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IN THIS ISSUE

In the Forthcoming issue

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From the Editor's Desk

We are thankful to all the Scientists and Engineers for sending us their articles in time and this is helping us in maintaining our schedules. It is our sincere request to all and particularly Scientists/ Engineers, who have recently completed their Ph.D programmes, to contribute research articles.

We would like to bring to your notice, that the soft copy of every issue of the BARC Newsletter is now available at three different websites. The first link is from the BTS homepage: **http://bts.barc.gov.in.** The second link is from the BARC website: **http://barc.gov.**in under the heading "Publications" and the third link is from the SIRD Divisional website: **http://saraswati.barc.gov.in.** We hope that you continue to give us your suggestions and feedback.

We have also invited award winning articles from BARC Scientists and Engineers, for the Founder's Day Special issue to be published in October. The last date for submission of the entire paper is 31st July, 2010 and recommended format for preparation of these articles is available at **http://saraswati.barc.gov.in.**
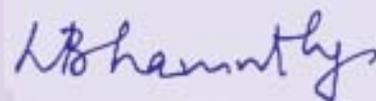
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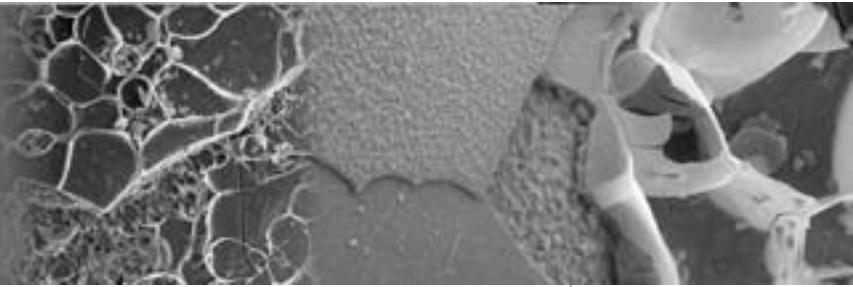
An Antioxidant from a Radioresistant Bacterium: its role in Radiation Resistance beyond Oxidative Stress Tolerance

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Summary

In living cells, reactive oxygen/nitrogen species (ROS/RNS) are produced as the byproducts of metabolic processes during aerobic respiration or during growth under unfavorable conditions. Organisms have evolved different strategies, involving both antioxidant enzymes and non-enzymatic antioxidant molecules to detoxify these species. These reactive molecules, if not detoxified, can cause oxidative damage to cellular components, resulting in metabolic defects, ageing, mutagenesis and eventually cell death. The level of oxidative stress tolerance, therefore, depends on the ability of an organism to counteract the deleterious effects of these reactive species. Organisms having higher tolerance to oxidative stress are believed to effectively scavenge ROS and hence, are good model systems to study oxidative stress tolerance mechanisms. These organisms can also be a preferred source for identification of novel antioxidant molecules. *Deinococcus radiodurans* has been widely characterized for its exceptionally high tolerance to γ radiation and hydrogen peroxide. The γ radiation produces both DNA single strand and double strand breaks (DSB) and imposes oxidative stress by generating reactive oxygen species. We are, currently, involved in understanding the molecular mechanisms underlying the extraordinary tolerance of *Deinococcus radiodurans* to ionizing radiation by studying the DNA repair as well as the oxidative stress tolerance in *Deinococcus radiodurans*. *Deinococcus* genome encodes a genetic system for the synthesis of pyrroloquinoline–quinone (PQQ) with anticipated antioxidant properties. We characterized PQQ for its antioxidant properties both *in vivo* and *in vitro*. *Escherichia coli*, a radiation and oxidative stress sensitive bacterium, when genetically engineered for making PQQ, showed higher tolerance to both oxidative stress and UVC radiation. On the other hand, the *Deinococcus* cells lacking PQQ become hypersensitive to γ radiation, perhaps, due to a defect in both oxidative stress tolerance and DSB repair. The proteins through which PQQ supports DNA repair and radiation tolerance were characterized from both *E. coli* and *Deinococcus*. PQQ stimulates the activity of these proteins *in vitro*. Deletion of a gene encoding deinococcal protein having PQQ binding site from this bacterial genome makes it sensitive to g radiation. These findings together suggest an additional role of PQQ in extraordinary radiation resistance and DSB repair in this bacterium. Further studies will be required to understand the mechanism of PQQ action in radiation resistance and DSB repair in bacteria and other organisms.

Introduction

Bacteria, the most primitive organisms, are well characterized for their ability to adapt to sudden changes in their environment. The adaptive response to adverse conditions is brought about by qualitative and quantitative changes in the protein composition of bacteria. These result in the synthesis of biomolecules required for adaptation to stresses. Because of the simplicity in their cell structure and ability to adapt to sudden changes in environment, the bacteria have been used as preferred model systems to understand the molecular mechanisms of tolerance to abiotic stresses (including those mediated by radiations and oxidants). Comparison

RESEARCH ARTICLE

of ionizing radiation resistance of different microorganisms suggests that all bacteria are not endowed with the ability to tolerate high doses of g radiation. But as far as g radiation tolerance is considered, the bacteria outperform the better-evolved higher organisms (e.g. mammals). In contrast to a few Grays of g radiation tolerated by humans, bacterial tolerance to ionizing radiation starts from a few hundred Grays to several thousand Grays (Fig. 1). The bacteria being mostly unicellular offer an easy system for both metabolic and molecular manipulations to understand the molecular mechanisms of radiation resistance.

Among the diverse bacteria present in the environment, those belonging to the family of *Deinococcacae* are non-pathogenic and are best characterized for their extraordinary tolerance to various abiotic streses including ionizing radiation [1]. *Deinococcus radiodurans,* a member of this family identified from X-ray sterilized meat in 1956, has been widely studied in several labs all over the world. Dr. Philip Lewis, a senior scientist at Bhabha Atomic Research Centre, India, had also identified a similar bacterium showing high tolerance to

Fig. 1: Comparison of γ radiation resistance of *Escherichia coli* and *Deinococcus radiodurans*. Both bacteria were grown to exponential phase and exposed to different doses of γ radiation and cell survival was monitored.

γ radiation. This bacterium, named as *Micrococcus radiophilus*, was isolated from g sterilized Bombay-Duck [2, 3]. Since, a dose of few Grays of γ radiation can produce lethal effects in human beings and kill most of the infectious agents, the amazing capacity of *Deinococci* to survive high doses of both acute as well as chronic exposure of ionizing radiation generated lot of interest in the scientific community as a whole. These features however, attracted biologists to investigate the molecular mechanisms underlying the extreme radioresistance in this bacterium. Since, ionizing radiation induces both DNA strand breaks and oxidative stress, the molecular mechanisms (underlying) these processes are being studied in our Division at the Bhabha Atomic Research Centre. Some of our findings on the effect of γ radiation on protein or DNA stability and DNA repair during post-irradiation recovery have been published [4-11]. A part of our study aimed to understand the mechanism of oxidative stress tolerance in this bacterium [6, 12, 13, 14], had resulted in identification and characterization of pyrroloquinoline quinone (PQQ) from this bacterium. This molecule was shown to function as an antioxidant. Subsequently, its role in radiation resistance and DNA strand break repair through its ability to function as an activator of DNA damage-inducible protein in *Deinococcus* was characterized.

Oxidative stress tolerance: a brief note on the role of PQQ

In a cell, oxidative stress is caused by an increased production of reactive oxygen species (ROS). Reactive oxygen/nitrogen species are produced under normal processes of energy metabolism. The levels of these species are, however, enhanced several-fold when cells are subjected to abiotic stresses like high temperature, dehydration salinity, radiation etc [15]. The levels of ROS are controlled by the combined action of both antioxidant enzymes (AOE) and antioxidant metabolites (AOM), both of which are an integral part of the cellular
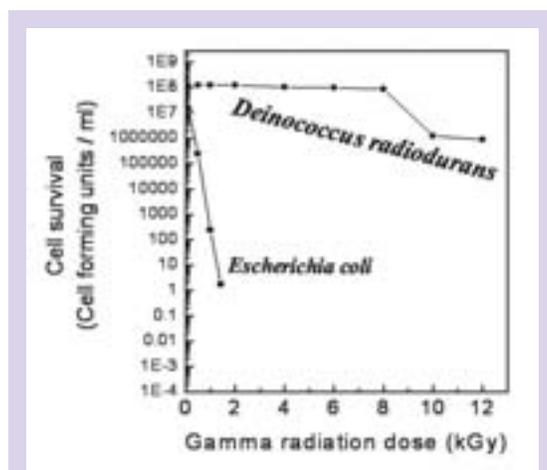
defense mechanism. Although, the mode of action of AOE and AOM in ROS neutralization differs, the net effect is detoxification of these reactive molecules, which results in the protection of biomolecules from damage and eventually cell survival. While AOE neutralize ROS by multi-step enzymatic reactions, AOM react directly with reactive species through a typical electron/proton donating reaction. Therefore, the AOE mediated ROS scavenging is relatively slower and safer than ROS scavenging by AOM. This is because the AOM reaction with reactive species can lead to the formation of a reactive adduct between AOM and ROS and, many a time, such adducts are much more toxic to the cells than ROS themselves. Hence, the radioresistant bacterium, natural antioxidant metabolites are safe for a cell as harmful adducts (if formed) can be easily metabolized.

Since *Deinococcus radiodurans* can tolerate a biologically catastrophic dose of hydrogen peroxide (≥25mM concentration), studies were conducted to identify the natural antioxidants from this bacterium. Genome sequence of this bacterium is present in the public domain [16]. Genes encoding different proteins in this bacterium were examined. It was found that a gene encoding putative pyrroloquinoline quinone synthesis protein (hereafter referred as PQQ synthase) responsible for PQQ synthesis was also present in this organism. The PQQ has earlier been characterized as a redox cofactor for enzymes involved in microbial solubilization of insoluble rock phosphates. PQQ structure was examined for its probable antioxidant characteristics. Structural analysis showed PQQ to have a high electron density in its heterocyclic backbone, which could make this molecule a good substrate for ROS neutralization. Since this bacterium does not code for enzyme required for bio-solubilization of insoluble phosphates, the functional significance of this compound was questioned and investigated in *Deinococcus*. The PQQ synthase gene (*pqqE*) of *D. radiodurans* was engineered for expression in *Escherichia coli,* a bacterium sensitive

to both oxidative stress and γ-radiation. The *E. coli* cells, now making PQQ, were examined for UV resistance and oxidative stress tolerance. These cells showed ~four fold higher tolerance to the photodynamic effect of Rose Bengal at 5mg/ml concentration (Fig. 2), which produces high intensity of mixed ROS under aerobic illuminating conditions [17]. The *E. coli* cells producing high levels of PQQ showed ~four fold higher protection of proteins from γ radiation induced damage as compared to the non-PQQ producing control cells. These results indicate role of PQQ in protection of cells against oxidative stress [12]. A parallel study in mammalian
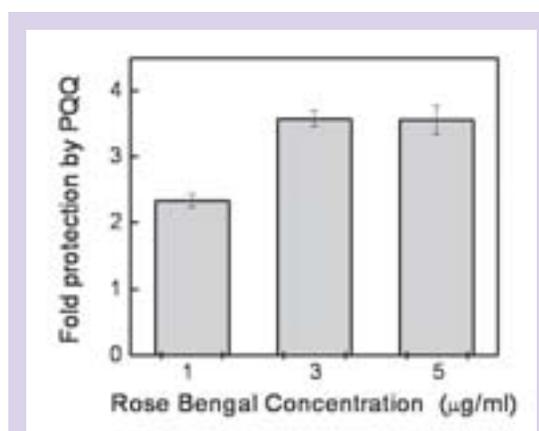
Fig. 2: Effect of PQQ on photodynamic killing of *Escherichia coli* with Rose Bengal. Both wild type and engineered *E. coli* cells synthesizing PQQ from *Deinococcus radiodurans,* were treated with different concentrations of Rose Bengal and cell survival was monitored. Number of cell forming units appeared in PQQ containing cells was divided with wild type to get 4 fold protection by PQQ.

system has also confirmed the role of PQQ in protection of mitochondria from oxidative stress [18]. These findings have confirmed the role of PQQ as an *in vivo* antioxidant in bacterial as well as mammalian systems.

The antioxidant potential of PQQ was tested *in solution* in collaboration with RPCD, BARC [13]. PQQ showed reactivity with hydroxyl, superoxide and oxygen free radicals produced by pulse radiolysis. The rate of reaction of this compound

with hydroxyl radical was marginally less compared to ascorbic acid and trolox. PQQ reacts with superoxide radical at a faster rate than ascorbic acid and trolox (Fig. 3). PQQ at 10µM concentration shows ~six fold protection of double stranded DNA and 2.5 fold protection of purified protein from γ radiation induced damage (Fig. 3) [13]. This suggests that PQQ works efficiently as an antioxidant *in vitro* and can protect biomolecules from deleterious effects of radiation. Since majority of antioxidants and radioprotectors show desired activity *in vitro* and not *in vivo,* the ability of PQQ as an antioxidant, both *in vivo* and *in vitro*, was highly appreciated.

PQQ roles beyond oxidative stress tolerance in bacteria

Our findings have so far, established PQQ as an antioxidant and protector of cells and biomolecules from oxidative damage, both *in vivo* and *in solution*. Genetically engineered bacteria producing PQQ was checked for cell survival response to UV (254nm) induced DNA damage. These cells showed ~thousand fold higher tolerance to UVC and less than ten fold improved tolerance to γ radiation [10]. The UVC radiation contributes very little (< 0.1% of total effect) to oxidative stress and its lethality to living cells is largely through DNA damage as demonstrated by others [19]. Thus, the higher UVC tolerance in *E. coli* cells that only differ from control, in PQQ synthesis argued for the possible role of PQQ in DNA repair (revision in sentence may be needed).

PQQ is known to enhance the functions of certain enzymes by interacting directly with them. Such proteins contain the conserved amino acid sequences for PQQ interaction, called PQQ binding motif. The PQQ binding motifs were searched in all the proteins submitted to different protein databases, by bioinformatics analysis. Several proteins from different organisms such as yeast, plants, animals and bacteria show PQQ binding motifs. This list
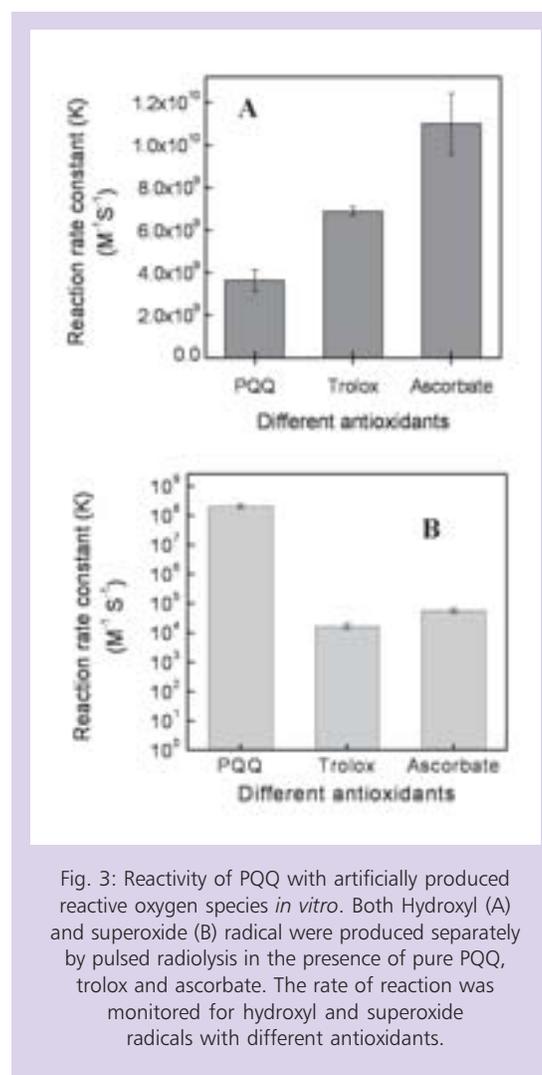
Fig. 3: Reactivity of PQQ with artificially produced reactive oxygen species *in vitro*. Both Hydroxyl (A) and superoxide (B) radical were produced separately by pulsed radiolysis in the presence of pure PQQ, trolox and ascorbate. The rate of reaction was monitored for hydroxyl and superoxide radicals with different antioxidants.

includes both previously characterized PQQ interacting proteins and several new proteins including protein kinases. PQQ producing *E. coli* that shows exceptionally higher tolerance to UVC radiation, also contains two such proteins namely glucose dehydrogenase (*gcdA*) and a periplasmic protein kinase (*yfgL*). Similarly, *Deinococcus,* host bacterium producing PQQ, also contains five uncharacterized proteins [16] having multiple sites for PQQ interactions (Fig. 5). We, subsequently, characterized YfgL one of the two proteins in *E. coli*, for its involvement in UVC resistance and DNA strand break repair and demonstrated both functional and physical interaction of PQQ with YfgL
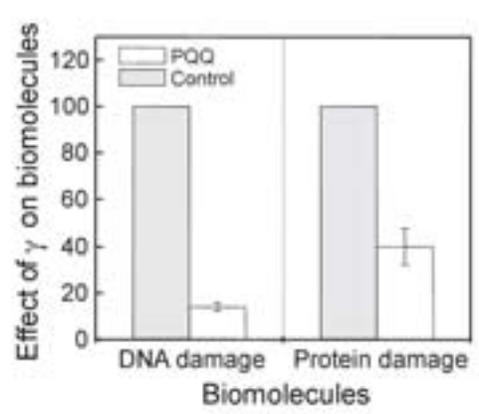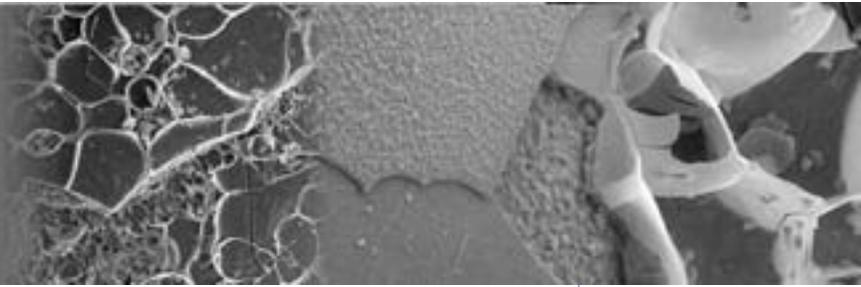
Fig. 4: Effect of PQQ on γ radiation damage of biomolecules *in vitro*. The bovine serum albumen (protein) and covalently closed circular (CCC) plasmid (DNA) were incubated with 10mM PQQ and exposed with 100Gy and 7Gy γ radiation, respectively. Protein damage was measured as carbonyl formation and DNA damage as the generation of single strand break in CCC plasmid molecules.
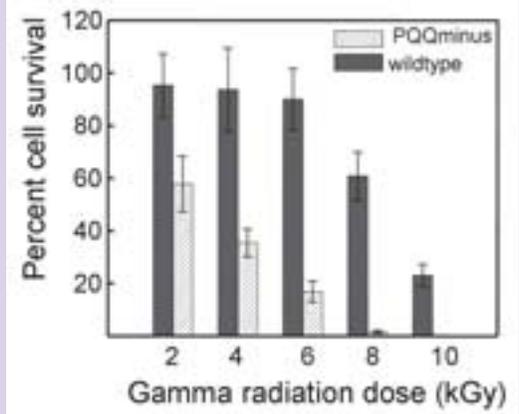
Fig. 5: Effect of PQQ synthesis on γ radiation resistance of *Deinococcus radiodurans*. Both wild type (PQQ plus) and PQQ minus cells were treated with different doses of γ radiation and cell survival was monitored.

How does PQQ work in radiation resistance of *Deinococcus*?

