The excitement of mission oriented research and development (R&D)

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Abstract

An essential ingredient of excitement in any activity is the existence of a challenge. In basic R&D the challenge lies in either discovering, or in understanding the hitherto unknown. In mission oriented R&D, on the other hand, the challenge lies in reaching a well-defined objective under several constraints. Taking three examples from different fields, the paper highlights the building up of excitement in mission oriented R&D.

(**Keywords** : mission /R&D /nuclear /mutation /reactor)

1. Introduction

Discovery of new knowledge is always exciting, whether or not its immediate potential is conceivable or otherwise. Several important scientific discoveries have had their societal application many decades after the initial findings were made. On the other hand, one has several examples of R&D being moulded to reach certain deliverable products within given time frames to fulfil important needs of the society. Such R&D, which we call mission oriented R&D, provides an excitement which stems from being able to visualise the immediate application of a product, a realisation of reaching a well defined goal through collective team work, and the satisfaction arising out of testing new ideas and making discoveries along the path of such R&D. Department of Atomic Energy has the advantage of working in a multi disciplinary scientific environment with infrastructure specifically tuned to carrying out mission oriented R&D. The paper highlights the building up of excitement in mission oriented R&D, with the help of the following three case studies:

a) Development of carbide fuel for FBTR

b) Mutation research at Trombay for the development of new crop varieties, and

c) Development of coolant channel life management technologies

2. Development of Carbide Fuel for Fbtr

2.1 The Backdrop

The Indian nuclear power programme began with the setting up of two Boiling Water Reactors (BWRs), using slightly enriched uranium fuel, at Tarapur in collaboration with the USA in the 1960s. This was followed by beginning a collaboration with Canada for setting up two Pressurised Heavy Water Reactors (PHWRs), fuelled with natural uranium, in Rajasthan, to start the first stage of the three stage Indian nuclear power programme[1] based on indigenous resources. The initial step towards the second stage of the Indian nuclear programme was taken when a collaboration was started with France in the 1970s to set up a Fast Breeder Test Reactor (FBTR) using a fuel composition of 30% PuO_2-70% enriched UO_2 (85% enrichment). This fuel was to have been supplied by France for the initial core of the reactor. However, after the Indian peaceful nuclear experiments in 1974, nuclear fuel supply for the BWRs at Tarapur and the international collaboration programmes with Canada and France closed. This denial of fuel supply and the ceasing of international collaboration meant that alternate fuel for the BWR and FBTR had to be developed within the country.

The scenario was therefore set for the excitement to establish our credentials of being capable of selecting, characterising and fabricating nuclear fuels indigenously. This required a mission oriented approach and the laboratory set-up at Trombay for handling of plutonium bearing material was converted into a facility for carrying out research and development on plutonium bearing alternate fuels for the BWR and FBTR.

2.2 The Challenges

The original 30% PuO_2-70% enriched UO_2 (85% enrichment). fuel, which was to have been provided by France, was a tried and proven fuel. The technology for producing such enriched uranium-based fuel did not exist in the country then. We did, however, have an apparently feasible option of using plutonium-based fuel for the reactor. France was using the highly enriched uranium-based fuel in its fast reactor RAPSODIE. Since FBTR had been designed on the RAPSODIE model, the selection of an alternate fuel meant choosing one with characteristics closely matching those of the original fuel. In particular, it was essential to investigate all issues relating to neutronics, thermal behaviour, compatibility with clad and coolant, and structural properties - arising out of this change.

At an early stage of this evaluation, a decision needed to be taken concerning the chemical form of the new fuel.

The first option for the alternate fuel was the use of a larger fraction of plutonium in the mixed oxide fuel than in the original fuel. The composition sought was 76% PuO_2-nat UO_2 (mixed plutonium oxide - natural uranium oxide). Experiments at that time, however, showed that these fuels have a low compatibility with the liquid coolant sodium, and also have low thermal conductivity. It was also noted that the oxygen potential increases with increasing plutonium content and burn-up. The next choice was to select a larger fraction of plutonium in its carbide form. This plutonium-rich option was the only viable option available to us. Mixed plutonium carbide and uranium carbide as fuel have better properties as a nuclear fuel than mixed oxides. The higher thermal conductivity and fissile atom density permit the fuel to be used for higher specific power operation and leads to a higher breeding ratio. A composition of 70% PuC-30% UC (natural uranium) was chosen as the driver fuel (termed Mark-I fuel). This fuel composition was chosen to satisfy the fissile inventory with plutonium only rather than use enriched uranium.

The use of this fuel posed many challenges. The carbide fuel had not been, till then, used as a driver fuel for the core of a fast breeder reactor anywhere in the world. To begin with, relevant data on fabrication of this fuel was not available. The in-pile and out-of-pile properties of the fuel were also not available in open literature. The contents of reported literature on the thermo-physical properties at that time were mainly limited to mixed carbide compositions with less than 40 wt%.PuC. Unlike plutonium oxide, plutonium carbide is pyrophoric. This added another dimension to the complexities in the manufacture of this fuel.

