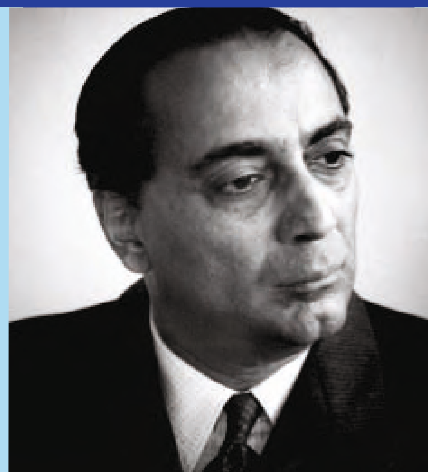
Utilization of Research Reactors at BARC, Mumbai

Bhabha Atomic Research Centre
Trombay, Mumbai – 400 085, INDIA
www.barc.gov.in



OUR FOUNDER

Dr. Homi Jehangir Bhabha

"For the full industrialization of the developing countries, for the continuation of our civilization and its further development, atomic energy is not merely an aid, it is an absolute necessity.

The acquisition by man of the knowledge of how to release and use atomic energy must be recognised as the third epoch of human history."

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ABSTRACT

The research reactors are important platforms for supporting research pertaining to material characterization using neutrons as probes, testing and qualification of reactor materials and related components under neutron flux environment and production of a large variety of radioisotope for health care, agriculture, industry and environmental related programme.

The programme of radioisotope production and neutron activation analysis in India was initiated with the commissioning of the Apsara in August 1956 and production of the radioisotopes on industrial scale commenced with the commissioning of 40 MW research reactor CIRUS in 1960. The quality and quantity of radioisotope production considerably improved with the operation of 100 MW research reactor Dhruva since 1985. Apsara and CIRUS being permanently shutdown in 2010 left Dhruva the only source of radioisotope production on large scale for some time. Total isotope production was further augmented by Apsara-U (the revamped version of Apsara), which went critical in 2018.

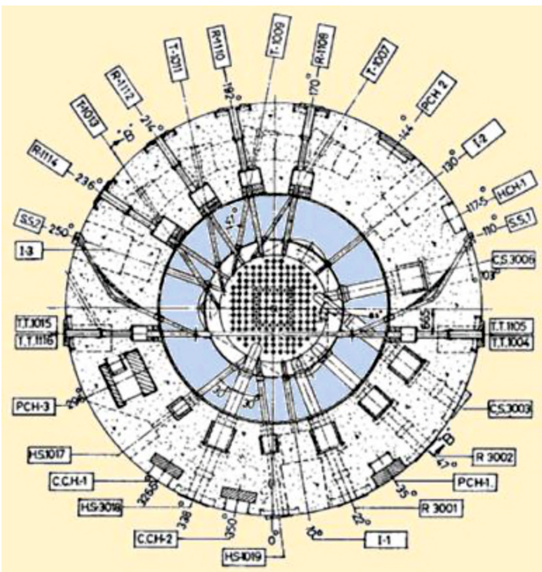
Presently, BARC has state of art facilities with neutron flux as low as 10^6 n/cm^2/s to as high as 2.2×10^{14} n/cm^2/s at Dhruva, Critical Facility and Apsara-U reactors. These Research Reactors are being well utilized by DAE and non-DAE organizations for Radioisotope production, Neutron Scattering and Spectroscopy experiments in beam tubes, Chemical characterization of materials using Neutron Activation Analysis, Neutron imaging and its applications, Nuclear Reaction and Fission study & Prompt Gamma ray coincidence spectroscopy, Development and testing of detectors, Geochronology, Testing of shielding material at shielding corner of Apsara-U, Irradiation damage study of materials, Development of radioactive nanomaterials for healthcare, Neutron Transmutation Doping (NTD)-Si, Reactor Anti-neutrino Research, Reactor Physics experiments, Education and Training for Human Resource Development. The important radioisotopes produced in the research reactor include ^{131}I, ^{125}I, ^{60}Co, ^{99}Mo, ^{32}P, ^{192}Ir, ^{64}Cu etc. The radioisotopes find their applications in various areas such as medicine, forensic science, neutron activation analysis, radiography, food, agriculture etc.

This brochure highlights various facilities available in the research reactors at Trombay and their utilization for societal benefit and R&D work. It would provide first-hand information about the facilities to the potential users of Research Reactors.

