Utilization Programmes For Low And Medium Flux Research Reactors

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Abstract. We consider various major utilization programmes that may be pursued at any research reactor and discuss relevance to low flux and medium flux reactors. These include neutron beam research and applications; radiography; radioisotope production; medical applications such as boron neutron capture therapy, industrial applications such as neutron transmutation doping; neutron activation analysis (NAA) and prompt gamma neutron activation analysis; research and development support and human resource development for nuclear energy programme; and education and training at university level in basic sciences and technology. Most of the above programmes have relevance to both low and medium flux reactors though the scales may differ. At low-flux facilities the focus would be more on NAA and radiography while crystal structure investigations and some isotope production are feasible. Low-flux reactors inherently have much simplicity that enables greater flexibility in designing new applications and testing of new ideas. These could generate valuable experience that could form the basis for advanced applications at higher flux reactors.

1. Introduction

The report of an IAEA Advisory Group meeting held in Vienna in 1999 provides an excellent overview of the applications of research reactors [1, 2]. In this paper we provide a perspective of various major utilization programmes that may be pursued at any research reactor and discuss relevance to low flux (10^{12} neutrons/cm^2/s) and medium flux reactors up to $1\text{x}10^{14}$ neutrons/cm^2/s. The programmes may include the following.

- Neutron beam research
- Neutron beam applications
- Neutron radiography
- Radioisotope production
- Medical applications such as boron neutron capture therapy (BNCT)
- Industrial applications such as neutron transmutation doping.
- Neutron activation analysis (NAA) and prompt gamma neutron activation analysis (PGNAA)
- Research and development support to nuclear energy programme
- Human resource development for nuclear energy programme
- Education and training at university level in basic sciences and technology

While the above programmes have relevance to most reactors, at low-flux facilities the focus would be more on NAA and radiography while crystal structure investigations and some isotope production are alos feasible.

Low-flux reactors inherently have low radiation field and much simplicity, and therefore, despite their limitations of flux, enable greater flexibility in designing new applications and testing of new ideas. These could generate valuable experience that could form the basis for advanced applications at higher flux reactors. For the sake of an example, we consider the Indian experience [3]. Various applications at the reactor facilities in India include neutron beam research and applications; neutron radiography; neutron activation analysis, support to nuclear energy programme, radioisotope production; as well as education and training, manpower development and teaching.

2. Neutron beam research

Thermal neutrons have been used to investigate various nano-scale structural, dynamical and magnetic properties of materials of scientific interest and technological importance. A variety of specific techniques are used such as diffraction, small-angle scattering, reflectometry, neutron depolarization, and inelastic and quasi-elastic scattering. The main advantages of using neutrons over much brighter photon beams are that the former provide (i) a sharp contrast between isotopes or between neighbouring atoms in the periodic table, (ii) high energy resolution of sub-meV, (iii) investigation up to large wave-vector transfer needed for liquids and amorphous structures, (iv) intense magnetic probe, (v) characterization of bulk samples and (vi) particularly large cross-section of scattering from hydrogen atom. Accordingly the following techniques are often used.

- Diffraction (to investigate atomic and magnetic structure at length scale of 0.1-100 nm) comprising Small-angle scattering (large molecules, thin films), Wide-angle scattering (crystals, strain distribution), Very-large angle scattering (glasses, liquids), and Reflectometry (surfaces, interfaces, thin films)

- Neutron polarization analysis (to further investigate magnetic structures)

- Inelastic and quasi-elastic scattering (to investigate dynamics at time scale of 1 ns to 10 fs corresponding to neutron energy changes of 1 μeV-500 meV) and Neutron depolarization (to investigate mesoscopic scale magnetic structures)

Some of the investigations of major current interest are the following.

- Atomic-level structure and magnetism studies

- Structural studies at mesoscopic length scale

- Reflectometry for thin-film structure, interface magnetism and surface morphology

- Atomic and molecular dynamics studies

All the above mentioned techniques may be fruitfully exploited at medium-flux facilities. However, experiments at low-flux facilities might be limited to using diffraction techniques on samples of relatively simple crystal and magnetic structures. The experimental results are usually of fundamental scientific interest, and are expected to lead to newer ideas and possible applications.