2.3 The Excitement

The first step, after the initial screening and reactor physics design aspects were taken care of, was to measure the thermo-physical properties of carbide fuel of target compositions in out of pile (laboratory) experiments. It was decided to make the FBTR core critical with a small fuel inventory, to begin with, for physics and safety experiments. The core was subsequently to be fuelled with a composition of 55% PuC-45% natUC (termed Mark-II fuel) for full power operation at 40MW(thermal). Fig-1 gives the measured thermal conductivity of Mark-II fuel.

The evaluation of the measured out of pile properties and chemical compatibility of the clad and fuel indicated that the two compositions for the FBTR fuel could be used for the intended objectives, i.e., Mark-I fuel for experiments and Mark-II fuel for operation of the reactor at a higher power. The experiments showed that Mark-II has a higher thermal conductivity and a lower thermal expansion compared to the Mark-I fuel. It also has a higher melting point. These properties indicated that the Mark-II fuel could be operated at a higher power and a higher linear heat rating compared to the Mark-I fuel. Measurements of other properties such as carbon potential and hot hardness, also indicated that the fuel performance would meet the specifications of the reactor operation. The production of the mixed carbide pellets is carried out by vacuum carbothermic reduction of mechanically mixed UO_2, PuO_2 and graphite powders to prepare carbide clinkers which are crushed and milled to fine powder before compaction and sintering in an inert gas atmosphere. The sintered pellets are then inspected for physical and dimensional integrity, before encapsulating the pellets into a stainless-steel tube along with appropriate hardware by welding end-plugs[2].

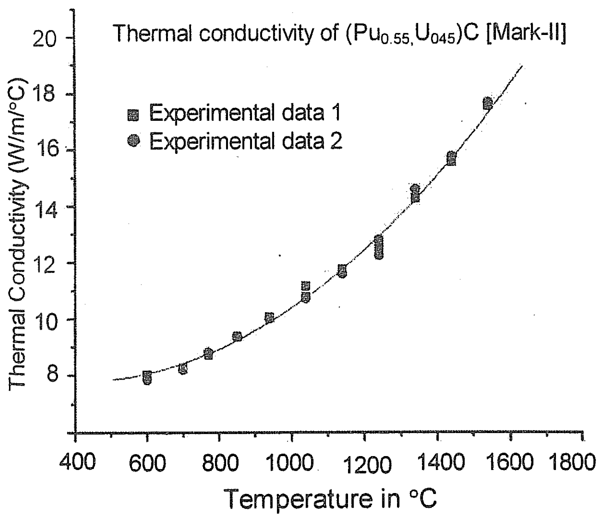

Fig 1– Thermal conductivity data as a function of temperature for 55%PuC-45%UC fuel.

In addition to radio-toxicity associated with plutonium bearing fuel, mixed carbide fuel pellets are prone to oxidation and hydrolysis in the presence of oxygen and moisture. Carbide powders are also very pyrophoric; hence these materials need to be handled in leak tight glove boxes maintained under sub-atmospheric pressure by continuous flow of high purity nitrogen gas having oxygen and moisture content less than 25ppm each

The simultaneous R&D efforts which were made in developing the flow-sheet for fabrication of advanced carbide and nitride fuels in the initial stages of the programme bore fruit, in the form of being able to manufacture the advanced mixed-carbide fuel, in-spite of being one of the most difficult fuels to handle. Fig-2 shows a view of the facilities used for the fabrication of this fuel.

The FBTR today is operating satisfactorily and has delivered most of the important data required for our fast reactor breeder programmes. Till date the FBTR fuel has seen operation of over 145000MWd/Te safely and is continuing without any failure.

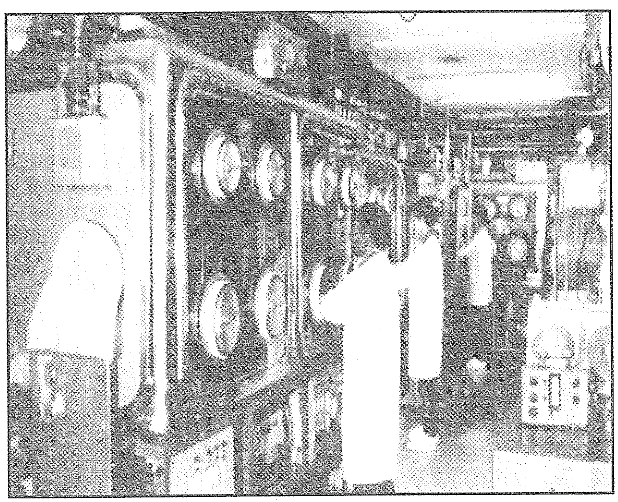

Fig 2–FBTR Fuel Fabrication Facility at BARC

3. Mutation Research at Trombay for the Development of New Crop Varieties

3.1 The Backdrop

India continues to import, year after year, edible oils and pulses to meet the growing domestic requirements. Considering the increase in demand for food due to increase in population, it is important to progressively develop new varieties having very high productivity along with good quality traits. Further, there is a remote chance to increase the area under cultivation of crops due to rapid urbanization. By developing newer varieties having superior agronomic and quality traits, India may be in a position to not only take care of its domestic food requirements but can also compete well in the international markets.