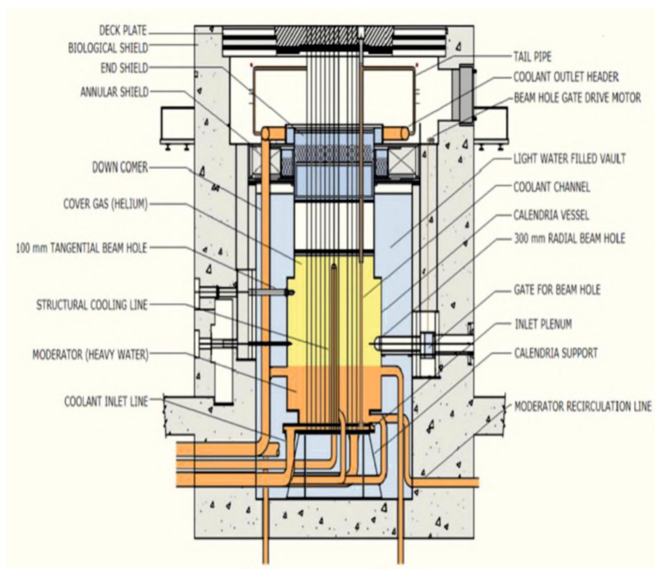
CONTENTS

Introduction

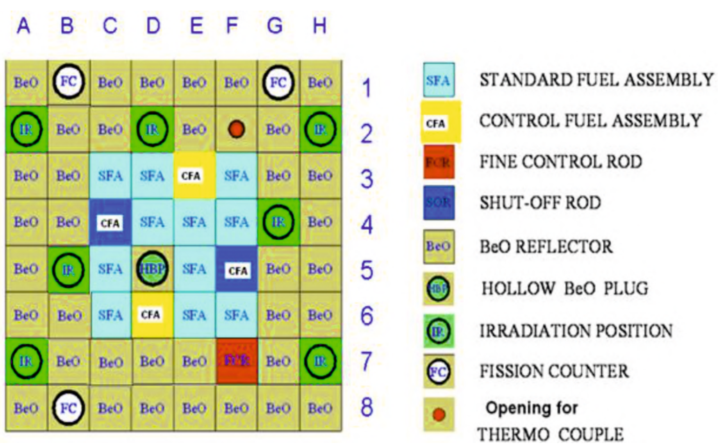
Research reactors primarily function as a source of neutrons, which can be utilized for several applications like production of radioisotopes for medical, industrial and agricultural uses, neutron beam research, material characterization, imaging etc. For more than 60 years, research reactors (RRs) have been the centre of innovation for nuclear science and technology in India. There are research reactors, namely Dhruva (100 MW) and Apsara-U (2 MW), currently under operation at BARC, Trombay.



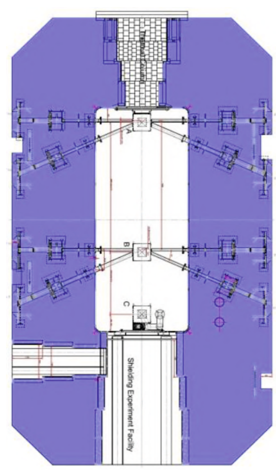
Dhruva Research Reactor (horizontal projection)



Dhruva Research Reactor (vertical projection)



Coremap of Apsara-U (Schematic)



Pool block of Apsara-U Research Reactor

Introduction

Tray rod assembly

Tray rod capsule

Self-serve ball and capsule

Tray Rod Facility (TRF) window and Master-Slave manipulator

Table- 1: Dhruva: Salient features

Item		**Description/Value**
Reactor type		Vertical tank type/thermal reactor
Reactor power		100 MW_{th}
Fuel / Clad		Uranium metal / Aluminium
Coolant/Moderator/Reflector		Heavy Water
Shut off rods		Cadmium
Tray rods for radioisotope production		2-3 (each contains 90 capsules) in number with a typical irradiation time from 1 week to year
Self-serve facility for material irradiation		1 in number (5 positions) with a typical irradiation time from few hrs to few days
Pneumatic carrier facility (PCF) for Neutron Activation Analysis (NAA)		1 in number with a typical irradiation time from 1 min to 15 min
Beam tubes for neutron imaging, scattering and spectroscopy experiments		14 in number
Other facilities:		- 1 adjuster rod for ^{60}Co radioisotope production of high specific activity - 2 creep and corrosion facilities
Tray Rods	**Thermal neutron flux (< 0.5 eV)**	0.4 - 2.2×10^{14} n/cm²/s
	Epithermal neutron flux (0.5 eV – 1 MeV)	1.0 - 3.5×10^{13} n/cm²/s
	Fast neutron flux (> 1 MeV)	0.5 - 2.8×10^{12} n/cm²/s
	Epithermal index	0.01
	Epithermal flux shape factor	0.10
	Cadmium ratio	5.2
Self-serve	**Thermal neutron flux (< 0.5 eV)**	0.2 - 1.3 $x10^{13}$ n/cm²/s
	Epithermal neutron flux (0.5 eV – 1 MeV)	0.3 - 2.0 $x10^{12}$ n/cm²/s
	Fast neutron flux (> 1 MeV)	0.1 - 5.0 $x10^{11}$ n/cm²/s
	Epithermal index	0.005
	Epithermal flux shape factor	0.003
	Cadmium ratio	20
Pneumatic Carrier	**Thermal neutron flux**	9.7×10^{13} n/cm²/s
Beam tubes	**Thermal neutron flux (< 0.5 eV)**	10^6 - 10^8 n/cm²/s
It is also possible to design special assembly for material irradiation/characterization, in addition to the above regular irradiation facilities to meet specific requirement of users.		

Tray rod and its sheath assembly

Tray rod capsule

Thermal Column

Shielding corner

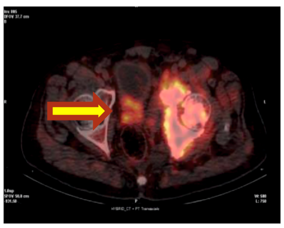
Table- 2: Apsara-U: Salient features

Item		Description/Value
Reactor type		Swimming pool type
Date of first criticality		September 10, 2018
Reactor power		2 MW_{th}
Fuel / Clad		U_3Si_2 dispersed in Al / Aluminium
Coolant/Moderator		Light Water
Reflector		BeO
Control / Shut off rods		Hafnium
Tray rods for radioisotope production		1 in-core at central location 7 in BeO reflector (each tray rod contains 15 capsules)
Thermal column for detector calibration, large size sample irradiation for NAA		5 experimental positions
Shielding corner for optimizing shielding thickness against neutron and gamma		1 in number
Beam tubes for neutron imaging, scattering and spectroscopy experiments		8 in number
Tray Rods	Number of tray rods	8
	Number of capsules in a single tray rod	5 (in-core), 15 (reflector)
	Thermal neutron flux (< 0.5 eV)	2.5 - 6.1×10^{13} (in-core) $n/cm^2/s$ 1.8 - 4.4×10^{13} (out-core) $n/cm^2/s$
	Epithermal neutron flux (0.5 eV – 1 MeV)	1.7 - 4.1×10^{13} (in-core) $n/cm^2/s$ 0.7 - 1.7×10^{13} (out-core) $n/cm^2/s$
	Fast neutron flux (> 1 MeV)	0.6 - 1.5×10^{13} (in-core) $n/cm^2/s$ 3.2 - 7.8×10^{12} (out-core) $n/cm^2/s$
	Epithermal index	0.011 (in-core, D-5) 0.015 (out-core, G-4)
	Epithermal flux shape factor	0.04584 (in-core, D-5) 0.02782 (out-core, G-4)
	Cadmium ratio	5.38 (in-core, D-5) 7.31 (out-core, G-4)
Thermal Column	Thermal neutron flux	10^6 - 10^8 $n/cm^2/s$
	Cadmium ratio	~2000
Beam tubes	Number of beam tubes	8
	Thermal neutron flux at target location	10^6 – 10^7 $n/cm^2/s$