The bioinformatic analysis shows that five previously uncharacterized putative PQQ- interacting proteins, namely DR0503, DR0766, DR1769, DR2518 and DRC0015, are present in *Deinococcus* (Fig. 6). The possibility of these proteins requiring PQQ for their activity and that PQQ contributes to radiation resistance through one or all of these proteins was

[10]. Requirement of PQQ and YfgL interaction for DNA strand break repair,further, suggested the role of PQQ in DNA repair. The mechanism of PQQ action was further investigated in radiation resistance bacterium *Deinococcus radiodurans*. The gene encoding PQQ synthase enzyme was deleted from *Deinococcus* genome and the bacterial cells lacking PQQ synthesis were confirmed by high-pressure liquid chromatographic technique. These cells become hypersensitive to γ radiation and the reassembling capability of g radiation shattered DNA fragments was severely compromised [14]. The D10 for γ radiation decreased to less than 6.0 kGy in PQQ deficient cells as compared to 12kGy in PQQ synthesizing wild type cells. Since an efficient repair of damaged DNA is an integral response to the extreme radiation resistance in wild type cells, the defect in DNA repair in *Deinococcus* cells lacking PQQ, suggested that role of this compound in γ radiation resistance by regulating DNA repair.

Fig. 6: Different proteins from *E. coli* and *D. radiodurans* showing multiple PQQ binding motifs. The interaction of PQQ with YfgL in *E. coli* and DR2518 in *Deinococcus*, has been demonstrated and their roles in radiation resistance are established.

hypothesized and tested. Firstly, the genes encoding these proteins were deleted from *Deinococcus* genome and subsequently, the survival of these genetically engineered cells upon exposure to γ radiation was evaluated. Only DR2518 deleted cells showed sensitivity to γ radiation (Fig. 7). The D10 of DR2518 deleted cells decreased to less than 3 kGy as compared to 12kGy for the wild type control. The remaining deletions showed D10 similar to the wild type control. DR2518 protein has functional signature of eukaryotic serine/threonine type protein kinase (i.e. a protein that can phosphorylate other proteins). The kinase activity of DR2518 was confirmed experimentally and this activity was stimulated by PQQ. Severe loss of γ resistance on deletion of DR2518 as well as stimulation of autokinase activity of DR2518 protein by PQQ together confirm the role of PQQ as an inducer of a protein kinase having role in radiation resistance and DNA repair. This characteristic of PQQ was found in addition to its role as an antioxidant. Various reports in literature suggest that protein kinases that undergo autophosphorylation in response to stress or when stimulated by a known inducer are stress responsive protein kinases. Since DR2518 showed a stress responsive protein kinase like features, the possibility of this protein regulating the γ radiation induced signaling at gene levels can be speculated. Effect of DR2518 deletion on expression of proteins required for radioresistance and DNA repair was studied by a high throughput microarray analysis.

Microarray allows us to measure the global change in gene expression in response to any change in environmental conditions. The microarray analysis of *Deinococcus* cells lacking DR2518 protein was carried out under normal and γ stressed growth conditions. Total 75 genes showed increased expression while 200 genes showed decreased expression by 1.5 to 15 folds (P≤0.05) upon treatment with γ radiation. Some of the important proteins showing changes in levels of expression in DR2518 mutant treated with gamma radiation are
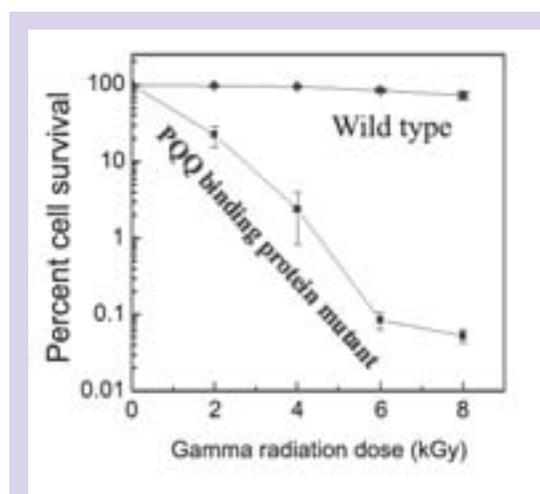
Fig. 7: Effect of γ radiation on cell survival of Deinococcus mutant lacking PQQ binding protein. Both wild type and DR2518, a PQQ binding protein, mutant cells were treated with different doses of γ radiation and cell survival was monitored.

shown (Fig. 8). Under normal growth conditions, DR2518 mutant shows increased and decreased synthesis of 24 and 64 proteins, respectively. These results indicate a strong possibility of the role of DR2518 in regulation of gene expression. Microarray data on DNA damage induced changes in gene expression profile of control and DR2518 depleted cells have been submitted to Gene Expression Omnibus database (Accession numbers GSE17722 (GSM442538 and GSM442540). Our findings provide a strong evidence to propose that PQQ, an antioxidant identified from a radioresistant bacterium, contributes to radiation resistance and DNA repair by working beyond its role as an antioxidant.

Presence of PQQ is not unique to this bacterium and all the PQQ synthesizing organisms do not confer higher tolerance to DNA damage. Therefore, the role of PQQ in radiation resistance and DSB repair is clearly unique to *Deinococcus*, which, possibly, has acquired this ability during course of evolution of this bacterium. Effect of γ radiation-induced DNA damage on expression of genes is

well-established concept in higher organisms including human beings. Demonstration of the role of an antioxidant like PQQ as a signaling molecule and further confirmation of its role in radiation resistance and DNA repair has indicated the possible existence of DNA damage response mechanism in this bacterium. This is a first such report from a prokaryote. In this study, we have provided experimental evidence to show that PQQ acts as an antioxidant both *in vitro* and *in vivo,* and also functions as an inducer of a DNA damage responsive protein kinase in *D. radiodurans*. The presence of PQQ binding motifs in several protein kinases from plants, animals and mammalian systems including neuronal growth factors, eIF2alpha/beta etc. suggests the ubiquitous role of this compound in different physiological processes. Further studies would help us understand the molecular mechanisms of this antioxidant molecule in stress responsive signaling mechanisms. The possible interaction of this compound with wide range of proteins postulates its greater role in regulation of growth and DNA repair in higher organisms. Thus, the role of PQQ in these processes, which may have implications in cancer therapy, radioprotection and other oxidative stress related dysfunctions, requires detailed investigation.

Hybridized Microarray chip	Proteins showing reduced synthesis		Proteins showing increased synthesis	
	DR1494	NADH dehydrogenase I,	DR2462	hypothetical protein
	DRB0003	hypothetical protein	DR0808	N-acetylglucosamine pyrophosphorylase
	DR2325	serine protease,	DR2229	hypothetical protein
	DR2040	ParA family	DR2535	hydrolase, putative
	DR2388	lipoprotein	DR1941	3-oxoacyl-acyl carrier protein synthase II
	DRA0037	glycosyltransferase	DR2444	putative, HRDC family
	DRA0186	cytochrome P450,	DR1842	hypothetical protein
	DR1629	GMP phosphodiesterase	DR2100	conserved hypothetical protein
	DRB0140	hypothetical protein	DR1129	hypothetical protein
	DR2604	hypothetical protein	DR0502	alanyl-tRNA synthetase-related protein
	DR1178	hypothetical protein	DR0809	conserved hypothetical protein
	DR0099	SSB	DR1588	aminotransferase, class I, putative
	DR1373	metal binding protein,	DR2273	DNA topology modulation protein
	DR1919	hypothetical protein	DR2028	transposase, putative, authentic frameshift
	DR0475	ABC transporter	DR1761	conserved hypothetical protein,
	DR1998	catalase (katA)	DR1601	nodulin 21-related protein
	DR0572	SpoIID-related protein	DR1877	conserved hypothetical protein
	DR2501	transcriptional regulator	DR1453	transposase, putative,
	DR0307	elongation factor G (fus-1)	DR0023	Phosphoribosylamino carboxylase,
	DR1913	DNA gyrase, subunit A	DR2370	pyruvate dehydrogenase complex, E3
	DRC0018	XerD recombinase,	DRA0309	hypothetical protein
	DRA0071	transcriptional repressor	DRA0208	peptide ABC transporter
	DRB0093	GGDEF family protein	DR1953	hypothetical protein

Fig. 8: Microarray analysis showing the effect of γ radiation on gene expression in *Deinococcus radiodurans* cells lacking PQQ binding protein DR2518. Total RNAs prepared from wild type and mutant cells lacking DR2518 were converted to cDNA using random primers. The cDNA of wild type was labeled with Cy3 while mutant with Cy5 and vice versa in two independent assays. These targets were hybridized with *Deinococcus* genomic DNA probes spotted on DNA chips. Specific softwares were used for data analysis and significance determination. Some of the important proteins showing both reduced and increased synthesis by >2.0 fold with statistical significance ($P \leq 0.05$), in response to γ radiation were shown.

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Studies on Electron Beam Vapour Generation in PVD Processes

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Abstract

Generation of metal vapour by electron beam heating is a complex phenomenon that involves many concurrent physical and dynamical processes in response to the impact of concentrated flux of energetic electrons on the metal target. These processes occurring at different stages need to be understood in detail for optimization of the process. Detailed investigations were carried out in our laboratory on various aspects of the e-beam evaporation process such as electron optics, stability of e-beam power, process monitoring, convective heat transfer in melt pool of the target and physical processes occurring in the metal vapour and plasma emerging from the hot zone. Our results on these aspects are presented in this article.

Introduction

High power electron guns with ratings 3-500 kW have found wide applications in research and industrial units especially for Physical Vapour Deposition (PVD). PVD is used in production of semiconductor devices, optical components, wear resistant coated mechanical parts as well as thermal and chemical barrier coatings and also in nuclear industry. In these processes, it is possible to create temperatures in excess of $\sim 3000^0$C in a small zone on the target which is sufficient to evaporate metals with high boiling point and even refractory materials at reasonably high thermal and material utilization efficiencies. As the metal target is placed in a water-cooled crucible in high vacuum and the molten zone at the center of the target is contained with its own cooler skull, chemical reactivity problem between target material and crucible on one hand and atmospheric gases on the other are averted and this results in purer deposits.

Basic process

In e-guns used for vapour generation, the chamber is evacuated to a pressure less than $\sim 10^{-5}$ mbar.

Electron emission occurs from a hot filament cathode of the e-gun made up of tantalum or tungsten by thermionic emission as given by Richardson-Dushman equation. The filament is heated by passage of current in the range of 60 to 80A while keeping it at a negative bias of -10kV to -60kV. Energetic electrons that emerge from the e-gun as a beam bombard the target with a power density ~ 20kW/cm^2 after being focused by suitable magnetic field. Depending upon the focusing scheme, the e-gun can be axial type or transverse type. In axial e-guns, use of a coaxial short magnetic lens (coil) after the anode exit hole results in bi-directional focusing leading to a circularly symmetric e-beam spot on the target. In transverse e-guns, magnetic field in a perpendicular direction is applied to achieve focusing of the beam along one dimension by beam-crossover after 90^0 or 270^0 rotation giving rise to a thin line-shaped beam spot on the target. Out of the incident electrons, about 30-50% electrons are backscattered from the target and rest are absorbed in it. The absorbed electrons transfer their kinetic energy in the form heat within a few microns from the top surface of the evaporant. Due to incident high-energy electrons, the temperature of a small zone on the surface rises to

a very high value that creates a molten pool of the target material around the impact point. There exists a steep temperature gradient within this melt pool leading to convective currents that cause enhanced heat transfer from the center of the melt pool towards the boundary. Despite this heat drain by convection, temperature at the e-beam impact point can rise to such a value that vapour pressure of the material of the target reaches a value of a few mbar. When this condition is reached, copious evaporation of the target material occurs which is then utilized for various purposes outlined before.

Quality of e-beam spot

In e-beam evaporation systems, the e-gun is normally so placed that it does not lie along the line-of-sight of the vapour-emitting zone. This is done to avoid entry of vapour and ions in the cathode-anode region of the e-gun causing electrical discharges [1] or instabilities [2] or unwanted coatings on the high voltage components. Thus, bending of the e-beam becomes an absolute necessity, which is normally carried out by application of an external magnetic field. This bending of e-beam however distorts the shape of the e-beam spot on the target in axial e-guns and reduces power density. Thus, the important advantages of the axial gun over the transverse type e-guns i.e. circular symmetry and high power density of e-beam spot are sacrificed.

To circumvent this problem, we have evolved a novel scheme for distortion-less bending of a converging non-paraxial e-beam [3]. We have analytically proved that the effect of bending on the size and shape of e-beam spot on the target can be completely eliminated *(theoretically made zero)* by choosing a radially decreasing magnetic field and a specific circularly asymmetric radial velocity distribution of electrons. The mathematical expressions derived are as follows:

a) The spatially varying magnetic field intensity should satisfy,

$$B = \frac{mV_{a0}}{eR} \tag{1}$$

Where V_{a0} is axial velocity of the electrons in the beam (which has to be same all electrons), R is radial distance from center of curvature of the bent beam, m is mass electron and e is electronic charge.

b) Initial radial velocity of the electrons within the beam which is bent by an angle a is given by:

$$V_{r0} = \frac{-V_{a0}}{\alpha \cos\theta_0} \ln\left(1 + \frac{r_0 \cos\theta_0}{R_0}\right) \tag{2}$$

Where radius of curvature of central ray of e-beam is R_0 and (r_0, θ_0) is the initial position of any electron on the cross sectional plane of the beam just before entering the region of magnetic field intended for bending.

However, in the paraxial case, distortion-less bending is possible with only a radially decreasing magnetic field as given in Eq-1 and circularly symmetric radial velocity distribution to which Eq-2 reduces and given by,

$$V_{r0} = \frac{-V_{\phi0} r_0}{\alpha R_0}$$

This can be achieved easily by a coaxial thin magnetic lens. This analysis is valid for any angle of bending of electron beam and is relativistically correct (only m has to be relativistic mass).

Using the above principle, we have proposed and evaluated the performance of a practical 270^0 bent-axial-type electron gun [4] which offers both the

advantages: (a) a high-voltage cathode assembly placed in a geometrical shadow region of the emerging vapour and (b) a compact electron beam spot with circular symmetry and high power density. Schematic diagram of the gun is shown in Fig. 1. This gun can be useful in deep welding, drilling and high rate PVD applications.

To quantitatively compare the size and circular symmetry of the e-beam spot for both the cases i.e. conventional transverse-type electron gun and our 270^0 bent-axial-type electron gun, complete trajectory of the e-beam that had a initial circular cross section at the anode was simulated up-to the target. The area of the elliptical e-beam spot was calculated by relation, $A=p.a.b.$ (where a is major axis and b is minor axis). Circular symmetry of the spot is indicated by the eccentricity of the ellipse i.e. $e=b/a$. When $e=1$, ellipse becomes a circle. When $e = 0$, the ellipse becomes a straight line, which is the most asymmetric condition for the spot. Variation of the spot area and eccentricity at different positions of the e-beam spot on the target

are given in Fig. 2. It is seen that most compact and circularly symmetric e-beam spot (with power density$\sim 5 \times 10^3$ kW/cm^2 for a typical 5kW welding e-gun) can be achieved in the case of our bent-axial-type electron gun.

Finally, the distortion-less bending principle was extended by modifying the expressions of magnetic field and velocity distribution so that it can be used in accelerators like betatrons where kinetic energy of the particles increase with time during bending [3].

Stability of electron beam power

Stability of the electron beam power is a desirable feature in e-guns used for evaporation of metals. As these e-guns are normally operated in temperature limited mode keeping high voltage fixed, stability of e-beam power is ensured by stability of emitted electron current from the filament.
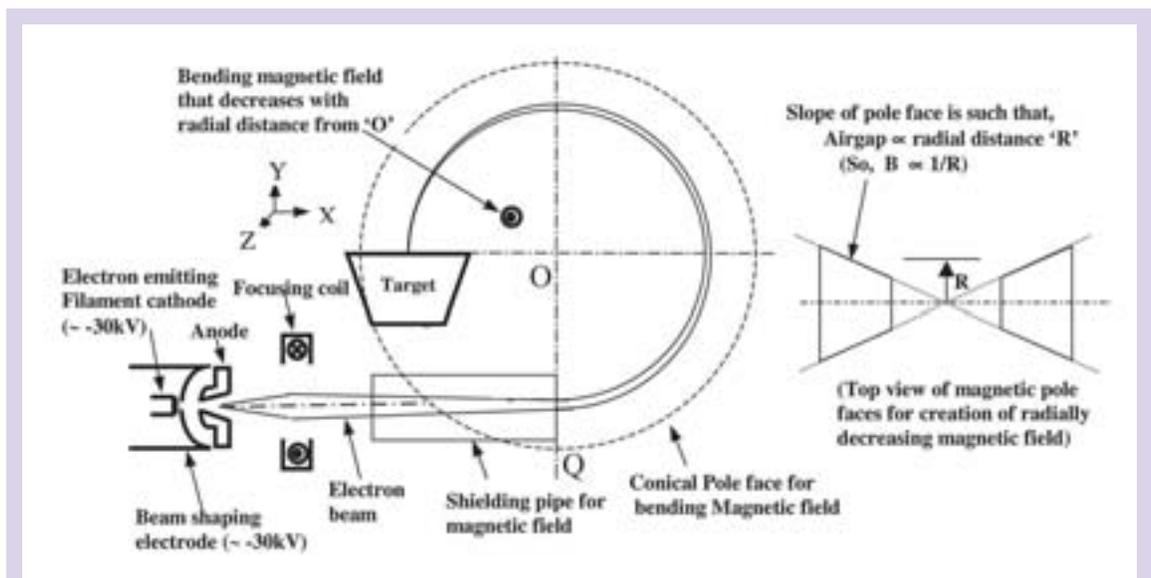
Fig. 1: Basic scheme of the proposed 270^0 bent-axial-type electron gun that ensures a compact and circularly symmetric electron beam spot on the target.
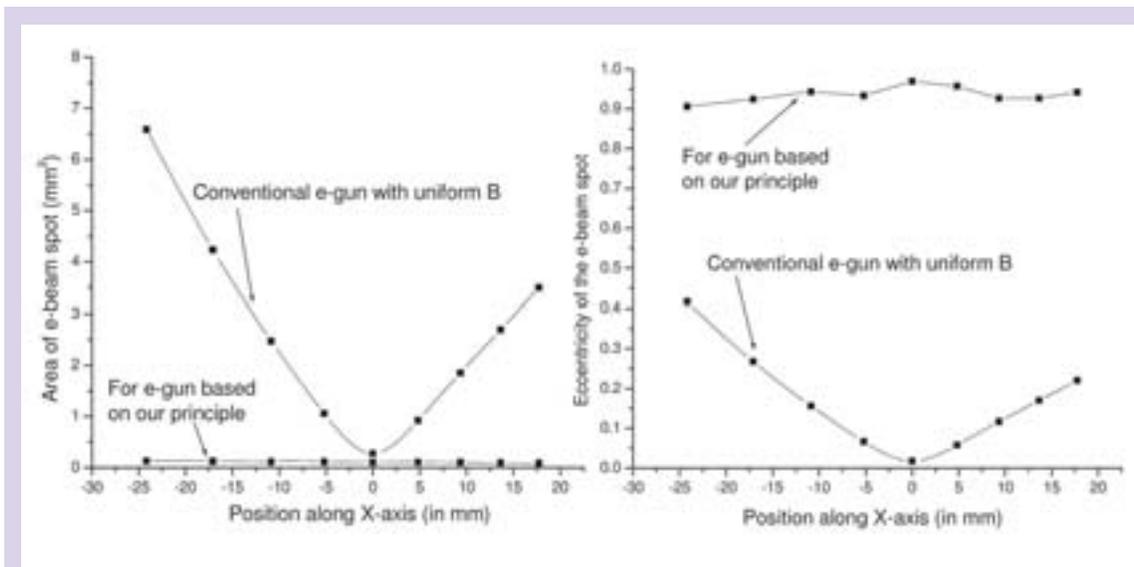
Fig. 2: Comparison of area and circular symmetry of e-beam spot for the cases of conventional transverse-type electron gun and our 270^0 bent-axial-type electron gun

In our experimental set-up, a region of instability in the form of hysteresis in electron emission current was observed when evaporation of metal begins. It was noted that in the forward direction of power change, the required filament-heating current for a specified e-beam current was significantly higher than the filament current required in the backward direction (see Fig. 3a). By analysis of the experimental observations [2], we were led to hypothesize that the ions generated along with the vapour might be trapped in the potential well generated by the electron beam which then move towards the filament cathode causing additional heating of it. This causes a positive feedback for electron emission current from filament and then results in the observed hysteresis effect. To verify this hypothesis, a small hole was drilled on the electron emitting filament so that the ions coming towards it along the e-beam pass through the hole and consequently the extra heating of filament by ion bombardment is avoided. The technique worked very well and the hysteresis effect was significantly reduced (Fig.3b).

