सत्यमेव जयते

Radiometallurgy Laboratory

25 Years Down the Lane

October 2010

RML CELEBRATES 25 years 1985 2010

Government of India
Department of Atomic Energy
INDIRA GANDHI CENTRE FOR ATOMIC RESEARCH
Kalpakkam - 603 102

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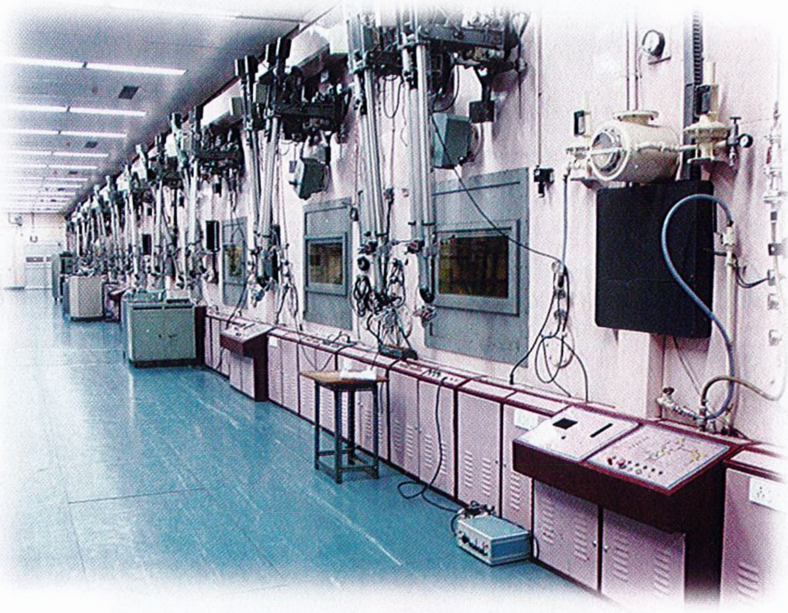

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1985 - 2010

डॉ. श्रीकुमार बॅनर्जी
Dr. Srikumar Banerjee

भारत सरकार
Government of India

अध्यक्ष, परमाणु ऊर्जा आयोग
व
सचिव, परमाणु ऊर्जा विभाग
Chairman, Atomic Energy Commission
&
Secretary, Department of Atomic Energy

August 24, 2010.

MESSAGE

Twenty five years of successful and purposeful operation of Fast Breeder Test Reactor and Radiometallurgy Laboratory is a significant mega stone in the annals of fast breeder and closed fuel cycle technologies not only in India but indeed the world.

Fast reactors are essential for the energy security of our country. FBTR was built in the seventies with an indigenous component of more than 80% and stands out as a symbol of our national pride. FBTR uses a unique U-Pu carbide fuel with high Pu content. The excellent performance of this novel fuel has won acclaims of the global fast reactor community. The safe and successful operation of FBTR has provided the necessary inputs for the design of PFBR, 500 MW(e) and was one of the major factors which gave us the confidence for launching its construction. It is heartening to note that the fuel cycle of the unique carbide fuel of FBTR has been closed with success. It is also a good augury that the MOX fuel of PFBR composition has been irradiated to its target burn-up of 100 GWd/t without failure of any of the pin in the sub assembly. Both these milestones signify that fast reactor technology has come of age in India. With an estimated residual life of ten Effective Full Power (EFP) years, I am sure that FBTR will continue to contribute to testing of metallic fuels and advanced structural materials for the next generation of safe and economic fast reactors, build experience and more important; human resources in this important technology.

The Radiometallurgy Laboratory (RML) of IGCAR has played a commendable companion role for FBTR in conducting the stage-wise post-irradiation examination of the fuel and providing the inputs to the fuel designers & manufacturing personnel in modeling the fuel behaviour, tuning the achievable specifications and progressively enhancing its burn-up to approx. 160,000 MWd/tonne. The hot cells of RML are unique since they handle fuel pins and subassemblies with very high burn-up values under inert atmosphere. The handling of the carbide fuel pellets and pins covered with unavoidable sodium demands high standards of safety. RML has accomplished these precise and high technology assignments with dexterity and confidence.

It is essential that the knowledge gained over the years, especially in an evolving technology, is enhanced and further strengthened. The initiative taken by IGCAR in knowledge management in the form of books on FBTR and RML is commendable.

I wish FBTR and RML a safe and exciting journey ahead with many more milestones and laurels to be achieved, in future. I am sure that the experience gained in the operation of FBTR and RML will provide a strong foundation for the success of our fast reactor programme.

Srikumar Banerjee

(Srikumar Banerjee)

पऊवि
DAE

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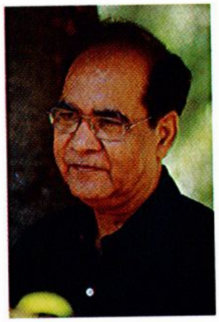
FOREWORD



It gives me immense pleasure to write this foreword for the book to be released on the occasion of Silver Jubilee of Radio Metallurgy Laboratory (RML). As I flipped through the draft of this book and its various chapters, I was taken aloft into the past with flashing of vivid dreams of my passionate and intimate association with this laboratory. I thought I would just pen down some of these which are quite relevant and complementary to the contents of the book.

RML has always been close to my heart, since after my training school period and a brief sojourn at Riso National Laboratory, Roskilde, Denmark for a year (1973-74) as a visiting scientist, I was posted at Reactor Research Centre and now Indira Gandhi Centre for Atomic Research, Kalpakkam and entrusted with the responsibility of designing and developing a Post-Irradiation Examination (PIE) laboratory for the fast reactor fuels and structural materials. This assignment demanded strong grounding in technology. My passion and heart was however in research. While I continued with my engineering assignment of building up the hotcell facility (a world class facility today) with the excellent support of the five adventurous colleagues who landed along with me at Kalpakkam and the other young team that joined me in the course of time, I also realized that a reliable and robust Post Irradiation Examination (PIE) could best be achieved through a matrix approach integrating not only the hotcell facilities but also NDE and remote handling / robotics based technologies. I could also visualize that the groups that would be created would become assets for the development of fast reactor technology. This led me to develop and nurture the groups on

NDE and Robotics. I still remember with passion my first few assignments challenging me to find innovative nondestructive solutions. These assignments related to: finding the exact location of defects in an austenitic cladding tube of Fast Breeder Test Reactor using eddy current encircling coil and establishing correlation of defects with optical and scanning electron microscopy, determining skewing of ultrasonic interrogation beam in thick austenitic weldments with the help of modeling, finding a defect in austenitic stainless steel casting amidst diffraction pattern, using signal-analysis to correlate weak signals in clean austenitic stainless steel with little inclusion contents, carbide precipitates and plastic deformation; to name a few.

During the course of years the NDE group found its niche nationally and internationally. RML as a team excelled in failure analysis and our robotics group started growing up. All these groups started contributing to the mission mode program of the Centre – developing the fast reactor technology. While right from 1985 onwards small scale hotcell activities had been undertaken, it was the 25,000 MWd/t irradiated fuel assembly that marked the real test for PIE and a challenge to me. My greatest satisfaction was when all the groups seamlessly knitted together to complete the PIE and provided the most wanted data such as the stack length, fuel-pellet gap and microstructure through X-ray radiography, metallography etc. to the designers which also provided the Centre with a strong case for increasing the burn-up. As we would all be aware, PIE facilities at IGCAR were the first of its kind α–β–γ facility in the country designed and commissioned entirely indigenously in the back drop of technology isolation from rest of the world. This successful comprehensive PIE campaign in which we handled highly irradiated plutonium-rich carbide fuel validated our technological capabilities and also made us visible nationally and internationally.

In 1992, I took over as the Director of the Metallurgy and Materials Group. It is needless to say that I kept myself in close harmony with the pulse and heart beat of RML that had been rechristened as the Division for PIE & NDT Development. While I continued to monitor the overall progress and the milestones of the PIE group, I nurtured the robotics and NDE groups which were now young and rearing to move forward. It was at this time we had the World Conference on NDT under my presidentship – an event that brought the NDE group of IGCAR into international limelight and NDE science and technology into focus in the country. From then on, we have never looked back. Today this group is internationally acclaimed with more than 600 research publications in peer reviewed journals and international conferences and more than 15 books in the area of NDE science and technology, and arguably the largest for any group worldwide.

By this time, the robotics group had also matured. The design of five axis manipulator for tomography, laser triangulation system for application in reprocessing or the ISI vehicle etc. put them as one of the premier groups nationally. This group also grabbed the opportunity to contribute to the nuclear fuel cycle by developing suitable remote handling devices for the reprocessing facility. It has provided automation solutions for the fuel fabrication plants also. The ISI device being developed by this group for PFBR and is close to finalisation. Thus this group is poised to deliver state-of-the-art solutions to the needs of the Indian FBR programme.

During the last decade, the PIE facility has successfully transformed into a globally renowned centre in the field of PIE of fast reactor fuels. With continuous updated technologies and state of art equipments and innovative techniques, it has delivered valuable results needed for enhancing the burn-up of the carbide fuel from the original design limit of 50,000 MWd/t to 1,55,000 MWd/t to provide the right answers at the right time. With limited international literature available on this unique mixed carbide fuel, understanding the irradiation behaviour at high levels of burn-up was vital for continued operation of FBTR. I am gratified that, the PIE community has been able to deliver this vital feedback required by the designers and safety regulators. In addition, this group has built-up proficiency in the areas of failure analysis of engineering components and small specimen testing. Our support to various missions of ISRO including Chandrayan through Neutron radiographic inspection of its critical components is a matter of pride. All these things once again prove the strength of the group that adopted "family approach" as their work culture for meeting the challenges.

I feel that all these achievements have been possible due to the coherent way the team had been knitted together right from the inception, the synergistic and “vectored” thought among all of us, total support from IGCAR and DAE management. But I feel that above all the crux is clarity of thoughts, capacity to involve colleagues in a transparent manner and capability coupled with credibility to take decisions as and when faced with ethical dilemmas. As a group, we had a vision, mission and the ability of daring to dream big and today the alumnus and colleagues of RML can feel proud of its achievements.

I always believe that history should be documented for posterity especially in such advanced and critical areas such as PIE where in individual experiences are vital for successful and sustained operations. I am very happy to see this "RML Silver Jubilee Book" which has captured the challenges, trials and tribulations undergone during the past two and a half decades of its inception, construction, commissioning and operational phases of this unique PIE facility built-up from scratch, with very little prior expertise to a world class facility. The growth of other facets of RML such as Irradiation Experiments, Non Destructive Evaluation (NDE), ISI, Remote Handling & Robotics have also been handled lucidly indicating the level of expertise achieved and the horizons that each of them endeavours to reach.

As one goes through these, apart from admiring the excellent work, one can also feel that what is more heartening and sets RML apart is that this multi disciplinary field of PIE has produced other groups of excellence making this entire group an international signia.

Personally speaking, as I look back at my career spanning forty two years in this organization, it gives me immense satisfaction when I realize that I have been able to contribute at various levels through ethical management and encouraging creativity and innovation. I believe and often tell my colleagues that we are in this world with a mission and our time spans are short. Within this short period, we should achieve the best in an ethical way for our society and try to leave a positive footprint on this beautiful planet. The legacy of RML started by the six dynamic young scientists/engineers moved forward by the dedicated teams and supported by proactive managements will continue to live on and it is through this silver jubilee volume we will speak to our younger generations and keep those glorious moments and joyful memories alive.

My sincere compliments to the entire editing team and to all my colleagues to have been a part of this wonderful team called "RML".

Baldev Raj

(Baldev Raj)

Director, IGCAR

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PREFACE

Nuclear Energy today has emerged as both economically viable and technologically proven alternative in power production. This gains further significance in the light of dwindling fossil fuel reserves. Dr. Homi Jehanghir Bhabha, the great visionary and Father of Indian Nuclear Program had envisaged this as early as 1950 and set on stream a three stage nuclear program based on a closed fuel cycle. The first stage being natural uranium fueled Pressurised Heavy Water Reactors (PHWR), has already matured into commercial stage in our country. Fast Breeder Reactors (FBR) utilizing the plutonium generated in the first phase forms the second stage to enhance the potential of the nuclear power generation.

Sensing the importance of the second stage, Dr Vikram Sarabhai, another farsighted legend of the Indian nuclear programme, had initiated the first step to setup a multidisciplinary and mission oriented research centre with all elements of Science and Technology required for developing the Fast Breeder Technology indigenously. Thus was born the Reactor Research Center (RRC) in 1971, which was later renamed as Indira Gandhi Centre for Atomic Research (IGCAR) in 1985.

The Fast Breeder Test Reactor (FBTR) was built, as the pivotal point of IGCAR, with two major objectives namely to gain experience in construction, commissioning and operation of sodium cooled fast reactors and to act as a test-bed where host of fuel and structural materials could be irradiated and evaluated for its performance. Such an experience was aimed at acquiring a comprehensive understanding of the Fast Breeder technology and its associated fuel cycle, resulting in the development of our own competence to design and build commercial fast reactors.

Program for experimental irradiation of materials necessarily have to be supported by Post Irradiation Examination (PIE) to gain maximum insight on the behavior of materials in nuclear reactors. The Radio Metallurgy Laboratory (RML) with a hotcell facility adjoining the Fast Breeder Test Reactor was meant to cater to these needs. The concept and design of such a facility was unique as it was a first of its kind α-β-γ facility in the country capable of handling high plutonium content fuels.

The task also became challenging due to limited literature available at that time along with the constraints of technology isolation by rest of the world.

Based on the initial conceptualization and planning from BARC and support received from many senior colleagues both at IGCAR and BARC, the construction of the hotcell facility was commenced in 1975 and coincided with the period of setting up of the FBTR.

Originally the hotcells were designed for handling uranium-plutonium oxide fuel. Subsequent change of FBTR fuel to advanced and pyrophoric uranium-plutonium carbide fuel necessitated an inert atmosphere inside the hotcells. With the hotcells already constructed, the challenge was to retrofit them for nitrogen ventilation and accommodate a nitrogen recirculation system within the limited space available in the laboratory. A dedicated team with diverse expertise provided innovative solutions to achieve successful conversion of hotcells to nitrogen atmosphere with required leak tightness. Meanwhile, the adroit team was also working from scratch on multiple fronts simultaneously for the development of remote handling devices, material transfer systems and in-cell equipment required for the hotcells. The painstaking efforts of incorporating modular design, scrupulous choice of materials for various in-cell equipment and rigorous validation through mock up testing and trials, led to the successful installation and commissioning of equipment needed for the initial post irradiation examination.

This was followed by meticulous preparation of hazards evaluation report to obtain clearance from Atomic Energy Regulatory Board (AERB) for commencing operations in the hot laboratory. Numerous deliberations with AERB appointed committee provided many helpful recommendations which were incorporated, finally resulted in obtaining the safety clearance for this laboratory.

The operational phase of RML hotcells kicked off with the receipt of the first experimental fuel subassembly from FBTR in 1994 for Post Irradiation Examination. The first few PIE campaigns, a voyage through uncharted waters, was a learning experience. The PIE techniques and the associated in-cell equipment were continuously evolved and upgraded to cater to the needs of examining high burn-up fuels. The stage-wise campaigns were interspersed with first-of-its-kind activities like installing new equipment, remote repair of existing equipment and waste transfer from hotcells which required intervention into an operating α-β-γ cell. All these could be accomplished with very low man-rem expenditure thanks to the in-built flexibility of the hotcells. The journey through this phase was finally a rewarding experience as it helped in the stage-wise enhancement of the burn-up of the unique fuel from an initial design limit of 50,000 MWd/t to 1,55,000 MWd/t. Over the years, this facility has grown to maturity generating valuable PIE results required for FBTR and is ready to face higher challenges required to cater to the needs of examination of PFBR fuel, which is undergoing test irradiation in FBTR. It is also gearing up for the PIE of metallic fuel envisaged to be test irradiated in the near future.

With FBTR as a test bed for irradiation experiments on various fuels and structural materials, a dedicated team undertook the design and planning of these experiments in FBTR. The Irradiation Experiment team has made rapid strides in the design and development of miniature precision devices and irradiation capsules, precision welding and fabrication work required for carrying out the irradiation experiments. This group works in collaboration with the designers, reactor operators, and the PIE team.

Post Irradiation Examination is a multi disciplinary field requiring support from a host of other areas like material science and technologies, non-destructive evaluation techniques, remote handling, automation and radiochemistry. Right from the inception of RML, non-destructive testing formed an integral part since the first confirmation of any failure or abnormalities in the irradiated fuel can be detected only by these techniques. What started as a supporting activity for the PIE in the RML underwent a phenomenal transformation from classical Non Destructive Testing (NDT) to Non Destructive Evaluation (NDE). The group of people working in this area under the eminent and able leadership of Dr. Baldev Raj widened their horizons to various other areas like materials evaluation, structure-property correlations, remaining life assessment in addition to societal applications such as health care and preserving of ancient heritage. The expertise developed was also translated to defense, aero-space and other core sectors like petro chemical and power. This group of RML is today acclaimed to be a world leader in the area of Non Destructive Evaluation.

The initial needs of remote handling for the hot laboratory were met with active collaboration with BARC. However, soon it was felt that the unique needs of the advanced hotcell facilities require modification in the design and construction aspects. Radio Metallurgy Laboratory along with colleagues from Reprocessing Group developed remote handling tools like master slave manipulators, in cell cranes, power manipulators etc. specially designed to meet the needs of the Fast Breeder Reactor fuel cycle.

The expertise thus accrued in the laboratory was later invested in establishing dedicated activities directed towards remote fuel fabrication and development of metallic fuel cycle activity. This group has not only helped in perfecting the remote handling technologies in this area but are engaged in the advanced concepts of converting the classical remote handling aids to tele-operated systems. The logical coupling of NDE techniques with robotics and automation pioneered by this Group has led to the development of comprehensive technologies for the in-service inspection techniques for PFBR and Fuel Reprocessing plant.

The journey of RML through the last 25 years which started with a modest beginning of first remote handling operation, to fabricate the neutron source fuel required for FBTR start up, eventually has taken us through various untreaded paths. The journey was not only challenging but also exciting and rewarding. This compilation aims at re-capturing the glimpses of this expedition and highlights some of the achievements accomplished.

By no means, this compilation is exhaustive. Even though this is meant to be a knowledge book for a general reader, there could be some descriptive portions, which were unavoidable. Bringing out a compilation like this is a stupendous task and the efforts taken by a large number of colleagues and the editorial committee require special mention.

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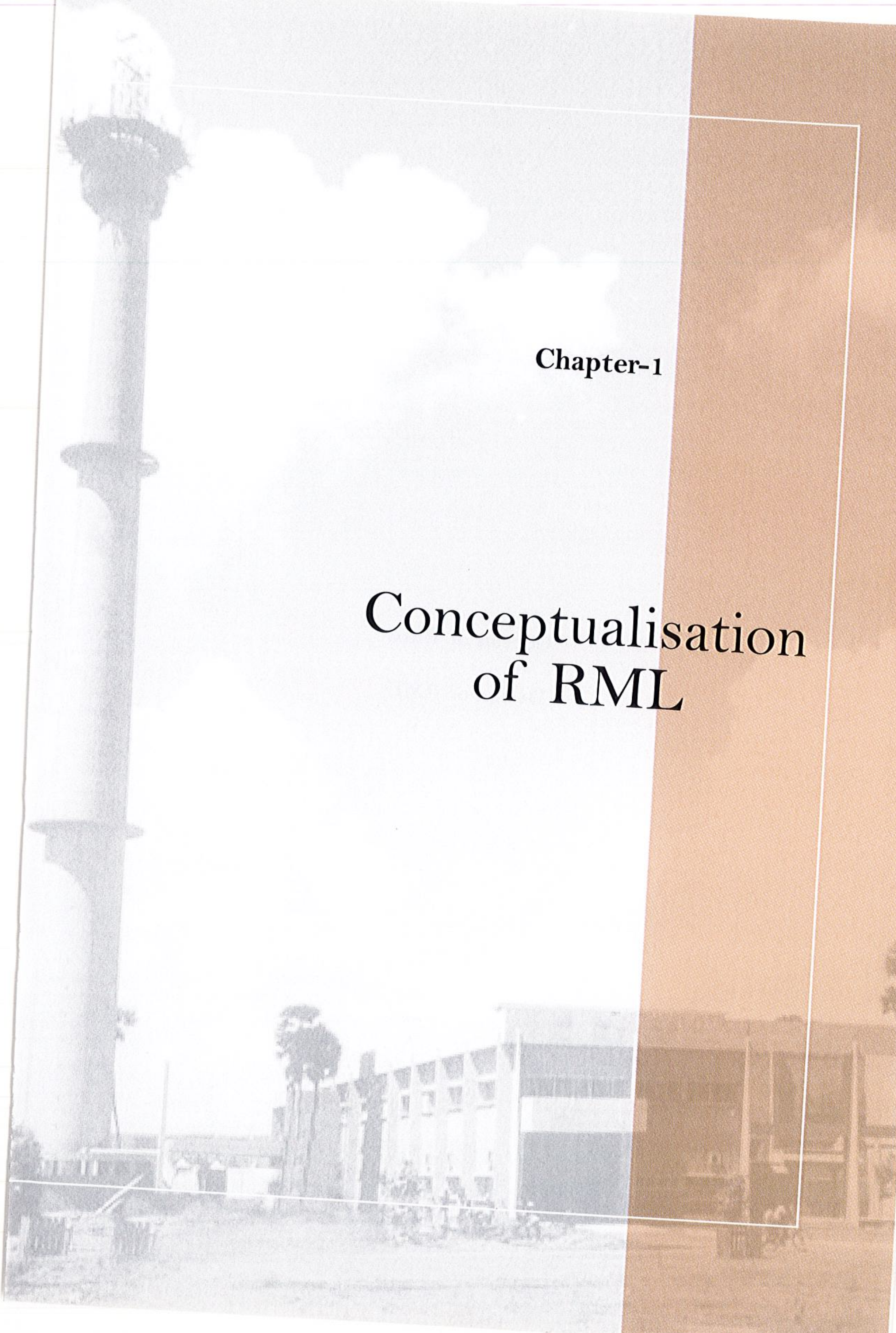


Chapter-1

Conceptualisation of RML

Genesis of RML

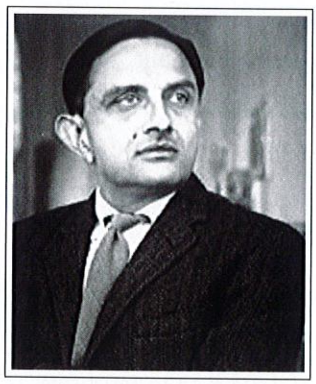
Design of RML

GENESIS OF RML

Introduction

Dr. Homi Jehangir Bhabha, father of Indian nuclear energy programme, was one of the eminent scientists who ignited a scientific revolution in India in the fields of atomic energy and cosmic rays. Dr Bhabha, an extraordinary visionary, envisaged a *three stage nuclear power programme* to effectively utilize indigenous Uranium and Thorium resources for meeting the fast growing energy demands of independent India. Kalpakkam was chosen as the launch pad for the 2nd stage of nuclear programme, involving fast breeder reactors. Dr Vikram Sarabhai [Chairman AEC 1966-1971] took keen interest in developing fast reactor technology in India, in collaboration with France. Dr.Sarabhai was instrumental in setting up Reactor Research Centre (RRC), Kalpakkam in 1971, which was later renamed as Indira Gandhi Centre for Atomic Research (IGCAR), by Late Prime Minister Rajiv Gandhi.

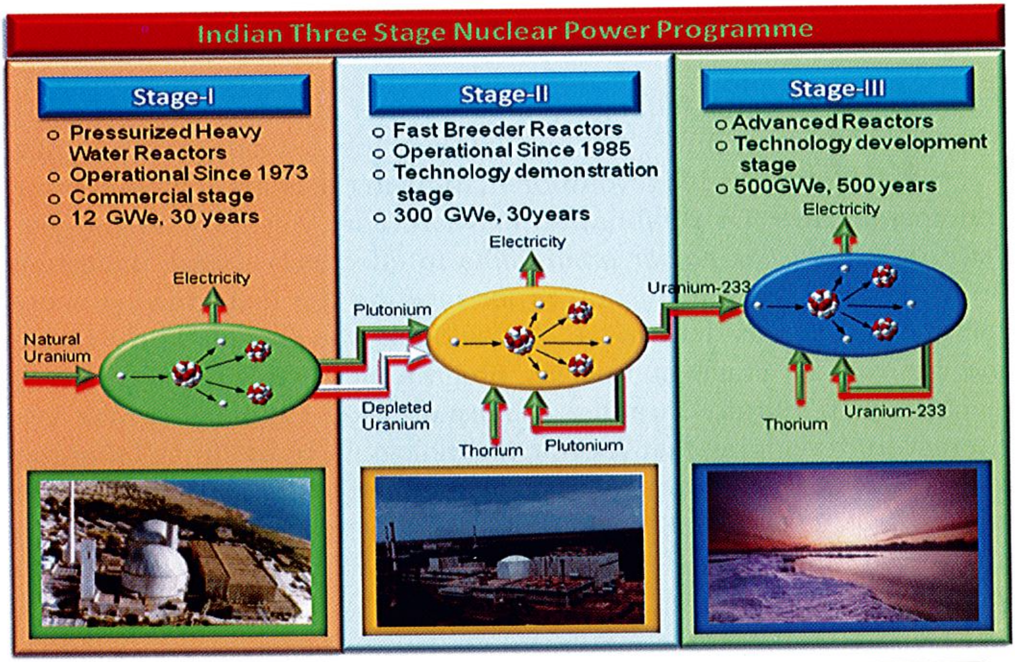
Dr.Homi Jehangir Bhabha



Dr. Vikram Sarabhai

Conceptualisation of RML

IGCAR was set up as a mission oriented multi disciplinary R&D institution working towards the comprehensive development of the entire fast reactor technology with a closed fuel cycle. A 40 MW(th) Fast Breeder Test Reactor [FBTR] acting as the nucleus was envisaged to be constructed to gain comprehensive experience in the design, construction and operational aspects of sodium cooled fast reactors. Another objective for building FBTR is to provide a test bed for the development of fuel, blanket and structural materials, with particular reference to the development of high performance fuels.



Three stage nuclear power programme conceived by Dr. Homi Bhabha is based on indigenous nuclear resource profile of modest Uranium and abundant Thorium. The program consists of a closed fuel cycle, where the irradiated fuel of one stage is reprocessed to produce fuel for the next stage. The first stage which is already in the commercial domain comprises of natural uranium fuelled Pressurized Heavy Water Reactors (PHWRs) producing electricity and converting U^{238} into Pu^{239}. The second stage comprises of Fast Breeder Reactors (FBRs) producing electricity using plutonium obtained from the first stage as fuel, and producing Pu^{239} and U^{233}. Second stage is in the technology demonstration stage with the construction of PFBR utilizing the operational experience of FBTR. The third stage is based on the thorium-uranium-233 cycle (Uranium-233 obtained by irradiation of thorium), which is in the technology development stage.

The indigenous development of the fast breeder reactor technology is an interesting and exciting challenge confronting our nuclear industry. One of the most important aspects of FBR program is the development and testing of high performance fuel and structural materials, operating in a hostile environment of high temperature, fast neutron flux and liquid sodium. A robust fast reactor programme requires a thorough understanding of various performance related issues in the fast reactor materials and extensive irradiation experiments for development of improved materials which can withstand high burn-ups. An essential component of this programme is the comprehensive post irradiation examination (PIE) to evaluate the performance of fuel and structural materials. The feedback to the designers, fabricators and operators through PIE facilitates optimizing fuel design, fabrication and operational parameters. PIE facility is hence an essential pre-requisite for carrying out physical, chemical and metallurgical characterization of fuel, structural and other materials irradiated in the reactor. Irradiated fuel and structural materials being highly radioactive, have to be handled in special enclosures called *hot cells*. Radiometallurgy laboratory was set up with a series of hot cells adjoining the FBTR to cater to the PIE needs of FBR programme.

Hot cell is an isolated shielded room that provides environment for handling /examining highly radioactive / radiologically contaminated materials with remote handling and viewing facilities in a safe and contained manner. In this context, hot does not mean high temperature but only indicates high levels of radioactivity.

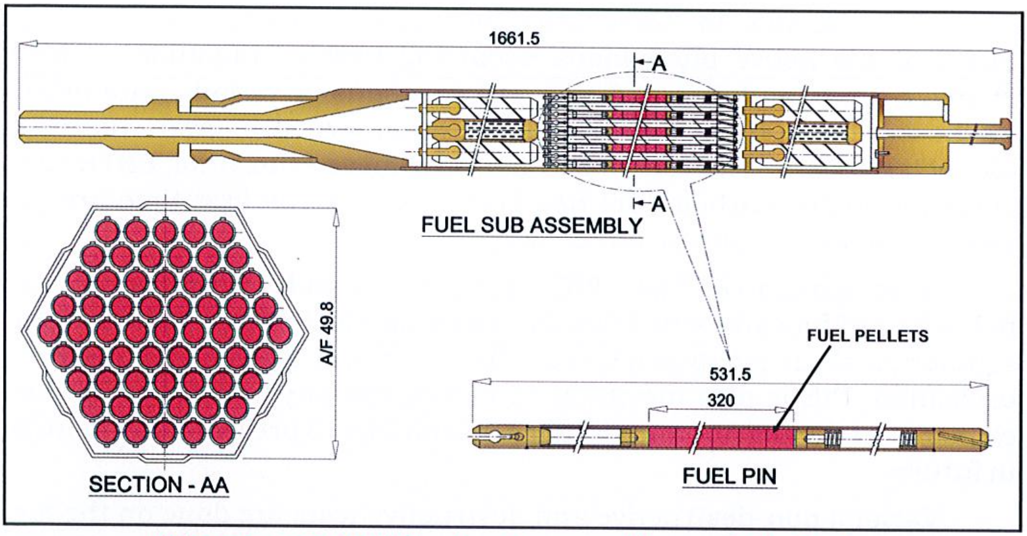
Conceptual design of RML was done by Shri S. Ananthakrishnan and Shri M.S.Ramkumar of BARC during the period 1970-1973. However the entire challenge of implementing the project was entrusted to a small team of young scientists. This team led by Dr. Baldev Raj arrived at Kalpakkam during June 1974 to finalise the design and carry forward the project. The team consisted of Dr. D.K.Bhattacharya, Shri P.V.Kumar, Shri K.V.Kasiviswanathan, Shri. P.Kalyanasundaram and Shri M.R.Krishnan. Soon after this, Dr. Placid Rodriguez also moved from BARC to Kalpakkam and took over the overall leadership of Metallurgy Programme of which RML was a major constituent. Shri N. Srinivasan the founder Director of the centre took keen interest in developing the laboratory and in mentoring and motivating the young team to achieve the goals. The task of building up RML was stupendous considering the complexity of realising a first of its kind alpha, beta, gamma hot cell facility in our country, with limited information available in the literature. This was compounded by the limited capabilities of the Indian industries at that time and the technology denial imposed on our nuclear programme.

Brief description of FBTR and its fuel

FBTR is a 40 MWt, loop type, sodium cooled fast reactor. Heat generated by fission in the reactor is removed by primary sodium loop and transferred to the secondary sodium loop. The secondary sodium loop is provided with steam generator modules where the heat is transferred to a steam-water circuit consisting of a turbine-generator and condenser. Stainless steel (SS 316) is the principal material of construction for the reactor core materials and coolant circuits.

In test reactors like FBTR where the core size is very small, fissile material content should be very high for achieving criticality. The fuel initially envisaged for FBTR was mixed oxide of uranium and plutonium with uranium enrichment upto 85%. Due to the difficulty in sourcing enriched uranium, mixed oxide with plutonium content of around 70% was subsequently considered. This fuel had some disadvantages with respect to fabrication, thermophysical properties and compatibility with coolant. Hence a unique, mixed carbide with 70% plutonium carbide and 30% uranium carbide was chosen and indigenously developed for FBTR. This fuel composition was being used for the first time in the world and the in pile behaviour of this fuel was completely unknown. FBTR became critical with 22 carbide ***fuel subassemblies*** in October 1985.

Fuel subassembly of a fast reactor typically consists of several fuel pins of around 5-8 mm in diameter and length of 0.5 – 3 m arranged inside a hexagonal wrapper tube forming a close packed lattice. Fuel pellets in ceramic form (oxide, carbides, nitrides etc) or as metal slug in rod form are encapsulated inside a cladding material (austenitic/ferritic steels) along with other hard wares to form one fuel pin. Subassemblies serve the purpose of handling a set of fuel pins as an entity for unloading the spent fuel from the reactor and for loading fresh fuel (fissile material) to compensate the loss of reactivity in the reactor core. Burn-up of fuel refers to the amount of energy extracted from unit mass of fuel, typically expressed in Mega Watt × day / tonne (MWd/t)



Sketch of FBTR fuel subassembly and fuel pin

Features of FBTR fuel subassembly and fuel pin	
No. of fuel pins in subassembly	61
Fuel	$(U_{0.3}Pu_{0.7})C$
Cladding material	20% CW SS 316
Fuel stack length	320 mm
Type of bond	Helium
Fuel density	90 % of T.D.
Smear density	83 % of T.D.
Outer diameter of fuel pin	5.1 mm
Clad thickness	0.37 mm

Features of a typical irradiated fuel subassembly after 150 GWd/t burnup and a cooling period of 300 days	
Gamma dose rate	5.3×10^3 Sv /h
Neutron dose rate	56 mSv /h
Maximum decay heat specified for receipt into hot cells	400watts

Role of PIE

A comprehensive PIE is expected to give information on the performance of the fuel and the structural materials under the aggressive environment prevailing in FBRs. In fuel materials, a host of irradiation effects occur at high burn-ups. These include swelling of fuel due to accumulation of fission products, redistribution of fission products and actinides, changes in the chemical state of the fuel, fuel restructuring, generation of internal pressure in the fuel pin due to release of fission gases etc. Similarly in structural materials, due to neutron irradiation, many defect structures are generated resulting in gross dimensional changes and degradation in mechanical properties limiting the burn-up.

The PIE aims to characterise the fuel and structural materials in terms of the above phenomena occurring under irradiation. These changes are cumulative and they are functions of various parameters such as fuel burn-up, operating temperature and material characteristics. The role of PIE is much more crucial for FBTR fuel, since the mixed carbide fuel has been used for the first time and its irradiation performance is not known.

Data generated from PIE provides valuable feedback on the behaviour of fuel and structural materials and facilitates prediction and estimation of the residual life of the fuel to ensure its safe and optimum utilization. PIE is also inevitable to investigate any failures of the fuel elements in the reactor and to suggest solutions to prevent such failures in future.

Various non-destructive and destructive tests are done on the fuel pins and fuel subassemblies in the hot cells to extract maximum information on their irradiation behaviour. Generally, one or more techniques are employed to study a particular irradiation behaviour.

PIE techniques for fuel/structural material characterization

Sr. No	Irradiation behaviour	Techniques used
1	Physical conditions of fuel subassembly	Visual examination, profilometry for measuring dimensional variations, distortion, Neutron Radiography for inter pin spacing
2	Clad failure	Visual examination, Eddy current testing, X-ray and neutron radiography, Leak testing, Optical microscopy, Electron microscopy and Electron probe microanalyser (EPMA)
3	Cladding corrosion in sodium	Visual examination, Eddy current testing, Optical & electron microscopy and EPMA
4	Clad swelling	Profilometry, Neutron radiography, Density measurements, Transmission electron microscopy (TEM)
5	Fuel-clad mechanical interaction	Profilometry, X-ray and neutron radiography and Metallography
6	Fuel-clad chemical interaction	Eddy current testing, Optical and electron microscopy, EPMA and Radiochemical analysis
7	Fuel microstructure	Optical and electron microscopy, Alpha, Beta and Gamma auto-radiography and EPMA
8	Production and migration of actinides & fission products	Gamma scanning, Alpha, Beta and Gamma auto-radiography, radiochemical analysis, Mass spectrometry and Neutron radiography
9	Fission gas release	Extraction of released gas under vacuum. Analysis by mass spectrometry / gas chromatography
10	Mechanical properties of clad and wrapper	Tensile testing, hardness testing, Stress rupture testing, Miniature specimen testing

DESIGN OF RML

Hot cell facility - Design philosophy

RML hot cell facility is mainly intended to carry out PIE of fast reactor fuels and core structural materials. It was also proposed to use this facility for dismantling of fuel subassemblies (which do not require detailed PIE) and subsequent despatch of fuel pins to reprocessing/radiochemical facilities. The hot cells also need to have enough flexibility to examine various types of fuel proposed to be irradiated in FBTR for testing and development. Since the PIE data to be generated remains practically the same for various types of fuels, only the in-cell equipment and the hot cell atmosphere have to be changed to suit the dimensional changes and other characteristics of the material being examined.

The hot cell facility was designed to handle about 10 subassemblies in a year. Experimental subassemblies irradiated in FBTR were also planned to be examined in the hot cells, in addition to normal fuel subassemblies. However, based on criticality safety considerations (discussed later), it was decided to handle only two fuel subassemblies in the hot cells at a given time.

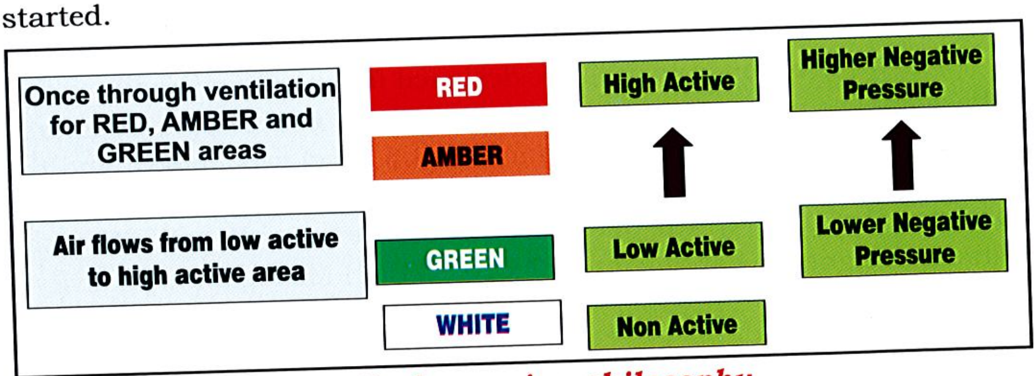
Shielding

The walls of concrete cells are designed for shielding irradiated fuel subassemblies with an activity not exceeding 5.5×10^6 G Bq with gamma energy of 1 MeV. High density concrete (3.5 g/cc) was chosen and the wall thickness of 1200 mm was arrived at based on the acceptable level of dose rate (1μGy/hr) in the operating side of the hot cell wall. The lead cells are designed to handle upto 3.7×10^4 G Bq (1 MeV gamma) activity.

Ventilation

Irradiated fast reactor fuel contains fairly large amounts of highly radioactive fission products and transuranic elements. To meet the stringent radiological safety requirements for handling high beta, gamma activity accompanied with high amounts of alpha emitting transuranic elements, sealed cell design philosophy was adopted. Hot cells are designed with high leak tightness to realise the sealed cell concept. Facilities handling high amounts of alpha, beta and gamma activity should have both static and dynamic containment to prevent the release and spread of radioactive particulates/aerosols from hot cells to the environment. Dynamic containment is achieved by proper ventilation systems which ensure that air flow is always from a low active area to a high active area. In the event of any failure of ventilation system resulting from unplanned events like power failure etc., static containment takes over where the inherent leak tightness of the system does the job of holding the radioactivity within the enclosure for long durations by which time remedial action can be taken.

RML hot cell facility incorporates both static and dynamic containment. The ventilation system in RML follows the general ventilation philosophy followed for the radioactive facilities. The laboratory has been divided into four different zones namely white, green, amber and red zones depending on the contamination and radiation levels expected in these areas. The zoning is based on effective isolation of areas with different degrees of contamination potentials. Differential negative pressures are maintained between the zones and they are separated by airlocks. To prevent occurrence of positive pressures, supply fans are electrically interlocked to the exhaust fans in such a way that they can be started only after the corresponding exhaust fans are started.



Radiation zoning philosophy

Hot cell materials & equipment

All walls, floor and ceilings of the hot cells were made of high density concrete to have better shielding properties. The materials used for cell floor and wall lining conform to stainless steel 304 grade to avoid corrosion and for ease of de-contamination. Wherever possible, the in-cell equipment were also designed with stainless steel as major material of construction. Wherever aluminium was used, hard anodizing of the surfaces was done to prevent surface degradation and subsequent pick-up of contamination during operation. All hot cell welding consumables were checked to ensure very low chloride content to avoid corrosion of welded components. Wherever stainless steel lining was not possible and painted surfaces were unavoidable, epoxy paints were used for ease of decontamination.

The insulation materials, gaskets, seals etc. used inside the hot cells were tested before use to check the radiation resistance properties. All such materials were tested in a gamma chamber to withstand a cumulative radiation dose of 10^6 to 10^7 Gy.

In-cell equipment required for various examinations were also designed to be modular for ease of replacement, maintenability, interchangability, decontamination and disposal. Since the electronic components are prone to radiation damage, as far as possible, the control units of the in-cell equipment were installed outside the hot cell for longer life. Disposal of equipment, components and parts after its end-of-life was also considered at the design stage itself. Equipment with long years of service in the hot cell may be difficult to be decontaminated to the acceptable levels for safe disposal due to accumulation of contamination. Hence, design features were incorporated to ensure equipment disposal with reduced radiation exposure to personnel.

Hot cell infrastructure

One of the design features adopted for RML hot cells was its modular nature with interconnectivity between the cells. This concept was chosen considering the nature of examinations and the maximum dimensions of the fuel elements which were proposed to be handled. This design also facilitates isolation of any particular cell from the remaining cells, for carrying out maintenance work. Remote handling devices were chosen keeping in mind the dimensions of the cell and the loads which are likely to be handled. Radiation shielding windows and other viewing devices were designed for maximum visual reach within the dimensions of the hot cells.

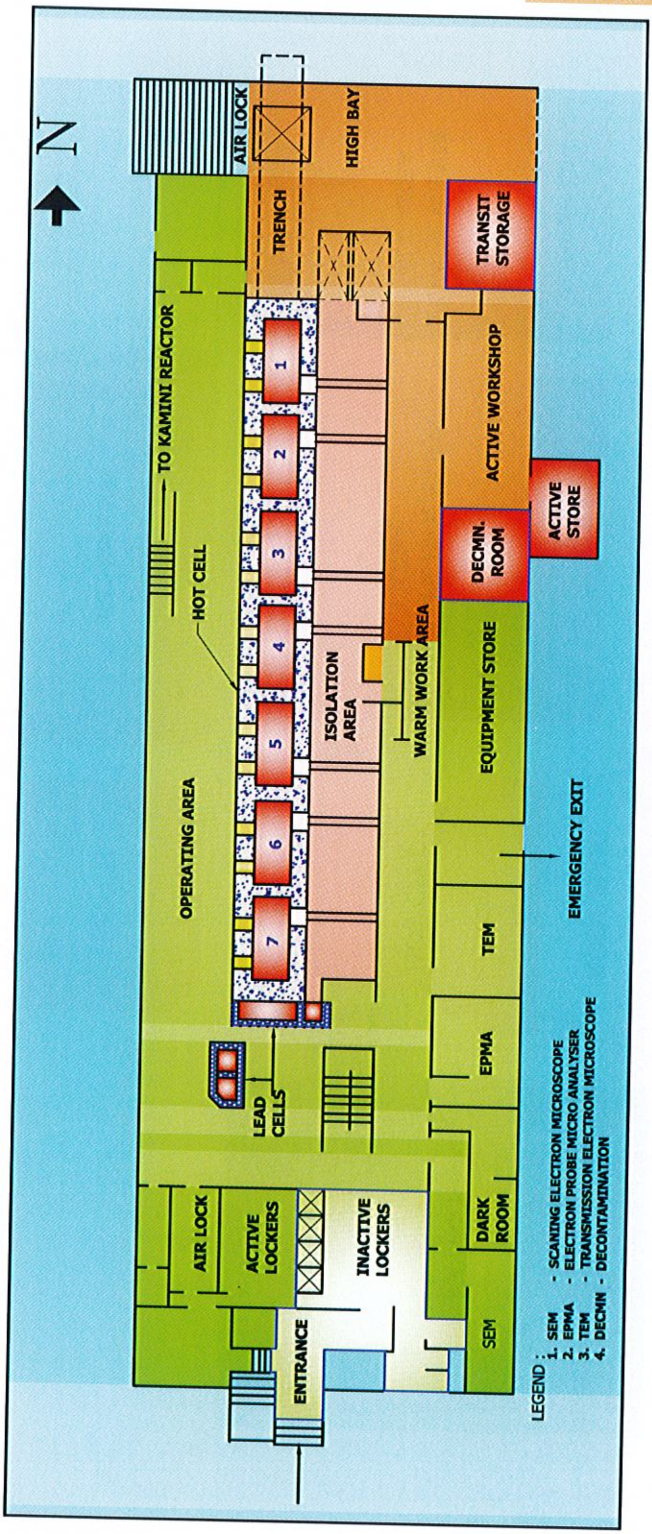
For receipt and dispatch of fuel from the RML hot cell facility, two leak tight transfer systems with adequate shielding have been incorporated. Service plugs and openings of various dimensions were incorporated in the design for routing electrical connections and signal cables, housing the manipulators and viewing equipment, as well as to cater to various requirement such as contact maintenance of equipment involving direct human intervention into the cells, installation of new equipment, transfer of consumables, decontamination, waste disposal etc. Adjoining the cells, different service areas were accommodated for meeting the operational requirement. All these areas are categorized into different radiation zones indicating the radioactivity potential and each zone is provided with air supply and exhaust ventilation system. These areas also house some of the interfaces with the hot cells like glove boxes where materials of lower radioactivity levels are handled.

Radioactive waste management

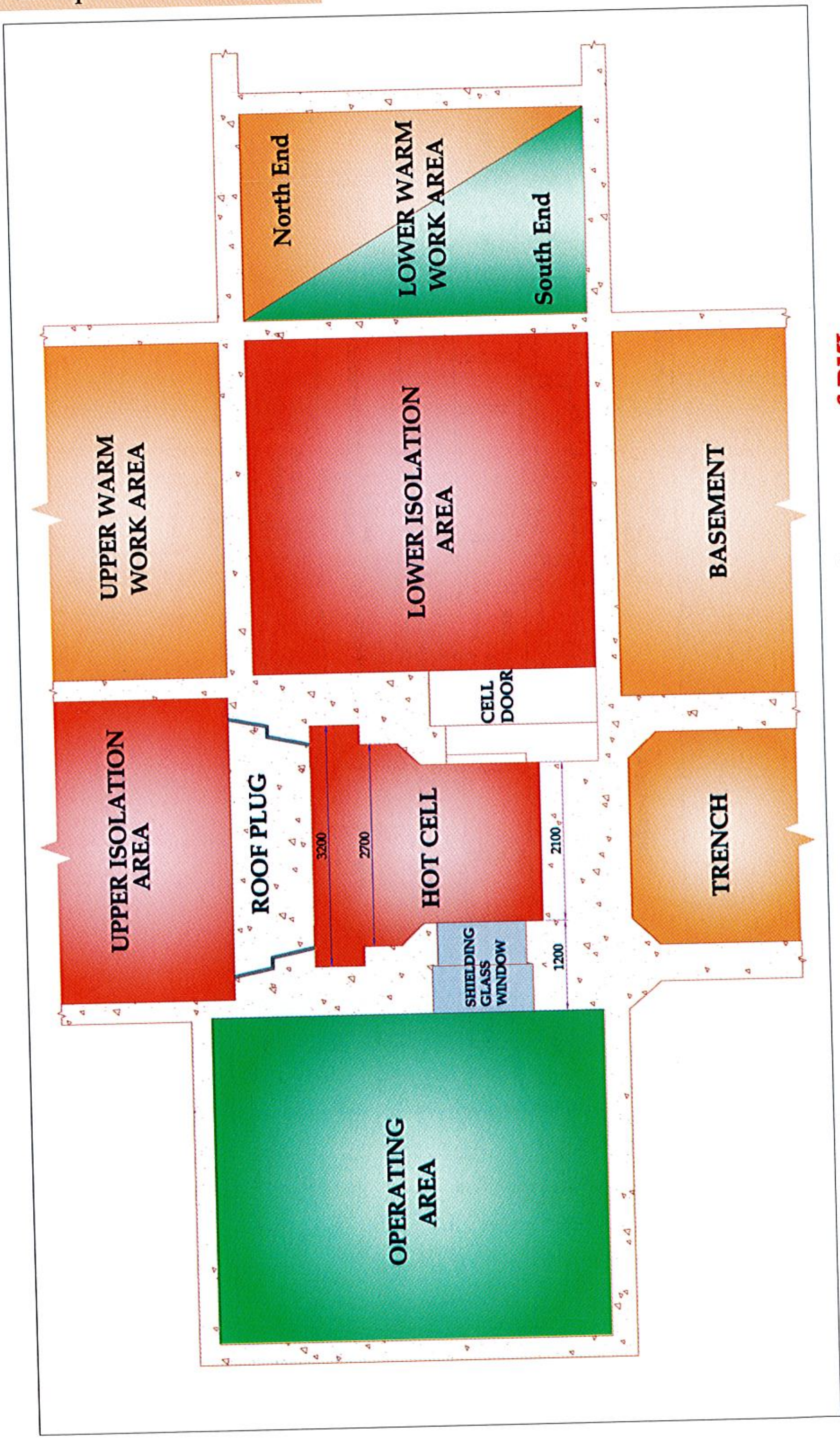
Adequate design provisions have been incorporated for safe handling and disposal of various radioactive wastes generated in the laboratory. The wastes originating in RML are handled depending on the nature and level of activity. Solid wastes having beta, gamma activity are categorized based on the surface dose on the waste package and despatched to CWMF in steel drums/shielded containers depending on the level of radioactivity. Wastes containing potential alpha activity are handled separately. Liquid effluents are also categorized based on their specific activity and transferred to CWMF through double envelope pipelines or in sealed drums. Gaseous effluents are discharged, after filtration, through the 65 m high stack common to FBTR and RML. Provisions have been made for analysing the activity content of the radioactive wastes before it is dispatched/discharged.

Layout of hot laboratory building

Hot laboratory building of RML consists of the hot cells and different service areas. The hot cells comprise of seven concrete shielded cells and two lead shielded cells. Adjoining the hot cells in the hot laboratory building of RML, different service areas are provided such as operating area, isolation areas, warm work areas, highbay, trench, basement etc. catering to different operational requirements. Operating area is situated on the first floor facing the hot cells. Personnel stationed in this area will carry out the operations inside the hot cells using remote handling devices. A 500 kg capacity hand-operated crane is provided in this area.



Plan view of the hot laboratory building



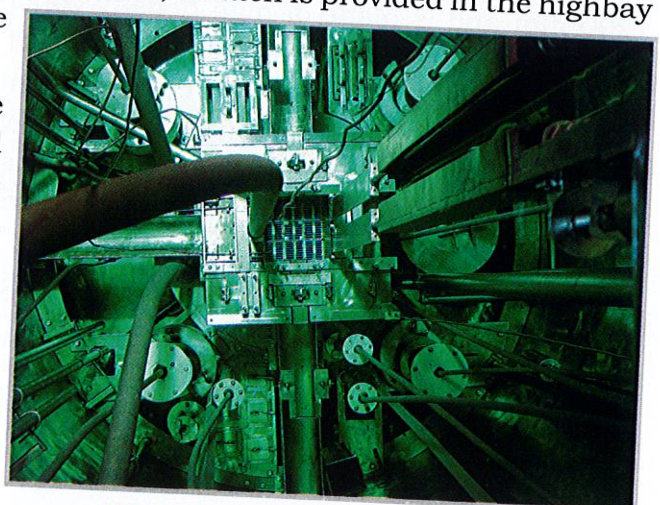
Cross sectional view of the radioactive areas of RML and zoning indicated by the respective colours

Lower isolation and upper isolation areas are located in the first floor and second floor of the hot laboratory building respectively. These areas act as isolation or barrier zones between the hot cells and warm work areas. Frog-suit-change-rooms and shielded sealing doors are provided respectively for man entry and equipment transfer from/to isolation areas. Access to the hot cells is made through the isolation areas for maintenance work. Two warm work areas; upper and lower warm work areas adjoin the upper and lower isolation areas. Six fume hoods are installed in upper warm work area which are used for repair of in-cell gadgets, metallography of contaminated components as a part of failure analysis, TEM specimen preparation etc.

High bay area is used for transfer of materials into/out of the laboratory. Shielded casks are used for transfer of irradiated fuel/materials from/to the hot cells. These lead shielded casks are subsequently transported using a truck to other radioactive facilities within IGCAR. A 20/5 t Electrical Overhead Travel (EOT) crane is provided in the highbay for handling of shielded cask /hatch etc. A truck entry airlock is provided in the highbay area for entry/exit of materials.

The basement area houses the hot cell inert gas recirculation and purification system. A 25 m long underground trench is located below hot cell No. 1 and high-bay area connecting to the western side of FBTR spent fuel storage area. This trench is used for transporting fuel from FBTR to RML. A vertical fuel transfer system (VTS) consisting of an electrically operated trolley with a 20 t lead shielded transfer flask is located in this trench area. For maintenance of VTS, a hatch is provided in the highbay which opens into the trench area.

Under one of the concrete cells, a small swimming pool type reactor, KAMINI, with a nominal power of 30 kWt is located. This reactor uses plate type U^{233}–Al alloy as fuel and is used for neutron radiography, activation analysis and shielding experiments.



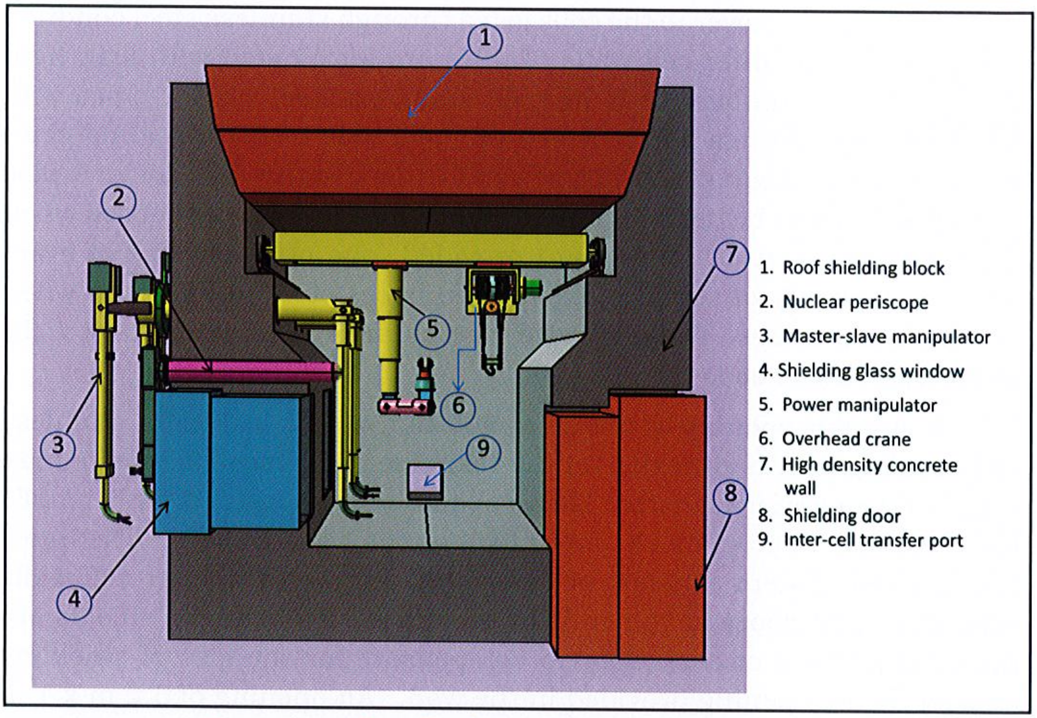
Top view of KAMINI reactor

SALIENT FEATURES OF KAMINI	
Nature of Reactor	Pool type
Nominal power	30 kWt
Fuel	U^{233}-Al alloy
Moderator/Coolant/ Shield material	Demineralized water
Beam tubes	Three
Flux at outer end of beam tube	10^{6}-10^{7}n/ cm^{2}/sec
Flux at irradiation site	10^{11}-10^{12}n/cm^{2}/sec
Core flux	10^{12} n/cm^{2}/sec

Description of hot cells & its common features

The concrete shielded hot cells are designed for handling 5.5×10^{6} G Bq of radioactivity with 1 MeV gamma energy. The concrete wall thickness is 1200 mm and is made of high density concrete with 3.5 g/cc density. Lead shielded cells have a wall thickness of 250 mm and can handle activity of 3.7×10^{4} GBq. All the cells can handle alpha, beta and gamma activity with provision to monitor and control various parameters such as pressure, temperature and gas changes. The seven hot cells are arranged in series and connected by inter-cell transfer ports. Each cell can be isolated with respect to other cells.

All concrete cells have a floor area of 5.5 x 2.1 m. Stainless steel liners are provided on the interiors of the cell wall to obtain the specified leak tightness of the cells (< 1.2 vol%/day). Dimensions of the cell are optimized for adequate reach in all the areas using remote handling devices.



Cross sectional view of a typical Hot Cell

For remote handling and viewing, *master slave manipulators,* power manipulators, in-cell crane, shielding glass windows & periscopes were incorporated in the design. Each cell has two viewing windows made of radiation resistant stabilized glass and two operating stations for carrying out remote operations. An opening has been provided above each window to install a periscope for closely examining the objects inside the cell.

Master Slave Manipulator (MSM) is a device used to remotely handle irradiated / radioactively contaminated materials in a hot cell. It has two arms where the controlling arm located in the operating side is called "master" and the responding arm on the hot cell side is termed as "slave".

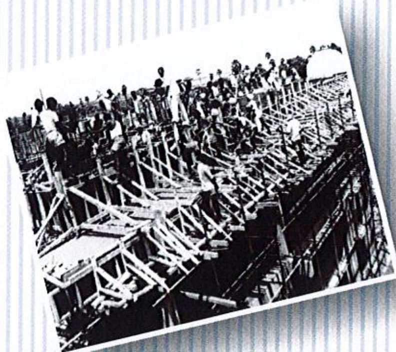
Concrete cells are equipped to handle complete FBTR fuel subassembly of 1.6 m in length & 16 kg weight whereas lead shielded cells can handle fuel pins or their cut sections only. Each of the first three concrete cells are provided with an in-cell crane and power manipulator, while the rest of the concrete cells are equipped with in-cell crane only.

The electric power to the cells is fed through stainless steel conduits embedded in the inter cell walls. Cables are terminated with leak tight fittings. Three numbers of 'S' shaped stainless steel service pipes with leak tight end fittings are provided on each side of the shielding glass window for routing power / signal cables from/to the cell. These S-pipe openings can also be used to connect a mini glove box to the hot cell when required. Two service sleeves are provided, one on each side of every window, for entry of services like cables, hoses etc. into the cells when specific need arises. These service sleeves are closed using leak tight plugs when not in use.

A circular opening of diameter 900 mm with a leak tight stainless steel sealing door is provided on the rear side of each cell to enable man entry and material transfer. These openings are shielded with mobile high-density concrete blocks mounted on motorized trolleys. The inter-cell transfer system consists of embedded ducts in the inter-cell walls with leak tight doors at the ends of the ducts. Mobile lead shields are provided in front of each door to compensate for the loss of shielding caused by the opening provided in the wall. An opening of 3.2 m x 1 m size is provided on the roof of each cell to enable servicing of in-cell cranes and transfer /maintenance of equipments through the upper isolation area. These are closed with plugs provided with gaskets. Each roof plug also has a cover plate to ensure better leak tightness. A 20/2 t overhead crane is provided in the upper isolation area above the cells to handle the roof plugs. Hot cell -1 is provided with two transfer ports for receipt and despatch of irradiated materials.

Storage wells are provided in the cells for storing irradiated materials/fuel pins/cut sections etc. These are in the form of pits in the floor of the cell with removable lead shielded covers. Steel and lead shields provided around and below the pits compensate the loss of shielding caused by the presence of pits in the floor. These pits have provision to purge inert gas in case the cell atmosphere has to be changed from inert to air atmosphere for maintenance purposes. Quick transfer systems are provided in the operating side of the cell wall to transfer small objects into the cell without disrupting the cell environment and in a leak tight manner.

With all the features as described above, the design of RML hot cell facility was finalised and it paved the way for civil construction in the year 1976.