- ❖ **Apsara-U, being an under-moderated reactor, offers fast neutron flux (> 1 MeV) of about 1.5×10^{13} $n/cm^2/s$, which can be utilized for the production of radioisotopes like ^{64}Cu, ^{32}P, ^{67}Cu and material damage study of about 1 dpa/year, which is very useful for studying mechanical as well as physical properties of material under irradiation before using them in power reactors.**
- ❖ **It is also possible to design special assembly for material irradiation/characterization, in addition to the above regular irradiation facilities to meet specific requirement of users.**

Utilization of Research Reactors

Bhabhatron



Detection of Carcinoma Prostate [^{64}Cu]$CuCl_2$ PET/CT

Radiopharmaceutical formulation

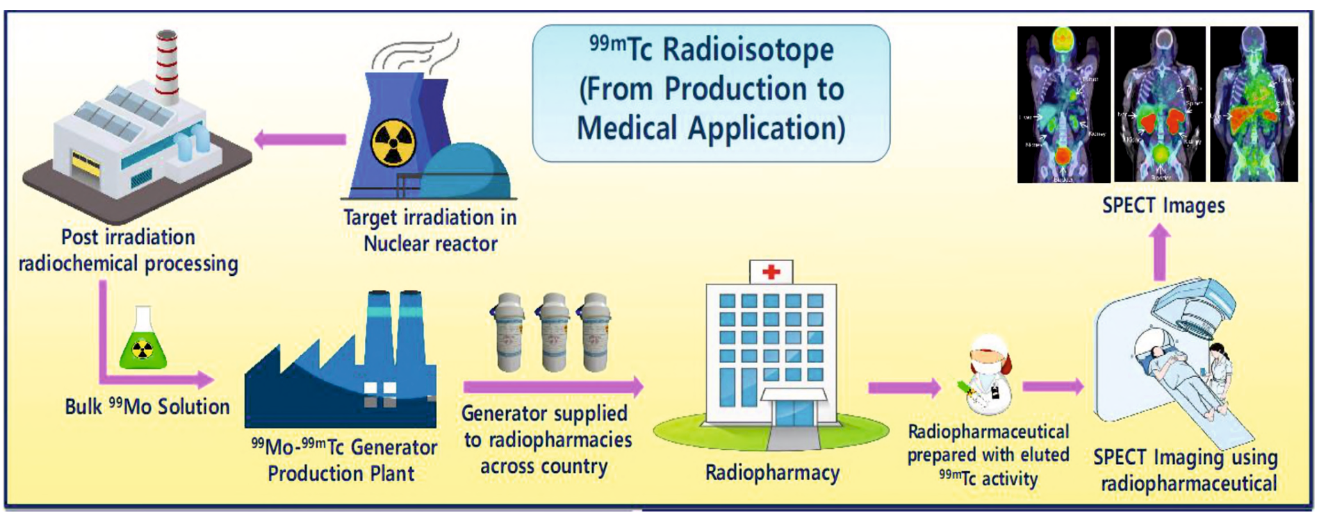
Radioisotope Production and its application

Use of Dhruva/Apsara-U research reactors for the production of radioisotopes for different applications constitutes an important program in India. Radioisotopes find innumerable applications in various fields that touch the lives of people, such as healthcare, industry and agriculture.

Healthcare

- Radioisotopes have both diagnostic and therapeutic applications
- ^{60}Co is extensively used for Teletherapy in cancer treatment
- ^{192}Ir, ^{137}Cs, ^{103}Pd, ^{125}I, ^{32}P, ^{198}Au etc. are used as sources for Brachytherapy in cancer treatment
- ^{99m}Tc (derived from ^{99}Mo via neutron capture and fission route) is the most widely used radioisotope for diagnostic imaging and is known as the 'work horse' of nuclear medicine. Recently, ^{64}Cu is emerging as a potent radioisotope for Positron Emission Tomography (PET) imaging.
- A host of reactor produced radioisotopes namely, ^{32}P, ^{131}I, ^{90}Y, ^{153}Sm, ^{177}Lu, ^{186}Re, ^{166}Ho etc. are used for formulation of injectable radiopharmaceuticals for treatment of cancers and other diseases namely, hyperthyroidism and arthritis.
- ^{125}I is used as radiotracer in Radioimmunoassay.

At present there are about 300 licensed nuclear medicine centers across India, majority of which utilize radioisotope produced at Dhruva for human healthcare, either diagnosis or treatment.



Industry

Leak Detection

- Sealed radioisotope sources such as ^{60}Co, ^{192}Ir and ^{137}Cs find applications in level gauging, density monitoring, thickness gauging, radiometric scanning, gamma radiography, tomography, blockage detection etc.
- Radioisotopes such as ^{82}Br, ^{131}I, ^{99m}Tc, ^{140}La, ^{46}Sc, ^{198}Au, ^{56}Co, ^{24}Na, ^{79}Kr and ^{41}Ar are used as radiotracers for leak detection in pipelines and heat exchangers, flow rate measurements, residence time distribution (RTD) measurements, mixing time measurement, wear and corrosion measurements, sediment transport investigations in Ports, effluent dispersion in water bodies, particle tracking and fluid flow tracing in oil fields etc.

Flow rate measurement

- Radioisotopes (^{60}Co) used for radiation processing in industry such as sterilization of medical appliances, hygienization of waste products, treatment of surfaces of materials like wires, rubber tyres, etc. for better performance, treatment of gems such as diamond for exotic coloration, treatment of hard polymers such as Teflon for better utility and so on.