Process monitoring

One of the important process parameters that needs to be continuously monitored during e-beam evaporation is the temperature of hot zone created by impact of energetic e-beam. Direct line of sight viewing of the hot zone for temperature measurement using an optical pyrometer on a continuous basis is ruled out due to opacity introduced by coating of the vacuum windows within a short time span (few seconds). Hence, continuous visual monitoring of temperature conventionally relies on a periscopic arrangement [5] that makes use of a process generated thin film mirror formed by deposition of evaporating metal atoms (see Fig. 4a). However, it was experimentally found that this periscopic method introduces significant error (as high as 35%) in temperature measured by optical pyrometer due to dynamically changing spectral reflectivity of the process generated metal thin film mirror. It was found that more reactive the metal, more was the error in measured temperature due to uncertainty in reflectivity of the mirror due to formation of metallic oxides.
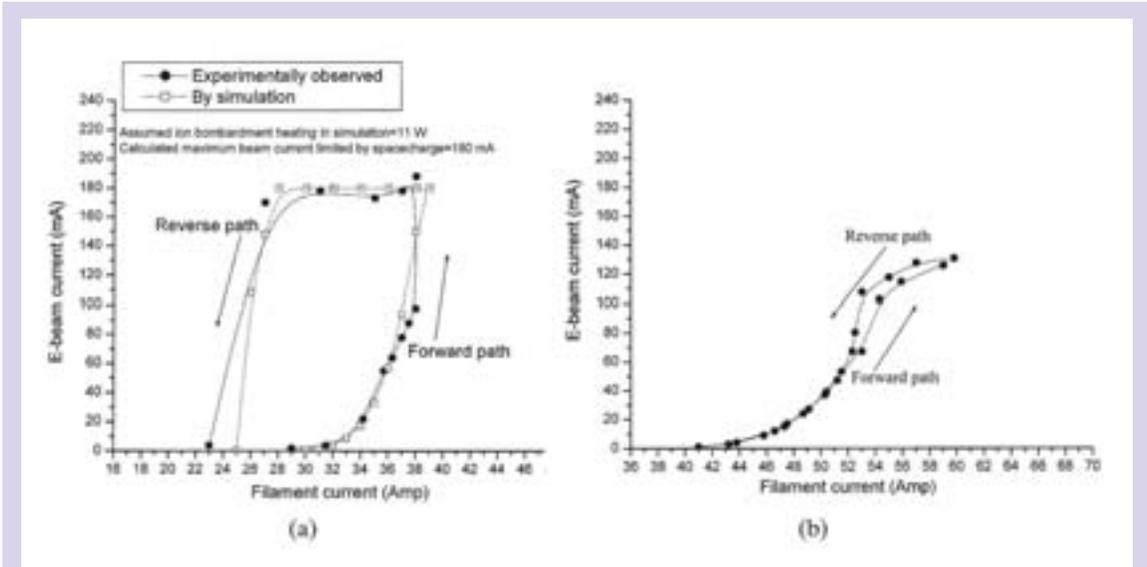
Fig. 3: (a) Experimentally observed and computer simulated e-beam current with filament heating current when filament without hole was used (b) Experimentally observed e-beam current with filament heating current when filament with hole was used
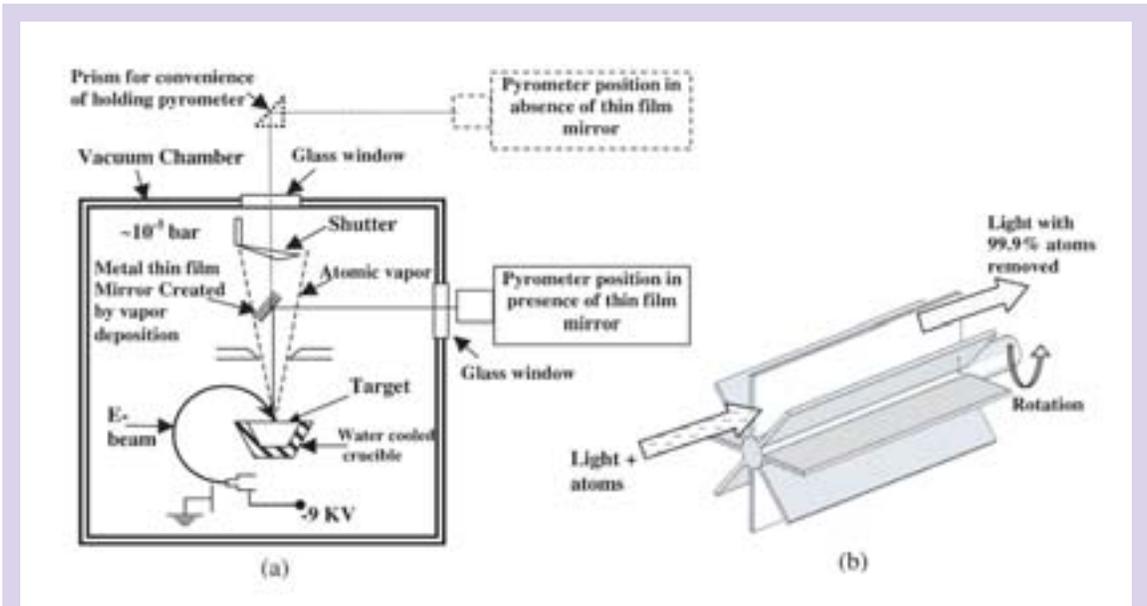
Fig 4: (a) Schematic of the experimental set-up for monitoring of temperature
(b) Schematic of rotating fin structure for removal of atomic vapor from incoming light.
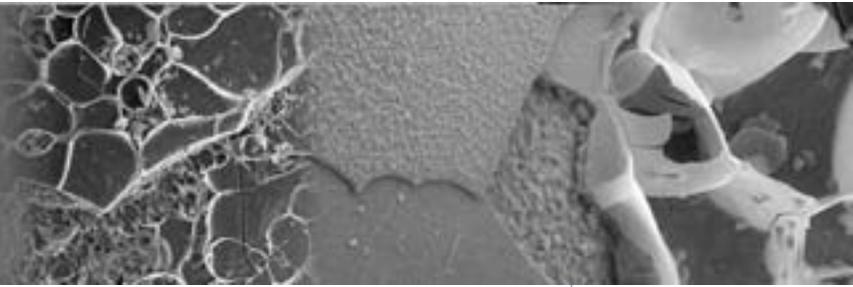
A solution that bypasses this problem was proposed and it was shown through calculations that this novel method avoids errors associated with the periscopic method and yet offers continuous monitoring of temperature for few hours [6]. Solution was evolved by utilizing the vast difference in velocity of propagation of atoms and light. A rotating cylindrical fin structure (as shown in of Fig. 4b) was proposed which is placed in the path of light coming from the vapour source. Due to high speed of the rotating fins that is comparable with the speed of atoms, these atoms are collected on the fins where as photons of the light escape with negligible reduction (velocity of light is larger by a factor of $\sim 3 \times 10^5$). An estimate of the required angular speed of rotor to remove 99.9% atoms from the light coming from the vapour source was found out and this was ~ 5000rpm considering 350 number of fins of length 20cm. Although, intensity of the incoming light is attenuated by $\sim 10\%$ due to thickness of the fins, this will not affect the measured temperature as we are measuring the temperature by two color pyrometer (i.e. from ratio of intensities at two monitor wavelengths). Thus, the time period of temperature measurement by directly viewing the e-beam spot was proved to be increased by 1000 times from few seconds to few hours.

Convective heat transfer in melt pool of the target

As there is a steep temperature gradient within the melt pool generated by e-beam heating, heat is transferred out from the e-beam spot by both convection and conduction. At higher beam powers, this convective heat transfer becomes so dominant that we see an approach towards saturation in the temperature of e-beam spot. This convective heat transfer in melt pool is normally quantified in terms a dimensionless number viz. Nusselt number. The earlier investigators [7-8] who had predicted Nusselt number had not taken the *curvature of the evaporating surface* into consideration which is

caused by back-pressure of the emitted vapour from the hot zone. In our studies, by including the effect of deformation of the evaporating surface on convection, we have proposed and experimentally validated the following hypothesis of evolution of convection in melt pool as a function of e-beam power [9].

The proposed hypothesis is as follows. There are three types of driving forces behind the convection in melt pool viz. temperature dependant surface tension (or Marangoni flow) [7-8], buoyancy due to temperature dependant density and finally concavity of the melt pool due to backward pressure of the emitted vapour on the surface of the liquid. As metals have a negative temperature coefficient of surface tension and density, hot fluid on the surface flows outward from the e-beam spot area as shown in Fig. 5a, thereby increasing the heat loss. However, when the beam power is increased resulting in significant metal vapour generation from central region of the melt pool, emitted vapour exerts a downward pressure at the center of the target. The surface of the melt pool attains a concave shape as shown in Fig. 5b (or keyhole effect). So, liquid metal particles on the surface tend to flow from outer region to the center by gravity. There is a major difference of this type of flow from that induced by surface tension/density. While the driving force for convection by surface tension/density is outward, the force due to concave surface of the fluid is inward. At lower powers, former force is dominant where as at higher powers the latter dominates. At some intermediate powers, the two forces may cancel each other and flow may attain a minimum value leading to minima in convective heat transfer.

Thus, evolution of the flow (or heat transfer) in the molten pool of metal with e-beam power can pass through the following three stages,

Stage I – Flow on the surface is *outward* and *increasing* with beam power, and it is mainly

1 5

Fig. 5: Driving forces for flow in melt pool (a) due to temperature dependent surface tension and density (b) due to crater generated by vapor pressure
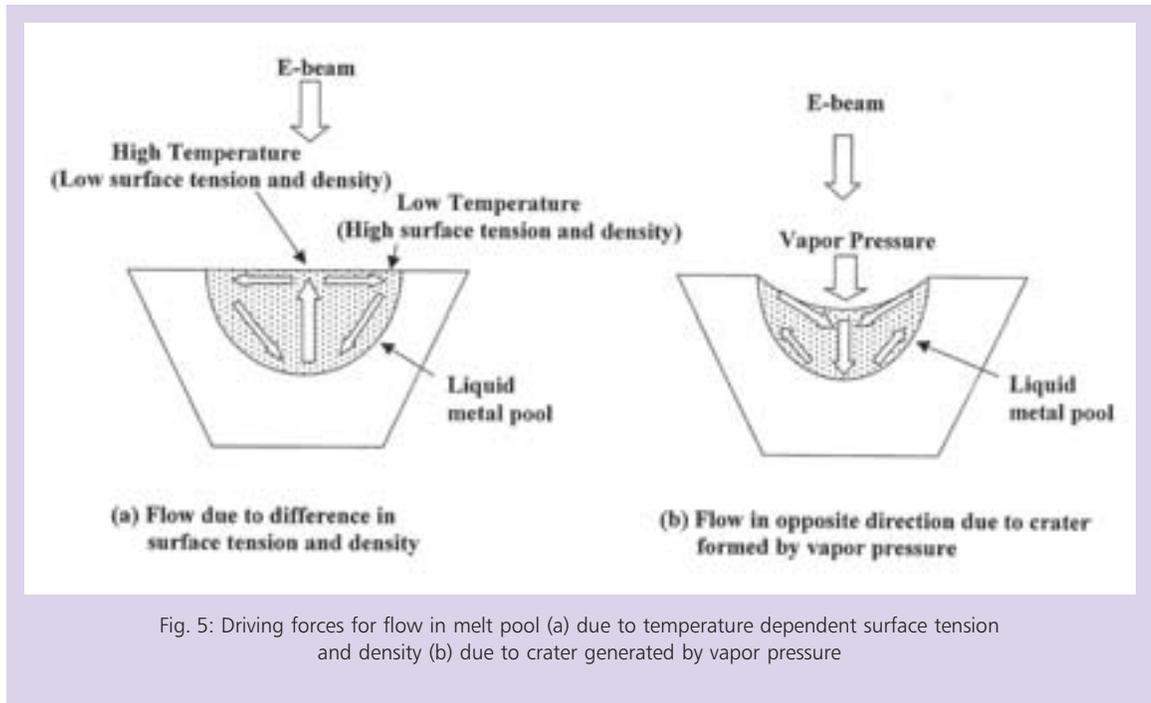
governed by surface tension/density effect (crater effect is negligible).

Stage II – Flow on the surface is *outward,* but *decreasing* with beam power due to gradual onset of the crater effect which opposes the flow by surface tension forces.

Stage III – Flow on the surface is *inward* and *increasing* with beam power, as it is mainly governed by crater effect (surface tension/density effect is negligible).

Between stage II and III, flow reversal occurs and minima in flow rate (or heat transfer) is expected to be observed. However, to observe this point of flow reversal (and stage-III), the range of e-beam power in the experiment has to be sufficient so that surface tension forces are completely overcome by the crater effect.

To validate above model for evolution of convective heat transfer in liquid metal pool generated by e-beam heating, experiments were carried out using three different materials as target viz. Al, Cu and Zr

with e-beam power varying from 0 to 6kW. From the experimental data of maximum temperature and melt pool size, we inferred the key parameter of convective heat transfer i.e. Nusselt number at different e-beam powers. The experimentally observed evolution of Nusselt number with e-beam power was consistent with the prediction of our theoretical model. It was concluded that curvature of the evaporating surface caused by back-pressure of the emitted vapour on the evolution of convective heat transfer in melt pool was extremely important in processes where high rate evaporation takes place from the surface of the melt pool.

Atomic vapour dynamics

In some spectroscopic applications, knowledge of atomic populations in metastable states that represents the excitation temperature of the vapour is important. The e-beam route to vapour generation however presents an interesting situation where metastable atom population after free expansion of vapour can differ substantially from the thermal equilibrium value given by Boltzmann's distribution
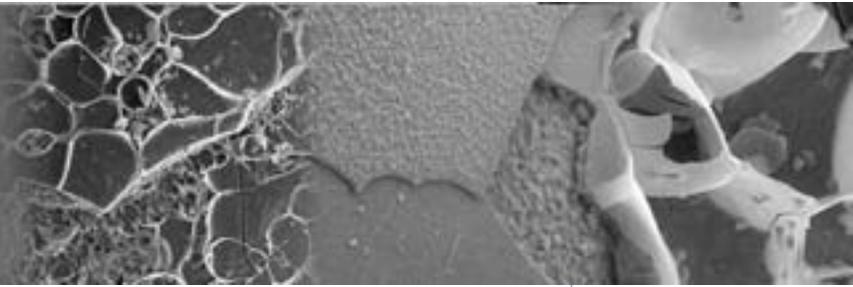
due to the possibility of atom-atom and electron-atom collisions during propagation. This calls for experimental measurements using spectroscopic techniques such as atomic absorption or atomic fluorescence. Recent investigations of atom populations in e-beam generated gadolinium vapour have revealed substantially lower excitation temperature [10] (one fourth to one fifth of the surface temperature of e-beam spot). Similar results were reported for neodymium metal by Chen [11] et al who suggested that electron-atom relaxation by low energy electrons was more important than the atom-atom collisional relaxation for lower excitation temperature observed in their experiments.

In our studies [12], we have carried out detailed experimental observations and theoretical analysis for the dynamics of low-lying metastable atom populations in e-beam generated uranium vapour at different e-beam powers (or source temperatures). Spectroscopic absorption technique was utilized for the measurement of state resolved atom densities in 620 cm^{-1} and 0 cm^{-1} states in the vapour column using a hollow cathode discharge lamp as an optical source. Measurements were carried out over a range of e-beam powers to ascertain the nature (cooling or heating) and the relative extent of de-excitation/excitation of atoms by electron-atom and atom-atom collisions. Quantitative expressions were derived to estimate the effect of atom-atom and electron-atom collisions on the excitation temperature of uranium vapour at different source temperatures. It was found that relaxation of the metastable atoms by collisions with low-energy plasma electrons was so large that it brings the excitation temperature below the translational temperature of the vapour. So, with increase in atom density, frequent atom-atom collisions are expected to establish equilibrium between the excitation and translational temperatures resulting in increase of the excitation temperature (i.e. heating of vapour). This was confirmed by analyzing the experimentally observed growth pattern of the curve for excitation

temperature with e-beam power. From the observed excitation temperature at low e-beam power, total de-excitation cross section for relaxation of 620 cm^{-1} state by interaction with low energy electrons was estimated to be $\sim 10^{-14}$ cm^2.

Plasma generated by e-beam heating

Generation of plasma by collisions during e-beam evaporation of metals is an inherent phenomenon of the vapour generation process. This is, however, a non-equilibrium plasma which consists of two different groups of electrons depending upon their origin (atom-atom or electron-atom collisions) and these groups are characterized by different energy spread (or temperature). While this plasma expands along with the metal vapour, thermodynamic equilibrium between these two groups of electrons is gradually established by electron-electron coulomb collisions and by cooling of high temperature electrons through electron-atom inelastic collisions. In this regard, Besuelle et al [13] have reported the observation of two groups of electrons in the plasma generated during e-beam heating (indicated by two slopes below plasma potential in Langmuir curve). However, they have not quantitatively studied the process of establishment of equilibrium between these two groups in the plasma.

In our work [14], we undertook experimental investigation of the process of attainment of thermodynamic equilibrium between the two groups of electrons in plasma generated during e-beam evaporation of Zirconium using a disc type Langmuir probe. The method of interpretation of the V-I characteristics of the Langmuir probe for diagnostics of a two-temperature plasma was developed theoretically. In addition to this, mathematical expressions for the effect of different interactions such as electron-electron coulomb collisions and electron-atom inelastic collisions on the evolution of electron temperatures of the plasma

were derived and applied to our experimental conditions. Taking the initial temperature of the plasma at the source of vapour, total cross section for electron-atom inelastic collisions was calculated and compared with the reported values, which agreed well with our value. Finally, contributions of each type of interaction (electron-electron and electron-atom) on the cooling of high temperature group of electrons in plasma were quantified and these are given in Fig. 6.
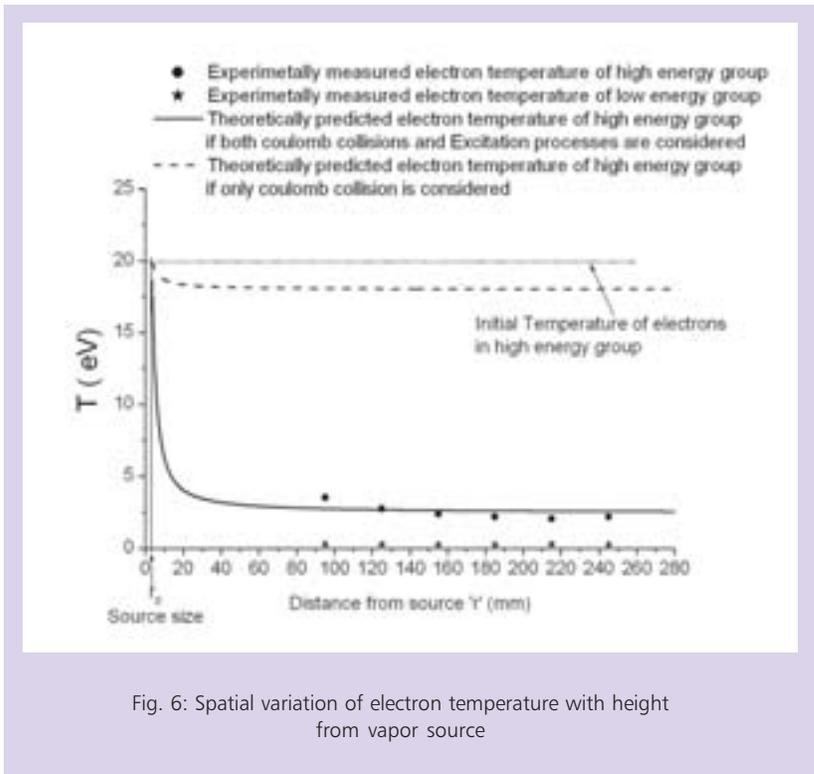
Fig. 6: Spatial variation of electron temperature with height from vapor source

Conclusion

Physical phenomena occurring at different stages of the e-beam vapour generation process were studied in detail. Theoretical and experimental works were carried out to improve the quality, controllability, process monitoring and understanding of the fundamental processes. Improvement in all these aspects results in better technology necessary to carry out PVD work with finesse even at larger scales of application.