Plant breeding is a continuous process involving stepwise genetic improvement of crops, especially for the polygenic traits like yield. In this endeavour, along with the conventional breeding efforts in the country, BARC, Trombay had developed new varieties by using atomic radiations such as gamma rays, fast neutrons, thermal neutrons, beta particles and X-rays[3]. One of the properties of radiations on biological systems is to induce genetic changes (mutations). Low dose radiations can result in a variety of mutations in crop plants. This property was made use of to create genetic variability in crop plants and in turn these mutants were used as such or after cross breeding to develop new crop varieties with desirable characters such as high yield, increased seed size, improved quality, resistance to diseases etc.

Being an important oilseed, food and feed crop groundnut was used as one of the potential candidates for genetic improvement through radiation treatment.

3.2 The Challenges

Groundnut is grown in India, in about 6.7-million hectares with a production of 6.1 million tonnes and productivity 910 kg/ha. Although India ranks first in the world with respect to groundnut acreage, productivity levels are lower than many countries. This is because 70% of the groundnut cultivated area falls under rain-fed situation, where, due to the erratic rainfall, crop is exposed to the vagaries of nature such as pests, diseases, drought, flooding etc. bringing down the yield levels as well as the quality of seed. Many farmers have no access to give at least one life saving irrigation to rescue the crop. Adding to the worries is the problem of pre-harvest germination inside soil due to end season rains. Although large groundnut seeds are valued by the industry for use as 'Table delicacies' and also for export, existing varieties in such category have lower yields, have late maturity and do not fit into the local cropping system.

Groundnut has several inherent constraints such as low yield, susceptibility to pests and diseases, late maturity, pre-harvest germination, low shelling percentage etc. It is a challenge to make genetic improvement for many of these traits because of polygenic inheritance which can be tackled by step-wise planned breeding. This is where radiation based breeding was exploited to create genetic variability leading to improved traits.

3.3 The Excitement

Mutation research at Trombay, along with recombination breeding, played a significant role in the evolution of unique desired agronomic traits in the Trombay Groundnut (TG) types. During a period spanning over last four decades ten varieties of TG varieties were commercially released. A chronology of these releases is given in Table-1.

Table 1– Chronology of commercial release of TG varieties:

Year of Release	Name of variety
1973	TG-1
1985	TG-17
1987	TG-3
1989	Somnath (TGS-1)
1991	TAG-24
1992	TG-22
1994	TKG-19A
1995	TG-26
2004	TPG-41
2004	TG-37A

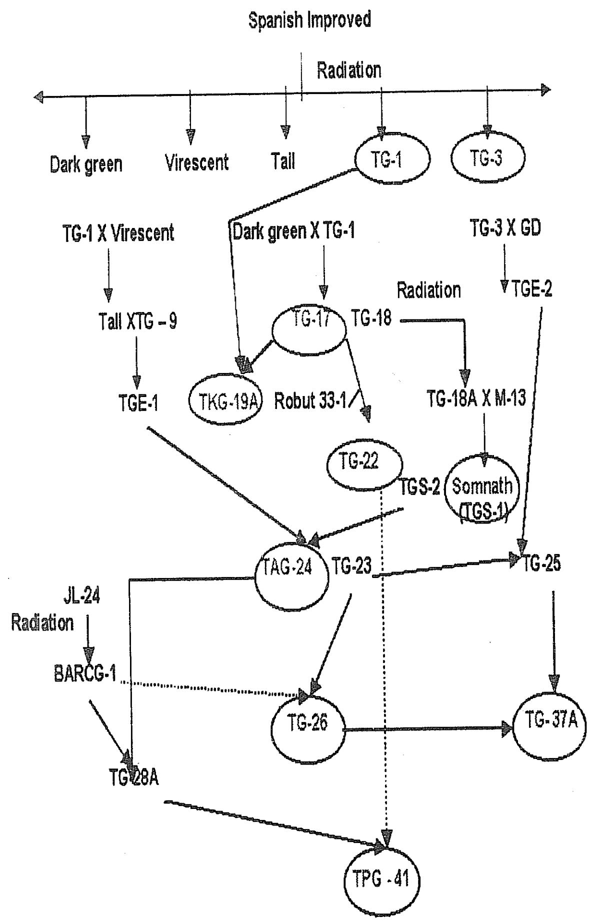

Fig 3– Flow chart showing the evolution of ten Trombay groundnut varieties

Fig. 3 Provides a flow chart how the ten TG varieties were developed by a judicious use of radiation and conventional breeding.