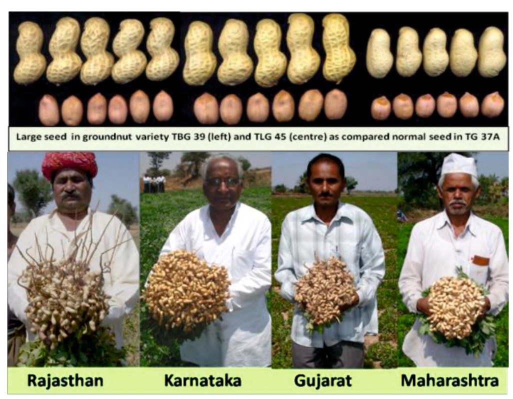
Food and Agriculture

- Development of crop varieties with higher yield, shorter maturing time, higher oil content, brighter color, disease resistance, etc.
- Radioisotopes (^{60}Co, ^{32}P, ^{35}S, ^{54}Mn, ^{57}Co) used for radiation processing in agriculture to obtain desired results like sprout inhibition (potatoes, onions, etc.), hygienization (spices, meat, fish etc.), shelf life extension (meat, fish, cut vegetables, fruits, flowers, etc.), quarantine (fruits, etc.), insect disinfestations (cereals, pulses, dry fruits, etc.) and sterilization of food
- Radioisotopes such as ^{32}P, ^{35}S, ^{54}Mn and ^{59}Fe are used in tracer studies in agricultural research.

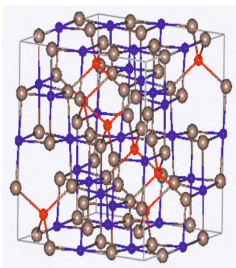
Food irradiation plants based upon ^{60}Co radioisotope are currently functional in the country.

Un-irradiated Irradiated (Shelf life extension)

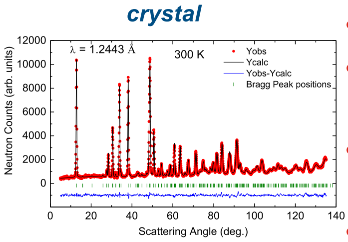
Trombay Rice Variety "Hari", a Dwarf mutant induced with Fast Neutrons



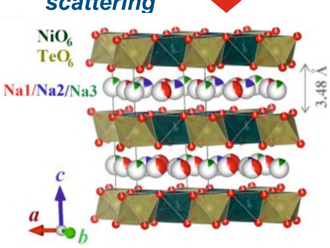
Neutron Scattering facilities in Dhruva reactor hall

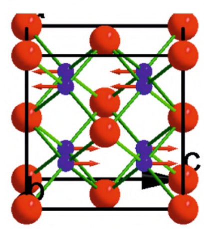


Arrangement of atoms in crystal



Structural correlation from Neutron Elastic scattering



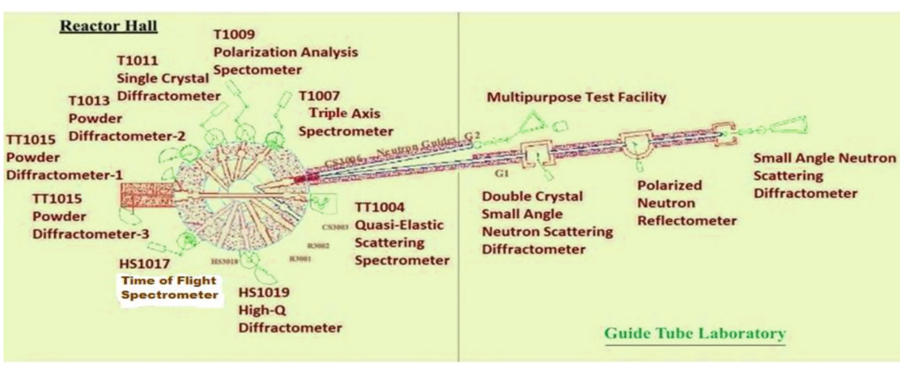


Periodic motion in solids

Neutron scattering activities and other applications in beam tubes

Neutrons are used as an important and complementary probe to x-rays and electrons in the study of various physical phenomena in condensed matter physics. Several neutron scattering facilities (under the National Facility for Neutron Beam Research) have been set up at Dhruva/Apsara-U beam tubes. Primarily they are being used to study the following.

- Arrangement of atoms and nature of bonding in crystalline materials, locating position of light atoms, arrangement of spins in magnetic systems through Neutron Diffraction (ND)
- Short range ordering in glasses, liquids and disordered systems through Neutron Diffraction (ND)
- Magnetic correlations through Polarized neutron scattering (PNS)
- Large scale structures in soft matter, biology and porous materials using Small Angle Neutron Scattering (SANS)
- Excitations through Inelastic Neutron Scattering (INS)
- Diffusion of atoms / molecules in confined geometry and in soft condensed matter through Quasi Elastic Neutron Scattering (QENS)
- Study of morphology and interfaces in thin films and multilayers through Neutron Reflectivity (NR)
- Neutron residual stress measurement of materials by neutron diffraction imaging
- Neutron depth profiling of such materials ^{6}Li, ^{10}B etc. by thermal neutron absorption at the surface
- Positron source derived from gammas (>1.02 MeV) can be used as particle probes, suitable to detect low concentrations of defects in materials.
- Neutron cross section measurements



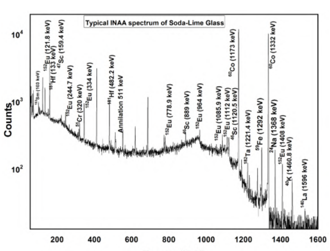
Layout of the neutron scattering facilities at Dhruva reactor

Utilization of Dhruva PCF for NAA

PGNAA facility using thermal neutron beam

Compton suppressed HPGe-BGO for Gamma ray spectrometry

Gamma ray spectrometry system for NAA at Dhruva



INAA of forensic glass sample

Neutron Activation Analysis (NAA) for Chemical characterization of materials

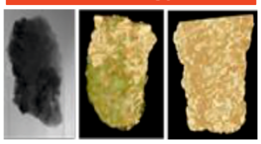
Neutron Activation Analysis (NAA) is a nuclear analytical technique for simultaneous multi-element determination of elements at major, minor and trace concentration levels in samples of diverse matrices. This involves measurement of neutron capture prompt gamma-rays **(Prompt Gamma-ray NAA or PGNAA)** or delayed gamma-rays **(Conventional NAA)** from activation products. PGNAA is useful for compositional characterization of materials as well as determination of elements like H, B, Cd, Hg, Eu, Sm and Gd, which are not suitable in conventional NAA. Pneumatic Carrier Facility (PCF) and Self-serve facilities of Dhruva and Apsara-U research reactors are routinely used for multi-elements (Na to U) by NAA of various samples for R&D, material characterization and preparation of radiotracers for analytical applications.