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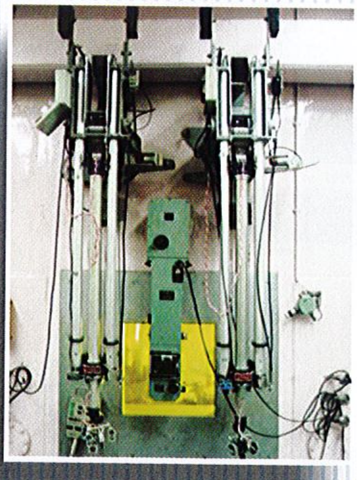
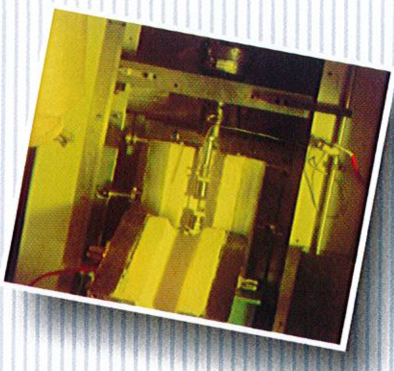


Construction & Commissioning



Construction Phase

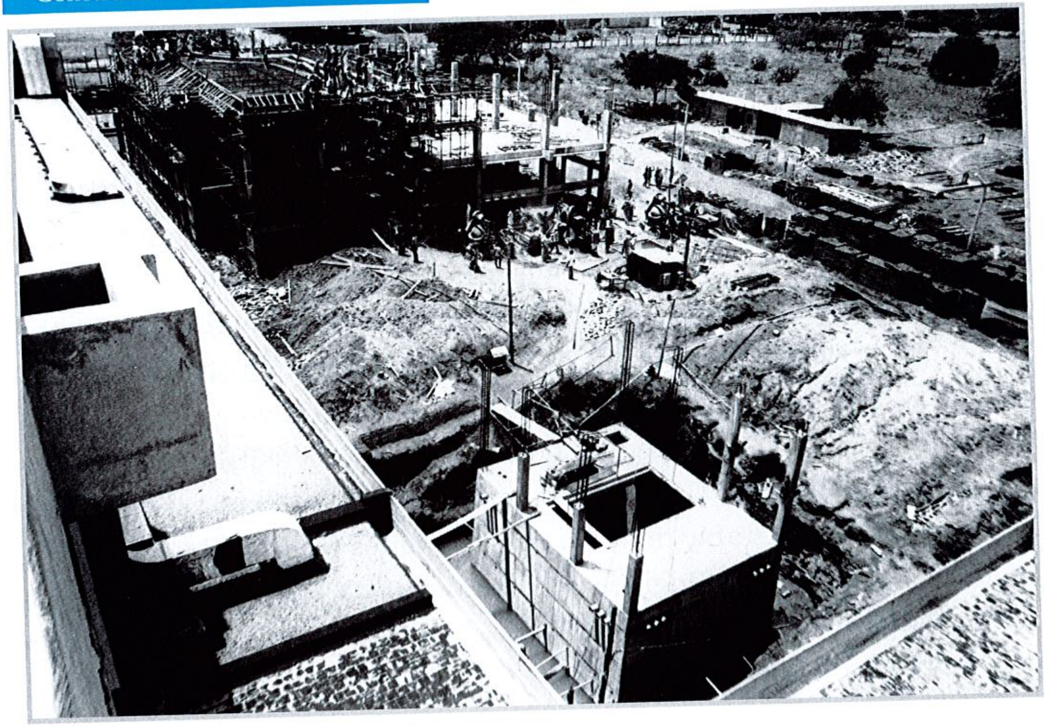
Commissioning Phase

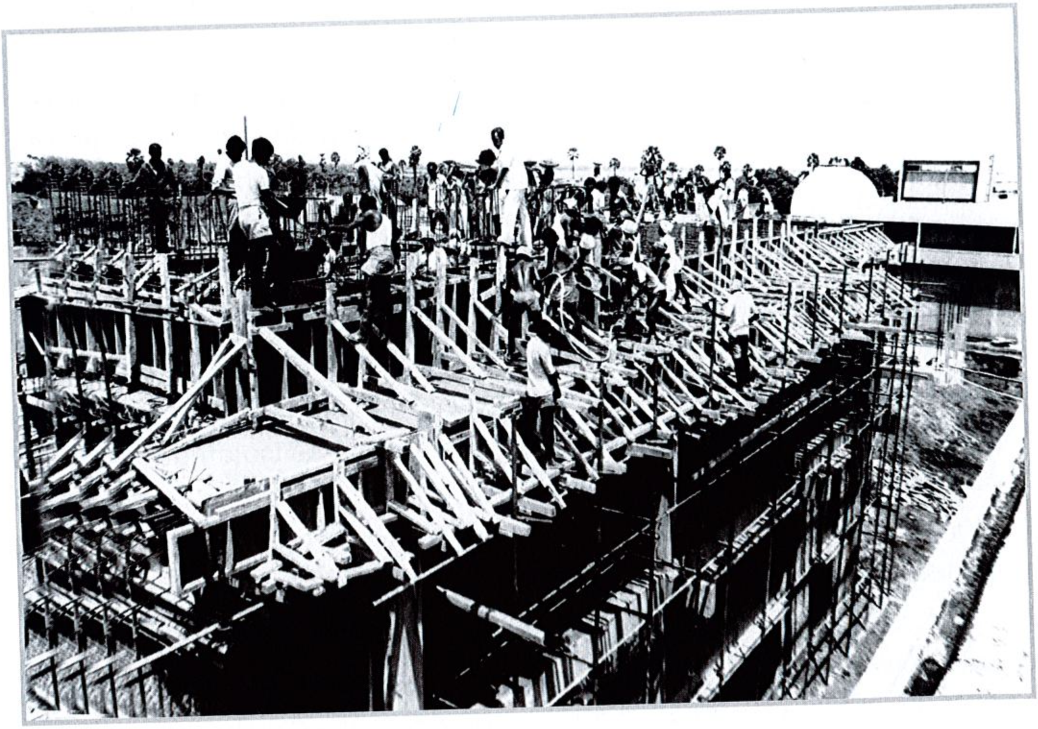
CONSTRUCTION PHASE

RML Building-Civil structures

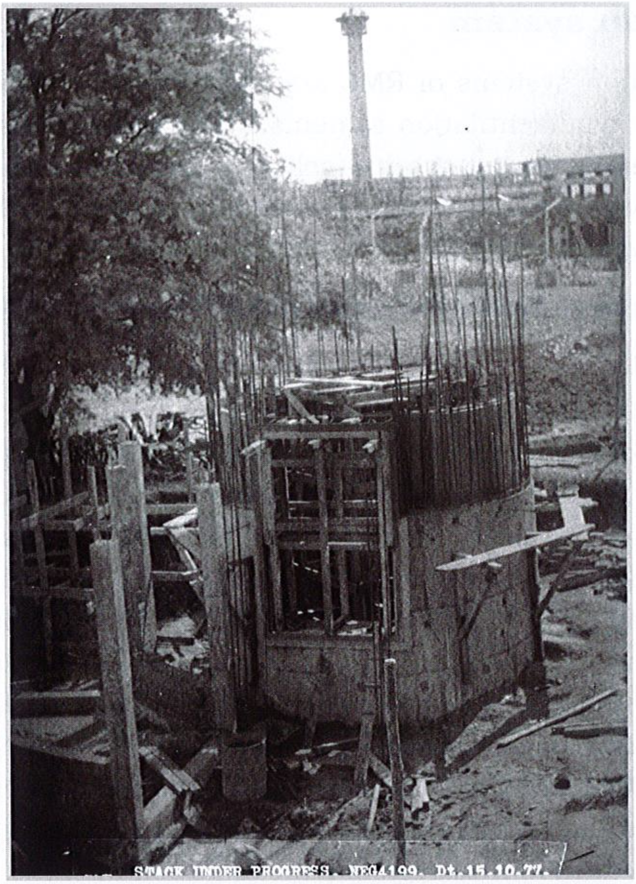
The architectural design of the laboratory was done in collaboration with colleagues from the Civil Engineering Division of BARC. The initial design of air conditioning and ventilation systems were finalised by the Technical Services Division of BARC. The civil structural design and construction was itself a challenging task involving special raft foundations, heavy columns and beams and high density concreting for the cell walls. The hot cell structure involved high density of reinforcement rods. This task was ably done by the colleagues from Civil Engineering Division of IGCAR. Engineering Services Group undertook the construction and commissioning work of the electrical, air conditioning and ventilation system for the laboratory.

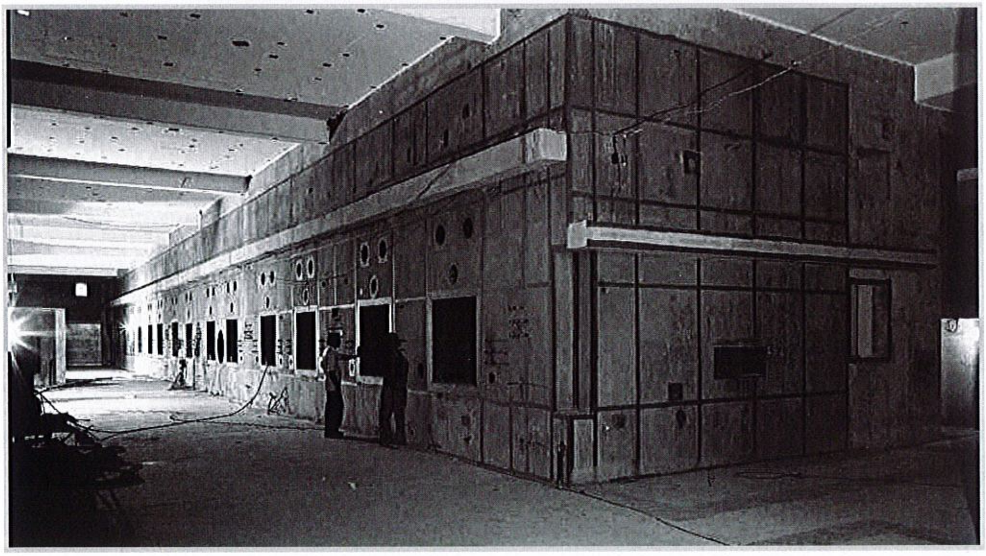
The laboratory is basically built in four structures: the service building, the hot laboratory building, the chilling plant/NDT laboratory building and the mechanical property evaluation building. The service building and the hot laboratory building are separated by a distance of 6 m to prevent transmission of vibrations to the hot laboratory building from the equipment in the service building. The hot laboratory building is a two-storied structure with a total plinth area of 3500 m^2. The boundary walls and floor of all areas located below ground level have been provided with water proofing treatment. Adequate storm water drainage system has been provided around the RML building to prevent water logging and entry of storm water into the building. All isolated columns of the building have been founded at a depth of 2 m below ground level where the soil bearing capacity was found to be 20 t/m^2. The basement is provided with a common raft foundation at a depth of 5.5 m below ground level where the soil bearing capacity was found to be 25 t/m^2. The common ventilation stack for RML and FBTR rises 65 m above the ground level and has been founded on an octagonal raft at a depth of 4.2 m below ground level.





RML under construction





RML under construction

Ventilation system

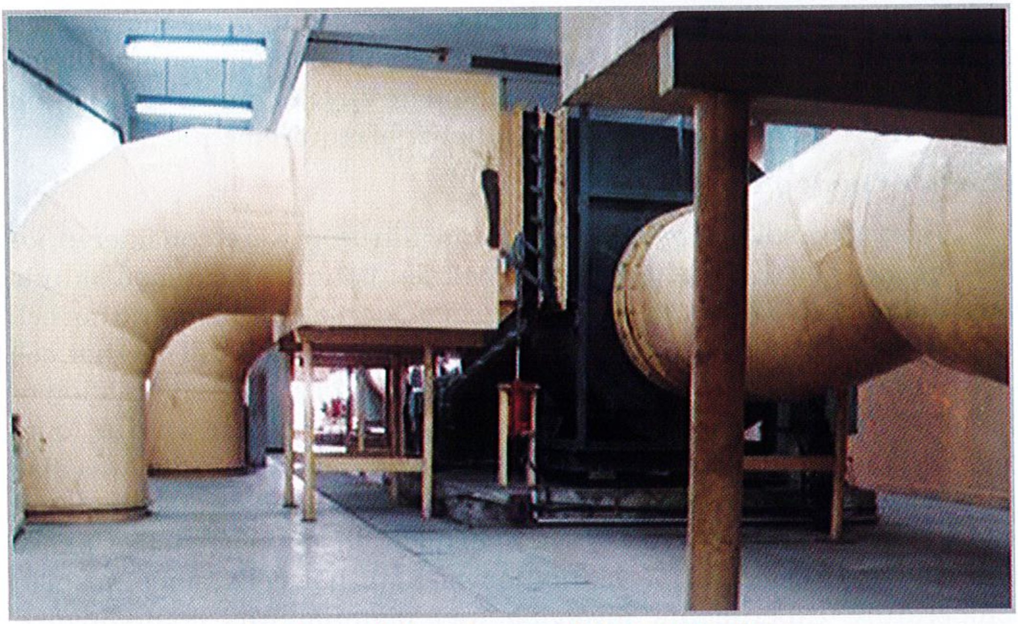
Ventilation systems of RML are categorized as once through and recirculatory type ventilation systems. All radioactive and potentially radioactive areas except the hot cells are provided with once through ventilation system whereas the hot cells are provided with recirculatory ventilation system.

Ventilation of radioactive areas other than hot cells

Ventilation system of RML is divided into four supply systems and three exhaust systems. A total of 1,45,000 m^3/hr of air is supplied to RML and a total of 1,60,000 m^3/hr of air is exhausted from RML. This takes care of the dynamic ventilation of the radioactive areas in RML. All these systems are once through systems where the air supplied is exhausted through the stack to the atmosphere after filtration by the corresponding exhaust systems. Both supply and exhaust systems are provided with filter banks consisting of pre-filters and HEPA filters. The HEPA filters have a filtration efficiency of 99.97% down to a particle size of 0.3 micron. The air is supplied and exhausted by separate centrifugal fans with 100% standby. The number of *air changes* for each area is decided by its zone classification. The air changes specified for some of the critical areas in RML are given in the table below:

Sl. No.	Area	No. of air changes per hour
1.	Highbay area	20
2.	Underground	10
3.	Basement corridor	10
4.	Upper warm work	20
5.	Operating area	12
6.	Lower isolation	10
7.	Upper isolation	10
8	Active laboratories	12

Air changes per hour is a value representing the number of times each hour an enclosure's total volume of air is exchanged with fresh or filtered air. The number of air changes determines the degree of air cleaning that can be achieved preventing accumulation of airborne activity.



A view of the air ventilation System

Out of the 4 supply systems, 2 systems supply conditioned air at 24°C & 55% RH. Chilled water is used in the cooling coils of these systems. The other 2 supply systems supply only fresh filtered air.

Ventilation system for the hot cells

The fuel originally proposed for FBTR was $(U_{0.8}\ Pu_{0.2})O_2$ with 85% enrichment in uranium which does not require inert atmosphere for handling during PIE. Hence once through air ventilation system was conceived and constructed. Later, plutonium rich mixed carbide fuel $(U_{0.3}\ Pu_{0.7})C$ was chosen as driver fuel for FBTR due to difficulty in sourcing enriched uranium required for the mixed oxide fuel. Since the carbide fuel is highly reactive with oxygen and moisture and the reaction is highly exothermic (pyrophoric in nature), it became necessary to provide inert gas ventilation for the hot cells. This is to avoid degradation of the fuel cut sections during metallography as well as to prevent fire in the hot cells in case of failure of the fuel pins during PIE. The inert atmosphere will be also beneficial to avoid fire hazard due to the reaction between the residual sodium trapped in the fuel subassemblies and air atmosphere in the cell. The once through air ventilation system provided for the hot cells of RML had to be changed to a recirculatory type ventilation with inert atmosphere. Retrofitting an existing facility with entirely new piping system and equipments for the recirculatory type ventilation system posed challenges in the design and execution of the project. Selection of pipe sizes, piping/equipment layout and pipe supports had to be done with utmost care to accommodate all the components within the restricted access meeting all the functional requirements.

Choice of inert gas

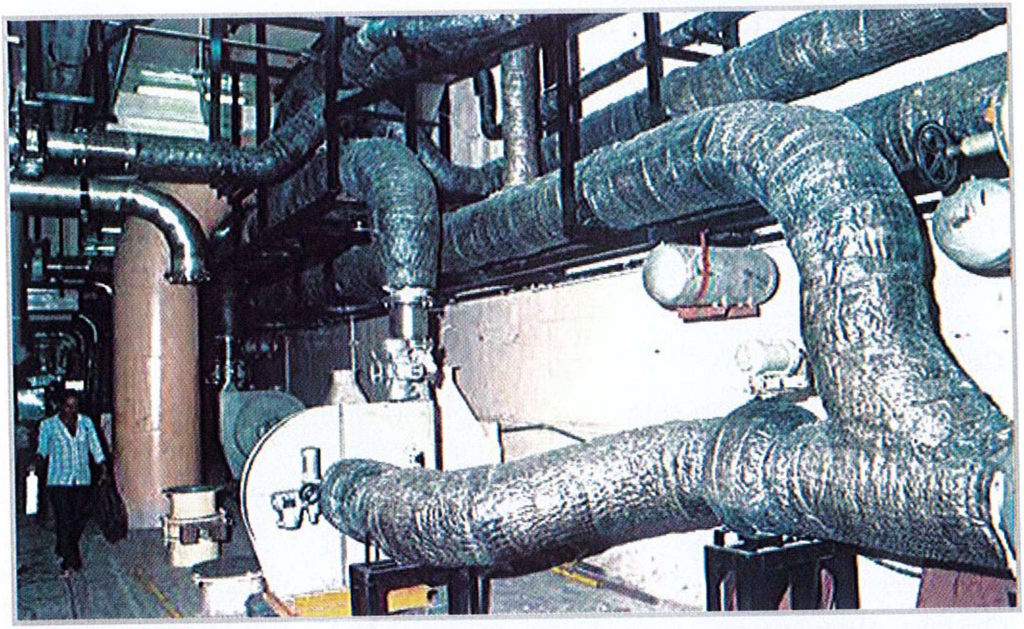
Inert gases like Argon, Helium and Nitrogen were considered for RML hot cells by the task force on hot cell ventilation. An extensive study was undertaken before choosing the correct inert medium for the hot cell ventilation. Taskforce also carried out a detailed survey of the hot cell environment adopted by various facilities elsewhere for examination of carbide, nitride and metallic fuels. Helium was not chosen due to its higher cost, limited availability and difficulty to contain. Argon was also not selected since it has poor dielectric strength, low specific heat and higher operational cost. Even though nitrogen gas is reactive above 450°C, it was selected for ventilation of RML hot cells since no high temperature experiments involving fuel material was contemplated during PIE. Operational experience at Karlsruhe Institute of Technology, Germany with nitrogen atmosphere in the hot cells indicated that it can be used without any undesirable consequences. Taskforce also concluded that even metallic fuels can be examined in a nitrogen filled hot cell if the fuel is cooled for a long duration to bring down the surface temperature of the fuel very close to cell gas temperature.

Inert gas system piping work

To ensure high purity inert atmosphere inside the hot cells, stainless steel was chosen for piping and equipment in the inert gas system. The stringent quality requirements were met by careful selection of welding parameters, procedure and care taken during each stages of construction. Leak testing was successfully carried out for the entire piping and equipments using a helium- nitrogen mixture at a pressure of 20 kPa.

Inert gas recirculation and purification system

General philosophy followed for any radioactive laboratory is to provide once through ventilation to avoid build up of air activity. With nitrogen as inert medium in the hot cells, it was not affordable to have once through ventilation system. Hence it was decided to have recirculatory type ventilation and to maintain hot cells under a nominal



A view of the inert gas recirculation systems

negative pressure of 25 mm water column with respect to operating area pressure. To prevent activity build up in the cells, it was decided to provide 10-15 gas changes per hour ventilation with absolute filtration, in recirculatory mode. Hence, dispersion of radioactivity to outside is not expected. A low moisture and oxygen content (100 ppm) in the nitrogen atmosphere is needed to avoid degradation of metallographic cut cross sections of the fuel. Hot cells atmosphere with very low moisture content can make it difficult to operate some brush type motors. To avoid this problem, a minimum moisture level of 45 ppm was specified for the hot cells.

Since the leakage of air into the hot cell could not be completely avoided, provision was made for removal of oxygen and moisture from the cell atmosphere by injecting stoichiometric quantity of hydrogen into the purification loop and passing this gas mixture through a catalyst bed. The moisture formed as a result of chemical reaction of hydrogen with oxygen and moisture contained in the cell gas is removed by adsorption in a dual bed molecular sieve column. Accommodating purification beds such as catalyst bed, molecular sieve bed, silica gel bed & various other components such as electric heater, hermetically sealed blowers etc. in the limited space was a challenging task.

Salient features of inert gas ventilation system for Hot Cells of RML

No. of Hot Cells:	:	Seven concrete cells and two lead cells
Total cell volume:	:	320 m^3
Leak rate of hot cells:	:	< 0.05 % of cell volume per hour
Cell Gas:	:	Nitrogen
Nitrogen recirculation rate	:	4000 Nominal m^3/h
No. of gas changes per hour	:	12
Cell pressure range:	:	(-) 15 to (-) 40 mm WG
Cell temperature range:	:	20 to 40°C
Cell Pressure control	:	By gas bleed/feed arrangement
Oxygen & moisture	:	max. 100 ppm each
Control of moisture	:	Silica gel bed / Molecular sieve bed
Nitrogen gas recirculation control	:	By Variable Frequency Drive for the recirculation fan motors
Filtration of Cell exhaust air/gas	:	Three stage HEPA filters

Cell gas cooling system

Due to acute space constraints, a low temperature brine of ethylene glycol with water was chosen for cell gas cooling instead of chilled water. Due to very low eutectic temperature of ethylene glycol brine, sizes of pipes and equipments such as cooling coils and hermetically sealed blowers could be reduced considerably. The sizes of the finally designed equipments could be brought down to nearly 1/3rd due to the above choice.

Evolution of instrumentation and control systems in RML

Recirculatory type of ventilation system for the hot cells consists of hermetically sealed blowers, filters, cooling systems, instrumentation and controls.

The instrumentation and control systems maintain the required negative pressure, temperature, moisture and oxygen levels in the hot cells within the desired limits. The continuous monitoring and control of various process parameters such as cell pressure, temperature, oxygen, moisture and radiation levels, is essential for the effective functioning of the inert gas system. The pressure control of the inert gas recirculation system was initially manually operated type. Currently the system has been upgraded to a differential pressure transmitter based automatic electronic control known as "feed and bleed controller". This controller gets input from a differential pressure transmitter (4 to 20 mA) and controls the loop pressure between -18mm and -25mm of water column. In this system fresh nitrogen is continuously introduced into the hot cells (feed) and a similar quantity of gas is simultaneously drained out (bleed) of the system. Bleed also includes the volume of air entering into the cell by leakage. This arrangement helps in scavenging air ingress and maintains the pressure inside the hot cells within the required range through automatic control of the feed and bleed valves.

Initially, most of the hot cell parameters were logged and controlled manually. Hardware based 64 channel data logger was first used for this purpose. The complexity involved and the nature of the signal conditioning requirements necessitated the design and development of a dedicated computer based data acquisition system which has evolved into the current intelligent 360 channel multi zone distributed system with alarms, trending and histogram facilities. The current system logs the cell parameters like temperature, pressure, oxygen, moisture as well as radiation parameters from area gamma monitors, continuous air monitors and stack monitor. This system also logs various critical parameters of electrical systems and supply & exhaust systems status, pressure drop across filter banks, etc. This system is split in to six zones of 60 channels each and is connected to the control room through fiber optic and ethernet links.

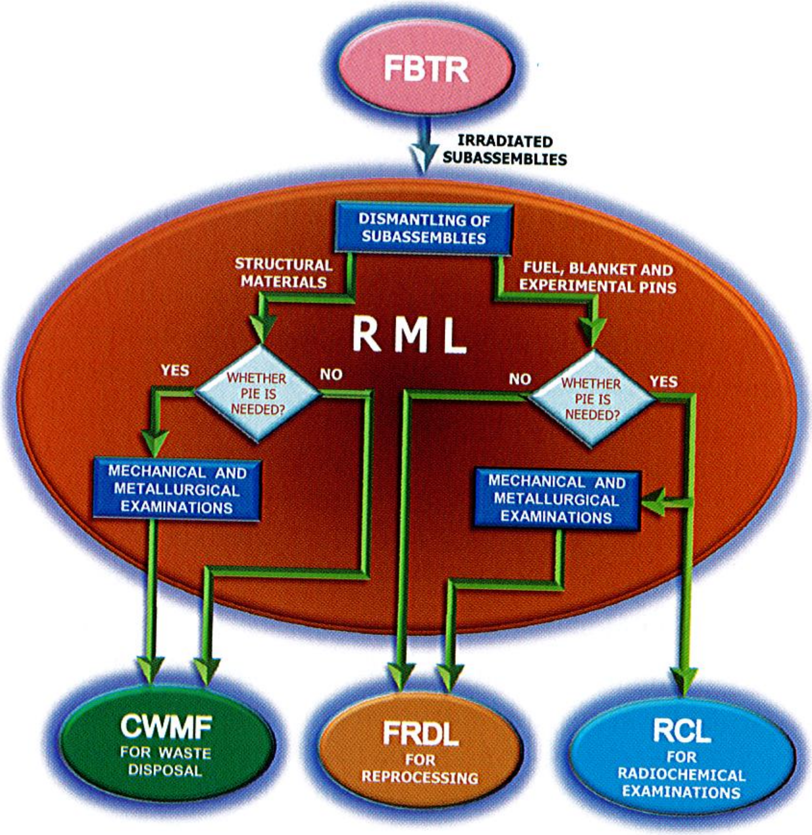
As the various plants and systems are located in different buildings and are not easily accessible during night shifts, surveillance cameras with CCTV system have been installed in all important locations covering most of the equipments. This system has 32 PTZ cameras linked through fiber optic & ethernet to the control room to a high capacity redundant storage and display system with alarm provision.

Irradiated material transfer systems

The movement of radioactive material in/out of the RML hot cells is through sealed *transfer systems.*

A schematic of the movement of the irradiated fuel and structural materials between RML and other radiological facilities is shown. Two fuel transfer systems have been installed in the concrete cell no 1 namely, Vertical Transfer System (VTS) on the cell floor leading to the underground trench and Horizontal Transfer System (HTS) on the northern wall facing the highbay area.

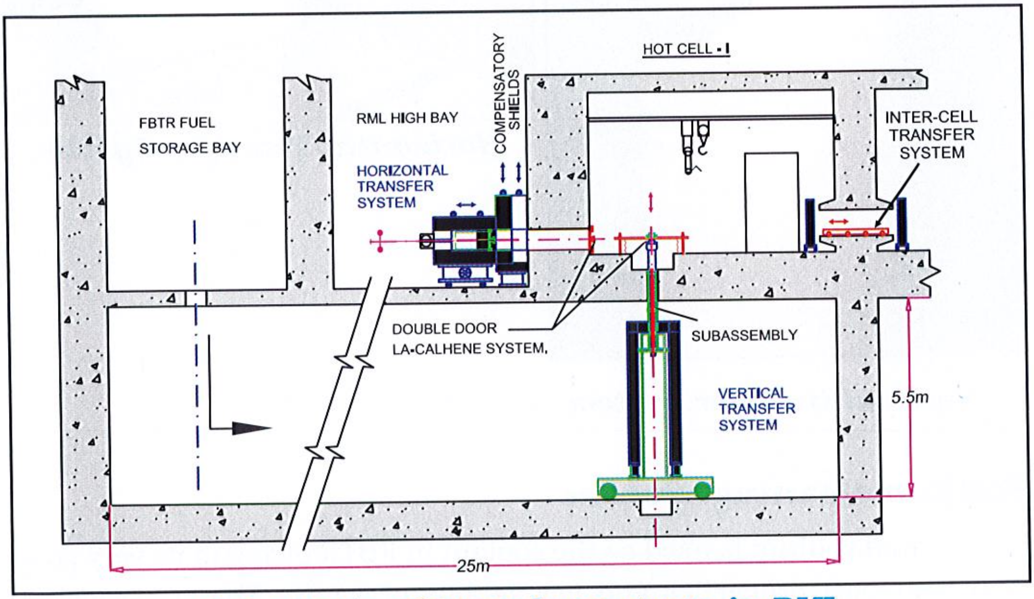
Transfer systems enable transfer of highly radioactive materials between two shielded facilities (such as hot cells) without breach of containment, spread of contamination and radiation exposure. For transfer of alpha bearing materials, a shielded double door transfer system with a leak tight container is commonly employed.



The movement of radioactive materials in/out of RML

Both the transfer systems are based on 'La-Calhene' method of transferring radioactive material in a leak tight manner. This method uses a double door system for transfer of materials in both directions without breaching the containment and shielding requirements.

The irradiated subassemblies from FBTR are received into RML concrete cell-1 through the VTS. The fuel assembly is transported in a shielded cask running on rails in the underground trench between RML and FBTR. The shielded cask contains a special pot with a leak tight La-Calhene lid into which the irradiated subassemblies are loaded at FBTR side. The movement of the cask is controlled remotely from RML operating area and monitored by a CCTV camera installed in the trench.



Schematic of transfer systems in RML

An opening from the underground trench leads to the floor of cell -1 where the pot containing the subassembly is aligned with the VTS and the subassembly is transferred from the pot into the cell in a leak tight manner.

HTS is used for transferring irradiated materials (like fuel pins/cut portions of fuel pins/highly radioactive wastes) through a sealed container in a shielded cask, from RML hot cell to Radiochemistry laboratory (RCL) / Reprocessing laboratory (RDL) / Centralised Waste Management Facility (CWMF).

Vertical transfer system

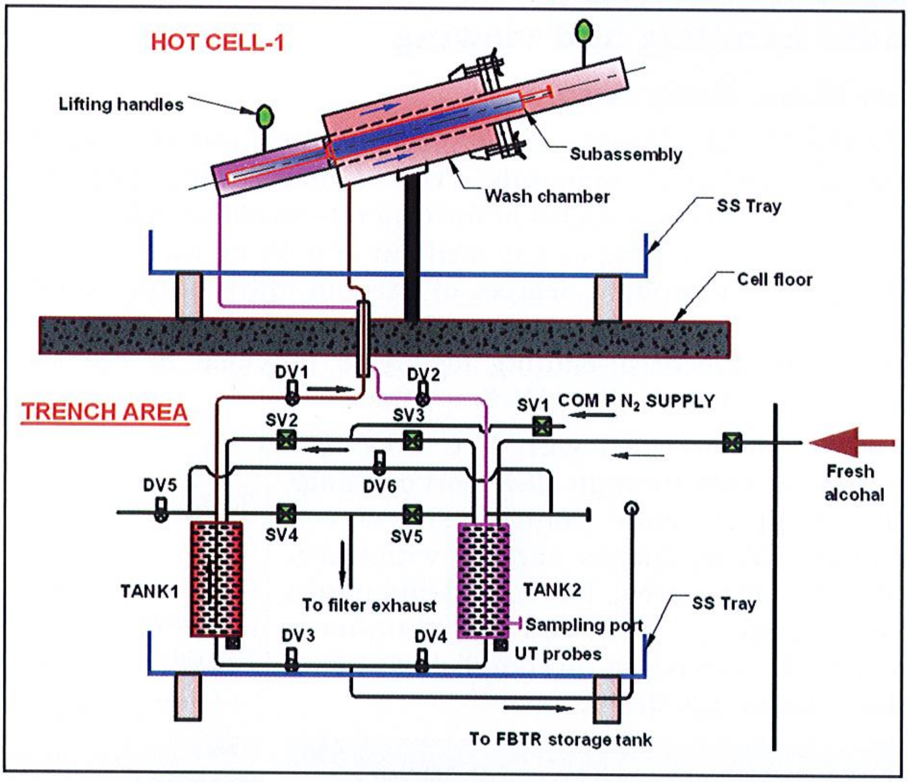
Horizontal Transfer System

Sodium cleaning system

Liquid sodium is used as the coolant in FBTR owing to its very good heat transport properties and low vapour pressure. The subassembly discharged from the reactor will have sodium trapped in the internals which needs to be removed before carrying out PIE. For this a sodium removal system has been designed and installed in the hot cells.

A detailed study was conducted on various options of the cleaning media like steam-inert gas mixture, vacuum distillation, alcohol cleaning etc. After considering various options and detailed analysis, alcohol cleaning using 99.9 % pure ethanol was chosen for the removal of residual sodium due to its ease of operation.

The sodium cleaning system consists of an inclined chamber into which the fuel subassembly is loaded and alcohol is circulated through



Schematic of sodium cleaning system

the chamber connected to two SS tanks housed in the underground trench. Compressed nitrogen with solenoid valves is used for circulating alcohol between the tanks and the cleaning chamber. The system is controlled remotely from the operating area.

The system has been designed in such a way that during the flow in one direction say from tank 1 to tank 2, the alcohol cleans the external surface of the subassembly, while in the other direction, it passes through the inner regions of the subassembly and cleans the surfaces of the internals like fuel pins. Provision also exists for holding alcohol in the chamber for soaking the subassembly to facilitate dissolution of large deposits of sodium, if any, in the internals.

The flow of the alcohol is monitored using ultrasonic level indicators fixed on the tanks and its temperature is sensed using a thermocouple attached to the tanks. A separate pipeline runs from the SS tanks to the medium level effluent tank of FBTR for pumping out the used alcohol.

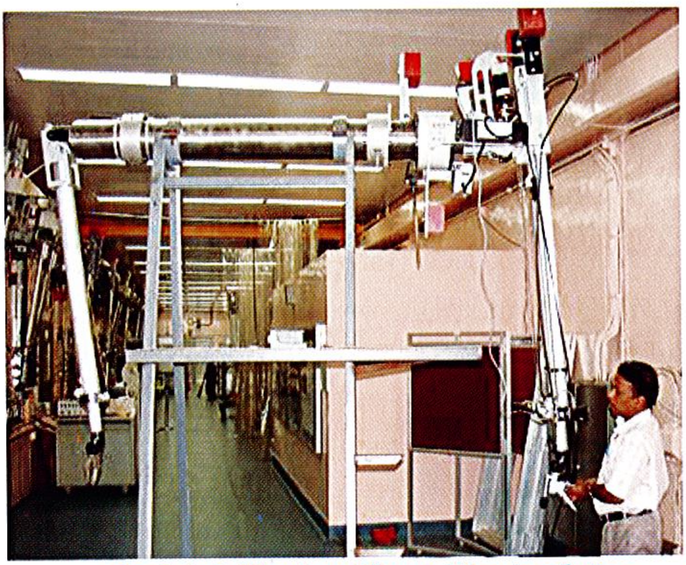
Remote handling and viewing

Master Slave Manipulators

Remote handling and viewing plays a crucial role in handling and examining irradiated materials. The widely used Model-8 type manipulator has been installed in the concrete shielded cells. They have a capacity to handle 9 kg in any position and 45 kg with load hook. It possesses six independent degrees of freedom, three of translation and three of rotation to position the gripping device and a tong squeeze motion to grip items. Electrical-canting facility is provided in the MSM to enhance the reach in the X and Y directions.

MSMs are provided with PVC *bootings* to arrest the leak path through MSM port openings thereby ensuring static containment of cell atmosphere. Manipulators can be withdrawn into the operating area, for any maintenance without breaking the cell containment. Changing of booting is accomplished using standard ejector type device.

Booting: A flexible sleeve covering the slave arm, to protect them from contamination and provide leak tightness to the hot cell.

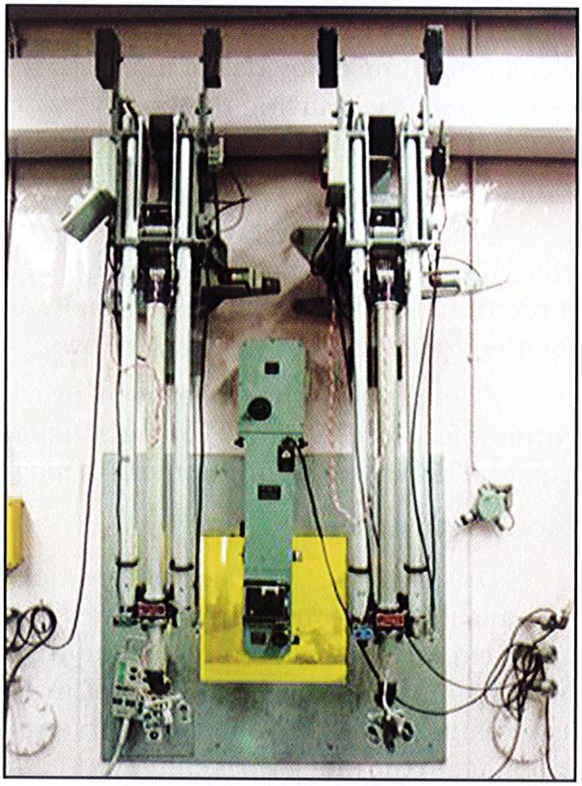


Model 8 Master Slave Manipulator

Booting fixed in the slave arm of the manipulator

Power manipulators and in-cell crane

Power manipulators are provided in the first three concrete cells which can handle 50 kg load. For handling higher loads beyond the capacity of MSM and power manipulators, 2 t in-cell crane is provided in all the concrete cells. In-cell crane is in the same gantry on which power manipulator is installed. The cranes have been designed such that the different parts are modular and the hoist portion can be withdrawn into the upper isolation area through the roof plug opening of the cell for carrying out maintenance without the need for man entry into the cell. For ease of maintenance, the Long Travel (LT) motors of the in-cell cranes are located outside the cell area.



View of the hot cell with shielding glass window and MSM

Shielding glass window & periscope

Radiation Shielding Windows (RSW) are intended to provide clear, undistorted, in-cell viewing while providing radiation protection with shielding equivalent to the concrete cell wall. The shielding window glass is made of various minerals to produce desired density, light transmission, resistance to discolorations /browning due to gamma dose and other desirable properties. Lead added in the form of lead oxide (PbO) increases the density of glass to improve the shielding property. An average density of 3.5 g/cc is maintained while selecting the properties of glass slabs used for assembling the window.

Two shielding glass windows are provided on the front wall of each cell. These windows are dry glass type of windows. The window consists of a steel frame in which radiation resistant glass slabs of thickness up to 275 mm are assembled. A separate 25 mm thick α tight cerium stabilized radiation resistant glass slab is fixed on the hot side wall of each window-opening with gaskets to prevent leakage of any particulate from the cells into the operating area. Cerium oxide content helps in stabilizing the glass from discoloration due to radiation exposure. The possibility of *dielectric discharge* in shielding glass is minimised by use of many layers of glasses having thickness not exceeding 100 mm each in hot side.

> *A dielectric discharge from shielding glass window is an instantaneous flow of electrical current to ground causing severe damage to the glass. This results from the generation and build up of electron-ion pairs in the glass by exposure to gamma radiation.*

Handling and erection of shielding glass assembly weighing more than 8 t was a challenging task. Air pallets were used successfully for erection of shielding glass windows.

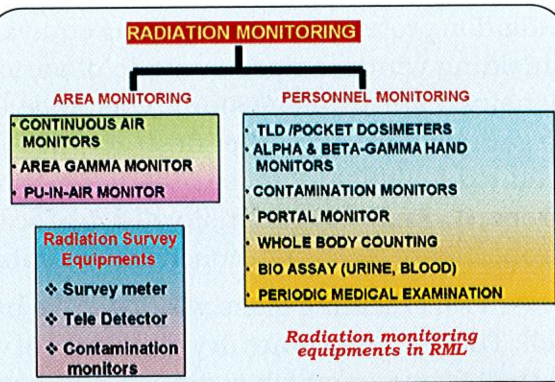
Nuclear periscope has been provided above each shielding glass window for close viewing of objects inside the cell. This has provisions for pan and tilt as well as adjustment of magnification.

Mock up facility

During the initial period of hot cell construction and commissioning, a mock up cell was constructed in Engineering Hall #2 to gain experience in remote handling using Model 8 Master Slave Manipulators as well as testing of in-cell equipments for remotization. Two pairs of MSMs, one power manipulator and one periscope were installed in the mock up facility.

Radiation safety systems

Many radiological safety equipment for personnel monitoring like α and β γ hand monitors, contamination monitors, dosimeters, portal monitors as well as area monitors like area γ monitors, α and β continuous air monitors, survey meters, stack monitoring system, tele-detectors and counting systems are in service and they are part of the overall safety requirements to ensure radiological safety of the personnel, plant and environment.



Radiation monitoring equipments in RML

Personnel using hand monitor

Waste handling

Various provisions exist in the laboratory for handling and safe disposal of radioactive wastes generated during routine operations.

Solid wastes originating from hot cells and its interfaces such as glove boxes and fumehoods having low beta, gamma activity are segregated, packed in steel drums and stored in the transit storage room located in the highbay area. These are subsequently transported to CWMF in a truck. Special shielded containers/cask are used for transferring high beta, gamma activity wastes like cut portions of subassemblies etc. from the hot cells. Alpha bearing wastes are transported in sealed containers using double door alpha tight transfer system. Activity content of the waste is estimated from the surface dose rate and density of the packages.

Low level liquid effluents generated from various areas (shower and hand wash) of RML flow through High Density Poly Ethylene (HDPE) pipelines to the underground delay tanks. They are pumped to CWMF through steel pipes laid above ground. Medium and high level liquid wastes from areas such as decontamination sinks, fumehoods and sodium removal system are transferred to storage tank located in FBTR, through SS pipelines. Provision exists to analyse the activity of the liquid waste in fumehoods.

The exhaust blowers in the once-through ventilation systems of radioactive areas discharge the air to the RCC duct which is connected to 65 m high stack. Intentional bleeding of gas from the nitrogen recirculation loop is also linked to this discharge. Gaseous effluents undergo three stages of filtration before discharge to the stack. Air discharged through the stack is continuously monitored using a sampling pump and radiation detectors.

All the activities described above including construction of massive civil structures for hot cell, mechanical, electrical, electronics and instrumentation control and various provision such as radiation safety and waste management were successfully completed in 1980s.

COMMISSIONING PHASE

The commissioning phase started with the testing of ventilation, radiological safety and instrumentation systems to achieve regulatory compliance. The installation of various in-cell equipment for PIE were also carried out in this phase

Radiometry of hot cells

Shielding effectiveness of all the concrete cells were tested by gamma radiometric inspection after its construction. A Cobalt source (Co^{60}) of 9.5 Ci activity was used for radiometry. The source was exposed inside the cell and the attenuated radiation field on the external surfaces of the hot cell was mapped using a scintillation radiation detector to assess the shielding integrity of concrete walls and inter-cell walls. The entire area of the hot cells was covered by moving the source and the detector in tandem. This testing confirmed the effectiveness of shielding of the concrete walls.

Criticality safety study

RML hot cells are designed for handling maximum of two fuel subassemblies at a time considering the operational requirements and various other factors including criticality safety. A detailed theoretical study was done by the safety group to assess the criticality safety of the hot cells in two different conditions: i) two fuel subassemblies without dismantling and ii) fuel pins after dismantling of the fuel subassemblies. The theoretical calculations done considering a worst case scenario of the fuel pins in water flooded condition (water acts as moderator which increases the probability of criticality) indicated clear margins for handling fuel pins worth of two fuel subassemblies.

Leak testing of hot cells

Nitrogen atmosphere was chosen for the RML hot cells for handling the pyrophoric carbide fuel. To maintain the required purity level inside the hot cells and to get good static containment of the hot cell atmosphere, it was necessary to obtain good leak tightness for all the hot cells. The desired purity levels specified were less than 100 ppm of oxygen and 45- 100 ppm of moisture inside the hot cells, under nitrogen atmosphere. To achieve the above purity levels, the overall leak rate in the hot cells had to be brought down to less than 0.05 % volume per hour [1.2 % vol per day].

With many openings / penetrations like fuel transfer ports, roof slab openings, cell sealing door, electrical feed-through, shielding windows, neutron radiography rig and many other service lines, it was really a challenging task to conduct the leak test and to obtain desired leak tightness, before commissioning of the hot cells. Persistent and committed involvement of a large number of colleagues for nearly 6 months led to the achievement of the desired leak tightness of all the hot cells.

The methodology followed for determining the leak rate was to evacuate the cells to a negative pressure of 150 mm water column [WC] with respect to surrounding area and monitor the pressure change as a function of time. The leak rate calculations were done in accordance with ASME–N-510-1980 standard which specifies testing under actual working conditions (negative or positive pressure). This standard was used as the basis as it was seen to be more applicable for the testing of the hot cells which are required to operate at a negative pressure of 25 ± 5mm WC. Initially, the time taken for all the hot cells to attain the ambient pressure from the test pressure was only a few minutes, indicating huge leakages.

Painstaking efforts were put in by the team for identifying & rectifying various leak paths including the small leakages inside the hot cells. Since all the hot cells have 1200 mm thick concrete wall, it was not possible to conduct meaningful leak testing without man entry inside the cells during the tests. For successful detection of leakages, after entry of personnel inside, the hot cells were sealed and evacuated to a pressure of (-) 150 mm water column and soap solution was applied to all the suspected leak paths. This procedure was allowed only after careful evaluation of safety of the personnel involved. This method was very effective in detecting all the leak paths.

Another problem encountered during the leak testing campaign was the fluctuations in atmospheric pressure leading to erroneous test results. This drastic un-noticed fluctuations in the atmospheric pressure played havoc for many days. The real cause of error was detected only after many brain storming sessions. Anomaly was related to the variations in the ambient pressure. The ambient pressure at Kalpakkam varies by as much as 50 mm of WC on an average in a day. If the test duration is long, say, 8 hours, the ambient pressure variation is seen to affect the leak rate measured as the test is a static pressure decay test and the driving force for leakage increases or decreases depending on the instantaneous ambient pressure. Later the cell pressures were compared with a fully insulated and isolated reference chamber for calculation of the leak rates, thus avoiding the error due to atmospheric pressure fluctuations.

After more than 5 months of continuous efforts, all the hot cells showed leak rates less than 0.02 % vol per hour against the requirement of 0.05 % vol /hr.

Safety review and regulatory approval

Before becoming operational, any radioactive facility has to prepare a detailed hazard evaluation report and undergo a thorough safety review by the Atomic Energy Regulatory Board (AERB). The safety assessment working group of AERB reviewed the design and operational safety aspects of the hot cell facilities. The review included the shielding integrity of the cells, fuel transport systems and leak tightness of the cells. The recommendations of the working group were implemented. All the features and facilities were found to meet the required specifications by the regulators. A detailed hazard evaluation report and operating procedures of the important systems were also prepared. Based on the extensive safety review, the regulatory board gave the authorization to operationalise the hot cells.

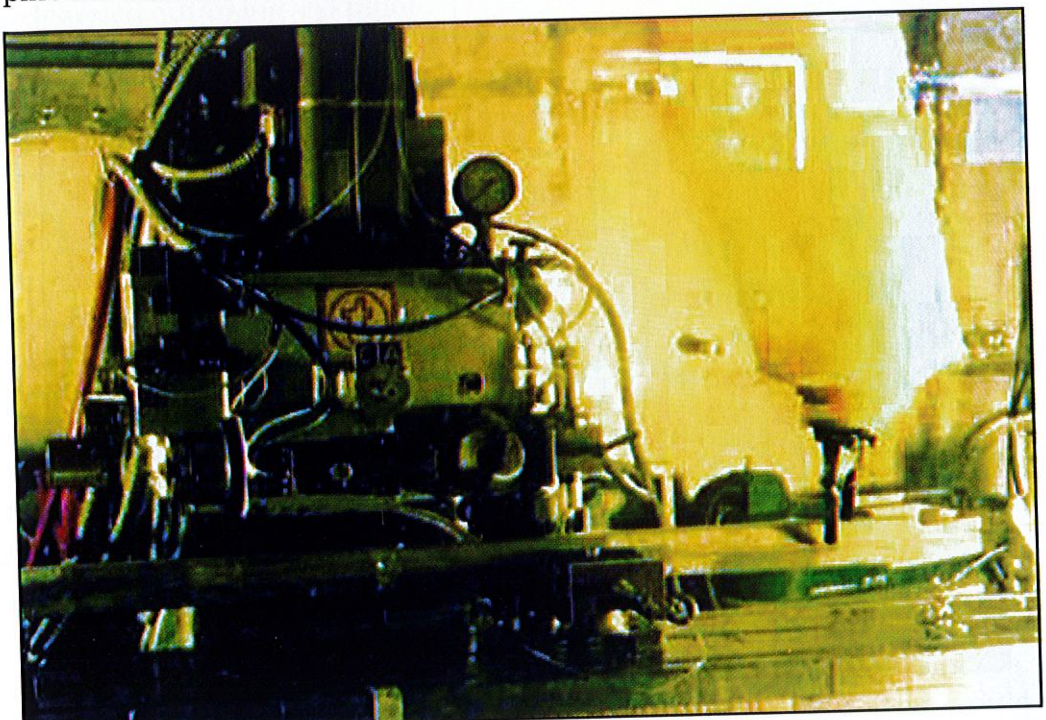
In-cell equipment for PIE

The techniques employed in PIE cover a wide spectrum of non-destructive as well as destructive examinations used in a logical sequence with an objective to obtain unambiguous conclusions regarding the irradiation behavior of materials with reliability and accuracy. The techniques include visual and metrological examinations, eddy current testing, X-ray & neutron radiography, gamma scanning, metallography of the fuel, fission gas release, optical and electron microscopy of the fuel and structural materials, mechanical testing including miniature specimen testing of clad/wrapper, void swelling estimation etc. The equipment for carrying out such examinations form the backbone of any hot cell facility.

Considering the various requirements of PIE of the FBTR fuel and experimental pins, many prototype equipment were developed indigenously. Most of the in-cell equipment were developed with painstaking prototype building, mock up trials prior to their installation and validation. Since many of the equipment procured were not directly amenable for remote handling, they were modified suitably before installation. The following section briefly describes various in-cell equipment successfully designed, developed, installed and operated in the RML hot cells over the years since the commissioning of the facility.

Dimensional measurements systems (Metrology)

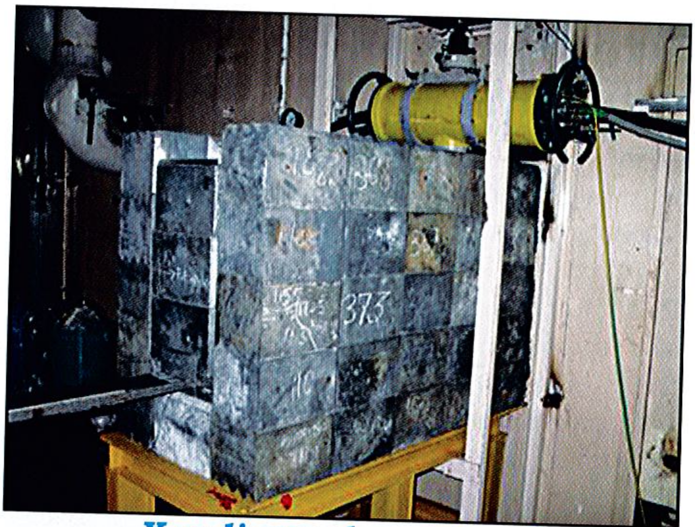
Dimensional measurement of the FBTR fuel subassembly and fuel pins constitute an essential part of the PIE. This is because, the changes in the dimensions of the hexagonal wrapper have a direct bearing on the fuel handling operations in the reactor, while increase in dimensions of fuel pins can affect the coolant flow and bundle hydraulics caused by the bundle-duct interaction. The main dimensional measurement of the hexagonal wrapper include the head to foot misalignment (bowing), variation in width across flats & corner-to-corner distance, while the fuel pins are examined for diameter and length changes.



CNC Milling-cum-Cutting Machine in the hot cell test, the impedance change in a coil due to interaction of induced eddy currents with the defect is measured. Eddy current testing of the fuel pins is carried out holding the pin vertically in the stepper motor driven bench and by moving an encircling ECT probe along the length of the fuel pin. The system developed has a sensitivity of detecting defects equivalent to 7 % wall thickness. A PC based data acquisition system is used to acquire the data. Analysis of the data is done by comparing it with the reference data acquired from a calibration pin containing artificial defects of different sizes.

X-Radiography system

X-Radiography of fuel pins give valuable information like variation in fuel pin diameter, increase in fuel stack length, pellet-to-pellet gap, pellet-to-clad gap and abnormalities like chipping and cracking of fuel pellets.



X-radiography system for irradiated fuel pins

For X-radiography of the irradiated fuel pins a leak tight extension of the hot cell into the isolation area was provided using an aluminium tube. The fuel pins are horizontally placed in a carriage and moved into the extended aluminium tube above which the X-ray unit is installed. Adequate shielding is provided around the aluminium tube extension. A sliding tray and cable mechanism is used for instantaneous positioning and retrieval of the X-ray films to minimize the gamma fogging of films and radiation exposure to personnel.

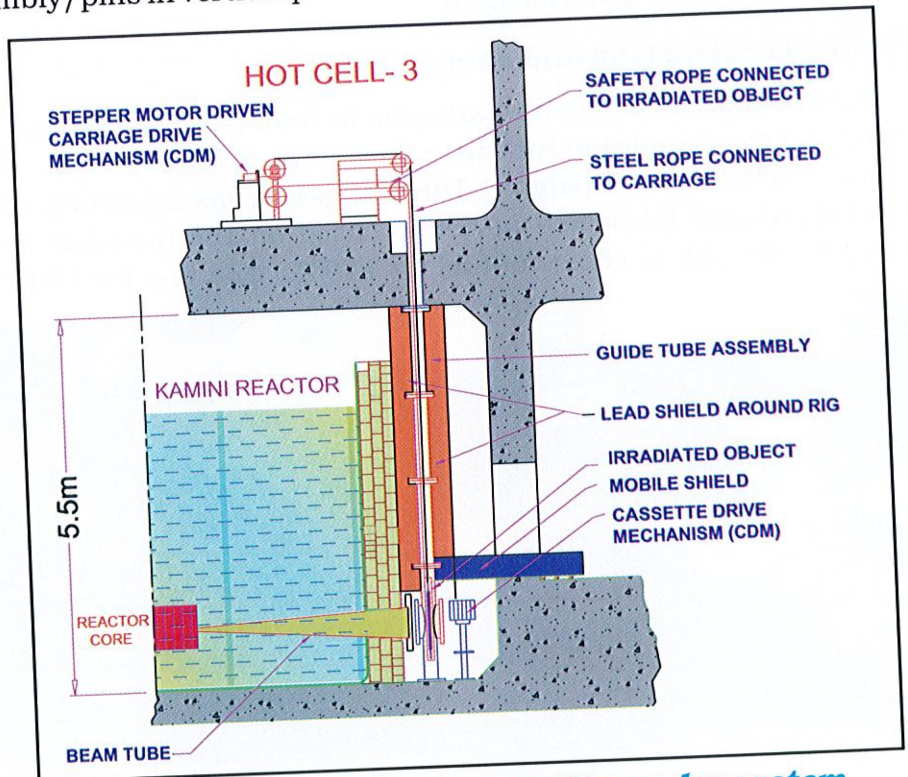
For the X-radiography of the fuel subassembly, provision exists to install a radiography system in the room below one of the hot cells.

Neutron-Radiography system

Neutron radiography is complementary to X-Radiography in that it has different attenuation properties from that of X-rays. It can reveal isotopic constituents and detect lighter elements in a dense matrix

A 30 KWt swimming pool type reactor (KAMINI) installed below the hot cells is used for neutron radiography of the fuel subassembly, fuel pins and control rod assembly. The reactor provides a collimated thermal neutron beam with a flux of 10^7 n/cm^2/sec at the radiography site. Indirect technique with dysprosium/indium foils is employed for imaging the fuel pins and control rods.

A neutron radiography rig connects Cell-3 with the radiography site of KAMINI to enable lowering of irradiated subassemblies/fuel pins. The carriage assembly moving up and down inside the guide tube consists of a rotatable aluminium container which can carry the irradiated fuel sub assembly/pins in vertical position. The carriage has rectangular cut-outs



Schematic of Neutron radiography system on two sides facing the neutron beam to allow neutrons to pass through without attenuation.

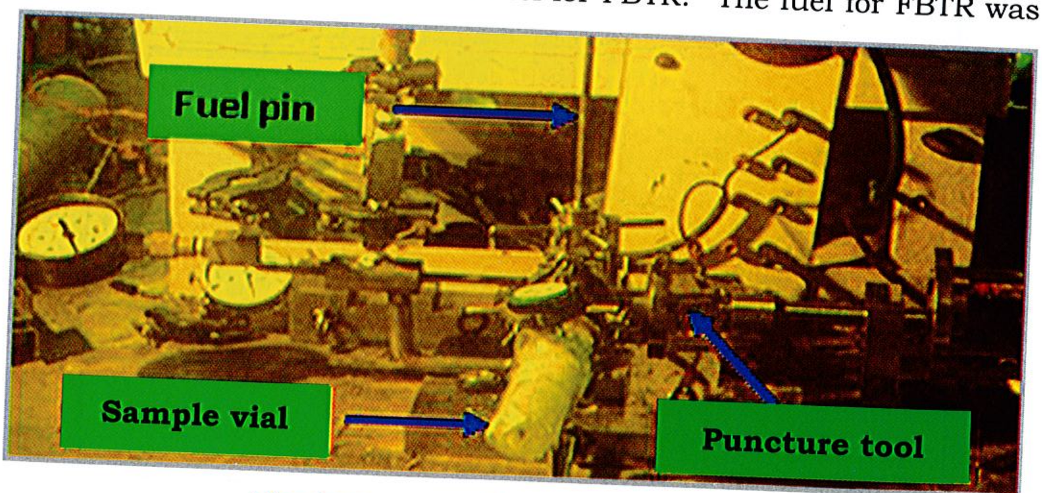
A precise positioning and indexing mechanism (0.5 degree steps) facilitates sequential neutron radiography of fuel pins and fuel subassemblies. Pin to pin spacing, actinide and fission product redistribution in the fuel due to irradiation and depletion of boron in the control rods can be studied using this facility.

A remotely operated cassette drive mechanism having ten cassette holders arranged in a decagonal fashion is made use of for imaging. The cassette drive mechanism has a stepper motor drive for indexing the cassettes in front of the neutron beam window and a central pneumatic cylinder to push forward the cassette holder towards the window to reduce the distance between the object and the film/foil. The cassettes are of top loading type and can be loaded in the required position and retrieved when the reactor is not in operation and no radioactive object is present inside the rig.

Provision also exists for neutron radiography of non radioactive objects directly at the beam location.

Fission gas extraction and analysis

Fission gas extraction and analysis in RML hot cells has matured over the last two decades in tune with the changing requirements during the course of the PIE campaigns. The first fission gas extraction system was designed and fabricated in-house based on the prevalent design philosophy and initial choice of fuel for FBTR. The fuel for FBTR was

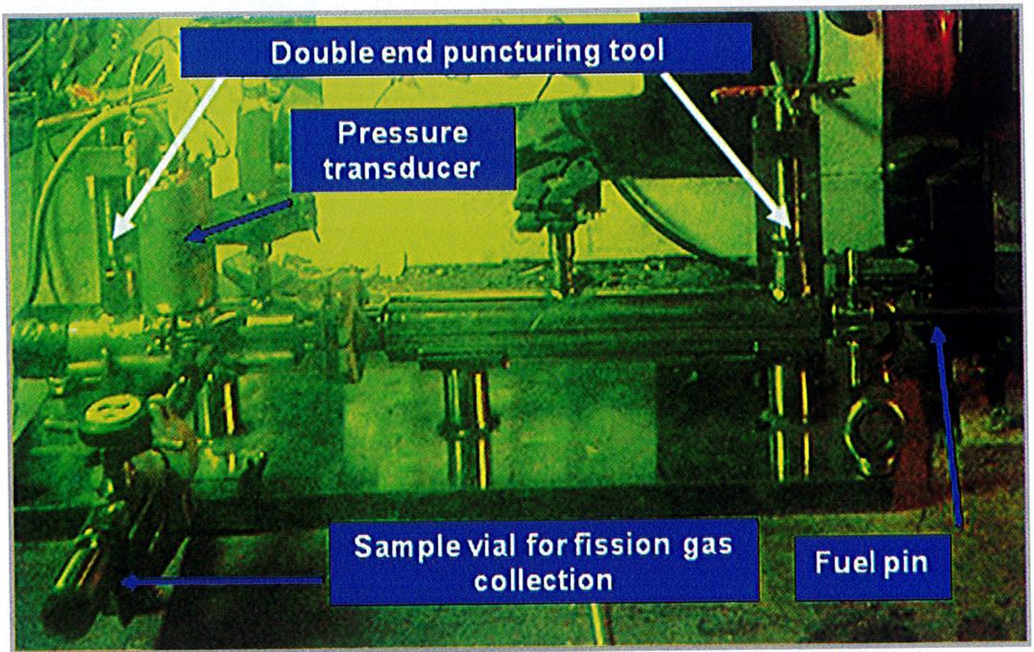


Fission gas extraction system

initially intended to be mixed oxide. The first fuel pin puncture chamber for fission gas extraction was designed with larger void volume since the plenum pressure expected was quite high for the design burnup limit of 50 GWd/t due to high fission gas release in Mixed OXide (MOX) fuels.

Subsequently the FBTR became critical with mixed carbide as driver fuel which is known to have low fission gas release than oxide fuels. It was thought prudent to have a fission gas extraction system with very low dead volume to facilitate higher collection efficiency and reasonable pressure in the sample vial for analysis. This chamber was designed to puncture the fuel pin in one of the plenum regions, either in the top or bottom plenum to collect the released fission gases.

Later a double end fission gas extraction chamber was designed and fabricated for simultaneous puncturing of both the plenums in high burnup fuel pins.



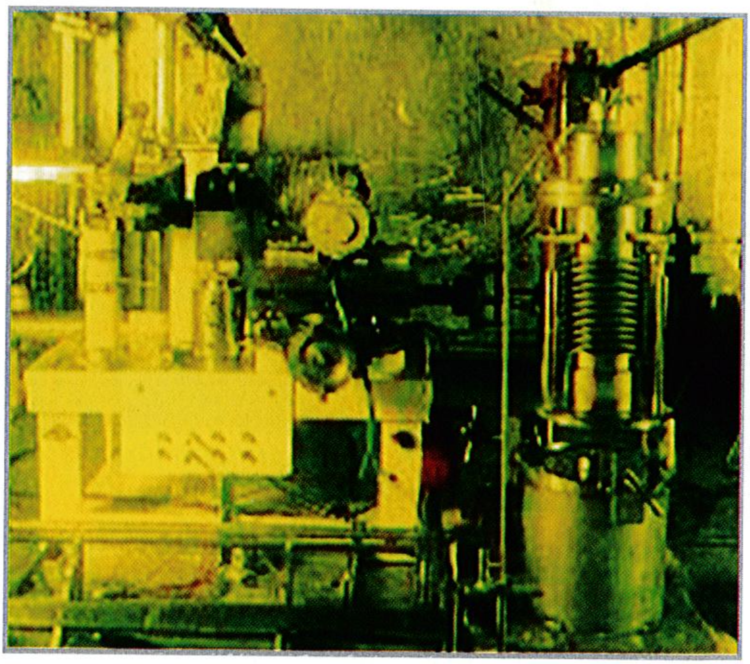
Improved double end fuel pin puncturing system for fission gas extraction

The analysis of the fission gas samples also has evolved along with the improvements in the fission gas extraction system. Since the facility for analysis of fission gas samples was not available at RML initially, the fission gas samples collected in stainless steel vials were decontaminated and transferred to RCL for analysis using mass spectrometry. The need for more statistical data on fission gas release and high alpha contamination on the sample vials necessitated setting up of exclusive facility for sample analysis in RML itself. Gas chromatography system was established to analyze the composition of gases. The choice of hydrogen as carrier gas enabled quantification of helium which essentially is present in the fuel pin as bond gas apart from the helium generated due to alpha decay and ternary fissions.

Remote metallography

Metallography in general is considered more of art than science. Even though remote metallography is similar to the conventional metallography, the challenges involved in the metallography of irradiated materials in the hot cells using remote handling devices and special procedures make it very unique. Pyrophoricity and reactive nature of the carbide fuel makes the specimen preparation more challenging.

Remote metallography of fuel pin involves special techniques like immobilization of the fuel pellets inside the clad using epoxy resin. Immobilisation of fuel column ensures that the pellet does not crack during cutting of fuel pin for extracting metallographic specimens and that cracks appearing in the micrograph are only of in-reactor origin.



Vacuum impregnation system & fuel pin cutting machine

Vacuum impregnation using epoxy resin also serves the purpose of investigation of any defects in the fuel pin detected by NDT through metallographic examinations without disturbing the relative position of the fuel pellets inside the clad.

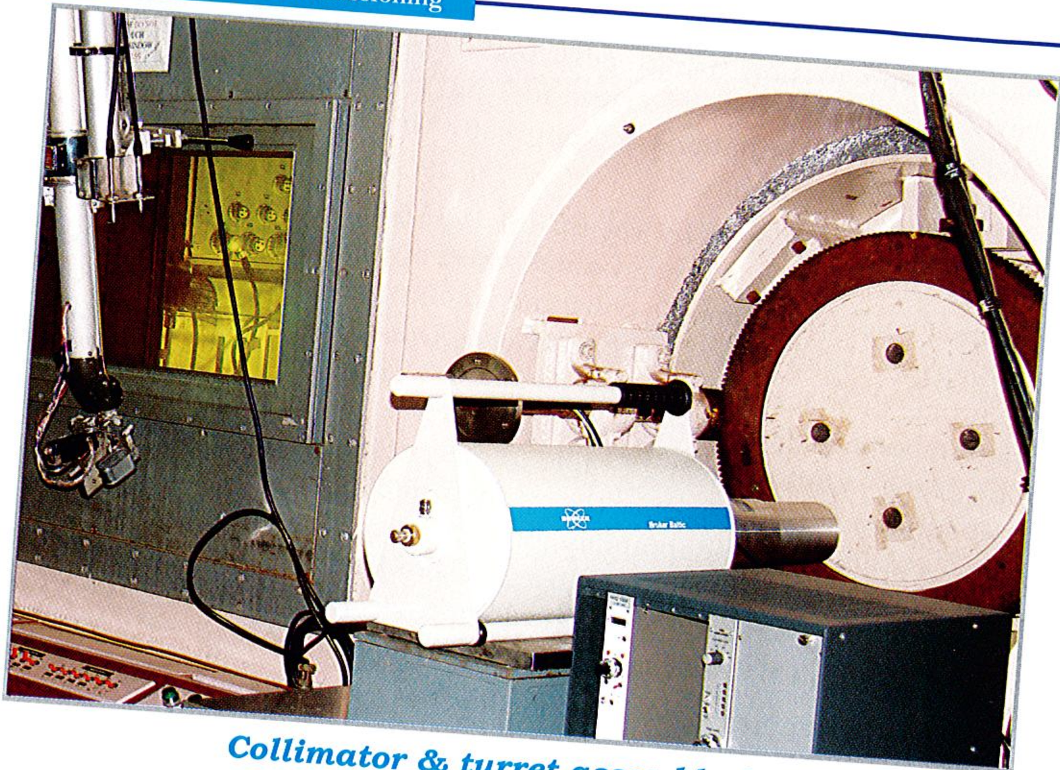
Remote metallography set up in RML hot cells include vacuum impregnation system, diamond wafer wheel cutting machine, electronic weighing balance, automatic polishing machines apart from fixtures for molding and replication of sample surface. Due to the high susceptibility of carbide fuel for oxidation, replication technique was adopted for examination of polished/etched sample surface. Initially replication was done using cellulose acetate tape. Later, silicone rubber replicating compound was used to reduce the artifacts and pickup of contamination apart from its better adaptability for remote applications. Replicas are taken out from the hot cell through a glove box interface, decontaminated and then gold coated for optical microscopy. This ensures the removal/fixation of transferrable contamination on the replicas.