In India a national facility for neutron beam research [4] is operated at the research reactor Dhruva (10^{14} neutrons/cm^2/s). It includes (Figure 1) single-crystal and powder diffractometers, a polarization analysis spectrometer, inelastic and quasi-elastic scattering spectrometers in the reactor hall, and small-angle scattering instruments and a polarized neutron reflectometer in the neutron-guide laboratory. A diffractometer for residual-stress measurements is being built. In addition a neutron radiography facility and a detector development laboratory are located at APSARA reactor (10^{12} neutrons/cm^2/s). All the instruments including the detectors and electronics have been developed within India. The National facility is utilized in collaboration with various universities and other institutions.

Important examples of neutron scattering research include studies of structures in triglycine family of hydrogen-bonded ferroelectrics, manganites showing CMR behaviour, cobaltates showing coexistence of ferro- and antiferromagnetism, phosphate and oxide glasses; cluster formation in hydrogen-bonded liquid methyl alcohol; pore morphology in sintered ZrO_2 - Y_2O_3 ceramic, pore surface roughening in rocks, multiple scattering due to very large inhomogeneties, micellar formation using Gemini surfactants and multi-head group surfactants under various conditions; structure and magnetic properties of ultra-thin multilayer of Fe-Ge; lattice vibrations in materials having negative thermal expansion and minerals of geophysical interest; alkyl chain dynamics in monolayer protected metal nano-clusters, and diffusivity of various guest molecules in zeolite cages.

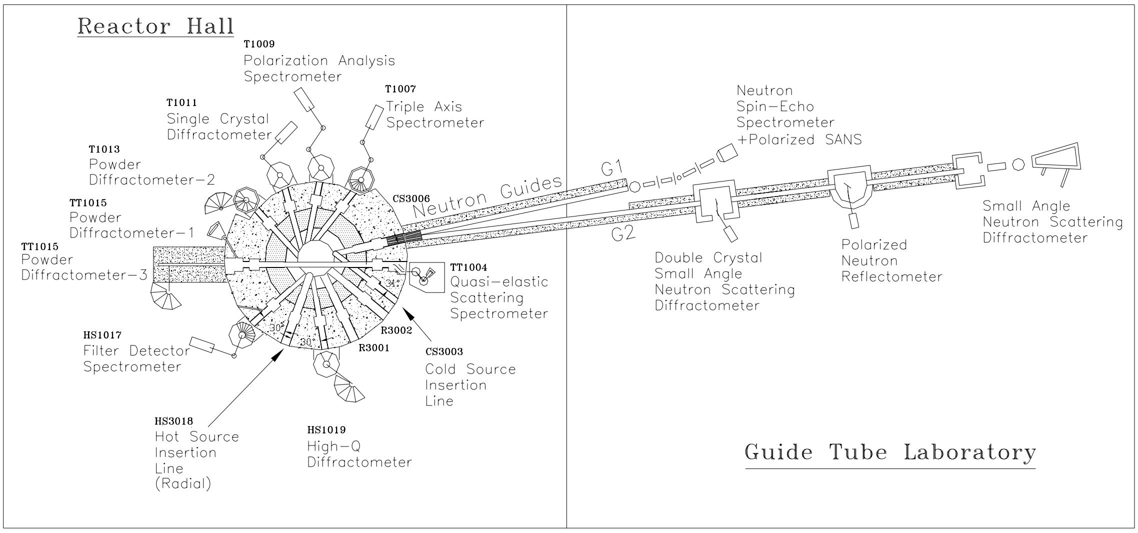

Fig. 1. Neutron scattering facilities at Dhruva reactor at Trombay.

3. Neutron beam applications

These involve characterization of various materials for their properties at microscopic or mesoscopic length scale. Typical examples are

- residual stress analysis;
- surface and interface characterization including corrosion in magnetic and nonmagnetic multilayers using reflectometry;
- hydrogen sensing including environment around the hydrogen atoms using diffraction and inelastic scattering;

- size and shape of large molecular systems such as hydrocarbons, micells, polymers and proteins using small-angle neutron scattering and

- voids in bulk materials such as steel, ceramic, coal and cement using ultra-small-angle neutron scattering. These applications, usually possible at medium-flux facilities, are expected to lead to improved materials and processes. As an example, the size distribution of carbide precipitates in solution-quenched PH 13-8 Mo stainless steel was determined by small-angle neutron scattering [5]. Such precipitates are known to hinder dislocation movement that causes hardening, and such measurements can be used for optimization of the material properties.

