ix) Triplicated Channels are provided to ensure reliability on the tripping actions and to avoid any faulty trip.

x) Off-site Power supply is backed up by On-site supply from Diesel Generators, Battery Backed up UPS and DC supply.

xi) Hot water layer is provided on the top of the pool for limiting the radiation field as low as reasonably achievable.

xii) Emergency Water Storage Tanks are available to take care of the core cooling. They are two independent large overhead storage tanks and one of them is adequate.

xiii) Direct injection in to the inlet plenum during loss of coolant accident scenario for taking care of cooling of the reactor core.

xiv) Siphon breakers are provided to isolate the pool so that water draining from the pool can be stooped in case of break in any of the pool inlet/outlet pipe lines [6].

Safety analyses have been carried out to evaluate the capability built in the reactor to accommodate and control disturbances or failures in order to ensure that the overall safety objectives have been met for HFRR. This involves analysis of response of the reactor to various postulated initiating events (PIEs). Various postulated initiating events have been categorised into anticipated operational occurrences and accident conditions on the basis of their expected frequency of occurrence and potential radiological consequences. Thermal hydraulic transient analyses have been carried out for various PIEs to show that reactor safety is ensured [7-9]. It was observed that the maximum fuel and clad temperatures are well within the acceptable limits.

10. Critical Developments and Experimental Validation for HFRR

Main coolant pumps of HFRR are required to provide forced cooling flow of 14000 lpm (each pump) with head of 70 m water column during normal operation. Each main coolant pump is provided with a flywheel to achieve flow coast down time of about one minute. A prototype main coolant pump (Fig. 10a) having vertical pump-motor flywheel assembly configuration has been designed, manufactured and successfully tested as per ASME Section III, Subsection NCD and the general requirements of API 610. This is as a first-of-a-kind design of vertical flywheel pump to be deployed in Indian research reactors.

A natural circulation valve (NCV) was also designed to facilitate coolant flow by opening with the aid of gravity in the decay heat removal mode. The valve takes the benefit of buoyancy force to act against the weight of the valve disc and stem to facilitate closing of the valve at very low pressure [2]. When system pressure below the disk of NCV reduces to a very low value, the valve disk falls by gravity and flow path for natural circulation is established. The natural circulation valve (Fig. 10b) was manufactured and installed in an Experimental flow test facility (Fig. 10c) and successfully tested.

An experimental test loop has been constructed at HFRR assembly bay, located near the site at Visakhapatnam, for carrying out experimental validation of critical reactor components (including reflector vessel, chimney, plenum structure etc.) prior to their installation in HFRR. The prototype MCP developed was installed in the experimental loop followed by extensive testing of its performance. Another experimental loop comprising of electrically heated test sections with rectangular flow channels, simulating the plate type fuel elements of HFRR,

Figure 10. Development of critical components and their experimental validation.

Figure 11. Test set up facilities for experimental validation at HFRR assembly bay, BARC, Vizag.

has been erected and commissioned to carry out measurement of heat transfer characteristics. Test setup facilities for experimental validation of design of process systems and critical components are shown in Fig. 11.

11. Conclusion and future Outlook

The High flux research reactor (HFRR) with its high neutron flux and large irradiation volume will play a major role meeting the current state of art in scientific and technological domains and also future requirements of advanced experiments. The research facilities being provided cover neutron imaging studies, neutron activation analysis, studies on radio-isotopes, neutron scattering etc. The reactor will support development of new nuclear materials meant for advanced reactors. It will have advanced research facilities like ‘cold neutron source’ and ‘corrosion test loop’ which are developed as first-of-a-kind facility in research reactors in India. The reactor also has provisions for production of Fission Moly and neutron transmutation doped silicon. HFRR once built will serve as a national facility for carrying out neutron beam research with advanced facilities and instruments by DAE and non-DAE users.

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In-Core Material Test Device for HFRR

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Abstract

High Flux Research Reactor (HFRR) is a 40 MW(th) pool type research reactor. The proposed reactor will provide advanced facilities for basic neutronic research and test capabilities to study the behavior of material under irradiation for the existing as well as future reactors. Maximum neutron flux in HFRR at core center is 1.0×10^{15} n/cm^2/s (Thermal flux) and 2.5×10^{14} n/cm^2/s (Fast flux) respectively. An in-core irradiation device is provided for irradiation of material as well as experimentation under controlled temperature. This test device will benefit to characterize new materials considered in advanced and existing nuclear reactors for fuel, cladding, and structures which undergoes significant dimensional and physical changes during irradiation. The design characteristics of the material test device allows to host sample holder as well as highly instrumented test rig. A specific design of instrumented sample holder for creep study is presented here.

Keywords: *In-core material Test Device, Material Irradiation, Creep Test, High temperature.*

1. Introduction

Characterizing the effect of neutron irradiation on materials is important in order to assess the integrity and lifetime extension of operating and future nuclear plants. These materials can undergo significant dimensional and physical changes during irradiation. During the last few decades, numbers of tests have been performed in Material Test Reactors (MTRs) to analyze the degradation of mechanical properties as a function of fluence and temperature. These tests are generally performed in MTRs with instrumented/non-instrumented sample holders. The non-instrumented tests are performed wherein the specimen evaluations are completed outside the reactor after irradiation in reactor operating conditions. Therefore, non-instrumented experiments are comparatively simple in design and enable larger numbers of specimens to be tested at a time. On the contrary, the instrumented tests are complex in design. They are performed with online monitoring and controlling of test conditions and real-time detection of creep rate and other test parameters. These instrumented experiments are limited in existing MTRs due to space and test position availability.

The development of irradiations rigs for material studies under high neutron flux in MTRs caters to the conditions encountered in the core of nuclear power plants. Several rig designs have been dedicated to studies of tubular samples used for fuel cladding in light water reactors. The important design requirements for these rigs have been the ability to apply controlled uniaxial or biaxial load and to measure axial and/or radial strains under neutron irradiation. Irradiation creep elongation was investigated in the High Flux Reactor (HFR) at Petten using Trieste facility [1] where 49 specimens could be irradiated simultaneously at various stresses and temperatures. The typical neutron flux density in the Trieste irradiation position in the HFR is 2×10^{18} n/m^2/s corresponding to a displacement rate of 1.7×10^{-7} dpa/s. A study on in-pile/post-irradiation creep [2] under different neutron spectra was performed using uniaxial tensile specimens in the Japan Materials Testing Reactor (JMTR). Different levels of stress can be applied to two creep specimens using bellows pressurized by helium gas. The elongation of each creep specimen was measured using an LVDT. The temperature of the specimen was controlled at 550 °C using the electric heater installed in the capsule. As a part of the European Fusion Development Agreement (EFDA), in-reactor uniaxial tensile tests at a constant strain rate were performed in the BR2 reactor at Belgium [3]. KAERI has also developed specialized capsules for creep and fatigue testing [4]. The Melodie device [5] provides real-time elongation and change in diameter data from in-core irradiation of a PWR fuel cladding tube at 350 °C. The test capsule includes controlled mechanical loading ranging from 60 to 180 MPa and variable bi-axial stress ratio. In the creep tests [6], samples are small tensile specimens (2.5 mm diameter and gauge length 50 mm) prepared from unirradiated, solution annealed 304 and cold worked 316 stainless steels. The specimens are subjected to constant displacement conditions during irradiation in an inert environment to different fluences levels. Load is applied to the specimens via bellows by means of gas pressure.

Many studies have been carried out since last few decades towards development of instrumented experiments offering control over experimental variables and improved accuracy of data. Considering the current state of art for material testing, an In-core material irradiation device is proposed in HFRR for irradiation of material as well as experimentation under controlled temperature at the core center of HFRR.

2. In-Core Material Test Device

The in-core material test device in proposed HFRR mainly consists of containment device, head assembly and sample holder. It can house specific sample holder based on experimental needs. A thimble of outer dimension equivalent to control fuel assembly is designed and provided at core centre for hosting the material test device as shown in Fig. 1. The sample holder is immersed in NaK thermal media. Table 1 shows the salient design features and experimental conditions for the test device.

Table 1. Salient Design features and experimental conditions of Test Device.

Location of Test Device	Reactor Core Central Position
Max Fast neutron flux (> 1 MeV)	2.5×10^{14} n/cm^2/s
Max Thermal neutron flux	1×10^{15} n/cm^2/s
Sample cooling fluid	NaK
Sample Temperature	450 ºC
Targeted sample temperature variation	±10 ºC
Gamma heating	26 W/g
Maximum heat exchange	40 kW
Cover gas and Thermal gap gas	Helium

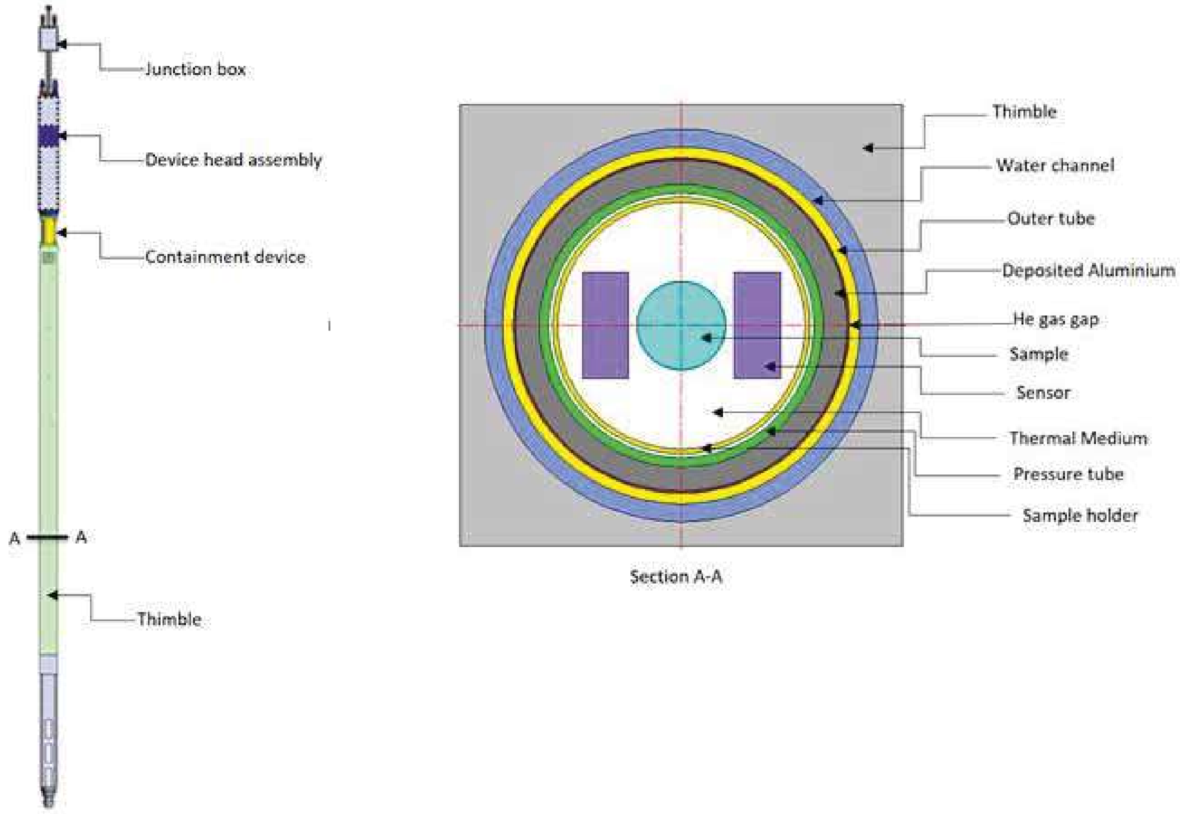

Figure 1. Design of In-Core Material Test Device.

2.1 Containment Device

Containment device is cylindrical in shape and with double wall construction to take care against possible hazard associated with thermal media. The schematic diagram of containment device is shown in Fig. 2. The internal diameter of pressure tube is 30 mm to accommodate the sample holder. Electric heating elements are placed on outer surface of the pressure tube ensuring fine control of temperature for the test samples and to adjust the temperature inside the thermal medium of pressure tube. The gas gap between the tubes is provided to ensure thermal insulation to reactor pool water. Maximum gamma heating will be 26 W/g. The sample cooling fluid is NaK and maximum heat exchange can be about 40 kW. The containment device is designed to meet the requirements of ASME Section III, Division 1, and Subsection NB being a safety class component. The stress analysis indicates that the induced stresses of containment device pressure tube and outer tube are well within the acceptable limits.

2.2 Head Assembly

The head assembly of the containment device hermitically seals the pressure boundary and provide space for electrical & instrument cables and tubing. Fig. 3 shows the schematic view of containment device head assembly with accessories. The design of device head facilitates monitoring of the interspace gas pressure, temperature, routing of various MI cables and tubing and also the connection of gas lines, electrical & instrument connectors.

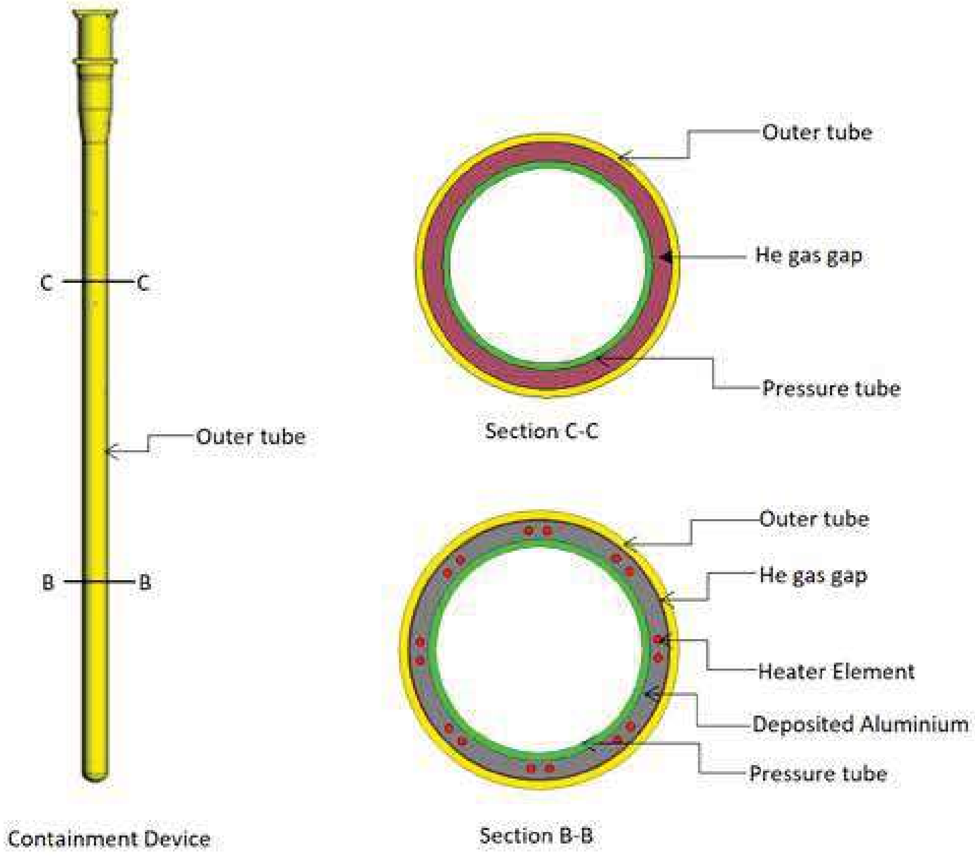

Figure 2. Schematic of Containment device.

2.3 Junction Box

A junction box is provided at the top of sample holder extension. Its main function is to facilitate the connection of various instrument cables coming out from the sample region of the sample holder to standard instrument connectors. It also provides the access to all these connections from the assembly and allows ease of maintenance. The test device is handled from a handling interface attached at the top of the junction box as shown in Fig. 4.

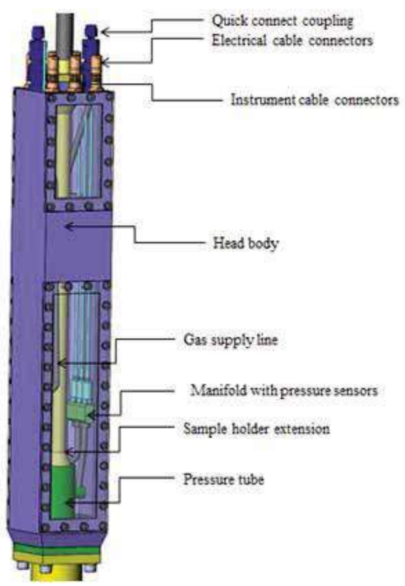

Figure 3. Containment device head Assembly.

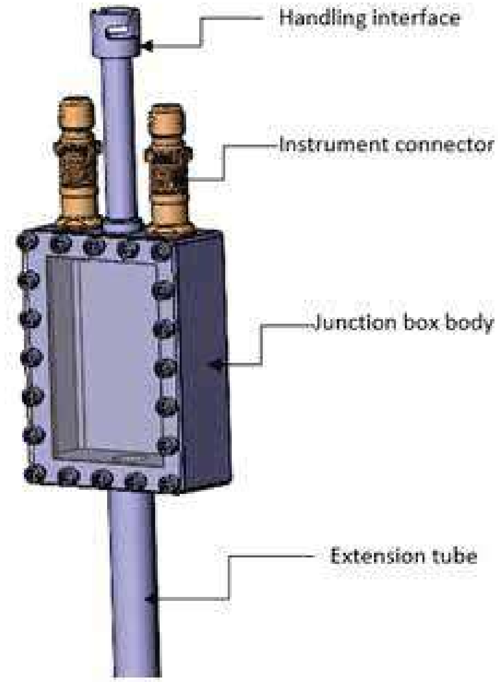

Figure 4. Junction box.

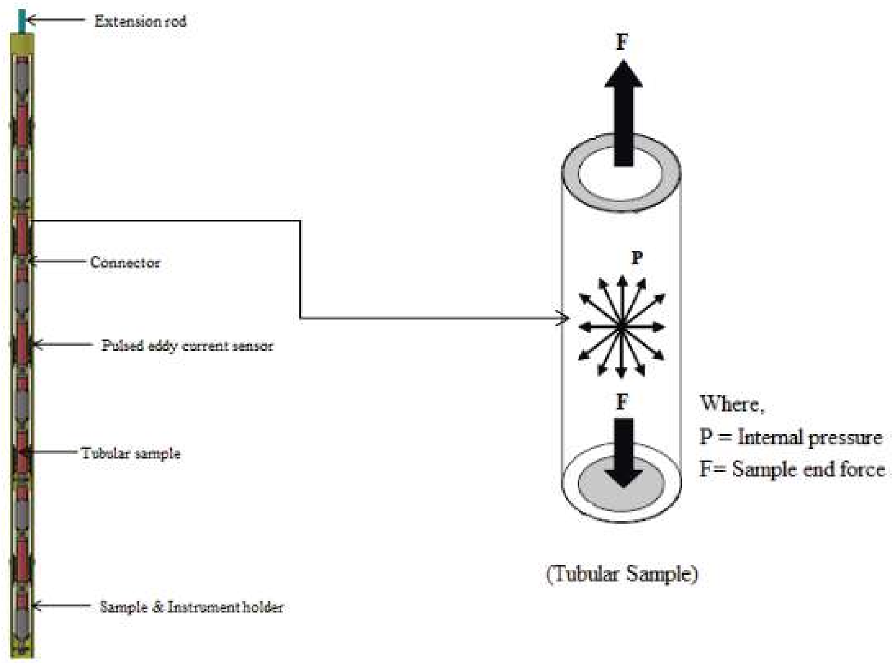

Figure 5. Sample holder for creep testing of tubular samples.

2.4. Sample Holder for Biaxial Creep Test

The sample holder performs the functions of holding samples along with the instruments dedicated for experimental purposes. It is contained inside the doubled walled pressure tube. Schematic view of sample holder for creep testing of tubular samples is shown in Fig. 5. Sample holder is designed to accommodate two numbers of instrumented samples along with sensors to measure diametrical changes. Pulsed current eddy sensors [7] developed by BARC will used for measurement of the change in sample dimensions and the same has been considered for design and engineering of the sample holder. The non-instrumented samples can also be attached for irradiation under controlled temperature for measurement of sample properties. The sample temperatures are achieved by equilibrium between gamma heating and heat losses through the test device to pool water. Uniform temperature of samples is obtained by immersing the samples in NaK liquid metal medium of the device.