Metallographic preparation facility has been adapted recently for examination of MOX fuel pins of different diameter (6.6 mm) since the existing equipments cater to FBTR fuel pins of 5.1mm diameter. A new vacuum impregnation system was designed and fabricated for metallography of experimental MOX fuel pins of PFBR composition irradiated in FBTR.

Gamma scanning

Gamma scanning is one of the powerful methods for non-destructive examination of irradiated fuel pins. The knowledge of the distribution of fission products in the fuel pin is important for understanding the behaviour of fuel elements during their residence time inside a nuclear reactor. Considering the importance of this technique, facilities for gamma scanning were incorporated during the design of the hot cells. A separate hot cell was dedicated for axial gamma scanning of the fuel pins. The different sub-systems required for the task are i) collimator and turret assembly, ii) precision bench assembly, iii) detector assembly and nuclear electronics, iv) computer hardware & software

One of the hot cells has a circular opening on the 1200 mm thick concrete front wall of the cell for housing the collimator-turret assembly. Lead shielding has been provided in the turret assembly to compensate



Collimator & turret assembly for gamma scanning of irradiated fuel pin

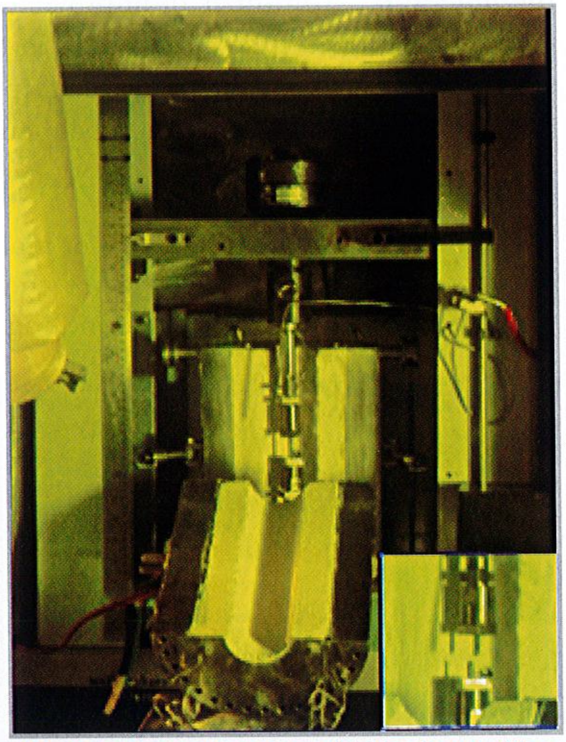
for the shielding loss created by the opening in the hot cell wall. Turret incorporates collimators of four different dimensions. The turret is mounted on ball bearings to facilitate rotation around its horizontal axis, to bring the desired collimator slit in front of the fuel pin. The primary collimator is an alloy of tungsten- copper-nickel (density 17.1 g/cc) having different collimator sizes followed by secondary coarse lead collimators. The collimators facilitate a small and well defined region of the fuel pin to be seen by the gamma detector.

Precision bench assembly located inside the hot cells has four axes movement (X, Y, Z & θ). It is intended to position the fuel pin in front of the collimator. The prototype precision bench assembly was initially designed with guide rods and ball bushes and a rack and pinion system for X,Y,Z movement. Based on the experience gained during trial operations and installation of the prototype bench, a new 4 axes gamma scanning bench has been designed and commissioned recently inside the hot cell. This state of the art bench is modular in construction and has Linear Motion (LM) guides with ball screws on all the linear axes using stepper motors for precision and smooth movement of the fuel pin. Fuel pin is gripped between two collets which can be rotated using a stepper motor.

Detector assembly is based on High Purity Germanium (HPGe) detector which has a resolution better than 1.8 keV at 1.33 MeV. The output pulses from the detector are amplified and fed to the multichannel analyser for obtaining the gamma spectrum. Nuclear electronics such as high voltage supply, amplifier and multichannel analyser are integrated in a PC with appropriate software for analysis.

Remote tensile testing facility

The residual strength and ductility of the cladding and wrapper after irradiation are very crucial input for the safe and continued operation of the reactor. One of the important milestones in the hot cell facility was the commissioning of a remote tensile test facility in cell-7 to estimate the mechanical properties.



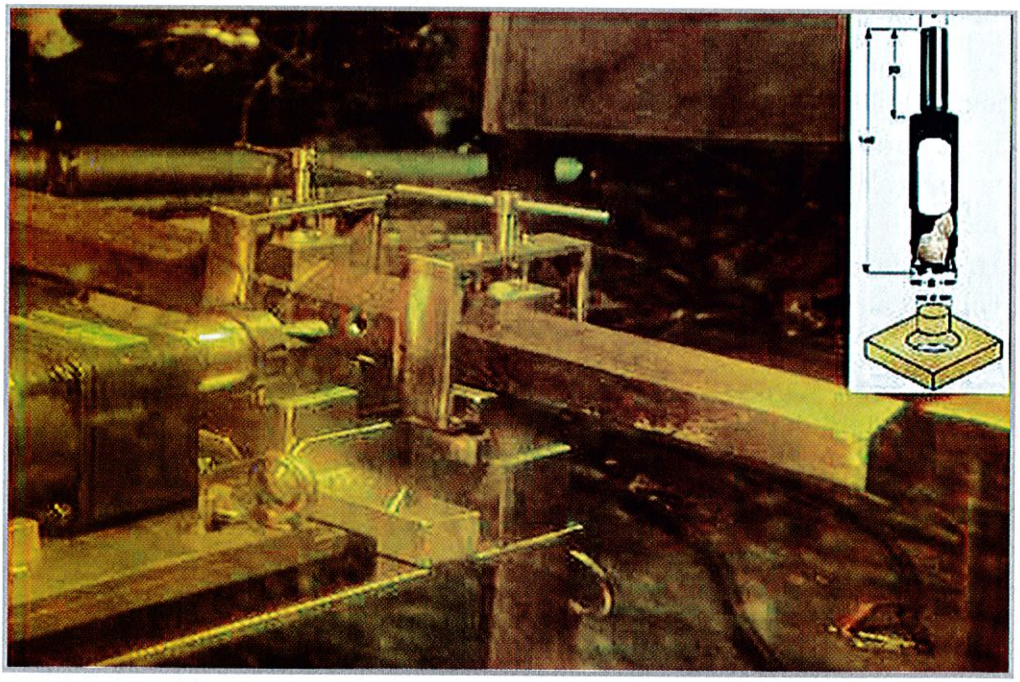
High temperature tensile test machine

This facility consists of a custom built computer controlled screw driven universal tensile test machine (2 kN capacity) fitted with a resistance heating furnace for characterizing the mechanical properties of the reactor structural materials at various test temperatures of interest. The specimens for testing were either from the cladding (tubular specimen), wrapper (flat type) or prefabricated miniature tensile specimens (flat type) subjected to irradiation.

The most challenging aspect of the remote tensile tests was standardizing the procedure for testing miniaturized specimens like (i) thin tubes of Φ5 mm with a wall thickness of 370 microns and (ii) flat specimens of 3 mm gage width and 1 mm thick. Special gripping techniques using an innovative collet type compression fitting for tubular specimens and wedge type gripping for flat specimens were developed in house and validated for tests at temperatures upto 600°C. The gripping technique was based on the application of a preset torque arrived through engineering calculations. A host of customized gadgets were employed for safe handling of the thin specimens, marking & measuring the gage length, to adapt the collet or wedge gripping method for remote loading and executing the tests. Use of special cassette type holders prevented bending or distortion of thin specimens during handling and loading on the machine. A number of improvisations have enabled executing the tests in a reduced time span using the master slave manipulators. One such development was a motorized gripping system with a DC motor and a torque sensor for automated specimen loading.

Small specimen extraction system

The use of small specimens for materials characterization has much relevance to PIE. This is because the reduced radiation dose from a smaller volume permits easy handling during testing. Also the smaller



Small Specimen extraction system

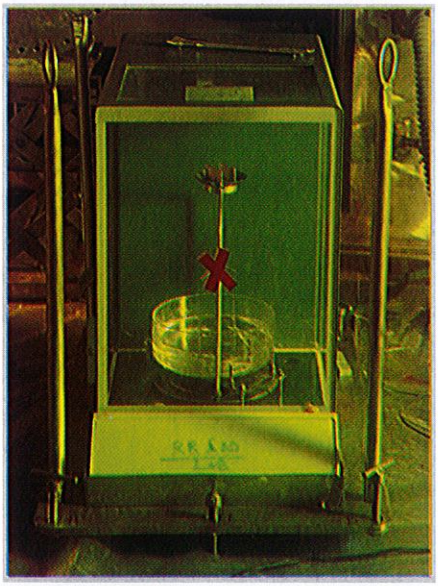
specimen ensures homogeneity of the radiation damage across its volume.

For extracting small specimens from the irradiated components, a specimen extraction system based on hollow end mill cutter was designed and adapted inside the hot cells. The device consists of motor assembly module, holders for clamping full subassembly, and precision guide for tool movement and a tool optimized for milling disc specimens of diameters ranging from 3 mm to 8 mm. The main design features of the specimen extraction system include coolant free cutting, reduced heat generation during cutting, minimized cut debris and modular design.

The small specimens extracted from the irradiated wrapper are used for density measurements and shear punch testing followed by transmission electron microscopic (TEM) examination. This enables correlating the mechanical properties in terms of the microstructural changes and swelling.

Density measurement system

The void swelling of the core structural materials and the consequent dimensional changes in the cladding and wrapper is one of the most crucial factors limiting the achievable burnup of a fast reactor fuel. The void swelling expressed as $\Delta V/V$ is thus a very valuable PIE data for the fuel designers.



Density measurement system for swelling estimation

A simple density measurement system based on Archimedes principle is employed for measuring the changes in the density of the clad/wrapper structural materials and assessing the volumetric swelling. The liquid used for density measurements by immersion technique is Di-Butyl Phthalate whose density variation with temperature is negligible. The void swelling estimated from the density changes is very useful for corroborating with the results of dimensional measurements of the cladding and the wrapper

Shear Punch testing

Shear punch (ShP) testing is a miniature specimen testing technique, in which a cylindrical punch with a flat end is forced to blank a hole in a clamped small disc specimen. The load-displacement curve obtained during the ShP test is similar to the load-displacement plot of a conventional tensile test and can be analyzed to extract the uniaxial tensile properties like yield strength (YS), Ultimate Tensile Strength (UTS) and % elongation. By using small specimens for testing irradiated materials, the radiation dose levels drastically decrease in proportion to its volume and it becomes possible to take them out of the hot cells and conduct mechanical testing in comparatively simple shielded enclosures with reduced radiological hazards.

The ShP test fixture that was designed and developed, consists of precision-machined upper and lower dies with bushings for punch travel, with the specimen held at the center in the cavity of the lower die. Small specimens of 8 mm diameter and 1 mm thick are extracted at different locations along the length of the hexagonal wrapper corresponding to different dpa. They are shear punch tested in a universal testing machine with local shielding around them. Using the tensile-shear correlations established through standardization experiments, the tensile properties are determined.

Shear punch testing of irradiated specimen with local shielding around test machine

TEM specimen preparation

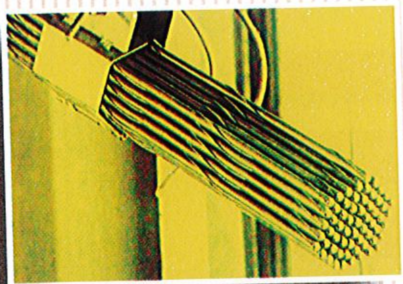
Neutron irradiation of core structural materials results in creation of defect structures of nanometer size like voids, dislocation loops etc. Transmission electron microscopy is employed to study such microstructural features. For TEM examination, specimens have to be prepared by mechanical and electrolytic thinning methods. TEM specimen preparation facility has been established in fumehoods for handling irradiated specimens. Procedures for mechanical and electrolytic thinning have been standardized for preparation of irradiated TEM samples starting from the 3 mm slug of the shear punch tested specimen.

TEM specimen preparation system for irradiated material

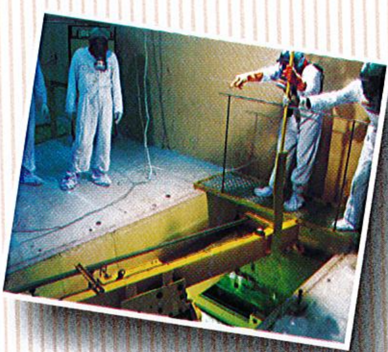
Charging of nitrogen in to the hot cells

To operationalise the hot cells, nitrogen was charged in to the recirculation ventilation system. This was a unique and challenging activity. Bulk nitrogen supply was provided by evaporating liquid nitrogen from a 2000 litre capacity tank at the time of changing the air atmosphere to inert atmosphere. Apart from this, nitrogen supply was made available from gas cylinders connected to a storage battery. There was continuous demand for nitrogen supply on a day-to-day basis as make-up gas for the feed and bleed arrangement and also to take care of the leakage of air into the cells. A gas generator using Pressure Swing Adsorption (PSA) technique with compressed air as feed gas was added to the system to generate nitrogen gas with low impurities of oxygen and moisture. The investment on two PSA nitrogen generators has been recovered within two years of continuous plant operation. The retrofitted system of recirculation type inert gas ventilation for the hot cells was commissioned satisfactorily, meeting the technical requirements to carry out PIE of irradiated carbide fuel of FBTR.

Chapter-3



RML in Operation



Hot Cell Campaigns

Operational Experiences

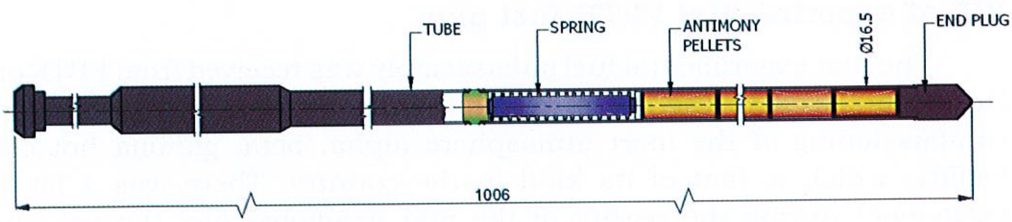
Road Map for Future

Fabrication of neutron source pin for FBTR

RML hot cells leaped into its operational phase during August 1985. The first campaign of handling radioactive material in the RML hot cells was the remote welding of the pin containing irradiated Antimony oxide (Sb_2O_3) pellets. This component was a part of the auxiliary *photo-neutron source* required for startup of the FBTR to achieve the first criticality.

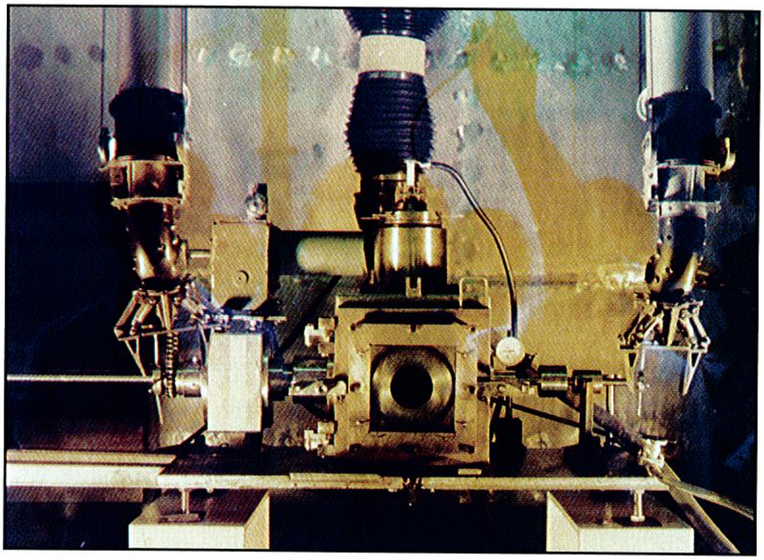
Photo-neutron Source: The auxiliary neutron source used in FBTR consists of a Antimony oxide (Sb_2O_3) pin placed in the centre of the six BeO_2 pins. On irradiation in a reactor, Sb^{123} transmutes to Sb^{124} which decays to Te^{124} by β, γ emission. The γ photon interacts with Be and produces neutrons facilitating the startup of the reactor.

The Antimony oxide pellets were irradiated in CIRUS reactor. Ten pellets with a total activity of 3.7×10^4 GBq (1000 Curies) were required to be used for fabrication of the neutron source pin. Since the Antimony oxide pellets were emitting high gamma radiation, the loading of the pellets into the SS tube and welding the end plug to seal the tube was carried out remotely in the hot cell facility of RML. The automated remote welding system designed for this purpose consisted of a leak tight chamber with provisions for filling the tube with the Antimony oxide pellets & Helium gas. Autogenous Gas Tungsten Arc Welding process was employed for welding the end plug to the tube.



Sketch of the neutron source pin

Since the assembled pin in the reactor core would experience high temperature and flowing sodium environment, the weld integrity was



Remote welding chamber in the hot cell

verified by Helium leak testing, X-radiography and metallography. Fabricated pin was transferred to FBTR in a shielded cask for loading in the reactor core.

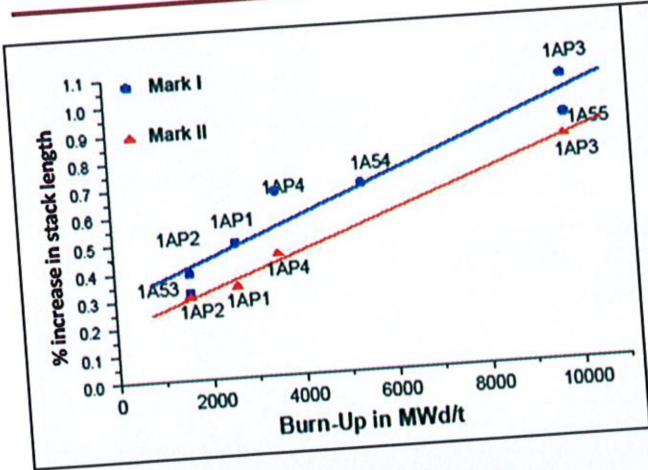
Successful remote welding of the first neutron source pin for FBTR marked the beginning of the operational phase of the hot cells.

PIE campaigns

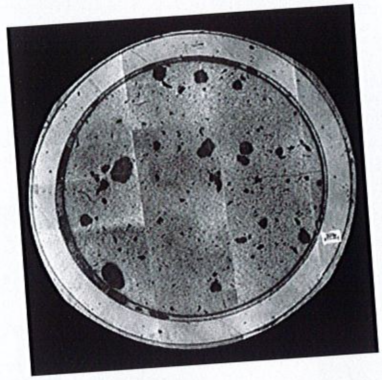
Since the commissioning of hot cells at RML, a number of PIE campaigns have been successfully completed on different core components of FBTR as well as on the Pressurised Heavy Water Reactor (PHWR) materials. The majority of the PIE campaigns were on the FBTR mixed carbide fuel in tune with the mandate of the laboratory.

PIE of experimental FBTR fuel pins

The first experimental fuel subassembly was received from FBTR on December, 1994. The receipt of this subassembly marked the hot commissioning of the inert atmosphere alpha, beta, gamma hot cell facility, which is first of its kind in the country. There was a lot of excitement during the receipt of the first irradiated fuel through the indigenously developed vertical transfer system which can handle 1.6 m long FBTR subassembly. The experimental subassembly contained one irradiation capsule with a single fuel pin of FBTR driver fuel composition $(U_{0.3}Pu_{0.7})C$.



Swelling rate of Mark I & Mark II fuel



Photomosaic of fuel pin cross-section

In all, seven such experimental subassemblies each containing one fuel pin with carbide fuel of Mark I $(U_{0.3} Pu_{0.7})C$ & Mark II $(U_{0.45} Pu_{0.55})C$ composition were examined at different burnups ranging from 1.6 GWd/t to 10 GWd/t. The examination of these fuel pins gave data on the beginning-of-life performance of the unique carbide fuel composition not tested anywhere else in the world. The photomosaic of the fuel pin cross-section revealed cracking resulting in gap reduction after 16 Effective Full Power Days operation corresponding to a burnup of 1.6 GWd/t. Mark II fuel was found to have lower swelling rate than Mark I fuel as indicated by the fuel stack length increase measured from X-ray radiographs. The data obtained from PIE of these fuel pins were helpful in increasing the linear power of FBTR fuel to 320 W/cm from the conservative design limit of 250 W/cm.

Requalification of irradiated fuel pins

One of the FBTR subassemblies had undergone distortion during fuel handling. This subassembly was received into the hot cells for visual examination and dimensional measurements. This examination gave information on the extent of damage of the FSA and was helpful in analyzing the fuel handling incident which caused the deformation.

The fuel pins of this subassembly had seen only low burnup levels and there was enough life left. To facilitate the reuse of the fuel, these fuel pins were requalified in a major campaign. Since the dismantling of FSA and requalification of the fuel pins were taken up after long period of

Bent fuel subassembly received for PIE

cooling, the radioactivity levels were low enough to handle them in a specially erected work station. The fuel pins retrieved from the subassembly after dismantling were thoroughly cleaned and visually examined. The fuel pins were subjected to quality control procedures similar to the fresh fuel pins after fabrication. Since the subassembly had undergone dimensional distortion, the condition of the fuel pins with respect to the spacer wire integrity and bow was comprehensively assessed. The integrity of cladding was evaluated through helium leak test and eddy current test. Two fuel pins gave indication of defects in eddy current test. One of the clad tubes was subjected to flattening test followed by metallography to detect any indication of caustic embrittlement. The microstructure did not reveal any clad attack. All the fuel pins excluding the two which gave defect indications in eddy current test were found healthy and those fuel pins were assembled using fresh subassembly hardware and put back in to the reactor core for re-irradiation. No failures have been reported so far in these pins.

PIE of FBTR driver fuel subassemblies

PIE of 25 GWd/t burnup subassembly

One of the significant milestones in the PIE activities in RML was the examination of FBTR fuel subassembly after attaining a burnup of 25 GWd/t. The results of this examination were eagerly awaited by the fuel designers especially with respect to the fuel swelling behaviour since it was expected to be the life limiting factor. When mixed carbide fuel with high plutonium content was chosen as the driver fuel, designers were anticipating a high swelling rate based on the extrapolation of swelling rate of the fuel with 30 % plutonium carbide for which data from open literature is available.

The subassembly with 25 GWd/t burnup irradiated in the central location of FBTR core was received in RML hot cells in September 1996. High surface temperature of the subassembly (around 100°C) needed extreme caution in preventing the damage to the manipulator bootings during handling. During sodium cleaning of subassembly using analytical grade ethanol, safety measures such as temperature monitoring and venting of ethanol charging tanks were adopted to ensure that build up of hydrogen does not take place due to sodium-ethanol reaction.

The scientists and engineers involved in PIE were in the learning phase and many of the prototype equipment fabricated for mock up trials during pre-commissioning were used in this campaign. These include the fuel pin diameter measurement system, fuel pin cutting machine, fission gas extraction system etc.

Indigenously developed CNC machine with inductive touch probe was successfully used for the metrology and cutting of the subassembly. Retrieval of the 61 fuel pin cluster after dismantling the head and foot portions was a momentous occasion. Shining appearance of the fuel pins and the easy identification of fuel pin numbers engraved on them confirmed the excellent purity of sodium maintained in the reactor. Nine fuel pins representing the spectrum of burnup variation within the fuel cluster were selected for detailed PIE. Different non-destructive examinations on fuel pins such as eddy current test, radiography and leak testing did not indicate any abnormalities.

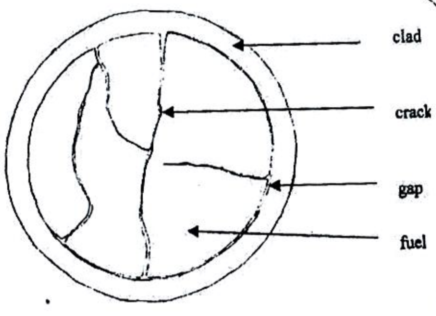
One of the crucial inputs required for the designer from the PIE is the axial fuel column elongation and the fuel-clad gap which give an indication of further swelling that can be accommodated in the fuel pin. The fuel column length increase was evaluated from X-radiographs. X-radiography of the irradiated fuel pins was challenging due to the high gamma radiations from the fuel pins (> 2000 R/hr) and innovative methods were adopted to obtain good quality radiographs, notwithstanding the high gamma fogging of films.

Photomosaic of fuel pin cross-section after 25 GWd/t burnup

The fuel-clad gap was measured from the metallographic specimens of fuel pin cross-sections. The pyrophoricity of carbide fuel necessitated high nitrogen purity during sample preparation. All the parameters indicating the purity of the inert gas recirculation system of the hot cells were excellent during remote metallography. Replication of the metallographic specimens was resorted to record the metallographic features before the sample gets oxidized. Remote replication of the prepared samples was mastered and the micrographs of the fuel pin cross-sections were prepared from the replicas. Micrographs gave a wealth of information on the cracking pattern and swelling rate of fuel.

Photomosaics of the fuel pin cross-section shows the radial cracks and fabrication porosities. Volumetric swelling rate and the fuel-clad gap reduction levels were important data required from metallography of fuel-clad cross-section. Image analysis technique was successfully employed to estimate the apparent fuel-clad gap (without considering the gap available in the fuel cracks) as well as the effective fuel-clad gap taking into account the gap available in the cracks. Image analysis technique

In any micrograph, resolution and area covered are complimentary in nature. To ensure high resolution as well as coverage over the entire fuel pin cross-section (5.1 mm diameter), photomosaic technique was adopted where several micrographs of magnification of around 40 X are stitched together.



Segmented image of photomosaic of fuel pin cross-section

was perfected using special methods like preparation of segmented image of the photomosaic to reduce noise, border killing etc.

Presence of the fuel-clad gap and also the volume available in the cracks indicated enough margin for further swelling to take place and discounted the earlier concern of high swelling rate of the carbide fuel composition chosen for FBTR.

Fission gas was extracted by puncturing a few fuel pins. The analysis of fission gas samples using mass spectrometer indicated very low fission gas release (<1%).

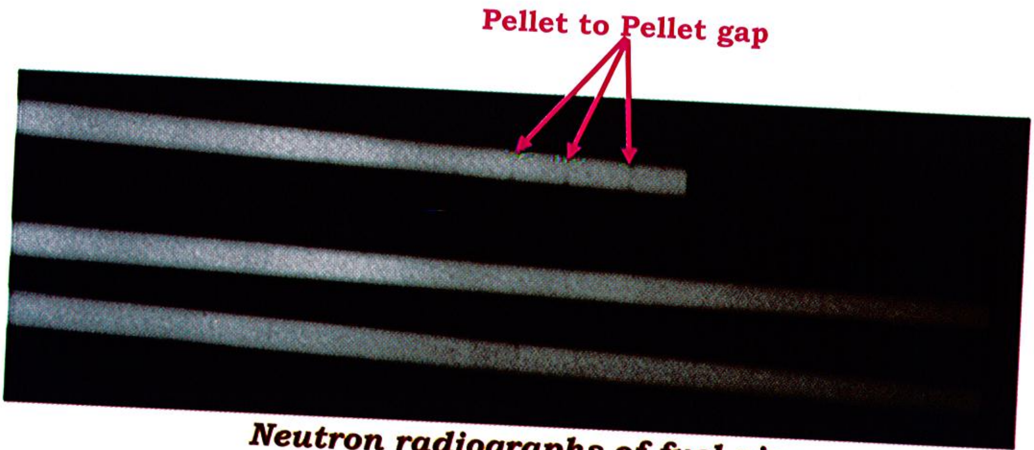
*When nuclear fuel undergoes fission in a reactor, many fission products are generated apart from release of a few neutrons and large amounts of energy in the form of heat. Some of the fission products exist in gaseous state and these gaseous fission products constitutes around 25% of the total inventory of fission products. Gaseous fission products predominantly consist of noble gases such as krypton and xenon. These gases being chemically inert, they exist as gas bubbles inside the fuel matrix. Due to the high temperature prevailing in the fuel, considerable amount of fission gases diffuse through the fuel matrix and get released from the fuel to the free volume (plenum) provided inside the fuel pin. Large amount of **fission gases** released to the plenum leads to build up of internal pressure inside the fuel pin and can lead to its failure whereas retention of fission gases in the fuel matrix along with other solid fission products results in swelling of the fuel.*

Dimensional changes were not observed on the fuel pin cladding and hexagonal wrapper due to the low displacement damage undergone (14 **dpa**) by them after 25 GWd/t burnup. This PIE campaign lasted for almost an year and the team could deliver the PIE data required by the designers, to extend the burnup to, 50 GWd/t with the necessary approval from the regulatory authorities.

*When neutrons bombard the structural materials such as stainless steel, atoms are displaced from the crystal lattice locations. Displacement of atoms leads to creation of point defects such as interstitials and vacancies in the lattice. These point defects, under favourable temperature regime, agglomerate to produce many defect structures such as voids, dislocation loops, helium bubbles etc. Creation of these defect structures along with the creation of new irradiation induced phases/precipitates results in changes in the macroscopic dimensions and mechanical properties. Extent of neutron induced damage in structural materials is expressed as displacements per atom **(dpa)** which is proportional to the neutron fluence (flux x time) seen by them.*

PIE of 50 GWd/t burnup subassembly

As the initial design burnup limit envisaged for FBTR fuel was 50 GWd/t, the results of this PIE campaign were very crucial for extending the burnup beyond the design limit. This subassembly was received in May 2000.



Neutron radiographs of fuel pins

This campaign witnessed the use of new techniques for non-destructive testing of fuel pins. The experience gained during the PIE campaign after 25 GWd/t gave immense feedback to improve the methodology of examinations and interpretation of results. Neutron source reactor "KAMINI" located below one of the hot cells had become operational. This facility was used for neutron radiography of the fuel pins. Extensive mock up trials involving the carriage drive mechanism for lowering the fuel pins into the neutron radiography rig preceded the neutron radiography of irradiated fuel pins. Indirect technique of transferring the radiographic image using dysprosium foils was optimised. Neutron radiography along with the X-ray radiography was used for measurement of fuel column length.

Metrology of hexagonal wrapper and cladding did not show any evidence of dilation or distortion which is justified considering its exposure to fluence level (28 dpa) below the incubation dose (around 35 dpa) for swelling of 20% cold worked stainless steel.

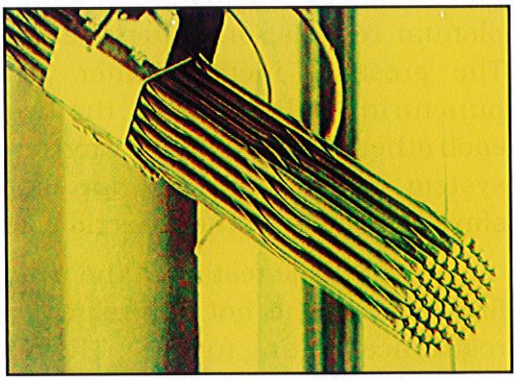
Fission gas release measurements showed significant increase in gas release (maximum of 22%) as compared to those of 25 GWd/t. Wide variation in the fission gas release obtained for different fuel pins was puzzling though the same was of no major concern with respect to the internal pressure in the fuel pin and the consequent limit on the burnup.

Photomosaics of fuel pin cross-sections showed significant reduction in the fuel-clad gap. Restructuring of fuel normally seen in oxide fuels was absent. The reduction in the gap was a concern due to possibility of clad carburization resulting from transfer of carbon from the fuel. Microhardness measurements on the cladding however did not indicate any effects of carburization.

Extensive thermo-mechanical analysis based on the PIE data was performed to predict the burnup limit. Considering the margins available with respect to various factors such as the fuel-clad mechanical interaction (FCMI) arising due to swelling, cladding stress due to fission gas pressure, burnup extension to 100 GWd/t was approved by the safety regulators.

PIE of 100 GWd/t burnup subassembly

With the FBTR fuel crossing the initial design limit of 50 GWd/t burnup, thorough investigations on the fuel performance was planned at 100 GWd/t burnup. This subassembly had accumulated a peak displacement damage of 56 dpa which is well beyond the incubation dose for swelling. RML geared up for the PIE of this high burnup fuel by augmenting the hot cell facility with techniques and equipment for mechanical testing of the cladding/wrapper, improved fission gas extraction system, swelling measurements of the cladding/wrapper, electron microscopic examination of wrapper etc. Fission gas analysis system based on gas chromatography was also added.



View of fuel pin cluster

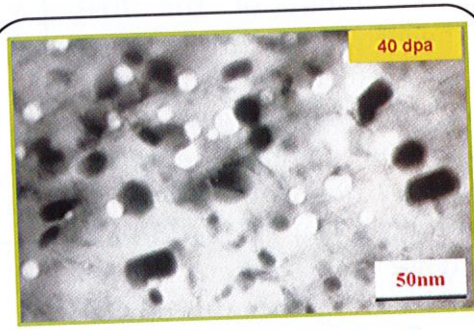
The 100 GWd/t burnup fuel assembly was brought into the RML hot cell in March 2003. It went through the usual operations of visual inspection and sodium removal through alcohol cleaning. The dimensional changes in the wrapper were measured using a set of custom built dial gage type gadgets. A measurable increase in the dimensions like flat-to-flat and corner-to-corner distances of the hexagonal wrapper was noticed for the first time in the metrological inspections. The dimensions of the fuel pins also showed significant increase both in the diameter and length.

The change in the cracking pattern from radial to circumferential as seen in the photomosaics of the fuel pin cross-section at the centre of the fuel column was indicative of the closure of fuel-clad gap and the restrained swelling phase. However, away from the center of the fuel column, some pellet-clad gap existed and cracking patterns were radial. The fission gas release in the fuel pins had some interesting observations. The closure of the fuel-clad gap prompted puncturing of the fuel pin in both the plenum regions, one after the other. The pressure increase after second puncturing indicated that the two plenum regions were isolated from each other. This paved the way for the design of a double end puncturing system where both the top and bottom plenums are punctured simultaneously for the collection of the fission gases.

Photomosaic of fuel pin cross-section after 100 GWd/t burnup

The tensile testing of the irradiated clad tube was taken up for the first time in the hot cell using a screw driven machine fitted with a resistance heating furnace. The results of the tensile tests were eagerly awaited as the residual ductility of the cladding was thought to be one of the factors that would decide the further increase in burnup with increasing stress levels due to FCMI and fission gas pressure. The complete closure of fuel-clad gap made it impossible to remove the fuel for testing the cladding. The fuel was removed by chemical dissolution at the radiochemistry hot cells, after which the clad was tested in RML hot cells. The tensile tests revealed retention of sufficient strength and about 3% ductility (uniform elongation) in the clad tubes. The cladding showed a volumetric swelling of about 4.5% consistent with the dimensional increase measured using the LVDT setup. The wrapper swelling was measured to be around 2 %. It was inferred that the most of the dimensional changes were contributions from void swelling phenomenon rather than irradiation creep.

A compact milling machine aided in extracting small specimens from the different locations of the wrapper for three-in-one purpose - small specimen mechanical testing, swelling estimation and transmission electron microscopic (TEM) studies. The shear punch technique was evolved for testing irradiated wrapper specimens outside the hot-cells by erecting local shielding around the test machines. The blanked slug of the shear punch test was used as the starting material for the transmission electron microscopic studies. The first "Indian voids" were captured from a thin foil of specimen under the transmission electron microscope.



TEM micrograph of irradiated wrapper

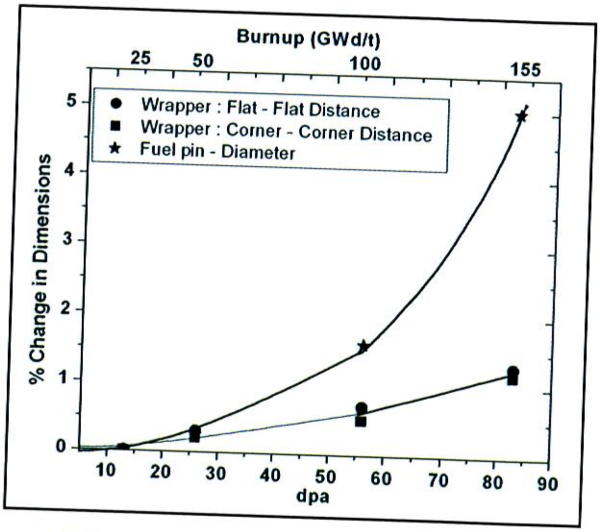
Another major issue with the increasing burnup of carbide fuel was the reduction in carbon to metal (C/M) ratio and the possibility of metallic phase formation. Extensive modeling of the fission product chemistry with respect to the formation of carbides predicted that reduction in C/M ratio to a value less than one occurs only at burnup beyond 165 GWd/t.

The swelling of fuel and closing of the fuel-clad gap, gradual increase in dimensions of wrapper and cladding and residual ductility of cladding were the factors considered for further enhancement of burnup. An exhaustive thermo-mechanical modeling of the fuel behaviour by the design group using the generated PIE data enabled enhancing the burnup to 155 GWd/t.

PIE of 155 GWd/t burnup subassembly

With burnup being pushed to higher limits and the irradiation damage accumulating in the fuel and structural materials, the techniques and methodologies for PIE evolved with innovation and state-of-art equipment for a comprehensive assessment of the irradiation behavior. This campaign had its share of new in-cell equipment like the 4 axes profilometer cum laser dismantling system (DMLD), double end puncturing system for fission gas extraction, gamma scanning system etc.

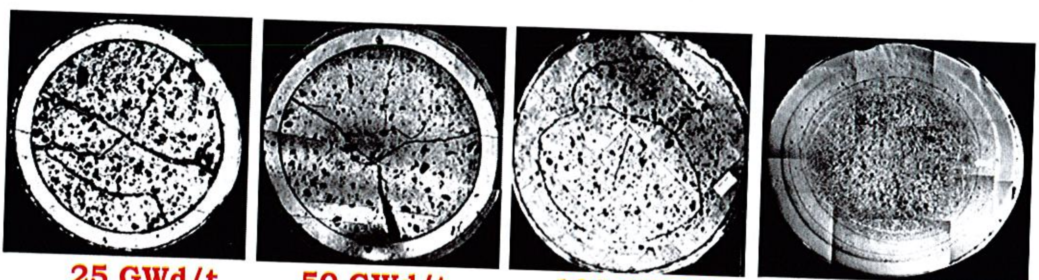
The 155 GWd/t fuel assembly was received in Feb 2007. Prior to this, the indigenously developed 4 axes profilometer cum Laser dismantling system was installed in the hot cell by opening the cell roof plug and commissioned. The equipment was standardized and used for a completely automated dimensional measurement of the fuel subassembly. An Nd-YAG laser integrated with this system was employed for the first time to cut the outer wrapper for retrieving the fuel pin bundle. Considerable difficulty was faced during the pull out of the fuel bundle from the wrapper tube which was overcome by introducing few horizontal slits on the wrapper and by using special gadgets.



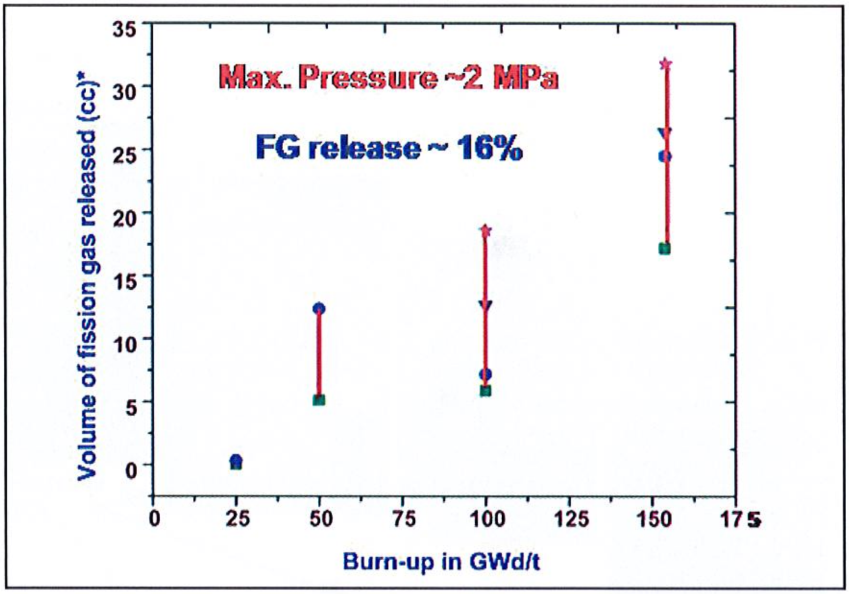
Dimensional variations in the wrapper and clad with 'dpa'

Both the wrapper and the fuel pins showed a faster rate of increase in dimensions as compared to that at lower burnups. The same was also evident in the void swelling values of the cladding (~ 11.5 %) and wrapper (~ 4 %). The increase in dimensions of the wrapper has a bearing on the fuel handling operations in the reactor.

The fuel micrographs showed the closure of fuel-clad gap along the entire fuel column signifying the restrained swelling phase. Distinct porous free zones were observed at the outer rim of the fuel indicating hot pressing/creep deformation of fuel under clad restraint.



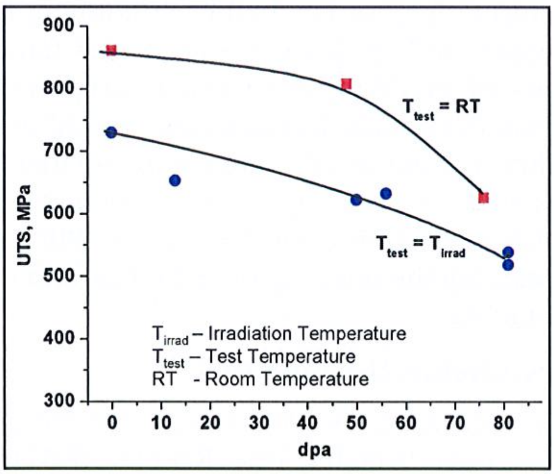
Comparison of photomosaics of fuel pin cross-sections at various burnups



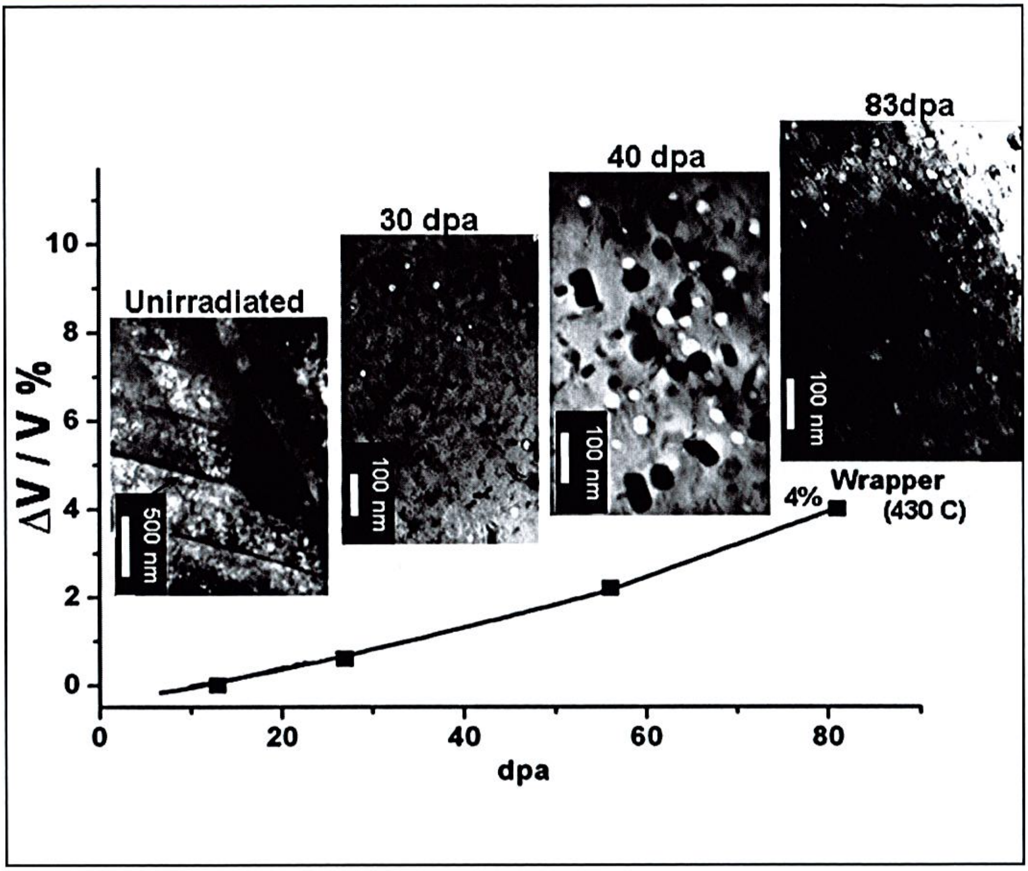
Variation of fission gas release with burnup

The fission gas release (~ 16%) and the plenum pressure (~ 2 MPa) were found to be very nominal at this high level of burn-up and it is not a limiting factor in enhancing the burnup.

The clad tubes showed considerable decrease in both strength and ductility. The wrapper properties determined using the shear punch technique revealed classical hardening with loss of ductility as a function of dpa. In addition to extensive void formation, the TEM images revealed the precipitation of Si rich M_6C (η) and cubic G phases at 80 dpa.



Trends in the UTS of SS316 cladding with dpa



TEM micrographs at various dpa superimposed on swelling curve

The main limiting factors for further enhancing the burnup were (i) dilation of wrapper and its impact on the fuel handling operations (ii) FCMI and loss of cladding mechanical properties. The thermo-mechanical analysis of the fuel subassembly based on the PIE results indicated possibility of a marginal increase in the fuel burn-up beyond 155 GWd/t. Presently, the burnup of one representative subassembly has reached 165 GWd/t without any fuel failure. PIE has thus played a crucial role in enhancing the burn-up of FBTR fuel and in understanding their in-reactor behavior.

FBTR fuel life extension through PIE

The stage wise performance evaluation of the Plutonium rich mixed carbide fuel of the Fast Breeder Test Reactor (FBTR), starting from beginning-of-life performance studies and subsequently at various stages of burn-up has led to a comprehensive understanding of the fuel and structural material behaviour. Compared to the initial design limit of 50 GWd/t, the burn-up has now reached 165 GWd/t without any fuel pin failure. PIE has thus played a crucial role in validating the design and choice of the unique fuel material of FBTR, thereby increasing its in-reactor life.

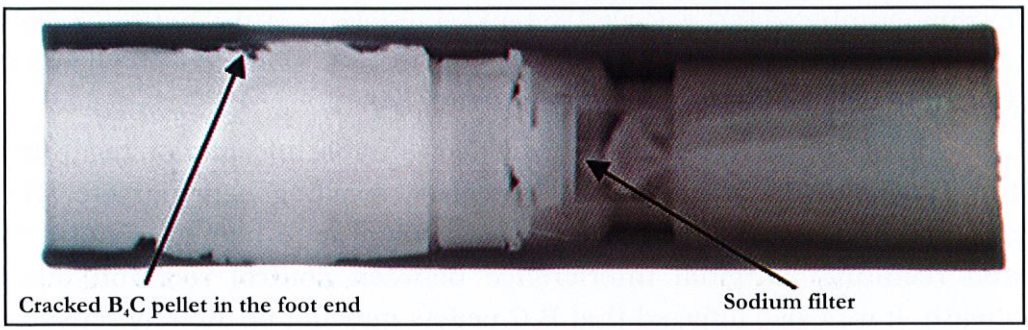
PIE of Control Rod assembly

FBTR has six control rod assemblies for reactor start up, shutdown and control of reactor power. Each control rod consists of nine sintered boron carbide pellets (90% enriched in B^{10} isotope) stacked to a length of 430 mm inside SS316 cladding. The control rod moves axially inside an outer hexagonal sheath made of SS316 during raising and lowering.

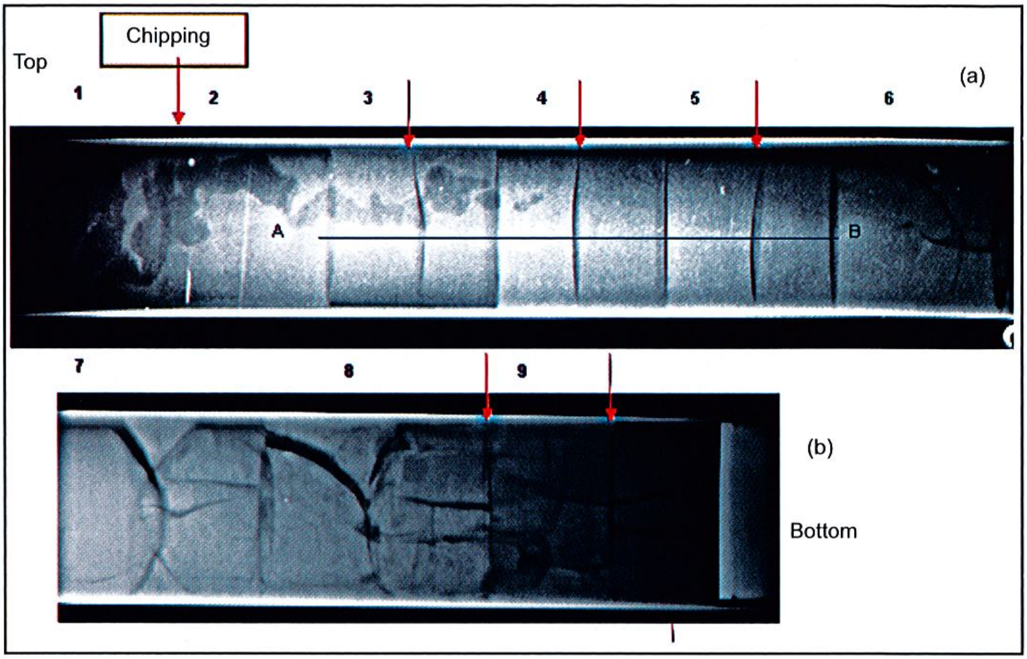
A few incidents of the dropping of the control rod of FBTR were reported while lifting it to increase the reactor power. This called for a detailed investigation to assess cause of the incident and study the irradiation behaviour of the B_4C absorbing material and SS316 cladding.

To investigate the possibility of interference between the control rod and the outer sheath, precise dimensional measurements were carried out using customized devices designed and fabricated exclusively for this purpose. Neutron radiography carried out to visualize the control rod internals revealed that internals are intact without any blockages that could restrict coolant flow.

Cracking behavior of boron carbide pellets was assessed by X-ray radiography. Since the existing X-ray radiography port can handle only fuel pins, a separate facility was erected by modifying one of the radiation survey ports for radiography of large diameter control rod. X-ray radiography clearly indicated extensive cracking and fragmentation of the pellets exposed to higher neutron fluence.



Neutron Radiograph of the control rod

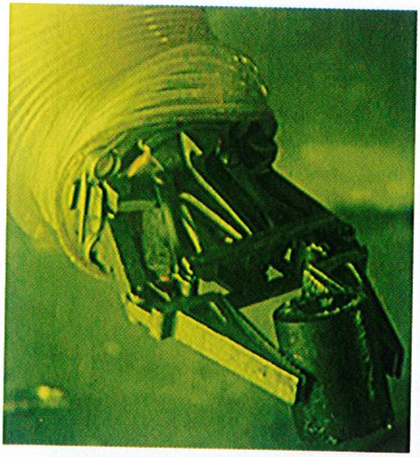


Radiography image indicate the pellet regions of the control rod (a) top portion. (b) bottom portion - The radial cracks at the centre of the pellets are marked by arrows

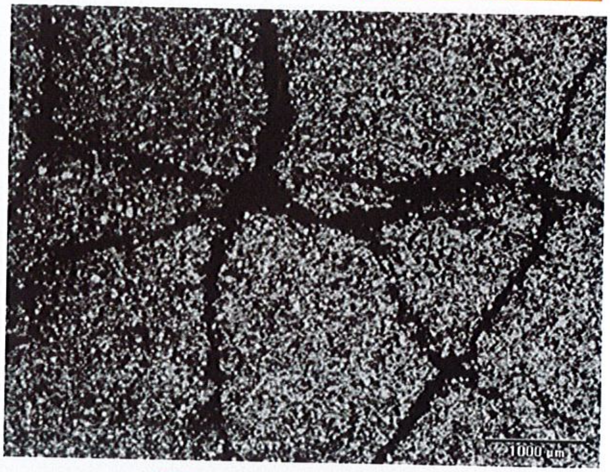
After cutting the control rod using Nd-YAG laser, considerable difficulty was experienced in the retrieval of pellets due to the presence of sodium and sodium oxide in the pellet-clad gap. The pellets were finally retrieved using a specially made fixture to push the pellets out of the control rod clad.

Volumetric swelling of the boron carbide pellets measured by density measurements indicated negligibly small swelling of around 2 % in the bottom pellets which has been exposed to higher neutron dose. Ceramography of B_4C revealed extensive cracking of the bottom pellets and clad microstructure did not indicate any evidence of chemical interaction between the B_4C pellet and the clad.

PIE of control rod assembly provided valuable information regarding the dimensional changes, pellet integrity, swelling behavior etc. The dropping incident encountered was possibly due to higher eccentricity and resulting marginal interference between control rod and outer sheath. It was also inferred that B_4C pellets may not be directly reusable due to extensive cracking and fragmentation. PIE has indicated that the



Photograph of irradiated boron carbide pellet



Micrograph of boron carbide pellet

boron carbide pellets and the structural materials have not reached life limiting conditions at a fluence level of $7.2 \times 10^{22} n/cm^2$.

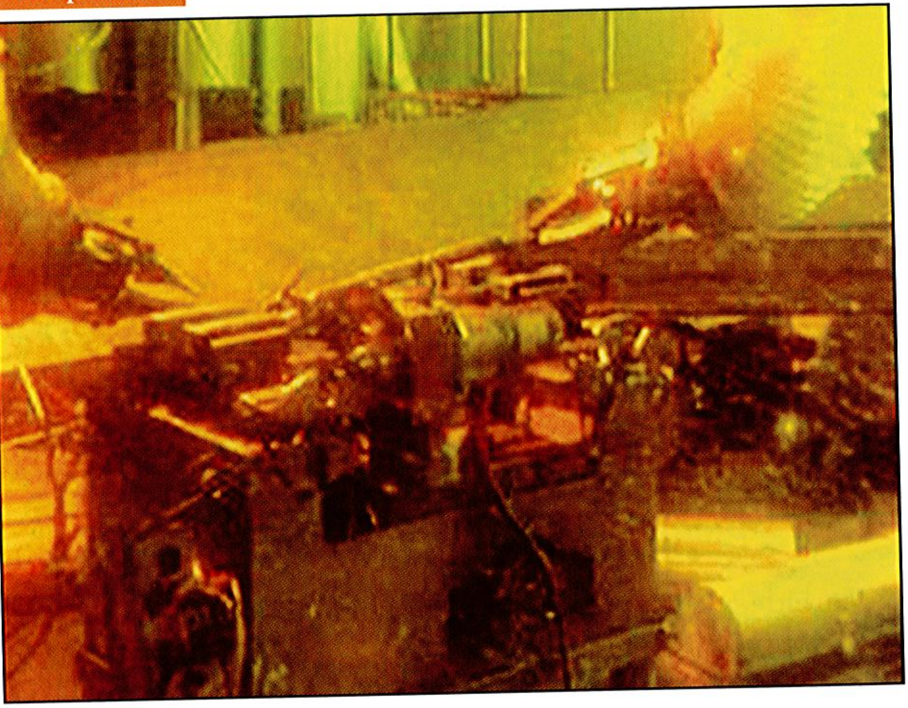
PIE of experimental subassemblies

FBTR is also being used as a test bed for irradiation experiments on various fuels and structural materials of importance to our FBR programme. In such irradiation experiments, hot cell facility is a very crucial link for post-irradiation handling and examination of the irradiated material and to provide valuable outcome and feedback to the designers.

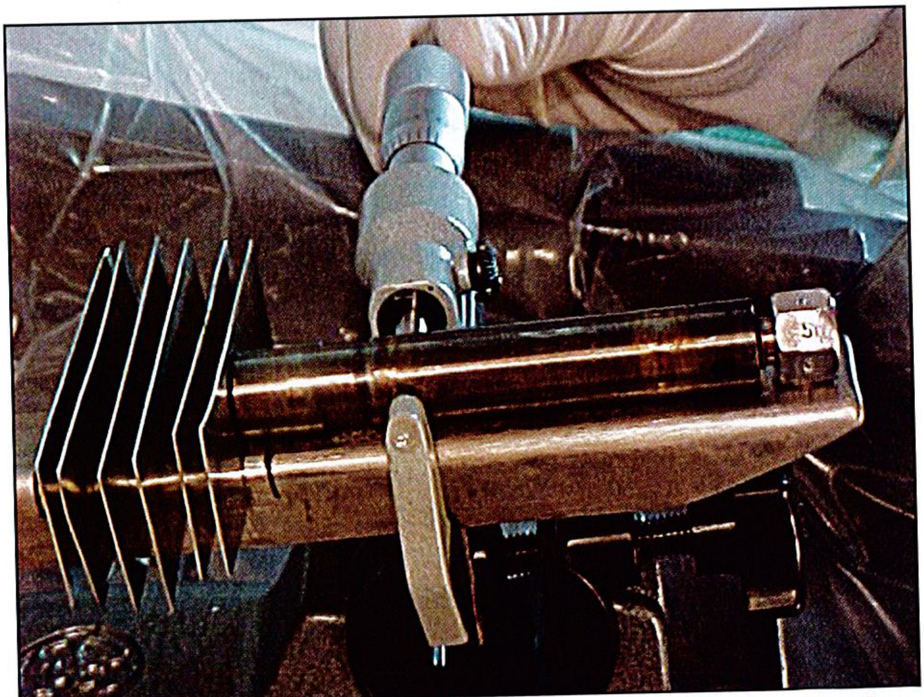
Creep studies on PHWR pressure tube material

PIE campaign on the indigenous pressure tube material was a significant contribution to the PHWR technology which continues to be the main stay in our nuclear power programme. Around 30 pre-pressurised capsules made from Zircalloy 2 and Zr-Nb alloys were irradiated in FBTR in six subassemblies for different duration and received for PIE to establish the steady state creep rate of these alloys. This accelerated irradiation in the high flux core of FBTR is equivalent to about ten years of irradiation in the PHWR.

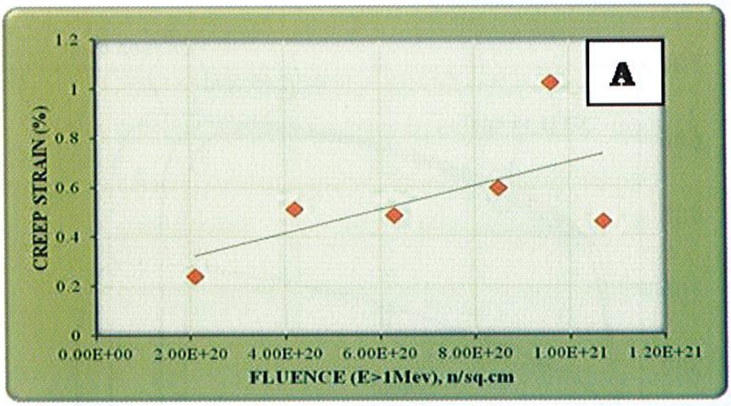
This PIE campaign required development of special in-cell equipment for cutting the irradiation capsule milling and subsequent

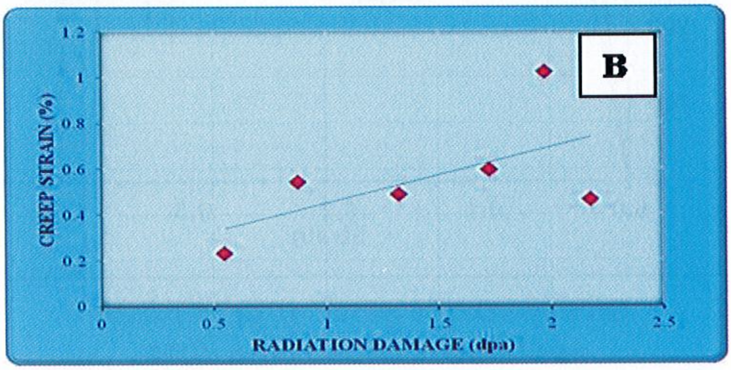


Equipment for retrieval of pre-pressurised capsules



Diameter measurement of the pre-pressurized capsules



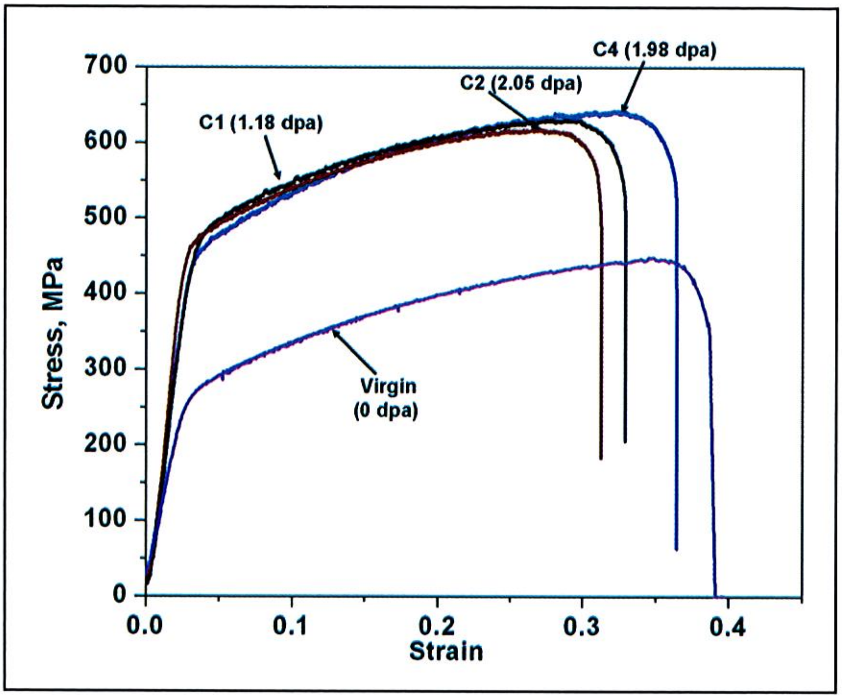


Creep of Zr-2.5% Nb at 314°C and average stress 150 MPa
A. Creep strain vs Fluence
B. Creep strain vs radiation damage (dpa)

retrieval of the pre-pressurised capsules. Diameter measurement were carried out on the pressurised capsules at different radial and axial locations to determine the increase in diameter and thereby the creep strain accumulated and the creep rate of the indigenous alloys.

Residual life assessment of FBTR grid plate

With FBTR in operation for more than 24 years, it was necessary to assess the residual life of the grid plate. Irradiation damage to grid plate is one of the main life limiting factor. Irradiation experiments were carried out to calculate the dpa rate on the grid plate of FBTR and to evaluate the changes in the mechanical properties of the grid plate material. Foils of NpO_2 along with Th, Nat. U, depleted U and Ni foils were irradiated in FBTR. The special subassembly containing the foils were dismantled in the RML hot cells and the recovered foils were transferred for measuring the activity and hence the dpa rate.



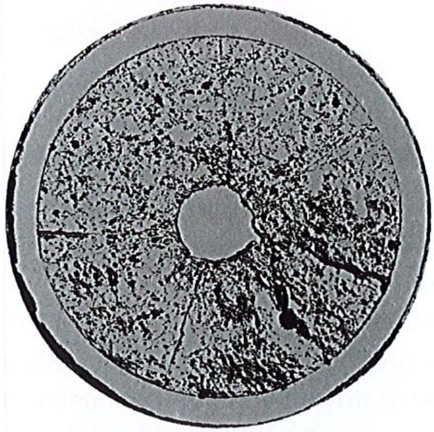
Stress-strain plots of grid plate specimens at various 'dpa'

An accelerated irradiation test was performed with pre-fabricated tensile and disc specimens of SS316 simulating the dose level received by the FBTR grid plate over its life time. This experiment was aimed for ageing assessment of FBTR grid plate and its life extension. The tensile test results of the irradiated grid plate material (SS316) show radiation hardening accompanied with ductility loss for the various irradiated specimens above 1 dpa. The uniform elongations were in the range of 20-30 % for various irradiated conditions.