4. Neutron radiography

This technique is complementary to gamma-ray and x-ray radiography. Specifically large engineering systems can be characterized by neutron radiography due to bulk penetrability of thermal and epithermal neutrons and their sensitivity to hydrogen. Of particular interest are investigations of internal defects in thick samples. A typical application is the characterization of hydride blisters in pressure tubes.

Special techniques, such as hydrogen-sensitive epithermal neutron radiography, could detect rather low concentration of hydrogen atoms. Real-time images may be observed by dynamic neutron radiography. These applications are well suited at both low and medium-flux reactors.

5. Radioisotope production

A large variety of radioisotopes with different half-lives for applications to industry, health care, agriculture, education and research, and other societal benefits can be produced by neutron absorption in reactors. These production activities are well suited at medium-flux facilities. The following gives a typical list of isotopes for various applications as radiotracers or as sources of radiation that impart energy and cause some changes [6].

- Medical applications
  - Medical diagnosis using radiotracers
    - Imaging with Gamma emitters with moderate energy (^{99m}Tc, ^{131}I, ^{123}I, ^{125}I etc.)
    - Laboratory tests using radiotracers – low energy gamma emitter (^{125}I)
  - Radiation therapy
    - Teletherapy of cancer – high energy gamma emitters (^{60}Co)
    - Radioactive implants for brachytherapy of cancers – gamma/beta emitters (^{192}Ir, ^{198}Au, ^{125}I)
    - Internal administration of therapeutic radio-pharmaceuticals – beta/ Auger electron emitters (^{131}I, ^{32}P, ^{153}Sm, ^{177}Lu, ^{90}Y, ^{166}Ho, ^{175}Yb, ^{125}I , $^{142/143}$Pr etc.)

  - Radiation sterilization of medicines or medical equipment (^{60}Co)

- Industrial applications
  - Radiotracers in chemical processes (^{82}Br, ^{203}Hg); in hydrology and water management (^{3}H, ^{46}Sc); in trouble shooting such as chemical industries, buried pipelines etc.
  - Radiation source for radiography (^{192}Ir, ^{60}Co); for level gauging (^{192}Ir, ^{60}Co)

- Agriculture and Food Processing
  - Radiation mutation (^{60}Co, ^{137}Cs)
  - Radiotracers in agriculture (^{32}P, ^{35}S, ^{45}Ca, ^{54}Mn etc.)
  - Food preservation, disinfestation, sanitization etc. (^{60}Co)

- Research on reaction mechanisms using tracers (^{14}C, ^{3}H, ^{32}P etc)

6. Medical applications such as boron neutron capture therapy (BNCT)

While such applications are indeed highly desirable, they require large infrastructure involving nuclear and medical professionals.

7. Industrial applications such as neutron transmutation doping.

Neutron irradiation can provide excellent uniformity of dopants by transmutation in large size ingots of silicon etc. For practical application, fairly large sizes of 15 cm or more are required.

8. Neutron activation analysis (NAA) and prompt gamma neutron activation analysis (PGNAA)

These form major programmes at low and medium-flux reactors for trace-level detection of many elements in a variety of samples of geological, nuclear and other materials.

Some typical applications investigated in India are listed below.

- NAA of variation of trace elements & trends in the formation of gem stones indicate segregation of these elements & also weathering away from rocks after gem formation
- NAA of finished products such as nuclear cladding materials, zircaloy-2 & 4, ss and 1s-al metallic alloys and ss crms

- PGNAA of milk powder, lake sediment hay, alumino silicate, graphite, meteorite

9. Research and development support to nuclear energy programme

Research reactors may be used for testing of nuclear materials, fuel and other power reactor components; and neutron irradiation and radiation damage studies. These include neutron beam applications such as residual stress analysis, neutron imaging and radiography already noted above.

10. Human resource development for nuclear energy programme

Low and medium flux reactors provide an ideal environment and the necessary flexibility to train manpower for reactor operation and applications, and to gain invaluable experience.

11. Education and training at university level in basic sciences and technology

Neclear reactors, as they are not widely available, provide a very rare opportunities for education in fundamental nuclear science and enginnering. Reactor neutron sources may be ideally used for neutron beam experiments by university faculty and research scholers for their research in physics, chemistry, biology and materials science.

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