To enhance the yield, selections were made for various characteristics like ideal plant type (ideotype) such as plant with increased number of branches, semi-dwarf habit, high harvest index, early maturity, better nutrient/input response etc. This resulted in the development of the most popular high yielding variety, TAG-24.

One of the important challenges in this effort was to prevent pre-harvest in-situ seed sprouting/ germination due to end season rains, especially during maturity. Since, the seeds start germinating in soil before harvest, it leads to huge losses to the farmers. Although our earlier varieties like TG-1, TG-17 and TG-22 have about two months seed dormancy (during which in-situ seed germination is prevented), they have other deficiencies. This problem was solved by introducing optimal seed dormancy character of about 15-20 days in the new varieties by using radiation and recombination breeding. The result of this was the development of another popular TG variety, TG-26, with an ideal seed dormancy of 20 days.

In the course of time, TAG-24 and TG-26 encountered certain deficiencies like lower fodder value, adaptation to rainy season etc. As depicted in Fig-3, with a blend of beneficial traits of both TG-25 and TG-26, a new variety TG-37A was recently released. It has wider adaptability for both rainy season and summer across different agro-climatic regions in India.

Groundnut production is drastically curtailed by the incidence of several pests and diseases. Since, chemical control is a costly affair and also pollute the environment, developing varieties with genetic resistance against the pests and diseases is a viable option. In this direction, in TAG 24 and TG 26, sustained selection pressure was maintained to incorporate tolerance to peanut bud necrosis disease. Subsequently, several new high yielding breeding lines with resistance to late leaf spot, rust and peanut bud necrosis diseases were developed which are currently undergoing evaluation in various national and state level trials.

Groundnut industry is looking for large groundnut seeds to be used for table/confectionery purpose. The major hurdle for the farmers in cultivating such large seed types was longer crop maturity (140-150 days), which do not fit into the normal cropping system. Secondly, low shelling percentage (seed outturn from the pods) leds to poor seed recovery. It was a challenge to obtain large groundnut seeds which could mature early (in ≤120 days). Usually large seed size and late maturity are genetically tightly linked traits, which are difficult to break through conventional breeding methods. This linkage was successfully broken using mutation breeding and the result is TKG-19A variety which matures in 120 days, with 100-seed weight of about 60 g (compared to 35 g in normal varieties), with 20 days dormancy. Another challenge was to select a new variety with all traits of TKG-19A with an increase in proportion of large seeds per hectare. Concentrated breeding efforts, utilising ideal parents resulted in the development of our latest variety TPG-41.

Other strong linkages which prevent further genetic improvement include negative correlation between large seed and less seed oil content. This could be broken successfully by the release of Somnath, which has high oil content and large seed. In addition, several breeding lines with normal seed size with low oil content and large seed with high oil percentage were evolved.

The final challenge was to make available these superior varieties to the farming community. This challenge was met by establishing linkages with several Agricultural Universities, ICAR institutes, Seed Corporations, NGOs, progressive farmers etc., interacting with the Ministry of Agriculture, and also producing large quantities of quality (breeder) seed by ourselves.. As a result of these concerted efforts, Trombay Groundnut varieties have reached the farmers in almost all the groundnut growing states in the country. The full impact and the real excitement arising out of this development was felt when the farmers from Maharashtra, Gujarat, Karnataka and Andhra Pradesh started obtaining consistently higher yields by using TAG-24 and TG-26 varieties, harvesting >5,000 kg/ha in rainy season and >9,000 kg/ha under irrigated summer situation, compared to the national averages of about 900 and 1,500 kg/ha, respectively. Fig-4 shows some of these productivity figures.

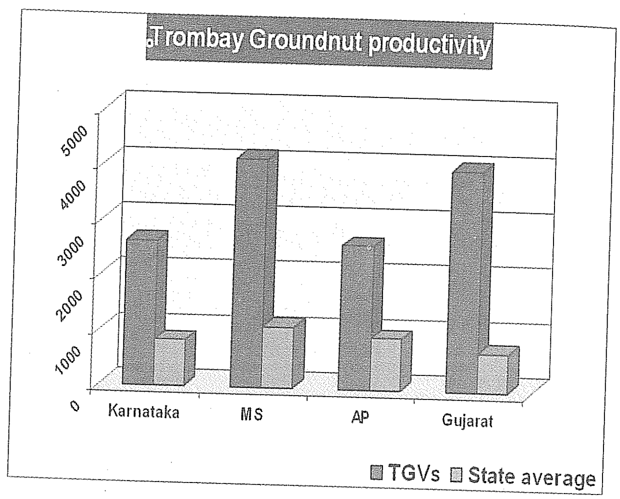

Fig 4– Productivity of Trombay Groundnut Varieties (TGV)