PFBR MOX fuel test irradiation

In another experiment, the MOX fuel of PFBR fuel composition was irradiated in FBTR for 20 days at a linear power of 400 W/cm for understanding the beginning of life gap closure behaviour. This experiment was aimed to optimize the duration of pre-conditioning of the MOX fuel in PFBR at lower linear power (400 W/cm) before raising the linear power to the design value of 450 W/cm. X-ray radiography and metallography of fuel pin cross-sections were the main examinations carried out.

The in-cell equipment were originally designed for examining carbide fuel pins of 5.1 mm diameter. The examination of experimental MOX fuel pin of 6.6 mm diameter necessitated either modifications in the existing setup or design and fabrication of new equipment. For example, the X-radiography pin holder was modified for holding a larger pin diameter, while the vacuum impregnation system (for immobilizing the fuel column during slicing of metallographic sample) was redesigned and fabricated for handling larger diameter pins.



Photomosaic of fuel pin cross-section of MOX fuel pin

Metallographic examination of fuel pin cross-sections involved vacuum impregnation of the fuel pin with araldite, slicing the fuel pins at various axial locations, molding, stage wise grinding and polishing and replicating the surfaces for optical microscopic examination and image analysis. The fuel-clad gap measurement at different locations indicated that the apparent gap (without taking into account crack area) had reduced from average pre-irradiation value of 75-110 microns to uniformly around 12 - 13 microns in all the locations. The gap reduction during beginning of life indicates the feasibility of increasing the linear power of PFBR fuel to the design value after the initial pre-conditioning of 20 EFPD. A fuel subassembly consisting of 37 MOX fuel pins of PFBR composition has achieved a burnup of 105 GWd/t and is being planned to be taken up for a detailed PIE.

Production of Radio Isotopes

The hot cell facility has also played an important role in the centre's programme of production of radioisotopes using FBTR. Strontium ^{89}Sr produced by the irradiation of yttria ^{88}Y pellets in a special capsule was retrieved in the hot cells and transferred to radiochemistry laboratory for further processing. Strontium is used extensively as radiation medicine to relieve the bone pain associated with certain kinds of cancer.

Inert gas recirculation blower

During the initial operating period of inert gas system, one of the main problems encountered was overheating of the motor of hermetically sealed recirculatory blower [VENTI]. In one of the VENTI blowers, overheating resulted in seizure of the impeller shaft with the bearings damaging the impeller assembly. This impeller had to be replaced with a spare impeller. The excessive heating problem led to breakdown of the system which caused nightmares to all the operation/maintenance personnel.

The motor used for the blower was a constant speed motor & flow control was achieved by varying the damper positions. The heating problem was finally attributed to the low initial flow requirements to the hot cells, since only four out of seven concrete cells were connected to the inert gas loop. This led to lower flow through the blower, moving the dampers to near close position, while the motor runs at full speed. This imbalance resulted in excessive heating of the motor. The problem was carefully analyzed and solved by introducing a Variable Frequency Drive [VFD] in the motor circuit. After introduction of VFD, fine tuning of flow control was very easy and the blower never overheated and is in trouble free service for more than 16 years. Introduction of VFD resulted in huge savings.

Instability in hot cell pressure

After successful resolution of excessive heating problem of VENTI blower, gradually the hot cell pressure showed undesirable deviations from the desired values. This was due to gradual deterioration of components like MSM bootings, which led to in-leakage of air in to the hot cells, which resulted in excess inventory of cell gas and instability in cell pressure. The increased leak rates caused higher oxygen and moisture levels inside the cells and the loop. The higher moisture levels caused condensation in the cooling coils, leading to unplanned draining of condensate water from cooling coils.

The cell pressure fluctuations beyond design values were analyzed and to resolve the same, an automated feed and bleed system was introduced in the system. When the cell pressure tends to move towards ambient value, automatically a fraction of cell gas is released to atmosphere through absolute filters & stack. When cell pressure tends to reach below the set value, automatically fresh nitrogen gas is injected into the system. To maintain the required purity levels inside the hot cell, continuous feeding of pure nitrogen to the hot cells is done. The emergency exhaust system ensured that the cell pressure never attains positive with respect to ambient pressure. With the introduction of feed and bleed system, the undesirable cell pressure fluctuations were extremely rare.

Vibration Analysis for Rotary equipment at RML

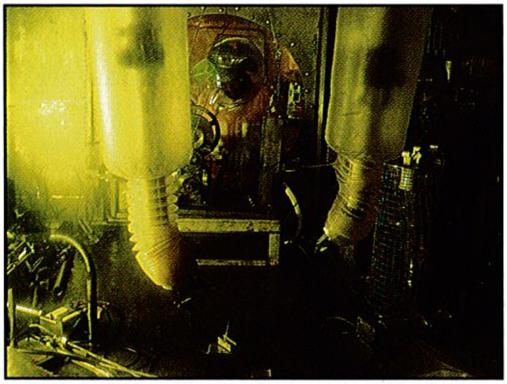
During the initial period of cell commissioning, various bearing failures and equipment noise level problems were encountered and frequency of maintenance operations was very high for rotary equipment like compressors, brine chilling plants, blowers and pumps. Periodic vibration analysis was carried out to assess the overall healthiness of such rotating machineries. By conducting this analysis, it was possible to identify the root cause of vibration and bearing failures in various machines and corrective action were taken.

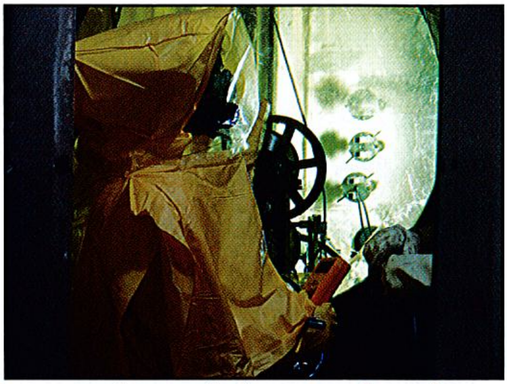
For example, modifications were done in the brine chilling plants (3 units) by introducing vibro-mounts and bellow in compressor discharge line. This isolated the vibrations from the brine chilling plant compressor getting transmitted to the accessories of the plant and building structures. By introducing these vibro mounts, refrigerant gas leak was practically nil bringing down the gas inventory required to be maintained. Sound level of the machines also got reduced considerably, thus improving the overall healthiness of the system.

In the centrifugal blowers also, vibro mounts were introduced and plumber block bearings were changed to pillow block bearings. Down time of the machines was brought down resulting in reduction of maintenance man-hours and inventory of spares.

Repair of critical equipment in a radioactive facility

A number of equipment housed inside the inert atmosphere shielded RML hot cells have served for more than fifteen years without any need for direct contact repairs / maintenance. This is due to the design philosophy adopted for the in-cell equipment which envisages long term maintenance-free operation with provision for essential remote repairs using Master Slave Manipulators (MSMs). However, unexpected failures as in the case of the following equipment necessitated direct contact repair. (1) The Carriage Drive Mechanism (CDM) of the neutron radiography system was incapacitated due to failure of a transmission coupling and (2) An in-cell crane became inoperative due to the overlapping of steel rope on the groove of steel drum. In both cases,





Repair of neutron radiography carriage drive mechanism

Repair of in-cell crane after removing the roof plug

contact repairs were executed by evolving special methodologies and using protective devices.

Attempts for remote repairs of the CDM using specially designed gadgets assisted by CCD cameras and LED array lighting indicated that due to the complexity involved and the inaccessibility of some components, it was preferable to carry out the work by resorting to direct contact repair.

In order to facilitate repair work without man-entry into the hot cell, a scheme was made to disassemble the affected module of the system remotely and to locate it within the hot cell such that it is accessible from a specially established work area outside the hot cell by opening the cell door. Before opening the door, the inert atmosphere in the hot cell was converted to air. Radiation level in the work area was brought down by relocating all radioactive sources to the adjacent hot cells. Radiation field in the cell was measured using "Teletector" through MSM port openings and also by inserting TLDs into the cell and analyzing them.

To further minimize the exposure of personnel during contact repair, all repair activities were broken down into sub-activities and detailed procedures and check lists were prepared and validated by rigorous mock-up drills. The extent and duration of contact work was minimized by executing all possible sub-activities through MSMs as far as possible.

To avoid over exposure and particulate ingestion by personnel and spread of contamination, all participants of the campaign were trained rigorously before the actual work regarding the essential principles of time-motion management, health physics, ventilation and air monitoring, rubber station and dress codes and other general safety provisions and regulations. Full dress rehearsal was carried out wearing fully ventilated suit / frog-man suit and breathing apparatus. For effective coordination between various groups of personnel working simultaneously at various locations such as the operating area, isolation area, warm work area, and control room, audiovisual communication was established.

The Carriage Drive Mechanism (CDM) was dismantled remotely and taken from its home to the location near cell door opening and the repair was carried out. The mechanical coupling and the stepper motor of the CDM were replaced and the system was put back into operation.

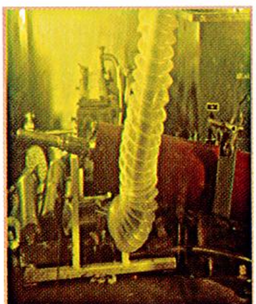
For the maintenance of in-cell crane, the roof plug on the top of the hot cell was opened and the crane module was removed through the roof opening to the work station. The damaged portion of the rope was removed and the balance rope was put back into operation. A specially fabricated safety platform was erected on the roof to prevent accidental fall of tools/personnel into the hot cell. In addition, a safety belt/rope was strapped around the personnel during the crane repair. Other maintenance works like changing the limit switches, changing of roof-plug gaskets etc. were also carried out during this repair work.

Both the campaigns were executed successfully with minimum man-rem expenditure and spread of contamination, thus boosting confidence level of the personnel and preparing them for planning and taking up more challenging jobs in radioactive environments.

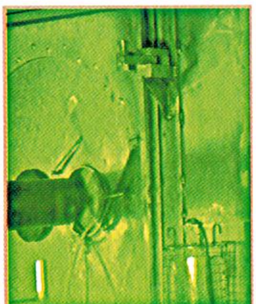
Solid Waste Disposal

The hot cells of Radio metallurgy Laboratory generate considerable amount of radioactive wastes during each post irradiation examination campaign. The major component of the waste includes the irradiated stainless steel structurals of fuel subassemblies, control rod subassemblies, special subassemblies, irradiation capsules, failed equipment components, etc. To avoid accumulation of wastes in the precious hot cell space, they have to be disposed off periodically.

Since these wastes are β-γ type of very high activity (28 TBq), a special campaign was undertaken for transferring them from hot cells to CWMF tile holes. A special waste transfer container, a shielded cask and

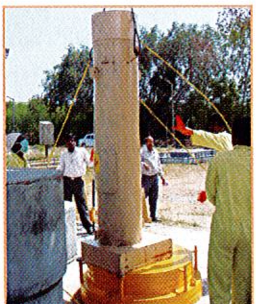


Loading of solid waste into the container



Transfer of container through cell door opening

Transfer of container to shielded cask



Disposal of solid waste in tile hole

Disposal of irradiated structural material

a top shield matching the tile hole were fabricated for this purpose. The rear door of the Cell-4 was provided with a 200 mm diameter opening. A mobile shield was placed behind the cell door to provide compensatory shielding. The shielded cask was aligned with the mobile shield to facilitate the remote transfer of waste filled containers from the cell and transported to CWMF. The shielded cask was placed vertically on the tile hole top shield and the waste transfer container was transferred to the tile hole by opening the door of the shielded cask.

A very meticulous planning along with theoretical estimation of waste activity, shielding calculations for the cask, top shield and compensatory mobile shielding, preceded the campaign. This resulted in minimum man-rem exposure and a successful transfer of about 200 kg of irradiated structural materials of experimental and fuel subassemblies was carried out.

Leak Detection

As plutonium rich uranium carbide fuel handled in RML hot cells is highly reactive with oxygen and moisture, it is necessary to maintain high purity inert atmosphere in the hot cell. Online oxygen and moisture sensors monitor the purity of hot cell gas.

Any leak of atmospheric air to hot cell dilutes the desired purity. The sources for leak may be due to breach of leak-tight-sealings of various openings like MSM port, VTS, HTS, man entry door, roof plug door, glove box port, cabling ports, ventilation pipe lines etc. Various leak testing techniques, such as smoke test, air flow velocity meter (anemometer) and oxygen sensor positioned inside the hot cell are being exploited to locate/identify the leak point. A high volume of smoke is generated using a harmless chemical smoke generator and injected into the suspected port/locations. In case of a leak, the smoke will be sucked into the hot cell due to the negative pressure in the cell and can be observed through glass window and periscope. In the case of large opening like MSM ports, VTS and HTS, the opening are partially sealed leaving a small opening and the air velocity measured using a sensitive anemometer detects and quantifies the leak if any.

The flexible PVC bootings of the MSMs have been found to be the weakest point because of continuous use and prone to mechanical damage like puncturing and tears.

Replacement of MSM booting

The replacement of the defective booting is carried out using a Remote Booting Changing Device (RBCD). Fresh booting in a specially folded condition is loaded in RBCD and fixed to MSM port using compressed air. This also ejects out the old booting into the cell. A step wise procedure is adopted for replacing the booting without spread of contamination and breach of containment.

Radiological Safety

The seven concrete hot cells and the KAMINI reactor in the laboratory are the main areas where highly radioactive materials are handled in RML. To comply with the basic objectives of radiation protection viz., to protect occupational workers, members of public and the environment from the adverse effects of radiation while at the same time allowing the justified activities of the laboratory, a comprehensive plan for radiation hazard control is available. Towards this, radiation protection procedures were established and are available in the form a manual. This manual gives in detail the responsibilities of various agencies involved, the work techniques, use of protective equipment, radiation surveillance schedule, management of waste disposal, training of personnel, monitoring of personnel for external exposure and contamination, assessment of internal contamination and effluent monitoring.

The zoning philosophy adopted for the laboratory combined with proper ventilation of different areas on a once through principle with adequate number of air changes ensures control of contamination and minimize internal exposure. The discharge of different radionuclides through the stack is monitored for particulate and gaseous activity on a continuous basis with the help of installed radiation monitors.

Radiation monitors such as Area gamma monitors and continuous air monitors are installed in all the strategic locations of the laboratory. These monitors in combination with radiation survey done using portable monitors help in controlling the radiation exposures to occupational workers.

All radiation work in the laboratory is controlled by a radiological work permit system. Personnel monitoring devices like Thermo Luminescent Dosimeters (TLD) are issued to all the personnel to assess the external exposures. Internal exposures are evaluated by whole body counting annually. The laboratory is fully equipped with various kinds of protective clothing and equipment. Liquid effluents generated in the laboratory are monitored and the activity estimated before they are disposed. Solid waste generated are classified, segregated, packed properly and tagged before they are sent to CWMF. All material movement in and out of the laboratory is administratively controlled with proper radiological surveillance.

To discuss and implement additional safety procedures during special work like openings of cell roof plug and cell door for maintenance work, disposal of highly active cut pieces of irradiated subassembly wrapper, shear punch testing of structural materials, a Hot cell Operations Review committee (HORC) is constituted. This committee convenes meeting at regular intervals for review and implementation of safety measures.

The Atomic Energy Regulatory Board (AERB) has been carrying out regulatory inspection of the laboratory every year. The suggestions and recommendations given by the AERB regulatory inspection team have been strictly complied with by the laboratory management.

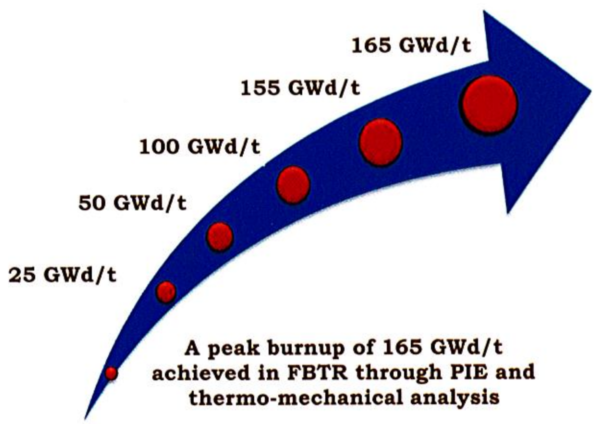
Radiation protection training courses and refresher courses are conducted regularly, as part of creating safety work culture and awareness about radiation among occupational workers and temporary workers.

The fifteen years of experience of radiological safety surveillance at RML has been very rich and of interest to the Health Physics (HP) Unit.. The emphasis placed on calibration and appropriate laboratory surveillance procedures have ensured that all the radiation monitors have worked as intended. This proved to be useful in providing an effective HP surveillance. The HP Unit acquired expertise in tackling unique special operations such as contact maintenance of in-cell equipment. There were no cases of internal exposure so far. The negligibly low man-rem expenditure have reaffirmed the fact that the radiation protection procedures were well established and complied with. The efforts put forth by the HP Unit, in association with the plant management has paid rich dividends in setting an impeccable radiologically safety record in RML.

Utilisation of PIE facility

The hot cell facility at RML has catered to the requirements of Indian fast reactor programme by carrying out performance assessment of various core components of FBTR and has provided valuable feedback to the designers and reactor operators. So far 24 subassemblies have been handled in the hot cells over the last 15 years as summarized in the table.

Subassembly details	No. of subassemblies
Driver fuel subassemblies	5
Control rod assembly	1
Nickel reflector subassembly	1
Experimental subassemblies	
Test fuel pins (Mark I carbide fuel)	7
Pre-pressurised creep capsules of Zircalloy and Zr-2.5% Nb	6
Activation foil for fluence measurement	1
Medical isotope production	1
FBTR grid plate material irradiation	1
Test irradiation of MOX fuel pin (PFBR composition)	1



ROAD MAP FOR FUTURE

With the fast breeder reactor entering commercial domain, attaining high fuel burnup is very crucial for producing power at competitive rates. Economy of fast breeder reactors is critically linked to the performance of fuel and the structural materials. Hence the importance of R&D on developing high performance fuels and structural materials cannot be overemphasized. Development of metallic fuel with high breeding gain and advanced structural materials capable of withstanding radiation damage upto 200 dpa are underway. The post irradiation characterization of the high burnup advanced fuels and structural materials require sophisticated analytical techniques, simulation and modeling studies.

Considerable expertise has been gained in various activities related to PIE during the last 20 years. It is imperative to sustain the progress and activities already made in PIE and further establish new techniques and adding state of the art facilities which can give more information on the irradiation behavior of the advanced fuel and structural materials. PIE team is gearing up towards establishing the facilities and human resources for achieving this goal.

The road map and future directions in the activities of PIE are need based and are briefly summarized below.

Microanalytical techniques for the PIE of advanced fuels

Microanalytical techniques are inevitable for comprehensive understanding of fuel behaviour such as fuel-clad interaction, fission product redistribution and phase evolution. Towards achieving the above goal, it is planned to establish electron optical equipment like shielded electron microprobe and XRD equipment in shielded containment box with inert atmosphere. The challenge includes modification of electron and X-ray detectors of SEM for examination of irradiated specimens.

To evaluate the performance of advanced cladding and wrapper materials such as D9, D9I, ferritic steels etc, microstructural studies using TEM is necessary. Reliable evaluation of tensile and fracture toughness properties (DBTT) for the performance assessment of advanced structural materials such as ferritic steel are the areas of focus for structure property correlation.

Safety related simulation studies

One of the important inputs required by the designers, reactor operator and regulators is the behavior of the fuel and structural material under off normal operations / transient conditions. This requires setting up of facilities like remotely operable high temperature furnaces with close control of environment & temperature and characterization using metrology, mechanical property and microstructural techniques.

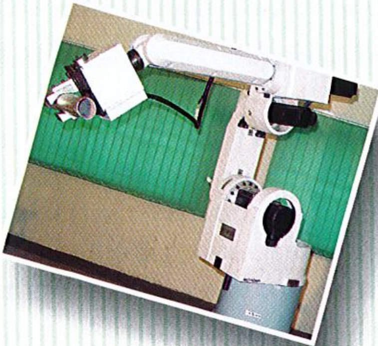
Facility for refabrication and reirradiation

Refabrication and re-irradiation is another important area in the hot cell technology which needs to be established. Refabrication and reirradiation of fuel pins already subjected to PIE will result in considerable savings in irradiation time to reach high burnups /dpa and optimum utilization of reactor space. It also enables examination of the same fuel pins/structural materials at different burnups/radiation damage dose.

The facility needed in the hot cells for this challenging task involves setting up of high precision welding facility and qualification of the refabricated irradiated capsule by various techniques and its transfer to the reactor core. These equipment have to be conceptualised, developed and validated along with thermal and mechanical modeling to study the integrity of the re-fabricated capsules.

Modeling Studies

Modeling helps in reducing the experimental matrix and at the same time extending the predictive capabilities using the valuable PIE data generated. Very often, the structure of an irradiation experiment is determined by the modeling done for understanding a particular irradiation behavior and fine tuning the generated model. This iteration also facilitates fine tuning the PIE methods. Future directions include extensive modeling and irradiation experiment studies to gain a better understanding of the fuel and structural material behaviour.



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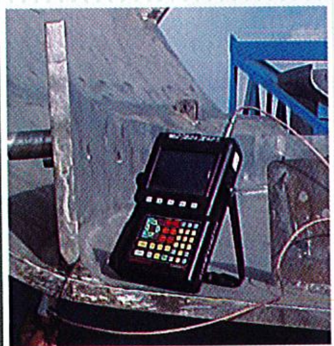
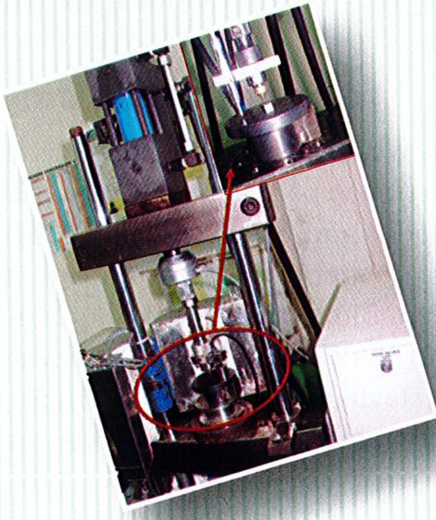
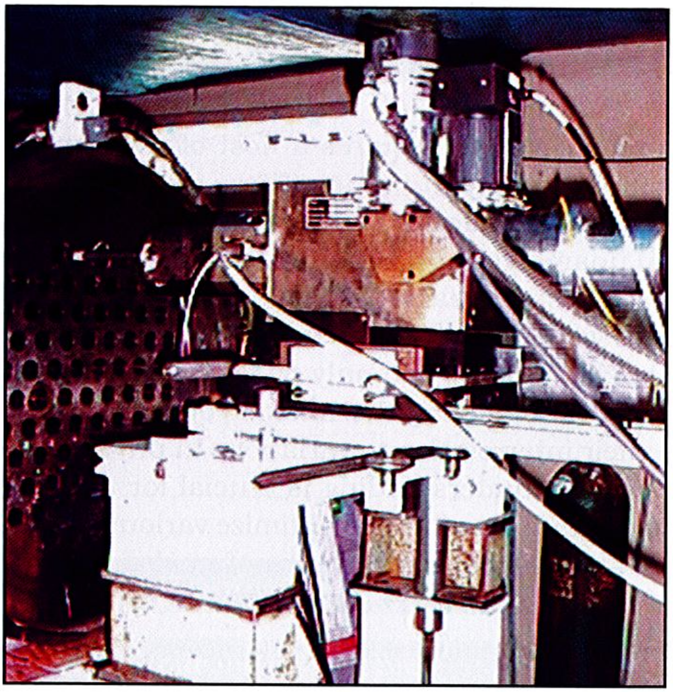


Other Facets of RML

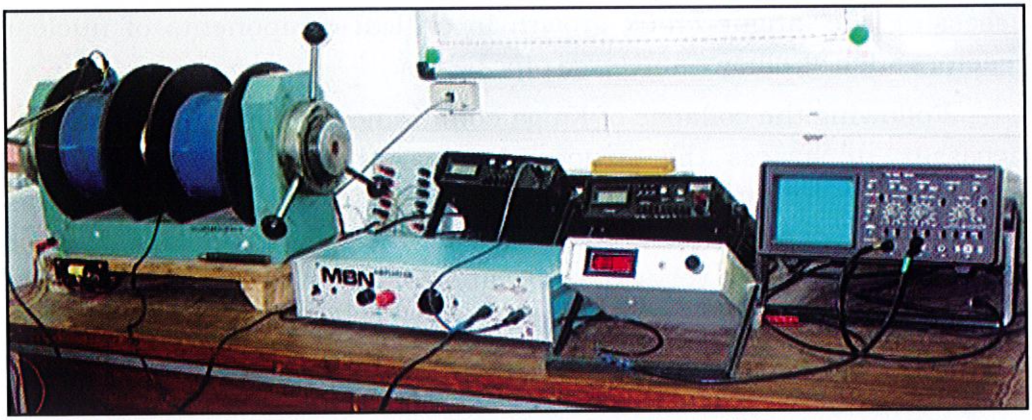




Microfocal radiography of TTS weld joints of PFBR SG

first time. In the later stages, in order to detect defects in cladding tubes having chatter (periodic wall thickness variations of ~ 15 microns), multi-frequency, artificial neural network and wavelet transform based methods have been developed. Laser profilometry has been developed to measure the banded structure of cladding tubes. For quality assurance of end plug welds, as a replacement for metallography, ultrasonic technique with signal processing method was developed. For quality assurance of hexcans and hexcan seal welds of PFBR fuel subassemblies, guided wave based ultrasonic methods have been developed after detailed studies on calibration blocks.

Quality assurance and pre-service inspection of modified 9Cr-1Mo steel tubes of steam generators (SG) of PFBR was a major task. As the material is ferromagnetic, saturation based eddy current methodology was developed and implemented at the tube manufacturing site at Nuclear Fuel Complex (NFC). All the tubes were quality checked by this methodology. In order to qualify the welding procedure of tube-to-tube sheet welds (TTS), microfocal radiography technique was developed and



Magnetic Barkhausen Emission measurement system

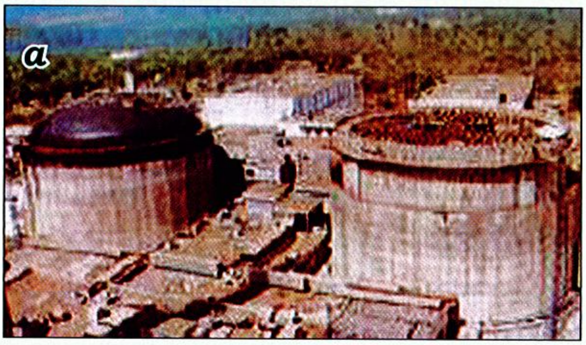
this was successfully implemented for fabrication of steam generators of PFBR.

For optimizing the post weld heat treatment that is adopted for the TTS weld joints, a procedure based on Magnetic Barkhausen Emission (MBE) has been developed. It was required to assess the concavity of the weld profile and an internal replica based method was successfully developed and implemented at Larson & Toubro (L&T), Mumbai.

Facility and procedures were established for X-radiography of irradiated fuel pins to delineate plenum, spring and fuel regions. Image processing techniques were developed and implemented for enhancing the information of defects in X-radiographs. Emphasis was also given to develop image analysis techniques to obtain quantitative information from fuels and structural materials. Procedures for automated measurement of grain size, second phase particles, and fractal dimensions of microstructures have been developed. Expertise gained in conventional, real-time and digital X-radiography has also been used for quality assurance. Eddy current technique and probes have been developed for PIE of FBTR fuel pins in hot cells of RML. These were used during the PIE campaigns on fuel pins at various levels of burn up. Saturation based eddy current technique has been developed for NDE of Modified 9Cr-1Mo oxide dispersion strengthened (ODS) fuel clad tubes. Simulation studies have been performed for detection of sodium voids in sodium bonded metallic fuel pins.

Acoustic emission technique has been used for structural integrity assessment of steam generators during hydrotesting and also for assessing the fatigue crack growth in critical components of nuclear reactors such as elbows and large pipe bends.

Following the collapse of Kaiga containment building dome, it was necessary to assess the structural integrity of ring beam of inner containment structure using a suitable NDT technique. The concern was whether the damage has propagated to the ring beam also, whose replacement would be very expensive and complicated due to its massive size (inner dia ~ 42.5m and thickness ~1.2 to 1.6m). RML has successfully adapted impact echo technique for ensuring the structural integrity of the ring beam. As no codes and standards existed for the impact echo testing, procedures were developed for testing large concrete structures by carefully conducting experiments on mock-up blocks. These studies enabled to establish the sensitivity, advantages and limitations of the technique for testing large concrete structures. Based on this rich experience, the condition assessment of the ring beam of the dome was successfully completed. This has enabled the regulatory authorities to give a go ahead decision and the reactor dome was further constructed on the same ring beam. A Bureau of Indian Standards (BIS) document has been released based on this experience.



(a) Collapsed dome of reactor containment building

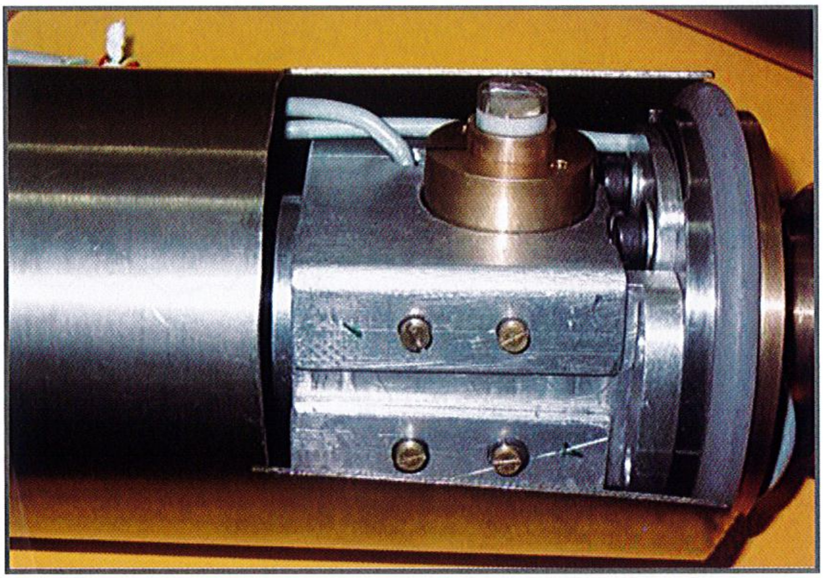
(b) Mock-up block of the ring beam used for experiments

Similarly, whenever there is a fire, one of the suspects in integrity assessment is concrete. It has been demonstrated that impact echo testing can be used to assess the average damage in concrete after exposure to sodium fire. The depth of damage due to sodium fire has also been determined by low frequency ultrasonic velocity and relative attenuation measurements on specimen extracted from concrete blocks exposed to sodium fire. This would help in deciding the thickness of the sacrificial layer of lime stone aggregate concrete over the structural concrete in the steam generator building of PFBR.

Development of sensors

It was realised at a certain stage that NDE activity would not be complete without development of specialised sensor. Therefore concentrated efforts were put in to develope sensors in-house.

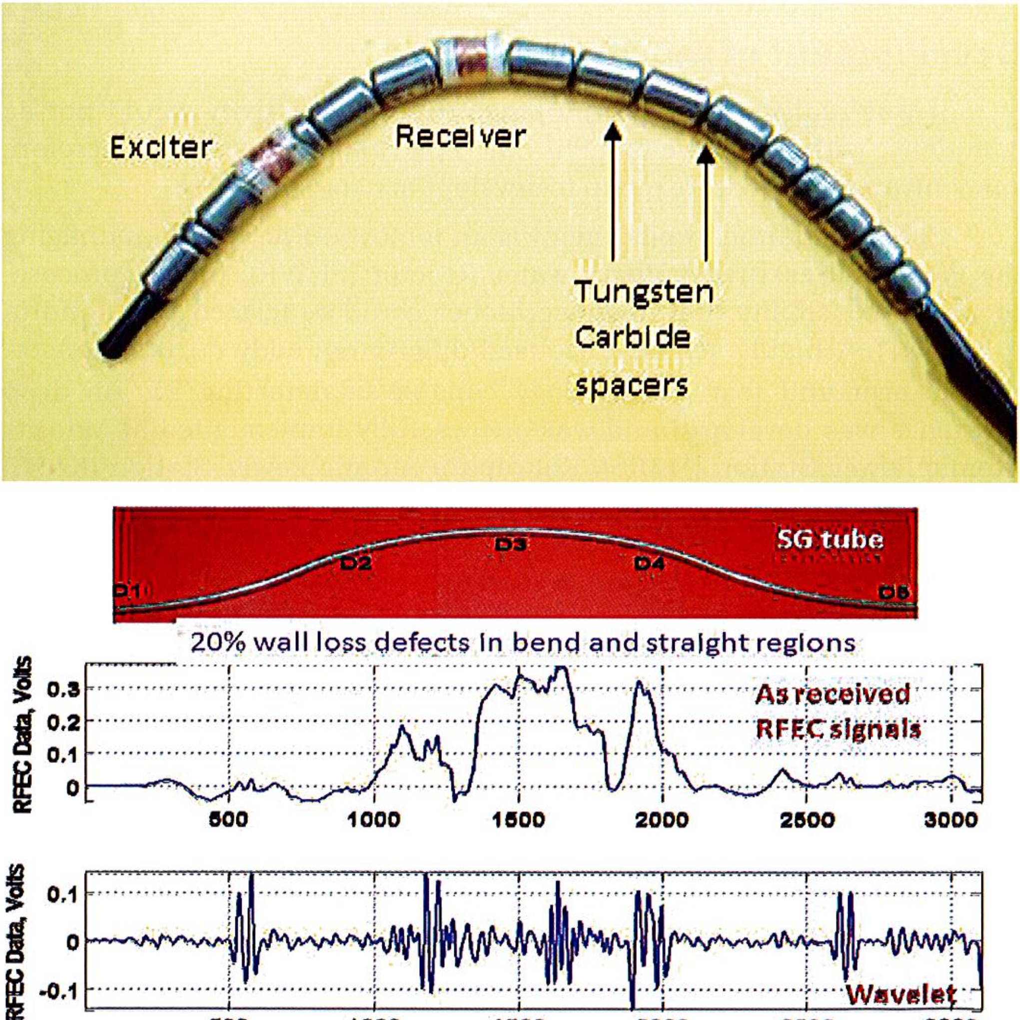
Coolant channel replacement is an important activity in managing the life of a Pressurized Heavy water Reactor (PHWR). In this process, there is a possibility that micro scratches could be formed on calandria tubes (CT). A highly sensitive focused differential eddy current sensor, robotic arm and test methodology capable of detecting 25 μm deep scratches was developed and was successfully implemented at Madras Atomic Power Station (MAPS), Kakrapara Atomic Power Station (KAPS)



Focused eddy current sensor for scratch detection in calandria tubes

and Rajasthan Atomic Power Station (RAPS) during *en masse* replacement of pressure tubes.

For in-service inspection of installed SG tubes of PFBR, a comprehensive Remote Field Eddy Current (RFEC) technology comprising of instrumentation, flexible bend-negotiable-probes, methodology and robotic devices has been developed after detailed three-dimensional finite element model based optimization. Wavelet transform based signal processing method has been developed to suppress the



RFEC probe for SG tube inspection and signal processing around the bend region to extract defect information

influence of bend regions, Inconel support plates and electrically conducting sodium deposits on the outside surface of SG tubes.

An indirectly excited eddy current based position sensor has been developed for Diverse Safety Rod of PFBR. This is in the final stages of validation.

Fibre optic technique has been developed for *in situ* distributed measurement of temperature and strain on sodium loops of PFBR etc. This technique is further extended for detection of sodium leaks in the sodium circuits of PFBR.

In another situation involving detection of intergranular corrosion, eddy current giant magneto-resistive sensor based methodology has been developed. NDE laboratory of RML has nurtured systematic synthesis and characterization of nanoparticles and ferrofluids for a variety of novel applications. Ferrofluids are proposed to be used for developing mechanical seals of primary pumps of PFBR.

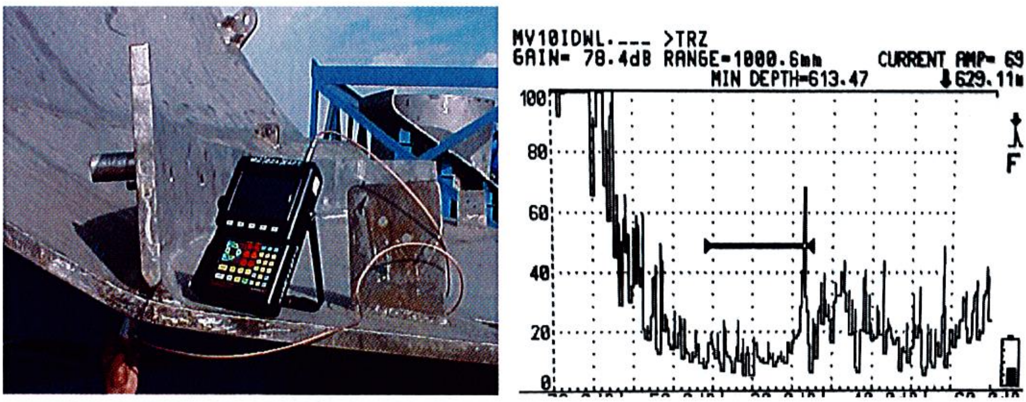
NDE in ISI

Any component or structure, while in use over a long period of time, will undergo changes in physical and mechanical properties. The load cycles and / or thermal stress cycles may nucleate defects, which in due course may grow and ultimately lead to failure. If we could detect these defects in time through In-Service Inspection (ISI), a planned shutdown can be done for repair/replacement of the component. ISI of components or structures, if carried out regularly, can detect such defects at an early stage and keep a tag on them to take necessary action in time. ISI will also help in assessing the remaining life of components and structures. While quite a few NDE techniques are adopted during fabrication stage, not all of them are suitable for ISI. NDE laboratory of RML has taken special interest in this direction and has come out with suitable solutions for various ISI requirements of our nuclear programme.

Catering to the challenging requirements of pre-service inspection (PSI) and in-service inspection (ISI) of PHWR Zircaloy-2 pressure tubes used in PHWRs, eddy current probes and techniques were developed to precisely locate garter springs and measure gap between pressure tube and calandria tube. The probe dimensions were optimized using axi-symmetric finite element eddy current model. Several ISI campaigns at Narora Atomic Power Station (NAPS), MAPS, KAPS and RAPS were undertaken by RML personnel jointly with the NPCIL engineers.

Observation of leaks in the end shield of RAPS#1 unit demanded development of an on-line technique. RML took up developmental work by using acoustic emission technique and time and frequency domain based methods. This enabled successful detection of leaks during pressure testing of the end shield by employing very low air pressure. Similarly, acoustic emission technique was also developed for identification of a leaking coolant channel in MAPS.

In-service inspection of shell weld of core support structure of PFBR is a challenging task. This was because, once the main vessel is filled with sodium, there is no direct access to the weld region. All the inspection has to be done from the outer surface of the main vessel. An innovative multiple reflection based ultrasonic inspection methodology has been developed to circumvent this problem. This has been demonstrated on a full scale mockup sector of PFBR. CIVA numerical modeling has been performed to understand and verify the procedure developed for inspection of shell weld of core support structure.



Ultrasonic inspection of shell weld region of mockup sector of PFBR and corresponding A-scan signal of a defect

Eddy current imaging based method has been developed for weld centerline determination to facilitate ultrasonic inspection of main vessel welds. Ultrasonic methodologies for in-service inspection of secondary sodium circuit components of FBTR have been developed.

For detection of hydrides in Zircaloy-2 pressure tubes, method based on ratio of ultrasonic velocities was developed and for detection of oxide inclusions in Zircaloy-2 end plug rods, a unique multi-NDE methodology was developed.

ISI of steam generator test facility (SGTF) in IGCAR consisting of 19 tubes with expansion bend regions identical to steam generators of PFBR has been successfully performed using the flexible remote field eddy current probe, instrument and winch mechanism developed in-house.

NDE laboratory of RML is the one of the first few laboratories in India to put infrared thermography to use. Condition monitoring of electrical sub-stations, switch yards and transmission lines of MAPS and IGCAR were some of the important tasks handled using thermography, besides assessment of health of transformer.

In order to assess in-service fatigue damage in MAPS turbine blades, X-ray diffraction (XRD) technique has been used to measure redistributed residual stresses. Depending on the challenging inspection situation, available access and desired sensitivity level, NDE techniques and inspection methodologies have been developed for meeting the challenges in ensuring safe and reliable operation of nuclear reactor components and structures.

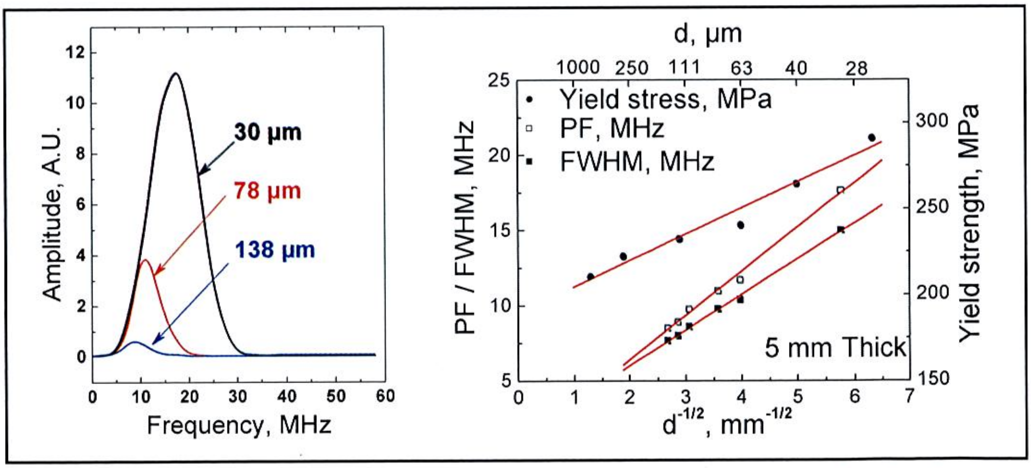
During the *en masse* replacement of coolant channels of MAPS 1&2, NAPS 1&2 and KAPS 1, scratches were suspected to be formed inside the calandria tubes. Since the wall thickness of the calandria tube is only 1.25 mm, it is necessary to find out the scratches formed if any and its depth before inserting new coolant channels inside calandria tubes. For detection of scratches, RML has designed and developed a highly sensitive focussed differential surface eddy current sensor. A sensor head with special design features was fabricated for the purpose of inserting and positioning of the sensor precisely inside the calandria tube at various locations. The special features of this system are a spring loaded sensor to minimise lift off variations and special mechanical fixtures with reduced weight for smooth passage of the sensor assembly inside the tube. Based on this in-service inspection, clearances were given for re-tubing.

Characterisation of materials and microstructures

NDE laboratory of RML has developed several first of the kind NDE methodologies for characterization of microstructures, deformation and damage in various alloy systems including ferritic steels, austenitic steels, maraging steel, zirconium alloys, nickel base superalloys and titanium alloys using ultrasonic, micromagnetic, MBE, eddy current, acoustic emission, thermography and X-ray diffraction techniques. It has been demonstrated through these efforts that finer aspects of microstructural features at submicroscopic level and sometimes even nanoscale level can be characterized using NDE techniques. These studies were specifically oriented towards ensuring suitable microstructures and mechanical properties at the fabrication stage and for monitoring damage and degradation in service. Fundamental research was focussed on understanding material behavior and interaction of various probing media with materials.

A new correlation has been established between two independent elastic properties viz. ultrasonic shear wave velocity and Poisson's ratio, for isotropic solid materials such as various elements, alloys, polymers, intermetallics, ceramics, nano-crystalline materials and bulk metallic glass. The study has revealed, for the first time, that Poisson's ratio decreases with increase in both elastic moduli (Young's and Shear) and ultrasonic velocities. A thickness independent approach has been developed for material characterization based on the measurement of Poisson's ratio (using ratio of longitudinal to shear wave velocity) and this has been successfully applied for *in situ* characterization of precipitation / embrittlement in Inconel 625 ammonia cracker tubes in heavy water plants at Thal and Tuticorin.

Various ultrasonic methodologies have been developed for measurement of grain size in austenitic stainless steel, such as ultrasonic attenuation, ultrasonic relative attenuation, ultrasonic



Autopower spectra of ultrasonic backwall wall echoes obtained from 316 stainless steel specimens with different grain sizes and variations in yield stress, peak frequency and full width at half maximum of the autopower spectra of the backwall echoes with the grain size

velocity, spectral analysis of the ultrasonic backwall echo and joint-time frequency analysis. The change from analog to digital and then to advanced signal analysis approaches for enhancing the sensitivity and reliability of the techniques demonstrates the progressive and dynamic approach of the NDE laboratory of RML. Over the years, developments took shape from single point measurements to imaging.

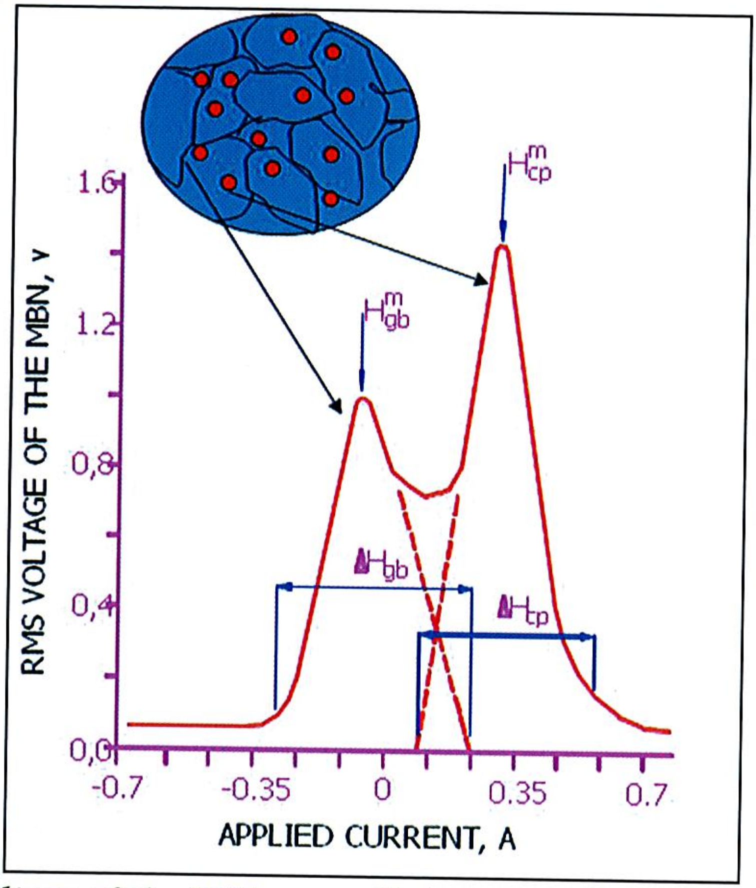
Based on investigations in Ni-base alloys, Zr-base alloy and maraging steel, it has been established for the first time that the elastic properties of a precipitation hardened alloy is primarily governed by the contraction of the lattice of the matrix. For characterization of microstructures of titanium alloys, ultrasonic and eddy current methods have been developed. Beta-transus temperature has been accurately determined using ultrasonic method and conductivity of α′ martensite phase using eddy current method.

Using MBE parameters, a two-stage magnetization process has been proposed for sufficiently tempered microstructures, considering the grain boundaries and the carbide precipitates as the two major types of obstacles to the domain wall movement which produce two distinct peaks. The model has been validated in carbon steel, 2.25Cr-1Mo steel and 9Cr-1Mo steels.

MBE technique has also been used to characterize various stages of tensile deformation and assess low cycle fatigue (LCF) damage in 9Cr-1Mo ferritic steel. The RMS voltage peak of the MBE profile has also been correlated to tensile strength in simulated heat affected zone microstructures of weldments of Cr-Mo steels and short-term thermally aged microstructures in 17-4PH steel and impact toughness in aged 17-4 PH steel. MBE has also been used for measurement of the depth of induction hardened layer and extent of in-service carburization in ferritic steels.

It is often difficult to characterize completely complex microstructural changes occurring in a material by a single NDE technique. For such cases, multi-parametric approach has been followed. A typical example for this is the characterization of various simultaneous and complex microstructural changes occurring in M250 grade maraging steel upon ageing using parameters from ultrasonic, positron annihilation, XRD, MBE and eddy current techniques.

Dynamic NDE techniques such as acoustic emission and thermography have been used for understanding the deformation



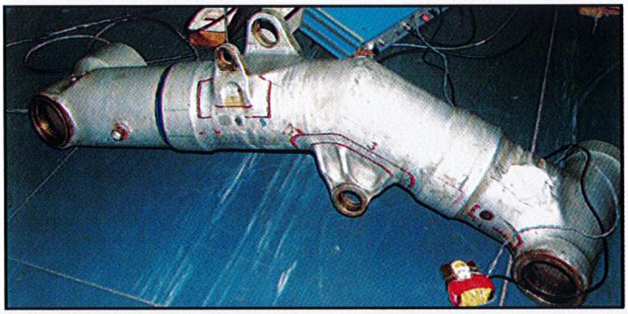
RMS voltage of the MBE vs. applied current showing two stage magnetization process in tempered steels: $H_{gb}{}^m$ and $H_{cp}{}^m$ correspond to obstruction of the movement of domain walls due to grain boundary and carbide phase respectively

mechanism in ferritic steels, nimonic alloys and austenitic stainless steels. Acoustic emission technique has been used for mechanistic understanding of dislocation dynamics, deformation processes, phase transformations, detection of early fatigue damage, understanding fracture behaviour and oxidation behaviour in nuclear structural materials.

Acoustic amplification, a new phenomenon, where hibernating acoustic emission sources are amplified by external ultrasonic injection, has been successfully demonstrated in a variety of materials. Non-linear ultrasonic technique has been established for characterization of microstructures in maraging steel, carbon steel and stainless steel and also for evaluation of tensile strength in cold worked stainless steel.

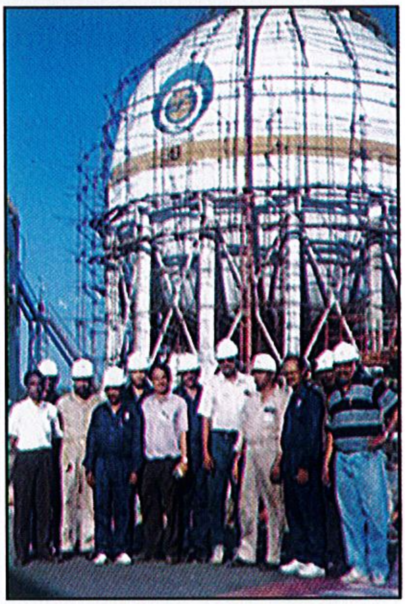
NDE for core sectors

RML has extended its NDE expertise in providing unique solutions to critical problems of national importance in defence, space and core industries. XRD and MBE have been applied for assessment of fatigue damage in landing gears of fighter aircraft. Other areas where NDE techniques have contributed are for the ultrasonic examination of liquid propellent tanks of satellites for ISRO and acoustic emission testing for qualification of LPG Horton sphere.



Fatigue damage of landing gears of fighter aircraft assessed using X-ray diffraction and MBE techniques

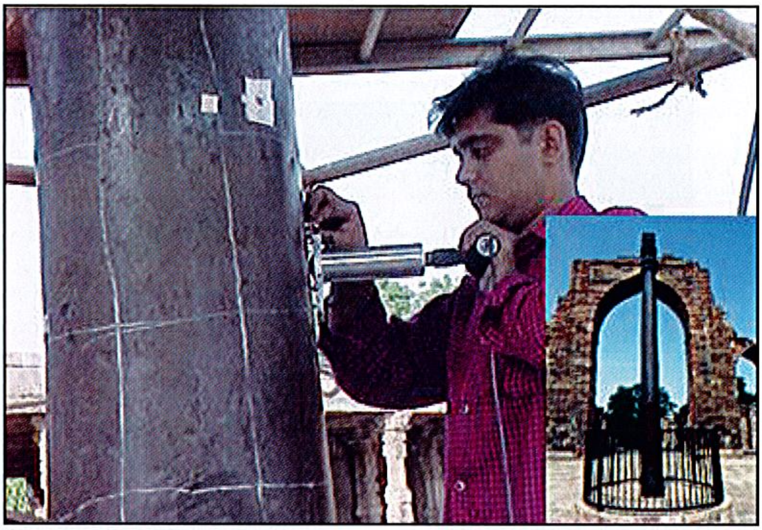
Ultrasonic examination of IR-Satellite propellant tanks of ISRO at LPSC, Bangalore



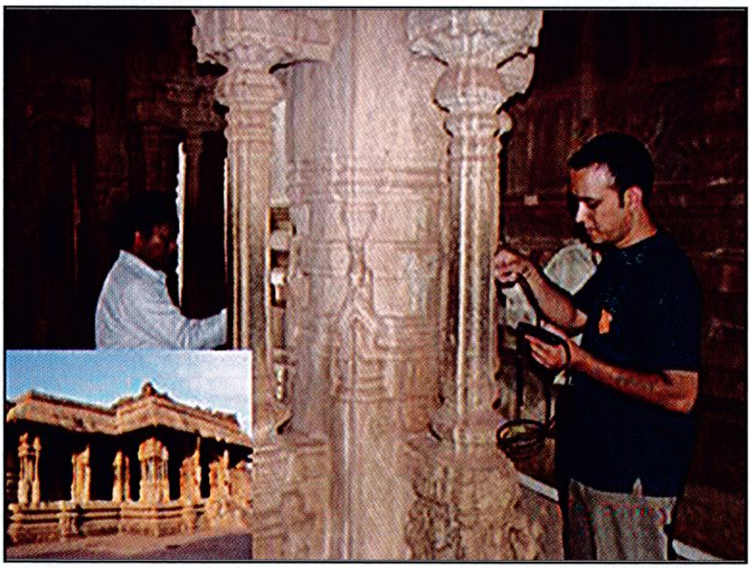
Qualifying LPG Horton Sphere using AE technique during the proof testing

NDE for societal applications

NDE laboratory has carried out campaigns of importance to the Indian culture and heritage such as study of Delhi Iron pillar, fingerprinting of South Indian bronze idols at Government museum, Chennai, metallurgical investigation on Roman coins and study of acoustical aspects of musical pillars at Hampi.



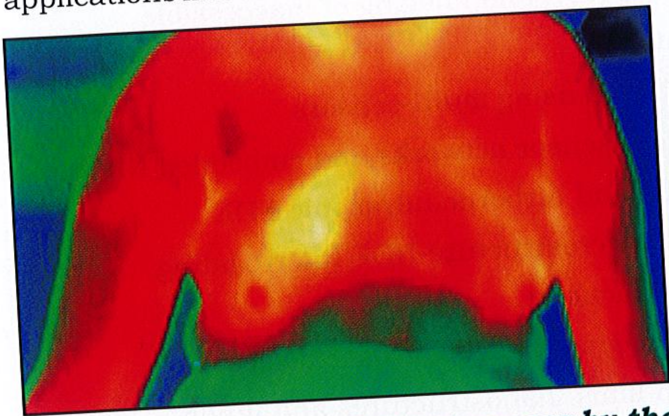
A scientific study on Delhi iron pillar - the 'rustless wonder'

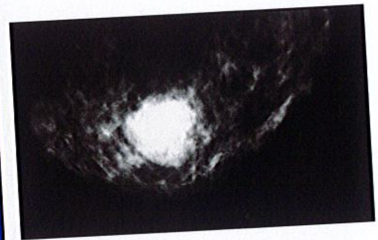


At Hampi, investigating the melodies of 'musical pillars'

The imprint of NDT laboratory of RML is cast on social sector also. For example in healthcare, quality control procedure was evolved for artificial heart valves developed by Sree Chitra Thirunal Institute of Medical Science and Technology, Thiruvananthapuram.

Thermographic techniques were developed for clinical diagnostic applications like detections of neuropathy and breast cancer





Early detection of breast cancer by thermography (left) and confirmation by mammography (right)

Quality control of the silver and gold content in the zari used in silk sarees is conventionally done by time consuming and destructive chemical analysis. RML, in a TIFAC sponsored project, has developed a non-destructive X-ray fluorescence (XRF) based methodology for M/s Tamil Nadu Zari Ltd. This technique can be applied directly on actual sarees which is a boon to the consumer.

A customer getting her saree tested by XRF based zari analysis system

The Future......

- Rapid NDE of large structures
- *In situ* and on-component NDE
- Guided wave NDE and imaging of inaccessible components
- Integrated NDE using multi-sensors
- NDE wireless sensor networks and embedded NDE
- Non-contact and Airborne ultrasonic NDE
- Modeling of microstructure-NDE interrogating medium interactions
- Terahertz imaging for deep surface defects
- NDE of thin films, nanostructures and fluids
- Intensifying research, collaborations and institutional networks

IRRADIATION EXPERIMENTS IN FBTR

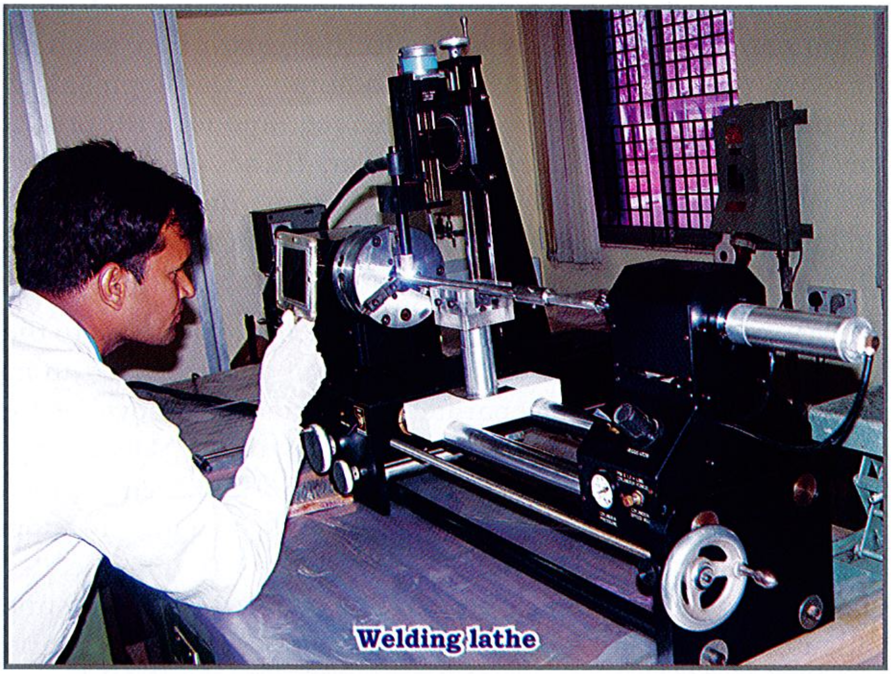
Fuel and structural materials undergo degradation of properties due to the harsh conditions prevailing in the reactor core such as high neutron flux, temperature and liquid sodium. Development of high performance fuel and structural materials required for FBR programme requires testing of the materials under these conditions. This requirement is met by conducting custom designed irradiation experiments to extract information either on-line in the reactor or by PIE in the hot cells.

In view of the importance of the irradiation experiments to the FBR programme and the amount of developmental effort needed to initiate and carry out this activity, a separate section named Innovative Design, Engineering and Synthesis Section (IDEAS) under Metallurgy and Materials Group was formed in the year 1995. The irradiation experiments programme has been nurtured and passionately supported by Dr. P. Rodriguez and Dr. Baldev Raj. Shri P.V.Kumar headed this section and established a separate laboratory for this activity and was instrumental in developing the capability to carry out a variety of experiments.

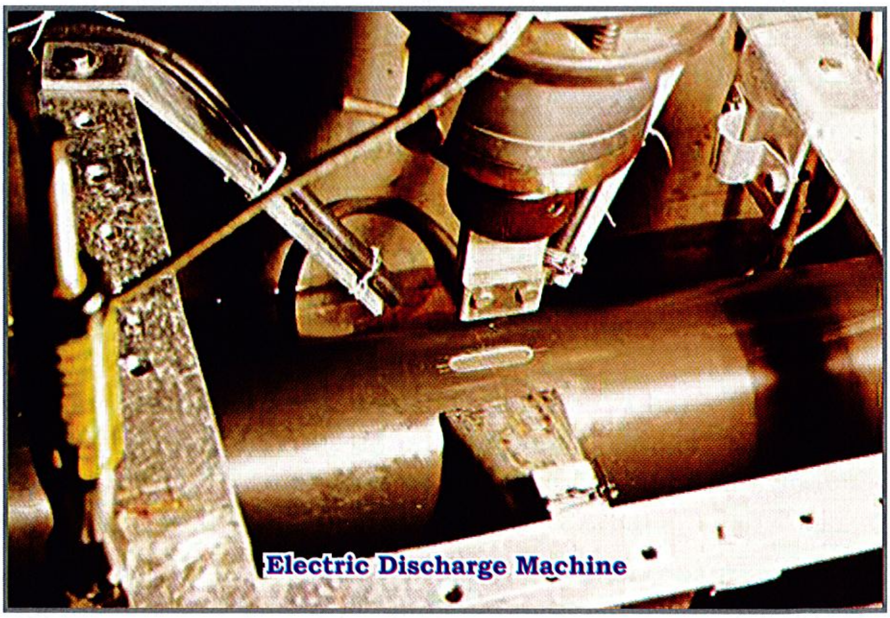
Generous technical guidance was provided by senior members of Reactor Engineering Group and Reactor Physics Division of IGCAR, particularly by Shri S. Govindarajan, Shri A.S. Dixit and Dr. S.M. Lee. Various irradiation experiments carried out in FBTR were made possible with active support of several colleagues belonging to design, reactor operations and post irradiation examination groups. NFC, BARC, and NPCIL, have also contributed significantly to this programme.

IDEAS has specialized in design and planning of irradiation experiments in FBTR including the design and development of miniature precision devices and irradiation capsules required for carrying out the irradiation experiments. Theoretical analysis and modeling work, out-of-pile laboratory experiments, precision welding and fabrication work etc. are carried out in IDEAS.

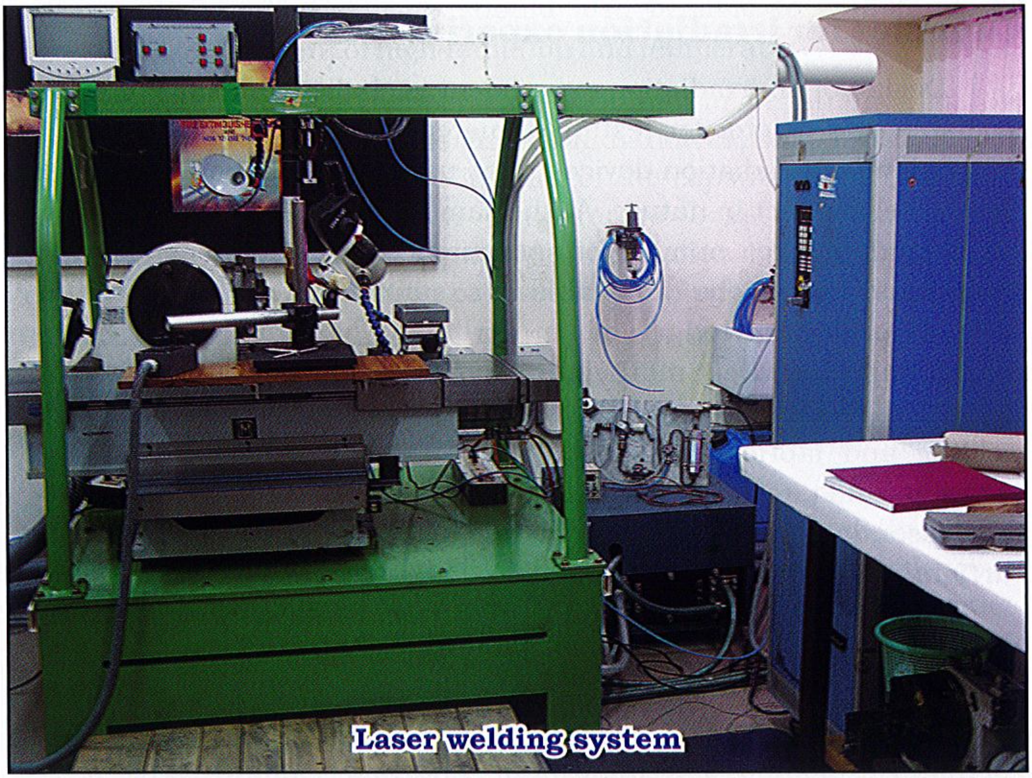
Precision machine shop, laser welding system, clean room facility and electric discharge machining facility are some of the main facilities established in IDEAS. Indigenous capability and expertise has been developed to carry out a variety of irradiation experiments in FBTR. Efforts are made continuously to improve the infrastructure, expertise and capabilities.