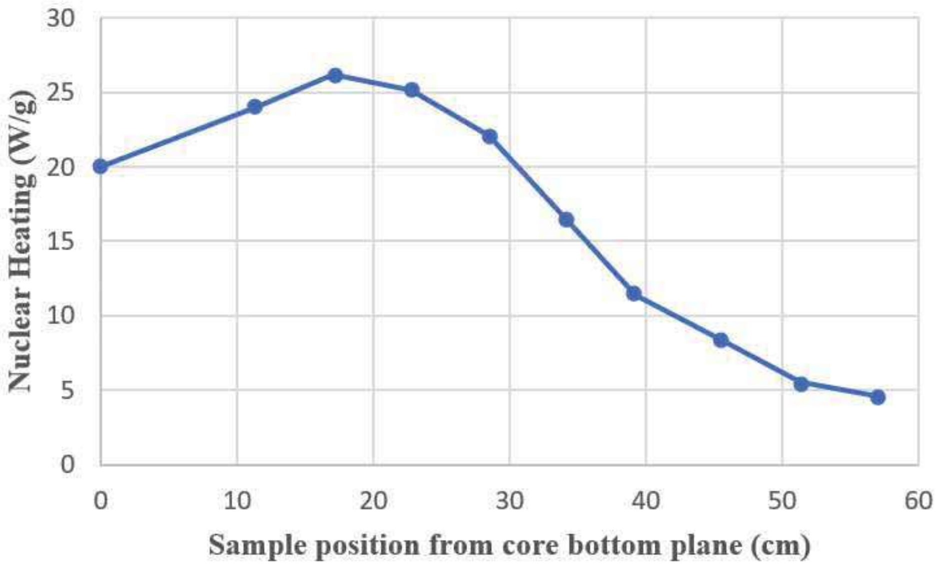

Figure 6. Axial variation of nuclear heating in samples.

3. Reactor Physics

The reactor physics estimations of various parameters related to the in-core test device, including neutron flux, nuclear heating, and radiation damage, were conducted with detailed consideration of all relevant factors. These estimations were based on a comprehensive modeling approach, where the geometry and characteristics of the test device, along with the reactor core, were explicitly modeled using advanced Monte Carlo based simulation at 50% IN condition. The nuclear heating, which arises from both neutron and gamma interactions with matter, was estimated for the Zr-4 sample and structural components. Analyses were done for the proposed HFRR considering all 4 CS of the test device. The Displacement per atom (DPA) for the sample and the structural materials were also estimated. The maximum DPA for the Zr-4 sample, stainless steel components and the aluminium tube were found to be 11.3, 8.2 and 21.1, respectively, which are important for assessing the materials integrity and performance under reactor irradiation conditions. The variation of sample nuclear heating along the core height is shown in Fig. 6.

4. Conclusion and future Outlook

The high flux research reactor (HFRR) with its high neutron flux and large irradiation volume will play a major role meeting current state of art in scientific and technological domains. In-core material test device can host instrumented as well as non-instrumented sample holder. The design of sample holder for creep test with in-situ measurement of specimen diametrical change by pulse eddy current sensors under irradiation will be able to offer more detailed information of creep behaviour of material.

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Corrosion Test Loop of High Flux Research Reactor

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Abstract

A Corrosion Test Loop (CTL) has been developed for in-situ studies of Irradiation Assisted Stress Corrosion Cracking (IASCC) in the 40 MW High Flux Research Reactor (HFRR). A compact test device of CTL integrates pressure flask, multi-specimen loading, flow amplifier, and instrumentation. The test device is connected to a high-pressure, high-temperature process system simulating Pressurized Water Reactor (PWR) and Boiling Water Reactor (BWR) thermal hydraulics and chemistry conditions. Precision control of thermal-hydraulics and water chemistry parameters enables representative irradiation environments of power reactors. A high temperature facility has been installed and commissioned to support qualification of First-of-a-Kind (FOAK) components, process validation, and endurance testing. The CTL offers a unique platform for long-duration IASCC experiments towards advancing materials development and improving reactor core component reliability.

Keywords: Irradiation Assisted Stress Corrosion Cracking (IASCC), Corrosion Test Loop, High Flux Research Reactor, Pressurized Water Reactor, Boiling Water Reactor

1. Introduction

The structural integrity of core components in power reactor is increasingly challenged by irradiation assisted stress corrosion cracking (IASCC), particularly in stainless steels and nickel-based alloys. Decades of operational experience and numerous failure cases, such as the cracking of baffle-former bolts and core shrouds, have confirmed the role of neutron irradiation in exacerbating material degradation through various mechanisms. As future reactors aim for higher burn-up and neutron flux levels, understanding and mitigating IASCC has become a critical priority in ensuring long-term component reliability and nuclear safety.

To address this concern, experimental investigation under representative reactor conditions is essential. The High Flux Research Reactor (HFRR) is designed to provide a high temperature material irradiation facility called Corrosion Test Loop (CTL) which provides a unique infrastructure for such studies. The development of CTL within HFRR allows for in-situ testing of materials under controlled stress and irradiated environments, simulating both PWR and BWR water chemistry. This facility enables a systematic exploration of IASCC phenomena by integrating mechanical loading, real-time monitoring, and neutron irradiation, thereby offering valuable insights into the corrosion behaviour and resistance of new materials for existing and next-generation nuclear reactors.

The test device of CTL is located within reflector tank in the High Flux Zone (HFZ), near to core where the thermal flux and the fast flux are expected to be 2.4×10^{14} n/cm^2/s and 7.2×10^{12} n/cm^2/s, respectively. Normal operating temperature and pressure maintained inside the test device is 340 °C and 190 bar respectively. The CTL facility will cater for the following functional requirements.

- To carry out IASCC related experiments under PWR and BWR environments.

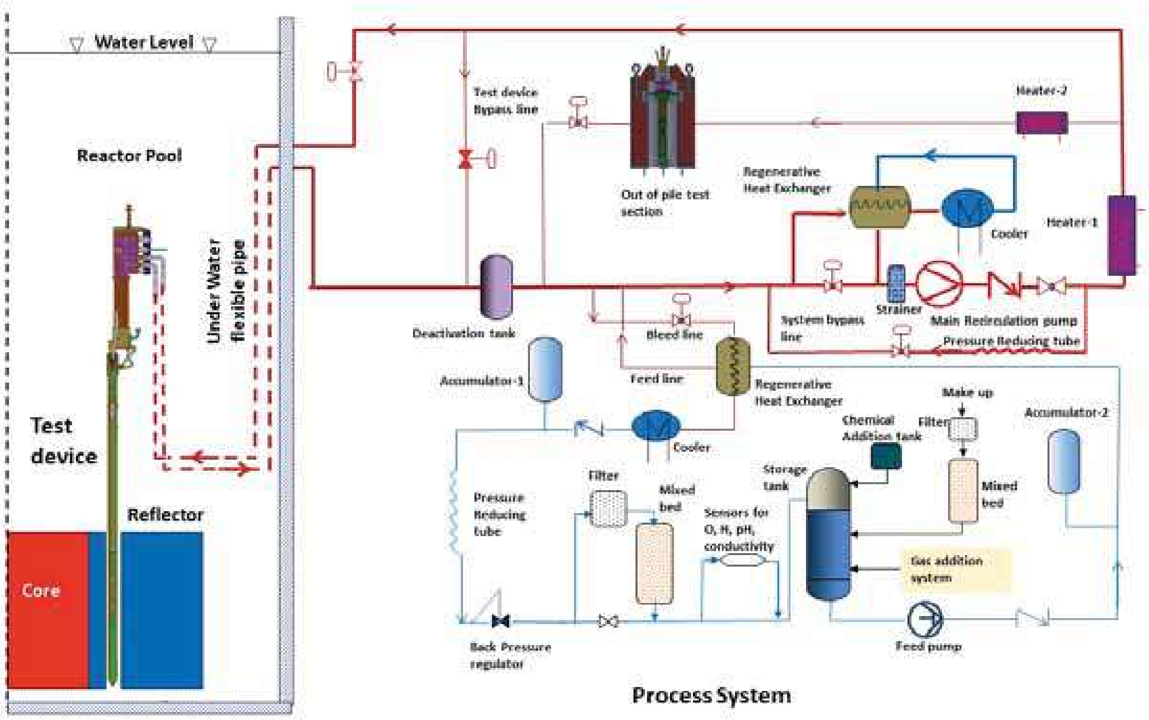

Figure 1. Schematic flow diagram of Corrosion Test Loop (CTL) of HFRR.

- To use pre-irradiated test specimen up to threshold of IASCC to expedite the testing.
- Online monitoring of water chemistry, in-situ crack measurement, test section corrosion potential, in-situ loading of samples.
- To accommodate multiple samples to investigate the effect of neutron flux and sample temperature.

2. Corrosion Test Loop

A schematic representation of the CTL is provided in Fig. 1. The CTL comprises a test device and a process system, interconnected via an underwater flexible pipe, which allows easy movement of the test device within the reactor pool. This configuration facilitates easier assembly and disassembly of process and instrumentation connections to the test device between experimental runs.

The test device consists of a test rig that incorporates test specimens, mechanical loading mechanisms, instrumentation, cabling, and a supporting framework. This rig is housed within a pressure tube acting as a pressure boundary. At the upper end of the test rig, the jet pump assembly is mounted comprising multiple jet pumps that amplify the incoming flow to deliver the required test rig flow rate.

The boosted flow from the jet pump assembly is directed downward through a narrow annular water gap, defined between the pressure tube and the flow tube. At the downstream end of the annulus, the flow reverses its direction and moves upward through the inner pipe. Beyond the test rig region, a portion of this flow is drawn into the suction chambers of the jet pumps, while the remainder exits the test device.

The process loop comprises all essential components required to control and maintain the desired thermal-hydraulics and chemistry conditions within the test device. Fluid exiting from the test device first enters a deactivation tank, which provides sufficient residence time for the decay of short-lived radioactive species generated during irradiation. Downstream of the deactivation tank, the flow passes through a strainer and is routed to the Main Circulation Pump (MCP), which delivers the necessary flow rate and pressure to sustain loop circulation. The MCP discharge is routed to Heater-1, which serves two primary functions: it raises the system temperature during start-up and compensates for heat losses during steady-state operation to maintain the desired temperature. The heated fluid from Heater-1 is then returned to the test device. The main cooling subsystem, located upstream of the strainer, comprises a regenerative heat exchanger and a main cooler. Flow through this subsystem is modulated by a control valve installed in a bypass line. This bypass arrangement ensures that the required flow is directed to the test device by throttling the control valve, while any excess flow is diverted through the cooler path. A pressure-reducing tube is installed upstream of the control valve to establish a fixed pressure drop across the bypass line. A secondary line branching from the downstream side of Heater-1 supplies flow to the Out-of-pile test section via Heater-2. This section replicates the thermal and chemistry environment of the in-pile test device, enabling comparative IASCC studies for samples with and without neutron flux. Heater-2, in coordination with Heater-1, maintains the required temperature in the Out of pile test section and compensates for the temperature increase due to nuclear heating present in the test specimen of in-pile setup.

A connection from the feed, bleed, and purification system is integrated into the main loop downstream of the deactivation tank. The bleed flow from the regenerative heat exchanger and cooler is directed to the purification unit after passing through a secondary cooler and a pressure-reducing tube to lower its temperature and pressure. System pressure is controlled by a back-pressure regulator and two accumulators (Accumulators 1 and 2). The purification unit, equipped with filters and ion exchange columns, ensures that water quality remains within specified limits. A storage tank provides buffer inventory to accommodate filling operations, start-up conditions, and thermal expansion. A feed pump located downstream of this tank supplies flow back to the main loop via the purification regenerative heat exchanger.

The main loop (indicated by red lines in Fig. 1) operates at elevated temperature and pressure conditions, reaching up to 350 °C and 200 bar. In contrast, the purification loop (depicted with blue lines) operates at significantly lower temperatures, typically below 40 °C. The primary loop uses tubing with outer diameters of ¾" and ½", whereas the purification system employs ¼" tubing. All components and piping in high-temperature are adequately insulated to minimize heat loss and ensure operational safety.

3. Test device

3.1 Pressure flask

The pressure flask is a cylindrical vessel composed of two concentric tubes. The primary function of the pressure flask is to withstand the high-pressure, high-temperature loop water and isolate it from the reactor pool water. Thermal insulation is achieved by filling the 2 mm annular gap between the tubes with helium gas. The flask outer diameter is 86 mm to fit into the thimble. The design optimizes to minimize water inventory while accommodating the specimen loading mechanisms and maintaining favourable thermal-hydraulic conditions.

3.2 Test rig

The test rig for crack propagation test comprises Compact Tension (CT) specimens, a loading device, sample holders, and instrumentation for experimental measurements. The rig is designed to accommodate three specimens within the 600 mm active core height. A scissor type loading mechanism with bellows applies independent, in-situ loading to each specimen. This is achieved by controlling the differential pressure across the bellows using pressurized helium gas, maintained at a

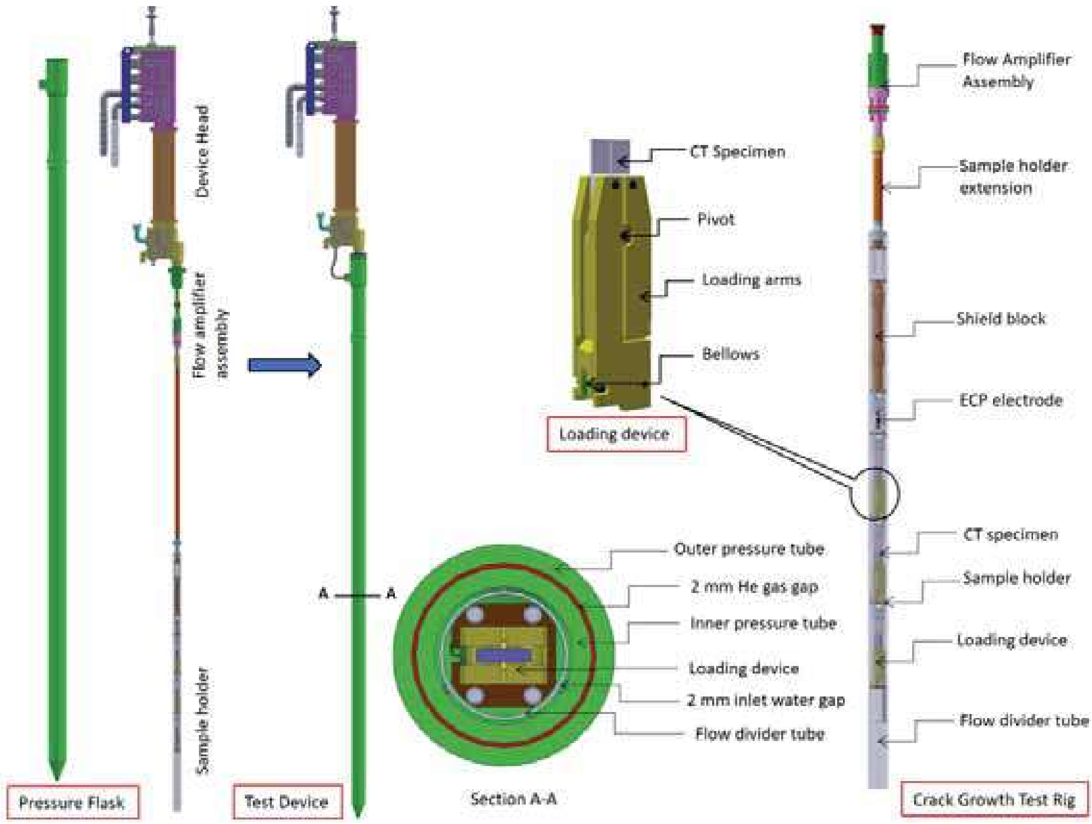

Figure 2. Different components of Test device of Corrosion Test Loop (CTL) of HFRR.

pressure up to 135 bar above the loop water pressure. The Instrumentation includes i) Electrochemical Corrosion Potential (ECP) electrodes for corrosion monitoring, ii) Direct Current Potential Drop (DCPD) instruments for crack growth measurement, and iii) Temperature sensors to monitor both water and specimen temperatures.

3.3 Jet pump (Flow amplifier) assembly

The inlet flow to the test device is limited by the size constraints of the underwater piping, which is kept minimal to ensure handling flexibility. To overcome this, a flow amplifier assembly is integrated into the test device to amplify the inlet flow to the level required for effective heat removal from the nuclear-heated components in the active section. The flow amplifier comprises three jet pumps arranged in parallel to achieve the necessary flow amplification. Integration of flow amplifier also, reduces size of the process components and thus foot print of loop room and reduces the hold up of active high enthalpy fluid.

3.4 Device head

The device head is bolted to the top of the pressure flask and serves as the interface for water connections from the process system, as well as for the routing of instrument cables and tubing. It includes an inner high-pressure retaining section, and an outer envelope that contains the insulating gas. The envelope includes a dedicated gas space that thermally insulates the high-temperature components of the device head from the surrounding reactor pool water.

During pre- and post-experimental operations, the test device is required to be moved within the reactor facility. For this purpose, a dedicated handling interface is provided at the top of the device, enabling safe and efficient movement.

4. Process system

The process system comprises various components, including an underwater flexible pipe, deactivation tank, main recirculation pump, regenerative heat exchangers and coolers, heaters, accumulators, a back-pressure regulator, a storage tank, a chemistry control system, and an instrumentation and control (I&C) system, as shown in Fig. 1. The design features incorporated into these components to meet the required functional objectives are described below.

4.1 Underwater flexible pipe

Corrugated hoses tend to trap stagnant water and residual chemicals, potentially causing issues with chemistry control. Therefore, a flexible mini-tube (6 mm ID, 8 mm OD) with a smooth inner surface has been selected. Multi-layer insulation comprising solid and gaseous media along with mechanical protection, is provided on the exterior of the mini-tube.

4.2 Deactivation tank

The deactivation tank is designed to provide a minimum residence time of 80 seconds to sufficiently delay the short-lived radioactive species ^{16}N and ^{19}O generated in the core. An internal arrangement of perforated plates ensures a near plug-flow profile, thereby minimizing the required volume to achieve the specified delay time.

4.3 Main Circulation Pump (MCP)

The MCP is a multistage, very low specific speed, canned-motor pump developed specifically to deliver high pressure head at low flow rates. It provides the hydraulic energy required for the test device's flow amplifier as well as to overcome other system hydraulic losses.

4.4 Heaters

Heaters 1 and 2 are custom designed in a hairpin configuration to achieve a high heat transfer coefficient, even at low flow rates. This design also offers the advantage of reduced hold-up volume, simplifying mechanical design requirements. The heating system incorporates a DC drive mechanism with a PID controller, which is tuned to achieve precise temperature control.

4.5 Regenerative heat exchangers and coolers

The purification regenerative heat exchangers and coolers are of hairpin, tube-in-tube construction, designed to provide high heat transfer coefficients at low flow rates.

4.6 Pressure control system

Accumulators 1 and 2 dampen pressure fluctuations in the system arising from the inherent characteristics of the feed pump or other sources. A back-pressure regulator maintains system pressure by adjusting the bleed flow rate. Through appropriate accumulator sizing and back-pressure regulator tuning, precise pressure control can be achieved. A feed pump is provided for system pressurization during start up and to ensure a constant feed flow during steady state.

4.7 Chemistry Control system

The chemistry control system consists of a filter, ion-exchange beds, storage tank, chemical addition tank, and gas addition system. The ion-exchange beds can be configured in various forms (H^+, Li^+, OH^-, and borate) to achieve the desired chemical conditions. Chemicals such as lithium hydroxide and boric acid can be introduced into the storage tank via the chemical addition tank.

The gas addition system allows oxygen or hydrogen to be added either directly to the system or to the storage tank. This arrangement enables simulation of the required chemistry conditions corresponding to Boiling Water Reactor–Normal Water Chemistry (BWR–NWC), Boiling Water Reactor–Hydrogen Water Chemistry (BWR–HWC), and Pressurized Water Reactor (PWR) operating environments.

Figure 3. Photos of high temperature experimental test facility.

4.8 Instrumentation and control system

The system is equipped with various instruments for measuring pressure, temperature, and flow. Additionally, sensors for dissolved oxygen, dissolved hydrogen, pH, conductivity, and electrochemical corrosion potential are installed at selected locations. The control system manages pressure and temperature regulation, data monitoring and recording, and implements trip, alarm, and interlock functions.

5. Design validation of Corrosion Test Loop

Considering the several First-of-a-Kind (FOAK) components in the test device and process system of the CTL, a high-temperature experimental facility has been developed. Photographs of the high-temperature experimental facility are shown in Fig. 3.
The experimental test facility has been utilised to meet the following objectives:

a) Qualification of critical test device components such as jet pumps, DCPD, cable feedthroughs, bellows, and the loading unit.
b) Process design validation of the system, including verification of process parameters at different locations.
c) Qualification of various customized components and mechanical joints under high-pressure and high-temperature conditions.
d) Process design validation of customized components such as heat exchangers and heaters.
e) Tuning of control loops and establishment of pressure and temperature control.
f) Validation of start up and shutdown procedures to ensure smooth operation of the loop.
g) Endurance testing of the multistage high-pressure, high-temperature canned motor pump.

6. Conclusion and Future Outlook

A high-pressure, high-temperature Corrosion Test Loop (CTL) has been successfully designed for integration with the High Flux Research Reactor (HFRR) to enable controlled in-situ studies of Irradiation Assisted Stress Corrosion Cracking (IASCC) under representative light water reactor conditions. The system combines a compact, instrumented test device with controlled process system capable of simulating both PWR and BWR thermal hydraulics and chemistries condition. Key First-of-a-Kind (FOAK) components and instrumentations have been incorporated to meet stringent functional requirements.

A dedicated high-temperature experimental facility supports the qualification and design validation of critical components. The CTL provides a unique capability for long-duration, high-fidelity IASCC experiments, thereby generating essential data for understanding material degradation mechanisms and supporting the development of mitigation strategies. This facility is expected to contribute significantly to the reliability and safety of current and future light water reactor designs.