Acknowledgement

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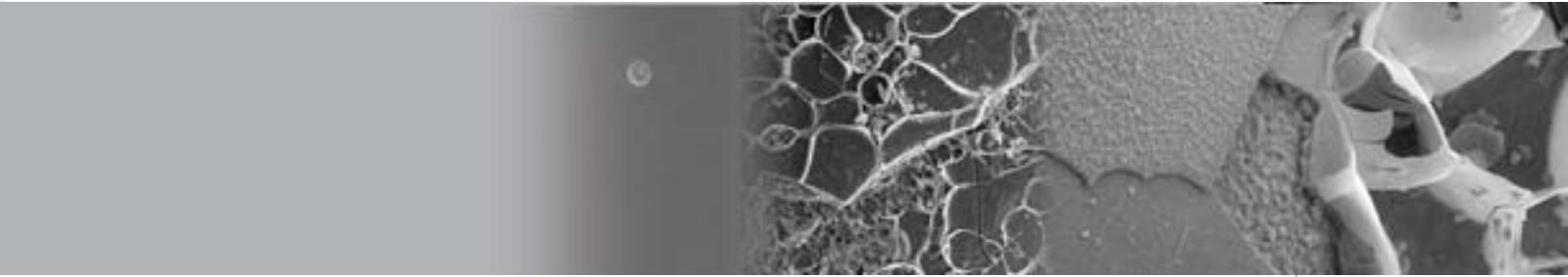
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FEATURE ARTICLE

Challenges in Development of Matrices for Vitrification of High-level Radioactive Waste

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Abstract

Majority of radioactivity in entire nuclear fuel cycle is concentrated in HLW. A three step strategy for management of HLW has been adopted in India. This involves: i) immobilization of waste oxides in stable and inert solid matrices, ii) interim retrievable storage of the conditioned waste under continuous cooling and iii) disposal in deep geological formations. Glass has been accepted as most suitable matrix world-wide for immobilization of HLW because of its attractive features like ability to accommodate wide range of waste constituents, modest processing temperatures, adequate chemical, thermal and radiation stability. Borosilicate matrix developed by BARC in collaboration with CGCRI has been adopted in India for immobilization of HLW. In view of compositional variation of HLW from site to site, tailor make changes in the glass formulations are often necessary to incorporate all the waste constituents and having the product of desirable characteristics. The vitrified waste products made with different glass formulations and simulated waste need to be characterized for chemical durability, thermal stability, homogeneity etc. before finalizing a suitable glass formulation. The present paper summaries the studies carried out for development of glass formulations for vitrification of HLW having wide variation in their compositions

Nature of the waste

Composition of waste plays vital role in finalizing the glass matrix. Detailed radiochemical analysis of waste provides qualitative and quantitative information about the elements present in the waste. These elements may have different solubilities in the glass. Estimation of waste constituents assumes importance to optimize the waste loading and the glass formulations having desired properties of the conditioned product. The major components of HLW are

a)   Corrosion product like Fe, Ni, Cr, Mn etc
b)   Fission products from mass no. 80 to 160 such as ^{90}Sr, ^{106}Ru, ^{137}Cs, ^{144}Ce, ^{147}Pm etc

c)   Actinides such as ^{241}Am, ^{245}Cm and unrecovered U , Pu,, Th
d)   Various chemicals which are introduced at different stages of reprocessing like HNO_3, Al, Na^+, PO_4^{3-}, SO_4^{2-}, fluoride etc. and degraded product of tri-butyl Phosphate.

HLW being processed at WIP Tarapur is generated from reprocessing of PHWR spent fuel. It contains nitric acid (about 4M), beta-gamma activity of 30-45 Ci/L. Presently stored historic high-level liquid waste at Trombay is characterized by relatively higher concentration of uranium, sodium and sulphate. This waste is acidic (1-1.5M HNO_3) with average activity of 8-10 Ci/L. Salient properties of both wastes are presented in Table 1.

Table 1: Salient properties of HLW being processed at Tarapur and Trombay

Property	Tarapur		Trombay
	WT-1	WT-2	
Molarity (free acid, M), HNO_3	4.25	4.10	1.34
Density (g/mL)	1.17	1.18	1.22
Total Solids (Major elements as Na,U,Fe,Al,Cr,Ni,Mn,Ca in the form of nitrates, g/L)	48.5	65.1	317
Sulphate (g/L)	—	—	9.95
Gross β activity (Major isotopes as ^{137}Cs, ^{90}Sr, [106]Ru, [144]Ce Ci/L)	18.46	30.05	8.77
Gross α activity (mCi/L)	47.39	83.11	4.22

Desirable Characteristics of the Solidified Waste Product

The solidified waste form must have certain properties so that its interim storage followed by its ultimate disposal is technologically feasible, safe, economical and environmentally compatible. These desirable properties include:

(i) Good chemical durability i.e. low leachability in ground water.

(ii) Good thermal conductivity.

(iii) Resistance to alpha, beta and gamma radiations.

(iv) Ability to contain high proportion of waste and to have high volume reduction.

(v) High mechanical strength and shock resistance.

(vi) Readily available raw materials at reasonable cost.

(vii) Acceptable processing temperature.

Matrix Development

In India, borosilicate glass matrix has been adopted for vitrification of HLW [1]. Suitable modifications based on leach rates and melting temperature are carried out (Fig. 1) in order to accommodate site-specific waste compositional changes like concentrations of sulphate and sodium [2]. Waste loading, glass additives and the processing temperature are the essential parameters to be taken into account for development of suitable glass formulation (Fig. 2). Compositional details of the glass formulations adopted for vitrification at Tarapur and Trombay are presented in Table 2.

In various laboratories around the globe, research and development efforts are directed to investigate other matrices for immobilization of HLW. Glass-metal composites and ceramics have attracted maximum attention. Glass metal composite is made by encapsulating glass beads in vacuum-cast lead alloy matrix. This type of multi-barrier matrix not
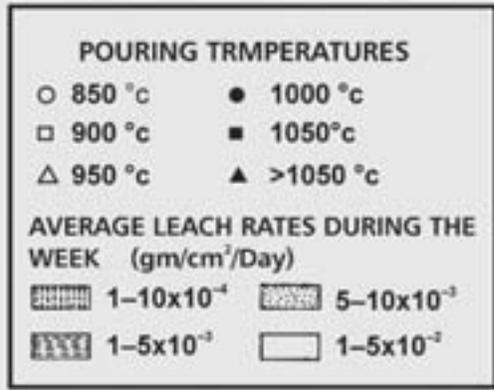
Fig. 1: BSG matrix: leach rates and melting temperatures
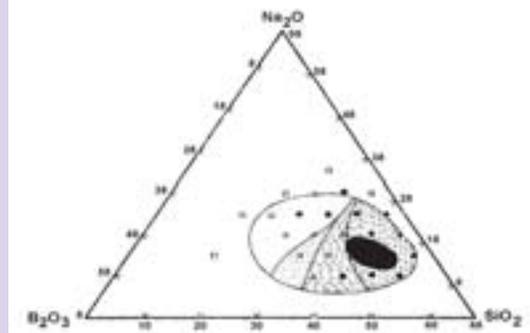
Fig. 2: Development of glass formulations for HLW vitrification
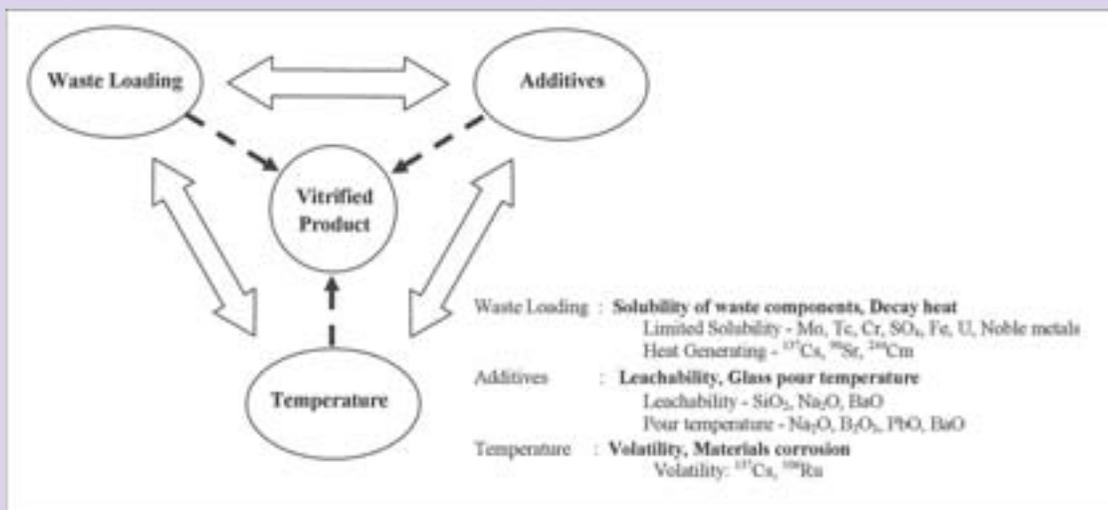
Fig. 3: Basis for development of glass matrix

only results in higher chemical durability but also improved thermal conductivity. Thermodynamically stable waste forms such as ceramics are also under development. These are multi-assemblage of polycrystalline and poly phase ceramics. Pioneering work has been done in Australia for development of SYNROC (synthetic rock) containing mainly titanate minerals viz. zirconolite, hollandite, pervoskite & titanium oxide. High temperature and pressure are the essential requirements for formation of ceramic waste products. In our country, a program is jointly being pursued by Indira Gandhi Centre for Atomic Research (IGCAR) & BARC on development of multiphase titanate assemblage for the incorporation of reprocessed waste from fast breeder reactor origin. Among vitreous matrices, various glass systems like sodium borosilicate, lead borosilicate, barium borosilicate, vanadate bearing borosilicate and phosphate glasses are studied and adopted as per specific needs. The parameters like formation temperature, electrical resistivity of molten glass, processing rate, material of construction of process vessel and nature of waste to be reprocessed are taken into consideration while

Table 2: Glass matrix compositions (Wt%) used at WIPs Tarapur and Trombay

Composition	Tarapur		Trombay	
	Basic Sodium Borosilicate IR110I	Modified Borosilicate R111	Sodium Lead based borosilicate WTR-62	Barium based borosilicate SB-44
Glass formers ($SiO_2+ B_2O_3$)	46	46	50	50.5
Glass network intermediate (TiO_2)	7	7	—	—
Glass modifiers ($Na_2O+MnO+PbO+BaO$)	26	16	30	28.5
Waste Oxide	21	31	20	21

selecting the system. Lead borosilicate and phosphate glasses are formed at relatively lower temperature. Phosphate glass offers a high processing rate, yet it is not widely adopted because of its corrosive nature. Lead borosilicate and barium borosilicate glasses are used for immobilization of sulphate bearing waste. Sodium borosilicate glass has proved to be a good matrix for plant scale adoption because of several attractive features [3].

Product Characterization

Detailed evaluation of the Vitrified Waste Product (VWP) is carried out during inactive vitrification runs with simulated waste. Based on the desired product quality, various process parameters are standardized. Conditioned products are evaluated for various properties like product melt temperature, viscosity and resistivity of molten glass, waste loading, homogeneity, thermal stability, radiation stability and chemical durability using advanced analytical instruments.

Glass forming and pouring characteristics

This is one of the most important characteristics

with respect to glass formulation as it has direct impact on the glass melter design and various other parameters like viscosity, volatilization of radio-nuclides and total waste loading. The knowledge of viscosity of a glass is needed with respect to its pouring characteristic and fluidity. Viscosity of 50 to100 Poise was found within the temperature range 900 to 1150°C for selected glass compositions (Fig. 4). At this viscosity, glass is free-flowing and

Fig. 4: Pouring of molten vitreous mass in laboratory

is suitable for pouring through an orifice. Fig. 5 indicates viscosity–temperature curve for typical borosilicate glass composition.

The glass formulation selected for immobilization of HLW at WIPs Tarapur and Trombay using induction heating metallic melter have glass melting temperature in the rage of 950-1000°C. However, with the advent of new technologies like Joule Heated Ceramic Melters (JHCM) and Cold Crucible Induction Melters (CCIM), it is possible to process glass formulation with higher glass meting temperatures to enable higher waste loading and resultant improved product characteristics.

Glass-Transition Temperature

Estimation of glass transition temperature for a vitrified waste product is important with respect to the limit of radioactivity which can be incorporated so that the decay heat on account of different radionuclides does not increase the temperature more than the glass transition temperature. It is important to note that divitrification tendency of the vitrified waste product significantly gets enhanced above transition temperature because of decrease in viscosity of the product. Glass transition

temperature of the glass product has been evaluated by DTA as given in Fig. 6.

Molten glass electrical resistivity

Electrical resistivity of molten glass at various temperatures during vitrification process is very important for the design of JHCM and CCIM. Electrical resistivity should be in the range of 6-10 Ohm cm for JHCM and for CCIM, this should be about 5 Ohm cm. This property depends on the temperature and variations in the glass formulation. Electrical conductivity in the molten glass is mainly due to presence of alkali metal ions responsible for electrolytic conduction of ionic species. Hence, electrical resistivity of the molten glass can be modified by alkali cations like Na, K & Li which act as glass modifiers. At the same time, however, higher alkali content reduces the chemical durability of the final waste product.

A high accuracy, calibration- free technique consisting of co-axial electrodes was employed [4]. The co-axial electrode system was designed and fabricated in-house from high Ni-Cr alloy Inconel-690. The impedance was measured at various frequencies from 100 Hz to 10 MHz. The average
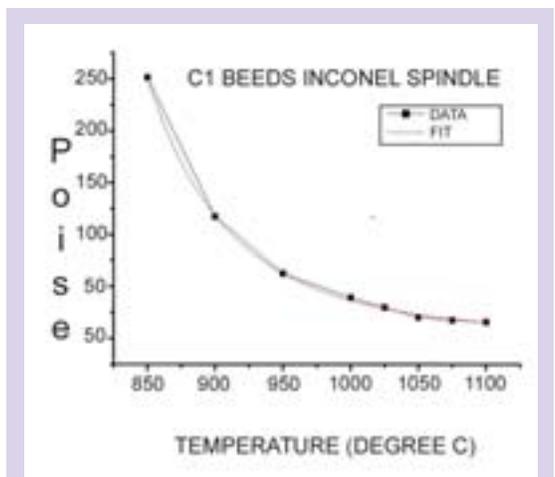
Fig. 5: Viscosity – temperature relationship for a borosilicate glass
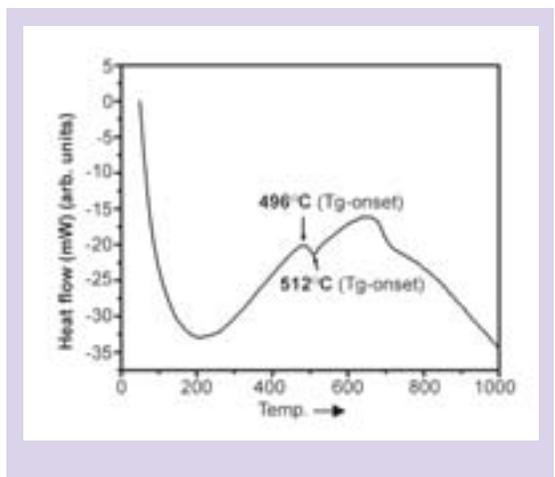
Fig. 6 : DTA pattern of barium borosilicate glass (SB-44)
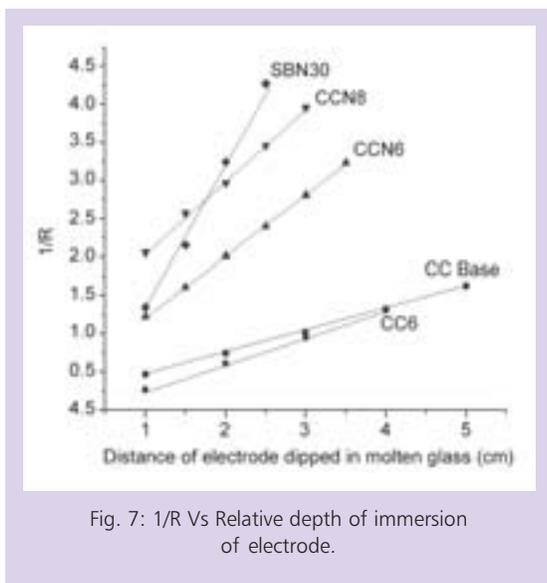
Fig. 7: 1/R Vs Relative depth of immersion of electrode.

Fig. 8: Leaching pattern of barium borosilicate glass

impedance value was plotted against relative depth of the electrode immersed in molten glass and slope of the linear graph was noted (Fig.7). The resistivity was evaluated from the slope.

Chemical durability of glass

Leaching test

The chemical durability of the glass is the most important characteristics among all the product characteristics from the point of view of the environmental impact of disposal of HLW. For the screening of various formulations, standard leach test in boiling water conditions under reflux is employed to estimate the leach rates of major elements like Na, B, Si. Fig. 8 shows leach rate on Na loss basis for typical waste glass composition.

Water - Vapor hydration test

In a geological disposal facility, radioactive waste product may slowly alter over a period of time if it comes in to contact with water. A surface layer may then get formed on glass whose morphology depend strongly on composition of glass and alteration conditions. The layer formed itself will

serve as confinement material thus deserves a complete study of its physical and chemical properties. The accelerated leaching test by water vapor hydration is useful in qualifying the glass product for its acceptance criteria. Water and vapor hydration test (VHT) is carried in laboratory under induced accelerated conditions in Parr vessel at high temperature and pressure, Fig. 9. The SEM analysis
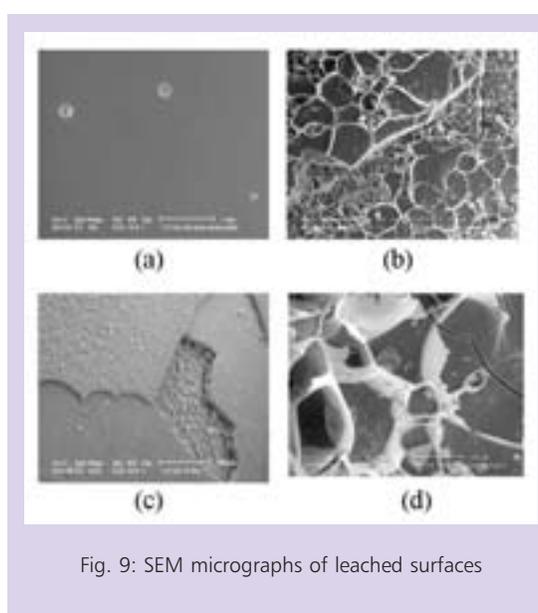
Fig. 9: SEM micrographs of leached surfaces

of unaltered and altered glass after 72 hours of test shows that these unaltered glass is homogeneous (Fig.9a), where as the surface of altered glass shows formation of multiple alteration layers of varying thickness (Fig. 9b). Formation of gel layer and secondary Products has been noticed (Fig. 9c) as well as the formation of phyllosilicate on the altered glass surface is seen (Fig. 9d).