Welding lathe

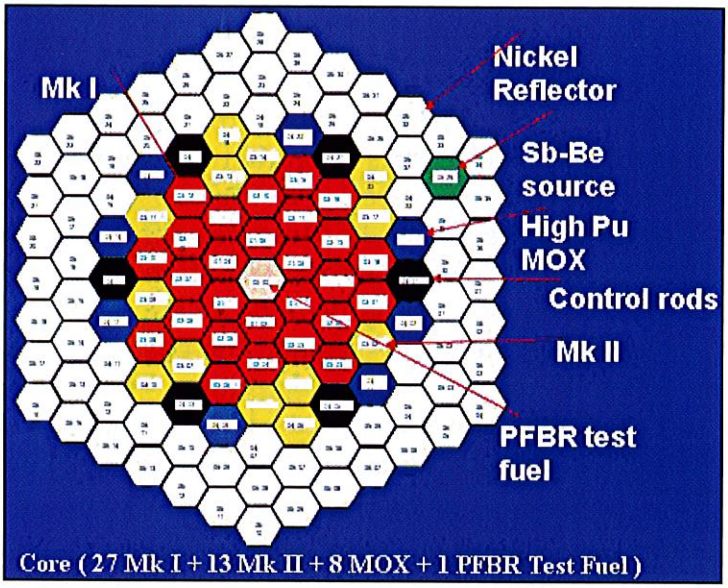


Electric Discharge Machine



Laser welding system

Clean Room



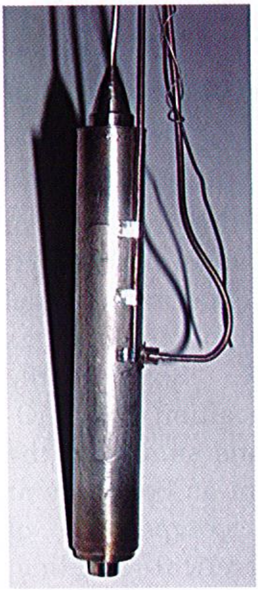
Core of FBTR (upto 6th ring)

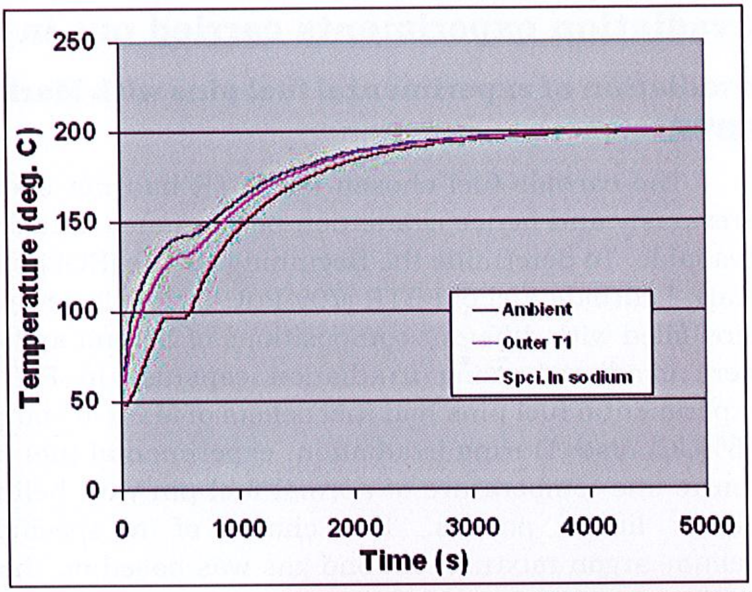
special subassembly will be loaded in the core of FBTR at any ring including the core centre depending on the flux and temperature conditions required. There are many positions available in FBTR for irradiation of non-instrumented capsules. Positions for instrumented capsule irradiation in FBTR are limited. The central 0-0 position of the core of FBTR, where flux is maximum, can be used for instrumented irradiation experiments.

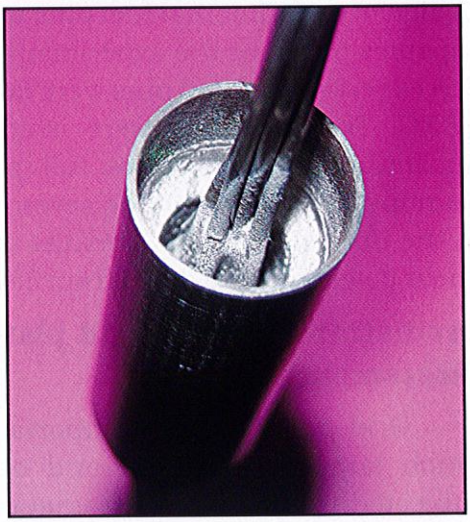
Development of irradiation capsules

Many new approaches are followed for development of capsules for irradiation experiments. Compact pressurized capsules of zirconium alloys and D9 alloy have been developed in IDEAS to determine the in-reactor creep behaviour of core structural materials of thermal and fast reactors respectively. Non-instrumented irradiation capsules with vent holes for irradiation in the temperature range of 400 to 425°C and high temperature gas-gap capsules for irradiation at temperatures upto 600°C have been developed in IDEAS.

Instrumented fuel irradiation capsule to measure the fuel central temperature and clad temperature on-line during irradiation and instrumented structural materials irradiation capsule to measure and control the specimen temperature during irradiation using thermocouples and heater coils are under development.







Development work of nicrobrazing of thermocouples with a solid plug by induction heating method

In a typical development work for instrumented irradiation experiment, a capsule of 20 mm OD has a sub-capsule arranged within it containing specimens immersed in sodium and with attachment of three thermocouples. Argon is filled in the annular space between capsule and subcapsule. This capsule is inserted into a furnace maintained at a constant temperature of 200°C. The temperature of the capsule is gradually increased to 200°C and the graph shows the transient temperature distribution indicated by the three thermocouples, viz., temperature of specimens in sodium, temperature of the outer surface of the capsule and the ambient temperature in the furnace.

Irradiation experiments carried out in FBTR

Irradiation of experimental fuel pins with Mark-I carbide fuel of FBTR

The carbide fuel chosen for FBTR had not been used anywhere previously and hence irradiation performance data on this fuel was not available. To determine the Beginning Of Life (BOL) behaviour of Pu-rich Mark-I carbide fuel of FBTR (70%PuC-30%UC), seven experimental fuel pins filled with different compositions of helium and argon as bond gas were irradiated using irradiation capsules in FBTR. Some of the experimental fuel pins had fuel pellets of Mark-II composition (55%PuC-45%UC) also. During irradiation, experimental fuel pins simulated the centre line temperature of normal fuel pin with helium as bond gas at higher linear powers. The choice of a specific composition of helium–argon mixture as bond gas was based on theoretical modeling. Design of experimental fuel pins and design and fabrication of irradiation capsules to house the experimental fuel pins were carried out at IGCAR. The experimental fuel pins were fabricated at Radiometallurgy Division of BARC. The fuel pins were irradiated for different durations upto a maximum of 99 effective full power days (EFPDs). Post irradiation examination (PIE) of all the seven experimental fuel pins was carried out in the hot cells of RML. Results of PIE gave the confidence to raise the linear power of Mark-I fuel from 250 W/cm to 320 W/cm.

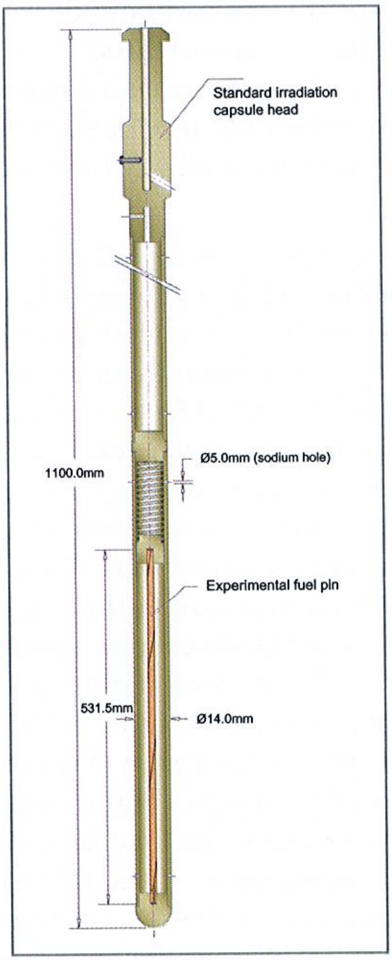
Irradiation of FBTR grid plate material specimens for ageing assessment

Grid plate is a very important permanent core structure of FBTR which supports the fuel and other subassemblies of FBTR and is subjected to a low dose irradiation for a long period of time (about 40 years). The chemical composition of FBTR grid plate is similar to that of type 316 stainless steel.

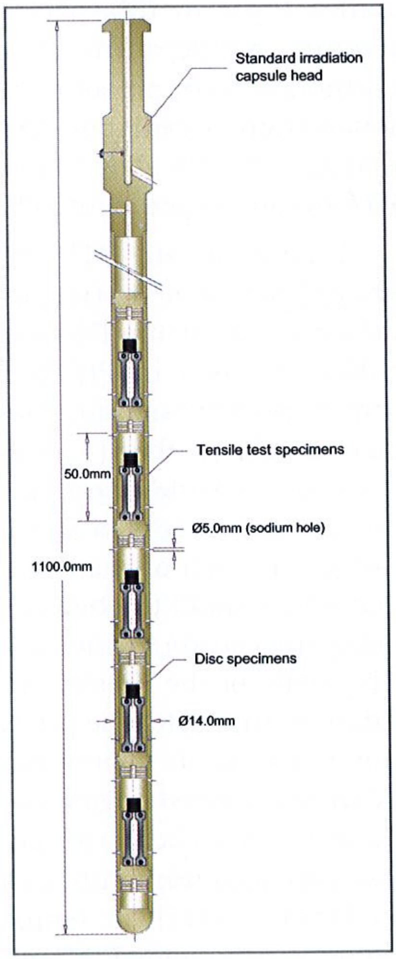
To assess the change in mechanical properties of grid plate due to prolonged low dose exposure, an accelerated irradiation test has been carried out on similar 316 SS material specimens with dose levels upto 2.6 *dpa* (at 350°C) in FBTR. An irradiation capsule was fabricated with five compartments and all the compartments contained small size flat tensile specimens and disk specimens. This irradiation capsule was assembled in a special steel subassembly and loaded in 4th ring of FBTR for irradiation. The irradiation temperature of specimens was 350 to

Displacement per atom (dpa) is a measure of the amount of damage caused by high energy neutrons in structural materials. For instance, 30 dpa means each atom in the material has been displaced from its lattice location an average of 30 times due to interactions between atoms of the material and the fast moving neutrons. As a thumb rule, the dpa and fluence in stainless steel can be related by the expression: 1 dpa = 2×10^{21} n/cm^2 (E>0.1 MeV). Fluence is the product of neutron flux and duration of irradiation.

370°C. The duration of irradiation was about 58 EFPDs. The PIE results indicated hardening accompanied by a decrease in uniform elongation of about 20-30 % for the various irradiated samples of dose level above 1.08 dpa, as compared to specimens of un-irradiated material.



Irradiation capsule for experimental fuel pin irradiation in FBTR



Irradiation capsule for grid plate specimen irradiation in FBTR

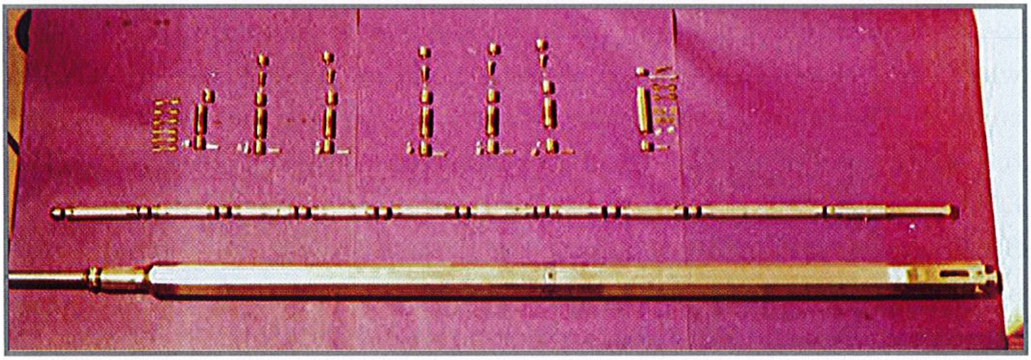
Experiments to determine creep rate of pressure tube materials

Creep is the time dependent deformation under the action of temperature and stress. Normally significant amount of creep occurs only at higher temperature. If the structural component is exposed to fast neutrons, creep manifests at a much lower temperature and is known as irradiation creep.

Pressure tubes are important components of Indian PHWRs and are made of cold worked Zircaloy-2 and Zr-2.5% Nb alloy. Pressure tubes are loaded with fuel bundles and coolant at a pressure of about 9 MPa flows through the pressure tube to remove the heat generated in the fuel bundles. Pressure tube acts as a primary heat transport boundary. The operating temperature of pressure tube is about 300°C. Creep deformation of the pressure tube during reactor operation is a life limiting phenomenon. Irradiation creep rates of indigenously developed Zircaloy-2 and Zr-2.5% Nb alloy were determined experimentally by carrying out an irradiation experiment in FBTR.

Irradiation in FBTR offers the advantage of simulating neutron damage levels in a shorter period of time due to the higher neutron flux and harder spectrum. This aspect has been exploited for determination of irradiation creep in PHWR materials by irradiating them in FBTR. Compact pressurised capsules were developed at IDEAS using small size zirconium alloy tubes (15.3 mm OD and 0.65 mm wall thickness). Six irradiation capsules were fabricated with five numbers of pressurised capsules (2 numbers of Zircaloy-2 and 3 numbers of Zr-2.5% Nb alloy) arranged in each of them. These pressurised capsules were filled with argon and a small fraction of helium at a high pressure (5.0-6.5 MPa at room temperature) in such a way that the target stresses were simulated in the walls of the pressurised capsules at the desired temperature of irradiation in FBTR. The pressurised capsules were anchored within the irradiation capsule to prevent possible movement due to any unexpected leak in the welded region of the pressurised capsule. The irradiation capsules were locked in special steel subassemblies and loaded in FBTR. These capsules were subjected to fluence levels up to 1.1×10^{21} n/cm^2 (E>1 MeV) in FBTR at temperatures from 306 to 319°C. During this irradiation campaign, FBTR was operated at 8 MWt power to have an inlet temperature of about 306°C which was close to the temperature of PHWR pressure tube. After irradiation, PIE was carried out in RML hot cells.

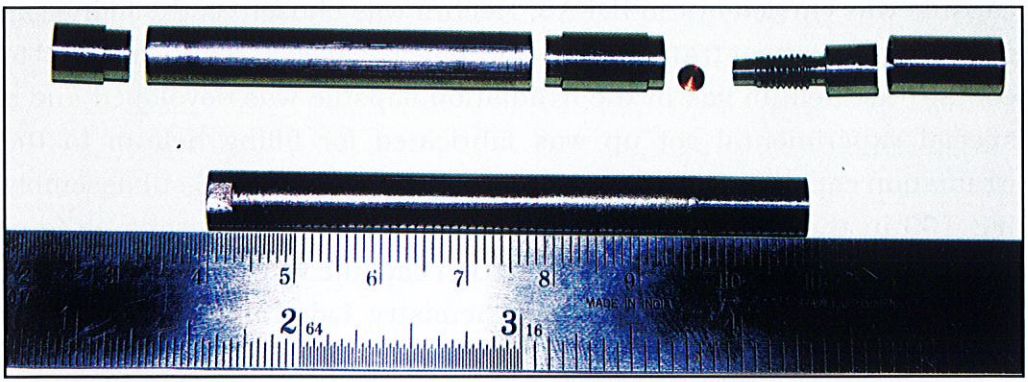
Diameter measurements were carried out on the pressurised capsules at different radial and axial locations to determine the increase in diameter and thereby the creep strain accumulated and the creep rate of the indigenous alloys. This experiment provided valuable data on the irradiation creep rate of indigenous PHWR pressure tube material.



Irradiation capsule and components with steel subassembly

Experiment to determine irradiation creep of D9 alloy

D9 alloy (stainless steel type 316 with appropriate modifications of chromium and nickel and controlled additions of titanium and silicon) is the cladding and wrapper tube for PFBR. Pressurised capsule of D9 alloy has been developed at IDEAS to determine the in-reactor creep performance of indigenously developed alloy.



Photographs of D9 alloy capsule pressurised to 65 Kg/cm²

Pressurised capsules were fabricated from indigenously developed D9 alloy clad tube of outer diameter 6.6 mm and 0.45 mm wall thickness. D9 tube is closed by welding at one end and fitted with special end plug at the other end, which enables filling of gas at the desired pressure into the tube using a pressurising system. A gas mixture of 97% argon and 3% helium is used for the pressurisation. The length of the pressurised capsule is about 70 mm.

Irradiation of D9 alloy pressurised capsules is progressing in FBTR to determine the irradiation creep behavior at a temperature of 380°C which is the temperature of flowing sodium around the irradiation capsule. The filling gas pressures at room temperature were 2.1, 4.2 and 6.3 MPa respectively. The corresponding hoop stresses developed in the D9 alloy pressurised capsules at the irradiation temperature are about 30, 60 and 90 MPa. After attaining a peak dose of more than 50 dpa in the specimens, the irradiation capsule will be discharged from FBTR and brought to RML and PIE will be carried out to determine the creep rate.

Irradiation Capsule for production of Strontium – 89 in FBTR

The isotope Stontium-89 is used in medical application to alleviate pain associated with certain forms of cancer. Stontium-89 can be produced by irradiation of yttrium oxide pellets in a fast neutron spectrum. An irradiation capsule was fabricated with sintered yttrium oxide pellets stacked in it to produce the radioisotope Strontium-89 by irradiating in FBTR. The design and development of this irradiation capsule was carried out in IDEAS. Helium was chosen as the filling gas due to its better heat transfer characteristics. A special sealing method to contain the helium gas in the irradiation capsule was developed and a special experimental set up was fabricated for filling helium in the irradiation capsule. This capsule was loaded in special fuel subassembly IFZ 100 in the first ring of FBTR for irradiation. After discharge from FBTR, yttria pellets inside the irradiation capsule were retrieved in RML hot cells and dispatched to Radiochemistry Laboratory for chemical processing to separate Strontium-89.

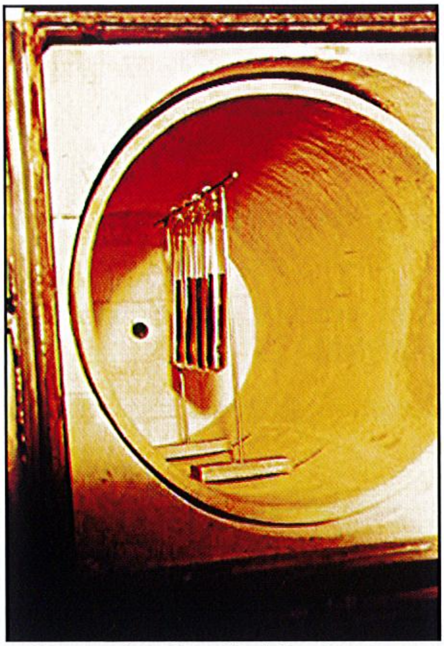
Out-of-pile experiments

Several *out-of-pile experiments* have been carried out in IDEAS in support of irradiation experiments programme. Some of them are described here.

Thermal creep rate of zirconium alloys

Out-of-pile experiments are carried out to assess or verify some of the main experimental uncertainties prior to implementing irradiation experiments as well as to provide additional information in order to interpret the data obtained from irradiation experiments.

Out-of-pile experimental work was carried out to determine the steady state thermal creep rate of the pressure tube materials (Zircaloy-2 and Zr-2.5% Nb alloy). Pressurised capsules made of Zircaloy-2 and Zr-2.5% Nb alloy were encapsulated in quartz tubes with argon environment and subjected to test temperatures of 306°C and 340°C in electrical furnace for different durations. Encapsulated capsules were taken out periodically from furnace and the diameter of the pressurised capsules was measured. After measurements, the pressurised capsules were encapsulated again in quartz tubes and kept back in furnace to continue the exposure at test temperature. Measurements were carried out after 357, 828, 1214, 1497 and 1935 hours of exposure. Steady state creep rates obtained in Zircaloy-2 and Zr-2.5% Nb at 306°C and 340°C at different stress values have been determined. This experiment was carried out to determine the contribution of thermal creep in the creep strain measured during the irradiation experiment on zirconium alloys.



Capsules loaded in furnace

Sodium-zirconium compatibility experiments

In this experimental work, the effect of thermal ageing and the effect of exposure to sodium along with thermal ageing on tensile behaviour and associated acoustic emission in Zirconium alloys were investigated. Tubular specimens of Zircaloy-2 and Zr-2.5% Nb alloy were exposed to flowing sodium in an experimental loop at a temperature of 340°C at Radiochemistry Laboratory. Similar tubular specimens of these two alloys were also given thermal treatment at 340 °C for equivalent time duration in a furnace to determine the effect of temperature alone (without sodium) on these alloys. Tensile tests were carried out on all the specimens at ambient temperature. During tensile tests, acoustic emission (AE) signals generated were recorded. The results indicated slight reduction in strength of both sodium-exposed and thermally-treated specimens of the two alloys as compared to unexposed specimens. The changes in strength and ductility for both the alloys due to either thermal treatment or sodium exposure were found to be almost similar. AE generated in the region prior to and during yielding is significant for these specimens and higher AE in the sodium exposed and thermally treated specimens beyond yielding as compared to non-exposed specimens has been attributed to the occurrence of micro-cracking and was supported by metallography.

Recent developmental activities

Following developmental activities have been recently carried out / are in progress.

- Design and development of D9 alloy pressurised capsules to withstand a temperature of 600°C (completed)
- Design and development of non-instrumented high temperature irradiation capsules (completed)
- Development of nicrobrazing method by induction heating to route the shielded thermocouples through a solid end plug in a leak tight manner to be used in instrumented capsule (completed)
- Development of indirect temperature monitor based on differential thermal expansion of sodium and stainless steel (in progress)
- Development of out-of-pile experimental set up for instrumented fuel irradiation capsule (in progress)
- Development of instrumented fuel irradiation capsule (in progress)
- Development of out-of-pile experimental set up for instrumented structural material irradiation capsule (in progress)
- Development of instrumented structural material irradiation capsule (in progress)

Recent additions to infrastructure

The development of various devices for irradiation experiments requires continuous enhancement of infrastructural facilities to cater to miniaturization involving very high precision machining and fabrication. The following facilities have been added recently towards this objective.

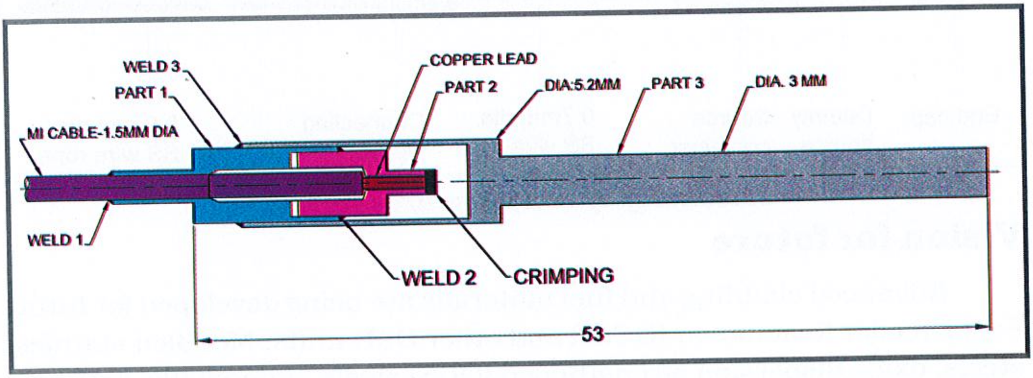
- Establishment of a new Nd:YAG laser welding facility
- Establishment of dust control room to install the laser welding system
- Establishment of clean room facility
- Development of a remotely operable diameter measuring system of D9 alloy pressurised capsules

Expertise offered in precision machining and fabrication

The expertise gained in the area of precision machining and fabrication has been utilized for critical applications at IGCAR and other units of DAE. Precision notches for use as standards during non-destructive testing of pressure tubes of PHWRs and clad tubes of PFBR have been made using Electric Discharge Machining process (EDM). Some of the precision welding works carried out using laser welding system are given below:

Laser welding of Eddy Current based Position Sensor (ECPS) for PFBR

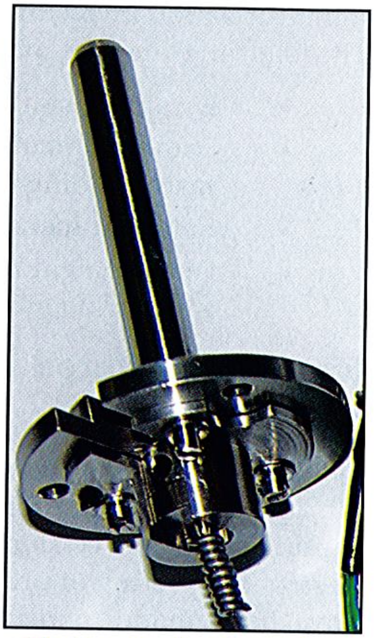
ECPS is a critical component in the Diverse Safety Rod Drive Mechanism (DSRDM) of PFBR which monitors the position of the safety



Sketch showing the general coil termination arrangement of ECPS rods and gives confirmation that they are all dropped in case of a reactor scram. Mineral insulated (MI) cable of 1 mm diameter used as the eddy current coil in the ECPS has been terminated with suitable end configuration using laser welding.

Sodium Leak Detector (SLD) in DSRDM of PFBR

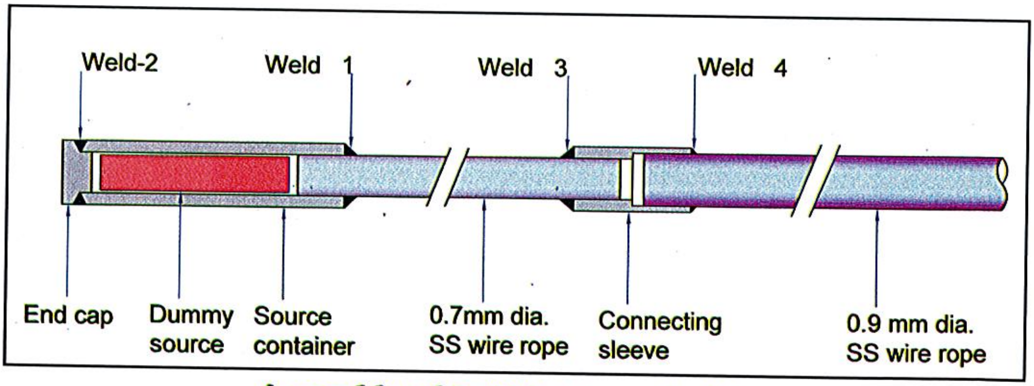
SLD is housed inside the electromagnet assembly of DSRDM to indicate if there is any leakage of sodium into the electromagnet. The fabrication of SLD required precision laser welding of a few of its components.



Photograph of sodium leak detector

Fabrication of Ir-192 Source Holder for Board of Radiation and Isotope Technology (BRIT)

For the indigenous development of Ir-192 source assembly for use in high dose rate (HDR) Branchy therapy, the feasibility study has been carried out for the fabrication of the miniature source holder by laser welding process.



Assembly of Ir-192 source holder

Vision for future

Advanced cladding and fuel materials are being developed for future Fast Breeder Reactors at IGCAR and other DAE units. Modified stainless steels, oxide dispersion strengthened (ODS) steels and metallic fuel are a few of them.

Irradiation testing in FBTR will be carried out to assess the irradiation performance of the newer fuel and structural materials developed indigenously. Irradiation testing at high temperature and high fluence / burnup levels will be carried out. Instrumented fuel and structural material irradiation capsules will be developed and deployed in FBTR. Irradiation capsules to detect on-line the stress rupture of pressurised clad tubes during irradiation will be developed. Work will be carried out towards re-irradiation of fuel pins and structural material specimens in FBTR.

Theoretical modeling of radiation damage and correlating with experimental work, theoretical and experimental work of laser material processing, and research work in precision welding, precision machining and non-conventional machining process such as EDM are also envisaged.

REMOTE HANDLING AND ROBOTICS

Remote handling and manipulation has been practiced for many centuries by our early ancestors, using simple sticks/twigs to manipulate food on an open hearth fire without getting themselves or the food burnt, and special tools known as tongs of the blacksmith to manipulate and heat the work piece in the hot embers during forging, to name a few. However, the key developments in remote manipulation and handling took place in the middle of the last century during the pioneering days of the nuclear industry, once the extreme radiation hazards became apparent.

Remote handling integrated with robotic technology play a crucial role in almost all facets of the nuclear fuel cycle, right from the uranium ore mining, processing of ore, fuel fabrication, reactors, spent fuel handling, fuel reprocessing, nuclear waste handling and management. Interestingly, remote handling techniques evolved from the backend of the fuel cycle (fuel reprocessing and waste management) to cater to the needs in a hostile, unstructured and inaccessible environment with high radioactivity and acidic fumes. From relatively simple tongs and mechanical devices, there now exists extremely sophisticated computer controlled telerobotic systems and virtual environments that allow humans to plan and execute complex tasks that would otherwise be impossible to undertake because of the nature of the environment involved.

At IGCAR, ever since the inception, the development of remote handling technology followed the requirements pertaining to fast breeder reactor (FBR) and associated fuel cycle. The development of master-slave manipulators and α-tight transfer/transport systems was initiated at the erstwhile remote handling section way back in 1985 at IGCAR. Many of the early developments of remote handling equipment like master slave manipulators, in-cell cranes, etc. were achieved in active collaboration with Bhabha Atomic Research Centre (BARC). Subsequently, efforts were directed towards the development of remote handling and robotic devices for hot cells and fuel reprocessing plants and automated NDE devices for inspection. Recent focus is on the development of remote devices for the in-service inspection (ISI) of the upcoming Prototype Fast Breeder Reactor (PFBR) and Fast Reactor Fuel Reprocessing Plants.

Robotics is a multi-disciplinary area involving mechanical, electrical, electronics & communication, instrumentation, and software engineering. Application-based robotics requires more cross-fertilization from various other disciplines of science and technology. The in-house R&D activities along with reputed academic and R&D institutions, initiated and sustained in this area, have enriched the knowledge base at IGCAR. This has enabled the evolution of a comprehensive strategy for the conceptualization and deployment of customized robotic devices in order to meet the challenges involved in the remote handling and ISI of nuclear facilities for FBR fuel cycle. The current phase of activities at IGCAR, with respect to ISI of PFBR and Reprocessing plants has matured into implementation from the concepts, which were consolidated through the previous painstaking prototype developments, with the support from the Indian industries.

The following sections present, in brief, the spectrum of the activities and developments that have been undertaken at IGCAR in this fascinating area highlighting the achievements, challenges and future directions in pursuit of excellence.

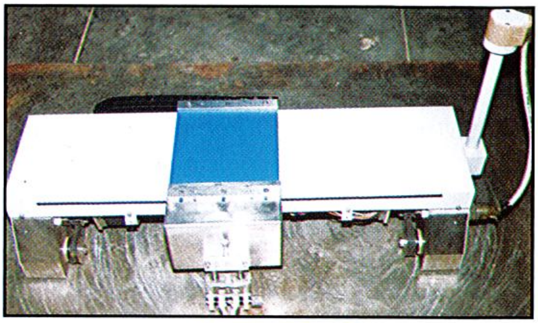
Automated devices for NDE

Automation of NDE techniques results in increase in efficiency, accuracy/precision of defect detection, consolidation and archival of test results for future reference. Developments in the area of sensors, electronics and control coupled with software capabilities for data acquisition and analysis enabled high speed NDE with high precision. Aided by robotics and automation, these capabilities can be extended to 3-D visualisation of the detected defects for better understanding and representation of the NDE results. Various automated and robotic systems have been developed for carrying out inspection using NDE techniques. The following section illustrates few of such automated devices developed.

Mobile Scanner

Automated inspection of large plates proves to be a boon to any kind of industry for the reasons well known. A versatile scanner known as MOBSCAN has been developed to automate the inspection of raw products like plates. It is a wheel-based scanner having scan-stroke of 500 mm and can travel for 15 m. The MOBSCAN being modular mainly comprises of two wheel modules and a scanning head module.

The scanner can be controlled by a computer and a hand-held pendant as well. A Graphic User Interface is used for computer controlled automated scanning. The scanner can also be used for inspection of vertical plates with suitable magnetic wheels. The MOBSCAN can either be used as a small payload (15 kgf) carrier or for visual examination with a camera on its scanning head. The versatility of the scanner makes it capable of being used for performing surveillance/inspection in inaccessible areas like ventilation ducts, isolation areas, etc.

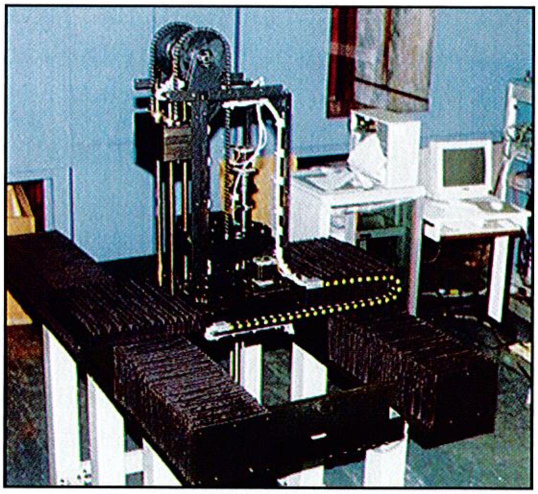


MOBSCAN

5-Axis Manipulator

Advancements in contour following for ultrasonic imaging have been addressing the evolving needs for inspection of components of complex shape and geometry. Multi-axis robotic manipulators enable "complex contour following" for scanning of components.

A five-axis manipulator capable of complex contour following has been developed for immersion ultrasonic testing and imaging. This system with ultrasonic transducer has been used for detecting stress corrosion cracking in the mock-up end shield assemblies of 500 MWe PHWR. The system has been upgraded by adding the ULTIMA-200 system developed by BARC to have C-scan facility.

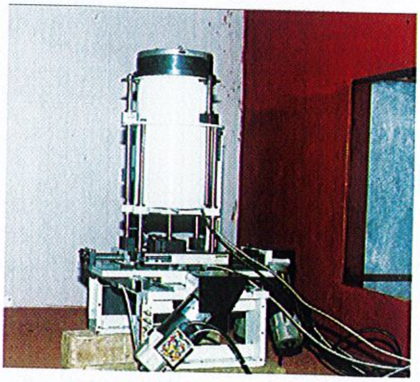


Five-Axis Manipulator

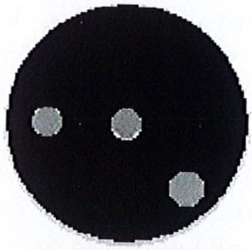
C-Scan Images of one rupee coin

Tomography System

High resolution X-ray tomography for visualizing features in the interior of opaque solid objects in different planes requires high precision manipulators for positioning and orienting the objects. High-resolution X-ray Computed Tomography (CT) differs from conventional medical Computerized Axial Tomography (CAT) in its ability to resolve details as small as a few tens of micrometres in size, even when objects being examined are made of high density materials. This requires an ultra precision, compact, servo controlled 4-axis manipulator, which has been developed for high resolution X-ray tomography. The system has been integrated with an X– ray source, real time X – ray detector and image grabber card for data acquisition.



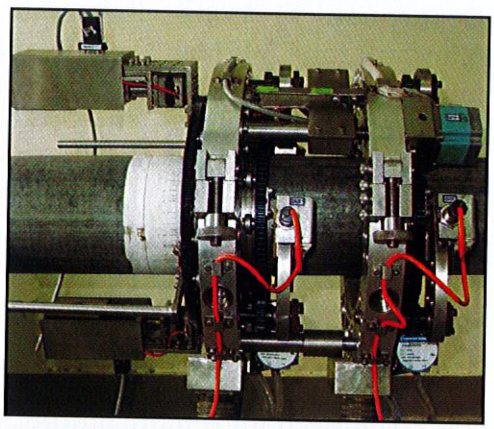
X-ray Tomography System



Tomographic slice of aluminium cylinder with holes

Pipe inspection system

Manual inspection / monitoring of pipelines using NDE techniques is cumbersome and time consuming. This necessitates the use of special scanners and crawlers, which can be easily clamped onto the surfaces of the pipes and can do accurate inspection. An external pipe inspection system has been developed for the inspection and monitoring of pipelines using NDE techniques. The system can carry UT / Eddy current probe, vision system,

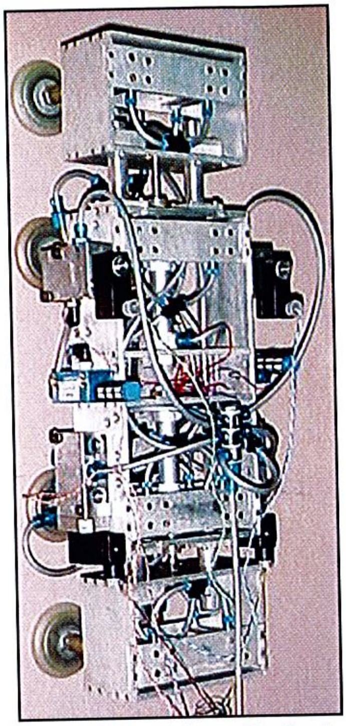


External Pipe Inspection System

etc. The system has been designed to facilitate crawling on the pipelines between two supports. A helical scan facility using the simultaneous motion of the linear and circular scan motors is also provided so that inspection of whole volume of the pipeline can be carried out.

Wall Climbing Robot

Man has always been fascinated by biological creatures, which can climb, creep, crawl, etc., and has been trying to mimic these creatures, for their potential applications. In process or power plants, periodic inspection of very large vertical surfaces is a necessity as part of preventive maintenance. The operating environment could also be hazardous and hostile. A wall climbing robot with suction cups, controlled by a programmable logic controller (PLC) has been developed. This robot is pneumatically operated, lightweight, compact and modular in construction. It can carry a small scanning arm fitted with desired probes for NDE and CCD for visual observations. The system is capable of moving in vertical or horizontal directions and can carry a payload of 5 kgf.



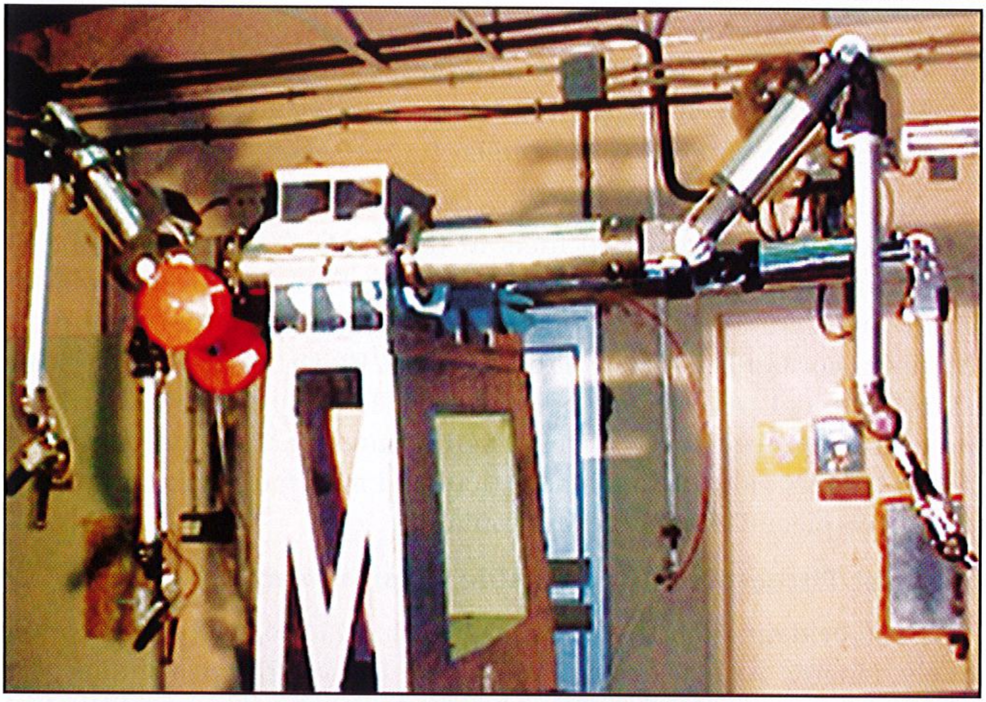
Wall Climbing Robot

Remote handling

There have been significant developments in this crucial area in the Department of Atomic Energy in the past few decades. Master Slave Manipulators (MSMs) are the prime workhorses in nuclear research laboratories and reprocessing plants where large quantities of highly radioactive materials are handled. The MSM, as the name implies, has a master arm and slave arm, which are mechanically coupled through linkages, wires, pulleys, and chains. By virtue of their simple/ ergonomic design and bilateral force reflection coupling their performance is highly reliable and robust. In this section manipulators developed in IGCAR are discussed.

Master-Slave Manipulator

The need for remote manipulation on the work side (hot side) of the cells spurred the development of MSMs. Many variations of MSMs like



Articulated type mini manipulator

Gas-tight-three-piece-detachable manipulator

the Model-8, Extended Reach, Gas-tight-three-piece-detachable type and Articulated type have been successfully developed indigenously at IGCAR. They have been exclusively designed with features for handling of plutonium bearing fuels in α-tight cells.

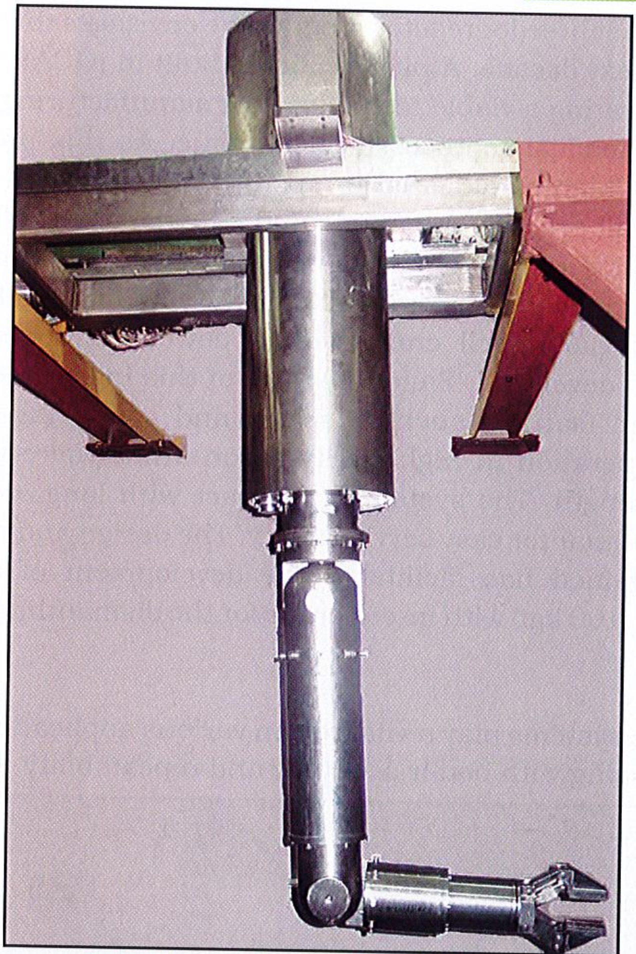
Articulated type mini MSMs are the mainstay in COmpact facilities for Reprocessing of Advanced fuels in Lead cells (CORAL) and are also intended to be used in Demonstration FBR Fuel Reprocessing Plants (DFRP) and remote fuel fabrication facility where large amounts of plutonium-containing fuels will be handled. By virtue of the rich design and operational experience of MSMs at RML and the expertise at reprocessing group, these developments have reached maturity levels that led to MSM variants such as articulated mini manipulator and Gas-tight-Three-piece-Detachable Manipulator.

Gas-tight Three-piece Detachable Manipulator

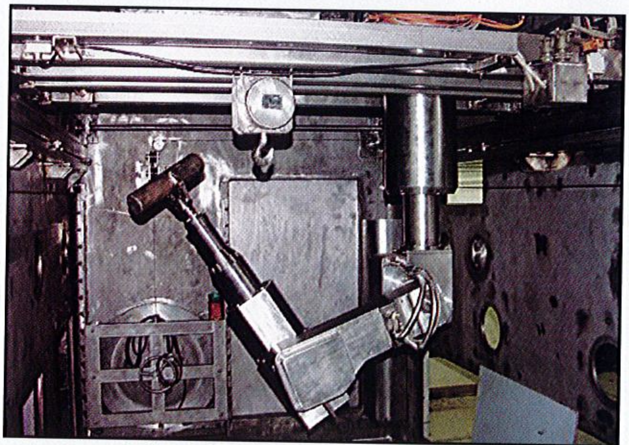
As is evident from the name, this manipulator has three modules namely Master Arm, Through-tube and Slave Arm assemblies. The payload of the manipulator is 25 kgf. Through-tube provides leak-tightness, shielding and motion transmission. Its modularity is the main feature of this manipulator which helps easy maintenance of the manipulator without disturbing other modules. Unlike conventional manipulators motions are transmitted through transmission shaft with bevel gear and pinion arrangements. Though the manipulator is heavy, the moving and fixed counter weights makes the manipulator perfectly balanced both statically and dynamically, thus facilitating the operation of the manipulator. Electrically assisted movements are provided in X, Y and Z motions using motorized linear actuators for extra reach. One of the special features of this manipulator is that it does not require booting for ensuring leak tightness.

In-cell crane and Power Manipulator

Very often in the hot cells, there is a requirement of handling of equipment/devices that would be difficult to carry out with MSMs due to restrictions of their reach and capacity. These manipulations are usually along specific directions and traversal paths inside the cell. These manipulations are achieved by in-cell gantry crane integrated with power manipulator. Many variants of power manipulators have been designed and developed for use in lead-shielded and concrete hot cells.



Prototype Power Manipulator

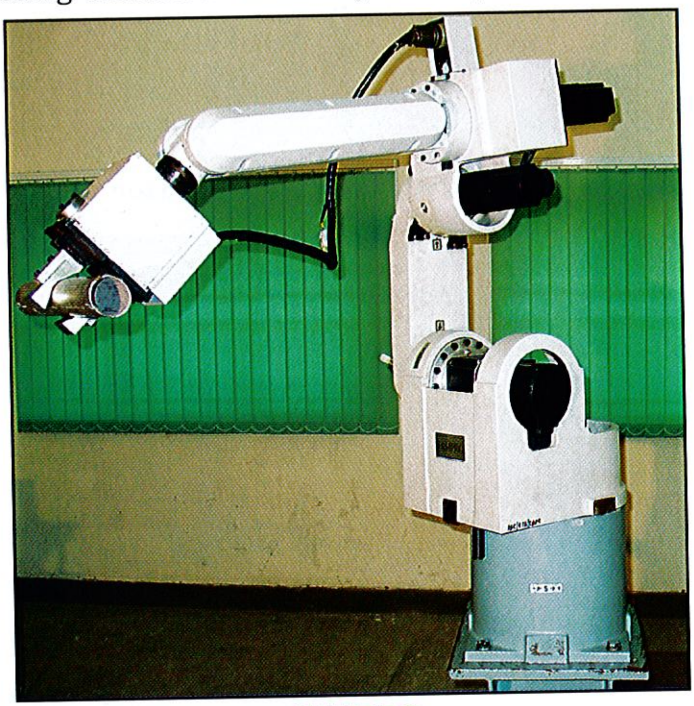


In-cell crane with power manipulator installed in the containment box of pilot pyro-chemical processing

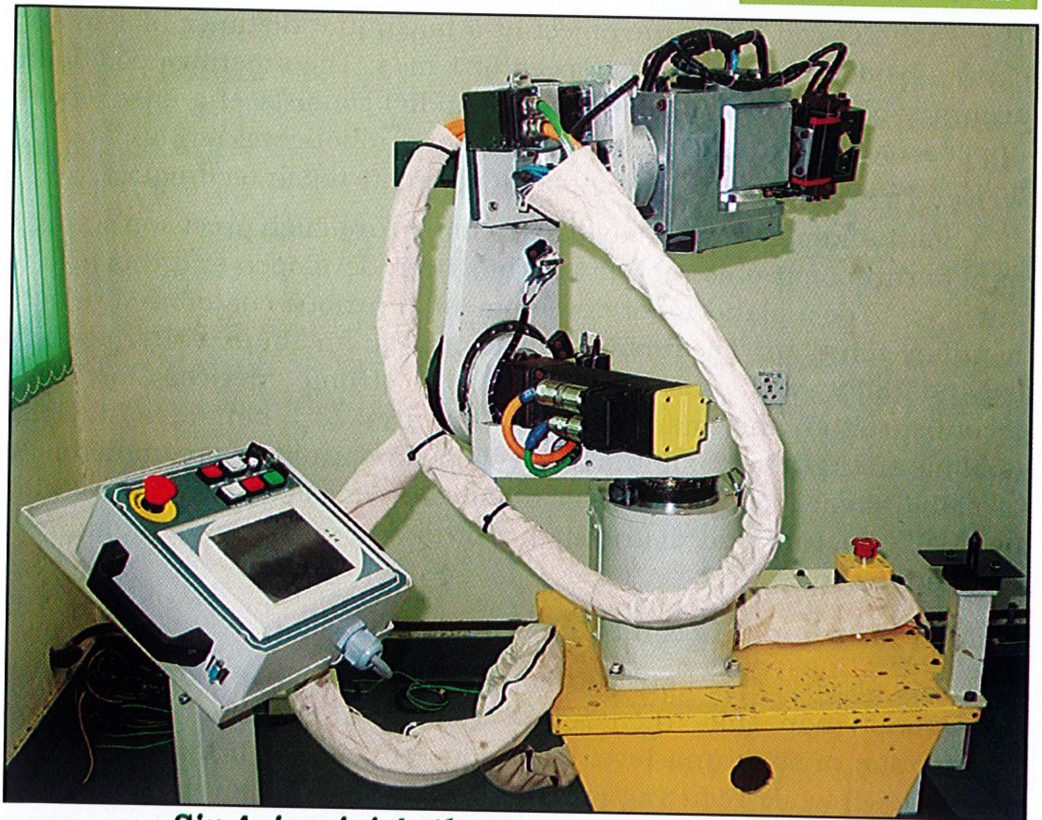
Indian fast breeder reactor programme envisages the use of metallic fuels in the next decade. A pilot facility is built in IGCAR for developing and demonstrating a viable technology for manufacturing metallic fuels using pyro-chemical reprocessing technique. As this process involves handling of highly radioactive spent fuels in high purity inert atmosphere, all process operations and associated handling have to be necessarily carried out using remote techniques. For demonstration of the remotisation of the processing inside the containment box in the pilot facility, a special in-cell crane with a power manipulator has been designed and developed. Salient feature of this integrated system is its special design features such as sealed and low voltage drive motors facilitating operation in high purity argon atmosphere which has low dielectric strength. The system is compact with long cross travel and hoist and modular for easy serviceability. The design and manufacturing experience gained has facilitated the development of a large power manipulator (100 kgf) with in-cell crane for the dismantling cell of PFBR.

Robotics

Robotic systems play a vital role in various applications, facilitating faster processing with better accuracy and repeatability. Robots provide



SAMPRO



Six Axis mini Anthropomorphic Robotic Arm

the exceptional flexibility for "real time world space" positioning of various payloads, on very complex geometries thus making them indispensable during automated manufacturing and remote handling.

Inspection and maintenance tasks often require a high degree of maneuverability considering the intricacies of the job at hand. These needs become even more exacerbated with issues of remote operation and with stringent quality controls in place. In such an event dexterous/articulated robotic arms are the right choice to carry out these operations. These arms provide the dexterity required in such tasks with the added advantage of remote operation by personnel. To meet such exigencies, a Six Axis Multi-Purpose Articulated Robotic arm (SAMPRO) has been developed indigenously to serve as an application development platform for variety of tasks such as remote repair and maintenance. The salient feature of this arm is its modularity which facilitates reconfigurability depending on the application demands.

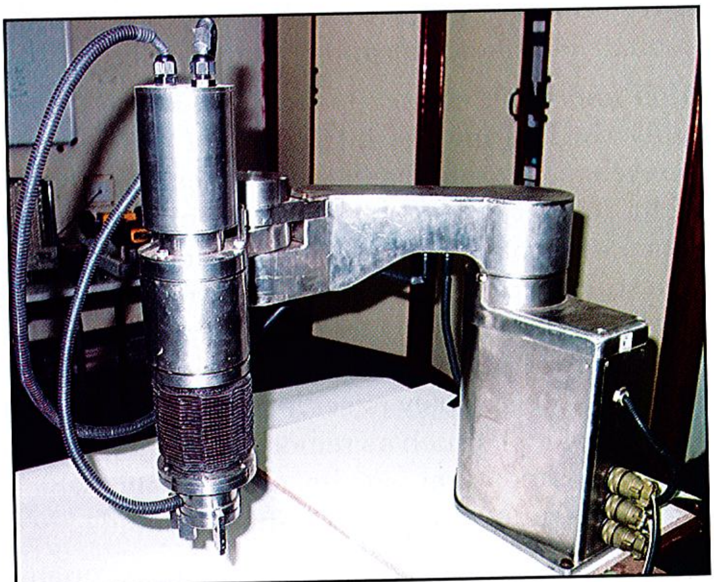
The SAMPRO has six motorized revolute joints through suitable gear reducers, which makes it possible to position and orient objects / tools.

The SAMPRO can reach the object at a maximum distance of 1 m and carry a payload of 10 kgf at a speed of 1 m/s. The repetitive positional accuracy of the robot is ± 200 µm. SAMPRO consists of a base, waist, upper arm, forearm and wrist. As a first case, robotic welding application has been taken up for the development of remote repair techniques.

For handling of small payloads, a miniature, high precision six-axis mini anthropomorphic robotic arm has been developed and this arm is intended to be a platform for development of various customized remote handling solutions. The robotic arm is modular and built with necessary expandability with mechanical and electronic devices for easy reconfiguration and maintenance. The arm can handle a payload (tooling) of 3 kgf at a maximum reach of 600 mm. Unlike the commercially available similar robotic arm, this robotic arm has PC-based control with open architecture and distributed control and off line programming / simulation capabilities.

Robots for remote fuel fabrication

The process of remote nuclear fuel fabrication has many unit-level operations that lend themselves well to automation procedures. Automation of such unit-level operations ensures high throughputs in the process, while reducing radiation exposures to operators, with the added benefit of ensuring close manufacturing tolerances. These robots make it possible for a 100% inspection of the fuel pellets and they



SCARA

decrease the downtimes by working in collaborative modes between each of the procedures. A Selective Compliance Assembly Robotic Arm (SCARA) has been developed for automated remote handling of green fuel pellets, inspection and handling of sintered pellets, their sorting and stacking, and loading into fuel pins. The currently developed model is a precursor to the two devices that are being manufactured for use in the SOLGEL fuel fabrication facility.

Sensor for fuel pellet handling

Handling of green fuel pellets is a delicate operation and a controlled gripping is essential so as not to damage the fuel pellets, thereby necessitating the use of sensory feedback for force control. In this context, a PolyVinyliDene Fluoride (PVDF) based slip sensor and a hybrid control system was developed in collaboration with IIT Kanpur, for detecting friction force and micro-vibration during pellet handling.

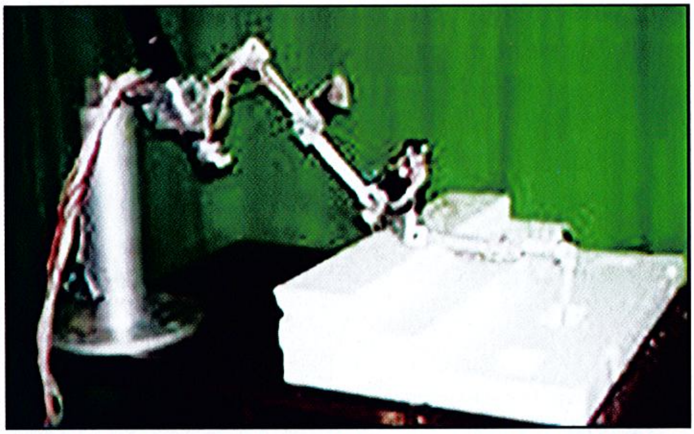
Slip Sensing test set-up

Spatial Hyper Redundant Manipulator

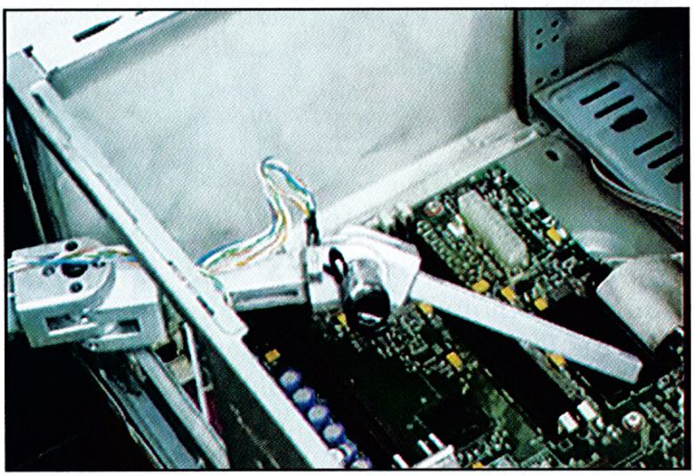
As the need for manipulators with higher payloads and greater reach increases, the flexibility of the arm has to be taken into account. This requires a whole host of new developments in the areas of dynamic control of the arm to maintain position, accurate tip location, operator control and much more. These systems could be used where long reach is required such as lifting objects out of tanks or deep storage pits and remote inspection or repair. Use of robotic manipulators for inspection applications continues to increase as more dexterous and redundant manipulators are developed and become available. The vision of a fully flexible mechanical manipulator, capable of bending in any desired direction to reach through a field of obstacles to any desired point in the operating space, is a motivating factor to develop such a manipulator like a snake/elephant's trunk which has applications in all spheres of nuclear energy programme right from inspection, repair, maintenance, etc.

Snake-like robots

Redundant robots are a special class of serial robots possessing more degrees of freedom than are required for the end-effector to reach its



Prototype Snake-like robot reaching out to a task-space location



End-effector inside a cluttered workspace

desired location. A hyper-redundant (also termed as multi-link) robot builds up on this concept by provision of a large number of actuated degrees of freedom bestowing them with a serpentine architecture. Snake-like robots are devices in which the links are attached end-to-end/multi-link manipulator in other words, serially. Manipulators such as Snake/elephant's trunk manipulator can be used for deploying fiberscope and miniature CCTV cameras to examine areas of interest in regions of restricted access as in the case of nuclear reactor internals.

The snake-like robots would enhance the inspection capabilities in the reprocessing plants and waste-vaults as compared to the restricted ease offered by other methods. Initially a computational software application tool was developed, in collaboration with IIT Kanpur, to tackle the analytical issues in the development of a snake-like robot. A developmental desktop prototype with 8-degrees of freedom was built and demonstrated to validate the mathematical models and the feasibility of the concept. A variety of experiments has been performed to evaluate the functionality of the developed manipulator. This rich experience will be used now for taking up customized developments required for real world nuclear applications.

In-Service Inspection (ISI)

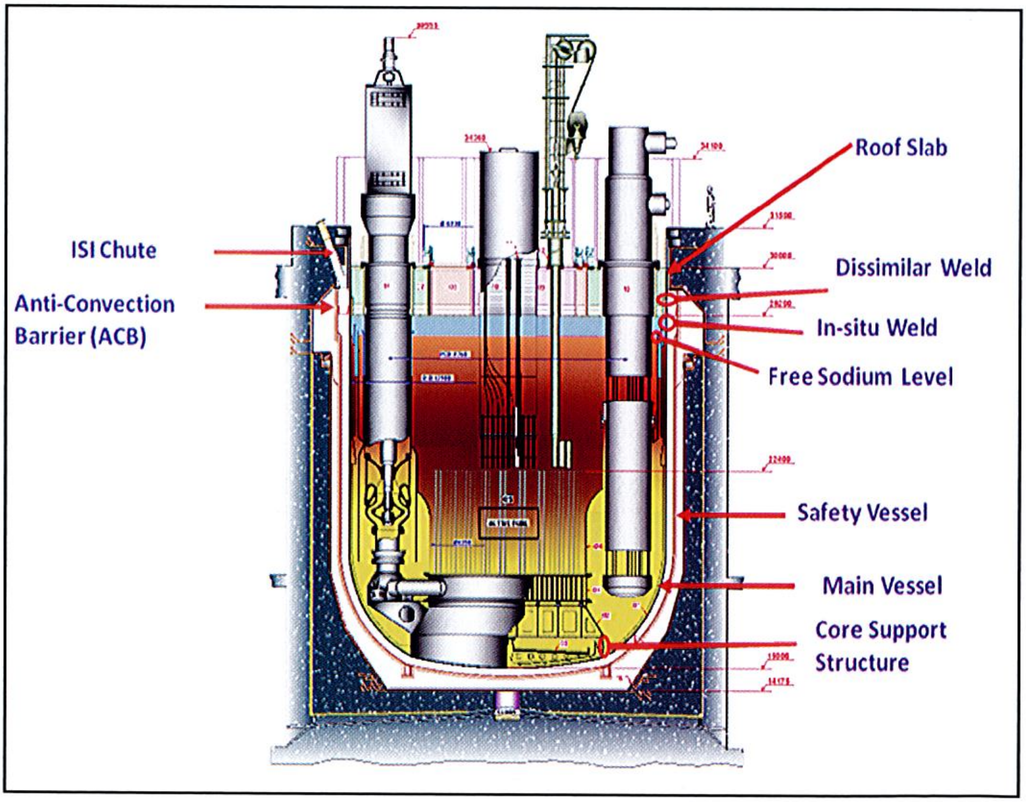
ISI is one of the tools to assess the safety and integrity of the components of the plant assuring the productive plant availability and extending the fruitful life of the plant. The compounded needs of inspection with limited access and high radiation level and temperature necessitate the use of remote NDE techniques using automated/robotic devices.

In-Service Inspection (ISI) device for main and safety vessels of PFBR

A 500 MWe Prototype Fast Breeder Reactor (PFBR), is under construction at Kalpakkam. There are various diverse safety systems in the reactor for continuous surveillance and monitoring of critical components. Supplementing the continuous surveillance and monitoring, the integrity of the reactor components has to be assessed periodically by ISI. In this context, ISI systems have been developed for various components of the PFBR and are described in the forthcoming sections.

Prototype Fast Breeder Reactor (PFBR) is a pool type reactor comprising of main vessel, safety vessel, and reactor roof structure providing the primary safety containment. The main vessel and reactor roof slab confine the primary coolant and cover gas with any associated radioactivity.

As part of ISI, comprehensive periodic inspection of main vessel and safety vessel of PFBR shall have to be carried out by visual inspection of the main vessel and safety vessel surfaces and volumetric inspection of specific welds on the main vessel during the reactor shut down conditions as stipulated by ASME B & PV Code, Section XI, Div.3. The critical areas that are to be periodically inspected during ISI namely, dissimilar metal weld between main vessel and roof slab, core support structure weld, weld between support shell and main vessel and in-situ weld on the main vessel require mandatory volumetric examination using ultrasonic test technique.