Fuel Test Loop of High Flux Research Reactor

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Abstract

A fuel test loop will be provided in High Flux Research Reactor (HFRR) to support fuel and material testing under simulated conditions as present in pressurized water reactors (PWR). It is a high temperature and high pressure test loop with operating pressures reaching up to 175 bar whereas the temperatures as high as 330 °C representing the operating conditions of the modern PWRs. The test loop consists of an in-pile test section located in the reflector vessel of the HFRR for neutron irradiation of the fuel sample. The pressure boundary is provided by a Zircaloy pressure tube to contain the coolant operating at high pressure & temperature condition in the FTL. Coolant circulation and heat removal systems are provided to ensure continuous flow through the test section and removal of the nuclear heat from the test fuel during normal and off-normal conditions. Specific provisions are also made to allow the irradiation of the test fuel sample for required water chemistry environment. To ensure the safety of the test fuel and the reactor structures surrounding the in-pile test section during accident conditions, emergency cooling system is provided to inject the cooling inventory in case of unlikely event of pipe break in the primary process system. This chapter elaborates on the details of the fuel test loop of HFRR and its importance in development of advanced nuclear fuel for the advanced PWR reactor.

Keywords: *Nuclear Fuel, PWR, Fuel Testing.*

1. Introduction

Nuclear fuel testing in research reactor has, historically, played a key role in development of advanced fuel & clad material for power & propulsion reactors. These tests are crucial for understanding material behaviour under irradiation, validating designs, and ensuring the safety of nuclear power reactors. In the Indian context, the government has set an ambitious target of 100 GW nuclear power capacity by 2047, positioning nuclear energy as a major pillar in India's energy mix [1]. This will require development and deployment of next generation pressurized water reactors & small modular reactors (SMR) for which testing of advanced fuel concepts will be required to demonstrate nuclear safety. Furthermore, advancement in accident tolerant fuels (ATF) technology will require testing of new fuel & clad concepts to generate irradiation data. This will allow the development of high-performance fuel with higher burn-ups, better resistance to irradiation damage, and improved safety margins during severe accidents.

To fulfill this critical requirement, research reactors are equipped with specialized experimental facilities that enable the controlled irradiation of test fuel assemblies under conditions that closely simulate those found in commercial nuclear power reactors. These reactors also provide flexibility to support test fuel transfer & handling operation in the pre- and post-irradiation phases.

One such fuel & material irradiation test facility was Pressurized Water Loop (PWL) of CIRUS research reactor at BARC. The PWL provided test environment similar to light water power reactors at pressure up to 115 bar and temperatures up to 260 °C. The test loop had heat removal capacity of 500 kW.

The facility was used extensively for fuel & material testing of various structural materials of the power reactors such as end shield and Zircaloy pressure tubes of PHWRs. These experiments built the confidence for design and operation of indigenous power reactors [2]. Post permanent shut-down of CIRUS reactor in year 2010, the PWL facility is undergoing decommissioning.

OSIRIS, a 70 MW pool type research reactor located at France also had a closed loop pressurized light water test facility designed for experimental irradiations of nuclear test fuels. This was known as ISABELLE 1 Fuel test facility which was used to perform tests in thermal-hydraulic and chemical operating conditions representative of those used in industrial power and prototype reactors. It was operated at the pressures up to 170 bar and temperatures up to 315 °C. The loop was utilized for single PWR fuel rod testing to generate irradiation data using the in-pile instrumentations [3].

HANARO, a 30 MW open pool type research reactor also has a Fuel test loop located in the reflector region to conduct fuel irradiation tests. This test loop provides high pressure and temperature test conditions similar to those of commercial PWR and CANDU reactors. The system could operate at pressures up to 175 bar and temperatures up to 350 °C. It has a heat removal capacity of 800 kW. The test section could accommodate multiple fuel rods for irradiation testing [4].

The proposed High Flux Research Reactor (HFRR) also provides a Fuel Test Loop (FTL) facility, as a part of a self-contained independent test system designed to support various material & fuel tests under simulated power/light water reactor conditions. It is a high pressure & high temperature loop with maximum operating pressure as 175 bar and maximum operating temperature of 330 °C. The in-pile test section in the FTL has sufficient volume to allow multiple fuel rods/fuel bundle testing under neutron irradiation. The FTL is located in one of the irradiation thimbles of the reflector vessel of HFRR. The reactor, HFRR is a 40 MW pool type research reactor being developed at Bhabha Atomic Research Centre (BARC). It uses Low Enriched Uranium (LEU) U_3Si_2 dispersed in Aluminium matrix as fuel and Aluminium alloy as clad. The reactor core is cooled using light water which also acts as a moderator. Heavy water is used as reflector in the annular reflector vessel surrounding the reactor core. The neutron flux in the FTL position is of the order of 2×10^{14} n/cm^2/s (thermal flux) and 2.6×10^{12} n/cm^2/s (fast flux), respectively. Nominal neutron flux encountered in typical PWR reactors is of the order of $3–5 \times 10^{13}$ n/cm^2/s (thermal), hence, the availability of higher neutron flux in HFRR for irradiation in FTL facility will allow more flexibility to carry out tests at higher rated power for the test fuel bundles.

Another critical aspect of the FTL design is minimizing the reactivity perturbation on the HFRR reactor core power. The presence of the loop introduces additional fuel and structural materials, which alters the core's neutron balance. In case of HFRR, the core physics design is such that the effect of any perturbation/transient in FTL will have a minimum effect of the core power. In the subsequent sections, the design features of the FTL are elaborated in detail.

2. IN-PILE TEST SECTION

FTL consists of in-pile test section and out of pile process system. In-pile test section provides a pressure boundary enclosure to the test fuel bundles and also a separation between test section high temperature/pressure water with the pool water. The in-pile test section has an internally insulated pressure tube surrounded by jacket tube. Details of the in-pile test section are shown in Fig. 1. Irradiation samples such as test fuel cluster & materials for irradiation testing are installed in the fuel tube section. The fuel tube has internal diameter of 71 mm to accommodate the test fuel cluster.

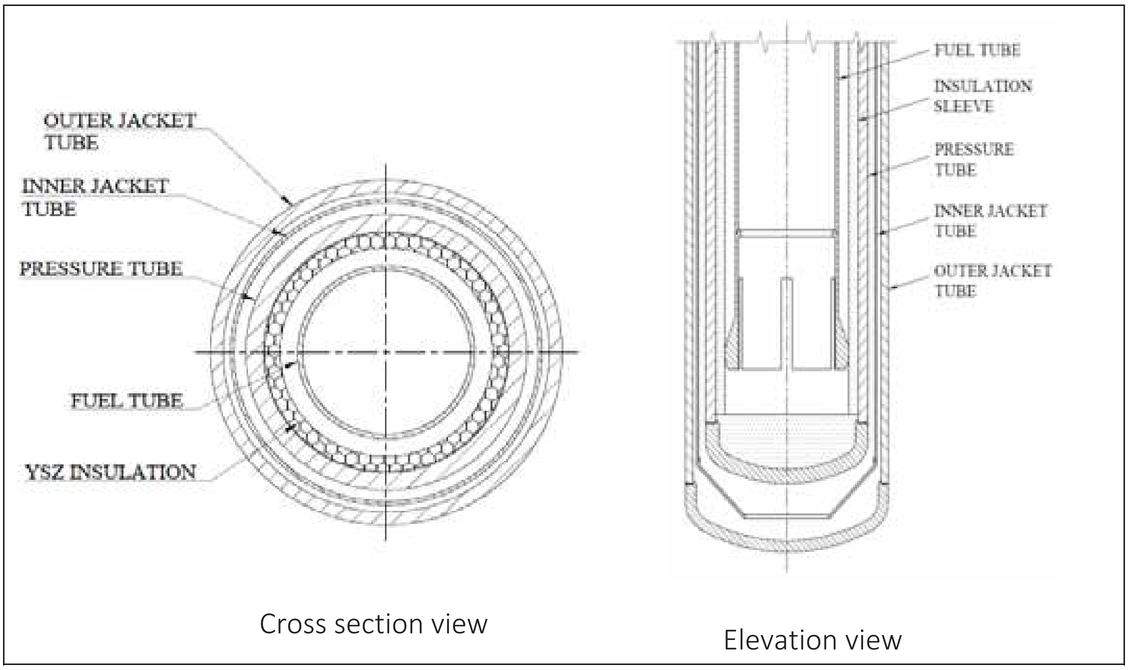

Figure 1. Details of FTL In-pile test section.

The coolant flows through the annulus created by the fuel tube inside the pressure tube; the coolant flows downward through the outer annulus region between fuel tube and the pressure tube; after reaching the bottom of pressure tube, the flow reverses in the upward direction through the fuel tube where the irradiation sample is located to remove nuclear heat generated during reactor operation. The in-pile components are made of Zircaloy (Zirconium tin alloy) for neutron economy considerations. To avoid loss of heat to the reactor pool and reduce the pressure tube temperature, Yttrium Stabilised Zirconia (YSZ) insulation sleeve is provided in the test section as shown in Fig. 2. Porous Zirconia ceramics have many advantages which makes universally acceptable for thermal isolation, such as low thermal conductivity, low density, corrosion resistance and high temperature resistance; therefore, it is chosen as insulation material for the FTL pressure tube. Jacket tubes are provided which surround the pressure tube to remove structural heating and to reduce heat loss to the reactor pool.

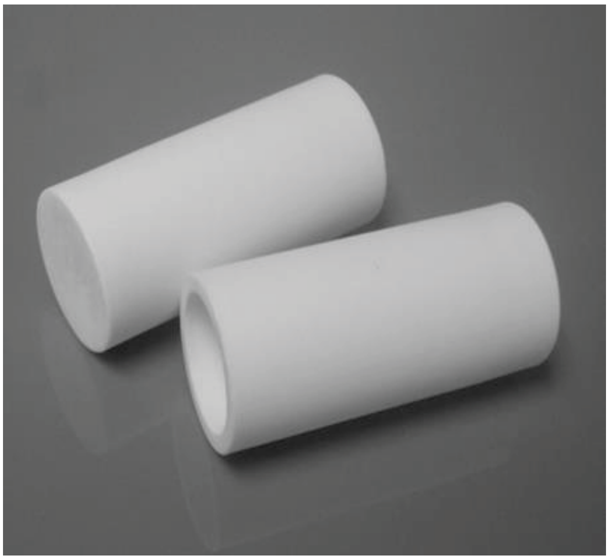

Figure 2. Yttria Stabilized Zirconia (YSZ) Insulation.

3. OUT-OF-PILE SECTION

Out-of-Pool section consists of various process systems (such as Main Loop System, Purification and Sampling System, Pressurizer System, Jacket Coolant System etc.), piping and equipment necessary to maintain the required temperature, pressure and flow conditions inside the In-Pile test section. Process system schematic of the FTL is shown in Fig. 3.

The main loop system of FTL will provide cooling flow up to 4.5 kg/s with heat removal capacity of 800 kW. The cooling medium of main loop system is DM water. The primary cooling system consists of main cooling pump and auxiliary cooling pumps to circulate the coolant through the test fuel sample located in the in-pile test section. The auxiliary pumps are provided with Class II power (battery-based power supply) to allow circulation of coolant in FTL in case of unavailability of AC power supply.

The main loop system transfers heat to the Dowtherm cooling system through the shell-tube heat exchanger; Dowtherm cooling system is an intermediate cooling system with Dowtherm-A as a cooling medium. Dowtherm-A is a commercial thermal fluid which is a eutectic mixture of Diphenyl & Diphenyl oxide. It was chosen due to its high boiling point (257 °C) for the system pressure. To regulate temperature of the main loop coolant at the inlet of the test section, a flow control valve is provided to regulate flow of dowtherm coolant to the main loop heat exchanger. The Dowtherm cooling system transfers heat to the Decay Heat Removal System (DHRS) which rejects the heat to atmosphere via cooling towers.

Electrical heater is provided at the test section inlet to regulate the temperature of loop water entering in the test section at the desired value as per the set point. It is also used for warming up the loop to the required operating temperature during start-ups.

The pressurizer maintains main loop system pressure and accommodates the volumetric changes occurring in the main loop due to temperature changes as well as due to feed or bleed in the system. The system pressure is maintained by generating saturated steam by evaporation of water in the pressurizer vessel using electrical heater elements. To mitigate the radiological consequences of test fuel failure in the event of loss of coolant accident (LOCA) due to breach of primary loop pressure boundary, a two stage Emergency cooling system (ECS) has been provided which comprises of high-pressure light water injection from gas pressurized storage tanks called Accumulators and also low-pressure water injection by virtue of gravity head from water storage tank (EWST) located at higher elevation in HFRR reactor building. Safety relief valves are also provided in the main loop system for the protection of system equipment and piping during over-pressurization transient.

The FTL is provided with instrumentation to monitor the important parameters of the process system and to protect the system against transient/accident events. For detection of failure of test fuel, bulk gamma monitoring and delayed neutron detector system are provided in the main loop system. Reactor trip is provided on crucial process parameters important to maintain safety of the test fuel sample.

4. Coolant Chemistry Control

Chemistry control in Pressurized Water Reactors (PWRs) is crucial to maintain the coolant's chemical environment to prevent corrosion, control reactivity, and minimize radioactive corrosion product build-up. It is important to study the irradiation effect on the fuel & clad material in specific coolant chemistry prevailing in the PWR reactors.

Typically, boric acid is added to the primary coolant as a chemical shim to control long-term reactivity changes due to fuel burn-up. To adjust the pH of the coolant in response to the addition of the boric acid, alkali compounds are added in the coolant. In western reactors, Lithium hydroxide (LiOH) is added to maintain a slightly alkaline pH in the primary coolant, which helps to reduce the corrosion rates of structural materials. Potassium hydroxide (KOH) is also another candidate which is used in VVERs for chemistry control.

In addition to the pH control, chemical regents are also added to control oxygen

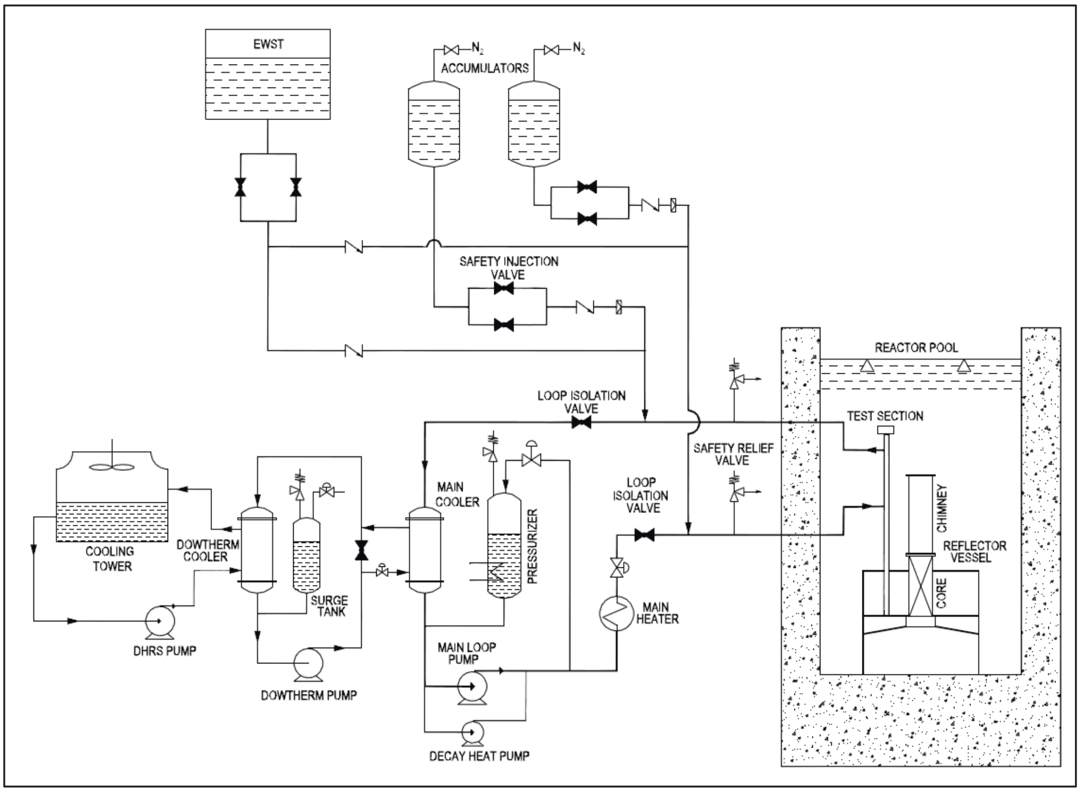

Figure 3. Schematic diagram of process system of FTL.

content in the primary coolant system. To suppress the radiological oxygen & hydrogen peroxide formation due to radiolysis of the coolant, hydrogen is added in the system to counteract the formation of the radiolytic oxidizing agents.

Purification & Chemistry control system of FTL allows the user to add the chemical regent in main loop coolant to maintain specific chemistry environment during the fuel test campaign. It consists of a chemical addition station and series of ion-exchanger beds to regulate the coolant chemistry. The coolant chemistry is monitored in the system with the help of instrumentation such as conductivity meter & dissolved gas monitoring system.

5. Post Irradiation Examination

At the end of irradiation campaign of the test fuel, it is taken out from the in-pile test section and kept in the service pool of HFRR to allow the decay heat to reduce to a lower value. The test fuel sample is then transferred to the post-irradiation examination (PIE) facility to study the behaviour of the fuel under irradiation environment. Suitable arrangement is provided in the spent fuel storage bay and hot cell area of the HFRR to allow handling and transfer operation of the test fuel to the PIE facility for further investigation.

The PIE facility has its own dedicated hot-cell set-up for destructive & non-destructive examination of the fuel sample. The PIE of the test fuel sample is, generally, carried out in following stages:

a) Physical examination to check for swelling and hot spot formation on the fuel surface.
b) Fission gas assessment formed within the fuel sample during the irradiation.
c) Evaluation of clad material to assess formation of oxide layer over the

surface and mechanical properties such as yield strength, ductility etc.

d) Evaluation of fuel material to check the behaviour of the fuel matrix under irradiation, chemical/mechanical interaction of clad material with the fuel.

The PIE of the test fuel is deemed as the last stage of the fuel test cycle in research reactors. Subsequently, the test fuel will be sent to reprocessing facility for long-term storage.

6. Conclusion and future Outlook

Fuel testing loop (FTL) of HFRR reactor will serve as a key facility aimed towards development of next generation fuel for advanced PWR reactors. The facility is designed to allow the fuel developers to test new fuel concepts under high pressure and high temperature environments. The process system of FTL provides flexibility to the user to configure the environment conditions of the test fuel to simulate appropriate temperature, pressure, and coolant chemistry needed for the irradiation campaign. Furthermore, the FTL facility is designed with adequate safety features to maintain test fuel safety and the safety of the HFRR core during normal and accident conditions.

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Cold Neutron Source Facility of High Flux Research Reactor

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Abstract

Neutrons have a neutral electrical charge giving them the ability to penetrate deeply into materials and interact with nuclei. Neutrons are also spin-half particles allowing interactions with unpaired electrons for studies related to magnetic materials. Hence, neutrons are widely used as a probe for studying condensed matter. Neutron scattering began with thermal neutron beams at some of the first high flux reactor sources in the world. However, cold neutrons (i.e. neutrons having energy <5 meV) with large wavelengths open up different areas of studies of materials through both elastic and inelastic scattering. The upcoming High Flux Research Reactor (HFRR) at the BARC Campus in Visakhapatnam, Andhra Pradesh will push the boundaries of research reactor utilization facilities in India, especially in the field of condensed matter research through neutron scattering. One of the crown jewels of this reactor is the Cold Neutron Source (CNS) facility. The device proposed in HFRR utilizes Liquid H_2 as a moderator bringing down the neutron energy of thermal neutrons to the level of cold energy. Cold neutrons thus generated (or converted) are then led to a number of experimental stations through the use of neutron guide tubes. This article describes the engineering aspects of the Cold Neutron Source of HFRR.

Keywords: *CNS, Moderator pot, Neutron scattering, Liquid Hydrogen.*

1. Introduction: Neutrons as Probes

The neutron is a charge neutral nucleon having a mass of about 1.67 x 10^{-27} kg. Further, it is a spin-half particle having a magnetic moment of about -9.6 x 10^{-27} J/T. Sir James Chadwick was awarded the Nobel Prize in Physics in 1935 for his 1932 discovery of the neutron. In 1940, the first accurate measurements of the magnetic moment of neutrons were made. The charge neutrality of the neutron allows the neutron to penetrate deep into matter, without interacting with the electron cloud, and interact with the nucleus through strong nuclear forces. This enables the investigation of the bulk properties of matter. Further, as neutrons interact with the nucleus, it can be used as a sensitive probe for light atoms like hydrogen, lithium etc. These light atoms have sparse electron clouds which cannot be easily detected by X-rays, neutrons thus provide complementary information regarding matter. At the same time, neutrons also interact with heavy nuclei. Neutrons can also be used to detect different isotopes of the same element. The magnetic moment of the neutron can be used to carry out dipole-dipole interactions between the neutron magnetic moment and atomic magnetic moment. The French physicist Louis De Broglie proposed that every particle in motion (including neutrons) exhibits wave-like properties. The De Broglie wavelength of the neutron is related to the energy (and the velocity) of the neutron. The equation that relates the energy with the wavelength is $E=h^2/2m\lambda^2$, where E is the energy, h is the Planck constant, m is the mass of the neutron and λ is the De Broglie wavelength.