Homogeneity analysis

The glass is examined with SEM-EDX for its homogeneity. In general the glass is found to be homogeneous and amorphous in nature except few crystals of insoluble RuO_2. However, heat treatment of this glass at 700°C for 24 hours indicates crystallization of mineral phases (Figs. 10 a & 10b).
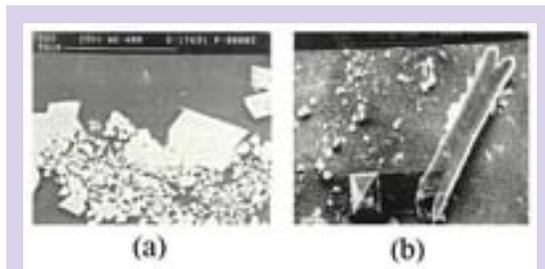
Figs. 10 a &10b: Crystals in heat treated glass

Fig. 11: (a) CaF_2 phase in glass (b) CaF_2 with varying amount of F

High-level waste generated by reprocessing of spent fuel from Advanced Heavy Water Reactor (AHWR) contains high concentration of Al_2O_3 and fluoride ions besides thorium. Barium oxide and calcium oxide were found to enhance the solubility of thorium oxide in the borosilicate glass matrix. Calcium oxide was found to suppress the volatility of fluoride during vitrification process. This will help in reducing the off-gas system corrosion. Fluoride has limited solubility in the borosilicate glass. The excess fluoride beyond its solubility limit is separated as CaF_2 phase (Fig.11a). The same has been identified by XRD analysis (Fig.11b).

Fast reactor generated high level waste of reprocessing origin will contain substantial amount of gadolinium oxide added during reprocessing as neutron poison. It also contains higher concentration (about two fold) of fission products compared to PHWR high level waste. A suitable glass composition was developed taking these features into account.
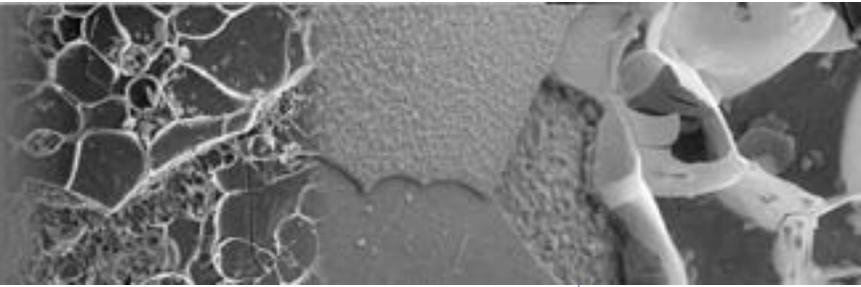
Table 3: Salient properties of Vitrified Waste Product (VWP)

Properties	Sodium Borosilicate Glass(IR-111)	Lead Borosilicate Glass (WTR-62)	Barium Borosilicate Glass (SB-44)
Mechanical Properties :			
Density (gm. cm^{-3})	2.99	3.5	3.0
Impact strength (RIAJ) #	1.06	1.12	0.85
Thermal Properties:			
Thermal conductivity, 100°C (Wm-1K^{-1})	1.045	1.15	0.95
Co-eff. of thermal expansion (°C^{-1})	102×10^{-7}	83×10^{-7}	101×10^{-7}
Viscosity, 900°C (Poise)	40	135	70
Pouring temperature (°C)	1000	950	925
Softening temperature (°C)	540	490	536
Chemical Properties			
Average stabilized leach rate @ (gm $cm^{-2}day^{-1}$)	9.2×10^{-6}	1.8×10^{-5}	4.2×10^{-6}
Waste Oxides (Wt.%)	31	20	21
Homogeneity Microscopic examination	Homogeneous very few crystals observed.	Homogeneous by and large, little phase separation is observed.	Homogeneous, no phase separation observed.

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FEATURE ARTICLE

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Development and Microstructural Characterization of ThO$_2$-UO$_2$ Fuels

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Abstract

Several technologies are under development for the fabrication of (Th-^{233}U)O$_2$ fuel to reduce man-rem problems associated with ^{232}U daughter nuclides. A comparison of five different routes, namely powder-pellet, co-precipitation, sol-gel microsphere pelletization (SGMP), coated agglomerate pelletization (CAP) and impregnation, has been made in this study in terms of radio-toxicity, microstructure and waste generation. The microstructure of the pellet made by CAP process showed a duplex grain structure while the other methods yielded a uniform grain size. The micro-homogeneity was found to be slightly inferior for the pellets made by pellet- impregnation and CAP processes.

Introduction

The current challenge in nuclear technology, is in the area of the development of an environmentally friendly and proliferation-resistant fuel, which exhibits higher performance under irradiation. This can be achieved by selecting a fuel in which ^{238}U fertile matrix is replaced by ^{232}Th. In view of the large thorium reserves in India, the third stage of Indian nuclear power programme will be based on Th–^{233}U fuel cycle. ThO$_2$-UO$_2$ fuel is expected to exhibit better performance due to its higher thermal conductivity and lower thermal expansion coefficient in comparison with UO$_2$ fuel under similar conditions. In terms of waste management issues, Th matrix fuel not only reduces plutonium production but also reduces some of the isotopes responsible for the high fraction of the dose to the public [1]. The advantages of the use of mixed ThO$_2$-UO$_2$ fuel for existing Light Water Reactors (LWRs) can be summarized as follows:

(a)   Generates lower amount of minor actinides,
(b)   Results in a more stable and insoluble waste form and
(c)   Generates less spent fuel per unit energy production.

The majority of options for utilizing thorium have relied on highly innovative energy systems or reactor concepts, such as accelerator driven systems, molten salt reactors etc. Studies on the use of thorium with existing reactor and fuel technology have also been published (in most cases PHWR/PWR specific). The Advanced Heavy Water Reactor (AHWR) is being developed in India with the specific aim of utilizing thorium for power generation since India has vast reserves of thorium and its resource profile needs a closed cycle involving utilisation of thorium [2]. AHWR is a vertical, pressure-tube type, heavy water moderated and boiling light water cooled natural circulation reactor, designed to produce 920 MW(th). The AHWR is fuelled with (Th–^{233}U)O$_2$ pins and (Th–Pu)O$_2$ pins[3]. At

equilibrium, the core of AHWR will consist of composite fuel assemblies each having 24 (Th,[239]Pu) MOX and 30 (Th,[233]U) MOX pins. The fuel is designed to maximize generation of energy from thorium and to maintain self-sufficiency in [233]U[4]. Since the [233]U required for the reactor is to be bred *in situ*, the initial core and annual reload for the initial few years will consist of only (Th–Pu)O$_2$ clusters. Some of the problems associated with Th cycle are:

1. The reprocessed, [233]U is always associated with [232]U, whose daughter products are hard gamma emitters and therefore requiring shielded operation. Also the alpha activity of U[233] is three orders of magnitude higher than that of HEU and about one order of magnitude less than that of weapons grade plutonium.

2. In reactor, [232]Th on neutron absorption produces [233]Th which decays first to [233]Pa before converting into [233]U. [233]Pa has a half-life of 27 days. This rather long half-life of [233]Pa results in a reactivity increase after reactor shutdown due to [233]U production (opposite to Xe effect experienced in U reactors), and this must be taken into account.

Problems in fabrication of ThO$_2$-[233]UO$_2$ fuels

With the advent of the thorium fuel cycle wherein large quantities of [233]U will be generated and handled, methods for containment of this isotope become increasingly important. Not only is the [233]U hazardous from the standpoint of a toxicity and criticality, but the presence of [232]U and its γ emitting

daughter products cause personnel exposure problem. [233]U, which has a half-life of 1.62×10^5 years (as compared to 2.4×10^4 years for [239]Pu), becomes more hazardous because of its [232]U content (and consequently by its daughters), which varies from a few ppm to >500 ppm, depending on the flux characteristics of the reactor, in which Th was irradiated and the duration of the exposure. Because the [232]U (half-life 68 years) and first four members of its daughter chain are highly energetic α- emitters (see Fig. 1), with half-lives ranging from 0.15 s to 1.9 years, it is obvious that [233]U containing even few ppm of [232]U, on inhalation, would significantly increase the radiotoxicity. The subsequent daughters of [232]U, namely, [212]Bi and [208]Tl, emit strong gamma radiations of 0.7-1.8 MeV and
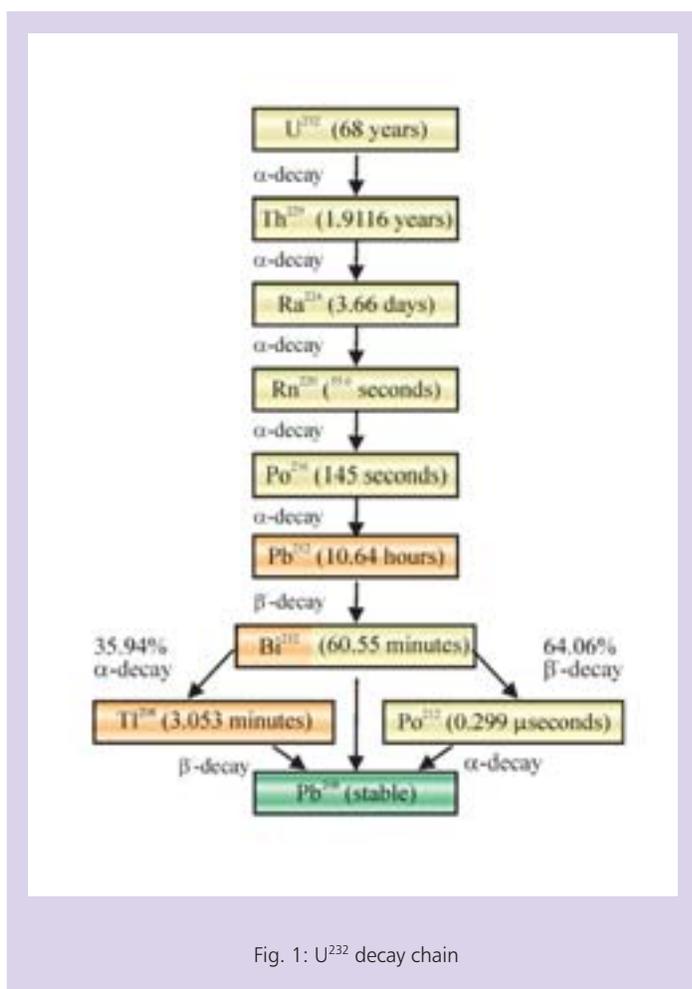
Fig. 1: U[232] decay chain

2.6 MeV, respectively and makes heavy shielding mandatory for the protection of personnel handling aged ^{233}U. A general practice in handling ^{233}U containing ^{232}U in the range of about 10 ppm is to remove the ^{228}Th and ^{224}Ra, the longer lived daughters in the decay chain, as completely as possible and to allow the remaining short lived daughters to decay before further processing[5]. Fig. 2 shows the ^{208}Tl activity from ^{232}U decay as a function of post purification time for various purification processes. A "safe time window" of about one month is obtained for fabrication, when the various operations involved can be completed with minimum of personnel exposure in lightly shielded facilities. This time window depends up on the ^{232}U content and decreases with increase in ^{232}U content. Following are the other issues associated with AHWR fuel fabrication:
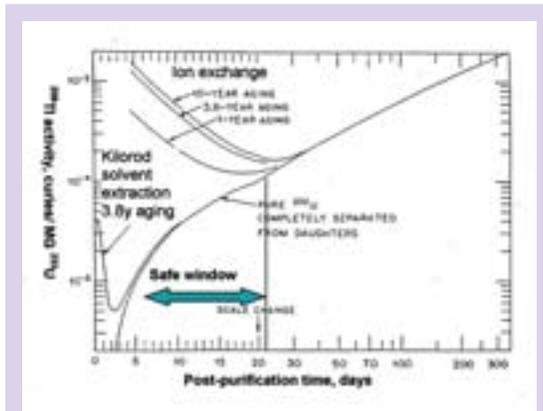
Fig. 2: ^{208}Tl activity from ^{232}U decay as a function of post purification time, method of purification and aging time before purification

Dose in Thorium Product

Thorium recovered from the irradiated spent fuel will contain ^{228}Th ($T_{1/2}$ = 1.91 yrs) isotope, formed from the decay of ^{232}U, produced during irradiation apart from that is normally formed due to radioactive decay of ^{232}Th. Handling of recovered thorium will be difficult if processed after a short cooling period

due to the hard gamma emitters (^{212}Bi and ^{208}Tl) formed during ^{228}Th decay[6]. Approximately 20 years ($\sim$ 10 half life of ^{228}Th) of cooling is required to bring down the gamma dose.

Fabrication

At present at BARC, R&D is being carried out on five fabrication routes each with distinct advantages and disadvantages [4]. These are:
1. Powder route (mechanical mixing)
2. Co-precipitation technique
3. Sol-Gel Microsphere Pelletization (SGMP)
4. Coated Agglomerate Pelletization (CAP)
5. Impregnation.
We will briefly describe each of the above processes and their merits and demerits.

Powder route

The Ceramic nuclear fuels are generally fabricated as cylindrical pellets by powder metallurgy technique, starting from UO_2 and ThO_2 powders followed by co-milling, compaction and sintering in reducing atmosphere at around 1700°C. The key step in the production of the above mixed oxide fuels, is the preparation of homogeneous oxide mixtures. However, when fabrication of fuels containing highly radioactive materials, like ^{233}U, americium, curium, fuels is considered, dust production and consequent radiation exposure to personnel could limit the applicability of the above mentioned process. The disadvantages of powder-pellet route are:
1. Handling of large amounts of fine powders ($<1\mu m$) generating radiotoxic aerosols
2. Large number of fabrication steps in the flow sheet
3. Increase in personnel exposure due to build up of fine powders on equipment surfaces.

Therefore, alternate fabrication routes that are more amenable to remote controlled operations and automation procedures are being considered.

Co-precipitation Technique

The requirement for high homogeneity of the distribution of the actinides in the fuel is essential for most new generation (Gen IV) reactors. The presence of fissile rich region causes a problem during the reprocessing operations, since these pellets will not dissolve completely in nitric acid, without the addition of hydrofluoric acid. Hence, it is essential to avoid the formation of such fissile rich regions by adopting proper manufacturing procedures. Among the various techniques, co-precipitation is an excellent route to obtain a very homogeneous mixture. The co-precipitation process is generally not preferred by fuel manufacturers since it involves handling of enormous amount of liquid waste. If one can incorporate the co-precipitation steps in the reprocessing route, then this method would be really advantageous. The advantages of the wet process include [4]:

1. Very low generation of radiotoxic dust
2. Easy availability of cheap reactants
3. Reduction of the accessibility to pure plutonium or other fissile actinides and reduction of risks of proliferation.
4. This method is easily amenable to glove box operation.

Also the co-precipitated powder can be further utilized as a master blend, to dilute to the required concentration by the addition of required constituents. In this process, the nitrate solutions of Th and U are mixed in the required ratio which is followed by co-precipitation and by the addition of oxalic acid. The precipitate is then dried and calcined to get a homogenous mixture of ThO_2 and UO_2 powders. ThO_2-30%UO_2 and ThO_2-50%UO_2 powders were characterized in terms of particle size, particle shape, surface area, phase content, O/M ratio etc. The pellets are made by using the above powders. The characterization of the sintered pellets was carried out by optical microscopy, Scanning Electron Microscopy (SEM) and Electron Probe MicroAnalysis (EPMA). XRD data for ThO_2-30%UO_2 and

ThO_2-50%UO_2 pellets showed the presence of a small amount of U_3O_8 phase besides the fluorite phase. A typical microstructure is shown in Fig. 3. The co-precipitation method was found to be suitable for obtaining mixed oxide pellets of high density and excellent microhomogeneity.
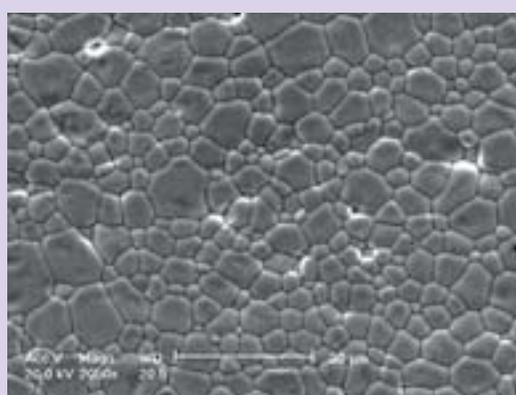
Fig. 3: Microstructure of ThO_2-30%UO_2 pellet sintered in air and etched thermally

Sol-Gel Microsphere Pelletization Technique

This process is ideally suited for the manufacture of (Th, U[233]) MOX fuel, since in this technique, use is made of liquids or Free Flowing spherical solids which are amenable to automation and remote handling. The process flow-sheet for obtaining dense (Th, U[233]) MOX pellets using SGMP technique has been developed (Fig. 4). The process employs free flowing dust-free sol-gel derived microspheres, as starting material for the fabrication of pellets instead of powders. In order to obtain good quality pellets from microspheres, the microspheres should have a low crushing strength, reasonably high tap density and a high surface area. BARC has generated a gelation field diagram for ThO_2 microspheres that define the feed compositions suitable for making opaque and soft microspheres for SGMP.
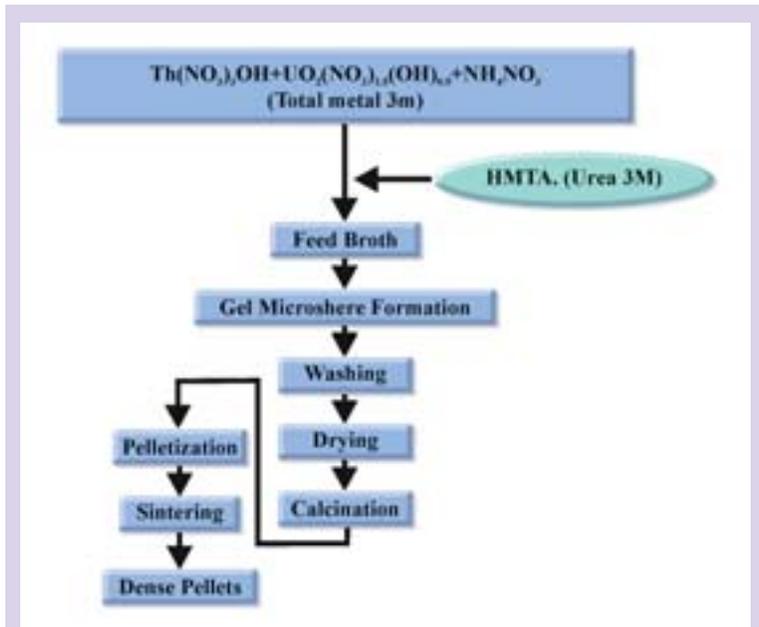
Fig. 4: Flow-sheet for the fabrication of $(Th,U)O_2$ pellets through SGMP route
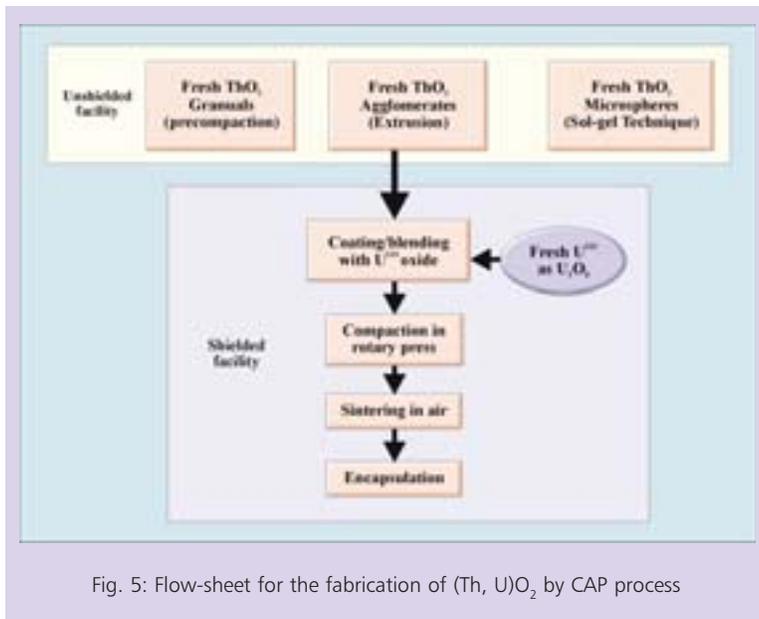
Fig. 5: Flow-sheet for the fabrication of $(Th, U)O_2$ by CAP process

Coated Agglomerate Pelletization (CAP) Technique

The Coated Agglomerate Pelletization (CAP) process was developed by BARC to replace the conventional powder metallurgy process that consists of

pre-compaction and granulation. The flow sheet of the CAP technique is made from the segmented flow-sheet to be performed partly in the unshielded and shielded facilities, on the assumption that freshly prepared [233]U oxide and natural ThO_2 (unirradiated) are used, in order to minimize man-rem problem. The main reasons for developing the CAP technique to produce $(Th-U)O_2$ fuel are[4]:

- to minimize the dusty operations
- to minimize the number of process steps inside shielded cell/glove box
- to reduce the man-rem problems since the highly radioactive [233]U is confined to only certain steps in the fabrication route.