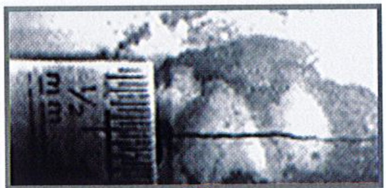
Vertical sectional view of the PFBR under construction showing the ISI chute and interspace between the main vessel and safety vessel

The main vessel of PFBR is inaccessible from inside and hence its inspection can only be performed from outside. The main vessel (MV) of PFBR is 12.9 m in diameter and the safety vessel (SV) surrounds the main vessel forming an annular gap of 300 mm referred to as interspace, which varies by ± 50 mm during the service. The interspace can be utilized for the inspection. The interspace is filled with high purity nitrogen and the temperature in this region during the inspection would be 423 K.

Since man-access to the inter space is ruled out, the ISI of the main vessel and safety vessel has to be performed by deploying a remote-controlled device which can move around the inter space with inspection modules for carrying out the inspection. Prototype non-destructive evaluation (NDE) modules such as ultrasonic testing, eddy current testing and visual examination modules have been successfully developed and validated at IGCAR.

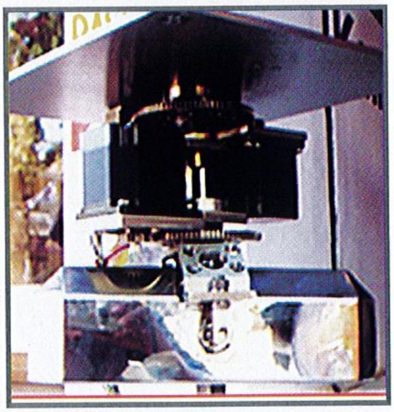
Another essential feature of the ISI is the formulation and establishment of permanent reference markers on the MV and SV to identify the location of the ISI device in the inter space. SV of the PFBR is provided with a number of permanent reference markers on its internal surface and coded with alpha numerals, indicating the MV and SV weld locations. MV is provided with few reference markers for identifying the locations of dissimilar metal weld, in-situ weld and core support triple point. Using these reference marks, it will be possible to locate as well as position the ISI device on the welds of the MV or SV in the inter space during the ISI.

(a)



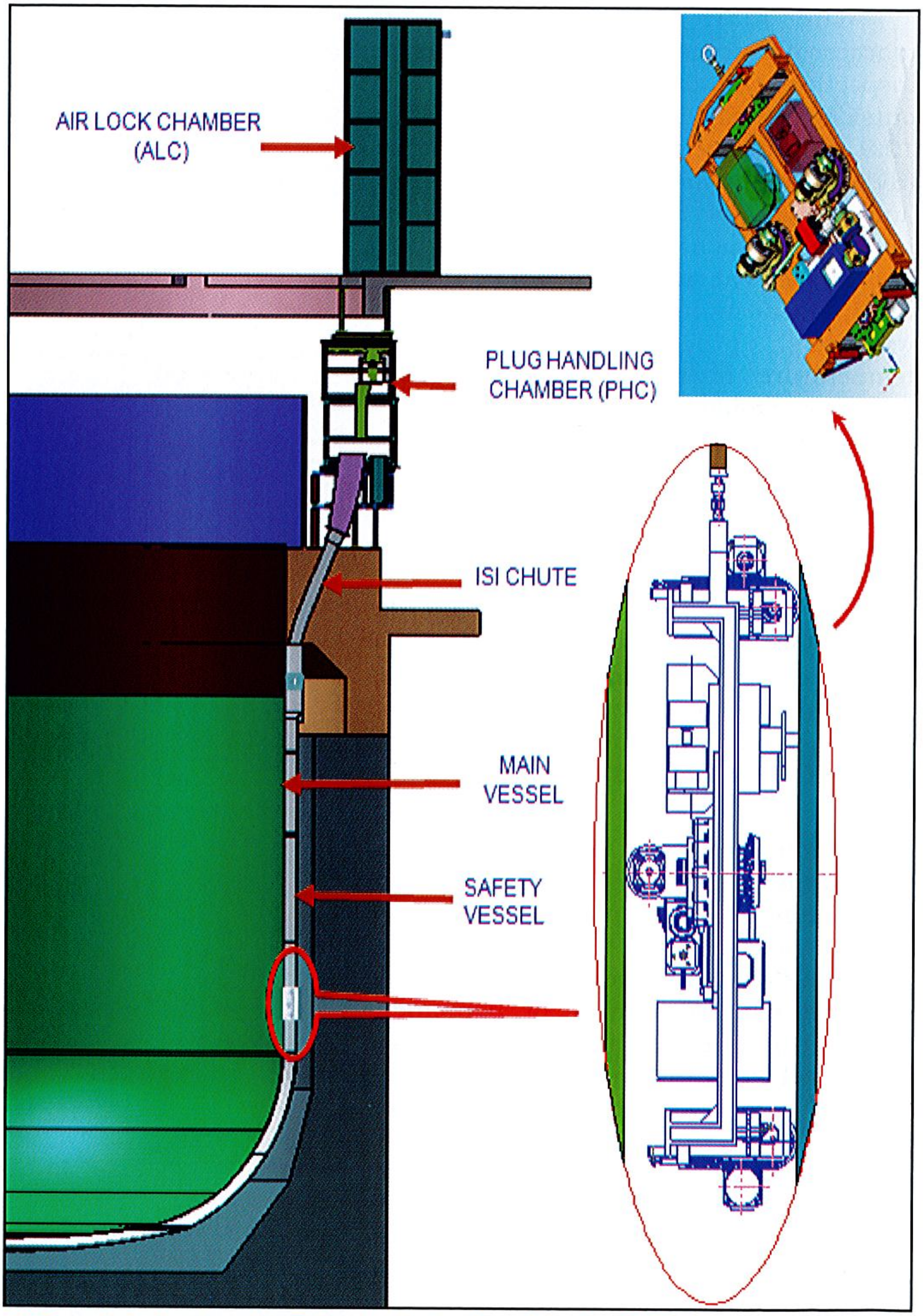
(b)

(c)



(d)

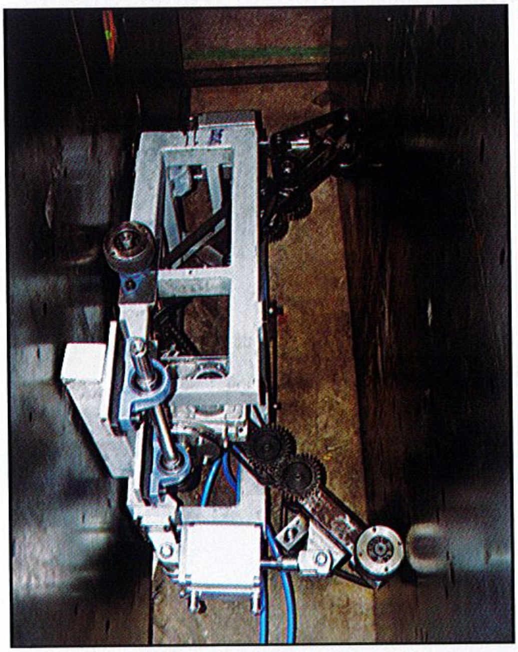
(a) Visual examination module,
(b) the image of simulated weld crack
(c) the ISI markings on safety vessel
(d) Ultrasonic Test module



CAD model showing the ISI vehicle deployed in the PFBR MV-SV interspace

Based on the prototypes, a comprehensive ISI system for use in 423 K has been evolved. The comprehensive ISI system will consist of two independent devices namely, VENTURE and DISHA for the inspection of welds on MV and SV and inspection of dissimilar weld and in-situ weld and cable handling system with leak-tight enclosure. Both the devices will have access to the annular space through the six ISI chutes provided at the top of the reactor vault.

Both VENTURE and DISHA are remote-controlled 4-wheeled robotic vehicles carrying NDE modules for inspection. These devices differ only in the arrangement of the four wheels and the motion given to them, with VENTURE having two wheels resting on each vessel (MV and SV) clamped by a pneumatic cylinder providing friction grip on the respective vessels in the interspace. VENTURE will be maneuvered by means of all-wheel steering and two traction wheels and DISHA will be maneuvered by driving the rear wheels with passive steering of the front wheels guided by the curvature of the roof slab shell. Each device is provided with navigation camera modules for guiding the devices in the interspace during ISI. Both the devices are provided with essential sensors such as position feedback resolvers, temperature sensors, inclinometers, slip-skid sensor, LVDT, load cells, etc for monitoring and control of the robotic vehicles during ISI.



Test Trolley for Traction Trials

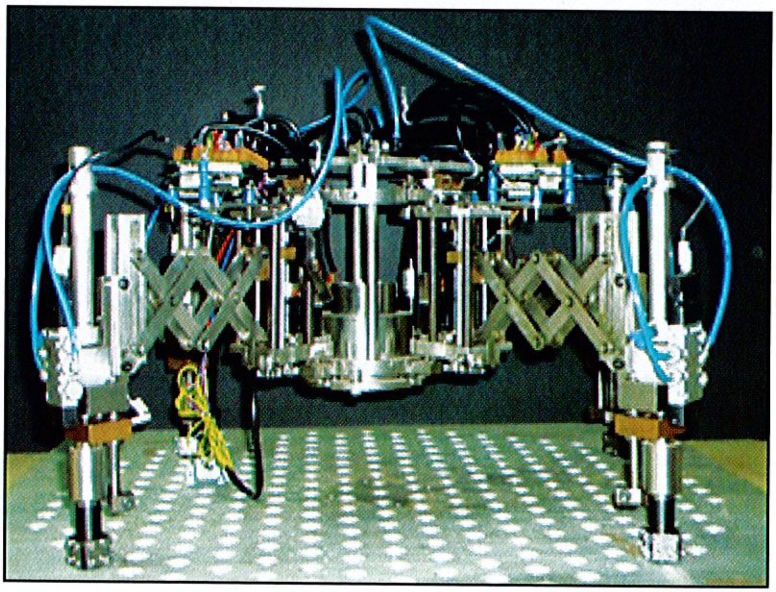
VENTURE in test setup

ISI of Steam Generator

Steam generator (SG) is one of the critical components in the secondary heat transfer circuit of PFBR wherein the heat transfer from hot sodium to water takes place. The availability of the reactor for power generation is dictated by the flawless performance of the steam generator. Pre and in-service inspection and monitoring of the steam generator tube bundles are a critically important means of reducing the probability of water/steam and sodium leakages.

SG tubes, with limited access requires special robotic devices for precise positioning of various NDE probes, for carrying out ISI and their accurate translation inside the tubes to detect defects.

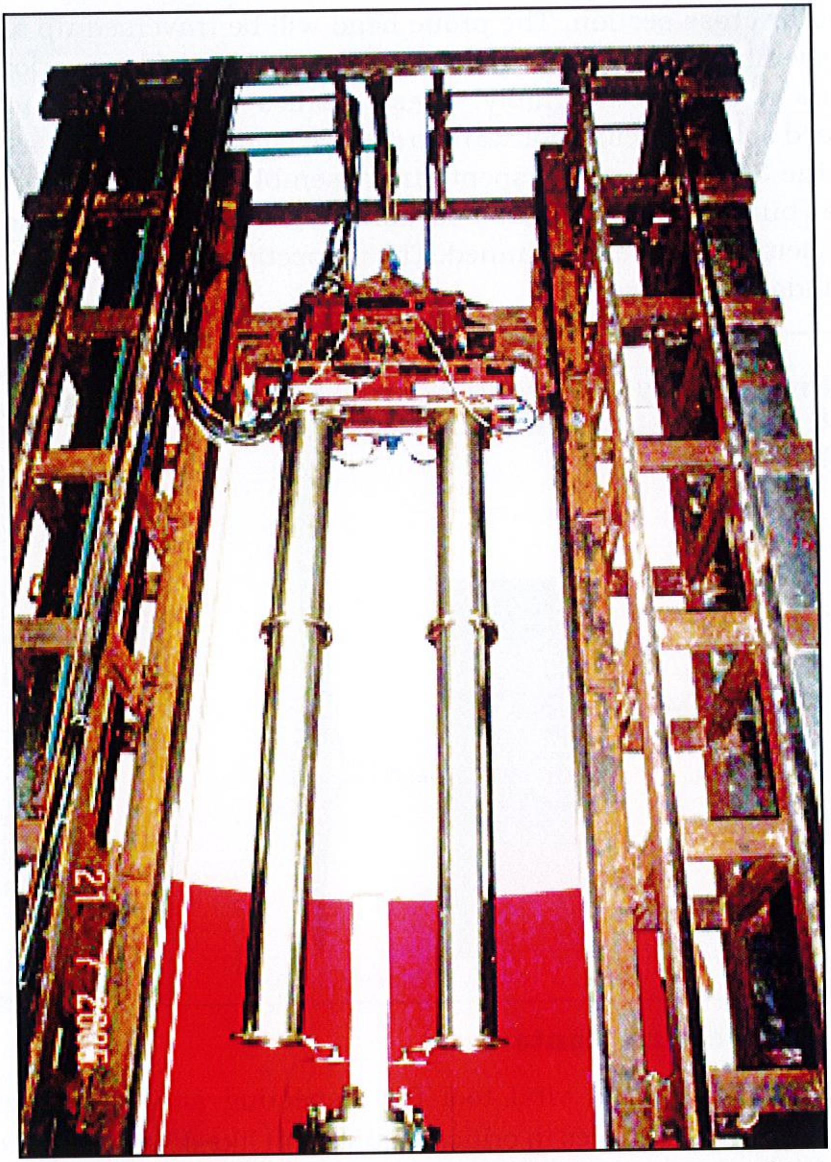
A novel design approach has been adopted for easy inspection of SG tubes with high reliability and speed. This design uses a four-legged walking robotic device, deployed on the top tube sheet of the SG for positioning the probe on the tube to be inspected. There are 547 tubes in the PFBR steam generator. The robot is designed in such a way that in the collapsed condition, it has an overall size of Ø 260 mm × 175 mm (H), which facilitates deployment of the robot through the Ø 380 mm manhole provided on the top side of the SG steam side dished end. The robot, as is evident by its name, has four legs to perform a walking motion over the SG tube sheet. The system also has a motorized winch for translating the probe inside the SG tube.



Steam Generator Inspection Device on mockup tube sheet

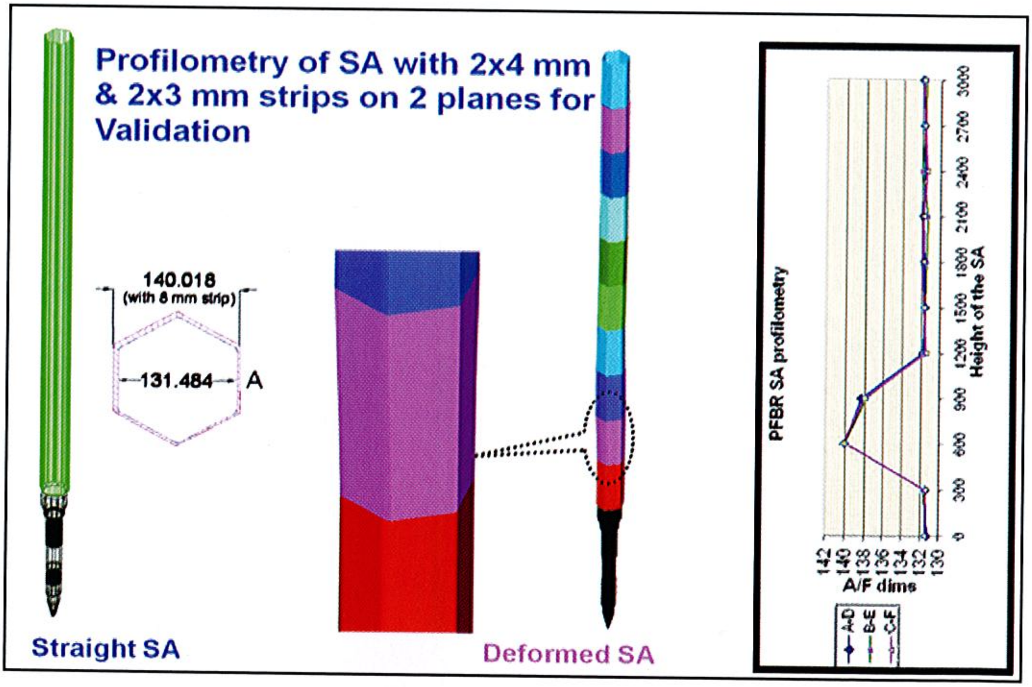
Poolside Inspection of Spent SA of PFBR

Preliminary PIE of spent PFBR subassemblies (SA) are planned to be carried out underwater in the reactor spent fuel storage pool to give quick feedback about its performance. Visual examination and metrology of the spent subassemblies are envisaged as part of this PIE. For this purpose, a prototype special purpose inspection bench has been developed to carry out the dimensional measurements.



Poolside Spent Subassembly Inspection Bench

The inspection bench is a four-axis programmable manipulator driven by stepping motors. The bench is designed in such a way that all moving components excepting the measuring probes, are kept above the storage pool eliminating the need for expensive underwater compatible components and this design will not hinder the fuel handling operations. A single LVDT is used as a simple touch probe to register the co-ordinates of points on the surface around the sub-assembly at a particular cross section. These co-ordinates will be reconstructed to get the profile at the particular cross section. The probe head will be traversed up along the sub-assembly at user-defined intervals to get the profile of various cross sections of the sub-assembly. These profiles will be integrated using standard solid modeling software to get a 3D model of the sub-assembly. From the 3D model of the spent sub-assembly, extent of deformations such as bulge across the faces / corners, bow, twist and elongation of the sub-assembly can be determined. The inspection bench has been tested and validated underwater.

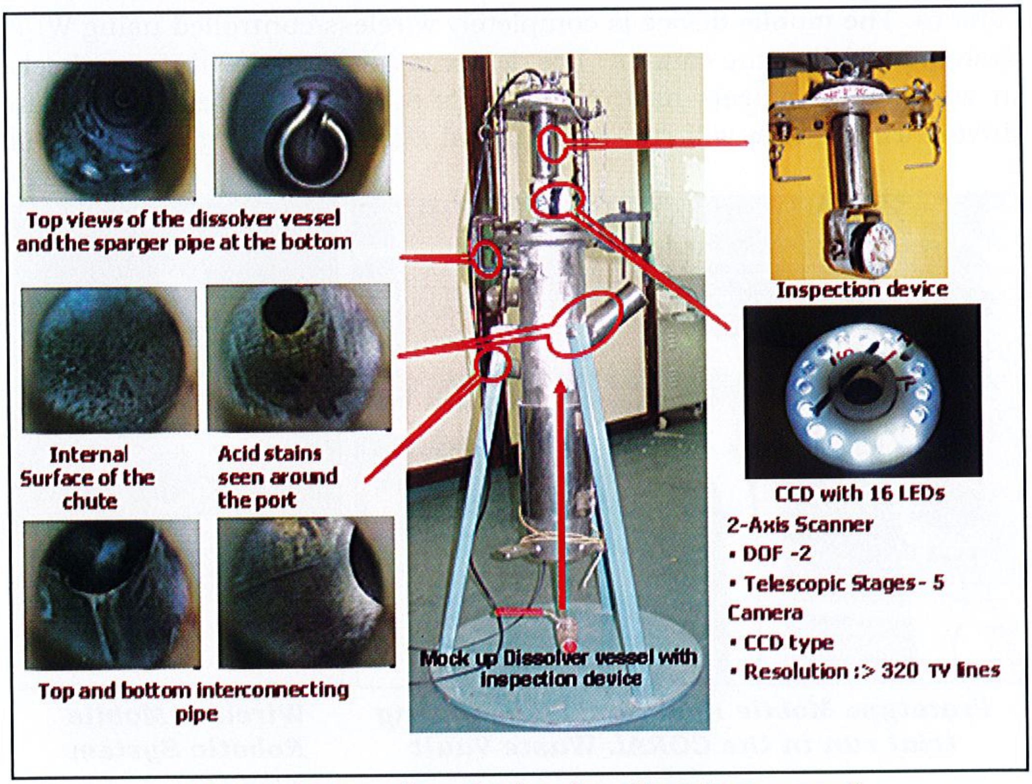


ISI of reprocessing plants

ISI has become a vital tool for inspecting and taking remedial measures to avoid failures in critical equipment like dissolver vessel, pipe lines carrying radioactive chemical solutions, storage tanks, etc., in the reprocessing plants. In view of the prevalent harsh environment, the ISI has to be carried out largely through remote operations. The development work carried out for this domain is detailed in the following sub-sections.

Visual Inspection Device for Dissolver Vessel

As part of the program for comprehensive in-service inspection of critical components of the reprocessing plants, the dissolver vessel of the CORAL is required to be inspected periodically using NDE techniques to assess its health and integrity. One of the NDE techniques envisaged is visual examination using a camera and remote device.



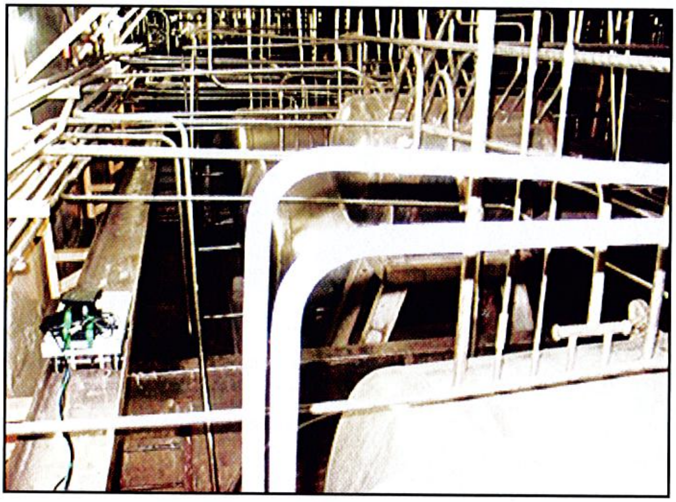
Visual inspection device for dissolver vessel

The device including the camera is light weight and compact in view of the limitations in transferring the device into the cell and the in-cell handling equipment. A remotely operable telescopic device with a compact camera has been made for this purpose. Overall size of the device in the collapsed state is 195 × 305 mm. Preceded by extensive mock-up tests and trials, visual inspection of the dissolver vessel limb in CORAL was successfully carried out using the remote device.

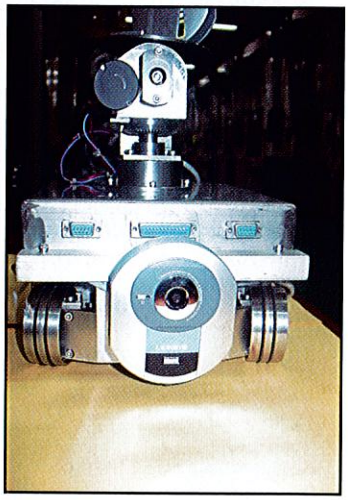
It was seen that the vessel remains free of remnants after dissolution of the fuel and there is no clogging of chute. All accessible welds and surface of the vessel limb were examined closely. The campaign did not reveal any significant degradation of the inner surfaces or weld joints. This development and successful implementation in the plant has provided the confidence for extending the ISI campaigns to other areas of reprocessing plants.

Mobile Inspection device for ISI of CORAL waste vault

A wireless mobile device has been and developed for carrying out a global visual examination of the CORAL waste vault using a CCD based camera. The mobile device is completely wireless controlled using Wi-Fi system including the camera. The device is configured with four wheels, in which front wheels have Ackerman's steering and rear wheels are driven. The vehicle will run over special stainless steel guide rails laid



Prototype Mobile Robotic System during trial run in the CORAL Waste Vault



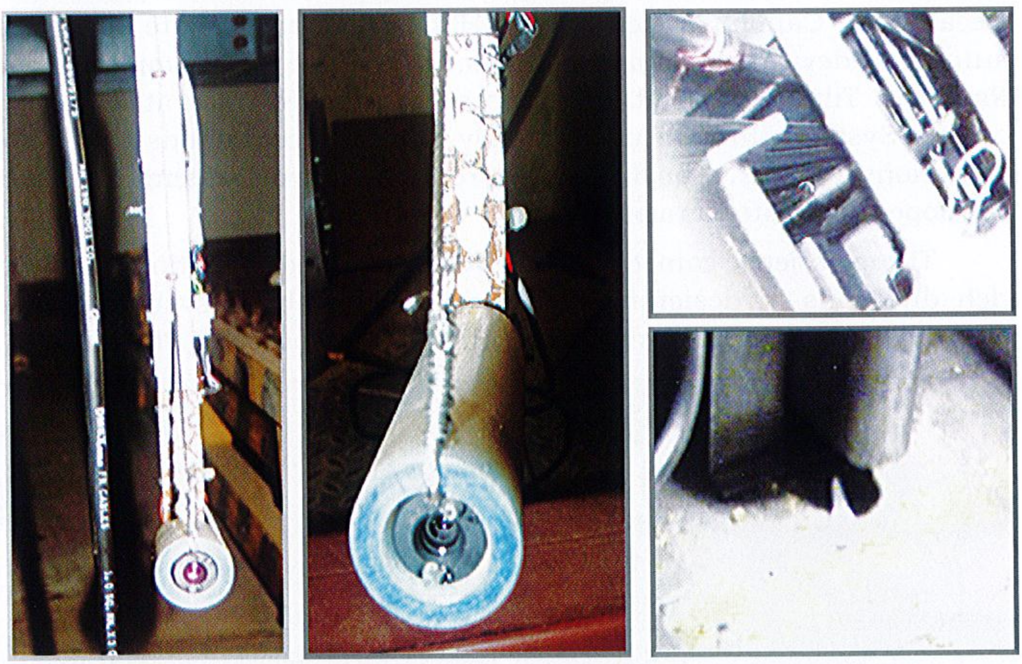
Wireless Mobile Robotic System

along one of the walls of the CORAL waste vault. The motors of the vehicle are mounted on the base plate and gear trains are used to transmit the power to the drive wheels and steering wheels. The overall size of this device is 275(L)X 215(B) X 276(H) mm. Speed of the vehicle can be adjusted to 0 m/min-2 m/min. The device can be remotely operated through a pendant and a joystick. In view of the acidic atmosphere and radiation environment, SS 304 is chosen for the structural material of the vehicle.

In-Service Inspection of Process tanks below the containment box in CORAL

One of the ISI tasks identified in CORAL is the visual inspection of the space below the containment box where tanks and vessels containing highly active process solution are placed. The stainless steel containment box is shielded by using lead bricks all around the box and the process tanks and vessels with highly active process solution are kept below the containment box. The gap between the containment box and the lead brick wall is nominally 100 mm and decrease wherever the window protrudes from the lead wall towards the containment box. The difficulty comes in the form of restricted access, lack of ISI-Specific penetrations available in the lead cell, narrow space between the lead cell and the containment box and piping work between the lead cell and containment box.

A manually actuated multi-link manipulator consisting of series of small links having a length of 60 mm has been made with the end-effector having two degree of freedom, namely pan and tilt.



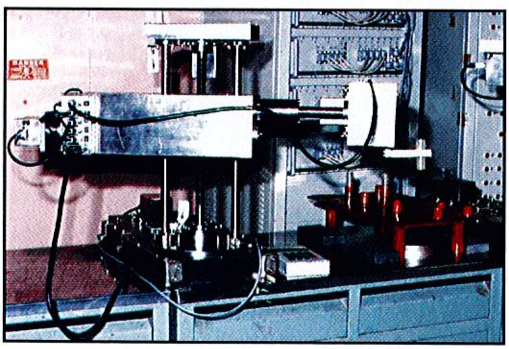
Device for ISI of space below containment box and the snapshots obtained during the inspection

A CCD-based camera has been used as the end-effector for carrying out the inspection. The pan and tilt motions facilitate the camera to achieve maximum coverage of the space below the containment box during the inspection. The configuration of the manipulator is such that it is rigid in one direction and flexible in opposite direction in the same plane making it steady during the actuation of the pan and tilt motions. Subsequent to extensive trials, the device has been used in the CORAL plant. The inspection did not reveal any abnormalities as can be seen from the images obtained.

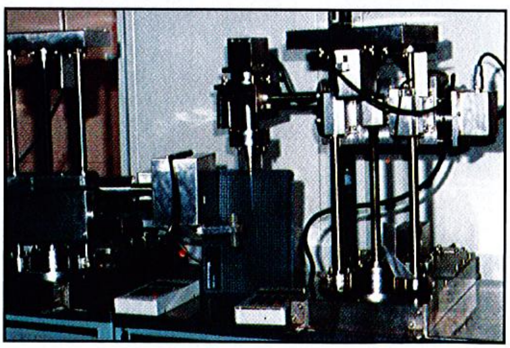
Integrated Robotic System for remote analytical cell

Reprocessing of spent nuclear fuel, to recover valuable fissile material, is a complex chemical process that requires continuous monitoring of process parameters by collecting and analyzing the samples of process solution at various stages. Remote sampling and analysis with automation play an important role because of highly radioactive nature of the process solution. In this perspective, an integrated robotic control system (IRCS) has been developed for automated sampling and dilution of samples of process solution in Remote Analytical Cell (RAC) of reprocessing plant. The RAC consists of Decapping / Capping Robot, Sample Handling Robot, Pipette Robot and automated devices viz. sample stations, Linear slide way, Sample Storage Rack and Tilting carousel. A microprocessor based Integrated Robotic control System, through user friendly software, commands the entire operations of RAC. The Integrated robotic control system has been developed and tested as a prototype.

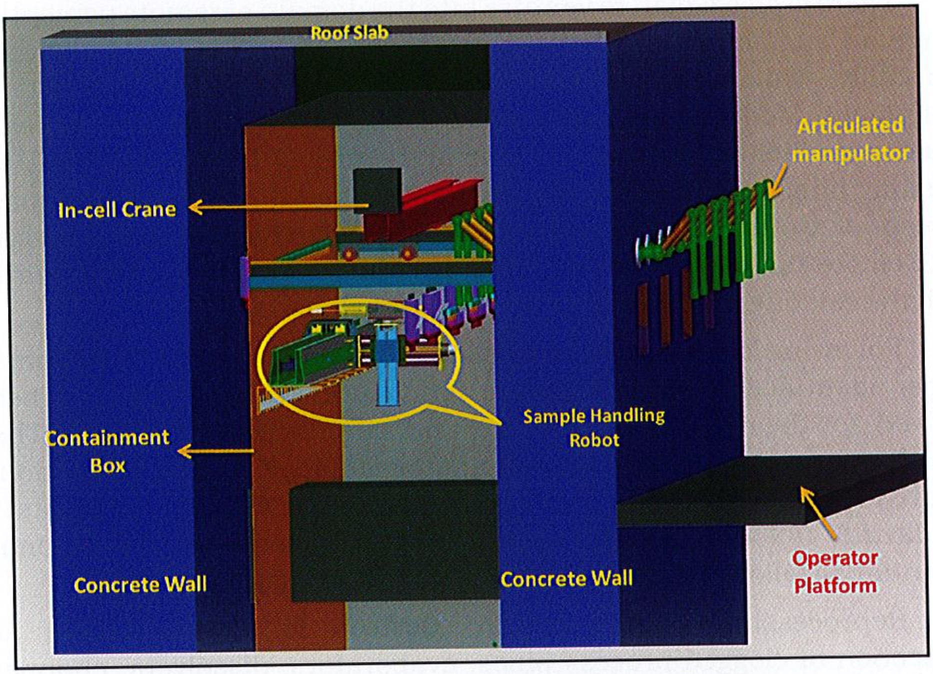
The experience gained in this development and validation has given rich dividends in designing a comprehensive robotic system for the analytical cell of the Demonstration FBR Fuel Reprocessing Plant (DFRP).



Sample Handling Robot



Pipette Robot



CAD model of the conceived robotic system for DFRP remote analytical cell

The Future ....

The future work programme of Remote Handling and Robotics is focussed on generic research aimed at extending the range of tasks that can be undertaken with novel devices. There is also a strong commitment for mission-critical specific developments to provide the methodology and means to undertake tasks such as inspection and repair. Objective collaborations with renowned academic and research institutions with the support from Indian industry would enhance our efforts in addressing the technological needs in the offing.

Teleoperation, is the technical term for the operation of systems or equipment in a physically remote location, carried out using specialized electronic communication and robotic engineering.

Seamless transfer of classical remote handling technology from *teleoperation* towards robust telerobotics is a future direction. Development of servo manipulators with bilateral force feedback is intended to be a first milestone leading to telerobotics which would be of immense use in the domain of remote maintenance and repair.

There is also a plan to venture into the domain of remote perception, where an augmented display can assist the user of the remote system, especially while carrying out maintenance and repair of hot cell equipment. Modeling and simulation in conjunction with virtual reality could consolidate the development and training in a methodical way avoiding large Man-Rem exposure. Haptics, another important sensory perception would add great value to the remote perception while carrying out remote maintenance and it requires development and integration with the existing robotic and manipulator systems.

Following closely on the heels of PFBR ISI system development under identified tasks, ISI device for future FBRs (CFBRs) is being evolved, for the reduced main vessel and safety vessel interspace. There is a strong need to develop ISI techniques and tools for the inspection of future FBR internals in the cover gas and under sodium components. As a natural fallout, development of repair techniques is becoming essential, to follow the development of ISI techniques and tools.

Reprocessing plants require devices for identification and inspection of clogged process pipes, evaporators, dissolvers, choppers, etc, towards achieving maximum availability of the plant.

Complete automation is on the anvil for the upcoming metallic fuel fabrication facility. *Servo manipulators* are planned to be used for remote handling operations in this facility.

Snake-like robots, being in a nascent stage would be taken to the end-product level for real world applications like remote inspection/repair /surveillance in the reactor / reprocessing plants.

General purpose electric servo manipulators are designed for work in remote, hazardous locations, providing a natural feel of the work being done directly by the hand.

The current developments have been catering to the needs of PFBR, and pilot fast reactor fuel reprocessing plants, albeit partially and enlarged scope of remote handling and ISI needs for these plants would have to be addressed.

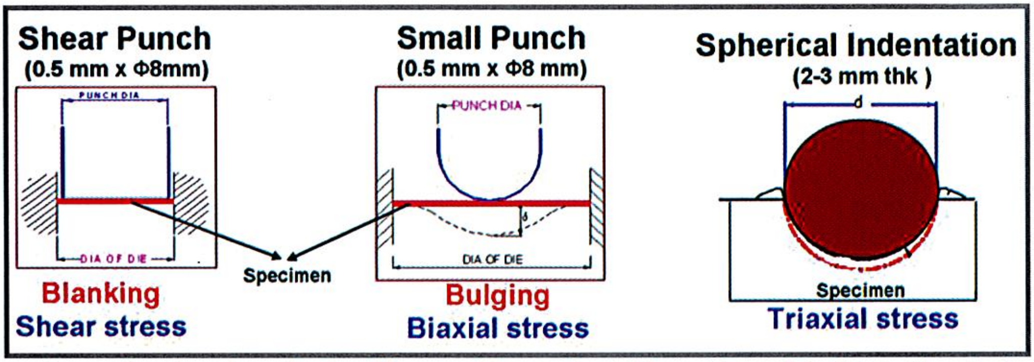
On the other hand, the very fast-paced developments in the field of robotics and automation have made it even more imperative that the current expertise must be transformed to an even higher level that could be possible only through generic and domain-specific research. In a nutshell, it can be said that technology, science, human resource, zeal, strategy, inspiration, mission and vision would be the distinctive ingredients of this challenging and stimulating arena.

DEVELOPMENT OF SMALL SPECIMEN TESTING

Mechanical properties of materials indicate its elastic and plastic behavior in response to applied stresses. Some of the commonly measured mechanical properties include the Young's modulus, yield strength, ultimate tensile strength, work hardening coefficient, hardness numbers, creep strength and fracture toughness. A need to evaluate the mechanical properties using small amount of test material got tremendous importance during materials/alloy development for nuclear fission and fusion reactors in the early 80's. Due to the limited space in the reactor core for test irradiations, the specimen sizes were miniaturized for fitting into the available space from which an assessment of changes in mechanical properties and microstructure could be made. Other considerations specific to our nuclear industry that favored the specimen miniaturization were (1) gamma heating, which limits the mass of the material that can be placed at a given irradiation location for a given temperature range; (2) flux gradients, which may be sufficiently large in large test specimens; (3) material availability from experimental heats of development alloy and number of desired tests; and (4) doses received during post-irradiation handling & testing. As a spin off, the miniature specimen test techniques also find applications in the field of remaining life assessment, failure analysis, properties of weldments, coatings etc. A number of specimen designs and techniques based on use of small specimens have evolved and come into main stay for the evaluation of mechanical properties.

Sensing the potential applications of small specimen techniques in PIE and irradiation experiments (at FBTR), a programme on small specimen testing at RML, IGCAR was initiated in the early 90's. With only few published literature in this area as our reference material, the programme was kick started with the design of test fixtures for the non conventional test techniques based on the use of small disc specimens of 3-8 mm diameters and 0.3-0.5 mm thick. These tests broadly involve loading a clamped specimen with a specific indenter and analyzing the resulting load-displacement data obtained during the deformation process. The popular techniques in this category are (i) Miniature Disk Bend Test (MDBT), (ii) Small Punch (SP) (iii) Shear Punch (ShP). The other technique that was considered for ab-initio development was the Ball-Indentation (BI) test which was based on the indentation with spherical indenters for determining the material stress-strain properties.

These non conventional techniques were evolved and standardised with respect to specimen preparation, its dimensional control and a high precision of loading and measuring systems and analysis of the test results. The test machines for conventional mechanical tests were initially adapted for the small specimen tests.

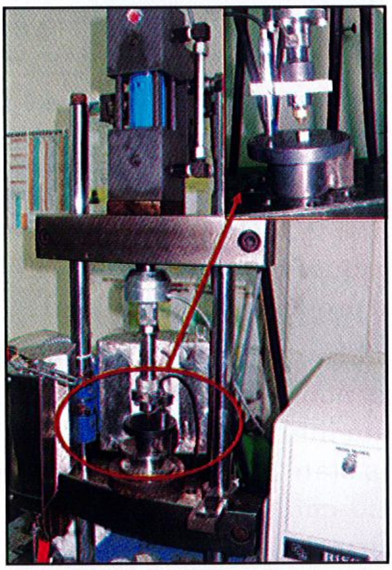


Schematic showing the loading configuration of punch and indentation tests

In one of the first applications, the MDBT was successfully employed to examine a failed aluminium nozzle of a chemical vessel in a gas cracker complex. The mechanical properties of the aluminium weldments near the failed locations were determined from MDBT tests. Prior to this, the technique was validated with the results of conventional uniaxial tensile test using the base material. The innovative use of online acoustic emission monitoring during the MDBT test was attempted for the first time ever. This helped in understanding the various deformation regimes during the test and also in interpreting the test results. Using the MDBT technique, the yield strength and relative toughness of weld and base metal were determined and correlated to the microstructural variations in the failed component. This helped in analysing the causes of failure of the weld joint in the chemical vessel.

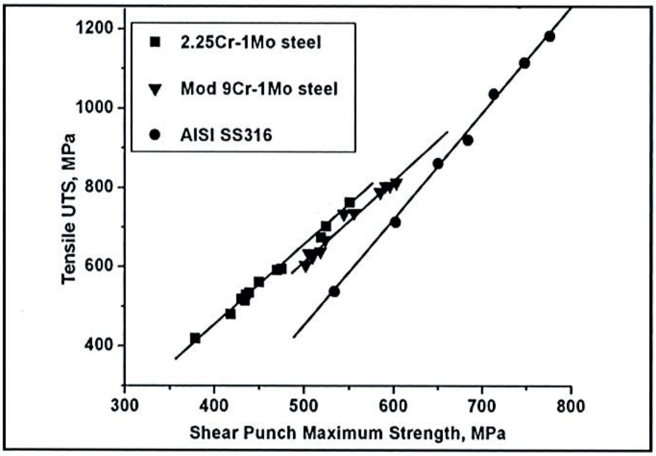
The shear punch technique which involves blanking a small specimen was then extensively studied and benchmarked. The major advantages of this technique were the simplicity of the loading configuration and the similarity of the resulting load-displacement data to the tensile test data. The resulting slug which is Φ3 mm disc can be directly a starting material for TEM studies thus enabling structure-property correlations. Thus this technique was ideally suited for characterising both the tensile properties and the microstructure of irradiated materials. Nevertheless, the complex stress states during deformation made interpretation of the test results more difficult. Preliminary results revealed considerable scatter in the prediction of the yielding during shear punch test. This was due to the difficulty in locating the point of deviation from linearity in the load-displacement curve. The use of online AE monitoring during the test greatly aided in locating the point of onset of yielding during the shear punch test. The results of this innovative use of NDE tool in small specimen testing was well appreciated in the III ASTM conference on small specimen test techniques, USA in 1996.

The other technique that was developed ab-initio was the spherical indentation test. Hardness tests using spherical indenters are unique because the geometry of indentation changes with increasing penetration, corresponding to unique stress-strain value for a particular depth. The Ball-Indentation (BI) Test involves progressive indentation of a metal surface by a spherical indenter with partial unloading performed at the same test location. The applied indentation loads and associated penetration depths acquired during the BI test were used to calculate true stress-strain values using well established analytical expressions. Two custom built test systems namely a servo-hydraulic test system and a miniature motorized electro-mechanical system were designed and developed in-house for standardizing the BI test technique.



Custom built servo hydraulic machine for ball-indentation test

These non-conventional punch/indentation based techniques needed extensive standardization on the laboratory scale with a wide variety of materials along with their microstructural variations and validation with its conventional counterpart for acceptance before putting it to use for its intended applications. Thus a methodology was devised for the standardization process wherein wide variety microstructures of 2.25Cr-1Mo, 9Cr-1Mo steels and SS316 generated by heat treatments, cold working etc were used. Both the conventional tensile and the small specimen tests were performed on these material conditions and the relationship between the small specimen test results and the tensile test properties were analysed. Through the standardisation process, tensile–shear correlation equations were established for the YS, UTS and work hardening exponent.

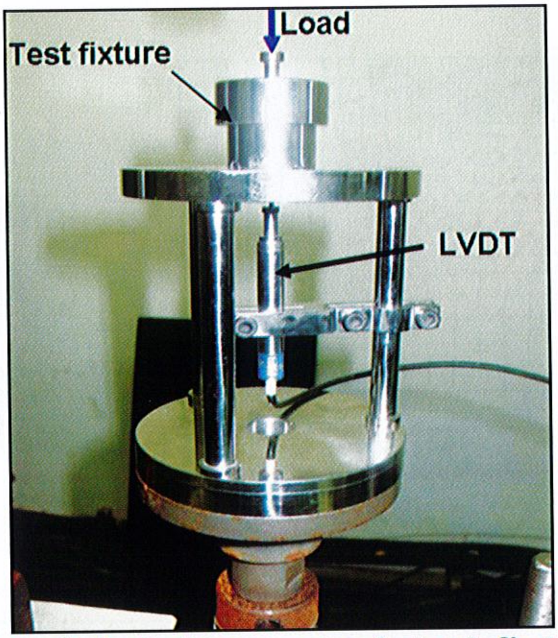


Tensile to shear correlation obtained for various alloys

Following the standardisation process, the technique was successfully employed for evaluating the tensile property gradients across the weld joints of 2.25Cr-1Mo and 9Cr-1Mo steels. In another application, the technique was integrated with PIE for evaluating the changes in mechanical properties of irradiated SS316.

The smaller specimen dimensions coupled with complex loading configuration leads to non-uniform deformation across the specimen volume making the data interpretation difficult. Therefore, studying the deformation and stress state of the specimen analytically or numerically is a very important and challenging component in the standardization procedure for understanding the deformation sequence, data interpretation and validation, and in translating the deformation behaviour at small scales to that of the conventional sized specimens. Modeling also aids in analyzing the interplay of various parameters of the deformation (like size of punch, specimen diameter, thickness, fixture dimensions and clearances etc) and helps in optimizing the experimental design, reducing the number of experiments for standardization and contributing towards developing science based correlations with conventional specimen results.

The Finite Element (FE) modeling of the shear punch test upto yielding was taken up. The FE results indicated a large influence of the punch compliance on the elastic portion of load-displacement plot. By shifting the point of displacement measurement from punch movement to the bottom surface of specimen in the experiments, the elastic loading lines of experimental curve matched well with the FEM generated curve. Based on development of plasticity through the specimen thickness, the stress state was found to be primarily shear up to yielding. This was also reflected in the observation that the experimental yield stress values satisfied the von Mises relation $\sigma_{ys} = 1.73\tau_{ys}$. This study was used to rationalize the method of estimating shear yield strength using the 0.2% offset definition so as to enable reliable estimation of tensile yield strength of irradiated alloys from shear punch tests using the von Mises yield relation.

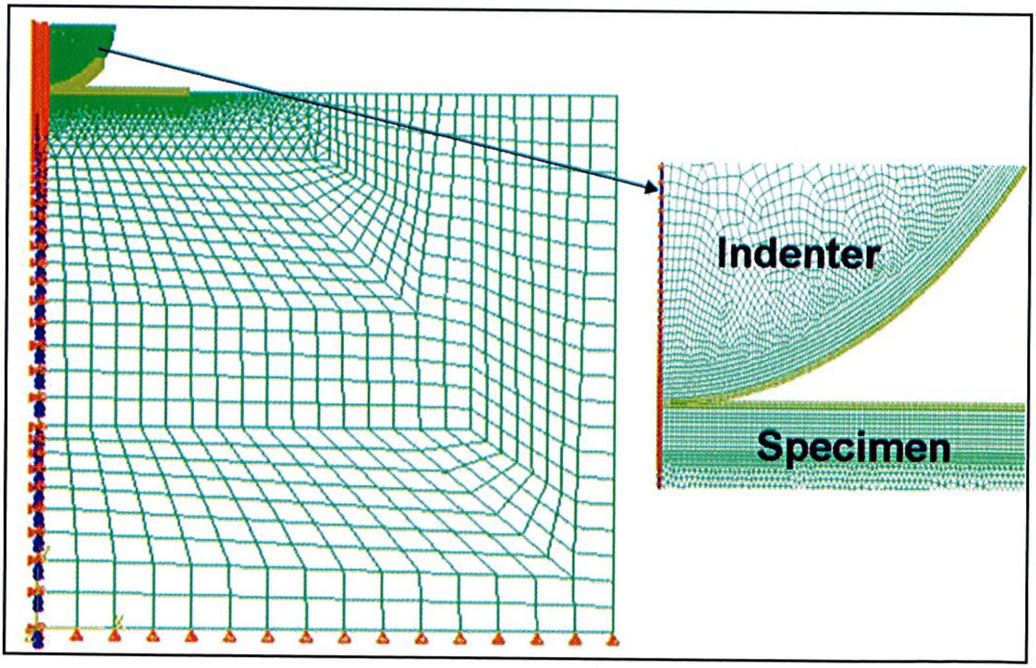


Modified shear punch test fixture

The FE modeling of Ball-Indentation test carried out in collaboration with IIT Mumbai, has aided in identifying the compliances of the test fixtures and in visualizing pile-up effects associated with indentation process. After validating the FE model with experimental data, the effects of pile-up were visualized through simulations and expressions for pile-up corrections were verified. The FE model is being used for generating a set of L-h (load-depth) curves for various combinations of YS and strain hardening exponent, and to develop an inversion methodology based on an optimization technique for a direct evaluation of σ-ε (stress-strain) curve from a given experimental L-h data.

With these insights and standardization, the indentation technique was applied in a novel way to evaluate the changes in mechanical properties of modified (mod) 9Cr-1Mo caused by thermal and creep exposures using the head and gage portions of the creep specimens.

The small punch (SP) test involving the deformation of a clamped disc specimen (10 mm x 10 mm x 0.5 mm) under a spherical punch (2.5 mm diameter) has also been modeled using a general purpose finite element solver to understand deformation behavior in the specimen. For successful implementation of inverse methodology, the sensitivity of the load-displacement curve of SP test to factors such as the friction between



FE model of the spherical indentation

the ball-specimen and specimen-die interfaces, initial clamping force and input material stress-strain properties have been examined.

Efforts are underway to develop an in-house finite element code to study the specimen deformation in small specimen test. The code development is based on the updated Lagrangian formulation to simulate the finite elasto-plastic deformation. An automatic triangular mesh generator is built in to the code for generation of meshes of varying sizes. The code is capable of handling the contact nonlinearities that arise during the simulation of the small specimen test.

The established experimental test facilities and the insights gained from FEM and analysis will be valuable for predicting the mechanical property changes of irradiated advanced fast reactor structural materials and for remaining life assessment of critical power plant structures.

NEUTRON RADIOGRAPHY

Radio Metallurgy Laboratory (RML) is supporting various organizations such as Indian Space Research Organization (ISRO), Indian Air force and Defence Research Development Organization (DRDO) in qualifying critical components by Neutron Radiography (NR).

Application in Space programme

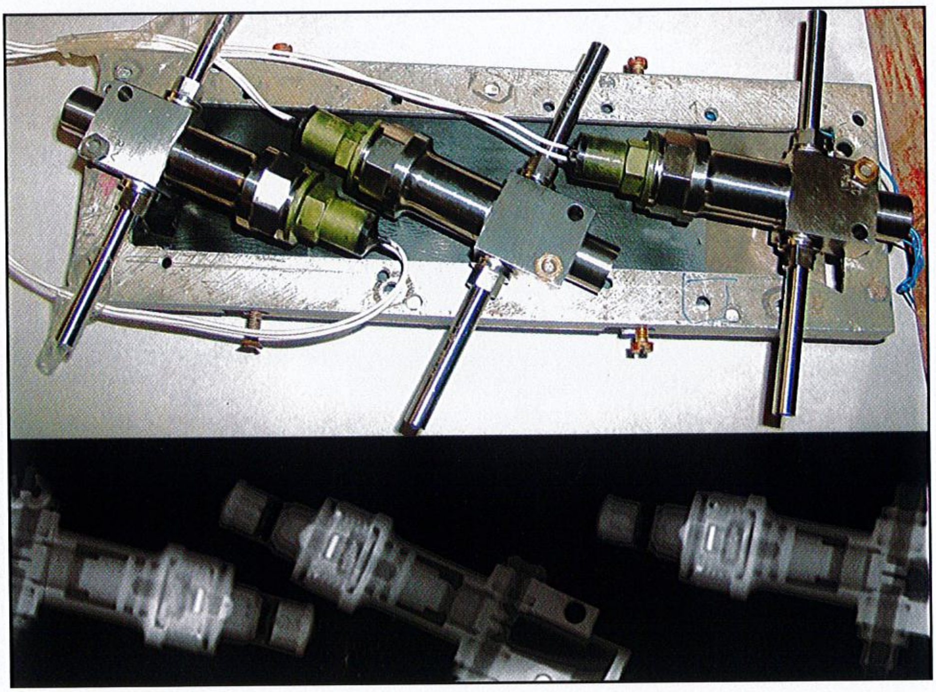
The space programme has become largely self-reliant with capability to design and build its own satellites and to launch them using indigenously designed and developed launch vehicles.

In a space launch, hundreds of pyro devices are used in the launch vehicle as well as in the satellites. Pyro devices are basically pyro-chemical based mechanical devices, which contain a small amount of explosive mixture inside a thick metal casing, and are extensively used in all the stages starting from ignition of the strap-on motors up to positioning of the satellite in the required orbit. Pyro devices are also used to shear very thick fasteners to sever burnt out stages and for jettisoning the heat shields from the launch vehicle after it has cleared the dense atmosphere. In satellites, pyro devices are used to deploy solar panels, antennae and for parking satellites in desired orbits. Pyro devices are also required for de-orbiting a spacecraft to bring it back to Earth. Hence, reliability of pyro devices is critical to the success of any space mission.

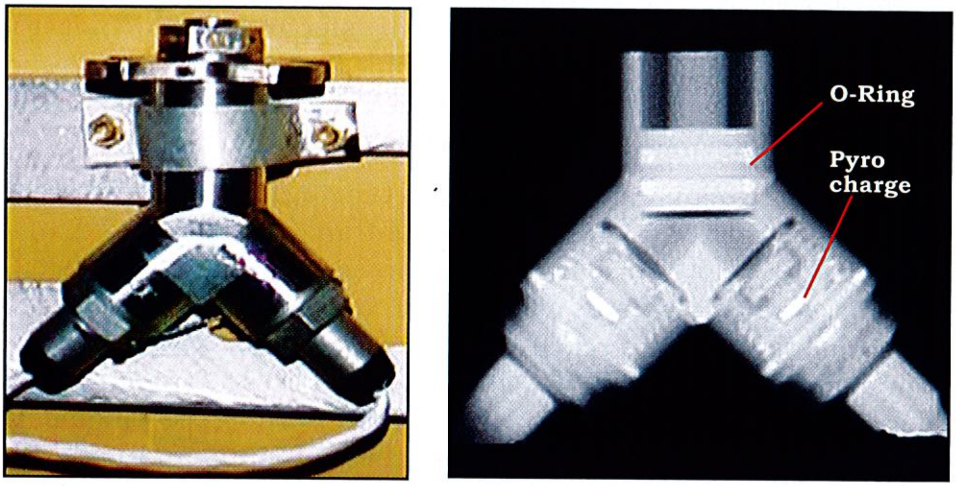
Thermal neutron scattering cross section is high for hydrogen based explosive materials and presence of explosive charge encased within the metal casing is easily imaged by neutron radiographic method by adopting transfer technique. Neutron radiographic inspection of pyro devices are carried out to ensure the presence of explosives, continuity, uniform charge density and presence of "O" rings inside the sealed metal casings of the devices, to ensure total reliability. During the period 2001-2010, more than 7000 pyro devices such as Explosive Transfer Assembly (ETA), Cartridges, Pyro valves, Cable cutter, Explosive manifold, 12 inches diameter. Bolt cutter and pyro thruster etc. were examined by NR for qualifying for use in launch vehicles In Chandrayaan-1 moon mission, one of the payloads was a moon impact probe (MIP) intended to make a landing on the moon. MIP pyro thruster and MIP cartridges were qualified using Kamini neutron radiographic facility. The contribution of NR in the quality control of the pyro devices has ensured the successful landing of MIP carrying our tricolour in the lunar soil.

Pyro devices can be in different sizes ranging from a tiny detonator to a heavy bolt cutter or a lengthy explosive transfer assembly. Whatever may be the device, it has to be carefully integrated within the frame and kept in close contact with the dysprosium converter screen for facilitating image formation in the transfer technique. The number of frames chosen for radiographic investigation depends on the type of component, its dimension and the explosive charge content. A stepper motor driver Cassette Drive Mechanism (CDM) enables loading and indexing of multiple components and multiple exposures in single reactor startup. 10 cassettes can be loaded in to the CDM at a time and up to 10 exposures can be carried out without reloading.

During exposure, the converter screen kept behind the object is exposed to neutron beam. Dysprosium foils are used as converter screens. The activated converter screens are transferred latter to a dark room and keep in contact with X-ray films to produce image.

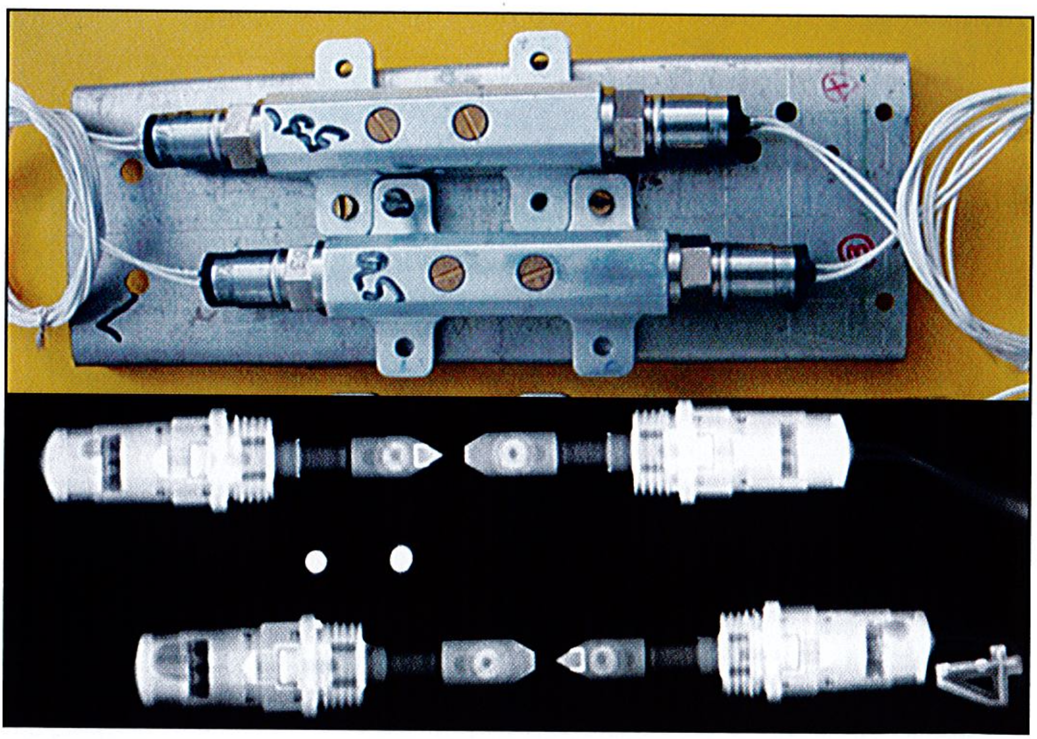


Photograph of a dual pyro valve and its digitized NR image



Photograph of pyro thruster and its digitised NR image

Excellent radiographic contrast and sensitivity enable clear delineation of the pyro charges, elastomers, filling and integrity of the potting compound, internals present, ceramic cup and quality of the brazing etc.

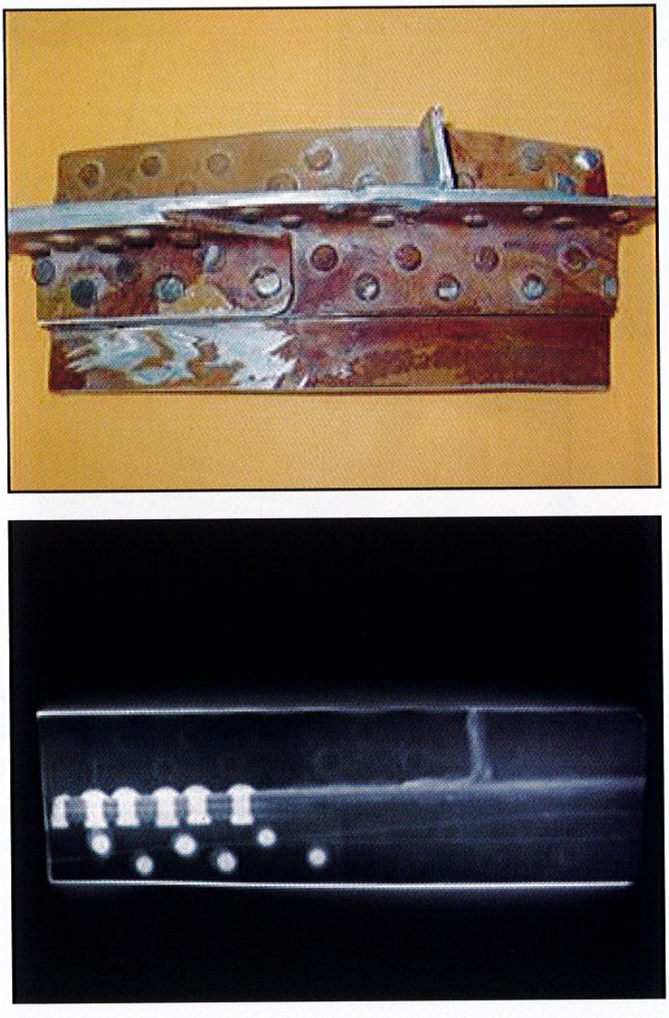


Photograph of satellite cable cutter and its digitized NR image

Applications in Defence

Indian air force

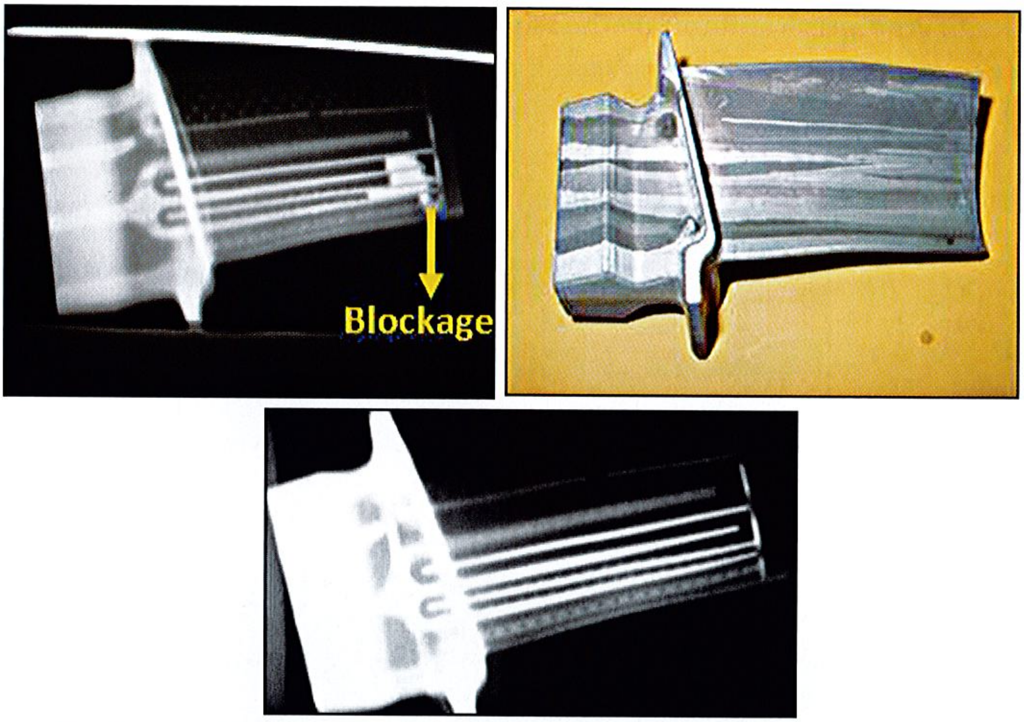
Neutron radiography is a widely applied NDT technique used in aerospace industry to detect corrosion damages. Aluminium, which is commonly used in the aircraft industry, is prone to various types of corrosions due to ageing, frequent changes of environment and moisture ingress. These corrosion damages are elusive to aircraft maintenance personnel for evaluation of "safeness" of ageing aircraft. Neutron Radiography is a suitable method for detecting such defects.



Photograph of riveted aluminium airframe and its digitized NR image indicating ingress of moisture inside the riveted lap joint in an airframe

Defence Research Development Organization

In the defence production sector, hollow turbine blades are being widely used in the gas turbine of light combat aircraft. In these hollow turbine blades, air cooling passages are sometimes blocked with remnant core particles from the casting operation. These core particles have high thermal neutron scattering cross section and hence their presence can be detected easily by neutron radiography.



Neutron radiograph of a cored turbine blade showing clear cooling passage and blocked passage in the aerofoil region

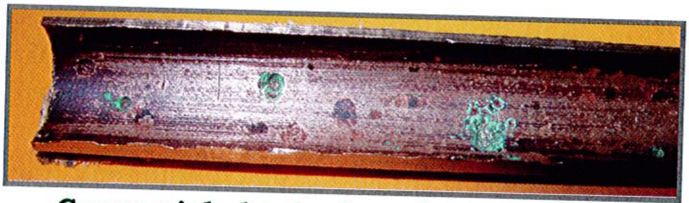
FAILURE ANALYSIS

Engineering failures often are due to complex synergism of parameters like design deficiency, material/manufacturing defects, inadequate quality control and unusual excursions during service like overloads, excessive temperature, corrosive environments etc. Detailed analysis of failure often requires a multi-disciplinary approach to identify sequence of events leading to predominant cause of failure. Failure analysis is one of the objectives of PIE where a series of non-destructive and destructive examinations are carried out in a logical sequence. Spin-off resulting from technologies developed for PIE and NDE has led to creation of expertise in RML in the area of engineering failure analysis. The first failure analysis was on a yoke body pin of MSM carried out in 1983 and published in Practical Metallography, 1984.