4. Development of Coolant Channel Life Management Technologies:

4.1 The Backdrop

We selected Pressurised Heavy Water Reactors as our vehicle for optimum utilisation of limited Uranium resources in the country. The PHWRs contain several hundred Zirconium alloy pressure tubes, which house the nuclear fuel and form a conduit for the passage of heavy water coolant. The pressure tubes located in the core of the PHWR reactor, operate under harsh operating conditions of pressure (10 MPa), temperature

(300° C) and nuclear radiation (neutron flux $3x10^{13}$ n/sq.cm/s; E>1 Mev). Fig-5 shows a schematic of the PHWR coolant channel. The calandria tube is an annular tube outside the pressure tube and is designed to serve the purpose of isolating the relatively cold (60°C) heavy water moderator from the relatively hot (300°C) pressure tube, as also, supporting the pressure tube in the transverse direction, through Zircaloy-2.5%Nb-0.5%Cu, garter spring spacers, located axially along the pressure tube, thus limiting the latter's excessive creep sag.

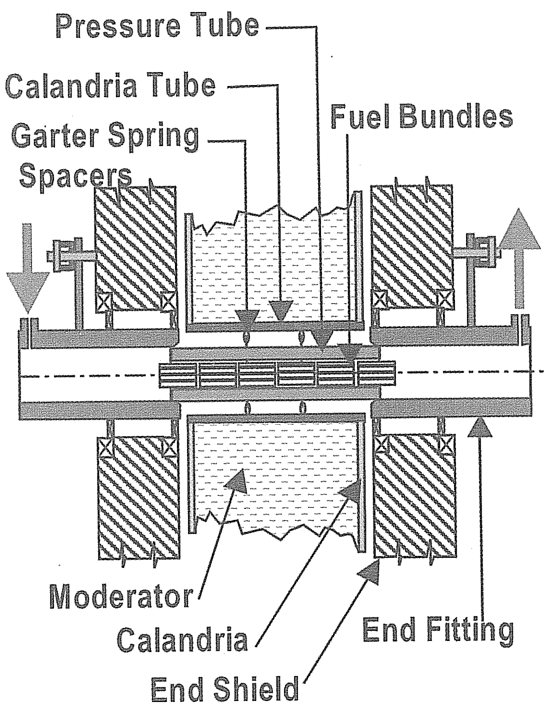

Fig 5– Schematic of a PHWR Coolant Channel Assembly.

In the initial stages, Zircaloy-2 was chosen as the material of construction for the pressure tubes, on the basis of a large number of experiments performed under simulated conditions in Canada, who supplied the first PHWR i.e. Rajasthan Unit No.1, to us. In the year 1983, one of the Zircaloy-2 pressure tubes at the Canadian Pickering-2 nuclear generating station had a catastrophic failure while the reactor was operating at full power. At that time, Canada had been operating two reactors with Zircaloy-2 pressure tubes while we had seven reactors with Zircaloy-2 pressure tubes either already in place or planned to be incorporated in reactors under advanced stage of planning and construction. The accident in Canada immediately led to a replacement of all the Zircaloy-2 pressure tube in Canadian reactors with Zirconium-2.5% Niobium pressure tubes, which were already planned for implementation guided mainly by economic considerations and not because of any apprehensions of a problem with Zircaloy-2. We had a tough challenge ahead, not only to develop the pressure tubes with the new material Zirconium-2.5% Niobium, as quickly as possible, but also to develop technologies to address the safety issues relating to the ageing of the Zircaloy-2 pressure tubes in as many as seven Indian reactors.

4.2 The Challenge

The primary cause for the rupture of the pressure tube in Pickering Nuclear Generating Station-A channel G16 was attributed to the excessive creep sag of the pressure tube as a consequence of its operation under hitherto unknown, displaced garter spring spacers. This led to a contact between the hot pressure tube with the relatively cold calandria tube over an extended length, with time. This contact span became the site for formation of hydride blisters, fuelled by the diffusion of hydrogen present in the pressure tube metal matrix in the as manufactured state, as well as, that picked up by it from the heavy water-pressure tube corrosion reaction. A series of blisters grew and colluded with each other with time to present an extended, partial wall thickness brittle front, through which, a crack grew from blister to blister, while the remaining pressure tube was sufficiently ductile. A time came when this partial wall thickness crack grew sufficiently to an extent that it reached its unstable limit and under a normal operating pressure transient grew extensively through the brittle front. The remaining ductile ligament of the tube was unable to contain the tube pressure and resulted in a longitudinal gaping fissure. It may be noted that this incident did not lead to any external release of radioactivity and the plant was shut down in a normal manner. This incident, however, was in violation of the Leak Before Break criterion, which is one of the design philosophies for these components.