In this process, a wide option is possible for the ThO_2 starting material. ThO_2 should be in the form of free flowing agglomerate which can be obtained either by pre-compaction and granulation technique or by extrusion of powders. The ThO_2 microspheres obtained by sol-gel technique can also be used in the CAP process. To make free flowing agglomerates in the extrusion route, the ThO_2 powder is mixed with an organic binder and extruded through perforated rollers. The CAP process is schematically shown in Fig. 5. The extruded ThO_2 paste is converted to agglomerates in a spherodiser. The agglomerates are sieved and subsequently dried to remove the organic binder. As only ThO_2 is

handled up to this stage, all these operations are carried out in a normal alpha tight glove-box facility. The operations carried out under containment and including shielding are:

a)   coating of ThO_2 agglomerates with desired amount of [233]U oxide

b)   compaction in a multi-station rotary press into green pellets

c)   sintering in air

d)   pellet loading and encapsulation into fuel rods.

Initial development work on this process has given very encouraging results. The agglomerate size, the coating technique, compaction and sintering parameters have important bearing on the homogeneity of the uranium distribution in thoria matrix. Studies in BARC have shown that the addition of uranium to ThO_2 in the form of U_3O_8 and sintering in air considerably reduce the sintering temperature from 1650°C to 1400°C. The microstructure of ThO_2-UO_2 pellets showed "rock in sand" structure with small grains in the center of granules and large grains along the periphery (Fig. 6). However, no delineation of granules could be found. The EPMA data confirm that uranium concentration was slightly higher in large grained areas (Fig. 7).

In a variation of this technique, the advanced CAP

Fig. 7: EPMA scan showing the variation of U concentration along small and large grained areas

(A-CAP), uses $(Th-U)O_2$ powders instead of U_3O_8 powder for coating. $(Th-U)O_2$ powders for the above process were made by co-precipitation technique. ThO_2-30%UO_2 and ThO_2-50%UO_2 powders are prepared by co-precipitation route. The major steps involved in the fabrication of the above powders are:

a)   Preparation uranyl and thorium nitrate solution

b)   Reduction of U ions from (VI) to (IV) valency state

c)   Co-precipitation using oxalic acid

d)   Calcination.

It was found that pellet sintered in air led to the formation of duplex grain structure and those sintered in Ar-8%H_2 resulted in very uniform grain structure with excellent homogeneity (Fig.8).

Fig. 6: The "rock in sand" type microstructure of ThO_2-UO_2 pellets
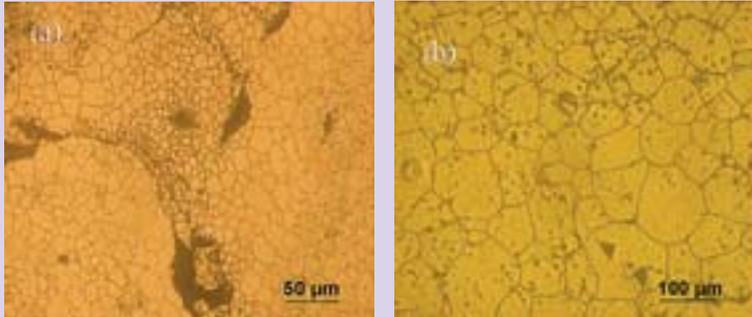
Fig. 8: Microstructure of ThO_2-4%UO_2 pellet sintered in air (a) and Ar-H_2 (b) atmospheres

Impregnation Technique

Impregnation technique is an attractive alternative for manufacturing highly radiotoxic [233]U bearing thoria-based mixed oxide fuel pellets, remotely in a hot cell or shielded glove-box facility. In this process, fresh ThO_2 green or pre-sintered pellets are impregnated with [233]U containing nitrate solution to the required enrichment. This involves first preparation of "low density" (<75%T.D.) and high open porosity ThO_2 pellets separately in an unshielded facility and further processing including impregnation to be done in a shielded glove-box/ hot cell facility. The ThO_2 pellets thus prepared are impregnated in uranyl nitrate ([233]U) solution of molarity in the range of 1 to 3, in a shielded facility, followed by sintering to obtain ThO_2–based mixed oxide pellets of high density and good microhomogeneity[4]. Thus, handling of fine [233]U bearing powders is avoided and these are restricted only in certain parts of the fuel fabrication plants. The advantage of this process is that, it can be so coupled with the reprocessing plant, that the purified uranyl nitrate from the plant may be straightway used as the infiltrant. The impregnation process can eliminate conversion step and eliminate several expensive stages from the operation. For example, process steps like precipitation of ammonium diuranate, filtration, calcination, mixing, grinding, granulation, etc., which are associated with 'radiotoxic dust hazard', are eliminated. As no

precipitation or washing steps are required within the shielded area, the radioactive wastes produced in the process are negligible.

The procedures for the fabrication of ThO_2-UO_2 pellets followed by BARC involve the following steps:

1. Fabrication of low density (~66%T.D.) ThO_2 pellets by powder route in an unshielded facility.
2. Impregnation of the above pellets by uranyl nitrate solution under vacuum in a shielded facility.
3. Drying and finally sintering at 1700°C in reducing atmosphere.

   The U loading in ThO_2 pellet can be varied by controlling the following parameters such as:

a) Density of the pre-sintered ThO_2 pellets,
b) Concentration of uranyl nitrate solution,
c) Duration of impregnation.

The density of the host pellets (ThO_2) is optimized by choosing the proper pre-sintering temperature. For attaining up to higher (4% U) loading with 1.5 M uranyl nitrate solution, multiple impregnation is necessary. Final sintered density of these pellets was in the range of 93-96%T.D. A typical facility and pellets after impregnation process are shown in Fig. 9.

In a variation of this process, the ThO_2 gel microspheres/ agglomerates can also be used for impregnation instead of low-density pellets. It is seen that gel/agglomerate impregnation permits more uniform and higher concentration of U loading resulting in more homogeneous ThO_2-UO_2 pellets. However, this will require compaction press also to be installed inside the shielded glove-box/ hot cell.
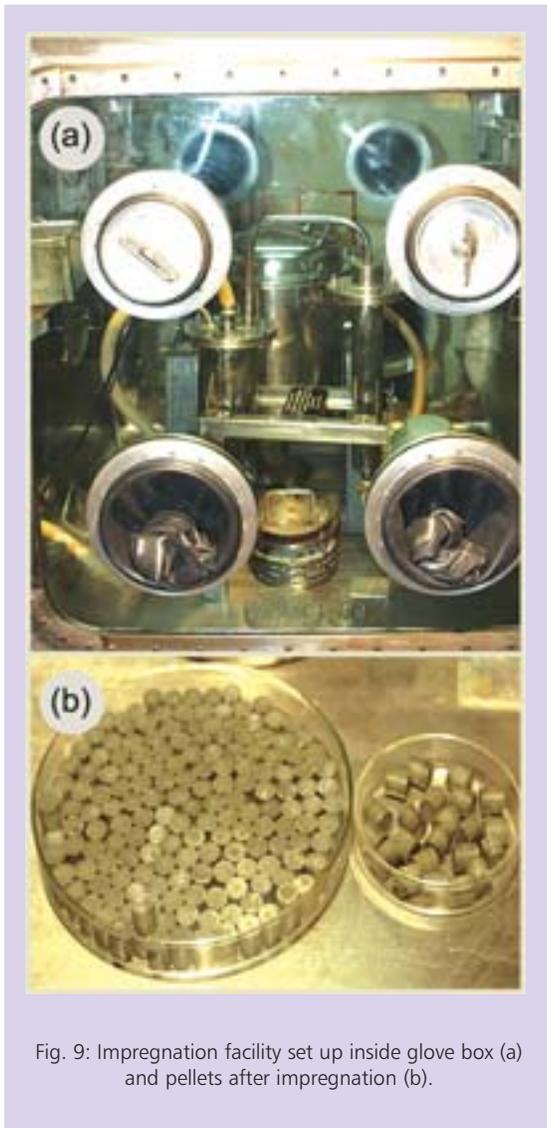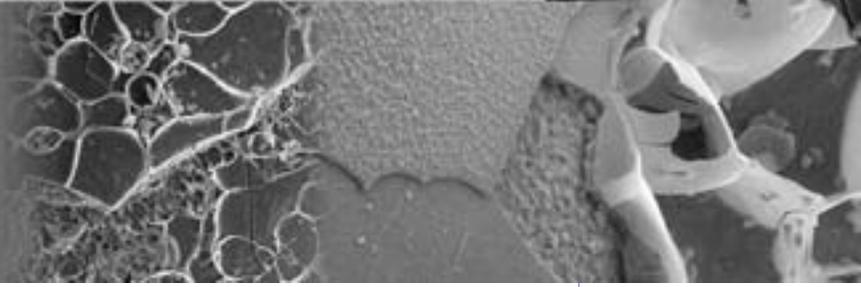
Fig. 9: Impregnation facility set up inside glove box (a) and pellets after impregnation (b).

Fig. 10: Steps involved in Impregnated Agglomeration Process

In CAP process, however, there is a possibility of powder specially $^{233}UO_2$ sticking to equipment and glove boxes. An attempt has been made recently to develop a new technique, Impregnated Agglomeration Process (IAP) at AFFF, Tarapur. In this process, uranium oxide is dissolved in concentrated HNO_3 and diluted to 0.25M. ThO_2 spheroids were coated with uranyl nitrate solution with the help of universal mixer. The dried spheroids are compacted and further processed as in CAP process (Fig. 10). In IAP, powder handling is minimized and it is advantageous when $^{233}UO_2$ is handled for fabrication of AHWR fuel.

Conclusions

The large scale utilization of thorium requires the adoption of closed cycle and many of the fuel cycle technologies of uranium can be adopted for thorium. There are however a few major challenges in re-fabrication and reprocessing posed by the stable nature of thoria matrix and radiological issues associated with thorium fuel cycle. Thorium utilization calls for addressing a lot of technological challenges. BARC has acquired expertise in the entire fuel cycle activities of Th-U[233] fuel. Several technologies are under development for the re-fabrication of (Th-U[233])O_2 fuel to reduce man-rem problems associated with U[232] daughter nuclides. A comparison of five different routes has been made in terms of radiotoxicity, microstructure and waste generation and has been presented in

Table 1: Comparision of five different routes for the fabrication of (Th-^{233}U)O$_2$ MOX

	Powder Route	SGMP	Impregnation	CAP Process	Co-ppt process
Radiation dose	♦ ♦ ♦ ♦ ♦ (highest)	♦ ♦ ♦	♦ ♦ (lowest)	♦ ♦ ♦	♦ ♦ ♦
Uranium Distribution	Uniform	Uniform	For pellet impregnation: Higher U concentration at periphery For gel impregnation: Uniform	Lower U concentration in ThO2 granules In A-CAP, better distribution of U	Extremely uniform
Grain size	Uniform	Uniform	Uniform	Duplex	Uniform
Waste	Solid waste	Liquid waste, organic waste	Less Liquid waste	Lesswaste	Liquid waste

Table 1. Apellets has to be made by, taking into consideration of the above factors.

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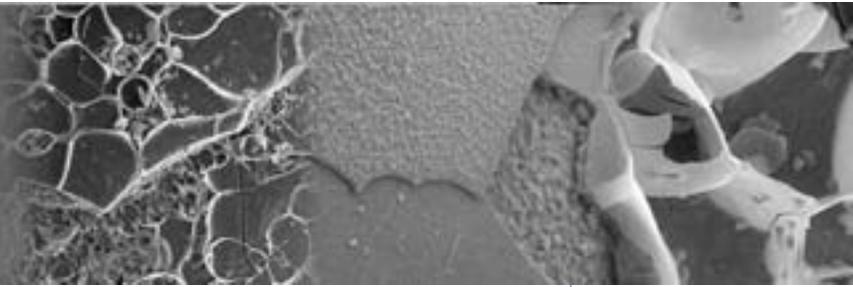
Research and Development Activities in Level-1 Probabilistic Safety Assessment and Aging Studies

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Abstract

Research and development activities that are in progress in Reactor Safety Division in the areas namely Level-1 Probabilistic Safety Assessment (PSA) and ageing of control and instrumentation components and cables are presented. The results of AHWR level-1 PSA studies carried out are presented. PSA studies have applications in many areas. A software "Risk Monitor" was developed that can be used to continuously monitor the status of the Nuclear Power Plant (NPP) with regard to the functioning or non-functioning of its different subsystems and assess the associated risk emanating from the facility on the basis of this information. Probabilistic precursor analysis studies have been initiated for assessing risk arising out of the events that occurred during the operation of the plant. A case study has been carried out for a typical NPP. All the PSA studies are dependent on failure parameters that enter into various component models. A case study has been carried out, along with NPCIL and AERB for assessing more applicable failure parameters for class IV failure frequencies using Bayesian methods. Fire PSA studies have been carried out for MAPS, as a case study, to identify the vulnerable areas. Pilot studies on Risk informed In-Service-Inspection studies have been carried out, for a typical NPP and a section of Heavy Water Plant, for categorizing the components for In-Service inspection based on their contribution to risk. These two pilot studies indicate that RI-ISI has a very high potential in reducing inspection requirements compared to the requirements as per the currently adopted standards. A neural network based diagnostic system for identification of accident scenarios in 220 MWe Indian pressurized heavy water reactors (PHWRs) has been developed for operator support and accident management. Various facilities have been set up and a few were updated for carrying out the Thermal & Radiation Ageing and Loss Of Coolant Accident (LOCA) Qualification Studies of Control & Instrumentation (C&I) components and Equipments. Instrumentation systems for carrying out these studies are also being up dated. Now-a-days digital systems are increasingly being used in instrumentation and control. Studies based on physics of failure are in progress to address the issues related to their failure, which are needed in PSA studies. Even though software that goes into these systems undergoes extensive validation and verification, quantification of the failure rates of these software are needed in PSA studies. Work on software reliability is also under way.

Introduction

Probabilistic Safety Assessment (PSA) is an analytical technique for assessing the risk by integrating diverse aspects of design and operation of a Nuclear Power Plant (NPP). In the context of Nuclear Power Plant, PSA can be carried out in three levels.

Level-1 PSA estimates the frequency of accidents that cause damage to the nuclear reactor core. This metric is commonly called core damage frequency (CDF). Level-2 PSA starts with the output of Level 1 studies and estimates the frequency of accidents that release radioactivity from the nuclear power

plant. It also estimates the magnitude, composition, time of release and duration of radioactivity release into the environment (source term). Using this source term, Level-3 studies estimate the consequences in terms of risk to the public and environment.

One of the early PSA for a Nuclear Power Plant is presented in the report WASH-1400[1], popularly known as the Rasmussen Study, showed that the risks associated with Nuclear Power Plant (NPP) operation are far less compared to the risks due to various other means of power generation. This study formulated a systematic procedure to carry out PSA. This activity gained momentum only after the Three Mile Island (TMI) incident (which was considered in WASH-1400) and further studies were conducted on various NPPs. In India, PSA was initiated with reliability analysis studies that were conducted on various systems of Dhruva and MAPS. However, the first PSA study was conducted was on Narora Atomic Power Plant[2].

In this paper, Level-1 PSA activities that are in progress in Reactor Safety Division are highlighted, with emphasis on applications to plant operation, maintenance, regulatory, accident management and ageing issues.

Probabilistic Safety Assessment Studies

PSA studies require
(a) Identification of initiating events and estimation of their frequencies.
(b) Construction of event trees for these initiating events and identification of accident sequences (combination of initiating event and subsequent failure/ operation of mitigation system(s) necessary for this initiating event)
(c) Construction of fault trees for these mitigation systems and generation of minimal cut sets (combination of minimal component failures that result in system failure).
(d) Quantification of fault trees and event trees,

using data on component failure, human errors, external events, etc.

AHWR PSA

A level-1 PSA has been carried out for AHWR[3] considering only internal IEs, full power operation state with reactor core as the source of radioactivity release. In this study, consequence of event trees have been categorized into four states as defined below:
(i) Core Damage State: The Core Damage State is defined as the accident condition which results in peak clad temperature beyond 1473 K
(ii) Core Degradation State: The Core Degradation State is defined as the accident condition which results in peak clad temperature beyond 1073 K, and within 1473 K.
(iii) Deviation from Safe State: The deviation from "Safe State" is defined as the accident condition which results in the peak clad temperature beyond 673 K, and below 1073 K, which is the fuel failure criterion
(iv) Success State: The Success State is defined as the safe condition, wherein fuel temperature is less than peak clad temperature 673 K.

The accident sequences have been binned to one of the above four states. The accident sequences resulting in Core Damage State have been considered in Core Damage Frequency (CDF) estimation. The Core Damage Frequency is found to be ~5.46e-8/yr. The frequency for Core Degradation is found to be 2.56e-7/yr.

Applications of Probabilistic Safety Assessment Studies

Probabilistic Safety Assessment analysis provides insights into plant processes and mechanisms and possible interaction between plant systems, both for existing plants with operating histories and for

plants still in the design stage. In addition to providing an estimate of base line risk, these studies do provide the information on plant vulnerabilities. Hence, these studies can be utilized in adopting optimal configuration control strategies, operational event analysis, etc. Some of these applications are realized in Reactor Safety Division and these are elaborated in subsequent sections.

Risk Monitor Development and Applications

Nuclear Power Plant configuration undergoes changes due to changes in component status and/ or operating/ maintenance procedures. Some components are randomly down and/or others are planned for test, maintenance and repair. These configuration changes result in a variation of CDF over operating time (called risk profile). Risk Monitoring can be defined as the process whereby a complex technical facility is continuously monitored with regard to the functioning or non-functioning of its different subsystems (configuration changes) and the associated risk emanating from the facility on the basis of this information is evaluated. This can be regarded as being part of the risk management of a plant.

As a result of the availability of level-1 PSA studies, there is a desire to use them to enhance plant safety and thereby reduce risk in the operation of NPPs in a most efficient manner. Towards this, Risk Monitor[4], a PC based and user friendly tool, which computes the real time safety level in terms of Core Damage Frequency (CDF), has been developed. Risk Monitor assesses the CDF of the plant in the "as it is" configuration and is useful in optimization of test and maintenance activities to reduce risk in the operation of Nuclear Power Plants. It also supports in deciding the effect of various operation and on maintenance strategies on risk.