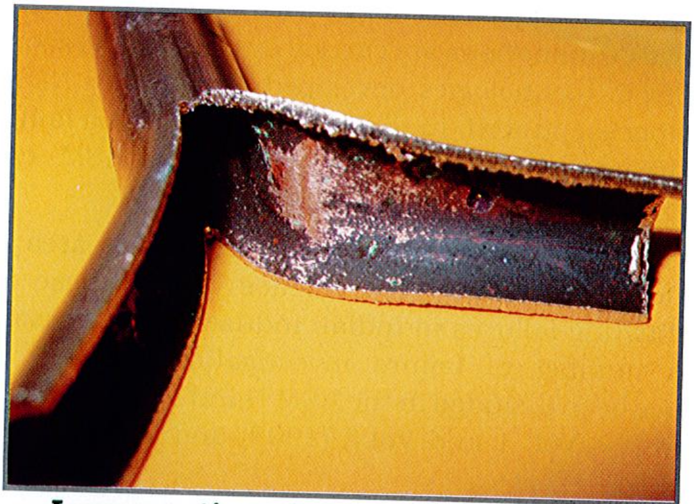
Technical/scientific expertise developed in this area at RML has contributed to understanding the science behind these failures and helped in mitigating failures in Indian industry by suggesting remedial measures. A number of failure investigations carried out in this laboratory have been included in the ASM Hand Book of Case Histories in Failure Analysis – Vol. 1 and Vol.2 (1992) and in many other leading journals.

RML has led a number of failure investigations of critical components such as Low Pressure steam turbine blades from Rajasthan Atomic Power Station, boiler heat exchanger tubes from Madras Atomic Power Station, Lube oil coolers, crane & wire ropes, stainless steel bellows of control rod drive mechanism and bellow-sealed valves in the sodium circuits of FBTR. RML has also extended this expertise to other sectors like defence, aerospace and core industries. The failure analysis of some major components for the defence sector include main landing gear of MIG-29 aircraft, MI 8 helicopter aero engine turbine blades , IL-76 structural components, AN-32 transport aircraft turbine blade, aero-engine compressor disc and aircraft structural materials. The investigations done for the petrochemical and power industries include heat exchanger tubes from a fertilizer plant, dissimilar weld joints in steam pipeline, ammonia refrigerant condenser tube and high pressure steam inlet valve. A few highlights of the failure analysis are presented below.

Failure of Copper tubes of lube oil coolers in the turbo generator of a nuclear power plant - Failure was attributed to the pitting corrosion due to the flow induced disruption of passive copper oxide film.



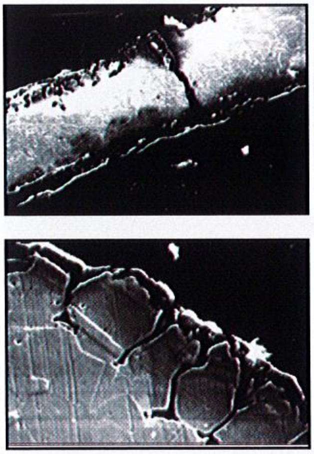
Cupro nickel tube from lube oil cooler

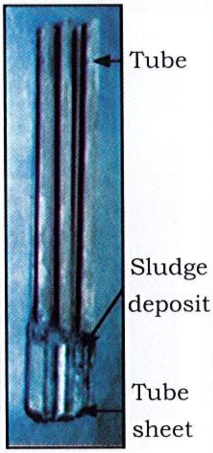


Inner portion showing pitting attack

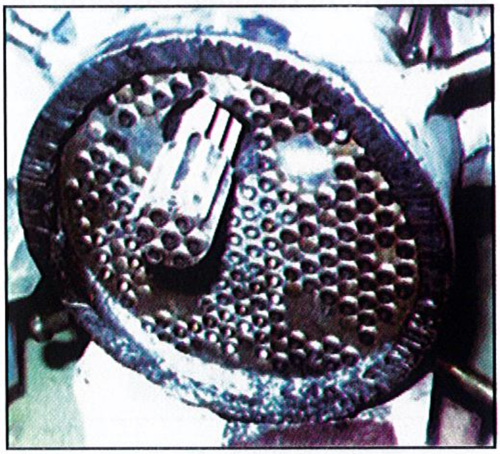
Extensive intergranular pitting attack on the surface of the tube the inner disruption of oxide scales

Failure of Monel heat exchanger tubes in a nuclear power plant was attributed to crevice corrosion caused by the accumulation of sludge deposits on the tube sheet.



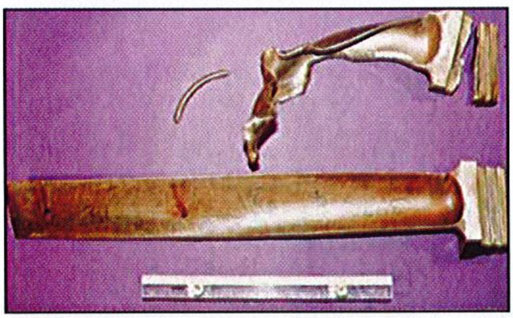


Through and Through Opening and Intergranular Corrosion at the Defective Location due to Sludge Deposit



Trepanned portion of the tubes with tube sheet

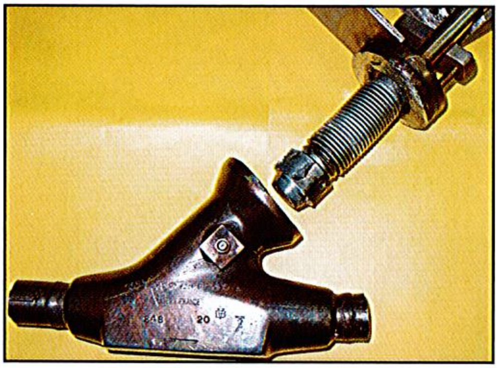
Failure of low pressure steam turbine of a nuclear power plant - cracking in the fir tree root was observed and the failure was attributed to corrosion fatigue.



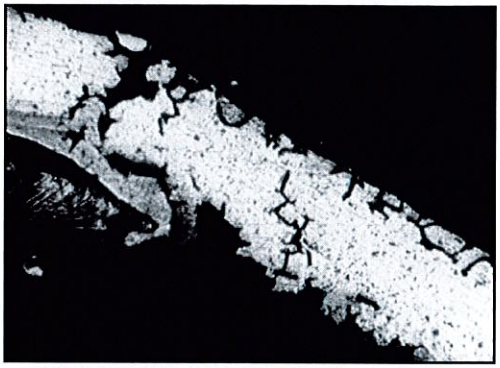
Failed and a fresh turbine blade

SEM Photograph showing crack initiation from a corrosion pit and a magnified view of the corrosion pit

Stainless Steel bellow sealed valve used for controlling the flow of liquid sodium in a nuclear reactor - The failure was attributed to the sensitization of the material during welding and intergranular corrosion in the heat affected zone (HAZ)

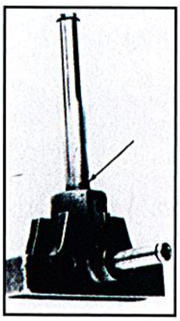


Failed SS bellow

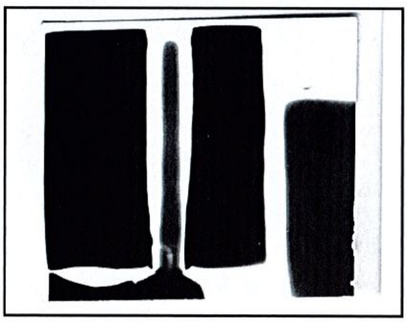


Photomicrograph showing intergranular cracking & carbide precipitation in the HAZ

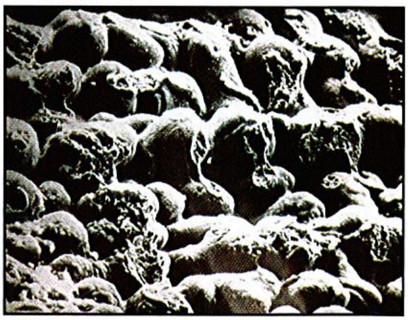
Failure of a yoke body pins of a remote handling device, was attributed to casting defects (shrinkage cavity) at the region of transition between slender pin and body of investment casting.



Failed yoke body

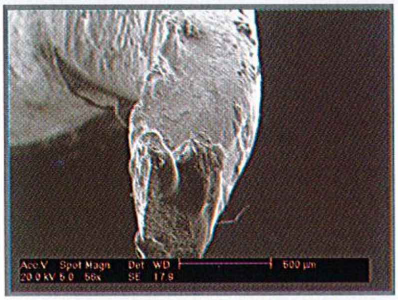


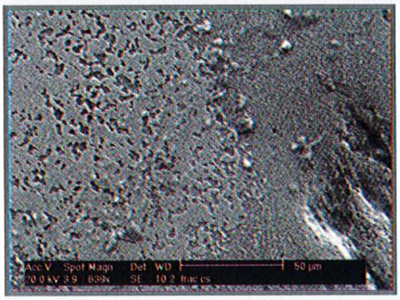
Radiograph showing shrinkage cavities at the transition portion



Shrinkage cavity in casting

Failure of a wire rope of a tower crane used in construction, was attributed to torsion fatigue due to low flexibility of rope used.

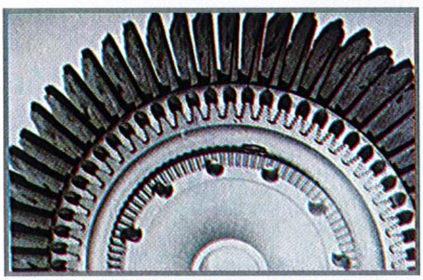




Fractograph showing torsional failure

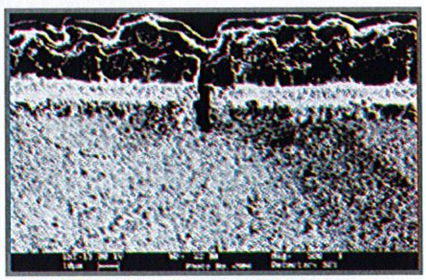
Decarburisation due to overheating

Failure of aero engine turbine blades of a transport aircraft, was attributed to over temperature exposure caused by the disruption of the protective aluminide coatings on the turbine blade



Failed turbine wheel of Aero engine

Turbine blades

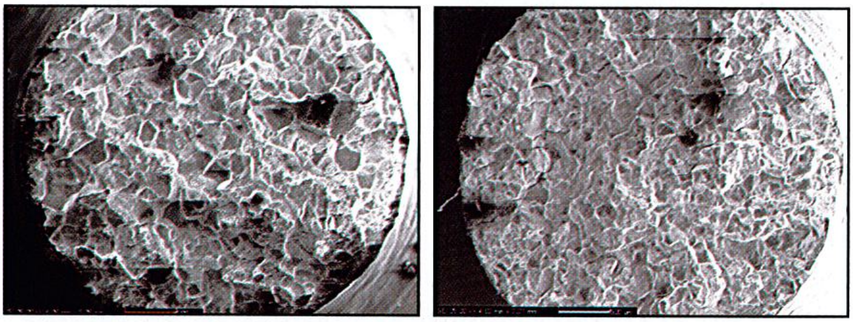


SEM photograph showing matrix depleted zone, crack in protective coating and grain boundary spikes

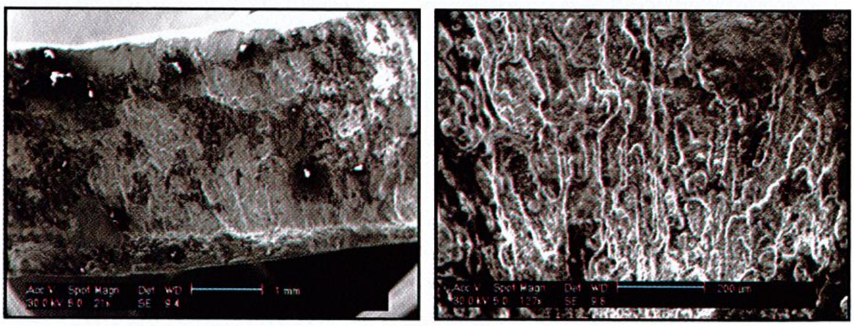
Failure of high pressure steam valve with stellite coated seat and disc of a combined cycle power plant. The failure of valve seat was attributed to improper pre heating and post weld heat treatment adopted during stellite deposition. The failure of valve disc made of high chromium steel was attributed to improper heat treatment which led to differential work hardening.

Valve seat showing delaminated stellite overlay

Valve disc showing crack over the body



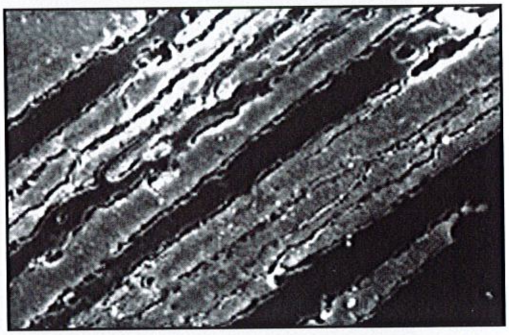
SEM fractograph of delaminated stellite, showing brittle failure along the dentrite



Fractured surface of failed disc showing cleavage and quasi-cleavage fracture

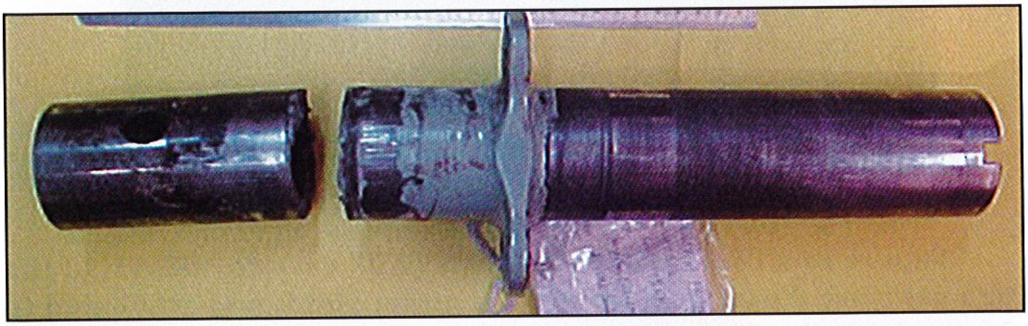
Failure of aluminium alloy airframe structure of a transport aircraft, was attributed to exfoliation type corrosion resulting from accumulation of water near the riveted joints.

Photograph of the damaged portion

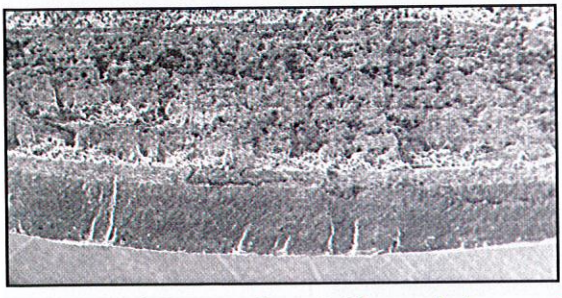


SEM photograph showing grain boundary delamination and corrosion products

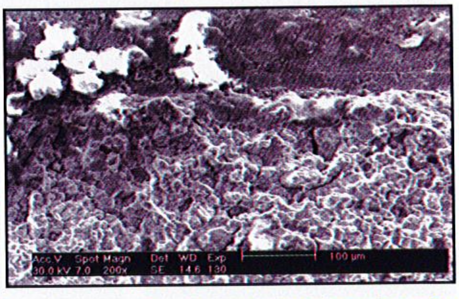
Failure of wheel axles of a fighter aircraft, was attributed to hydrogen attack at multiple crack initiation points and accelerated low cycle fatigue.



Failed axle after 1567 landing

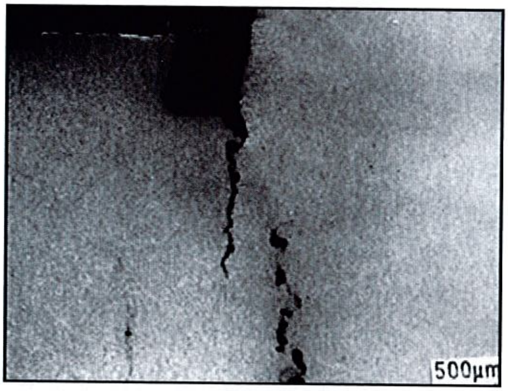


Ratchet marks at the origin

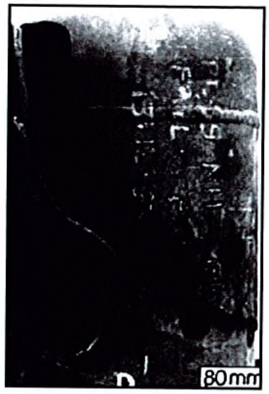


Fractograph showing decohesion of grains and intergranular (secondary) cracks

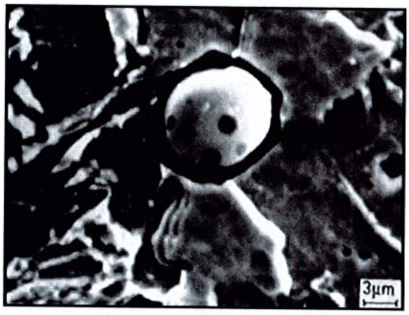
Weld failure in an ammonia refrigerant condenser tubes, was attributed to improper selection of welding electrode.



Lack of penetration



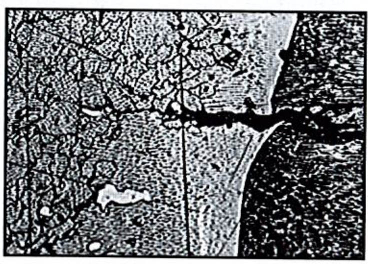
Failed condenser tube

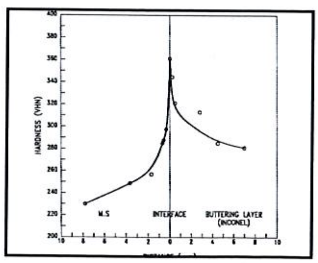


Decohesion of inclusion/matrix interface

Failure of a Dissimilar Weld Joint (2.25 Cr-1Mo/SS347) in the high pressure steam line header of a power plant, was attributed to sharp strength mismatch across the weld and differential co-efficient of thermal expansion.

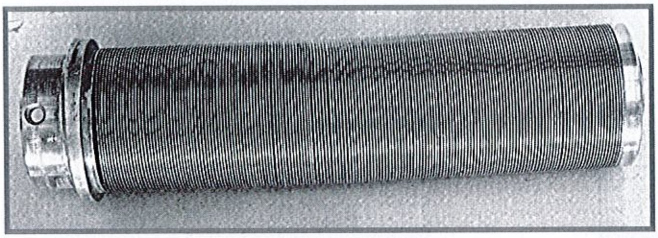
Failed conical reducer





Micrograph showing cracking in steel/buttering layer interface

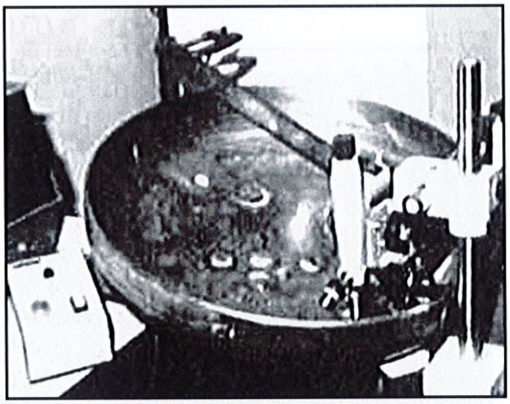
Failure of AISI 347 SS disc type bellow, used in the Control Rod Drive Mechanism (CRDM), was attributed to Stress Corrosion Cracking (SCC) during storage.



Failed CRDM bellow

Crack originating from the bottom of the pit

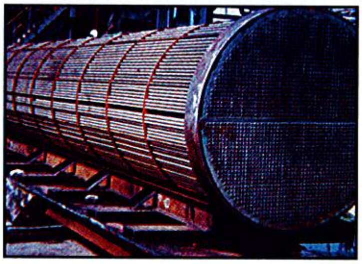
Failure of SS 304L dished ends during storage, was attributed to Trans Granular Stress Corrosion Cracking (TGSCC), initiated at the location of iron contamination during manufacturing.



Failed dished end

TGSCC crack networks

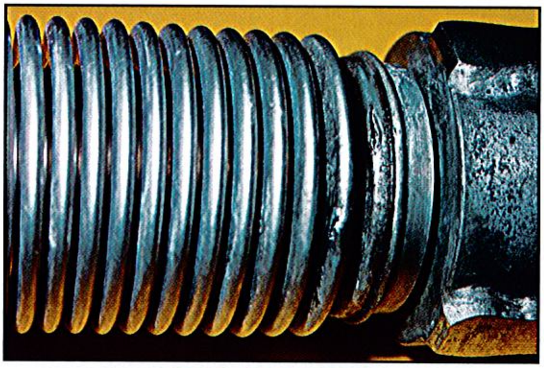
Failure of a carbonate re-boiler heat exchanger, was attributed to crevice corrosion between tube and tube sheet, due to improper design of the expansion joint.



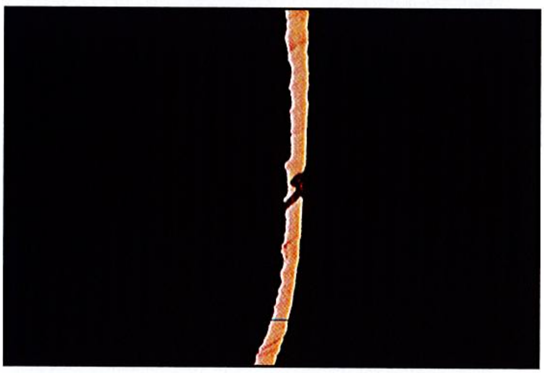
Carbonate re-boiler heat exchanger

Corrosion damage on tube sheet

Failure of AISI 316 SS bellow in a bellow sealed valve was attributed to corrosion fatigue due to improper heat treatment of bellow convolutes before welding to the stem.



Failed bellow



Through-the-thickness cracks in the bellow convolutes

Chapter-5

Summary

The Saga of RML through 25 years

Human Resources, Budget and Publications

Milestones

Partners from Industry

THE SAGA OF RML THROUGH 25 YEARS...

The journey of Radio Metallurgy Lab which started with a modest six member team consisting of young novices who landed at Kalpakkam after a brief stint at BARC, Mumbai, can be recapitulated as both exciting and rewarding. The task of setting up of a first-of-its-kind α-β-γ facility for handling plutonium-riche fuels and highly irradiated structural materials of FBTR was unique in Indian context. Excepting Dr. Baldev Raj and Dr. D.K. Bhattacharya, who had about one year exposure in a radioactive facility outside India, all the other team members had only limited experience in the β-γ hotcell facility then under construction at Radio Metallurgy Section of BARC. During 1974 when the team reached Kalpakkam, the Indian nuclear fraternity was isolated technologically from rest of the world. There was no possibility of direct interactions with the experts abroad or access to such sophisticated facilities in the world. Starting with an initial conceptual design finalized at BARC based on literature survey and the expertise available at that time, the team started their project in earnest. They collaborated with various agencies in IGCAR & BARC in the fields of civil, air-conditioning, ventilation and electrical systems to finalize the full fledged design drawings keeping in mind the operational needs and flexibility for the tasks which lie ahead. The ample guidance and mentoring from many seniors at IGCAR and BARC was the source of motivation and confidence. The initial construction activities involved massive civil structures for a heavily shielded facility which is integrated to the FBTR. Minute detailing of various constructional features for a complex radioactive laboratory keeping in mind the leak tightness of the cells, various embedment on the walls for cell utilities and operational needs, including safe receipt and dispatch of irradiated fuels, were worked out. Careful planning went into possible future addition or expansion of activities.

Just when, the construction of the Radio Metallurgy laboratory was nearing completion, a new challenge emerged. The driver fuel for the fast breeder test reactor was changed from oxide to mixed carbide. This meant innovating ways and means of transforming the existing hotcells designed for oxide fuel to handle the pyrophoric carbide fuel with an inert atmosphere – a mega challenge by itself considering the restricted spaces, tight time frames and cost considerations. The retrofitting of the originally designed hotcells with nitrogen recirculation system, including the purification of nitrogen by feed and bleed approach, procurement of specialized equipments such as hermetically sealed blowers, design, erection and commissioning of various mechanical and piping systems and a complete redesigning of the electronics and instrumentation with an innovative data acquisition and control, was a challenging yet gratifying task. These tasks were successfully implemented and the efforts put in have stood the test of time. It is a matter of pride that all these could be achieved in house by this dedicated group through meticulous planning, in-depth knowledge, careful selection of equipment and systems and more importantly working together in a coherent manner vectored by a dynamic group head.

The setting up of a comprehensive Post Irradiation Examination facility capable of handling plutonium-rich FBTR fuel, with limited resources, satisfying the aspirations of the fuel designers, plant operators and experimentalists in the area of nuclear fuel and structural materials was a Herculean task. This encompassed civil construction, electrical, ventilation, instrumentation & control systems, remote handling equipment, in-cell equipment for post irradiation examination, receipt and dispatch of materials in a leak tight manner and the whole lot of radiation level monitoring with radiological safety equipment. The group worked in close collaboration with various colleagues at IGCAR and BARC roping in support from the Indian Industry.

The remote handling tools required for the hotcells were at its inception stage with respect to indigenous developments. Imports of the remote handling equipment were ruled out due to embargo. The RML team members along with the colleagues at Reprocessing Development Laboratory of IGCAR actively participated in the development being pursued at BARC and the first indigenous manipulators were born as a result of this team effort. However, these manipulators had to be improved further to higher levels of perfection with respect to reliability and adoptability for α-β-γ hotcells, in which RML took a leading role. Many in-cell remote handling equipment like cranes, power manipulators, etc. were developed or sourced out after ab-initio design to suit our purposes. They were prudently evaluated with respect to remotization and their performance under inert gas atmosphere with very high levels of radiation.

Safety clearances for such a laboratory, that calls for elaborate documentation including demonstration of various safety related features were accomplished, thanks to the deep involvement of a multi disciplinary team that had been built-up by this time, coupled with the guidance and support received from the AERB appointed subcommittee and other senior colleagues from various groups of IGCAR.

At this juncture it is worth revisiting various milestones which led to the final commissioning and operation of the laboratory.

The handling of highly irradiated Antimony Oxide (Sb_2O_3) pellets inside the hotcells, encapsulation and remote welding of the same to make a neutron source pin for FBTR, during 1985, demonstrated the capability of the group in the areas of designing in-cell equipments for remote operation. The skills for the remote handling and welding of the neutron source pin followed by its safe dispatch to FBTR were also put to test. This activity gave us a lot of confidence and experience in meticulous planning required for many such operations to be undertaken subsequently.

The first time transfer of the experimental subassembly in a vertical mode through an in-house designed leak tight transfer system with provisions for precise X, Y, Z and theta motion was a matter of pride for the RML designers vindicating their capabilities. The receipt of this first experimental fuel subassembly containing irradiated plutonium carbide fuel with traces of sodium trapped inside it, in to the hotcell, without breaking the leak tightness of the inert gas system and its subsequent handling through a set of complex operations such as sodium cleaning, cutting and retrieval of the experimental pin, metrology and non-destructive examination culminating in the metallographic examination of cut sections was another moment of joy and pride. The metallography of carbide fuel is known to be a challenging task even in a glove box, hence accomplishing this remotely was gratifying. The journey continued with various Post Irradiation Examination campaigns on full fledged irradiated fuel subassemblies starting from 25 GWd/t burn-up to 155 GWd/t burn-up. The PIE of 100 GWd/t fuel subassemblies and the first time neutron radiography of the fuel pins using the KAMINI was a significant milestone for IGCAR. This PIE gave confidence on the fuel design and its performance. The journey of PIE has been fraught with challenges and surprises which could however be addressed through innovative and imaginative solutions. This journey has also taught us many technical and management lessons. Some of the initial equipments were replaced by meticulously planned intervention into active and operating hotcells. All the systems required for the safe and efficient operation of the laboratory were always kept poised and operational, as evident from the fact that the facility has been operated so far with near zero contamination levels in the adjoining areas and with low man-rem expenditure during various campaigns.

Many innovations in the PIE technology got initiated during this journey, like remote metallography of high burn-up carbide fuel, high temperature mechanical property evaluation of irradiated clad tubes and the pioneering work in the area of miniature specimen test techniques.

Another pioneering activity initiated at RML was the developments in the area of irradiation experiments. The work which started with establishing of a comprehensive facility for modeling, experimental validation, precision machining and fabrication of intricate components for irradiation capsules, instrumentation, etc. has blossomed into a full-fledged activity. Many innovative experiments were done using FBTR starting from the irradiation of experimental fuel pins to study the beginning-of-life behavior of carbide fuels and pre-pressurized capsules for irradiation creep measurements of the indigenous zirconium alloys. This group is very active today and has ventured into crucial areas like pre-pressurized capsules for FBR clad materials for irradiation creep studies, gas-gap capsules for simulating higher irradiation temperatures and instrumental capsules for online monitoring during irradiation, etc.

Post Irradiation Examination is a multidisciplinary domain encompassing hotcell operations, remote handling and remote inspections through conventional and advanced NDE. Successful PIE required adequate competence in all these areas which were simultaneously nurtured. At this juncture it was realized that there is likely to be a gestation period before routine and full fledged PIE could be undertaken and IGCAR after the successful commissioning of FBTR had embarked on the design and development of Prototype Fast Breeder Reactor. It was at this juncture that Dr Baldev Raj also realized that a reliable and safe fast reactor technology would demand availability of innovative and robust NDE and robotic technologies. This far sighted vision resulted in the NDE activity which originally started as a part of PIE for remote non-destructive testing of irradiated fuels to get diversified. Small innovations such as eddy current testing of inclusions in

You see things and say 'Why?' But I dream things that never were and say 'why not?'

FBTR clad, microfocal radiography of end-cap welds and tube to tubesheet welds, scratch detection in coolant channels through eddy current testing, thermal imaging for condition management of electrical subsystems and acoustic techniques for leak detection in PHWRs and evaluation of concrete structures (Kaiga dome) have become routine/mandatory requirements in the nuclear program as well as methodologies for similar challenging problems in other strategic and core sectors. NDE activity has blossomed during this period. This group of colleagues ventured into newer domains and developed various non-destructive characterization techniques for microstructural and mechanical properties, coupled with the innovative use of NDE for manufacturing technologies, pre and in-service inspection and failure analysis. The contributions of this group to the core and strategic sectors, healthcare, cultural heritage and NDE Science and Technology of our country are unique and stupendous. These activities of the group, nurtured and guided by Dr. Baldev Raj, brought national and international acclaim. RML can be proud of the fact that it had given birth and nurtured such premier research groups in this area in the world.

The remote handling and robotics activity which was primarily started for developing our own tools for the hot laboratory such as Master Slave Manipulators, in-cell cranes, power manipulators, transfer and transport systems for irradiated fuel has today matured into a full-fledged R&D group in this area. The journey through the development of initial Master Slave Manipulators for hotcells and lead cells has lead to realization of various remote systems in this area and today the group is poised for higher challenges in tele-operations and servo controlled manipulators. Development of robotic devices for remote fuel fabrication, specialized remote handling devices for metallic fuel pilot plant and support for automation for various process related activities for reprocessing program also took us through an exciting phase, spanning from concept to customization and realization of state of art equipment for the nuclear fuel cycle. The confidence gained has resulted in conceiving and designing comprehensive in service inspection system for PFBR and fast reactor fuel reprocessing facilities.

From a modest beginning, the human resources for the above activities have grown in a steady and calculated manner. So is the expertise of the group in the multi disciplinary areas. The initial investments made on the laboratory have been highly fruitful and have given enough returns, as evident from the various multi faceted outputs which have emanated from the laboratory in the fields of PIE, Irradiation Experiments, NDE and Remote Handling.

The future directions in individual areas have been outlined at the end of various sections. It can be said with confidence that the directions in which the activities of the laboratories will focus will be in tune with the increasing demands necessitated by the expanding Fast Breeder Reactor program, especially in the areas of PIE of advanced metallic fuels, under-sodium inspection, NDE and Robotics for future FBRs and various other developments for the fast reactor fuel cycle facilities.

Fusion of diverse perspectives leads to cohesiveness, coherence, creative and bench marking solutions.
- Baldev Raj

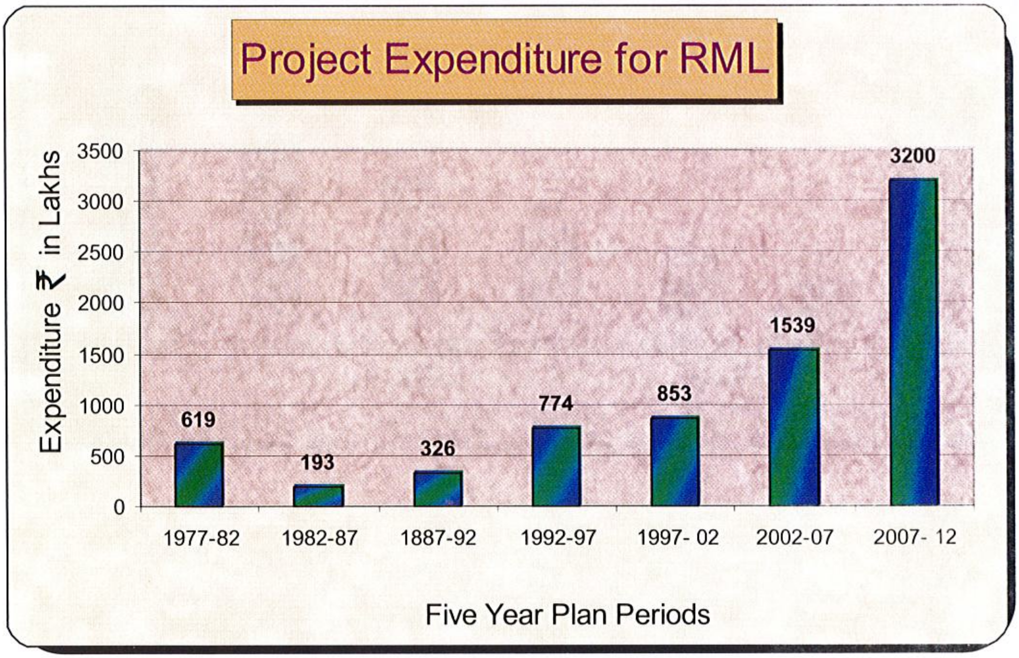
It is to be highlighted that an institution is not only known by the excellence it breeds but also by the excellence it extrudes through its alumnus. RML was a fusion of disciplines, fusion of expertise and fusion of scientists and engineers who had transcended the ethos and pathos to work together cohesively as a single knit family. It has also served as a cradle of human resources with multi disciplinary expertise. The fact that the small family of RML could contribute effectively not only to the mission programs of the Centre but to the overall program of the Department and also for other strategic, societal, science and technology based programs of the nation has been possible due to the ability of its leaders to harmoniously synthesize the multiple roles of operating in the "research mode" and "mission mode" and integrating it with ethical and imaginative management practices.

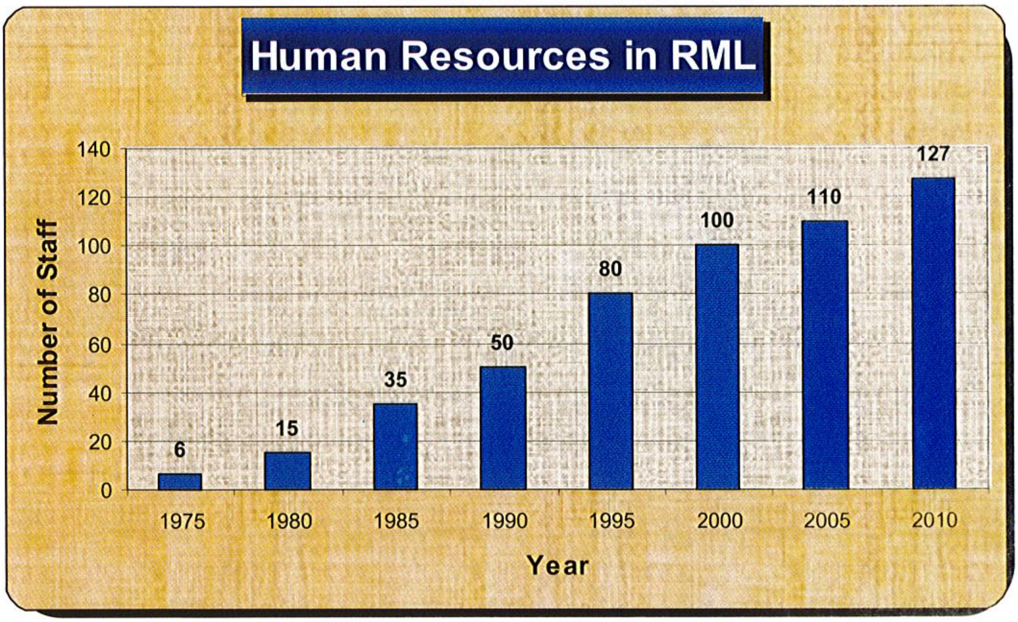
The RML team (present and past) at this juncture has enormous pride to be part of such an exciting and eventful phase of the Centre's activities and an opportunity to contribute to the FBR program. The team is having inherent strength and has high morale and confidence to face challenges involved in many future activities in these areas.

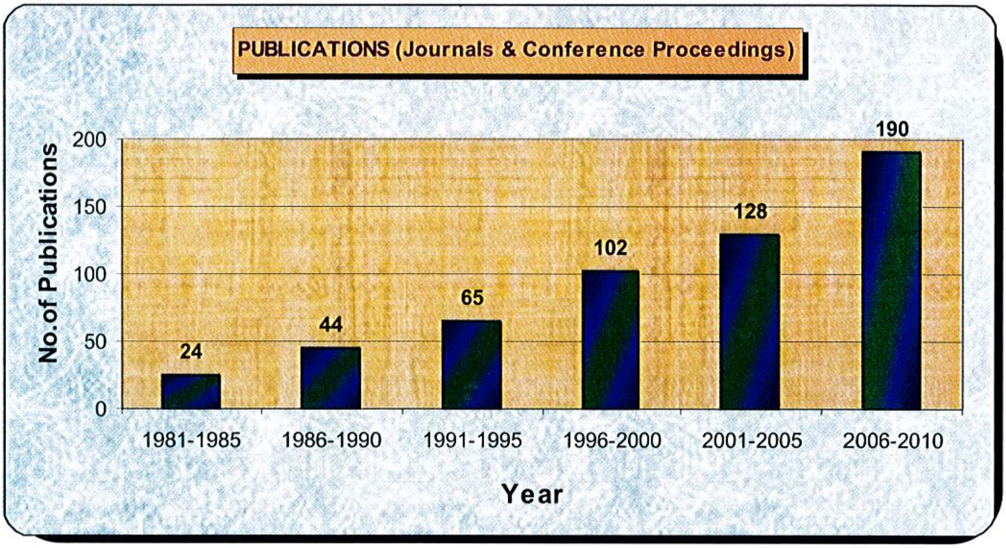
"A small body of determined spirits fired by an unquenchable faith in their mission can alter the course of history."

-Mahatma Gandhi

HUMAN RESOURCES, BUDGET AND PUBLICATIONS






PUBLICATIONS (Journals & Conference Proceedings)
No.of Publications
200
150
100
50
0
24
44
65
102
128
190
1981-1985
1986-1990
1991-1995
1996-2000
2001-2005
2006-2010
Year

MILESTONES

- Remote fabrication of Antimony pin for neutron source subassembly of FBTR (1985)
- Completion of campaign for detection of leaks in RAPP-1 end shield by AE techniques (1985)
- Completion of campaign for detection of leaks in pressure tubes of MAPS by AE techniques (1987)
- Development of NDE techniques for detection of location of garter spring and gap measurement in the coolant channel of PHWR (1988)
- Setting up of advanced NDT facility for material research and life extension (1990)
- Computer Numerically Controlled Remote Milling Machine commissioned in the hot cell (1992)
- Ten irradiation experiment capsules fabricated for LHR experiment in FBTR (1993)
- Conversion of hot cell atmosphere from air to high purity nitrogen (1993)
- Commissioning of hot cells facility with inert gas recirculation system (1994)
- PIE of experimental fuel pins (1994)
- PIE of 25 GWd/t burn-up fuel sub-assembly from FBTR (1997)
- Augmentation of PIE facility with respect to alpha tight fuel/waste transfer, remote handling, radiation monitoring and ventilation systems(2000)
- Development of NDE techniques for characterization of materials and components (2000)
- Commissioning of neutron radiography system (2001)
- PIE of 50 GWd/t burn-up fuel sub-assembly from FBTR (2001)
- PIE of Zircalloy and Zr-Nb pressurized capsules for irradiation creep studies (2002)
- Assessment of structural integrity of ring beam of inner containment of Kaiga unit I reactor building (2002)
- PIE of 100 GWd/t burn-up fuel sub-assembly from FBTR (2003)
- Development of techniques for NDE of PFBR components (2004)
- Life extension of Defence aircrafts (2005)
- PIE of 155 GWd/t burn-up fuel su-bassembly from FBTR (2007)
- PIE of irradiated control rod discharged from FBTR (2009)
- Receipt and dismantling of irradiated Yttria for separating Sr-90 (2009)
- PIE of grid plate specimen (2010)
- PIE of MOX single pin irradiated in FBTR (2010)

PARTNERS FROM INDUSTRY

Sl. no.	Supply / Work / Fabrication of:	Industry
1	RML Building civil construction	M/s ECC , Chennai
2	Ventilation equipments	M/s Blue Star Lts., Chennai
3	Shielding door, Shielded flask	M/s Variety Engineers, Baroda
4	In-cell cranes	M/s Consolidated Hoists, Pune
5	Brine chilling plants	M/s Alpha Lavel, Pune
6	Nitrogen circulation blowers	M/s Venti, France
7	Shielding glass viewing window	M/s Jena Schott, Germany / M/s Sovis France
8	Cell Lining work	M/s Prabha Industries, Chennai
9	Power manipulators	M/s ACB, France
10	PSA nitrogen plants	M/s MVS Engineering, New Delhi & M/s Inox Air products, New Delhi
11	Piping work for Inert gas system	M/s Symec, Mumbai
12	Master Slave Manipulators	M/s Visual Education Aid, Coimbatore &Ms Jayashree Industries, Hyderabad
13	Horizontal transfer system shipping cask, inter-cell transfer system	M/s Mehtha Enterprices, Mumbai
14	Vertical transfer system	M/s Panchal Iron Works, Mumbai
15	Laser dismantling & dimensional measurement machine, Gamma scanning machine, precision milling machine	M/s Eltel Shielding & Enclosures, Bangalore
16	Nuclear Periscope	M/s Clave, Paris
17	CNC milling machine	M/s Tool Craft, Bangalore
18	X-radiography machine	M/s Philips India Ltd
19	Incell Tensile testing machine	M/s FIE , Maharashtra
20	Delay tank lining work, Kamini south Shielding	M/s Powertech, Sadras
21	Lead cell shielding	M/s K.Gopalakrishnan, Sadras
22	Servo hydraulic testing machine	M/s BISS , Bangalore

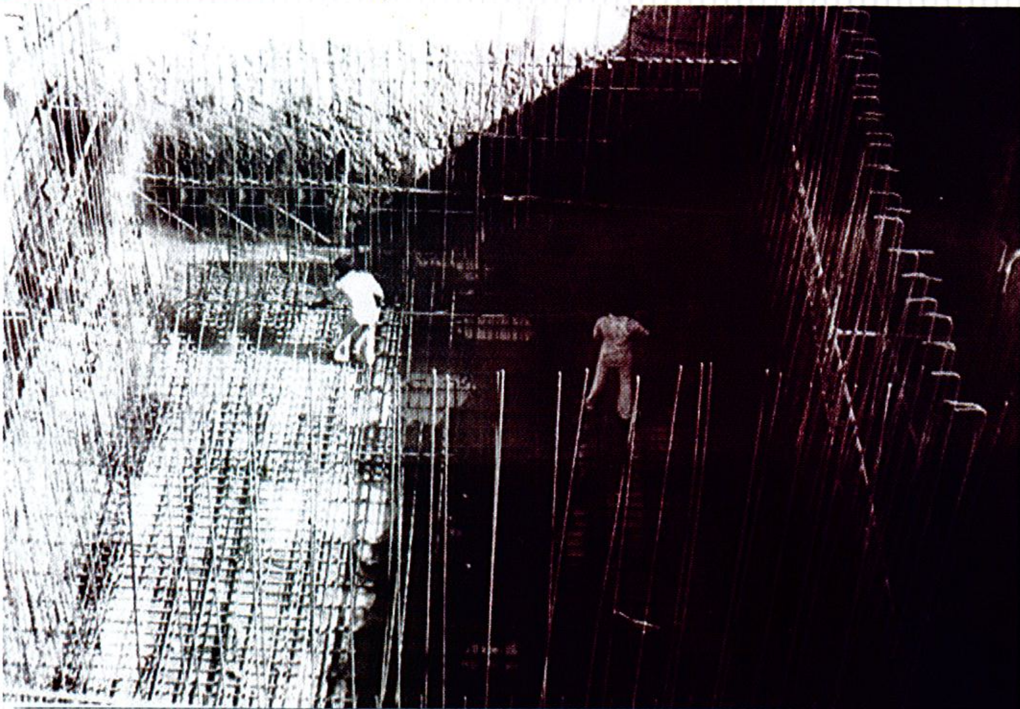
Photo Gallery

RML Old Photos

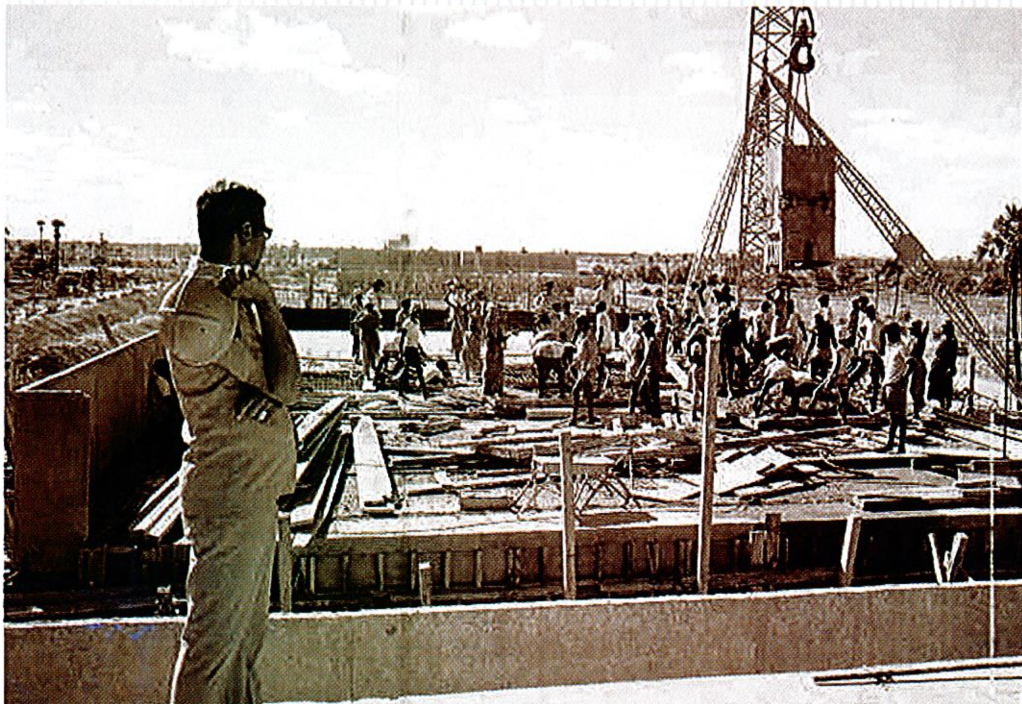
Eminent Visitors

RML Team

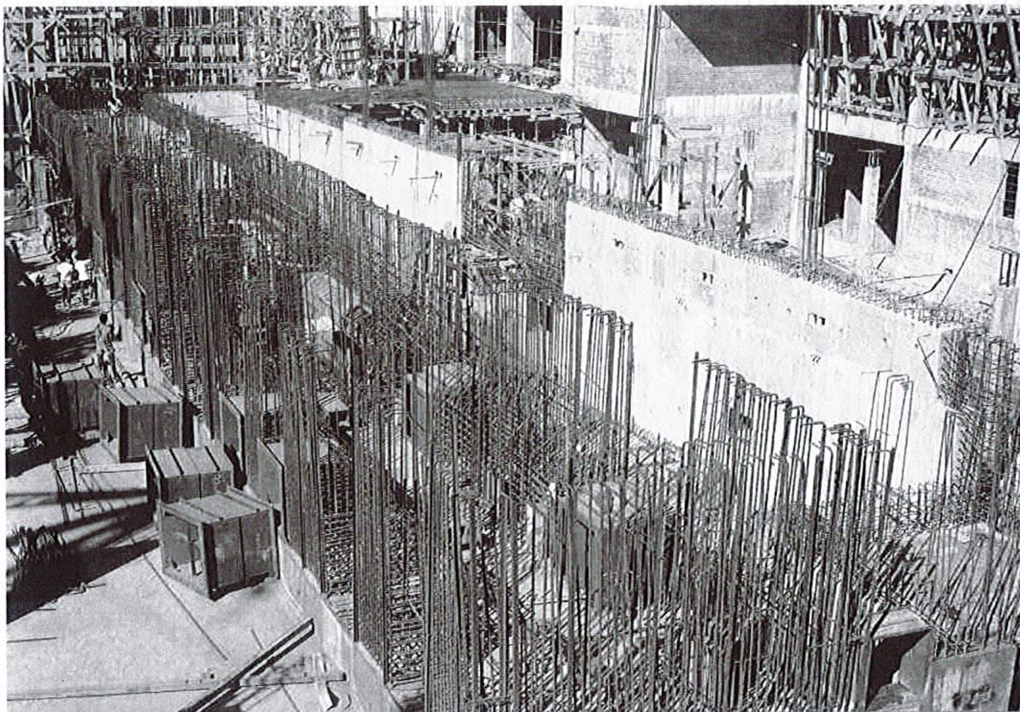
RML-Excavation



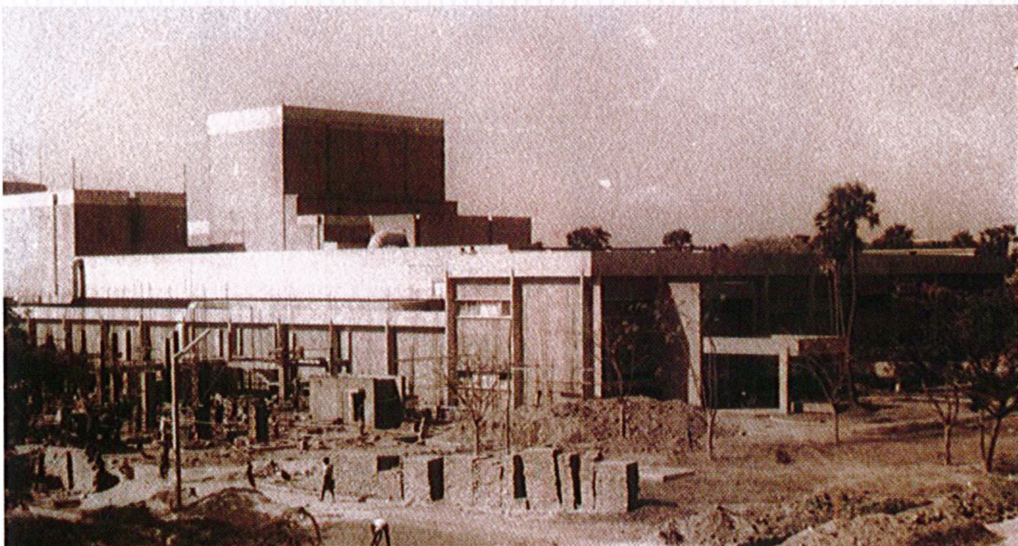
RML-Foundation



RML-Building work in progress



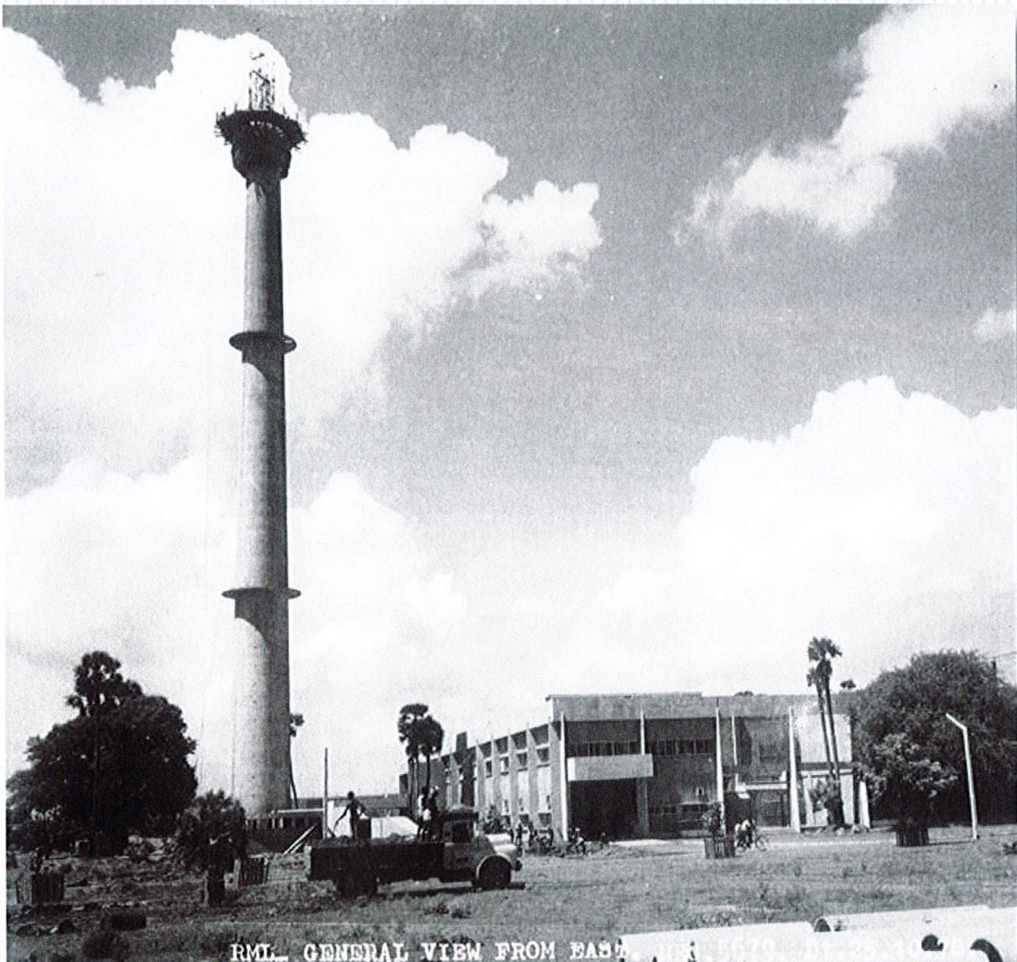
RML construction in progress



RML Building work in progress

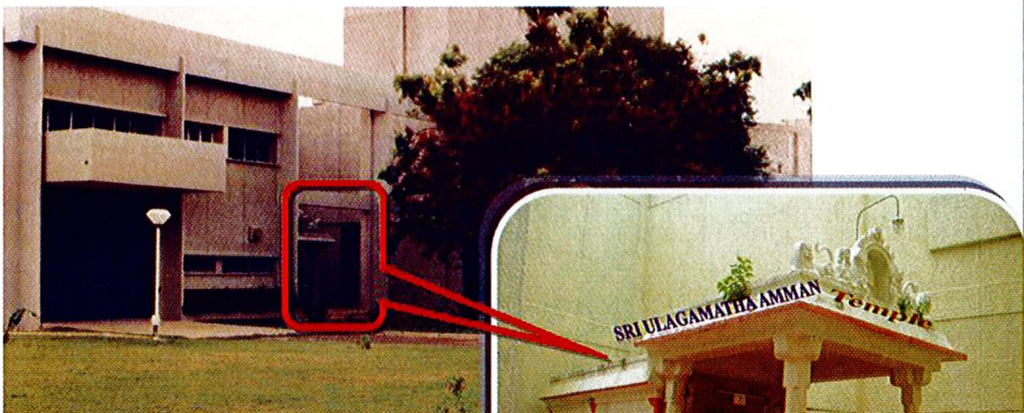
RML-Stack work in progress

RML-Stack after completion



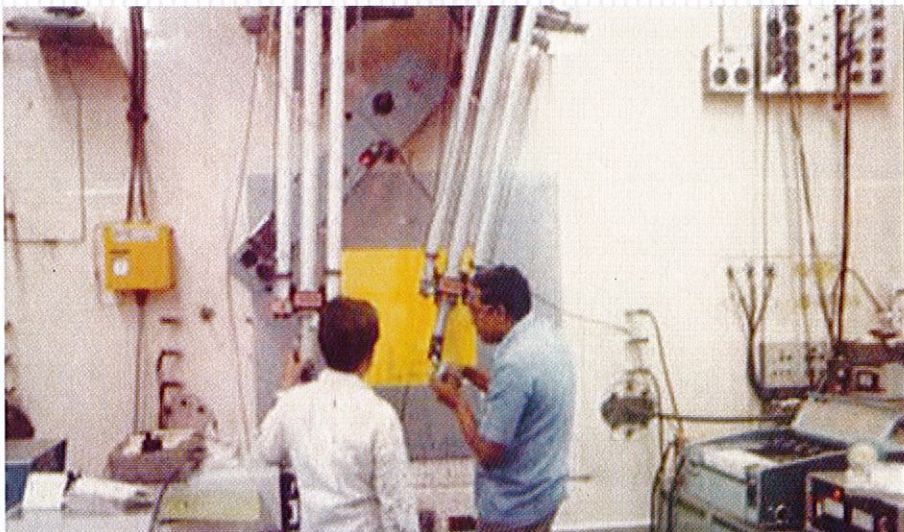
RML general view

RML-Front view



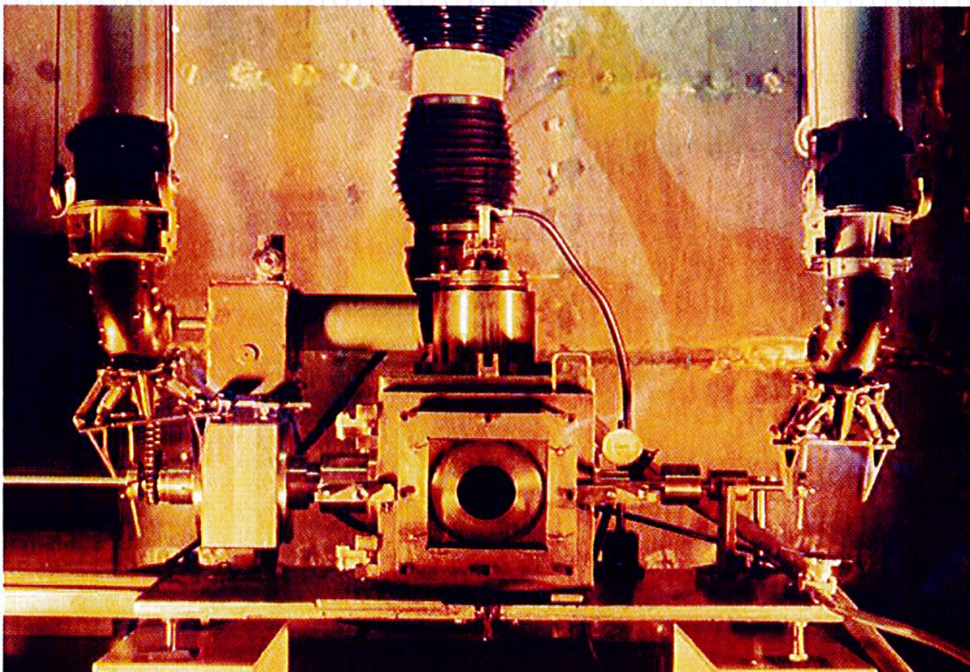
RML - Side view (ancient temple retained in RML structure)

Alpha tight glass plate erection

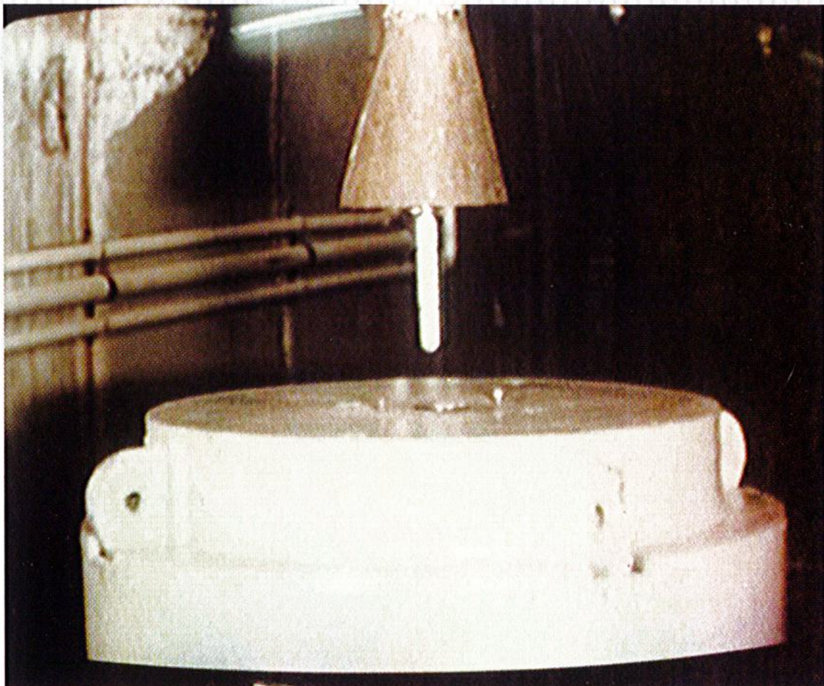


Inspecting Master Slave Manipulator

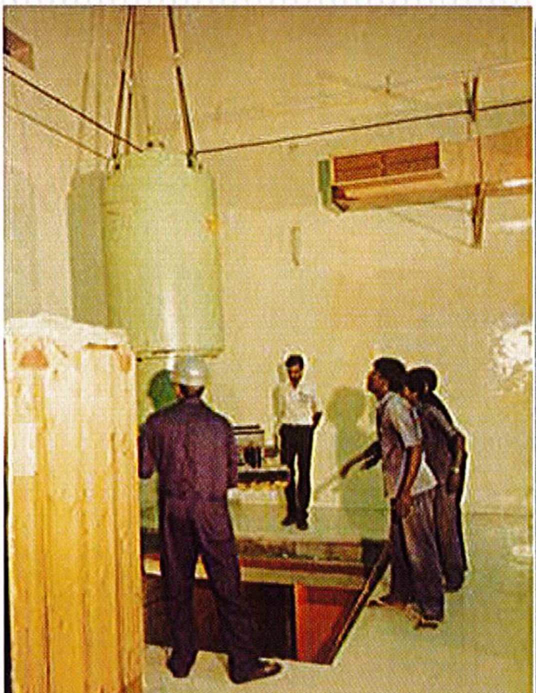
Neutron source pin welding trial operation