Table- 3: Application areas of NAA and PGNAA

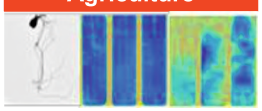
Field	Samples	Information by NAA/PGNAA
Materials Science	Alloys, Glass, Ceramics	Compositional characterization
Reactor materials	Fuel, Clad, control materials	Composition, trace elements and quantification elements like B, Gd etc
Geology	Rocks, ores, minerals	U, Th and Rare Earth Elements (REEs)
Biology & Agriculture	Soil, plant, tissue	Essential and toxic elements
Food & food products	Grains, cereals, baby foods	Quality Assurance of essential (Na, K, Fe, Zn etc) and toxic (Cr, As, Hg etc) elements
Environment	Coal, Coal ash, cement	Multi-elements, Coal quality, Cement quality
Archaeology	Glass, ceramics	Provenance study using transition elements and REEs
Forensic Science	Glass fragments, ceramics, drugs &narcotics, gunshot residue	Authentication, Source finding and provenance study using marker elements

Archaeology

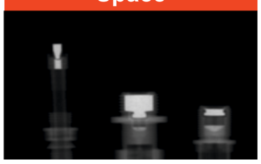
Geology



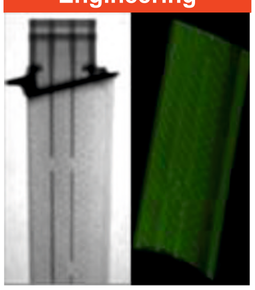
Agriculture



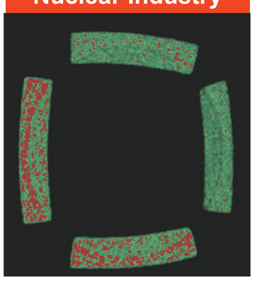
Space



Engineering



Nuclear Industry



Neutron Imaging and its applications

Neutron imaging as a non-destructive testing method that can be used for a broad spectrum of industrial/scientific applications. It provides similar capabilities as industrial X-ray i.e. radiographic images or 3D topographic views of samples with a size of a few centimetres up to tens of centimetres. The neutron imaging technique finds application in the following fields of science and engineering:

- **Fault detection in the engineering components**
- **Distribution of hydrogen, boron and cadmium in metals**
- **Water transport in soil/plant/fuel cell**
- **Study of cultural artefacts for preservation and restoration**
- **Real time neutron radiography for flow visualization and kinetics**

Table- 4: Important parameters of the neutron imaging beamline at Dhruva Reactor

Parameter	Value
Source	HS-3018 port at Dhruva reactor
Thermal neutron Flux	4 X10^7 n/cm^2/s
Beam collimation	160
Beam footprint	100 mm
Detectors	CCD, flat panel detector, ICCD
Spatial resolution	100 micrometre

(a) Photograph *(b) X-ray radiograph* *(c) Neutron radiograph*

Comparison of X-ray and neutron images of flower kept in 30mm lead cask

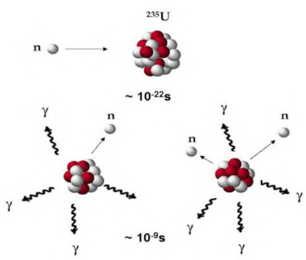
Prompt γ ray coincidence spectroscopy

A unique radial beam tube facility has been developed for the following high resolution prompt γ-ray coincidence spectroscopic measurements:

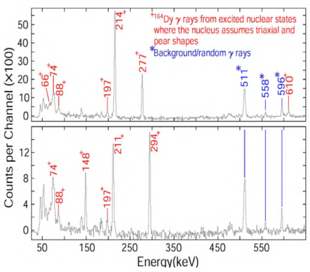
- Nuclear excitations in low and medium spin regime following Capture Gamma Spectroscopy (CGS)
- Prompt Fission-Gamma Spectroscopy of “neutron-rich” fission fragment nuclei (PFGS)
- Prompt Gamma Neutron Activation analysis (PGNA)

This facility consists of a high energy-resolution gamma detector array coupled to a state of art digital data acquisition system. The detector array in its state-of-the-art form comprises of eight Compton-suppressed HpGe Clover Ge detectors and eleven $LaBr_3$(Ce) scintillation detectors of fast timing capability. The mechanical frame of the array enables positioning of the detectors at predetermined complimentary angles with respect to the beam direction. Beam spot size at the target position is ~ 16 mm and the neutron flux at the target position is ~ 1.0 x10^7 n/cm^2/sec at close to the maximum thermal power of the reactor. The top- and a near-center inside visuals of the prompt gamma spectroscopy facility ‘DURGA’ (Dhruva Utilization for Research using Gamma Array) at DHRUVA reactor are shown in the bottom pan. The square faced Clover plus BGO-shield detectors and the circular faced $LaBr_3$(Ce) detectors look at the target foil/sample, placed at the center on a white Teflon ring. Collimated thermal neutron beam travel through air to induce nuclear reactions with the target nuclei in the foil/sample.

High resolution data obtained in the CGS and PFGS are important to understand the nuclear structure and exotic excitation modes, physics of nuclear fission process and the r- process nucleosynthesis of translead nuclei. In addition, the PFGS provide important nuclear data for the design of new types of reactors such as Generation III$^+$ and IV reactors.