When employing a neutron as a probe for material studies, researchers typically use the epithermal (energy: 0.5 eV–10 keV, wavelength: 0.4–0.03 Å), hot (energy: 0.1 eV–1 eV, wavelength: 0.3–0.9 Å), thermal (energy < 0.5 eV, wavelength ≳ 0.4 Å) and cold (energy < 5 meV, wavelength ≳ 4 Å) energy spectra of neutrons. Neutron energies are governed by the temperature of the medium through which the neutron traverses. The neutrons scatter with nuclei in the medium and achieve thermal equilibrium with the medium. The energy (E) of the neutron is related to the temperature (T) through the equation $E= k_BT$, where k_B is the Boltzmann constant.

Scientists direct a beam of neutrons from a neutron source (such as research reactor) through a beam tube onto a sample. The resultant scattering of neutrons is observed at various angles. Elastic Scattering provides information about static structures such as atomic positions and lattice arrangements. Inelastic scattering is used for studying molecular motion, vibrations, or diffusion [1]. The wavelength of the neutrons is chosen so that its wavelength is comparable to the length scale of interest in the sample being studied. Depending on the energy of the neutrons, and hence their wavelength, different aspects of materials can be probed, both in terms of length scales and in terms of time scales.

Thermal neutrons, are used for the study of atomic structures and crystal structures and also atomic vibrations, inter atomic forces, lattice dynamics and phase transitions. Fast neutrons are not used for structural investigations, but find use in radiography and fast neutron activation analysis. Cold neutrons due to their large wavelength can be used for studying structures having a large length scale such as polymers, proteins, colloids etc. They can also be used for studying slow dynamics such as diffusion, molecular rotations and vibrations in biological systems.

2. An overview of Cold Neutron Source facilities

A research reactor generally serves as a steady state source of thermal neutrons. In order to generate cold neutrons, a cold moderator is employed to down-scatter neutrons into the cold spectrum. As per a TECDOC by IAEA [2], the earliest attempt using a cold moderator was in 1956 in the UK. Since then, about sixty different CNSs were created at research reactors and accelerators. However, most CNSs are created at steady-state reactors. The moderator material chosen in each of these cold neutron sources worldwide include liquid hydrogen, supercritical hydrogen, liquid deuterium, solid deuterium, methane, liquid methane, liquid propane and mesitylene. The largest number of CNSs created are in Europe-69%, USA-16%, and in the Asia-Pacific Region comprising of Japan, China, Republic of Korea and Australia-15%.

3. Cold Neutron Source at HFRR

HFRR is an upcoming 40 MWth pool type research reactor at BARC campus, Vizag. The peak thermal flux in the reactor is 1×10^{15} $n/cm^2/s$. The reactor will provide a number of facilities for basic and applied research. One of the crown jewels of the reactor is the Cold Neutron Source (CNS) facility, which is first of its kind in India. The CNS facility in HFRR, (CNS-HFRR) converts thermal neutrons from the reflector region of HFRR to cold neutrons through the use of liquid hydrogen moderator.

The CNS-HFRR requires a number of systems in order to function safely and efficiently. There needs to be a cryogenic moderator, a system to maintain the temperature of the moderator, a system to cool the structural components of the CNS and finally a means to ensure that the reactor can operate independently of the CNS operation. These functional requirements are fulfilled by the use of a number of structures and systems as described below. A simplified process flow diagram of CNS-HFRR is shown in Fig. 1. The dotted line denotes the boundary between the in-pool portion and out-of-pool portion of the CNS system. The structures to the right of the dotted line comprise of the moderator pot which contains the liquid hydrogen

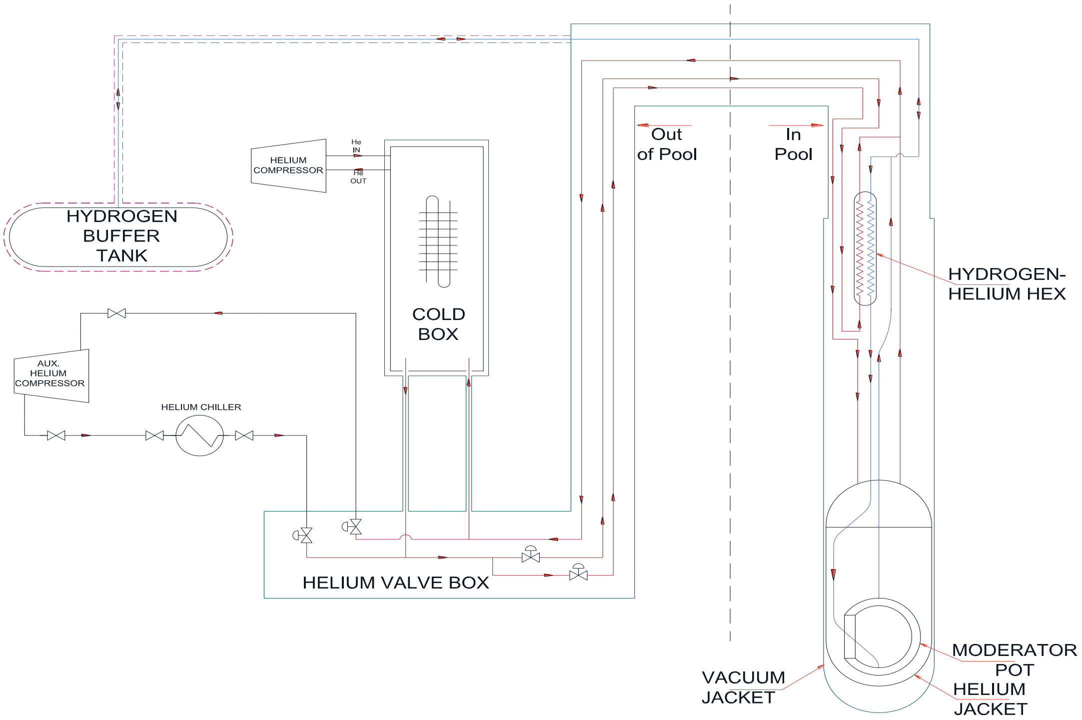

Figure 1. Simplified process flow diagram of CNS-HFRR.

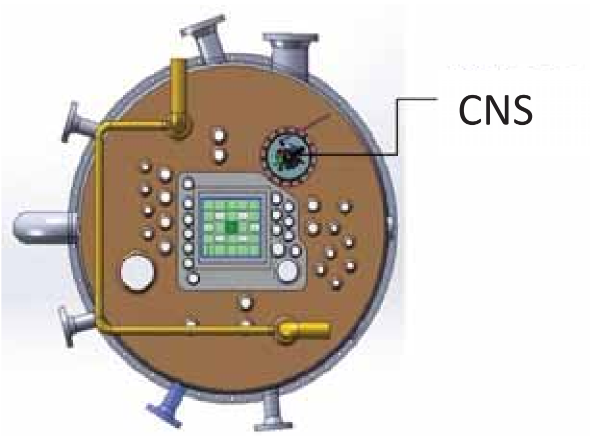

Figure 2. CNS of HFRR Reactor Structure (Plan View).

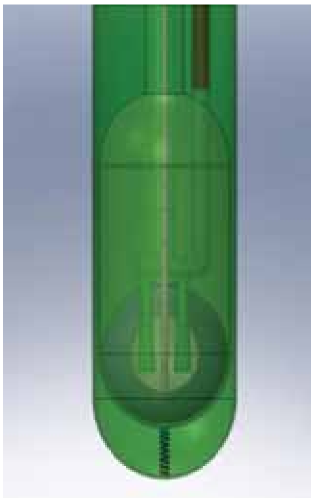

Figure 3. Elevation view of CNS-HFRR.

moderator, the heat exchanger which cools the moderator to cryogenic temperatures and two jacket structures which successively surround the moderator pot.

3.1 In-pool components of CNS

The moderator pot is an annular ellipsoidal vessel. The shape has been optimized for maximizing neutron & moderator interaction and allowing maximum cold neutrons towards the beam tube along with minimum nuclear heating load in the moderator pot [3]. The moderator pot is inserted into a vertical thimble of about 300 mm ID in the reflector region of HFRR. The thimble position (as shown in Fig. 2) is chosen based on optimization between large thermal neutron flux and manageable nuclear heating. The Elevation view of CNS-HFRR which is positioned inside the vertical thimble of the reflector vessel is shown in Fig. 3.

The moderator as well as moderator pot generates heat primarily due to the scattering of neutrons. The heat exchanger removes part of this heat. The secondary fluid in the heat exchanger is cryogenic Helium. Since the moderator as well as the moderator pot would generate heat due to the interactions with neutrons, it is imperative that this heat be removed whenever the reactor is operating. The moderator pot is housed inside a helium jacket which performs dual roles, firstly it forms a barrier between hydrogen and the atmosphere and secondly it removes structural nuclear heat. As the cryogenic parts of the CNS are located in the thimble of the reflector vessel, it is required to insulate these components from the ambient temperature conditions. The insulation is provided by the vacuum jacket. Fig. 4 shows the in-pile components of CNS which will be installed in the reflector region. The rest of the system resides outside the reactor pool and comprises of various piping, vessels, equipment and instrumentation.

Structurally in-pile part of Cold neutron source consists of three major components (vacuum jacket, helium jacket and moderator pot) as shown in Fig. 4. The outermost component is vacuum jacket which accommodates all the components under a high vacuum environment and thus thermally isolates the components at cryogenic temperature from reactor environment. It is maintained at 10^{-6} mbar vacuum. Inside the vacuum jacket, there is a helium jacket, which surrounds the moderator pot. Helium at 16 K is passed through this jacket at a mass flow of 6 g/s at 4.4 bar (abs) pressure to provide necessary cooling. The moderator pot inside the helium jacket is the most important component, where moderation of neutrons takes place to the cryogenic temperature of 20 K. Moderator pot is an ellipsoidal annulus containing about 2.4 litres of liquid hydrogen. The pot has an exit hole towards CNS beam tube i.e., CNS window as shown in Fig. 4.

3.2 Out-of-pool Cryogenic system

The cryogenic helium is generated and circulated by the combination of a cold box and Helium compressor. The moderator hydrogen system is passive in nature, and a large part of its volume is contained in the hydrogen buffer tank. Before the cryogenic helium system is started, the hydrogen remains in the gaseous phase at room temperature. Once the cryogenic helium system starts and brings the temperature of the hydrogen down, it starts to liquefy and condense in the moderator pot.

3.3 Thermo-siphon cooling

The moment neutrons start interacting with the moderator, a thermo-siphon is setup wherein heating occurs in the moderator pot and cooling takes place in the heat exchanger, thus maintaining the moderator temperature at 20 K. The interacting neutrons down-scatter and achieve cold energies and further travel into the cold neutron beam tube which then carries the cold neutrons into guide tubes for use in experimental stations. This basically summarizes the normal operation of the CNS.

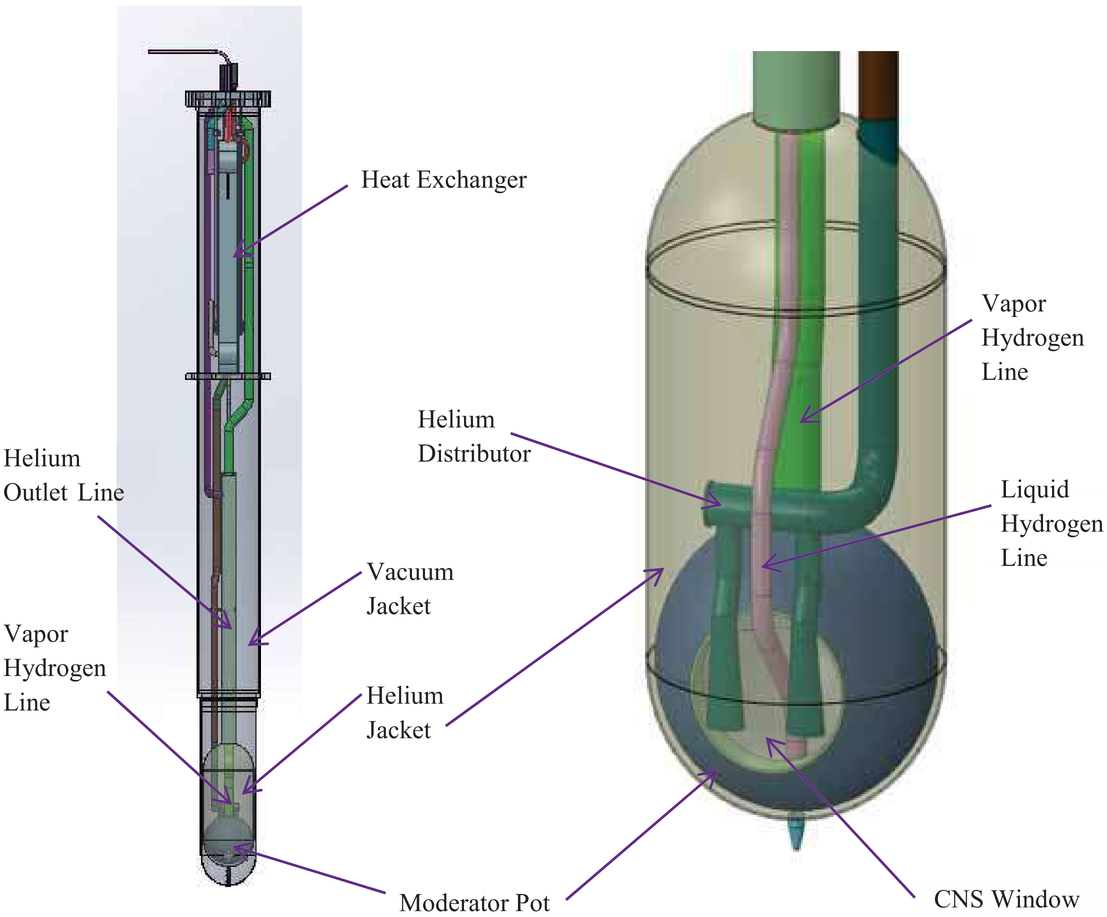

Figure 4. Three-dimensional model of In-pile components for CNS-HFRR.

3.4 Backup Helium chiller

In case the cryogenic helium system is not functioning for any reason, a backup helium chiller is provided which can supply Helium at 10 °C to ensure adequate cooling to the structural components of the CNS. However, as the cryogenic temperatures do not exist in this case, the cold neutron source will not function to generate any cold neutrons.

3.5 Gain factor of CNS

The performance of a steady state CNS can be judged based on its gain factor, which is defined as the ratio of the cold neutron flux at the inlet of neutron guides with the CNS to that without the CNS. Theoretical predictions of the neutron flux show that there is a gain of about 21. This implies that the experimentation can take place with much smaller samples, within faster durations and can effectively support multiple experimental stations.

3.6 Operational and Safety aspects

3.6.1 Operational aspects

- Normal Operation Mode

  The Cold neutron source will function in order to moderate neutrons to the cold spectrum. In this mode, the moderator pot will be in filled condition with liquid hydrogen. Due to nuclear heating, hydrogen gets vaporised and rises up through the central pipe and enters the heat exchanger, where it condenses. This condensed Hydrogen falls back into the moderator pot by gravity.

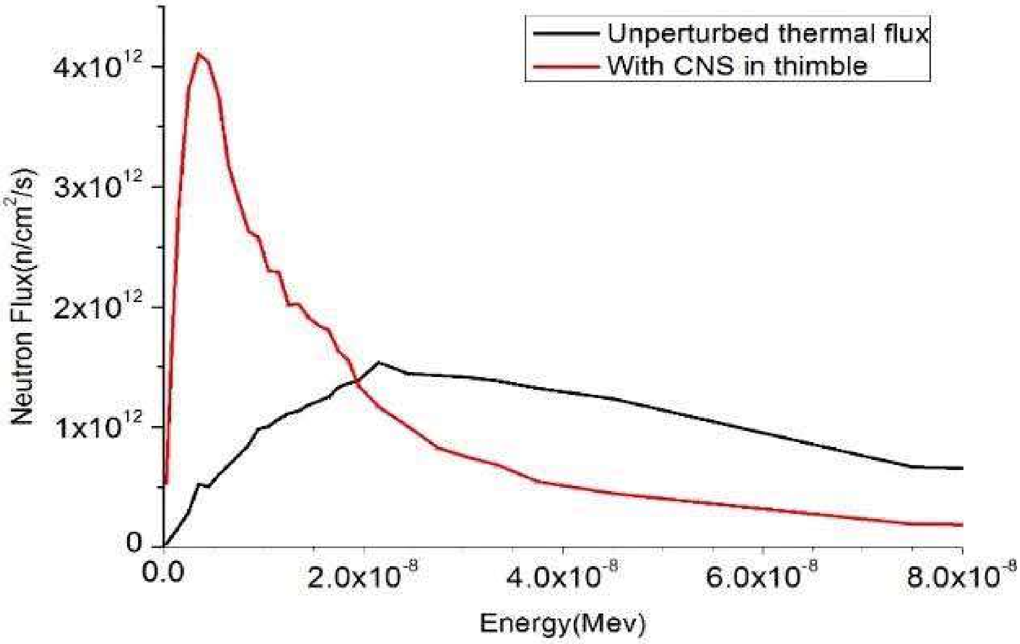

Figure 5. Comparison of cold neutron flux with and without CNS-HFRR.

- Standby Mode

  This indicates a situation when Reactor is operating but helium cryogenic system is shutdown, hence Cold Neutron Source is not in operation. This mode permits the continued operation of the reactor even in absence of the cryogenic system. In this mode, chilled Helium at 10 °C is circulated in the Helium jacket to take away the nuclear heat.

3.6.2 Safety aspects

Some of the major safety features provided in CNS design is indicated here.

(i) Inside the pool, hydrogen is present in the thermo-siphon loop including the moderator pot. The possibility of mixing of hydrogen with oxygen is eliminated, here by providing envelope of inert helium atmosphere and vacuum jacket.

(ii) Outside the pool, the hydrogen is jacketed by nitrogen atmosphere at slightly higher pressure than atmosphere, thereby, the mixing of hydrogen with atmospheric oxygen is eliminated.

(iii) However, even in case Hydrogen burns, the resultant product will be within the vacuum jacket as it is designed to withhold the resultant pressure due to burning of hydrogen.

(iv) Hydrogen tank will be vented to Buffer tank with adsorber Ti_2CrV in case of over pressure build up or leakage of Hydrogen or H_2-O_2 mixture formation.

(v) Provision of Hydrogen leak detection using ion pumps connected to the vacuum system and nitrogen environment separately.

3.7 Utilization of CNS

Cold Neutrons produced at moderator temperature of 20 K will be guided through a neutron beam tube, which acts a conduit between the reactor structure and the wall of the reactor pool. On reaching the pool wall, the cold neutron beam will be split into three cold neutron guides. The cold neutrons now travel along these guides into the guide tube laboratory, where there a number of experimental stations. It is planned to provide advanced instruments, which include Small Angle and Ultra Small Angle Neutron Scattering Spectrometer, Quasi Elastic Neutron Spectrometer, Neutron Reflectometer, Triple Axis Spectrometer, Spin Echo Spectrometer and others. These instruments can be used for studying proteins, micelles, macro-structure, magnetic excitations and lower energy vibrational states studies, diffusion and quantum tunneling studies, characterizing thin films and multilayers of advanced materials, dynamics in glasses, defects, voids in metallurgical samples and micron size inclusions in the materials among other utilizations.

4. Conclusion and future Outlook

The Cold Neutron Source in HFRR is a facility that will empower scientists in the country in exploring materials research especially in the large distance scale domain such as in the study of biological samples, polymers, thin films etc. and also in the large time scale domain such as study of diffusion, dynamics in glasses etc. The challenges exist in engineering the same owing to its complexity and first of a kind nature, which will be surpassed through development of proper manufacturing procedures and trial operations.

Acknowledgments

CNS-HFRR is a collaboration between various divisions in BARC including RRDPD, SSPD, RSD and CrTD.

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Pneumatic Carrier Facilities in Research Reactors

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Abstract

Pneumatic carrier facilities are built to facilitate short term irradiation of samples by ensuring quick recovery of the capsule for activation analysis of the irradiation sample. They ensure smooth to and fro transfer of the irradiation capsule between the sending/receiving (S/R) station and the irradiation position inside reactor. These systems are designed to ensure the safety of capsule against physical damage during its transfer between the two stations. Additionally, they provide adequate cooling of the capsule for removal of the heat generated inside the capsule and sample during irradiation. They also ensure, that the capsule is protected against overheating, in order to prevent the softening, melting, deforming and/or fusing of the sample inside irradiation position. One such Pneumatic carrier facility is provided in the proposed High Flux Research Reactor.