In addition to the data requirement mentioned above, Risk Monitor needs detailed:
(a)   Information on component data which

include type of model (Tested, repairable,non repairable, mission time etc.,) and their corresponding parameters.
(b)   Information on Common Cause Failures (CCF). This includes different number of CCF groups, basic events of each group and their corresponding factors (β factor, α factors etc.)

Data Flow Diagram of Risk Monitor is shown in Fig. 1.

Once the inputs are specified, Risk Monitor will calculate the risk coming from the plant (in terms of core damage frequency in case of nuclear power plants). This is called the base line risk which is based on the as designed/ recently updated configuration of the systems and components in the plant. Risks arising out of changes in configuration of systems/ components are also evaluated as a function of time as shown in Fig. 2. The figure has different colour bands. If the current risk is considered as completely acceptable if the risk is in the green band where as it is unacceptable if it falls in the red band.

The bands are usually selected based on industry experience or guidelines set by regulatory bodies. 'What if' feature in Risk Monitor helps to analyse various planned strategies and is useful in arriving at optimal solutions to configuration control.

Probabilistic Precursor Analysis Studies

Incidents occur during the operation life of a complex industrial facility and sometimes, these can act as indicators (precursor) of impending serious situations (for e.g. core damage). In Probabilistic Precursor Analysis studies, PSA results are used to assess whether the incident that occurred in a plant is a precursor or not. The metric, Conditional Core Damage Probability (CCDP), is used for analyzing precursors. The deciding value for precursor, based on CCDP, is dependent on national regulations (e.g. 10^{-6}).
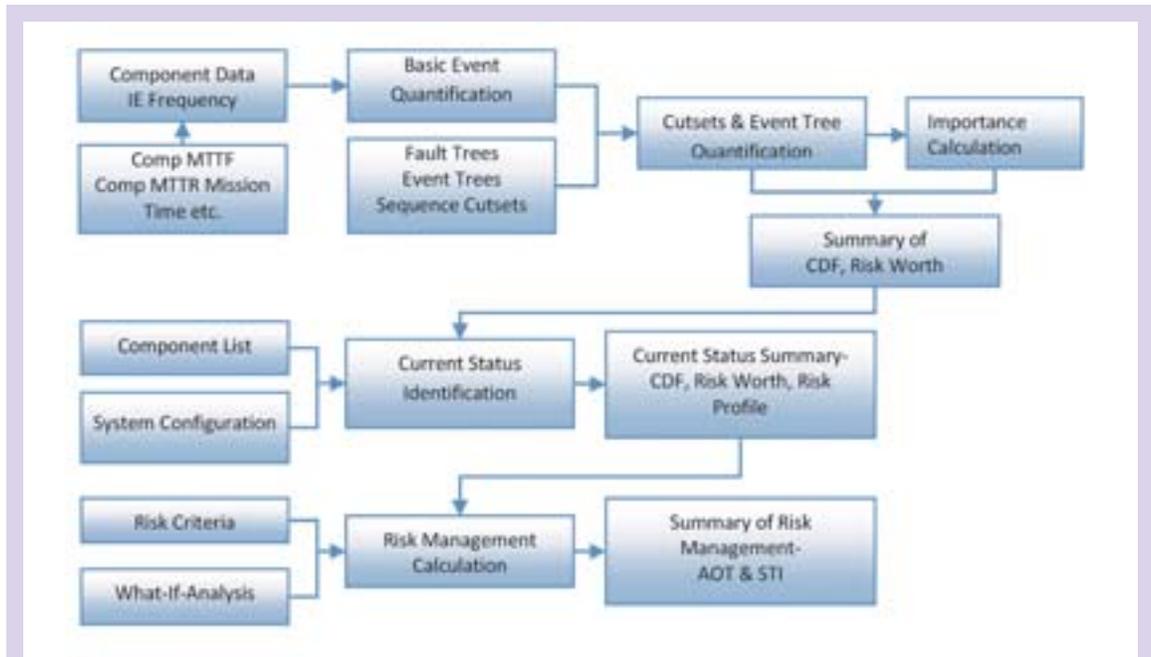
Fig. 1: Data flow diagram of Risk Monitor
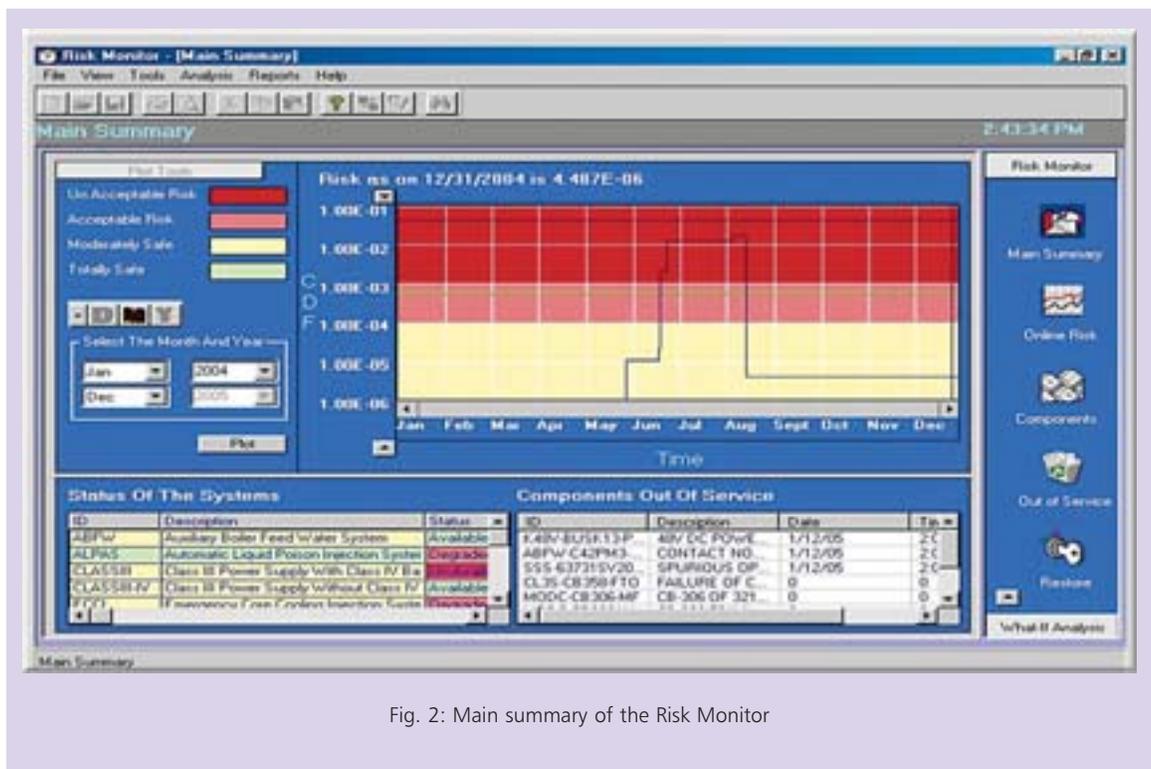
Fig. 2: Main summary of the Risk Monitor

Basically there are two types of precursor events:

(i) Transient which interrupts the normal operation of the plant. In this case the event can be easily related to an initiating event (IE) of the PSA model (if modeled). The accident scenarios affected by the event are those depicted in the event tree corresponding to this initiating event. CCDP for this type of events is calculated as

$$CCDP = f_{IE} / \lambda_{IE},\qquad(1)$$

Where f_{IE} is the sum of the frequencies of the accident scenarios affected by the event and $\ddot{e}_{IE}$ the frequency of occurrence of IE.

(ii) Unavailability or a degradation of equipment or systems without any immediate impact on plant operation. If the event is related to one (or several) safety functions, a systematic survey of the principal scenarios which the event impacts needs to be done. First, all the initiators which require the affected safety function(s) need to be identified. In the event scenarios or sequences developing from these initiating events, only the scenarios which entail the precursor event are retained. In this case, the CCDP is evaluated as:

$$CCDP = T_{event} \times (CDF_{event} - CDF_{base}) / A\qquad(2)$$

Where,

A is the fractional the duration of power operation per year,
T_{event} the duration of the operational event (yr),

CDF_{event} the core melt frequency during the event

(1/yr), and

CDF_{base} the base value of core damage frequency during power operation (1/yr).

Another metric, Risk index, is a measure of unacceptable consequences, typically either core damage frequency or beyond design basis frequency.

It is obtained by multiplying the conditional probability of the precursor event with the frequency (one event within the observation time), and summing up all precursor events within the observation time in reactor years.

$$\lambda = \sum_j \frac{CCDP_j}{Observation\,time}\qquad(3)$$

Based on the available event information, during the period of 2002-2006, from a NPP, precursor analysis has been carried out. For the plant under consideration, there were 9 events observed, out of which 7 events identified as IEs (type I above) that are amenable for PSA analysis where as the remaining two events were identified as not amenable for PSA analysis (these events have not been considered in the PSA analysis). This identified the need to update the PSA model to take care of the observed operational events.

In Table 1 the events are presented along with the grading assigned to them based on International Nuclear Event Scale (INES) and the CCDP values. The INES grading is in the order of increasing levels of severity. These levels are: 'anomaly', 'incident', 'serious incident', 'accident with local consequences', 'accident with wider consequences', 'serious accident' and 'major accident'. The aim in designing the scale was that the severity of an event would increase by about an order of magnitude for each increase in level on the scale (i.e. the scale is logarithmic). For example, the 1986 accident at the Chernobyl nuclear power plant, which had widespread impact on people and the environment, is rated at Level 7 on INES.

The results of precursor analysis are shown in the Figs. 3 & 4. Fig. 3 shows the CCDP values of events. It can be noticed from this figure that all the events are having the CCDP value well below 10^{-6}. Hence, no event is of 'precursor' type and all are of 'no precursor' type. Fig. 3 shows the total number of

events of a given type of category (important precursor, precursor and no precursor based on CCDP value) year wise. From this figure, it is found out that there is only one event of 'no precursor type' in the years 2002 and 2003. There are 3 events in the year 2004 and two events in the year 2006. There is no event in the year 2005. All these events are of 'no precursor type'.

From Table 1, it can be seen that for the first two events the INES values assigned are '0', and this means these are not significant events. The corresponding CCDP values (5.64E-10) obtained is also low for these events. INES value for the third event is 1 and the CCDP value is 9.00E-09. But, for the fourth event even though the CCDP value is 5.91E-09, which is less than that for the 3rd event, the INES value is given as 2. Similarly, CCDP value for the fifth event is 8.24E-09, which is in between the above mentioned two events (3 and 4), but the

INES value is given as zero. For the 8th event INES vale is given as zero, but the CCDP value is 3.21E-07 which is greater than the CCDP value of 3 and 4 events for which INES values have been given as 1 and 2 respectively. From the above discussion it is evident that INES values for some of the events are underestimated.

Risk index calculated for this plant (as per equation 3) is **8.78E-08/year**.

The major advantages of this approach are the strong potential for augmenting event analysis which is currently carried out purely on deterministic basis. From the observations it is found that there is slight discrepancy between CCDP values and INES scale associated to an event. Also, the risk index gives an indication about the safety culture followed in plant and can be used as a metric for comparing between various plants.

Table 1: Events observed, their INES level and the CCDPs

Sl. No.	Event description	INES level	CCDP
1	SG tube leak– IE	0	5.64E-10
2	SG tube leak– IE	0	5.64E-10
3	refueling- IE	1	9.00E-09
4	LORA- IE	2	5.91E-09
5	PCP trip – IE	0	8.24E-09
8	IE – Partial loss of Class IV supply	0	3.21E-07
9	IE – IRV open	1	6.27E-09
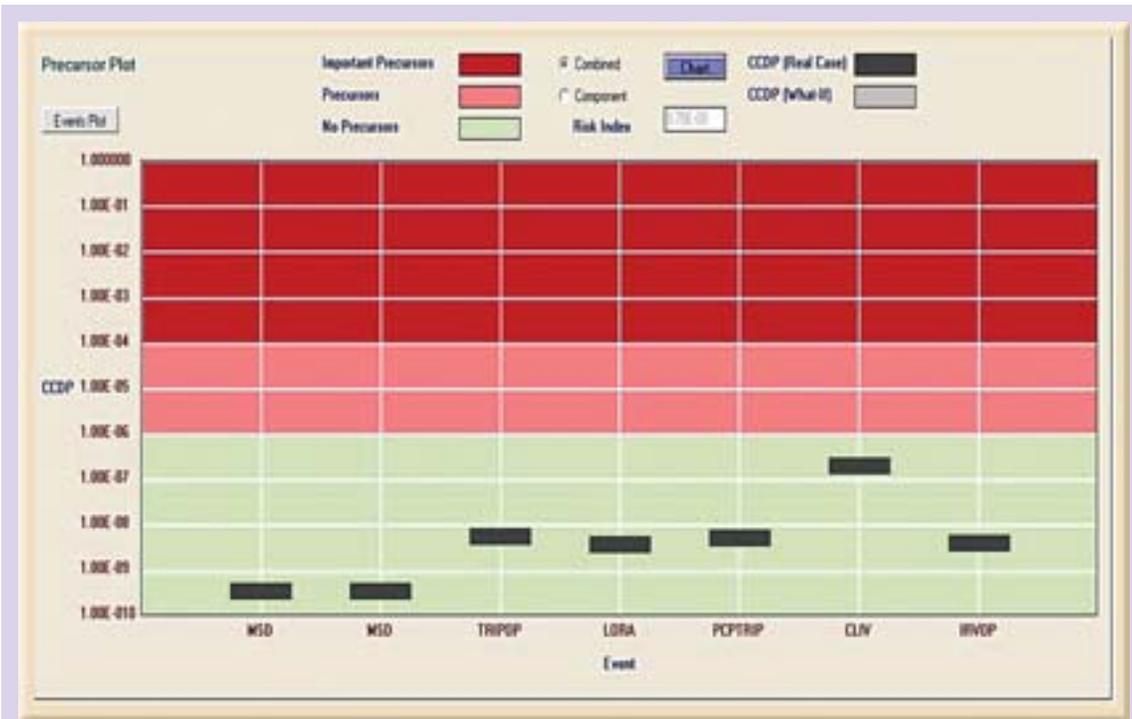
Fig. 3: Graph between CCDP Vs Event for NPP-1
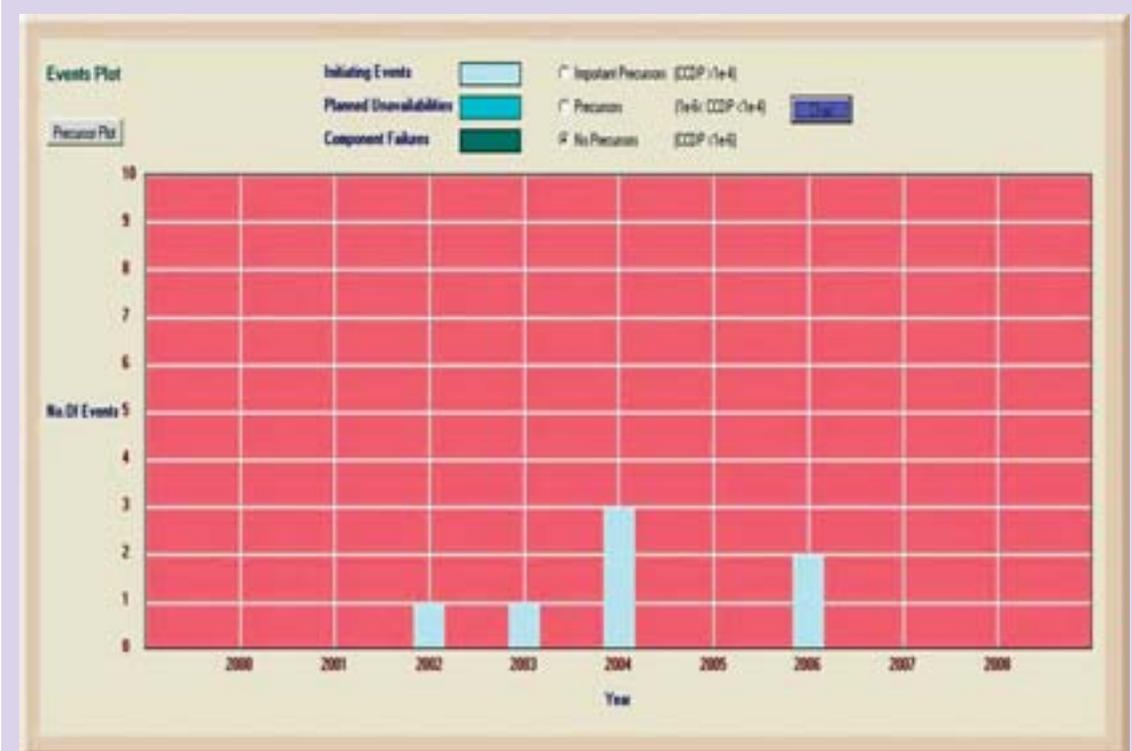
Fig. 4: Graph between number of Events Vs Year for NPP-1

Studies Related to Failure Data Base

The results of PSA are as reliable as the component failure and repair data that goes in to the evaluations. Components, used in NPPs, undergo strict quality control and hence their failure rates are, in general, very low. Use of generic component failure data, that is available, raises questions regarding the applicability of the results to our situations. To generate a component data base, data collection over a large operating time (component hours) is needed. Until enough data from our plants is collected for generating our own failure database, updating of data based on Bayesian analysis studies can be under taken. These studies combine the generic failure data and the limited operating experience available at our plants to arrive at more appropriate data that can be applied in the PSA studies of our plants. Presently Bayesian analysis studies are being carried out along with NPCIL and AERB to develop generic prior failure rate distributions for important components by pooling the failure information from all the NPCIL plants. Using this generic prior and the failure information for a particular plant, applicable posterior distribution of failure data can be generated for that plant.

A case study was carried out for the case of class IV power failure frequency. The data used for this corresponds to the failure records of class IV power failure at our power plants. These studies provide a sound basis for the failure data for use in the PSA studies of our NPPs. In addition, these help in estimating the uncertainty in risk indices due to epistemic reasons.

Fire PSA

Fire PSA is conducted by identifying fire scenarios that may affect the safe operation of the plant (through impacts on equipment and human actions), and estimating the frequency of occurrence of those scenarios. The primary output of a fire PSA is typically the estimated frequency core damage initiated as a result of fire. The various steps involved are as detailed below and shown in Fig. 5.

(1) *Plant walkdown*- start with listing out of fire zones. For each fire zone, fire hazards, combustible materials present and presence of safety related equipments are noted.
(2) *Screening analysis*- depending on fire loads and safety related equipments present, screening analysis shortlists the fire zones for detailed analysis
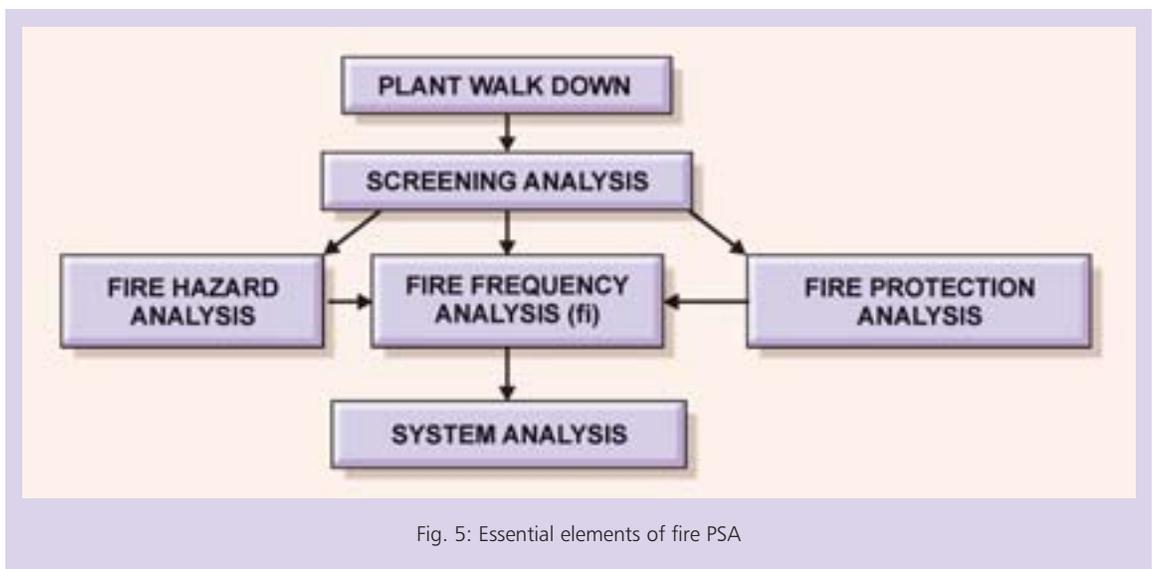
Fig. 5: Essential elements of fire PSA

(3) *Fire frequency analysis* – this involves (3a) Fire hazard analysis (FHA), which is a deterministic analysis for estimating the time available before fire can damage an equipment. Codes such as Fire Dynamic Simulator, COMPBRN IIIE, are used for FHA (3b) Fire propagation analysis – provides the probability that equipment can be damaged given the detection and suppression measures. (3c) fire ignition frequency from plant experience and finally

(4) *System analysis* – which considers the effect of equipment damage on system unavailability and finally to core damage.