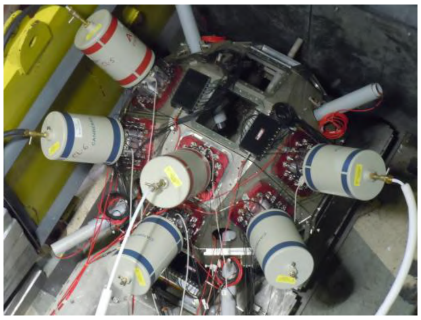


Prompt gamma emission in nuclear fission

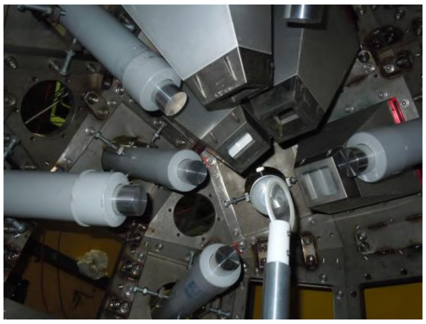


Representative energy-gated spectra from gamma-gamma coincidence matrix employing ^{163}Dy(n, v)^{164}Dy reaction

Digitizer based data acquisition system and control panel



Top view of the prompt gamma spectroscopy facility ‘DURGA’



Near-center inside view of the prompt gamma spectroscopy facility ‘DURGA’

Utilization of Research Reactors

SPNDs for in-core applications in Nuclear Power Plants

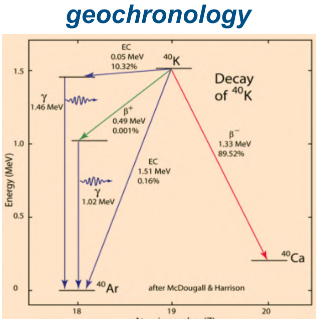
In-house developed radiation detectors

Development & Testing of Detectors

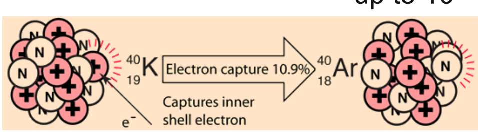
- Testing and Calibration of ionization chambers, fission detectors, ^{10}B lined proportional counters, ^{10}B lined gamma uncompensated / compensated ionization chambers
- Calibration of variety of miniature neutron detectors
- Neutronic channels viz. Start-up, Campbell and Power range
- Measurement of neutron sensitivity of Cobalt, Platinum, Vanadium Self Powered Neutron Detectors (SPNDs)
- Self-Powered Neutron Detector amplifiers for reactors
- ^{3}He and BF_3 gas detectors for neutron scattering experiments
- Solid state nuclear track detectors and its applications

Apatite *Zircon*

Fission track geochronology



Decay of K^{40} into Ar^{40}



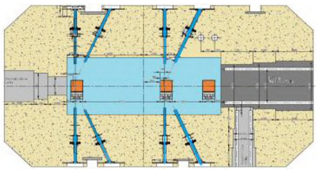
Geochronology

Use of research reactors for geochronology (dating) is a more specialized application. There are two geochronology methods.

- Fission track geochronology is a method for dating minerals containing uranium, particularly apatite and zircon. The sample age is determined by counting fission tracks in the material from spontaneous fission of ^{238}U. These tracks are a function of the U content and the age since the fission track clock started. A research reactor is then used to irradiate the samples and induce fission in the ^{235}U present in the sample. Comparing the before and after track count, the U content in the sample is determined.
- Argon geochronology is a dating method whereby the age of small quantities (~mg) of minerals/rocks can be determined based on the radioactive decay of ^{40}K into ^{40}Ar. Therefore, determining the amount of ^{40}Ar present and original quantity of potassium will determine the age of the sample. Amount of potassium is determined using $^{39}K(n,p)^{39}Ar$ reaction. Using automated gas extraction mass spectrometry systems, the ratio of $^{40}Ar/^{39}Ar$ is measured in the material after irradiation. Samples as young as 2000 years and as old as the earth itself (about 4.6 billion years) can be dated, depending on the nature of the sample. The requirement can range from a fast neutron fluence of about 2×10^{15} n/cm^2 for young rocks up to 10^{18} n/cm^2 for very old rocks.

Testing of shielding material at Shielding Corner of Apsara-U

Typical shield model and converter assembly arrangement in Shielding corner



Shielding corner (dark grey area on right side) in the biological shield of Apsara-U

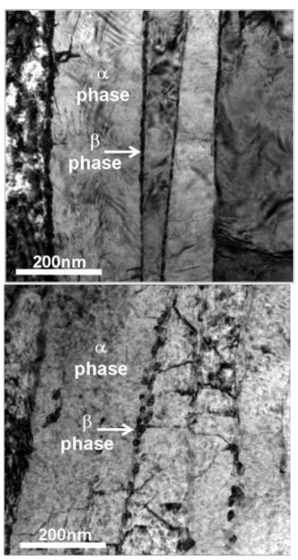
AHWR shield model assembled in the Shielding corner

Evaluation / qualifying of radiation shielding in any reactor project is a challenging exercise because it involves large attenuation, flux anisotropy, complicated geometry and wide energy range for both neutrons and gammas. Theoretical estimates are considered to be accurate within an error bound, which depends on uncertainties due to modeling approximations and nuclear data. These uncertainties are taken care of by using suitable bias factors (BF) obtained from experimental measurements. The BFs are used as multipliers in the theoretically estimated exit flux from a shielding set up. Over conservation of BF leads to cost penalties and under estimation may result in serious radiological problems. Hence, mock-up experiments need to be carried out prior to detailed shield design, to obtain BF and to optimize the shield.

A shielding corner facility has been designed at Apsara-U in order to carry out extensive experiments for the shielding design of new reactors and validating the computer codes used in shielding calculations.

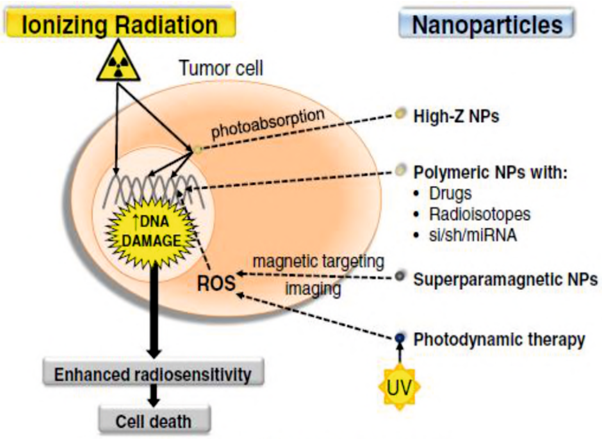
Irradiation Damage study of Materials

Fast neutrons cause damage in material structure by displacement of atoms. Depending on the composition and characteristics of materials, they become fragile, or hardened, and can swell, crumble, change their composition, release gas, etc. Each alloy, ceramic, and plastic has its own behaviour, which can be verified only by irradiation experiments. In fact, since research reactors are able to reproduce mechanical strains undergone by materials in power reactors, they provide essential support to study the ageing of currently operating Nuclear Power Plants, to optimize advanced reactors and to test fuels and materials for innovative reactors.