Keywords: *In-core material Test Device, Material Irradiation, Creep Test, High temperature.*

1. Introduction

Today's multipurpose nuclear research reactors are built to support wide range of neutron irradiation based scientific, medical and industrial applications. Many of these applications demand short-term, high-precision exposures under well-defined neutron energy spectra. Such applications are required for determination of trace elements using short lived isotopes produced by neutron activation with available higher neutron flux in the reactor. These studies are used for analysis of Environmental Samples including coal, coal ash, soil, sediment, and air particulate matter; Life Science Samples such as plants, leaves, grains, and food items; Reactor Materials including fuel clads, graphite, fuel materials, ores and minerals; Geological Samples such as rocks and meteorites; Archaeological Samples including clay, pottery, bricks and glasses. These analyses focus on determination of sample composition, adulterants, pollutants etc. Additionally, vital forensic studies are also performed on samples such as ceramics, glass, cloth, drugs and narcotic samples for finding trace elements etc.

First developed in the mid-20th century, PCFs have undergone substantial technological evolution, transitioning from manual systems to sophisticated automated platforms. Today, they are integral to multipurpose reactors such as the TRIGA (Training, Research, Isotopes, General Atomics), MNSR (Miniature Neutron Source Reactor), MAPLE (Multipurpose Applied Physics Lattice Experiment), and other IAEA-designated research reactors.

These Pneumatic systems can be typically integrated into either the radial irradiation channels near the reactor core periphery or the vertical irradiation positions in water-cooled reactors (e.g., pool-type designs). Reflector region ports, allowing access to moderated neutron fluxes for specific isotope production are ideal choice for such facilities. The neutron flux considered suitable for PCF are 10^{12} to 10^{14} n/cm^2/s in the thermal range. The fast-to-thermal flux ratios can be optimized by capsule positioning and shielding inserts (e.g. cadmium, boron liners). Flux uniformity is critical for precise activation

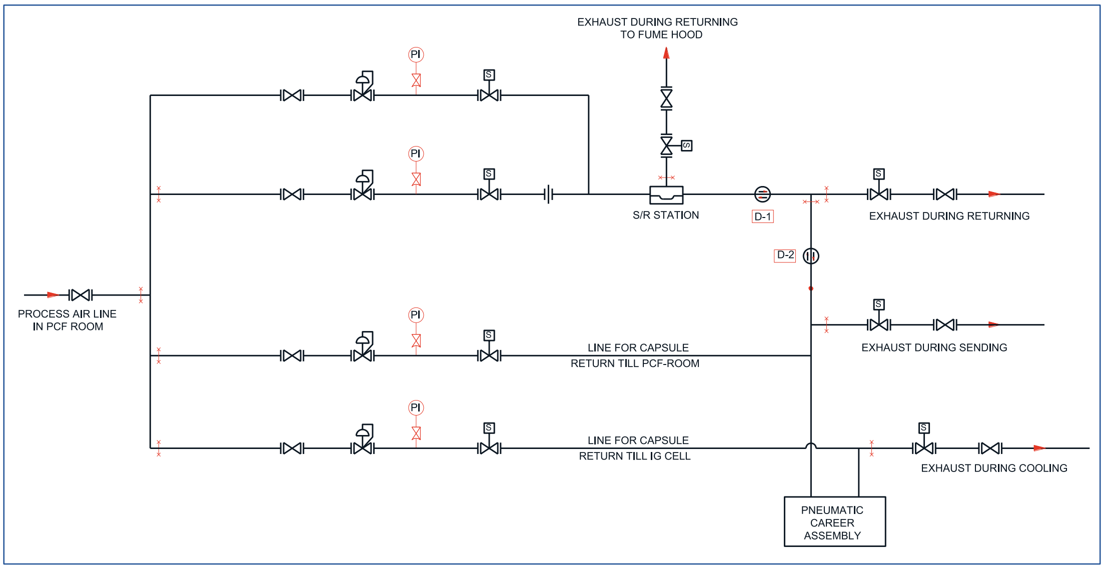

Figure 1. A schematic of Pneumatic Career Facility.

analysis, especially for quantification of short-lived nuclides.

The High Flux Research Reactor (HFRR) proposed to be constructed at BARC, Vizag will also have a Pneumatic carrier facility (PCF) to perform the activation analyses on samples that generate short lived isotopes having half-life of the order of few minutes. The facility is developed to permit samples to be placed in the reactor for irradiation as well as for post irradiation analysis in a very short time. The samples are sent into the reactor directly from the counting laboratory and retrieved back after completion of preset irradiation time. The samples can be taken up for counting (analysis) immediately in the same laboratory. The PCF is provided with a quick transfer system for reliable and repeatable transport of samples to and from specific irradiation positions within the reactor by placing the sample inside a light weight capsule which is pneumatically transported inside a pipe.

2. Description of PCF

The Pneumatic Career Facility of HFRR comprises of two important portions, a counting Laboratory and an irradiation thimble inside the reflector tank. The counting lab houses a capsule sending cum receiving station which is kept inside a glove box mounted with fume hood. On the other hand, the PCF thimble has a Pneumatic Career Assembly (PCA) which provides the irradiation station for the sample bearing capsule. Neutron flux of about 1×10^{13} n/cm^2/sec is available at the PCF thimble inside the reflector region of reactor. The capsule Sending and Receiving Station (S/R) is located inside a room on the first floor of the HFRR reactor building. The important components of PCF are described below. Fig. 1 illustrates the full pneumatic loop: loading station, propulsion valve system, rabbit tubing, in-core irradiation port, and receiving station. Modern systems incorporate optical sensors at tube entry for timing precision and safety interlocks for gas pressure sequencing.

2.1 Rabbit Capsules

Typically, the irradiation capsules also known as rabbit are made of material with low neutron absorption cross section, low neutron activation and adequate chemical stability. Some such capsule materials are aluminum, PTFE (Teflon), polycarbonate etc. The capsules to be used in PCF of HFRR are made of polypropylene material. The material has been selected due to its light weight, low neutron absorption characteristics and ability to withstand radiation environment. This material can withstand neutron fluence of the order of 10^{18} n/cm^2. Considering the flux of the order of 10^{13} n/cm^2/s, the capsule material is suitable choice. Capsule dimensions may vary based on reactor design with common capsule sizes ranging from 10 to 30 mm in diameter and 50–150 mm in length. In case of HFRR, the capsules size is 25 mm outer diameter and 38 mm overall length. The capsules are checked for proper size and shape by passing through a set of 'Go' – 'No-go' gauges to ensure its safe transmission into and from PCF thimble inside reflector region of the reactor.

The capsule is designed to withstand ressures of 2–6 bar, temperatures 100–150 °C and fast transient thermal loads. Thermal expansion and radiation-induced embrittlement are also considered in the design of irradiation capsule. The material and the quantity of sample for irradiation to be loaded into the capsule is so chosen that the temperature of the capsule does not exceed the safety limits for any point of time in order to prevent deformation of capsule.

2.2 Capsule Loading and Receiving Station

The capsule loading cum receiving station, as the name suggests, is a dual-purpose cubical box made of stainless steel. It is designed to ensure easy sample retrieval. The design often includes automated doors, mechanical grippers, or pneumatic lifters to handle activated samples remotely. In case of HFRR, it is a cubical box having four openings other than the top lid. They are as follows:

- One side to the Capsule line for sending/returning of capsule.
- Opposite side to Capsule Shooting Air Line.
- Rear side to Capsule return Air Exhaust Line.
- Bottom side to a Ball Valve for dropping the irradiated capsule into a shielded lead flask.

Heavy lead or borated polyethylene shielding is generally provided around the loading cum receiving station to ensure dose limits at the working interface. In case of HFRR this cubical box is kept inside a glove box to ensure adequate shielding to the working personnel. It is located inside a fume hood placed in the PCF room on the first floor of the reactor building.

2.3 Pneumatic Carrier Assembly

Pneumatic Carrier Assembly (PCA) is the irradiation station located inside the PCF irradiation thimble. Its purpose is to facilitate proper irradiation conditions for the capsule by providing adequate path for cooling air flow while ensuring that the capsule is properly seated at the desired position during the irradiation phase. Its design must also take care of the safe and easy ejection of the capsule from the irradiation position after completing the stipulated duration of irradiation. For this purpose, the PCA needs to have a path for the return air flow during the retrieving phase.

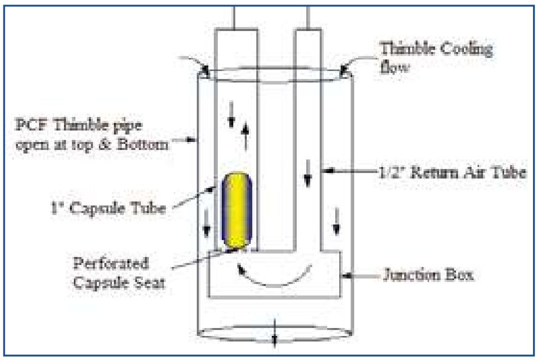

Figure 2. Schematic of the Pneumatic Career Assembly in HFRR.

In case of HFRR, PCA is placed inside the PCF thimble of reflector tank. It consists of two aluminium tubes (namely capsule sending tube & capsule cooling tube), which are geometrically kept separated using spacers. They are connected to an aluminium junction box of circular cross section. The junction box consists of a capsule seat with perforations for air flow and an air plenum. The schematic of PCF in HFRR is shown in Fig. 2.

2.4 Transfer Tubes

The two main stations of the Pneumatic Career Facility are connected with a Capsule line. Additionally, a capsule cooling line also runs along with the capsule line up to the PCA. These lines have sub branches with valves to perform different stages of the capsule sending, irradiation/cooling and returning stages. The capsule sending line is made of aluminium material for its better neutron economy and with low activation properties. It is a continuation of the stainless steel capsule line from PCF room. The aluminium line terminates at the capsule seat. Capsule cooling line terminates at the junction box inside PCA. It is also made of the aluminium material and it provides a return path for the capsule cooling air during irradiation. After the completion of capsule irradiation, the direction of air flow through this tube is reversed for driving the capsule back to the loading cum receiving station.

The tubing system of PCF at HFRR is divided into different zones as per their locations with the help of infrared detectors. These zones are defined to aid in the location of the capsule in case of any problems encountered during sending and receiving. The capsule line is carefully routed to minimize sharp bends and maintain laminar flow for ensuring smooth and obstacle free passage of capsule inside the line. U-bends or elevation changes are used to prevent direct radiation streaming from the irradiation thimble.

2.5 Propulsion System

The pneumatic carrier facility operates on the principle of differential gas pressure to transport the sealed sample capsule through stainless steel or aluminium piping to an irradiation position. The return cycle is similarly driven by a reversal or redirection of gas pressure, allowing rapid retrieval of the irradiated sample. Typically, compressed air or an inert gas (e.g., nitrogen or helium) is used as the propulsion medium to prevent oxidation or activation. Solenoid valves and pressure regulators are used in the system to maintain pressures between 2–10 bar. These valves are used to change the direction of flow by reversing the differential pressure between two points. The air flow is maintained such as to achieve optimum delivery speeds. While fast capsule delivery speeds are desirable, excessive speeds may cause damage of the capsule by banging it at the loading cum receiving station or the PCA. The sample transit times typically range from 0.5 to 3 seconds per direction, depending on tube length and geometry.

2.6 Control System

The PCF control architecture may vary from relay based control logic to programmable logic controllers (PLCs) and supervisory control and data acquisition (SCADA) software for timing, interlocks, and sequencing of the system operations. The control system also prevents unauthorized launches, gas overpressure, or sample ejection during reactor transients.

3. Applications of PCF

Short-lived isotope detection of elements such as ^{28}Al, $t_{½}$ = 2.24 min, ^{27}Mg, $t_{½}$ = 9.5 min, and ^{56}Mn, $t_{½}$ = 2.58 h using Neutron Activation Analysis (NAA) is the primary application. For these studies, the transit and handling times are optimized to reduce decay losses for radionuclides with half-lives below 5 minutes. Decay Counting Facilities: Proximity gamma spectroscopy stations with HPGe or NaI detectors are used for such applications.

Prompt Gamma Neutron Activation Analysis (PGNAA) is another application which is taken care in the radial irradiation configurations of the reactors. Real-time sample analysis during irradiation; requires collimated detection and precise control of capsule dwell time within the neutron beam.

Production of short-lived medical and industrial isotopes is also carried out in some pneumatic facilities. Isotopes such as ^{41}Ar gas tracer, ($t_{½}$ = 1.83 h) ^{18}F ($t_{½}$ = 109 min) for Positron Emission Tomography (PET) imaging and ^{24}Na, ^{82}Br, ^{38}Cl used for activation studies and tracers are produced in such cases.

Materials Irradiation Testing is also performed in some PCFs where small-scale specimens are subjected to neutron bombardment for radiation damage, swelling, transmutation effects, and defect accumulation studies.

4. Safety and Regulatory Compliance

Design of loading/unloading stations must comply with ALARA principles and national radiation protection regulations (e.g., ICRP 103, IAEA Safety Standards) for ensuring adequate radiation protection to the operating and analysing personnel. Additionally, pressure testing, leak testing, and interlock validation are conducted periodically to ensure pressure integrity. PCFs are part of the reactor's Safety Analysis Report (SAR) and require formal review for modifications or upgrades. Regulatory Licensing is required for operation of such systems as it involves radiation field and handling of radioactive isotopes.

5. New-Age and Upcoming Advancements

The evolution of pneumatic carrier systems is being shaped by innovations in digital control, smart materials, data analytics, and automated reactor operations. These advancements aim to increase the precision, reliability, throughput, and safety of irradiation experiments, while also enabling more complex and data-intensive research. The integration of Pneumatic Career Systems (PCS) into the broader framework of digital research reactors is driving a new paradigm in sample handling and irradiation science.

5.1 Smart Pneumatic Transport Systems

Modern research reactors can adopt intelligent PCS architectures that integrate Real-time monitoring sensors (pressure, flow, position, and temperature), Embedded RFID and QR-coded capsules for traceability and automation, Smart feedback loops that adjust gas pressure dynamically to optimize transit time based on capsule weight or tube friction, Predictive diagnostics to anticipate mechanical wear, seal degradation, or component activation. These upgrades improve system reliability, reduce downtime, and ensure irradiation accuracy for time-sensitive experiments. The major challenge in taking up such advancements is proving their reliability and their regulatory acceptance.

5.2 AI and Machine Learning Integration

Artificial Intelligence (AI) and Machine Learning (ML) can be deployed for Irradiation schedule optimization. AI can analyse decay half-lives, reactor flux maps, and detector readiness to prioritize sample order. ML algorithms trained on historical data can predict optimal irradiation times and expected radioisotope yields. AI can also monitor pneumatic system performance and alert operators to irregularities such as pressure anomalies, stuck capsules, or timing deviations.

5.3 Digital Twin Platforms

Digital twin technologies create a virtual replica of the pneumatic system and reactor environment. This allows simulated irradiation runs to optimize capsule positioning and timing. Flux mapping validation using historical and real-time data integration is also carried out. Such simulators are also useful for online training modules for new operators using virtual reality simulations of the PCS workflow. Error analysis for forensic troubleshooting and safety incident reconstruction can also be performed using such advanced tools.

5.4 Modular and Reconfigurable Systems

Emerging PCS designs focus on modularity. Quick-detach tube sections and interchangeable loading stations make such systems modular in nature. Multi-target irradiation systems with diverter valves to send different capsules to different core positions for dedicated reactors with several irradiation positions for short lived radio isotopes and NAA studies. Swappable irradiation end stations to support thermal, epithermal, and fast neutron applications without reactor downtime can also be thought of for such dedicated reactors. This flexibility may support dynamic experimental scheduling and cross-disciplinary research.

5.5 Robotics and Remote Handling Systems

In high-radiation environments, robot-assisted PCS handling is gaining more importance. Robotic arms with end-effectors capable of capsule loading/unloading in shielded hot cells are being developed. Integration with automated sample changers for gamma spectroscopy stations is being taken up by some reactors. Remote diagnostics and maintenance tools for inaccessible PCS components inside biological shielding are also under development.

5.6 Integration with Advanced Nuclear Facilities

As multi-purpose compact reactors (MPCRs) and next-generation modular research reactors (e.g., SLOWPOKE, RRI-30, and the upcoming IAEA SMR platforms), PCS designs are being tailored for Compact core geometries, High neutron flux per unit volume, Integrated isotope harvesting systems that work in synergy with PCFs. Moreover, space-based nuclear reactors for materials testing and isotope production aboard satellites may eventually adopt miniaturized PCS concepts for autonomous operation in microgravity environments.

6. Conclusion and future Outlook

Pneumatic carrier facilities are indispensable for facilitating high-throughput, precision-controlled short-term irradiations in research reactors. They enhance the experimental versatility of reactors by enabling rapid and automated sample handling, especially in applications where sample timing and irradiation reproducibility are paramount. With increasing demand for medical isotopes and advanced materials research, continued development of more efficient, intelligent, and safer PCFs will remain central to the evolution of nuclear research infrastructure.

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Neutron Transmutation Doped Silicon Facility

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Abstract

Neutron Transmutation Doped (NTD) silicon is a highly uniform and stable form of doped silicon produced via nuclear reactions. It holds significant advantages over conventionally doped silicon due to its exceptional homogeneity in dopant distribution. This report explores the fundamental principles, current applications, advantages, limitations, and future potential of NTD silicon. It highlights the increasing demand for high-performance semiconductor materials, especially in power electronics, space applications, and quantum computing, where NTD silicon is emerging as a material of choice.

Keywords: *Irradiation, NTD, NTD-Si, Quantum computing, Rotor, Silicon ingot*

1. Introduction

Silicon is the most widely used semiconductor material in the electronics industry. The electronic properties of silicon are modified through a process called doping, which introduces impurity atoms into the silicon lattice to control its electrical behavior. The most common doping techniques are diffusion and ion implantation. However, both methods struggle with limitations such as non-uniform dopant distribution, difficulty in controlling dopant profiles, and damage to the silicon crystal lattice.

2. Neutron Transmutation Doping fundamentals

2.1 Basic Principle

Natural silicon atoms are composed of three isotopes, ^{28}Si (abundance: 92.23%), ^{29}Si (abundance: 4.67%) and ^{30}Si (abundance: 3.10%). NTD relies on a nuclear reaction where specific isotopes of silicon capture thermal neutrons and transmute into dopant atoms (Fig. 1). In the case of ^{30}Si, thermal neutron capture leads to the unstable isotope ^{31}Si, which undergoes beta decay with a half-life of approximately 2.62 hours. The product of this process is a phosphorous atom, ^{31}P, resulting in exceptionally uniform n-type impurity doping in silicon material. [1]

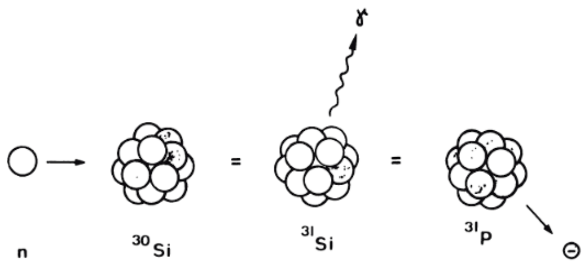


Figure 1. Schematic of NTD of Silicon

This doping method is fundamentally different from traditional surface techniques like diffusion or ion implantation, which introduce dopants only near the surface and require subsequent thermal processes to drive dopants into the bulk material.

2.2 Process Overview

The NTD process involves several stages:

(i) Selection of High-Purity Material: Only high-purity float-zone (FZ) silicon is used for NTD due to its low impurity levels and superior crystal quality. FZ silicon is preferred over Czochralski (CZ) silicon, which contains higher levels of oxygen and carbon that can interact adversely during irradiation.

(ii) Neutron Irradiation: The silicon ingots are exposed to a controlled thermal neutron flux inside a nuclear reactor. The neutron flux and irradiation time are carefully calibrated based on the desired phosphorus concentration.

(iii) Radioactive Decay: Following irradiation, the silicon is left to cool and decay, allowing the radioactive ^{31}Si to convert into stable phosphorus.

(iv) Annealing: A post-irradiation thermal annealing step is required to repair any damage to the silicon lattice caused by neutron bombardment. Annealing restores the crystal integrity and activates the phosphorus dopants.

2.3 Advantages of Nuclear Doping over Conventional Doping

The NTD process offers several distinct advantages:

(i) Unmatched Uniformity: Dopants are introduced uniformly throughout the bulk, resulting in exceptional homogeneity.

(ii) Reproducibility: High precision in neutron flux control ensures repeatable resistivity levels across batches.

(iii) Low Crystal Damage: Compared to ion implantation, which can severely disrupt the crystal structure, NTD induces minimal damage that is easily annealed.

(iv) Superior Electrical Performance: Devices built with NTD silicon demonstrate consistent and stable performance across a range of operating conditions.