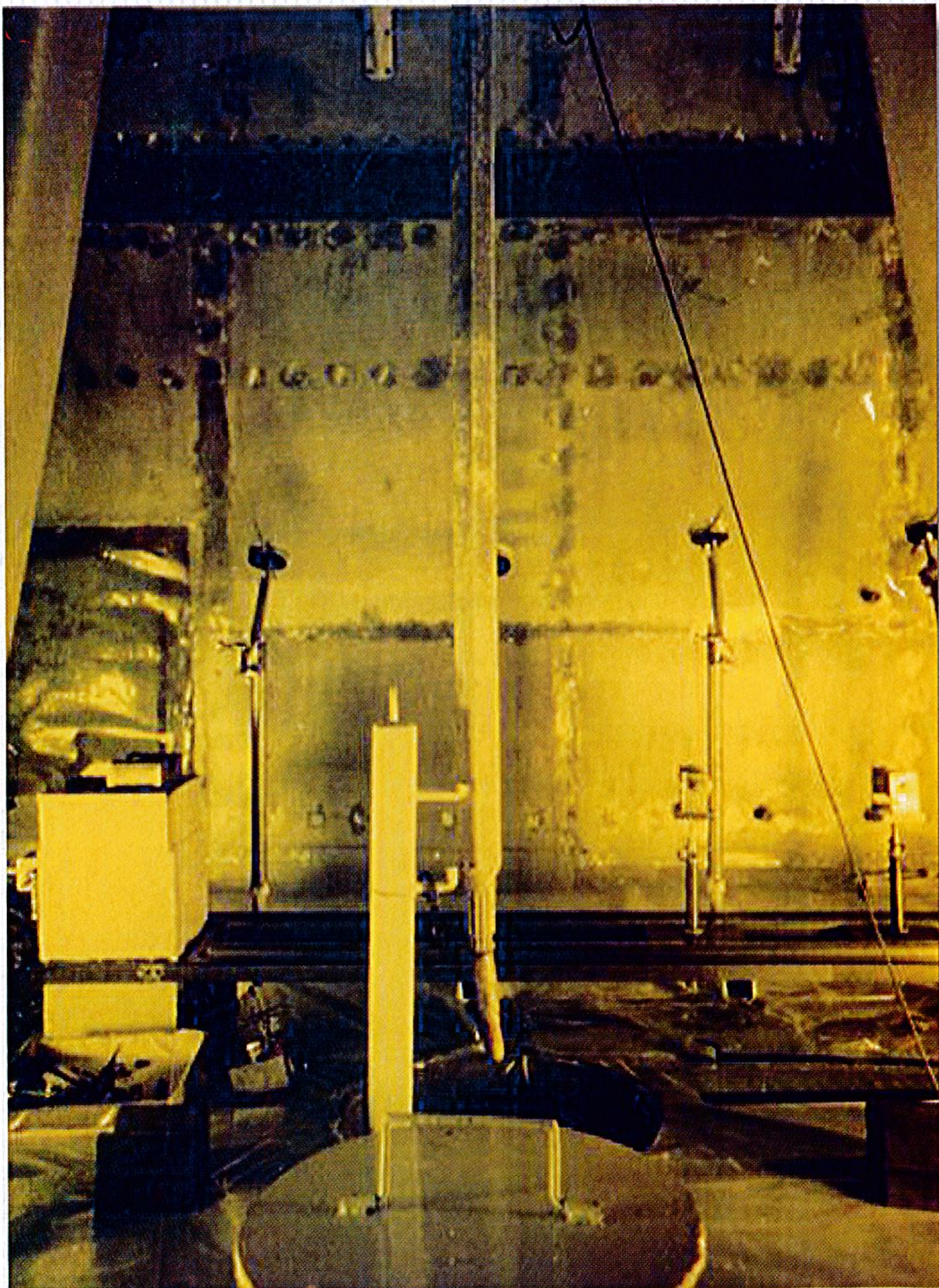
Neutron Source pin welding progressing inside the hot cell



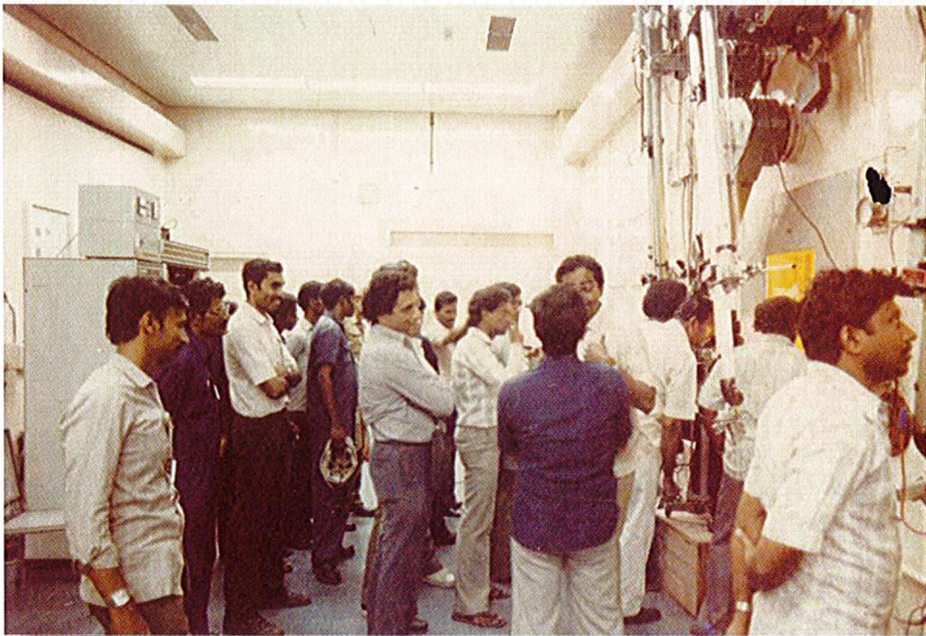
Lowering of neutron source pin into the cask



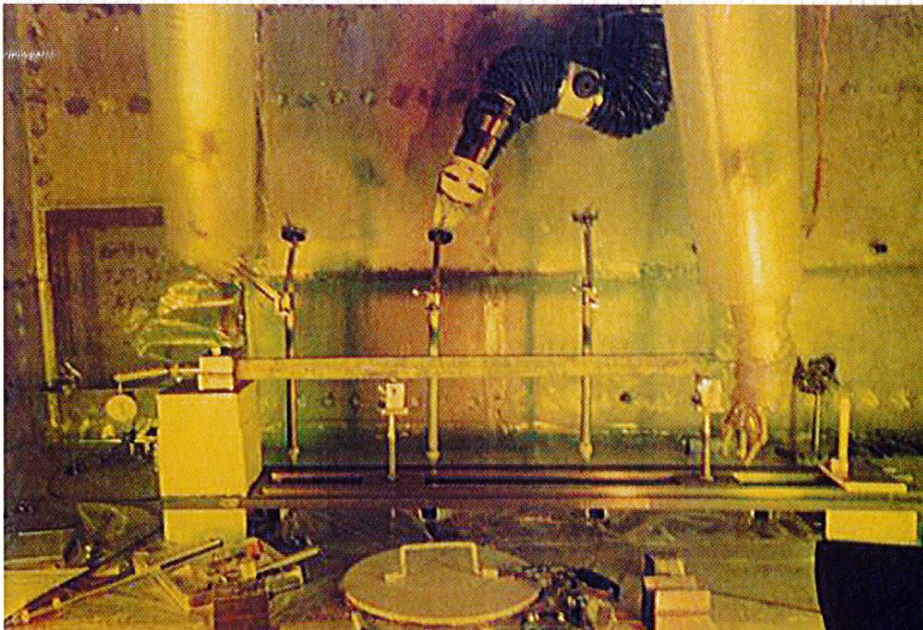
Transfer of neutron source pin to FBTR



Receipt of bent fuel subassembly inside hot cell

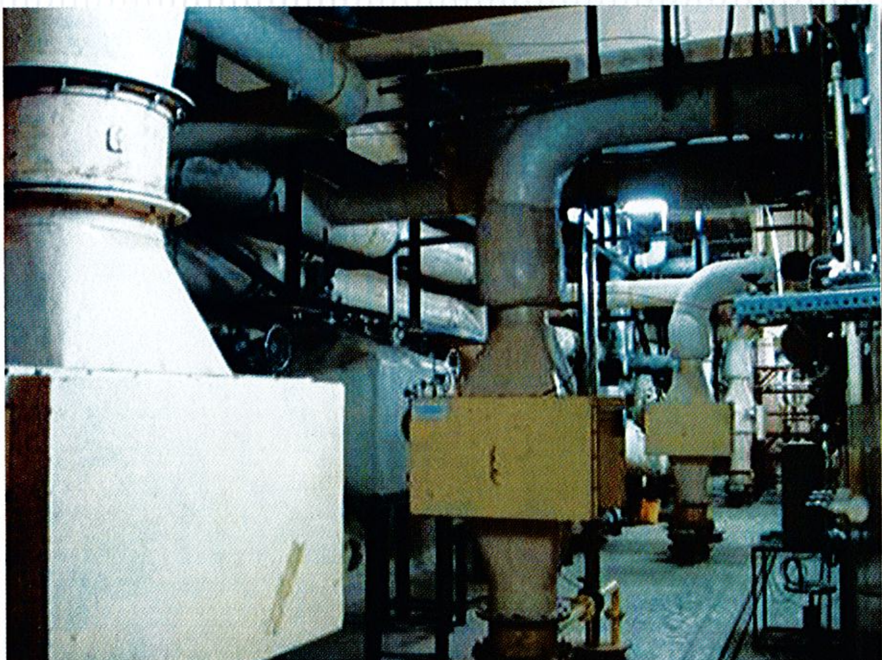


Dr. Placid Rodriguez with RML Staff during receipt of bent fuel subassembly



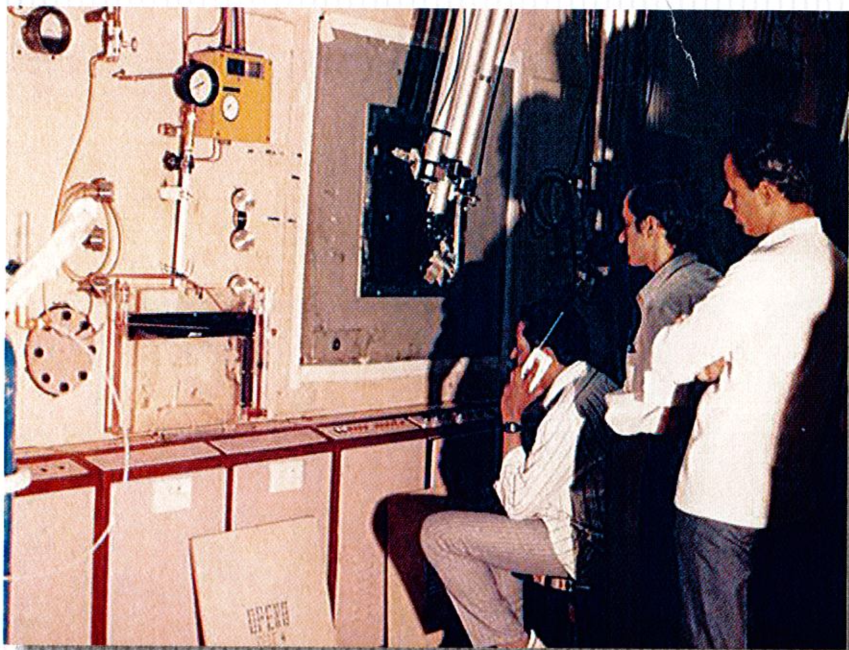
Bent fuel subassembly under examination

RML ventilation system

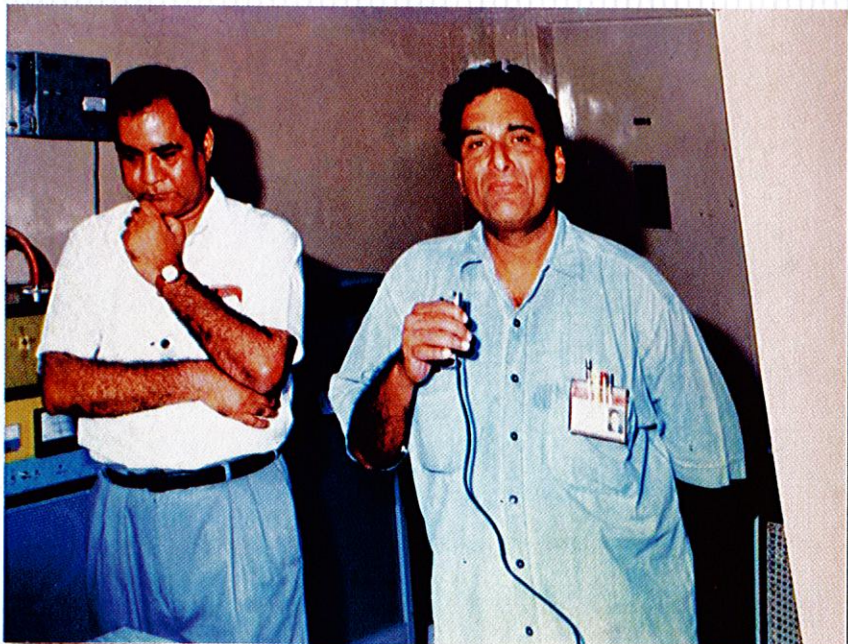


Hot cell exhaust ducts

Pressure Swing Adsorption Nitrogen Plant



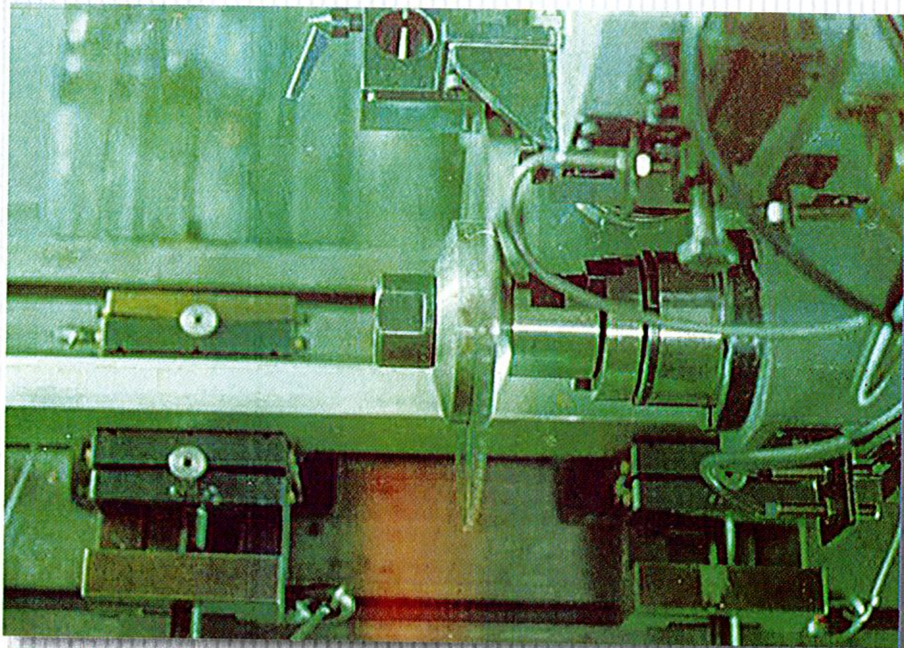
Commissioning of Inert gas system



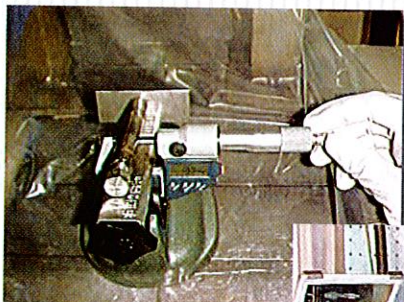
Dr. Placid Rodriguez & Dr. Baldev Raj after receipt of first experimental subassembly in hot cell, December 1994

RML staff after receipt of first Experimental subassembly

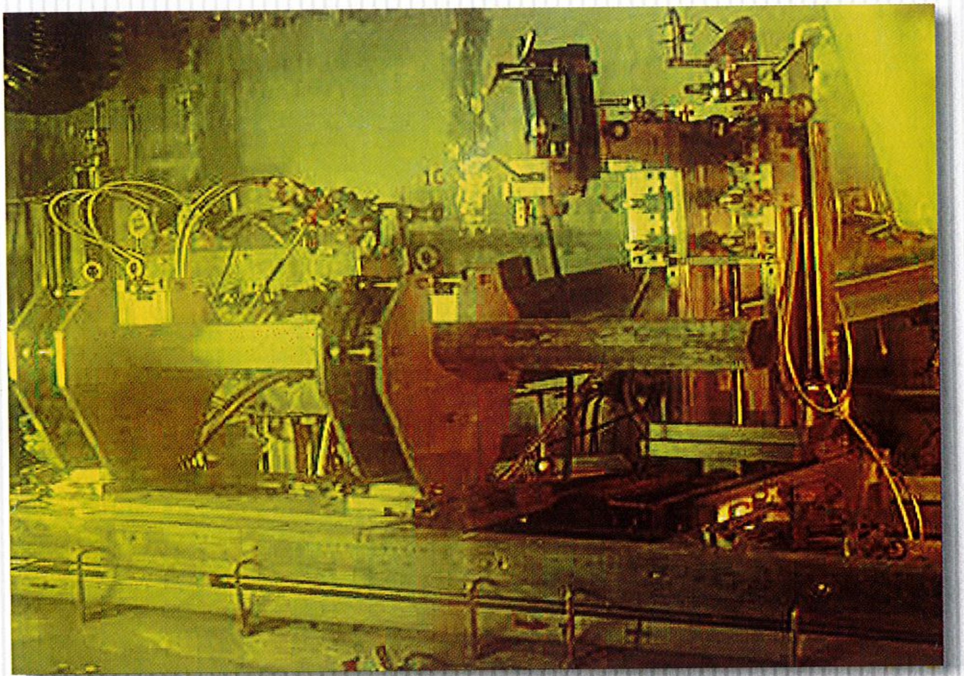
View of the operating area



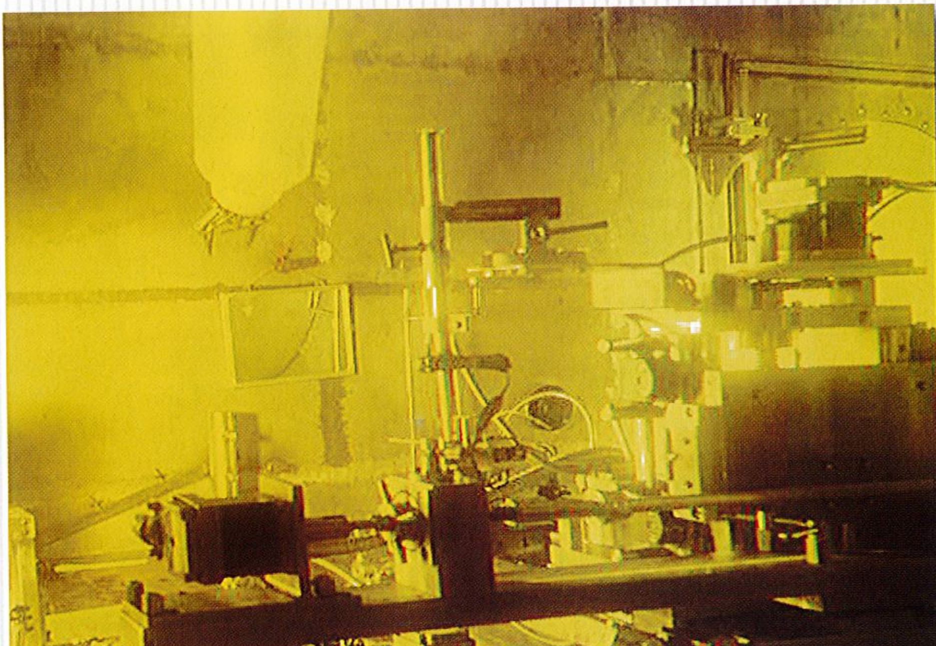
Cutting of fuel subassembly in CNC milling machine



Dimensional measurement of Irradiated zircaloy capsule



Dimensional Measurement cum Laser Dismantling (DMLD) system in hot cell



A view of gamma scanning system inside the hot cell

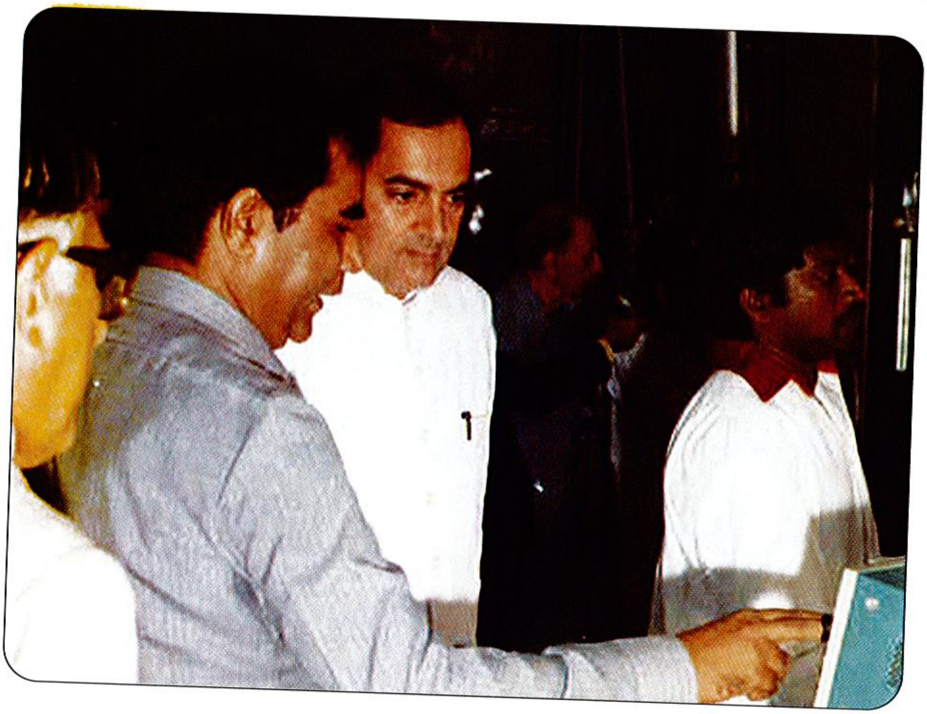
Maintenance crew with protective suits

Maintenance crew carrying out in-cell equipment repair

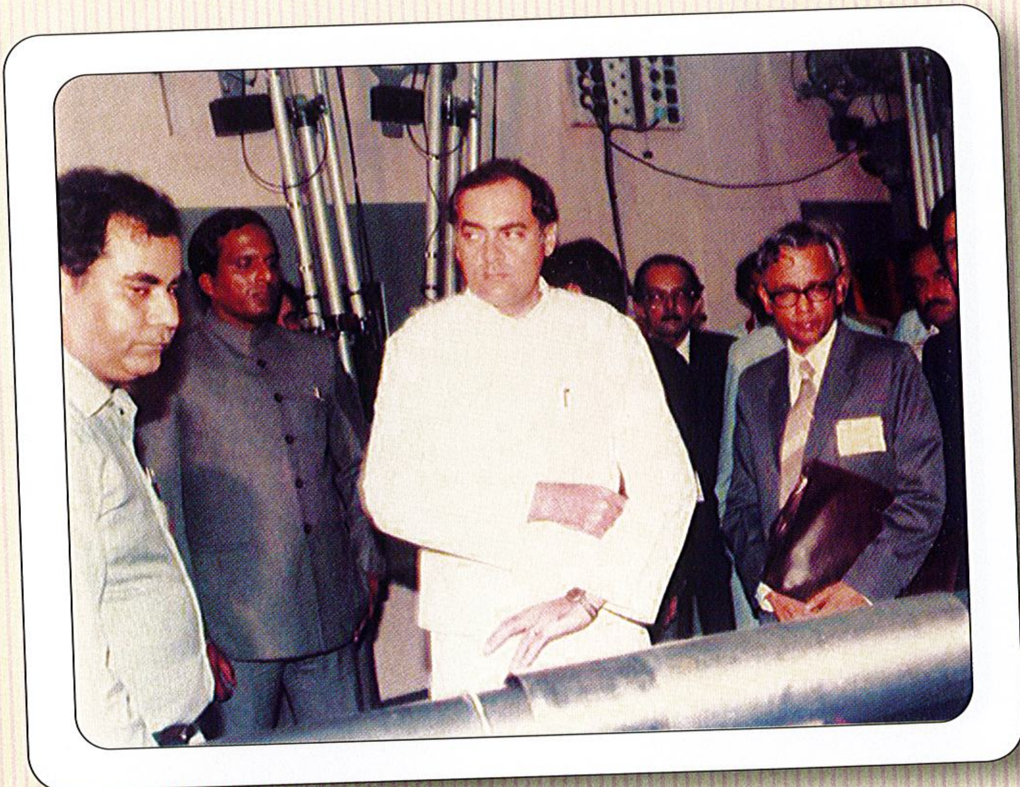
Repair of In-cell crane

Transfer of solid waste into the cask

Eminent Visitors

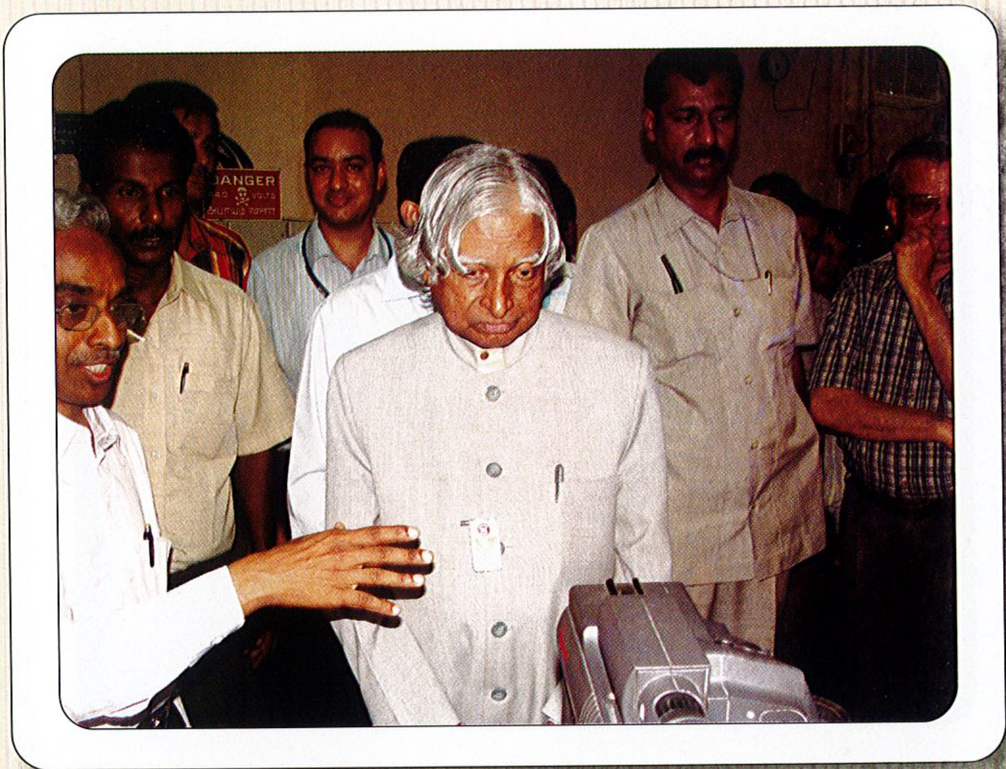


Visit of Honorable Prime Minister Shri. Rajiv Gandhi

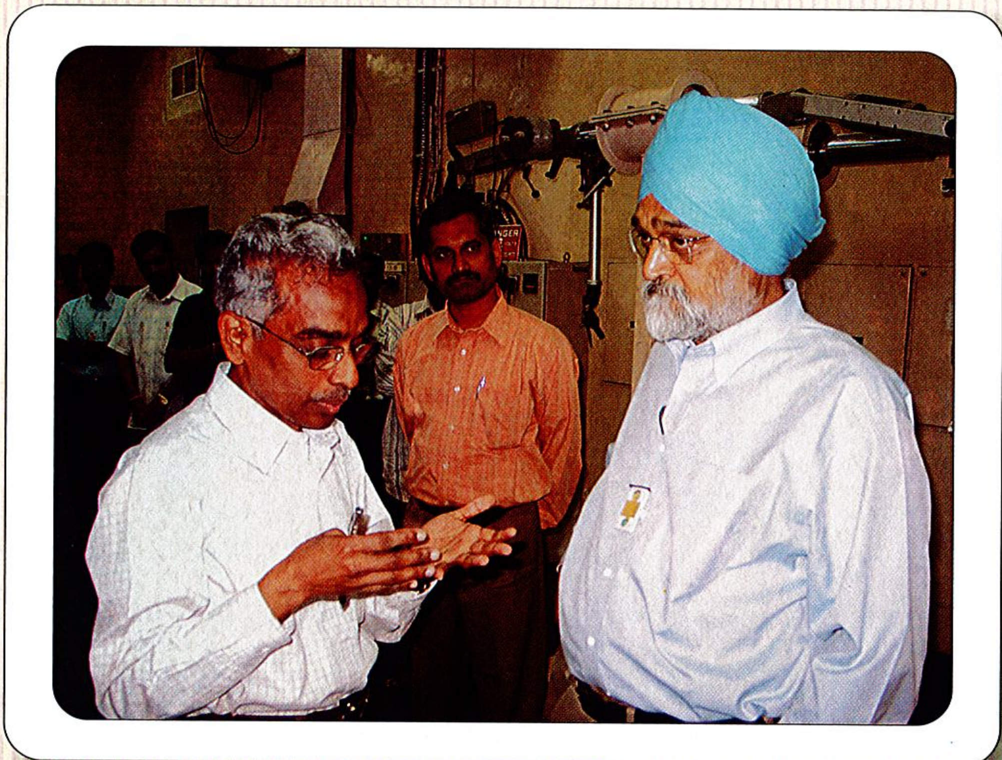


Visit of Honorable Prime Minister Shri. Rajiv Gandhi

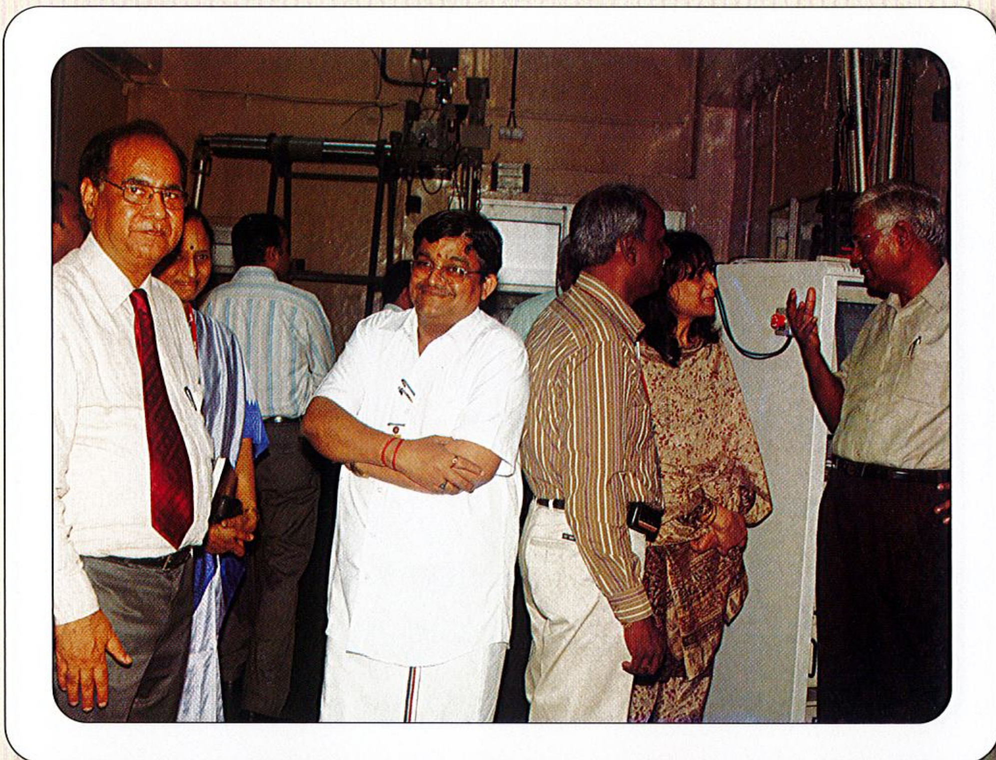
Visit of Honorable President Shri R. Venkataraman



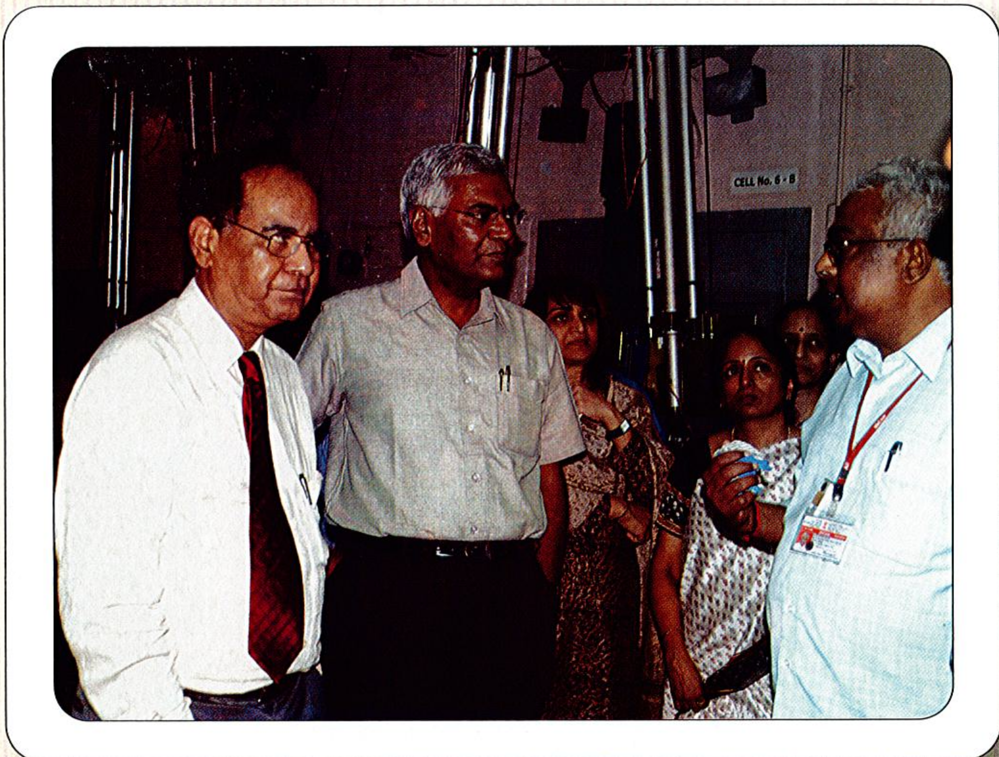
Visit of Honorable President Dr. A.P.J Abdul Kalam



Visit of Dr. Montek Singh Ahluwalia,
Deputy Chairman, Planning commission

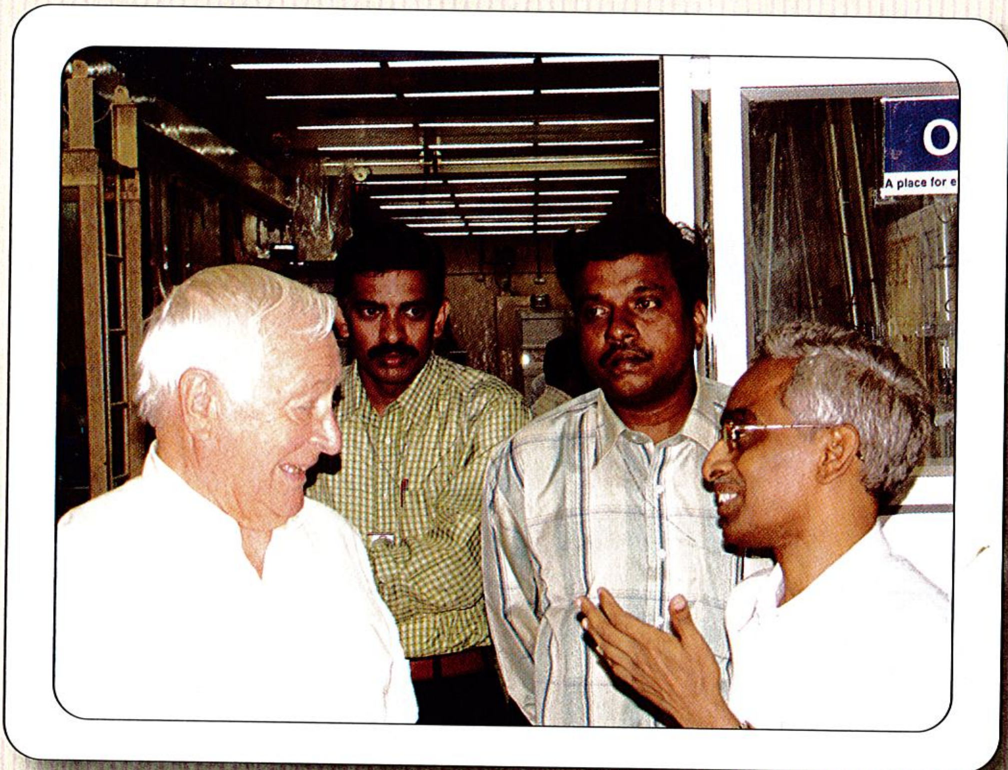


Visit of Parliamentary delegation



Visit of Parliamentary delegation

Visit of Dr. Mohamed ElBaradei,
Director General, IAEA



Visit of Dr. George Vendryes

Visit of Dr. S. Banerjee, Director, BARC

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Members of RML, not in the photographs

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1) Shri Balaraman.P
2) Shri Balasundaram. V
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27) Late Shri Patnaik M.J
28) Late Shri Razeed. B
29) Late Shri Robert Clive.S

Former members, presently engaged in other projects

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2) Shri Chandrasekaran.V
3) Shri Francis Angelus
4) Shri Jebaraj. R.E.M
5) Shri Kaliamurthy. S
6) Shri Kalyanasundaram. P
7) Shri Kumar. P.V
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9) Shri Padmaraj. B
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11) Shri Rakesh Kaul
12) Shri Sanjai K. Rai
13) Mrs. Shylaja Devan
14) Dr. Venkataraman. B

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The editorial committee sincerely acknowledges the invaluable contributions made by the following individuals / groups in compiling this book.

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Shri K. Ganesan, SIRD
Shri K. Varathan, SIRD
Shri N. Mahendra Prabhu, IDEAS

All members of GRIP & NDED, IGCAR have contributed one way or other in bringing out this book. Their contributions are gratefully acknowledged.

ABBREVIATIONS

AE	Acoustic Emission
AERB	Atomic Energy Regulatory Board
BARC	Bhabha Atomic Research Centre
BI	Ball-Indentation
BOL	Beginning of Life
BRIT	Board of Radiation and Isotope Technology
CAT	Computerized Axial Tomography
C/M	Carbon to Metal ratio
CDM	Carriage Drive Mechanism
CMM	Computer Co-ordinate Machine
CNC	Computer Numerical Control Machines
CORAL	Compact facilities for Reprocessing of Advanced fuels in Lead cells
CRDM	Control Rod Drive Mechanism
CT	Calandria Tubes
CWMF	Centralised Waste Management Facility
DBTT	Ductile to Brittle Transition Temperature
DFRP	Demonstration FBR Fuel Reprocessing Plants
DMLD	Dimensional Measurement cum Laser Dismantling machine
DRDO	Defence Research Development Organization
DSRDM	Diverse Safety Rod Drive Mechanism
ECPS	Eddy Current based Position Sensor
EFPDs	Effective Full Power Days
EPMA	Electron Probe Micro Analyser
ETA	Explosive Transfer Assembly
FBR	Fast Breeder Reactor
FBTR	Fast Breeder Test Reactor
FCMI	Fuel-Clad Mechanical Interaction
FRFRP	Fast Reactor Fuel Reprocessing Plants
HAZ	Heat Affected Zone
HDPE	High Density Polyethylene
HDR	High Dose Rate
HORC	Hot cell Operations Review committee

HP	Health Physicist
HTS	Horizontal Transfer System
IDEAS	Innovative Design, Engineering and Synthesis Section
IGCAR	Indira Gandhi Centre for Atomic Research
IIT	Indian Institute of Technology
IRCS	Integrated Robotic Control System
ISI	In-service inspection
ISRO	Indian Space Research Organization
KAMINI	Kalpakkam Mini Reactor
LCF	Low Cycle Fatigue
LM	Linear Motion
LVDT	Linear Variable Differential Transformers
MBE	Magnetic Barkhausen Emission
MDBT	Miniature Disk Bend Test
MI	Mineral insulated
MIP	Moon Impact Probe
Mod	Modified
MSMs	Master Slave Manipulators
MV	Main Vessel
NAPS	Narora Atomic Power Station
NDE	Non-Destructive Evaluation
NFC	Nuclear Fuel Complex
NR	Neutron Radiography
ODS	Oxide Dispersion Strengthened
PFBR	Prototype Fast Breeder Reactor
PIE	Post Irradiation Examination
PLC	Programmable Logic Controller
PHWR	Pressurised Heavy Water Reactor
PSA	Pressure Swing Adsorption
PSI	Pre-Service Inspection
PVDF	Polyvinylidene Fluoride
RAC	Remote Analytical Cell
RBCD	Remote Booting Changing Device
RCL	Radio Chemistry laboratory

RFEC	Remote Field Eddy Current
RML	Radio Metallurgy Laboratory
RRC	Reactor Research Centre
RDL	Reprocessing laboratory
SA	Subassemblies
SAMPRO	Six Axis Multi-Purpose Articulated Robotic arm
SCARA	Selective Compliance Assembly Robotic Arm
SCC	Stress Corrosion Cracking
SG	Steam Generators
SGTF	Steam Generator Test Facility
ShP	Shear punch
SLD	Sodium Leak Detector
SP	Small Punch
SS	Stainless Steel
SV	Safety Vessel
TEM	Transmission Electron Microscopy
TGSCC	Trans Granular Stress Corrosion Cracking
Th	Thermal
TLD	Thermo Luminescent Dosimeters
TTS	Tube-to-Tube Sheet
UTS	Ultimate Tensile Strength
VTS	Vertical Transfer System
XRD	X-ray diffraction
XRF	X-ray fluorescence
YS	Yield Strength

GLOSSARY

The definitions of some of the terms used in this book are given below.

Absorbed Dose (D): The fundamental dosimetric quantity D is defined as:

$$D = dE/dm$$

Where dE is the mean energy imparted by the ionizing radiation to matter in a volume element, and dm is the mass of the matter in this volume element. The SI unit of absorbed dose is joule per kilogram ($J.kg^{-1}$), termed gray (Gy). The old unit of absorbed dose is Rad (1 Gy = 100 Rad).

Activation: The process of making a radioisotope by bombarding a stable element with neutrons or protons.

Active fuel length: The end-to-end dimension of fuel material within a fuel assembly (also known as a "fuel bundle" or "fuel element").

Activity: It means the rate of disintegration (transformation) or decay of radioactive material. The units of activity are the becquerel (Bq) and the curie (Ci).

1 Bq = 1 disintegration per second (dps)

Curie (Ci) , 1 Ci = 3.7×10^{10} Bq

Airborne radioactive material: It means any radioactive material dispersed in the air in the form of dusts, fumes, particulates, mists, vapors or gases.

Air sampling: The collection of samples of air to measure the radioactivity or to detect the presence of radioactive material, particulate matter, or chemical pollutants in the air.

Alpha particle: A positively charged particle ejected spontaneously from the nuclei of some radioactive elements. It is identical to a helium nucleus that has a mass number of 4 and an electrostatic charge of +2. It has low penetrating power and a short range (a few centimeters in air). The most energetic alpha particle will generally fail to penetrate the dead layers of cells covering the skin, and can be easily stopped by a sheet of paper. Alpha particles are hazardous when an alpha-emitting isotope is inside the body.

Atom: The smallest particle of an element that cannot be divided or broken up by chemical means. It consists of a central core (or nucleus), containing protons and neutrons, with electrons revolving in orbits in the region surrounding the nucleus.

Atomic energy: The energy that is released through a nuclear reaction or radioactive decay process. Of particular interest is the process known as fission, which occurs in a nuclear reactor and produces energy usually in the form of heat. In a nuclear power plant, this heat is used to boil water in order to produce steam that can be used to drive large turbines. This, in turn, rotates generators to produce electrical power. Atomic energy is more correctly called nuclear energy.

Attenuation: Gradual loss of intensity of any kind of flux through a medium.

Background radiation: The natural radiation that is always present in the environment. It includes cosmic radiation which comes from the sun and stars, terrestrial radiation which comes from the Earth, and internal radiation which exists in all living things.

Becquerel (Bq): See Activity

Beta particle: A charged particle (with a mass equal to 1/1837 that of a proton) that is emitted from the nucleus of a radioactive element during radioactive decay (or disintegration) of an unstable atom. A negatively charged beta particle is identical to an electron, while a positively charged beta particle is called a positron. Large amounts of beta radiation may cause skin burns, and beta emitters are harmful if they enter the body. Beta particles may be stopped by thin sheets of metal or plastic.

Breeder: A reactor that produces more nuclear fuel than it consumes. A fertile material, such as uranium-238, when bombarded by neutrons, is transformed into a fissile material, such as plutonium-239, which can be used as fuel.

Cask: A heavily shielded container used for the dry storage or shipment (or both) of radioactive materials such as spent nuclear fuel or other high-level radioactive waste. Casks are often made from lead, concrete, or steel. Casks must meet regulatory requirements and are not intended for long-term disposal in a repository.

Chain reaction: A reaction that initiates its own repetition. In a fission chain reaction, a fissionable nucleus absorbs a neutron and fissions spontaneously, releasing additional neutrons. These, in turn, can be absorbed by other fissionable nuclei, releasing still more neutrons. A fission chain reaction is self-sustaining when the number of neutrons released in a given time equals or exceeds the number of neutrons lost by absorption in nonfissionable material or by escape from the system.

Collective Dose: An expression for the total radiation dose incurred by a population. It is defined as the product of the number of individuals exposed to a source and their average radiation dose. The collective dose is expressed in Person-Sieverts.

Cladding: The thin-walled metal tube that forms the outer jacket of a nuclear fuel rod. It prevents corrosion of the fuel by the coolant and the release of fission products into the coolant. Aluminum, stainless steel, and zirconium alloys are common cladding materials.

Containment building: The air-tight building, which houses a nuclear reactor and its pressurizer, reactor coolant pumps, steam generator, and other equipment or piping that might otherwise release fission products to the atmosphere in the event of an accident. Such buildings are usually made of steel-reinforced concrete.

Contamination: The presence of radioactive substances in or on a material or the human body or in a place where they are undesirable.

Control rod: A rod, plate, or tube containing a material such as hafnium, boron, etc., used to control the power of a nuclear reactor. By absorbing neutrons, a control rod prevents the neutrons from causing further fissions.

Control room : The area in a nuclear power plant from which most of the plant's power production and emergency safety equipment can be operated by remote control.

Coolant: A substance circulated through a nuclear reactor to remove or transfer heat. The most commonly used coolant is water. Other coolants include heavy water, air, carbon dioxide, helium, liquid sodium, and a sodium-potassium alloy.

Critical mass: The smallest mass of fissile material that will support a self-sustaining chain reaction.

Criticality: The normal operating condition of a reactor, in which nuclear fuel sustains a fission chain reaction. A reactor achieves criticality (and is said to be critical) when each fission event releases a sufficient number of neutrons to sustain an ongoing series of reactions.

Decay heat: The heat produced by the decay of radioactive fission products after a reactor has been shut down.

Decontamination: A process used to reduce, remove, or neutralize radiological, chemical, or biological contamination to reduce the risk of exposure. Decontamination may be accomplished by cleaning or treating surfaces to reduce or remove the contamination; filtering contaminated air or water; subjecting contamination to evaporation and precipitation; or covering the contamination to shield or absorb the radiation. The process can also simply allow adequate time for natural radioactive decay to decrease the radioactivity.

Derived Air Concentration (DAC): It is the activity concentration of that radio nuclide in air (Bq/m^3) which if breathed by the reference man for a working year of 2000 hours under conditions of light physical activity (breathing rate of 1.2 m^3/h), would result in an inhalation of one ALI, or the concentration which for 2000 hours of air immersion would lead to irradiation of any organ or tissue to the annual limit.

Detector: A material or device that is sensitive to ionizing radiation and can display its characteristics and/or produce a signal suitable for measurement or analysis.

Differential pressure: The difference in pressure between two points of a system, such as between the inlet and outlet of a pump.

Dose Constraints: It is the restriction on the individual dose, stipulated by AERB as a measure of optimization, for controlling the exposure of a person (an occupational worker or a member of public) below the specified dose limits.

Dose Limit: The value of the effective dose or the equivalent dose to individuals from controlled practices that have been specified as the primary limit by AERB.

Dose rate: means the dose per unit of time, such as Sievert per minute (Sv/min) and Sievert per hour (Sv/hr).

Exposure: Ionizing effects of radiation are measured by units of exposure. Coulomb/Kg is the SI unit of radiation exposure. Old unit is Roentgen (R).

External dose: It means that portion of the equivalent dose received from any source of radiation outside the body.

Fast fission: Fission of a "heavy" atom (such as uranium-238) when it absorbs a fast (high energy) neutron. Most fissionable materials need slow (thermal) neutrons in order to fission.

Fast neutron: A neutron with kinetic energy greater than its surroundings when released during fission.

Fertile material: A material, which is not itself fissile (fissionable by thermal neutrons), that can be converted into a fissile material by irradiation in a reactor. There are two basic fertile materials: uranium-238 and thorium-232. When these fertile materials capture neutrons, they are converted into fissile plutonium-239 and uranium-233, respectively.

Fissile material: A nuclide that is capable of undergoing fission after capturing low-energy thermal (slow) neutrons. Although sometimes used as a synonym for fissionable material, this term has acquired its more-restrictive interpretation with the limitation that the nuclide must be fissionable by thermal neutrons. With that interpretation, the three primary fissile materials are uranium-233, uranium-235, and plutonium-239. This definition excludes natural uranium and depleted uranium that have not been irradiated, or have only been irradiated in thermal reactors.

Fission: The splitting of an atom, which releases a considerable amount of energy (usually in the form of heat) that can be used to produce electricity. Fission may be spontaneous, but is usually caused by the nucleus of an atom becoming unstable (or "heavy") after capturing or absorbing a neutron. During fission, the heavy nucleus splits into roughly equal parts, producing the nuclei of at least two lighter elements. In addition to energy, this reaction usually releases gamma radiation and two or more daughter neutrons.

Fission gases: Those fission products that exist in the gaseous state. In nuclear power reactors, this includes primarily the noble gases, such as krypton and xenon.

Fission products: The nuclei (fission fragments) formed by the fission of heavy elements, plus the nuclide formed by the fission fragments' radioactive decay.

Flux: A term applied to the amount of some type of particle (neutrons, alpha particles, etc.) or energy (photons, heat, etc.) crossing a unit area per unit time. The unit of flux is the number of particles, energy, etc., per square centimeter per second.

Fuel cycle: The series of steps involved in supplying fuel for nuclear power reactors include the following:

- Uranium recovery to extract (or mine) uranium ore, and concentrate (or mill) the ore to produce "yellowcake"
- Conversion of yellowcake into uranium hexafluoride (UF6)
- Fuel fabrication to convert enriched UF6 into fuel for nuclear reactors
- Use of the fuel in thermal reactors
- Reprocessing of spent fuel from thermal reactor to separate plutonium and uranium
- Fuel fabrication for Fast Breeder Reactor (FBR)
- Reprocessing of spent fuel/blanket subassembly from FBR to separate plutonium and Uranium-233 respectively
- Fuel fabrication for FBR and KAMINI reactor
- Reprocessing of high-level waste to recover the fissionable material remaining in the spent fuel and use in reactor
- Final disposition of high-level waste

Gamma radiation: High-energy, short-wavelength, electroma gnetic radiation emitted from the nucleus of an atom. Gamma radiation frequently accompanies emissions of alpha particles and beta particles. Gamma rays are similar to x-rays, but are very penetrating and are best stopped or shielded by dense materials, such as lead or depleted uranium.

Gap: The space between the fuel pellet and the fuel rod cladding.

Gas chromatography: A way of separating chemical substances from a mixed sample by passing the sample, carried by a moving stream of gas, through a tube packed with a finely divided solid that may be coated with a liquid film. Gas chromatography devices are used to analyze air pollutants, blood alcohol content, essential oils, and food products.

Gigawatt (GW): A unit of power equivalent to one billion watts.

Gray: (Gy) is the SI unit of absorbed dose. One gray is equal to an absorbed dose of 1joule per kilogram (J/kg) (1 Gy = 100 rad).

Health physics: The science concerned with recognizing and evaluating the effects of ionizing radiation on the health and safety of people and the environment, monitoring radiation exposure, and controlling the associated health risks and environmental hazards to permit the safe use of technologies that produce ionizing radiation.

High-enriched uranium: Uranium enriched to at least 20 percent uranium-235 (a higher concentration than exists in natural uranium ore).

Hot : A colloquial term meaning highly radioactive.

Ionizing Radiation: means gamma rays and X-rays, alpha and beta particles, electrons, neutrons, protons, and other nuclear particles, or electromagnetic radiations capable of producing ions directly or indirectly in their passage through matter.

Irradiation: Exposure to ionizing radiation. Irradiation may be intentional, such as in cancer treatments or in sterilizing medical instruments. Irradiation may also be accidental, such as being exposed to an unshielded source. Irradiation does not usually result in radioactive contamination, but damage can occur, depending on the dose received.

Isotope: Two or more forms (or atomic configurations) of a given element that have identical atomic numbers (the same number of protons in their nuclei) and the same or very similar chemical properties but different atomic masses (different numbers of neutrons in their nuclei) and distinct physical properties.

Megacurie: One million curies.

Megawatt (MW): A unit of power equivalent to one million watts.

Megawatthour (MWh) : One million watthours, unit of energy.

Microcurie: One millionth of a curie. That amount of radioactive material that disintegrates (decays) at the rate of 37 thousand atoms per second.

Millirem: One thousandth of a rem (0.001 rem).

Milliroentgen (mR): One thousandth of a roentgen (R).
$1 mR = 10^{-3} R = 0.001 R$.

Mixed oxide (MOX) fuel: A type of nuclear reactor fuel (often called "MOX") that contains plutonium oxide mixed with either natural or depleted uranium oxide, in ceramic pellet form.

Moderator: A material, such as ordinary water, heavy water, or graphite, that is used in a reactor to slow down high-velocity neutrons, thus increasing the likelihood of fission.

Monitoring of radiation: Periodic or continuous determination of the amount of ionizing radiation or radioactive contamination in a region. Radiation monitoring is a safety measure to protect the health and safety of the public and the environment through the use of bioassay, alpha scans, and other radiological survey methods to monitor air, surface water and ground water, soil and sediment, equipment surfaces, and personnel.

Natural uranium: Uranium containing the relative concentrations of isotopes found in nature (0.7 percent uranium-235, 99.3 percent uranium-238, and a trace amount of uranium-234 by mass).

Neutron: An uncharged elementary particle, with a mass slightly greater than that of the proton, found in the nucleus of every atom heavier than hydrogen.

Neutron flux: A measure of the intensity of neutron radiation in neutrons/cm^2-sec. It is the number of neutrons passing through 1 square centimeter of a given target in 1 second. Expressed as nv, where, n = the number of neutrons per cubic centimeter and v = their velocity in centimeters per second.

Neutron source: Any material that emits neutrons, such as a mixture of radium and beryllium, that can be inserted into a reactor to ensure a neutron flux large enough to be distinguished from background to register on neutron detection equipment.

Neutron, thermal: A neutron that has (by collision with other particles) reached an energy state equal to that of its surroundings, typically on the order of 0.025 eV (electron volts).

Nonpower reactor (research and test reactor): A nuclear reactor that is used for research, training, or development purposes (which may include producing radioisotopes for medical and industrial uses) but has no role in producing electrical power.

Nuclear fuel: Fissionable material that will support a self-sustaining fission chain reaction when used to fuel a nuclear reactor, thereby producing energy.

Nuclear power plant: An electrical generating facility using a nuclear reactor as its heat source to provide steam to a turbine generator.

Nuclear reactor: The heart of a nuclear power plant or nonpower reactor, in which nuclear fission may be initiated and controlled in a self-sustaining chain reaction to generate energy or produce useful radiation.

Nuclear waste: Radioactive waste that includes unusable byproducts produced during the various stages of the nuclear fuel cycle, including recovery (or extraction), conversion, and enrichment of uranium; fuel fabrication; and use of the fuel in nuclear reactors.

Occupational exposure: Exposures of personnel incurred during the course of their work.

Personnel monitoring: The use of portable survey meters to determine the amount of radioactive contamination on individuals, or the use of dosimetry to determine an individual's occupational radiation dose.

Pile: A colloquial term describing the first nuclear reactors. They are called piles because the earliest reactors were "piles" of graphite and uranium blocks.

Plutonium (Pu): A heavy, radioactive, manmade metallic element with atomic number 94. Its most important isotope is fissile plutonium-239, which is produced by neutron irradiation of uranium-238. It exists in only trace amounts in nature.

Pocket dosimeter: A small ionization detection instrument that indicates ionizing radiation exposure directly. An auxiliary charging device is usually necessary.

Pool reactor: A reactor in which the fuel elements are immersed in a pool of coolant.

Power reactor: A reactor designed to produce heat for electric generation.

Radioactivity: means the disintegration (transformation) of unstable atomic nuclei by the spontaneous emission of radiation.

Radiography: When the radiation penetrates the material, it produces a shadow image by blackening a sheet of photographic film that has been placed behind the material, and the differences in blackening suggest flaws and unevenness in the material.

Radioisotope (Radionuclide): An unstable isotope of an element that decays or disintegrates spontaneously, thereby emitting radiation. Approximately 5,000 natural and artificial radioisotopes have been identified.

Radioactive material: means any solid, liquid or gaseous substance, which emits radiation spontaneously.

Reaction: Any process involving a chemical or nuclear change.

Reactivity: A term expressing the departure of a reactor system from criticality. A positive reactivity addition indicates a move toward supercriticality (power increase). A negative reactivity addition indicates a move toward subcriticality (power decrease).

Reactor coolant system: The system used to remove energy from the reactor core.

Reactor core: The central portion of a nuclear reactor, which contains the fuel assemblies, moderator, neutron poisons, control rods, and support structures. The reactor core is where fission takes place.

Reflector: A layer of material immediately surrounding a reactor core that scatters back (or reflects) into the core many neutrons that would otherwise escape. The returned neutrons can then cause more fissions and improve the neutron economy of the reactor. Common reflector materials are graphite, beryllium, water, and natural uranium.

Roentgen: unit of exposure. One roentgen (R) equals 2.58 x 10^{-4} coulombs per kilogram (C/kg).

Shielding: Any material or obstruction that absorbs radiation and thus tends to protect personnel or materials from the effects of ionizing radiation.

Sievert (Sv): means the SI unit of equivalent dose. The equivalent dose in Sievert is equal to the absorbed dose in Gray multiplied by the Radiation weighting factor W_R (1 Sv = 100 Rem).

Source of radiation: means any radioactive material or any device or equipment emitting, or capable of producing, radiation.

Spent fuel pool: An underwater storage and cooling facility for spent (depleted) fuel assemblies that have been removed from a reactor.

Spent nuclear fuel: Nuclear reactor fuel that has been used to the extent that it can no longer effectively sustain a chain reaction.

Thermal reactor: A reactor in which the fission chain reaction is sustained primarily by thermal neutrons. Most current reactors are thermal reactors.

Thermal shield: A layer, or layers, of high-density material located within a reactor pressure vessel or between the vessel and the biological shield to reduce radiation heating in the vessel and the biological shield.

Thermoluminescent dosimeter (TLD): A small device used to measure radiation.

Transuranic element: An artificially made, radioactive element that has an atomic number higher than uranium in the periodic table of elements such as neptunium, plutonium, americium, and others.

Transuranic waste: Material contaminated with transuranic elements—artificially made, radioactive elements, such as neptunium, plutonium, americium, and others—that have atomic numbers higher than uranium in the periodic table of elements. Transuranic waste is primarily produced from recycling spent fuel or using plutonium to fabricate nuclear weapons.

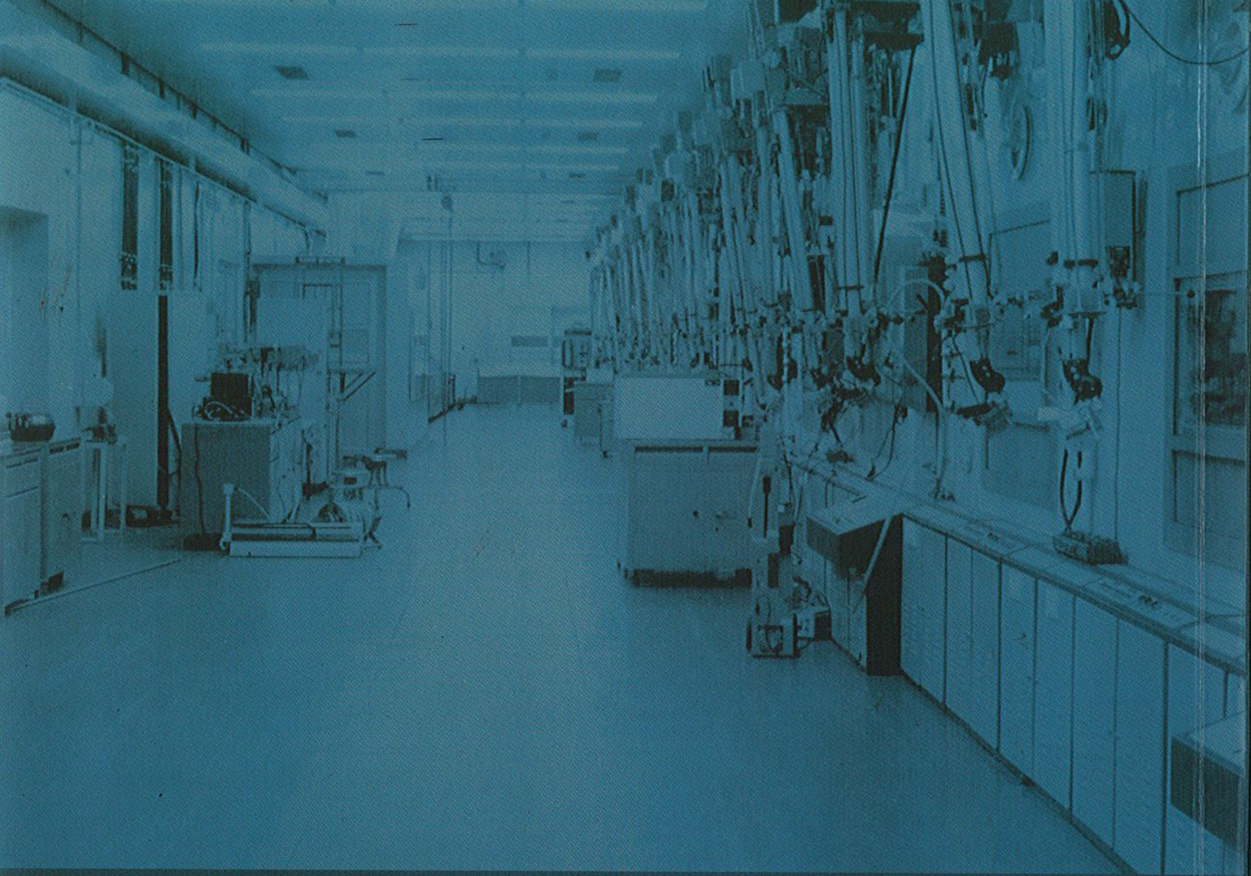
Watt: A unit of power (in the international system of units) defined as the consumption or conversion of one joule of energy per second. In electricity, a watt is equal to current (in amperes) multiplied by voltage (in volts).

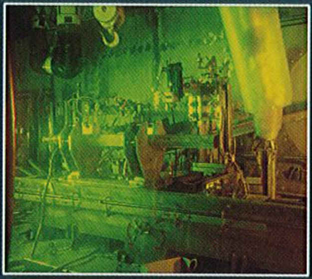
Watthour: An unit of energy equal to one watt of power steadily supplied to, or taken from, an electrical circuit for one hour.

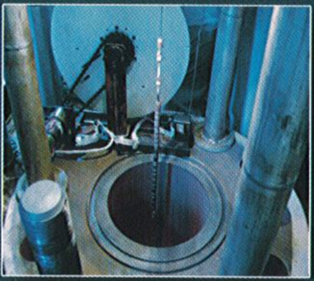
Whole Body counting: It is the determination of the kind, quantity, location and/or retention of the radionuclides in the body by direct measurement using gamma spectrometry.

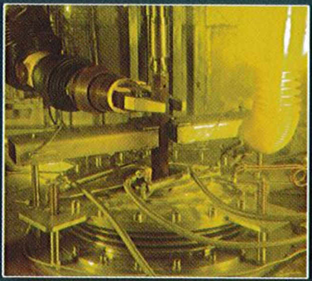
Swipe sample: A sample made for the purpose of determining the presence of removable radioactive contamination on a surface.

X-rays: Penetrating electromagnetic radiation having a wavelength that is much shorter than that of visible light. These rays are usually produced by excitation of the electron field around certain nuclei. In nuclear reactions, it is customary to refer to photons originating in the nucleus as x-rays.









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