Bright-field transmission electron microscopy images of unirradiated (top) and neutron-irradiated (bottom) Zr-2.5 wt.% Nb alloy pressure tube of Pressurized Heavy Water Reactor. After irradiation globulization and coarsening of β-phase, as marked by arrow, is noticeable in the microstructure.

Development of radioactive nanomaterials for healthcare



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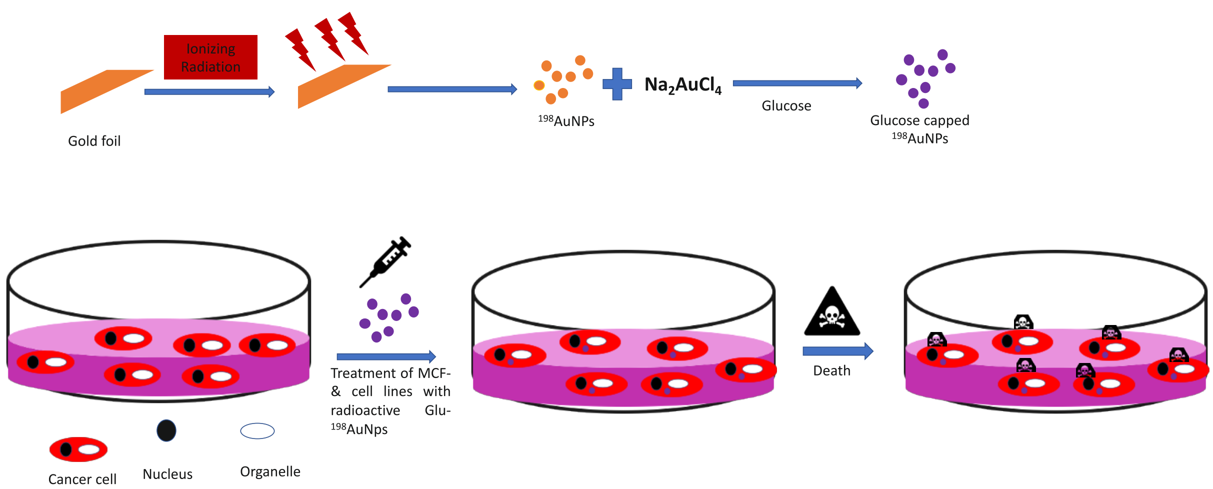
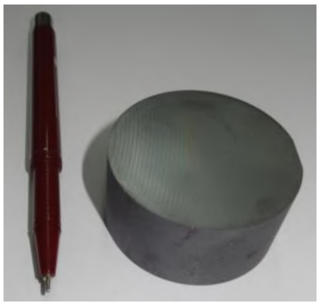
- Radiation Oncology focuses on approaches that aim to preferentially sensitize tumours to radiation whilst minimizing effects in normal tissues.
- The radio-sensitizing agents having high-atomic number can enhance the absorbance of ionizing radiations in tumour tissues. Gold nanoparticles (AuNPs) have the potential to interact strongly with the radiation beams and generate a variety of emission products and show great promise for multi-functional theranostic applications.
- Short lived Radioactive AuNPs conjugated with antibodies or functional groups that are selective for receptors over-expressed by cancer tissue, offer a possibility of sensitizing the cancer cell with minimum radiation dose exposure to other organs.
- Using the above strategy, short lived (2.7 days) radioactive AuNPs based nano-therapeutic agents can be delivered to cancer specific locations. *Neutrons are most suitable for producing suitable radioactivity due to a large neutron capture cross section.*
- The advantage of such radioactive AuNPs is that they will loose activity in three half-lives (typically ten days) and will have least effect on healthy tissues whereas cancer cells get exposed locally in close proximity for about ten days.

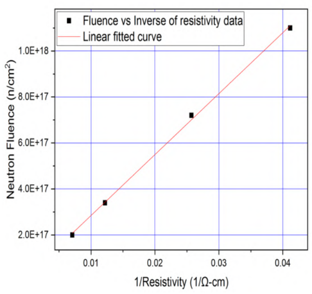


Schematic image of radio-sensitization process

Neutron Transmutation Doping (NTD)-Si



Si ingot irradiated at Apsara-U



Resistivity vs Fluence curve (NTD-Si at Apsara-U)

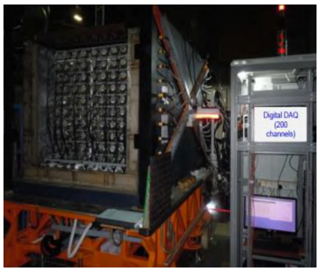
Neutron Transmutation Doping (NTD) of silicon is the process of making n-type silicon by transmuting host silicon atom into phosphorus impurity by thermal neutron irradiation. In conventional doping methods, desired impurity as dopant atom is introduced during the crystal growth from the melt. In this process, the concentration of dopant atom is found to be inhomogeneous and so the resistivity, which leads to formation of hot spot and undesirable variation in the parameters like blocking voltage, turn-on characteristics, on-state voltage drop, reverse recovery, turn-off time etc. In NTD-Si technique, greater spatial uniformity of dopant concentration as well as precise control over the resistivity is achieved. The quality of NTD-Si, both from the viewpoints of dopant concentration and homogeneity, has been found superior to the quality of doped silicon produced by conventional methods. Hence, NTD-Si has been used extensively in manufacturing of high-power semiconductor devices like thyristor (SCR), insulated-gate bipolar transistor (IGBT), integrated gate-commutated thyristor (IGCT), gate turn-off thyristor (GTO) etc.