2.4. Dopant concentration and resistivity relation in NDT section

In neutron transmutation doping, the initial resistivity of silicon to be irradiated typically ranges between 3000 and 20,000 Ω·cm. After irradiation, the resistivity is inversely proportional to the total concentration of phosphorus-31 atoms produced, as well as any pre-existing impurities in the silicon. The added phosphorus concentration is directly proportional to both the irradiated neutron fluence and the neutron capture cross-section of silicon-30. For n-type doping, the resistivity (ρ) of NTD silicon can be expressed as:

$$\rho = 1 / (\varepsilon \times \mu \times [P]) \qquad (1)$$

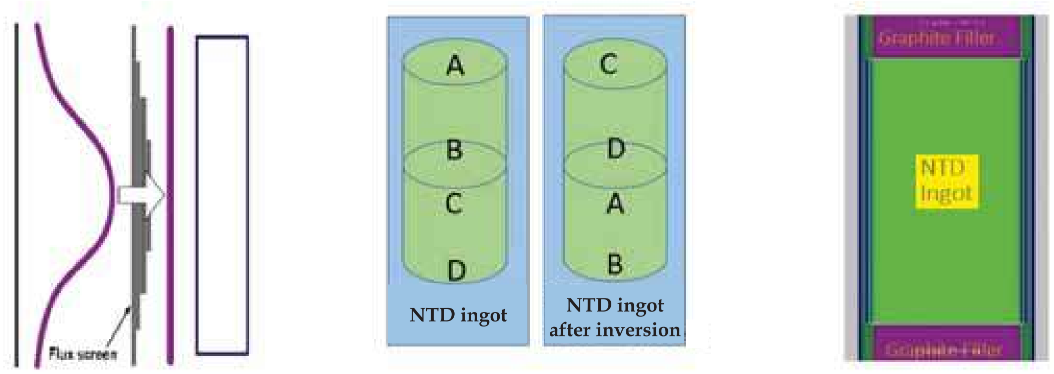
$$[P_{doping}] = N^{30,Si} \times \sigma^{30,Si} \times t_{irradiation} \times \phi \qquad (2)$$

where,[P] is the phosphorus atomic concentration in cm^{-3}, ε is the elementary charge (1.602×10^{-19} C), and μ is the electron drift mobility in the silicon lattice, which typically ranges from 1220 to 1500 $cm^2/V \cdot s$ depending on temperature. Φ is the thermal neutron flux, $N^{30,Si}$ is the density (g/cm^3) of ^{30}Si, $\sigma^{30,Si}$ is thermal neutron capture cross section of ^{30}Si.

This relationship highlights how precision control of neutron fluence directly enables accurate tuning of the final resistivity of the doped silicon, a unique strength of the NTD process. However, this process results in significant heat generation within the silicon ingot. This heating primarily stems from the gamma radiation, which dominates due to the short half-life (2.62 hours) of the intermediate isotope ^{31}Si. Additionally, the β^- decay of Si-31, transforming it into ^{31}P, also contributes substantially to internal heating during and immediately after irradiation. Thermal management and controlled cooling are thus essential aspects of post-irradiation handling to prevent crystal damage and ensure dopant activation.

2.5. Standardization

According to the International Atomic Energy Agency (IAEA), the thermal-to-fast neutron flux ratio should be at least 7:1, which ensures sufficient interaction with silicon-30 isotopes while minimizing unwanted transmutations. Additionally, the temperature should be maintained below 180 °C to prevent the diffusion of minority carriers and to reduce the formation of crystalline defects such as swirls or dislocations. Following irradiation, the silicon ingots are transferred to cooling area. The cooling duration depends on the neutron fluence.



(a) Conceptual Flux Screen (b) Conceptual inversion (c) Ingot with reflector

Figure 2. Methods to achieve longitudinal uniformity.

To assess the doping precision of NTD silicon, two critical parameters are evaluated: the radial resistivity gradient (RRG) and the axial resistivity variation (ARV).

The RRG quantifies the uniformity of resistivity (ρ) across the wafer's plane (radial direction) and is typically defined by

$$RRG = 100 \times \frac{\rho_{max} - \rho_{min}}{\rho_{min}} \; (in\,\%) \qquad (3)$$

For high-performance applications, RRG should not exceed 4–5%, ensuring consistent electrical properties across the wafer surface. This radial uniformity is achieved by rotating the ingot during neutron irradiation to compensates for flux asymmetries within the reactor core.

Similarly, the ARV evaluates the resistivity variation along the length of the cylindrical ingot.

$$ARV = 100 \times \frac{\rho_{max}^{plane} - \rho_{min}^{plane}}{\rho_{min}^{plane}} \; (in\,\%) \quad (4)$$

For industrial-grade NTD silicon, ARV should typically lie within 5–8%. Such longitudinal uniformity can be achieved by different methods as shown in Fig. 2 and given hereunder [2-3].

(i) Use of a flux screen (a specially designed moderator-absorber configuration placed around the ingot)

(ii) Reversing the ingot after half irradiation time

(iii) Using graphite reflector above and below ingot

(iv) Dividing the ingot in two parts and exchanging their position also called inversion method.

3. Comparison with Other Doping Techniques

NTD silicon distinguishes itself through its unique mechanism and output characteristics. However, to fully appreciate its position in the semiconductor landscape, it is important to compare it with the two most widely used conventional doping techniques i.e. diffusion doping and ion implantation (Table 1). The foremost advantage of NTD Silicon compared to other doping methods is the high uniform resistivity throughout the entire silicon ingot. Unlike surface-focused methods, NTD uniformly distributes phosphorus atoms (via transmutation of ^{30}Si to ^{31}P) across the entire volume of the ingot. This bulk uniformity is critical in high-power and high-voltage applications where resistivity fluctuations can lead to performance issues and failure.

Table 1. Comparison of different doping techniques.

S. No.	Specific Feature	NTD Silicon	Diffusion Doping	Ion implantation
1.	Doping Mechanism	Nuclear transmutation of Si isotopes	Thermally driven impurity diffusion	High-energy ion bombardment
2.	Uniformity	Excellent bulk uniformity	Surface-focused, variable profiles	Precise spatial control but with surface peaking
3.	Damage to Lattice	Minimal (annealed post-irradiation)	Low	High (requires annealing)
4.	Precision of Control	Very high, reactor flux controlled	Limited by diffusion length and time	High control of dose and depth
5.	Process Complexity	High (requires reactor access)	Moderate	High (requires vacuum systems)
6.	Scalability	Limited by reactor availability	High	High
7.	Cost	High	Low	Medium to high

4. Applications of NTD Silicon

Currently, the NTD market is primarily dominated by 125 and 150 mm diameter silicon ingots, which are widely used due to their compatibility with standard power electronic device fabrication processes. At present, the worldwide capacity of NTD facilities is estimated to be in the range of 150 to 180 tons per annum. However, this supply remains far below the projected future demand. For instance, it is anticipated that nearly 2000 tons of NTD silicon will be required annually by the year 2030, primarily to support the rapidly expanding hybrid electric vehicle (HEV) industry [2]. As demand increases and production technologies evolve, larger wafer sizes and higher throughput reactors are required to meet industrial requirements.

4.1 Power Devices

NTD silicon is a staple in the manufacture of high-power semiconductor devices, such as Thyristors, Insulated Gate Bipolar Transistors (IGBTs), Diodes etc. In all these applications, NTD silicon ensures precise control over doping levels, leading to optimized switching behavior, thermal management, and reliability.

4.2 High-Energy Physics Detectors

NTD silicon is used in the construction of radiation detectors for particle physics and nuclear experiments. Major research projects, including CERN's Large Hadron Collider (LHC), employ NTD-based sensors in tracking systems and calorimeters.

4.3 Space Electronics

The space environment imposes extreme demands on electronic components, including exposure to cosmic rays, temperature extremes, and vacuum conditions.

4.4 Quantum Computing

Quantum computers based on silicon qubits require atomically precise dopant placement.

5. Technological Challenges and R&D Trends

5.1 Radiation Damage and Annealing

While neutron irradiation introduces dopants uniformly, it also causes displacement damage in the silicon lattice. The primary damage mechanism is knock-on displacement, where silicon atoms are ejected from their lattice positions, forming vacancies and interstitials. Advanced annealing techniques, including Rapid Thermal Annealing (RTA), Low-Temperature Defect Recovery, Multi-step Furnace Annealing are being investigated to minimize residual defects while preserving dopant profiles. Research is also focused on identifying optimal neutron fluxes that balance doping effectiveness and defect minimization.

5.2 Residual activity

When the ingot is kept long for irradiation in case neutron flux is low or target resistivity is very low (less than 10 ohm-cm) along with the production of ^{31}Si various other radioisotopes like ^{32}Si and ^{32}P are produced and are shown as below:

$$^{31}Si + n \rightarrow {}^{32}Si\ (T_{1/2} = 172\ y) \longrightarrow {}^{32}P\ (T_{1/2} = 14.3\ d)\ (\beta^-) \longrightarrow {}^{32}S$$

$$^{31}P + n \rightarrow {}^{32}P\ (T_{1/2} = 14.3d)\ (\beta^-) \longrightarrow {}^{32}S$$

^{31}Si has relatively short half-life of 2.62 hours and decays sufficiently with a cooling of one or two days. The activity of ^{32}Si is also very low because of its very low production rate despite very long half-life. Therefore, the main source of residual radioactivity is ^{32}P.

6. NTD in HFRR

NTD Si is planned to be produced in HFRR and location has been finalized in the reflector region (as shown in Fig. 3a), where thermal neutron flux is approximately 2.3×10^{13} n/cm²/s. The silicon ingots with nominal diameter of 200 mm and length 600 mm will be irradiated. Typical irradiation time has been estimated to be about 6.64 hours for target resistivity of 30 ohm-cm and 24 mins for 500 ohm-cm.

The NTD-Si facility of HFRR is shown in Fig. 3(b). It consists two cylinders i.e., a stator shell and a rotor shell. The ingot is to be placed in the rotor shell and then the rotor shell will be rotated around its own axis using the hydraulic pressure. The stator shell is to be inserted in the NTD thimble of the reflector vessel and are in clearance fit with each other. To achieve radial uniformity in resistivity, the ingot is rotated slowly, around 2–10 revolutions per minute (rpm). This rotation is facilitated by a jet nozzle

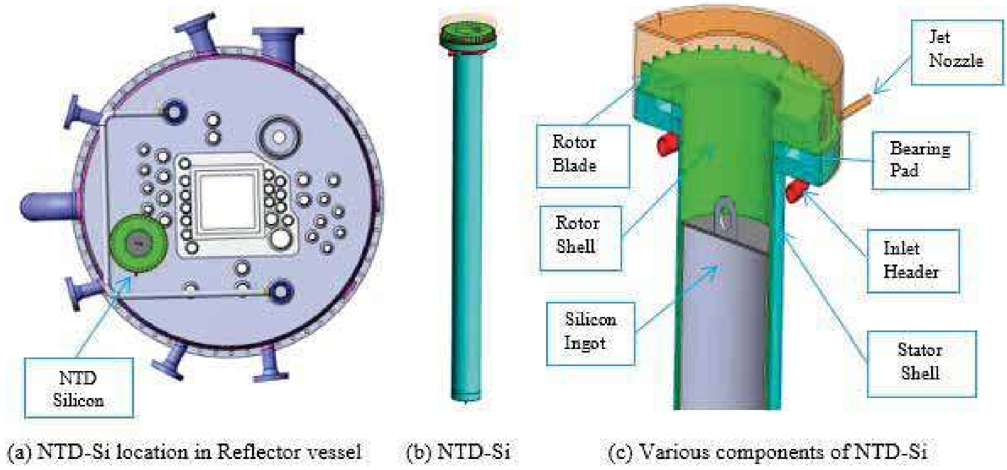


Figure 3. Details of NTD Silicon facility proposed in HFRR.

mechanism as shown in Fig. 3(c). Meanwhile, the inner shell of the ingot holder is levitated using a hydraulic thrust bearing system. This precise mechanical arrangement ensures stable and uniform exposure of the ingot to the neutron flux. As mentioned in end of section 2.4, cooling of the silicon ingot during irradiation in the reactor is very important. In the present arrangement a Silicon ingot of 200 mm will be cladded with Aluminium where a stagnant water gap of maximum 1.5 mm may be allowed. A cooling flow rate of about 30 lpm in the water gap between silicon ingot and the rotor shell shall be provided for keeping the maximum ingot temperature less than 150 ^{o}C.

7. Conclusion and future Outlook

India, with its strong foundation in nuclear technology and a growing demand for advanced semiconductor materials, is uniquely positioned to emerge as a global leader in the production of Neutron Transmutation Doped (NTD) silicon. Currently APSARA-U facility is going to start a pilot-project for production of 150 mm NTD silicon. High flux research reactor is also designed for NTD silicon production to industrial scale. Additionally, the presence of domestic silicon manufacturers and a growing semiconductor ecosystem bolstered by the SEMICON India program offers a timely opportunity to integrate NTD silicon into national supply chains.

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Proposed Neutron Scattering Facilities at HFRR for Structural Characterization of Advanced Materials

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Abstract

State of the art facilities for structural characterization in condensed matter research, enabling high resolution and also time resolved experiments under various sample environments, are planned at the upcoming HFRR, Vizag. In the first phase, four world class facilities, namely, i) Magnetic Material Diffractometer, ii) High-Q Diffractometer, iii) General purpose Small-Angle Scattering facility and iv) Polarized neutron reflectometer, are planned, with the intent of striking a balance between resolution and throughput, taking the advantage of higher available flux of HFRR. These facilities will be pivotal towards cutting edge research on wide range of challenging systems, starting from quantum materials to ceramics and from thin film heterostructures to bio and soft materials.

Keywords: *Neutron scattering, HFRR, Atomic structure, Magnetic ordering, Nanostructures, Thin Films and Multilayers, Liquids and glasses*

1. Introduction

The existence of a neutral particle with mass similar to the mass of a proton was hypothesized by Rutherford in 1920, and this was proved by the discovery of the neutron by J. Chadwick, a student of Rutherford, in 1932. Since its discovery, neutrons have been used as an imperative probe for research in condensed matter. Due to its various special properties, neutrons provide insight into the microscopic structures and dynamics in a wide class of materials. Neutron scattering is an indispensable technique that provides unique structural information about condensed matter spanning from the atomic length scale to sub micro-meter length scale.

The national facility for neutron beam research (NFNBR) at Bhabha Atomic Research Centre (BARC), Mumbai, which is conceived and operated by the Solid-State Physics Division (SSPD), caters to a large number of neutron scattering users from across the country in addition to the in-house research. Presently, the neutron scattering activities are centred around the Dhruva reactor, Mumbai. A pictorial view of neutron scattering facility and a layout of different techniques are shown in Figs. 1 and 2, respectively. For structural characterization, there are two powder diffractometers (another one powder diffractometer is developed and operated by DAE-UGC-CSR), one high-Q diffractometer (providing information about glassy and amorphous materials), two small-angle neutron scattering facilities (for probing nanostructured materials), and one neutron reflectometer (for studying thin film, heterostructures and multilayers).

Several state-of-the-art neutron scattering facilities are envisaged at the upcoming High Flux Research Reactor (HFRR), Visakhapatnam (Vizag), which will take advantage of the significantly higher flux of HFRR. The proposed reactor is a 40 MWt open pool-type research reactor utilizing enriched fuel with a designed thermal flux of ~5×10^{14} neutrons/cm^2/s and an epithermal flux of ~3

Figure 1. A view of neutron scattering facilities inside the Dhruva reactor hall.

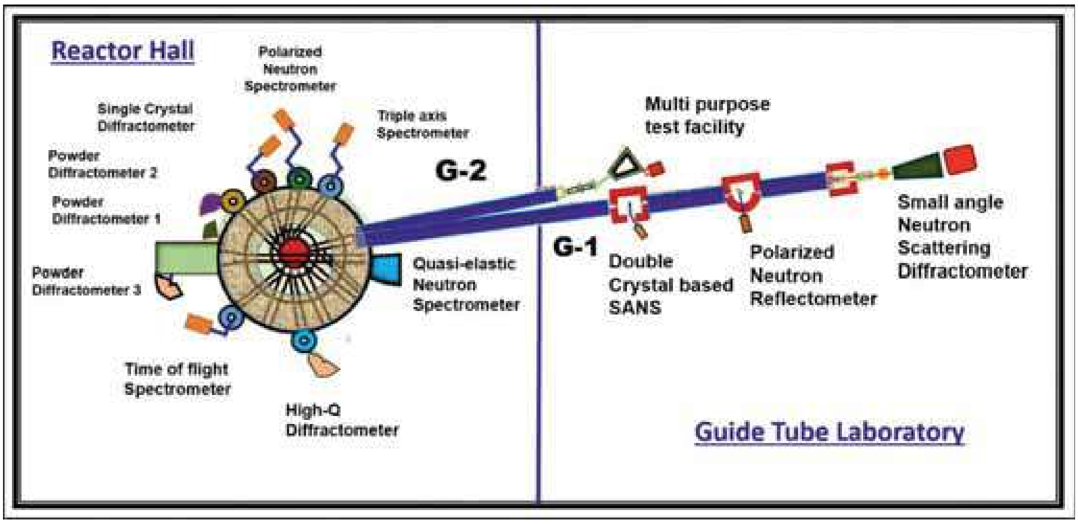

Figure 2. A layout of the neutron scattering instruments at Dhruva reactor and guide hall.

× 10^{14} neutrons/cm^2/s in the reflector. For structural characterization, in the first phase, 4 such advanced neutron scattering facilities are planned in HFRR for cutting-edge research, and glimpses of these planned facilities are described below.

2. General Purpose Small and Wide-Angle Neutron Scattering Facility proposed at HFRR

Small-Angle Neutron Scattering (SANS) is a powerful non-destructive characterization technique for investigation of mesoscopic length-scale structure (1–1000 nm) of varieties of materials, such as macromolecules, ceramics, alloys, polymers, thin films, porous grains, and soft materials [1–4]. SANS not only provides morphological information, but also the positional correlation among them. It is an elastic (kinetic energy is conserved) scattering technique where the distribution of scattered intensity around the direct beam is recorded as a function of wave-vector transfer. If an incident radiation of wave vector $\overrightarrow{K_i}$ gets scattered at an angle '2θ' with wave vector $\overrightarrow{K_f}$, n the difference between the incident and

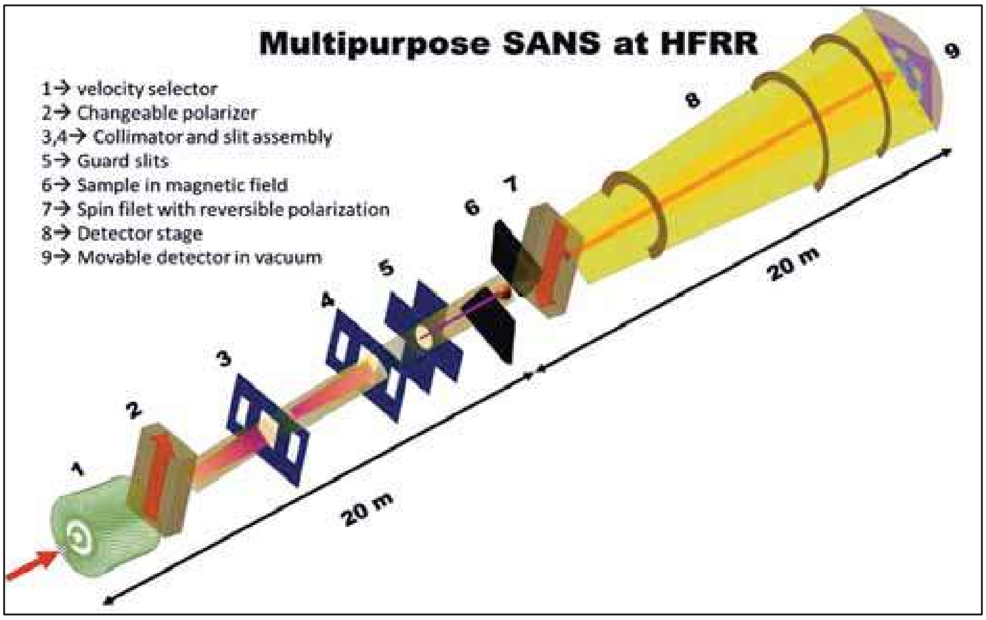

Figure 3. A layout of the proposed 40 m long SANS facility at HFRR.

scattered wave vectors ($\vec{K_f} - \vec{K_i}$) is called the wave-vector transfer ($\vec{Q}$) and its magnitude ($Q = \frac{4\pi\sin(\theta)}{\lambda}$) depends on the scattering angle (2θ) and the wavelength (λ) of neutrons. The scattering events from any individual scattering element of a particle depend on the type of incident radiation and the nature of the illuminated element. The scattering cross-section can be characterized by a quantity, called the scattering length [3]. For SANS, the observed length-scale is much larger than the individual scattering elements (atoms) and thus, for a homogeneous particle, the distribution of the individual scattering length can safely be considered uniform and the total scattering strength from the overall particle can be expressed by the scattering length density (SLD) (ρ).

Owing to the inherent characteristics of this widely utilized, popular, and non-destructive technique, SANS possesses a tremendous potential for scientific as well as industrial applications. One of the major strengths of the SANS technique is that it can be used to investigate a host of materials, covering a wide range of research disciplines encompassing Physics, Chemistry, Chemical Engineering, Soft Matter, Biology, Materials Science, etc. Materials that are routinely characterized using the SANS technique include biological materials, alloys, nanoparticles, ceramics, colloidal materials, complex fluids, polymers, surfaces and nterfaces, flux lattices in superconductors, self-assembled materials, and aerosolized materials. SANS is also a versatile technique for investigating food components, such as proteins, polymers, and emulsions. For pharmaceutical and chemical industries, SANS is a very important tool that can provide crucial information about the stability of the products that depend on the crucial balance between complex interactions in such useful materials. Presently, there are two SANS facilities at the guide tube laboratory, Dhruva. A slit collimated SANS facility [5] (1–20 nm) and the double crystal-based SANS facility [6] (20–500 nm). These facilities are used

Table 1. Design parameters for proposed SANS instrument.