Owing to the design similarity between the Canadian and the Indian PHWRs, of the old vintage, it was necessary to take appropriate corrective actions at our end to avoid any incident similar to the Pickering experience, as also, to address the safety of the coolant channel components in general, under the conditions of material degradation during in-reactor operation. The challenges involved in the programme for ageing management were mainly the following[4]:

1. Modelling degradation mechanisms in Zircaloy-2 pressure tubes without the benefit of any further international experience feedback with a view to assure continued safe operation of these Indian reactors till the predicted degradation limited life of any pressure tube in these reactor was reached.

2. Establishing an extensive system of validated inspection and allied technologies, that allowed identification of the most vulnerable pressure tubes in a reactor sufficiently in advance of their reaching their degradation limited, safe operating life.

3. Establishing an extensive system of high technology solutions, capable of remotely executing several complex tasks in high radiation areas, to perform the required inspection, life extension and large scale replacement of the coolant channels.

4.3 The Excitement

4.3.1 Degradation Models and Computer Codes to Monitor Fitness for Service

A number of computer codes were developed to model the various degradation mechanisms and to estimate the life limiting parameters pertaining to the coolant channels.

A computer code SCAPCA was developed to simulate the in-reactor, creep-growth behaviour of the coolant channels. The code was developed from scratch, using the first principles of mechanics of structures. It was validated on the basis of internationally published information and the extensive data available from the in-service inspection (ISI) of Indian PHWR coolant channels. Over a period of time, starting from 1986, SCAPCA has been used to address and resolve the creep-sag related safety issues, requiring the modelling of around four thousand cases.

It is an exciting experience to see SCAPCA estimations of the pressure tube calandria tube gap in good agreement with the ISI measurements in almost all of the safety relevant cases. Fig-6 shows one such comparison between SCAPCA estimations and ISI data for gap at the bottom, between the pressure tube and the calandria tube. SCAPCA has also been extensively used to model the behaviour of coolant channels during maintenance operations described later.

In parallel with the addressing of the creep-sag issue, came the need for the estimation of hydrogen in the pressure tube material. Hydrogen (deuterium) evolved during the in-reactor corrosion is partly absorbed by the pressure tube material. A computer code HYCON has been developed to predict the hydrogen pick-up. It has been periodically updated based on indigenously obtained Post Irradiation Examination (PIE) data, for obtaining which, the required infrastructure was set up. This code has been extensively used for the life management of Zircaloy-2 pressure tubes. In order to assure the safe operation of the pressure tube in the scenario of pressure tube calandria tube contact, it is required to estimate the blister depth with time. Computer code BLIST, was developed to model the hydrogen diffusion driven blister growth with time. BLIST code has so far been used to assess the safety of Zircaloy-2 pressure tubes. BLIST code has been validated with respect to the measured blister of J07 channel in RAPS-2 along with internationally reported field data. The fitness of pressure tube for service requires a demonstration of leak before break (LBB) capability. The LBB criterion for pressure tubes has been the basis for development of computer code CEAL (Code for the Estimation of Assurance of LBB). Using this code the estimated variation of maximum allowable operator response time with hydrogen concentration for Zircaloy-2 pressure tubes has been estimated.

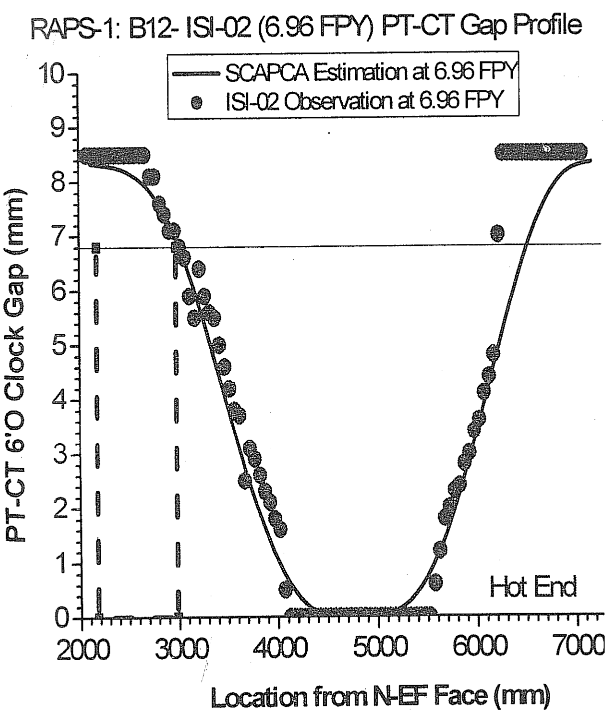

Fig-6 An example of fit between SCAPCA computation and In-service Inspection data

4.3.2 Tools and Techniques for Diagnosis and Inspection

A technique based on the measurement of vibration signatures at both the ends of the coolant channel, caused by excitation from an electro-dynamic shaker mounted at one end, was developed and used to identify the pressure tubes which could be in contact with the calandria tubes. This procedure, called Non Intrusive Vibration Diagnostic Technique (NIVDT) enables screening the entire reactor core in 3 to 4 days time. India is the only country in the world having this technology.