Several trial irradiations of small size silicon samples were carried out at Apsara-U to gather practical experience in various stages of NTD-Si. For out of core irradiation under a fluence of 10^{17}-10^{18} n/cm^2, measured resistivity is found to be ~ 20 to 140 ohm-cm, which is adequate for power semiconductor device fabrication purpose. For commercial production of NTD-Si, it is possible to irradiate larger sized silicon (~ 4-8 inch diameter) ingot in Apsara-U.

Wafer characterization facility at class 100 clean-room at HWD

Neutron flux characterization and Si irradiation in out of core region of Apsara-U

Neutrino physics studies using measurements of antineutrinos from reactors



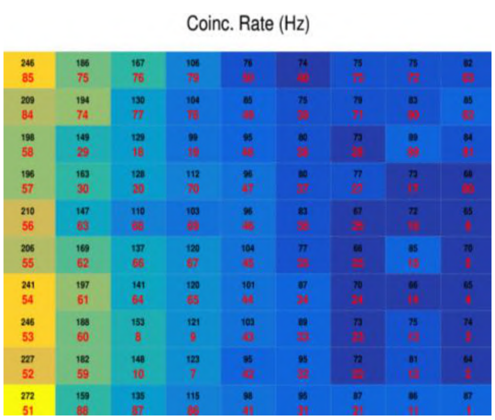
ISMRAN detector with passive shielding inside Dhruva reactor hall

Fully assembled ISMRAN detector mounted on a trolley

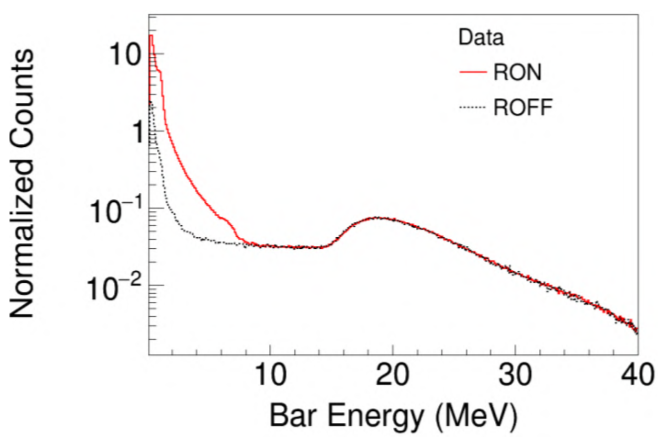
Reactors present a copious source of antineutrinos which can be harnessed for probing several exciting neutrino physics topics of fundamental importance. A large area plastic scintillator (PS) detector array ISMRAN (The Indian Scintillator Matrix for Reactor Antineutrino) with dimensions 10 cm x 10 cm x 1 m of each bar has been fabricated and installed inside Dhruva reactor hall for the measurements of antineutrinos through inverse beta decay (IBD) process. ISMRAN presents the first attempt in the country towards building capability to perform research in a totally new exciting area of reactor neutrino physics with primary goals as

- Studies for the resolution of reactor antineutrino anomaly
- First measurement of prompt energy spectra due to interactions of antineutrinos from the reactor with a natural Uranium core
- Demonstration of non-intrusive monitoring of reactor power through antineutrino events
- Sensitivity studies of active sterile neutrino search using ISMRAN detector

As a precursor, antineutrinos with a prototype detector, 4 x 4 PS bar matrix (mini-ISMRAN), have been successfully measured at Dhruva. In addition to the anti-neutrino program at Dhruva, a new experimental program has been started for the detection of anti-neutrinos using Coherent Elastic Neutrino Nucleus Scattering (CEνNS) process at APSARA-U reactor. The CEνNS studies opens up several other topics at the frontiers of physics research, such as, measurements of neutrino electromagnetic properties, detailed measurements of form factor of nucleus, tests of non-standard interactions, coherence tests using neutrinos.



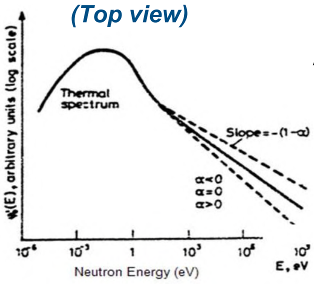
Normalized Count rates measured in the individual bars of ISMRAN scintillator matrix



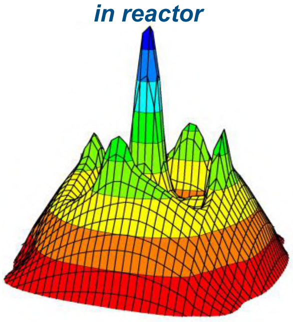
Typical measured spectra using one of the scintillator bars ISMRAN

Reactor Physics Experiments

Critical Facility core (Top view)



Typical Neutron spectrum in reactor



Typical 3D neutron flux variation inside core

Apart from Dhruva and Apsara-U, there is AHWR/PHWR-Critical Facility (CF) in Trombay, which has been designed for conducting lattice physics experiments to validate the physics design parameters of AHWR lattice and for conducting certain reactor physics experiments of 500 MWe PHWR. The Critical facility is basically a low power research reactor with built-in design features, which allow arrangement of fuel rods, safety rods and experimental assemblies in the variable lattice spacing to simulate different core configurations as per the requirements of various reactor physics experiments for AHWR and 500 MWe PHWR. Following Reactor Physics experiments are carried out at Dhruva / Apsara-U / CF for AHWR and Advanced PHWRs.

- Measurements of flux spectra at beam tubes and thermal columns
- Measurements of reactor kinetics parameters
- Subcritical multiplication and shutdown margin measurements during the approach to criticality
- Control rod calibration
- Excess reactivity and shutdown margin measurements
- Measurements of reactor period
- Measurements of temperature coefficients of reactivity
- Calorimetric heat balance and nuclear instrument calibration
- Absorber reactivity worth measurements
- Power decay and delayed neutron group measurements
- Void coefficient of reactivity measurements

Education and Training for Human Resource Development

Dhruva Simulator

BARC outreach programme for enhancing Public awareness

- Science teachers & students
- Engineering teachers & students
- Nuclear power plant operator
- Operational health physicists
- Regulators
- Full scale research reactor simulator
- Public awareness
- Universities having regular academic curriculum in nuclear science and technology

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Apsara-U building