Total length	42 m
Monochromator	Neutron Velocity Selector (NVS)
Wavelength and its spread	3–20 Å; 5–30 %
Q window	10^{-4} – 10 Å^{-1}
Resolvable length Scale	0.5–200 nm
Collimator	Removable guide sections (normal, supermirror or polarizer), each 5 x 5 cm^2 and 1 m long, 8 guide sections.
Collimator flight path	20 m (maximum)
Beam apertures	Variable apertures (0.5 × 0.5 to 1.5 × 1.5 cm^2); rectangular and square
Sample Stage	1 m^2 area available for the automatic changers, furnaces, magnets, cryostats, pressure cells, etc.
Sample changer	40 cuvette sample positions (20 in top and 20 in bottom slabs)
Attenuator	choice between 3–5 slitted cadmium sheets of different transmissions that can be combined to achieve variable attenuation factors
Monitor	Five BF_3 counters before and after (i) NVS; (ii) collimators; (iii) sample
Detectors	Multi-tube detectors for wide-angle scattering 2D position-sensitive area detectors for small angle scattering
2D-Detector area	80 cm x 80 cm or higher
Sample-to-detector distance	Continuously varying between 1.5 to 20 m (max) in z-direction 40 cm offset in x-direction
Detector resolution	1–5 mm^2
Polarizer	Super mirror, (Fe:Si sm, rf spin flipper), and/or ^{3}He
Magnetic fields	Magnetic fields to maintain the polarization state
Polarization analysis	Polarized ^{3}He filters/Super mirror
Sample environments	Cryostats, Water bath, Furnaces, Magnets, Rheometer, pressure cells, Gas handling facility, humidity control.
Vacuum Pumps and Gauges	4 multi-root dry pumps 4 Pirani gauges
Few comparable Instruments worldwide	(i) GPSANS of ORNL, USA (ii) D11 of ILL, France (iii) SANS-1 of PSI, Switzerland (iv) Quokka, ANSTO, Australia

extensively by users from universities and national institutes.

A 40 m long versatile SANS instrument with a variable collimation length (using guide sections) up to 20 m and a detector tube of 20 m (Fig. 3) is proposed at HFRR. Such long instruments allow for the versatile design and implementation of various options, such as polarization, wavelength selections and its spread, number of detectors and their positioning, sample environments (cryostats, pressure/load frames, high temperature furnace, rheometers, setups for strong electric or magnetic fields, shearing setups) etc. The creation of a polarized neutron beam and its maintenance do not affect the underlying concept of SANS design, as there could be multiple possible locations for a polarizer and polarization analysis (preferentially with ^{3}He). The separation of incoherent background is highly desirable for weakly scattering samples with important details at larger Q, especially so for biological molecules and complexes. The design parameters of proposed SANS instrument are listed in the Table 1 and a comparison of different SANS facilities worldwide is given in the Table 2.

Table 2. Comparison with three best instruments around the world.

Parameters	D11, ILL	GP-SANS, ORNL	QUOKKA, ANSTO
Incident wavelength	4.6 Å ≤ λ ≤ 40 Å	4 < λ < 20 Å	4.6 Å ≤ λ ≤ 40 Å
Wavelength spread	Variable, typical Δλ/λ = 9 % (FWHM)	Δλ / λ= 9 – 25%	
Collimator	11 guide sections (computer-controlled)	Eight removable guide sections, each 4 x 4 cm^2 and 2 m long;	^{58}Ni equivalent guides (50 mm x 50 mm) (4 m, 7 x 2m)
Guide-to-sample distances	(11 discrete distances)		
Flux at the specimen at the lowest resolution	5 x 10^7 $n \cdot cm^{-2} \cdot s^{-1}$ (at λ = 0.6 nm, as measured on the detector)	~10^7 $n \cdot cm^{-2} \cdot s^{-1}$	4 x 10^7 $n \cdot cm^{-2} \cdot s^{-1}$
Sample-to-detector distances (L)	continuously variable between 1.4 m and 38 m	1 –19 m; detector can be offset horizontally by up to 40 cm,	Sample – detector distance: 1.3–20.1 m (continuously variable); Horizontal offset 450 mm
Momentum transfer range	3 x 10^{-2} $Å^{-1}$ ≤ Q ≤ 0.8 $Å^{-1}$	0.001-1.3 $Å^{-1}$	6 x 10^{-4} $Å^{-1}$- 0.7 $Å^{-1}$
Detector type	^{3}He gas detector (256 number of 1 m long, 8 mm outer diameter stacked tubes from Reuter-Stokes	A total 192 array, 1m wide and 1m long ^{3}He LPSDs	Multi-wire ^{3}He proportional detector
Detector area	2 m^2	1 m^2	1 m^2

3. High-Q Diffractometer proposed at HFRR

Currently, one High-Q diffractometer [7] is operational at the beam-hole HS-1019 in Dhruva reactor, which caters to the study of the structure of crystalline powders as well as amorphous materials. A new High-Q diffractometer aiming for high angular range, and thus coverage of high reciprocal space as well as high resolution, is proposed as one of the Day-one instruments in the reactor hall of the proposed HFRR. This instrument has been proposed with the intent of striking a balance between resolution and throughput, and also to push the boundaries of the currently operating High-Q diffractometer at the Dhruva reactor, BARC, Trombay [7]. It is designed to cater to microscopic structure determination, including magnetic structure, pair distribution function analysis, and performing time-resolved diffraction experiments. It will be used for high-throughput, high-resolution neutron diffraction and pair distribution function experiments to understand short-range order in magnetic materials, glasses, liquids, and disordered materials. It will cater to the study of the structure of crystalline powders as well as amorphous materials. Experiments with smaller time frames, isotopic substitution of elements to acquire partial structure factors, are possible owing to high neutron flux at the sample position and enhanced throughput by accessing the larger solid angle of the diffracted Debye Scherer cone, possible due to higher flux at HFRR.

- Short and intermediate range order in liquid, amorphous, and nano-structured materials.
- Isotopic substitution methods for resolving partial structure factors in glasses with direct application in the radioactive waste immobilization program of the department.
- Magnetic structure studies on novel functional glasses. Magnetic Pair-Distribution Function (PDF) measurements can also be done.
- PDF / total scattering measurements of disordered polycrystalline, nanocrystalline, magnetic, and amorphous materials.
- Powder diffraction measurements for Rietveld refinements of atomic and magnetic structure to very high Q values to unambiguously determine accurate values of Debye-Waller factors.

High-Q diffractometer at HFRR is a conventional 2-axis neutron diffractometer which uses relatively shorter wavelengths of neutrons to measure diffraction patterns over a large Q-range with Q_{max} = 23.5 $Å^{-1}$. This instrument will be equipped with thirty 1-D position-sensitive detectors pressurized with ^3He gas up to 10–15 bar pressure for efficient detection of shorter wavelength neutrons. A schematic drawing of the proposed instrument is shown in Fig. 4.

Three different monochromator assembly positions, marked as M1, M2, and M3, are planned with take-off angles at 60° (M1), 90° (M2), 42° (M3), and 22.55° (M4) respectively. At M1 position Germanium crystal with mosaicity 12' and zone axis $(1\bar{1}0)$ has been selected for vertically focusing in (331) plane, and at M2 position, vertically focusing Ge (115) also provides plane along with other (hhl) reflections upon rotation when not in focusing mode. At the M3 position, Cu (220) crystal in vertically focusing mode is selected for a low wavelength of 0.5 Å. The wavelength of the monochromatic neutron is dependent upon the plane of the crystal and the take-off angle according to Bragg's law. This monochromator can be placed at any of the marked positions depending on the requirements of the experiment. To reduce the horizontal divergence of the neutron beam, a variable collimator system consisting of Soller collimators of multiple angular resolutions

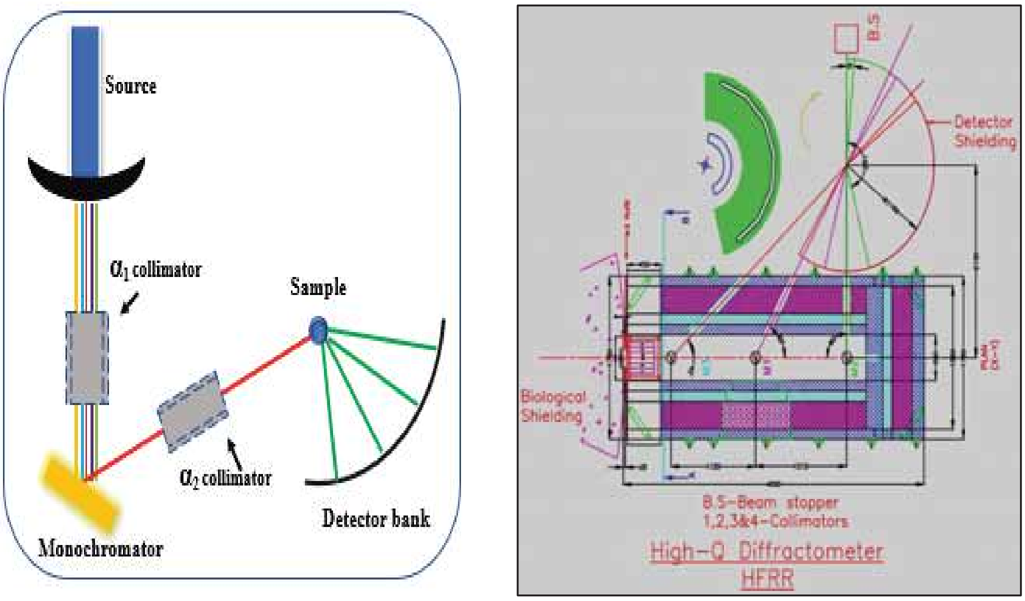

Figure 4. A layout of the proposed High Q facility at HFRR.

collimators of multiple angular resolutions (5′, 10′, 20′, and 40′) will be installed in front of the monochromator and sample. These collimators allow some freedom in choosing the in-plane collimation between the source, monochromator, and sample. A standard NACF ($Na_2Ca_3Al_3F_{14}$) polycrystalline powder sample in a Vanadium cylindrical container (diameter = 8 mm and height 30 mm) is used to simulate the Bragg profile and optimize various components of the diffractometer. The detector system consists of a total of 30 ^{3}He position sensitive detectors covering 2θ range up to 165°. Each detector has a length of 600 mm and a diameter of 25 mm. In this detector bank, a total of six sets, each consisting of vertically stacked five detectors, are placed in an arc to collect a large part of the Debye-Scherer cone to speed up the data collection. An Oscillating Radial Collimator is placed between the sample and detector bank to reduce the background and improve the signal-to-noise ratio.

The neutrons are traversing from source to monochromator to sample to detector in the air medium. The sample-to-detector distance is 1000 mm for both positions. The high flexibility in the choice of Monochromator reflection planes, different collimations, and the take-off angle at the Monochromator allows to adjust the instrument to meet the required optimization between resolution and total throughput.

Collimations in a diffractometer are of three types- Primary collimation (α_1) between the source and the monochromator, Secondary collimation (α_2) between the monochromator and sample, and Tertiary collimation (α_3) between the sample and detector. By rotating the monochromator assembly around its vertical axis, if it is aligned with a zone axis, it is possible to obtain different reflections and associated wavelengths. The specification of the proposed High-Q Diffractometer at HFRR and a compassion of it with other instruments worldwide are given in the Table 3.

Table 3. Comparison with other instruments.

Parameters	D4C, ILL	Upgraded High-Q, DHRUVA	High-Q, HFRR
Monochromator	Si(11L = 1,2,3), Cu(220) and Cu(331), all V.F and H.F	V.F.Cu(220) Cu(002) Cu(111) Cu(311)	Cu(220), Ge(331), and Ge(533)
Flux at Sample ($n/cm^2/sec$)	5.0×10^7 Cu(220); λ = 0.7 Å & 0.5 Å, 0.75×10^7 Cu(331); λ = 0.35 Å	2.0×10^6 Cu(111); λ=1.27Å 4.4×10^6 Cu(002); λ=1.10Å 1.5×10^5 Cu(311); λ=0.66Å 1.0×10^6 Cu(220); λ=0.78 Å	7.6×10^7 Cu(220) at M1, 7.1×10^7 Cu(220) at M3, 1.5×10^7 Ge(533) at M1, 1.9×10^6 Ge(533) at M3,
In-pile collimation	-	5', 10', 20', Open	5', 10', 20', Open
Scattering Angle	$1.5^0 < 2\theta < 140^0$	$4^0 < 2\theta < 140^0$	$3^0 < 2\theta < 165^0$
Q_{max} value	~ 25 $Å^{-1}$	9.2 $Å^{-1}$ – 17.6 $Å^{-1}$	9.7 $Å^{-1}$ – 20.6 $Å^{-1}$
Detectors	Microstrip detectors, 9 x 64 cell under 15 bar of ^3He	15 (1-D) ^3He PSD	30 (1-D) ^3He PSD
$\Delta Q/Q$ (resolution) (%)	1.0 – 4.0	0.73, 1.07, 1.22, 1.60	0.7 – 1.60
C-number ($n/s/0.05\ Å^{-1}/cm^3$ of V)	850	378 (λ = 0.783 Å, $\Delta Q/Q$ = 1.62%)	~ 750 (Calculated)
Experiments	Liquids, Glasses & Disordered Crystals	Liquids, Glasses & Disordered Crystals	Liquids, Glasses & Disordered Crystals

4. Magnetic Materials Diffractometer (MMD) proposed at HFRR

The neutron powder diffraction technique is a non-destructive probe for crystal and magnetic structures at the microscopic length scale [8]. It is a very powerful and unique tool to study magnetic properties of a variety of technological materials, such as quantum materials, multiferroics, and advanced magnetic materials, including magnetic recording media, metals, alloys, and ceramics. Understanding the importance of neutron powder diffraction on the crystal structural properties studies of various materials of scientific and departmental interest, three position-sensitive-detector-based powder diffractometers (viz. PD-1, PD-2, and PD-3) have been built at the Dhruva reactor, BARC [8]. These instruments are currently being used by in-house scientists and researchers from various universities and research institutes across India through the NFNBR programs.

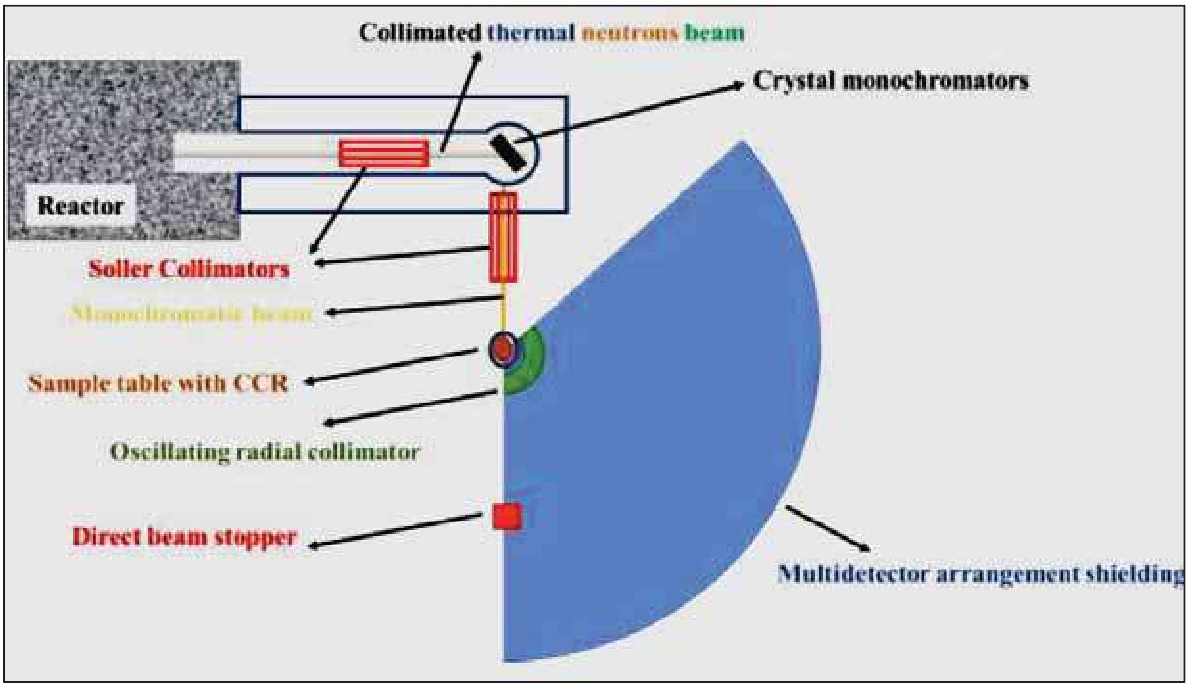

Figure 5. The layout of the magnetic materials diffractometer.

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Experimentally, a neutron powder diffractometer measures scattering intensity as a function of scattering angle (2θ), known as the diffraction pattern, which is a fingerprint of the average bulk (crystal/magnetic) structure at a microscopic length scale. The diffraction pattern includes several peaks due to Bragg reflections from the crystalline sample. The full width at half maximum of these peaks is related to the angular divergence of the neutron beam and the monochromator crystal mosaic spread. To measure the diffraction pattern from a wide range of materials with complex structures described earlier, one requires high intensity at the sample position as well as high resolution of the diffractometer. Thus, there is increasing demand for neutron powder diffractometers with better resolution and higher intensity to study the materials of present interest.

A new diffractometer called Magnetic Materials Diffractometer (MMD) is proposed to be built at HFRR. Fig. 5 shows the layout of the proposed MMD instrument. The high intensity in the proposed MMD diffractometer will be achieved by utilizing the near peak wavelength (1.16 Å) of a Maxwellian neutron spectrum. The good *Q*-resolution over the full angular range will be achieved by optimizing the design of the slit-widths and lengths of the Soller collimators. The MMD will include the state-of-the-art sample environments, including low temperature down to mK, high temperature up to 2000 K, magnetic field up to 7 T, high pressure up to 2 GPa, and high electric field up to 75 kV/cm. The detail specifications of the proposed MMD instrument and a comparison with other diffractometers worldwide is given in the Table 4.

Table 4. Comparison of different neutron diffractometers

Parameter	Magnetic Material Diffractometer (MMD)	High Resolution Powder Diffractometer	High-Resolution Powder Diffractometer : SPODI	Neutron Powder Diffractometer : HB-2A
Facility	HFRR	Neutron Beam Facility, Korea	FRM2	HFIR, ORNL
Location	INDIA	Korea	Germany	U.S.
Monochromator	Si	Ge (551)	Ge (331)	Ge (113)
Take off angle	90°	90°	155°	90°
Resolution (ΔQ/Q)	0.1%	0.2%	0.3%	0.2%
Collimation	5′, 15′,10′	20′, 30′, open	20′, 10′, 20′	60′, 16′, 12′
Detector Type	^{3}He bank	^{3}He bank	^{3}He bank	^{3}He bank
Temperature range	2 to 2000 K (with ^{3}He insert T_{min} =300 mK)	1.5 to 1800 K, Dilution 50 mK	3 – 1900 K (with ^{3}He insert T_{min} = 500 mK)	0.03 - 1800 K
Pressure	up to 2 GPa	Up to 1 GPa	-	up to 2 GPa
Magnetic field	up to 7 T	up to 10 T	up to 5 T	up to 8 T
Electric field	up to 75kV/cm	-	up to 35kV/cm	-
Wavelength	1.16 Å	1.836 Å	2.536, 1.111 Å	2.41 Å
Q range (Å^{-1})	0.3 – 9	1 – 11	0.7 – 4.8	0.14 – 8
Applications	Lattice & magnetic structures of quantum materials.	Lattice and magnetic structures.	Static & thermal disorder phenomena, Lattice & magnetic structures.	Magnetic and crystal structural studies of powdered and ceramic samples

5. Polarized Neutron Reflectometer proposed at HFRR

Polarized neutron reflectometry (PNR) is a unique non-contact and non-destructive technique to investigate depth-dependent (specular) and in-plane (off-specular) structural and magnetic properties of thin film heterostructures and multilayer superlattices with sub-nanometre resolution [9]. PNR is a potent tool to investigate emergent phenomena such as the magnetic proximity effect and exchange bias effect in complex oxide heterostructures, helical domain walls, and interfacial alloying in metallic multilayers, interfacial coupling of magnetic materials with topological insulators for spintronic applications, etc. In contrast to other techniques of macroscopic magnetization measurement, PNR can provide interface-specific information and completely avoid any

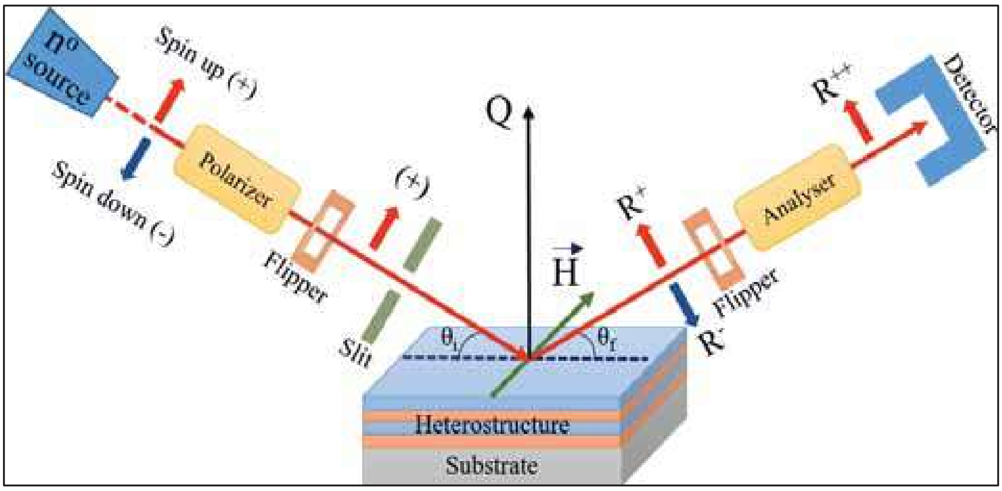

Figure 6. Schematic of a typical PNR setup with different components.

substrate contribution (diamagnetic or paramagnetic contribution from substrates), providing unique insights for unravelling the intricacies of nanoscale phenomena in these systems. The high penetration depth of neutrons makes PNR an excellent technique to study magnetism at the buried interfaces. Additionally, the weak interaction of neutrons with most of the materials also assists in implementing sophisticated sample environments such as low temperature, electric and magnetic fields, etc., for different PNR experiments.