In order to carry out ISI of coolant channels a special inspection system called BARCIS (BARC Channel Inspection System) has been developed by incorporating several ultrasonic and eddy current based sensors for carrying out measurements. The compact inspection head of BARCIS carries several eddy current and ultrasonic sensors and is driven remotely, from channel to channel, operated from a control room located outside the reactor building.

In order to measure the hydrogen concentration in the pressure tube material in-situ, without the removal of pressure tube and to reduce the downtime of the reactor, required for this activity, a technique was developed, wherein, thin sliver samples of the pressure tube material, about 50 to 100 microns in thickness, are scraped remotely, from the desired locations, without affecting the integrity and residual service life of the pressure tube. Meeting this requirement in a pressure tube with its ovality, sag and diametral creep was an extremely challenging problem in engineering design and development. Fig-7 shows a photograph of the scraping tool. This system has been successfully used in various Indian PHWRs, starting from 1998.

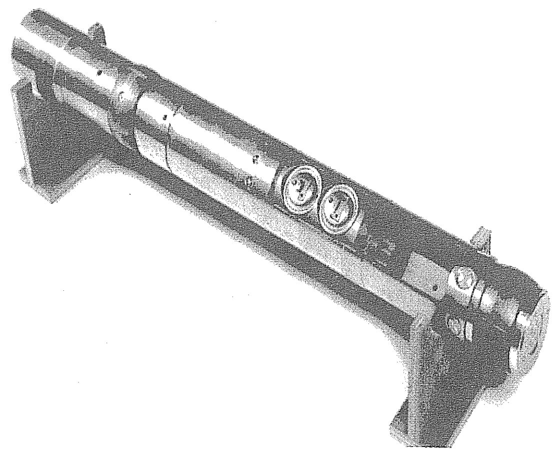

Fig. 7– Wet Scraping Tool (WEST)

4.3.3 Life Extension of coolant channels using garter spring repositioning systems

Concurrent to the R&D directed towards development of predictive and diagnostic codes, tooling, inspection and measurement technologies, R&D programmes for the development of life extension methodologies were taken up. The loose fit garter springs of coolant Channels, in the first seven Indian PHWRs were found to be susceptible to displacement from their initially installed locations A remotely operated repositioning system was designed and developed to precisely detect and relocate the displaced GS spacers in the coolant channels of fresh reactors after hot commissioning as well as operating reactor for extension of their service life. Such a repositioning was carried out in fresh reactors of NAPS-1 & 2 and KAPS-1 after their hot conditioning, using the Mechanical Flexing Technique (MFT) and pulsed electro magnetic technique. A computer programme RESET was developed to provide an animated representation of the relocation process while SCAPCA was used to estimate the tool settings and the creep limited life. To accomplish the task of relocation of garter spring spacers in operating reactors, the Integrated Garter spring Repositioning System (INGRES) was designed and developed. The INGRES system incorporates sophisticated electrical instrumentation, pneumatic, hydraulic and mechanical sub-systems. The various versions, INGRES-1 to INGRES-4 have evolved over a period of time to improve the relocation performance. Fig-8 shows the INGRESS-4 tool head assembly. The safe operating life of several coolant channels of MAPS-1 and RAPS-1 has been extended using this system over a series of campaigns.

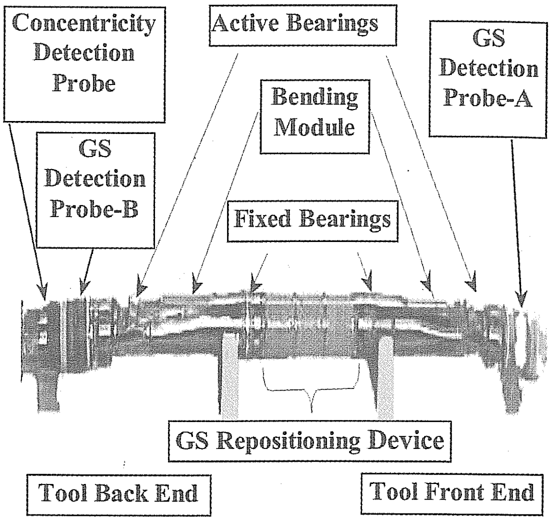

Fig. 8– INGRES-4S tool head assembly with its some sub modules and auxiliary components.

It is exciting to see the laws of electromagnetic induction in action within the core of a reactor, sitting in a control room located nearly a hundred meters away, as the spacers are repositioned precisely by the garter spring relocation device (GSRD) module of this tool, which works on the principle of a linear induction motor. This operation follows a sequence of steps starting with inspection for locating the garter spring, positioning the tool using special remote operated drives, and bending the pressure tube using hydraulic tools till the target garter spring is relieved of the dead weights acting on it. A set of thermal sensors and eddy current sensors complete the electrical and hydraulic hardware mounted on the compact tool head of about 80 mm diameter. The tool head is complemented by an equally complex external drive system for moving the heavy tool within the target channel. The mechanical design of the tool was precisely modelled and fine tuned to establish the highest possible hydraulic bending capability in the compact tool, without causing an overstress in either the coolant channel or the tool head. The excitement lay in seeing the successful results of this tool, as per its design intent, in several channels in which it has been used so far.