PNR works on the fundamental principle of neutron reflection from thin film samples. The refractive index (n) of neutrons is slightly less than 1 for most of the materials allowing total reflection at grazing angle of incidence. Moreover, the neutrons can be polarized either parallel (spin-up) or anti-parallel (spin-down) with respect to a magnetic field. Polarized neutrons are incident at grazing angle on the sample and the neutron reflectivity is recorded as a function of Q. The Q range is spanned by changing the angle of incidence ϑ at a fixed wavelength λ. Due to the different magnetic interactions of neutrons and magnetization of the samples, the spin-up (+) and spin-down (-) neutrons have different refractive indices ($n+$ and $n-$), giving rise to distinct reflectivity profiles from the same magnetic sample. These reflectivity profiles are recorded and analyzed to get quantitative information about the structure and magnetism of the samples including layer thickness, layer/interface roughness, neutron scattering length density profile and magnetization in different layers. To accomplish this a PNR setup consists of multiple components including a neutron source, neutron polarizer, flipper coil, slit combinations, sample table, polarization analyzer and detector. Schematic of a typical PNR experiment and its components are shown in Fig. 6.

A new PNR instrument is being designed at HFRR, which will be housed at the cold neutron guide in the Guide Tube (GT) Lab at HFRR. The instrument will benefit from the high flux of cold neutrons and operate at a wavelength of ~5 Å, allowing measurements on small samples of size ~ 1 cm x 1 cm. The higher flux will also allow spin-flip reflectivity measurements to identify the orientation of the in-plane magnetization and off-specular measurements to obtain in-plane structural and magnetic fluctuations in the thin films. The instrument will be equipped with a low-temperature sample environment (5–300 K) and variable magnetic field (up to 2 T) environment. The key parameters of the PNR instrument are given in the Table 5, and a comparison of this proposed instrument with other PNR instrument is given in the Table 6.

Table 5. Key parameters for the proposed PNR instrument at HFRR.

Flux of the CNS	8.5×10^{12} n /s/cm^2
Beam size at Guide Exit	12×5 cm^2
Monochromator	PG (002) based curved monochromator
Take off angle	84.24°
Wavelength	4.5 Å
Polarizer	Fe/Si based neutron supermirror
Flux at the sample	2.3×10^6 n /s/cm^2
Source to Monochromator distance (including guide)	30.5 m
Monochromator to Sample Distance	3.5 m

Table 6. Comparison of different Neutron Reflectometer Instruments

Parameter	**Polarized Neutron Reflectometer**	**SuperADAM**	**PolRef**	**MagRef**
Facility	HFRR, BARC	ILL	ISIS, RAL	SNS, ORNL
Location	India	France	U.K.	U.S.A
Monochromator	PG (002)	HOPG (002)	-	-
Polarizer	Reflection supermirror	Reflection supermirror & ^{3}He spin filter	Reflection supermirror	Reflection supermirror & ^{3}He spin filter
Orientaiton	Vertical	Horizontal	Horizontal	Vertical
Flux at Sample	1×10^6 n /s/cm^2	3.2×10^5 n /s/cm^2		
Detector Type	^{3}He PSD	^{3}He PSD	^{3}He PSD	^{3}He PSD
Resolution	3-5%	4-8%	3-10%	3-8%
Temperature Range	5-400 K	2 – 400 K	10-300 K	5 - 750 K
Magnetic Field	2 T	1.1 T	0.5 T	1.2 T
Q range	0-1.5 Å^{-1}	0-2.5 Å^{-1}	0-3.5 Å^{-1}	0-3.5 Å^{-1}
Wavelength	4.5 Å	5.21 Å	0.9Å - 15Å	1.8-14 Å

6. Conclusions and future Outlook

The neutron scattering facility, NFNBR, at Dhruva reactor, BARC, Mumbai, caters to a large number of users from different region of the country as well as in-house, for research activities on structural investigations of technologically relevant materials. While powder diffractometers, high Q diffractometer provide information on atomic length scales in materials, small-angle neutron scattering facilities and neutron reflectometer provide quantitative information in the mesoscopic length scale. State of the art facilities for structural characterization in novel condensed matter systems, enabling high resolution and also time resolved experiments at various thermodynamic sample environments, are planned at upcoming HFRR, Vizag. In the first phase, four such world class facilities, namely: i) MMD, ii) High-Q Diffractometer, iii) General purpose Small-Angle Scattering facility and iv) Polarized neutron reflectometer, are planned, with the intent of striking a balance between resolution and throughput, taking the advantage of higher available flux of HFRR. These facilities will be pivotal towards cutting edge condensed matter research on wide range of challenging systems, starting from quantum materials to ceramics in one hand and from thin film heterostructures to bio and soft materials on the other hand. In addition to the in-house research, these facilities will also cater to the needs of the users from national institutes and universities. Further, such state-of the art facilities will initiate a strong programme on the industry utilization of the neutron scattering facilities, including pharmaceutical and Fast Moving Consumer Goods industries.

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Proposed Inelastic Neutron Scattering Facilities at HFRR for Investigation of Atomic and Molecular Dynamics in Materials

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Abstract

The importance of the study of atomic and molecular dynamics in materials, as well as the uniqueness of inelastic neutron scattering for this purpose is discussed. At HFRR, in the first phase, for characterization of the atomic and molecular dynamics in materials, two advanced neutron scattering facilities are planned; some details of these planned facilities are elucidated. The design parameters, and some comparison with similar facilities worldwide, are presented. It is anticipated that these facilities will cater to the upcoming needs in condensed matter research extensively.

Keywords: *Inelastic neutron scattering, Quasielastic neutron scattering, HFRR, Atomic dynamics, Molecular dynamics, Phonon, Diffusion*

1. Introduction

In order to characterize the physico-chemical properties of a material, knowledge of both structure and dynamical behaviour is required. The structural investigation addresses the average position (and magnetic orientation) of the atoms and their spatial correlations, whereas the dynamics provides additional information about their temporal evolution (spatial and temporal correlations). For some purposes, the structural characterization is sufficient to explain macroscopic phenomena, like many phase transitions for example. To get a deeper insight into the microscopic behaviour as well as the transmission of perturbations and information across the material, however, the study of atomic dynamics must also be taken into account.

Depending on the considered timescale and the nature of the material, it will allow the observation of localized motions as well as propagating motions responsible for transport mechanisms such as thermal diffusion, thermal and electrical conductivity, sound, optical and dielectric properties, and more. Furthermore, the observation of the interplay between competing phenomena involving different energy- and timescales is also of interest for a better comprehension and production of smart and/or functional materials.

Inelastic neutron scattering, i.e. neutron spectroscopy, probes the atomic and molecular movements over length scales ranging from few angstroms to tens of nanometers, and over timescales from tens of picoseconds up to a few microseconds.

Therefore, it can be used to investigate a wide variety of different physical phenomena: diffusional or hopping motions of atoms, the rotational modes of molecules, sound modes and molecular vibrations, magnetic excitations or even electronic transitions. Presently, the neutron scattering activities in BARC are centered around the Dhruva reactor, Mumbai [1]. For investigation of the dynamics of atoms and molecules, two spectrometers (triple axis spectrometer [2,3], and time of flight spectrometer [4]) are operational.

Several state-of-the-art neutron scattering facilities are envisaged at the upcoming High

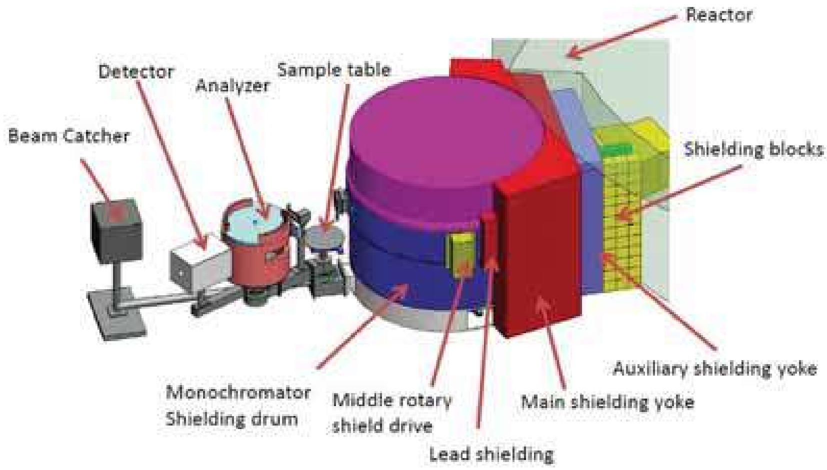

Figure 1. A layout of the proposed Triple Axis Spectrometer at HFRR.

Flux Research Reactor (HFRR), Visakhapatnam (Vizag), which will take advantage of the significantly higher flux of HFRR. In-house developed customized neutron detectors [5] and data acquisition instrumentation is expected to be employed on all the neutron scattering facilities. For characterization of the atomic and molecular dynamics in materials, in the first phase, two advanced neutron scattering facilities are planned; some details of these planned facilities are described in the following sections.

2. Triple Axis Spectrometer

Inelastic neutron scattering is a method for the microscopic investigation of reciprocal space and energy exchange (Q, ω) of a system, with Q being the wavevector and ħω the energy. During an experiment what is measured is the number of neutrons that have been scattered in a certain direction with a certain energy exchange. This information gives access to the scattering function of a system S(Q, ω).

The energy of the neutron decreases (increases) by an amount equal to the energy of a phonon for a normal mode of the material being investigated; so the scattering process is one in which the neutron creates(annihilates) a phonon. It is known as phonon emission (absorption). One of the most important applications of the coherent one-phonon scattering process is to measure the phonon dispersion relations for a single crystal, that is, to measure the frequency ω_s as a function of wavevector q and polarization index s. Whereas, in the case of scattering from single crystals, the scattering vector has a definite orientation with respect to the reciprocal space of the single crystal, in powder samples the reciprocal space axes belonging to the different grains of the powder have different orientations, and ideally all possible orientations are possible with equal probability. Thus, averaging over the various grains is equivalent to averaging over all orientations of the scattering vector. Further averaging over the magnitude of Q one gets the density of states S(ω), i.e. the density of excitations at the frequency ω weighted with the neutron scattering cross sections.

Lattice dynamical models are very useful in providing a microscopic understanding of the complex data. The information as obtained from performing experiments is required for research in understanding of anomalous thermal expansion, specific heat and phase

Table 1. Design parameters for proposed Triple Axis Spectrometer.

Monochromator	Dual double focusing monochromator (Cu and Pyrolytic graphite (PG))
Energy transfer range	0-150 meV
Momentum transfer range	1 – 10 $Å^{-1}$
Energy resolution	5 – 10 % of incident energy
Sample Temperature	4 – 1000 K
Beam apertures	Variable apertures (4 × 4 to 7 × 7 cm^2); rectangular and square
Sample Table	0.5 x 0.5 m^2 area available for furnace, cryostats, etc.
Monitor detector	BF_3 counter placed before sample
Signal detector	^3He detector

transitions of materials like multiferroics, nanomaterials, etc. Besides these, the proposed instrument will attract the scientific community from universities, and national laboratories and provide incentive to perform high quality neutron scattering experiments in the country. The proposed triple axis spectrometer at HFRR as shown in Fig. 1 will have several advanced features including stepper motor based hardware. This spectrometer would comprise dual double focusing monochromator (Cu and Pyrolytic graphite (PG)) and analyzer (Ge and PG) assemblies. The use of dual monochromator as well as analyzer assemblies with focusing would enable to collect data from single crystals in a large volume in (Q, E) space with smaller samples in shorter time. The neutron shielding around the spectrometer would be efficient and help us to achieve the best signal to noise ratio in the circumstances. The design parameters of proposed triple axis spectrometer are listed in Table 1.

3. Cold Neutron Time-of-Flight Quasi Elastic Neutron Scattering (CNTQS) facility

Based on the experience of developing and operating a Quasi Elastic Neutron Spectrometer [6, 7] at Dhruva reactor, the CNTQS has been designed to be a state-of-the-art direct geometry time-of-flight spectrometer for cold neutrons. It will facilitate advanced research on diffusion processes within complex media across diverse fields such as biology, soft matter, confined fluids, deep eutectic solvents, complex fluids, polymer nanocomposite materials, and energy materials. Additionally, CNTQS will probe very low-energy excitations, including Boson peaks in liquids and glasses, and quantum rotational tunneling phenomena in molecular materials. With enhanced resolution and sensitivity, a wide dynamic range, and integration of advanced data analysis techniques, CNTQS will drive interdisciplinary research and foster innovations. It will be the first cold neutron TOF spectrometer in India and is expected to

Table 2. Key design parameters of CNTQS facility at HFRR.

Flux from cold source (T = 20 K)	8×10^{13} n/cm^2/s
Beam size (at Guide exit)	12×5 cm^2
Length of collimator	1 m
Monochromator	Pyrolytic graphite (002) crystals
Take off angle	126 degrees
Wavelength	6 Å (Incident energy, Ei ~ 2.27 meV)
Flux at sample position	~ 3.1×10^6 n/cm^2/s
Disc-Chopper	
Number of windows	3
Dimensions	Radius: 0.25 m, Window height: 0.1 m
Frequency	≤ 10000 rpm
Fermi-Chopper	
Number of slits	100
Dimensions	Radius: 0.05 m, Height: 0.11 m
Frequency	≤ 30000 rpm
Distances	
Collimator – Disc chopper	0.75 m
Disc chopper – Monochromator	0.75 m
Monochromator – Fermi chopper	1.0 m
Fermi chopper – Be filter	0.2 m
Be filter – Sample	0.3 m
Sample – detector	2.2 m

Table 3. Comparison of CNTQS facility at HFRR with two instruments around the world.

Parameters	CNTQS (HFRR, India)	FOCUS (PSI, Switzerland)	PELICAN (ANSTO, Australia)
Wavelength range (PG 002 monochromator)	2.0 – 6.3 Å	2.0 – 6.3 Å	2.4 – 6.3 Å
Best energy resolution (at λ ~ 6 Å) with PG (002) at elastic scattering	44 μeV	46 μeV	50 μeV
Detector Type	^{3}He detector bank with time-of flight measurement	^{3}He detector bank with time-of flight measurement	^{3}He detector bank with time-of flight measurement
Q-range	0.1 – 4.5 Å^{-1}		0.08 – 4.5 Å^{-1}

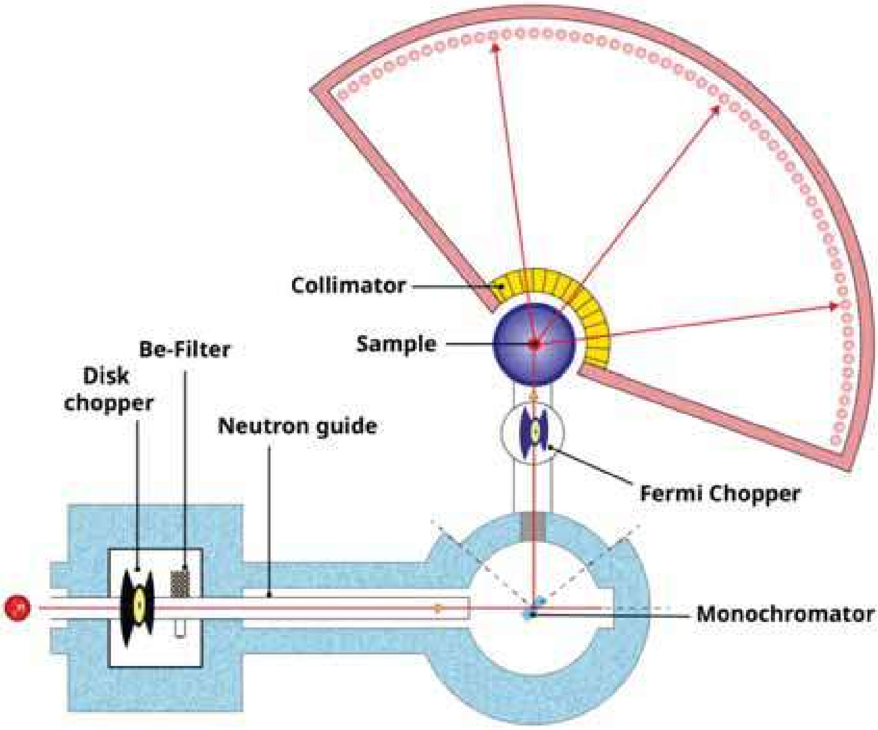

Figure 2. Layout of the proposed Cold Neutron Time-of-Flight QENS facility at HFRR.

serve a large user community within India. The CNTQS facility is expected to be installed at the end of a cold-neutron source guide tube (of length 30 m). The key design parameters of the proposed CNTQS at HFRR are given in Table 2 and a comparison of it with other instruments worldwide are given in Table 3. A schematic drawing of the proposed instrument is shown in Fig. 2.

CNTQS will find extensive use not only in fundamental research but also in various industrial applications. These applications span diverse fields, including biology, soft matter, confined fluids, deep eutectic solvents, complex fluids, polymer nanocomposite materials, and energy materials. The applications of CNTQS include (i) kinetics of drug capture and release, and dynamics of non-viral vectors for gene therapy, (ii) deciphering interactions of drugs/stimulants/antioxidants with lipid membranes, and protein structure-dynamics-function, (iii) Investigating diffusion mechanisms in battery materials, and understanding role of cation dynamics in hybrid organic inorganic perovskites, (iv) relaxation phenomena in network fluids with extensive hydrogen bonding: investigation of dynamical heterogeneity, viscosity-diffusion decoupling, etc., and (v) diffusion of water confined in clays, a potential material for radioactive waste disposals as also diffusion of hydrocarbons in zeolites for catalysis and molecular sieving applications.

4. Conclusions and future Outlook

The neutron scattering facility, NFNBR, at Dhruva reactor, BARC, Mumbai, caters to a large number of users from different regions of the country as well as in-house, for research activities on investigations of the dynamics of atoms and molecules in technologically relevant materials, leading to a microscopic understanding of the thermodynamics of the material.

Neutron spectrometers provide quantitative information in the energy scale of milli-electron-Volts. State of the art facilities for such investigations in condensed matter enabling high flux and high energy resolution, are planned at upcoming HFRR, Vizag. In the first phase, two such facilities, namely:, i) Triple Axis Spectrometer, and ii) Cold Neutron Time-of-Flight Quasi Elastic Neutron Scattering (CNTQS) facility are planned. In addition to the in-house research, these facilities will also cater to the needs of the users from national institutes and universities.

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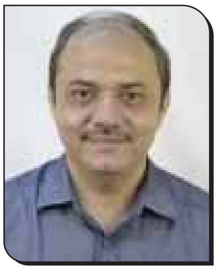

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Shri Amitanshu Mishra, *Scientific Officer (F), graduated in Chemical engineering in the year 2010 from MBM Engineering College, Jodhpur, Rajasthan and joined in 54th batch of BARC Training School, Mumbai. Presently, he is involved in thermal hydraulic safety analysis, uncertainty analysis, and heat transfer problems related to design of HFRR process systems.*

Shri Deependra Singh, *Scientific Officer (E), graduated in Mechanical Engineering in the year 2010 from MBM Engineering College, Jodhpur and joined the 55th batch of BARC Training School, Mumbai. Presently, he is involved in the design of mechanical components mainly reactor core components and mechanisms of High Flux Research Reactor (HFRR). He is also working on development of Aluminium Alloys forgings to be used in fabrication of core components of HFRR.*

Shri Vishesh Shrivastava, *Scientific Officer (E), graduated in Electrical Engineering in the year 2013 from SGSITS, Indore, and joined the 13th batch of BARC Training School, NFC Hyderabad. Presently, he is involved in the design of the electrical system for the High Flux Research Reactor (HFRR) and the stability analysis of the power control loop of HFRR.*

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