4.3.4 Life Management Strategy for the Zircaloy-2 Pressure Tubes

All the computational tools and technologies described above constitute a comprehensive life management strategy, illustrated in Fig-9.

In addition to the development of tools and technologies for exploiting the full potential of the Zircaloy-2 pressure tubes, we have also developed and mastered the technology of large-scale replacement of these tubes with the Zirconium-2.5% Niobium pressure tubes, to extend the life of the PHWRs to their full potential. Using this technology, we have already replaced all the pressure tubes in two out of the seven erstwhile Zircaloy-2 tubed reactors.

The R&D effort mentioned in the foregoing helped in maximising the gain out of the investment made or committed in the Zircaloy-2 pressure tubes and postponed the replacement of these tubes to a time when it became necessary and feasible to do so. Making an intelligent use of the know-how and the technologies developed, we have continued to safely operate our reactors using this alloy, till their safe operating life is consumed. Since 1984, when all other countries discarded the use of Zircaloy-2 as pressure tube material, we have produced more than 100 billion kWh of electricity, in seven reactors that continued to use the Zircaloy-2 pressure tubes.

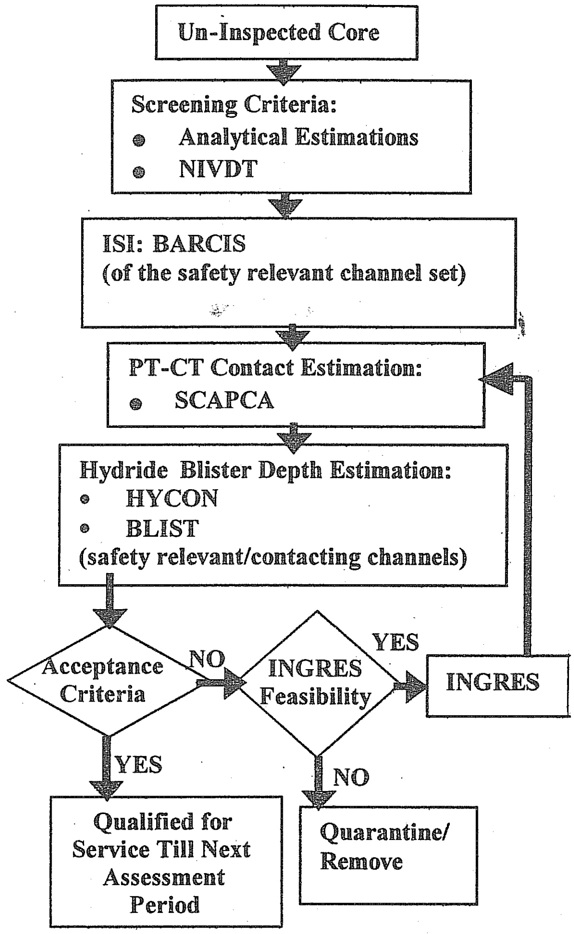

Fig. 9– Coolant Channel life management strategy

5. Discussion

The Department of Atomic Energy, as indeed, many other organizations in our country, have several examples of mission oriented R&D that relate to some urgent needs of the country. The three examples of the mission oriented R&D highlight the three essential drivers for such R&D, viz., a tangible objective with visible deliverables, a challenge in achieving the objectives, and a benefit that far outweighs the cost of doing the R&D. In all the three missions, we first decided what was to be achieved and prepared a road map accordingly. This road map included intermediate milestones, which in many cases needed to be reached by different individual groups, often belonging to different disciplines, and sometimes belonging to different organisations.

We have also noted that one of the important elements for the success of mission oriented R&D is to establish individual and group competences, which transcends the boundaries of a single scientific discipline. Building the special tools and equipment for scientific research - one such example - is in itself, often a cause for excitement on account of the inherent challenges. Furthermore, like in team sports, in mission oriented R&D, a shared goal, individual specialised skills, and group interactions in a multidisciplinary environment helps in moving forward in a focused and coherent manner to realise the best performance from a team. In particular, group interactions facilitate real-time definitions of challenges and problems of a scientific nature, which need to be solved by the concerned experts.

Summary

R&D in the Indian nuclear programme has many mission oriented success stories. Several of these success stories began by converting a challenge in the technology denial regime to an opportunity for enrichment of science and technology in the country. The results of such mission oriented R&D have provided wide ranging benefits to the society and nation as a whole, not only in terms of finding a way out of difficulty, but also leading to generation of confidence and setting up of an indigenous infrastructure to take up even more challenges in the future. Three case studies presented in the paper amply illustrate these points.

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