Fire-induced core damage frequency (CDF), can be expressed as the product of three terms. These three terms are (1) the frequency of the postulated fire or class of fires (f_i), (2) the conditional probability that the postulated fire will cause damage to some set of plant equipment ($P_{ed,j|i}$), and (3) the conditional probability that given the postulated equipment damage the plant operators will fail to recover the plant and core damage would result ($P_{CD:k|i,j}$). This is expressed mathematically as:

$$CDF = \sum_i f_i \left(\sum_j P_{ed,ji} \left(\sum_k P_{CDki,j} \right) \right) \qquad (4)$$

Fire PSA has been carried out for MAPS[5]. Screening analysis has identified four fire zones for detailed analysis, viz., Class II & III switch gear room, 250VDC battery room, Motor Control Centre and cable bridge area. It has been found that accident sequence frequency due to fire in class II & III switch gear and cable bridge area are major contributors to core damage frequency (Fig. 6). This is because, during a large fire in these areas, there will be a total loss of power supply or station black out situation will arise. Whereas in other areas, it will be possible to maintain Class IV power supply availability.

This study demonstrates the capability to conduct fire PSA studies.
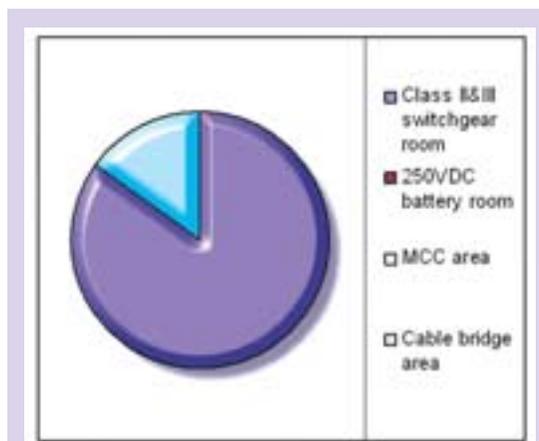
Fig. 6: Contributions of different areas to Fire induced CDF in MAPS

Risk Informed In-Service Inspection

Risk Informed In-Service Inspection (RI-ISI) aims at categorizing the components for In-Service inspection based on their contribution to Risk. Probabilities and consequence of component failures need to be computed for defining their contribution to risk. The failure probabilities are computed by understanding the possible degradation mechanisms that can be present. Statistical models, structural reliability models and expert judgement are normally employed for failure probability estimation. For nuclear applications consequence modeling is done using PSA whereas for non-nuclear application the consequences depend upon the considerations in their risk analysis such as toxic health effects. Depending on the severity levels of failure probabilities and consequences, various risk categories can be identified. The in-service inspection requirements of equipment are defined on the basis of these risk categories (Fig. 7).

RI-ISI has been applied for Primary Heat Transport System of Indian Pressurised Heavy Water Reactor (PHWR)[6] and CT1-HT1 tower of Hydrogen Sulphide (H$_2$S) based Heavy Water Plant (HWP)[7].
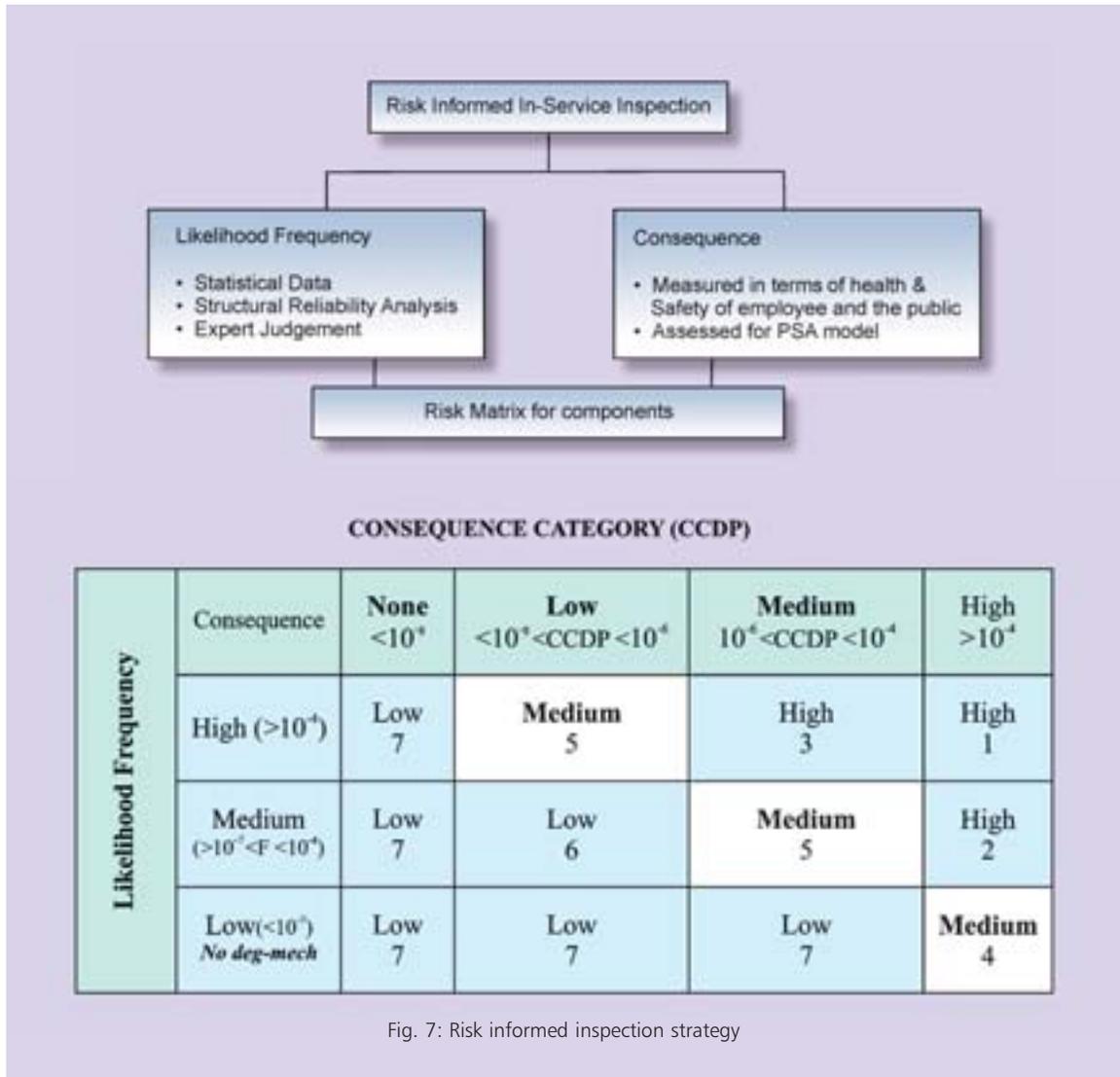
Fig. 7: Risk informed inspection strategy

(i) *RI-ISI of NPP*

During the last several years, nuclear industry has recognized that Probabilistic Safety Assessment (PSA) has evolved to be more useful in supplementing traditional engineering approaches in reactor regulation. In RI-ISI, consequence of failure of a component is expressed in terms of Conditional Core Damage Probability (CCDP). EPRI has designed a Risk matrix with different inspection categories, depending on the CDF/ CCDP values and degradation mechanism for determining the inspection interval.

The inspection currently followed at Indian PHWR is partly based on CAN standards, ASME Section IX and expert judgment derived from operating experience. Performance of RI-ISI over the current inspection has been studied through a risk impact analysis. CAN standards has categorized Steam generator and pump in high category which demands a 5 year inspection period. From RI-ISI consideration, they can be put in low and medium category, which allows for a relaxation in the inspection interval. Similar reduction in inspection activities were observed for other components.

(ii) RI-ISI of HWP

The production of Heavy Water in Hydrogen Sulphide (H_2S) based Heavy Water Plants (HWPs) involves handling of large quantities of H_2S, which is toxic and highly inflammable. The In-Service Inspection (ISI) practices in these plants are based on engineering judgement and operating experience. Recently, an ISI plan has been formulated based on operating experience, ASME Sec XI guidelines, Atomic Energy (Factories) Rules and API 510 guidelines. Consequence quantification for flammable, explosive, toxic release causing environmental impact and economic loss has been provided in Base Resource Document by American Petroleum Institute, API 581 as simple factors, which were not available in ASME code. In fact, API 581 builds upon the ASME efforts to develop usable tools that can provide the benefit of Risk Based Inspection (RBI) with a reasonable expenditure. API 581 deals ISI requirement for petroleum refineries and petrochemical industries. However, this can be safely applied to heavy water plants with certain degree of accuracy based on statistical input from past experience of plant operation and a few technical judgements.

H- High, VH- Very High, M- Medium, L- Low

Risk impact analysis has been conducted to study the benefit of applying Risk Based Inspection methodology. Current inspection plan puts almost 50% of its equipments considered in pilot studies in high category. But RBI puts on 4% of equipments in high category at the end of 15 years and 20% of equipments in high category at the end of 25 years. It has been found that large quantum of inspection is reduced by placing the equipments in inspection category based on RBI methodology (Table 2).

These two pilot studies indicate that RI-ISI has very high potential in reducing inspection requirements compared to the requirements as per the adopted standards.

Neural Networks Based Diagnostic System for Identification of Accident Scenarios

Nuclear power plants are highly complex systems that are operated by human operators. When faced with abnormal operating conditions, such as a plant accident scenario, equipment failure or an external disturbance to the system, the operator has to carry

Table 2: Comparison of risk categories based on current ISI and Risk Informed-ISI

Items	Quantity	Consequence category	Failure Probability category		Risk		Current ISI
			15 Yrs	25 Yrs	15 Yrs	25 yrs	
Towers	2 Nos.	H	H	VH	H	H	H
Process HX	4 Nos.	M	VH	VH	M	M	H
Coolers, Chillers Steam Heater	5 Nos.	M	VH	VH	M	M	H
Gas Lines	6 Nos.	H	M	H	M	H	4H 2M
Liquid Lines	30 Nos.	2H 28M	4H 24M 2L	27 VH 1H 2M	28M 2L	1H 29M	10H 20M

out diagnostic and corrective actions. The conditions that arise as a consequence of the disturbance may subject the operator to various types of stresses and these stresses may contribute to inappropriate and untimely actions that aggravate the situations. This necessitates the need for developing an operator support system to assists the operator to identify such accident scenarios during the early stages of their development. Early detection will help in minimizing or even mitigating the consequences of such transients.

A neural network based diagnostic system for identification of accident scenarios in 220 MWe Indian pressurized heavy water reactors (PHWRs) has been developed for operator support and accident management[8,9]. The objective of one such system, the plant diagnostic system, is to give the plant operators appropriate inputs to formulate, conform, initiate and perform the corrective actions in any potentially unsafe scenario that may arise in the plant. The aim of the diagnostic system is to identify the plant condition from the process

parameters, using intelligent tools. As a pilot study, large break LOCA in reactor inlet and outlet headers, and with and without the availability of ECCS has been analyzed.

The significant parameters are shown with red background for quick attention of the operator. The trend of important parameters and appropriate operator actions are also displayed under abnormal conditions.

Ageing Studies

Today we find that there are a significant number of nuclear power plants all over the world which have seen operation over 25-30 years. This means that the life of some of the components is approaching the end of their design life. Hence, it is very much essential to ensure that the components perform as intended during the remaining period of their life. In addition, life extension of NPPs is also being contemplated. In the light this Ageing studies play
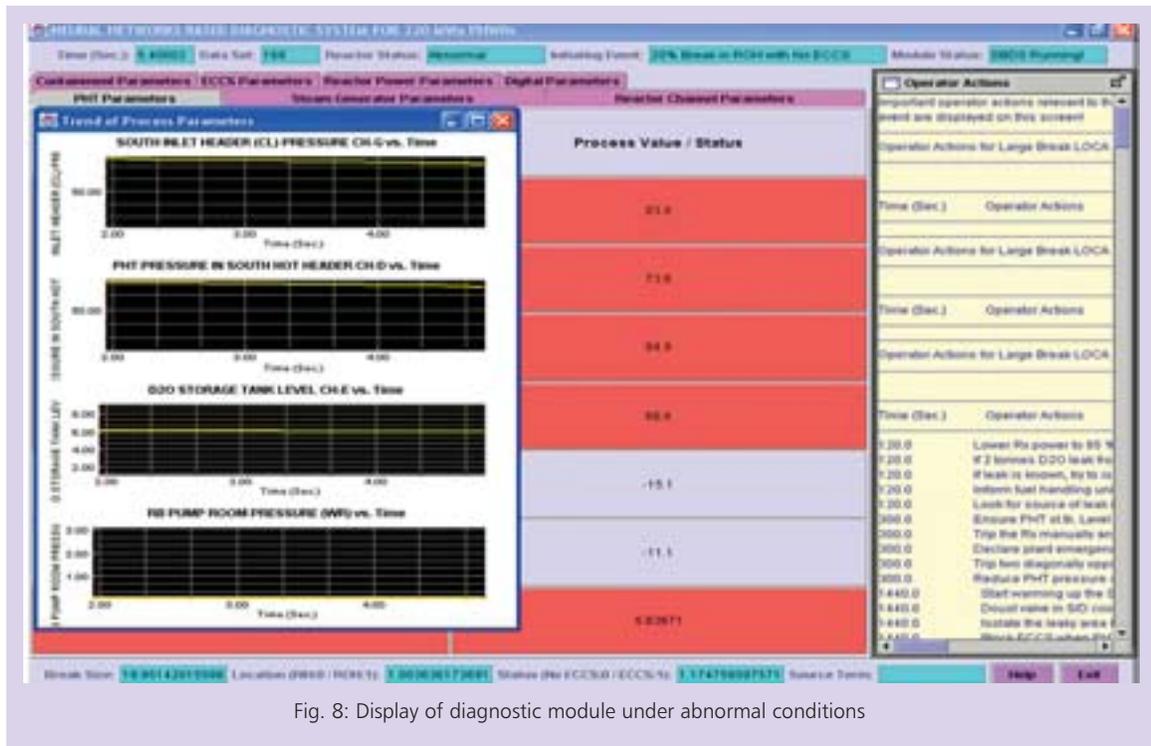

Fig. 8: Display of diagnostic module under abnormal conditions

a significant role. R&D activities related to the ageing of control and instrumentation components and cables are taken up as these constitute a significant part of replaceable components in NPPs.

Thermal & Radiation Ageing and Loss Of Coolant Accident (LOCA) Qualification Studies of Control & Instrumentation (C&I) components and Equipment

C&I components and equipment in various systems in NPPs may be subjected to harsh environmental conditions like high humidity, high temperature and high radiation during their designed life. Hence, it is essential to ensure reliable operation of these components during their designed life. Towards this objective, qualification approval and ageing studies on hardware systems/components/materials, used in NPPs, are needed to provide reasonable assurance regarding their survival capability under simulated environment even at the end of specified service life. Various facilities have been designed, developed and are in operation to carry out (i) thermal ageing (under accelerated conditions), (ii) radiation ageing and (iii) LOCA environment qualification studies of C&I components, equipment and cables.

Accelerated thermal and radiation ageing studies are carried out to estimate the life-spans of these items at operating temperature, in reactors, using Arrhenius Model. Accelerated temperature level should be selected in such way that no new failure mechanism, which is not prevailing during the natural ageing, is introduced during the course of ageing studies. Thermal ageing is done in thermal chambers whose temperature can be controlled according to the need.

The cumulative radiation dose the component is likely to receive during its life span is considered in radiation ageing studies. Radiation ageing is carried out using the ISOMED facility of BRIT available in Trombay. Usually C&I components, equipment and cables are subjected to an integrated gamma dose

Fig. 9: Thermal ageing test chambers

of 100 M rads to take care of the 40 years life of cable and occurrence of LOCA at the end of 40 years. It may be noted that many of the C&I components/ equipment do not get exposed to such a high radiation dose. In addition to the dose, dose rate is also controlled to be around 0.1 M rad/hour. Thermal and radiation ageing are done sequentially. However, in a real environment, the components undergo both thermal and radiation ageing simultaneously in a humid environment.

In order to study interaction effects of combined environments, prevailing simultaneously in NPP containment, synergism simulator has been set up. This facility consists of temperature & humidity chamber, gamma radiation source along with a provision for applying electrical stresses. It is possible to vary magnitudes of these stresses as per design of experiment. Temperature can be varied from room ambient to 80°C with relative humidity up to 95±5%. However, temperature can be varied from room ambient to 150°C when used as temperature chamber alone. Dose rates can be varied from 2 to 30krad/hr. It is also possible to study dose rate effects. Provision has been made for on-line measurement of performance parameters. Dose rate outside the synergism simulator can be varied from 1 to 900krad/hr depending upon the distance of test items with respect to source.
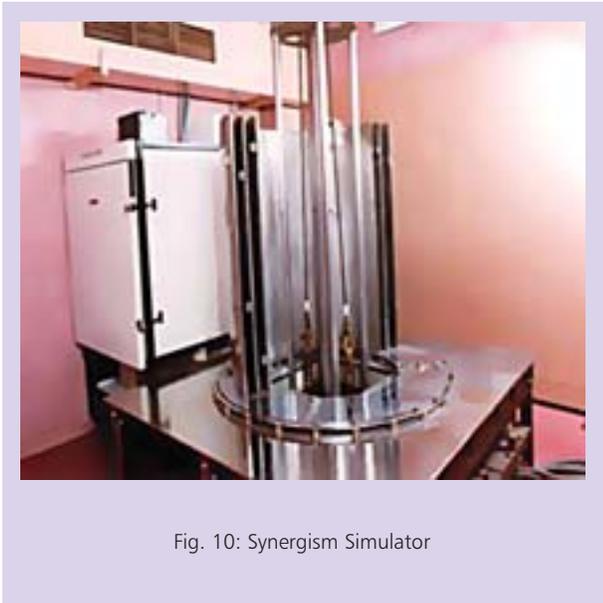
Fig. 10: Synergism Simulator

In LOCA environment qualification studies, C&I components/ equipment and cables are subjected to high humidity and high temperature that simulates the environment the components are likely to encounter, if at all LOCA occurs. LOCA qualification studies are carried out in LOCA simulation test facility that is designed by Reactor Safety Division. The facility is very useful to improve quality and reliability of critical items. Desired LOCA temperature/pressure test profile is achieved by automatic control through Programmable Logic Controller (PLC) using Proportional Control Valves (PCVs) to control the steam flow. The desired LOCA test profile is generated, by NPCIL, from thermal hydraulic calculations of LOCA in the reactor. A typical
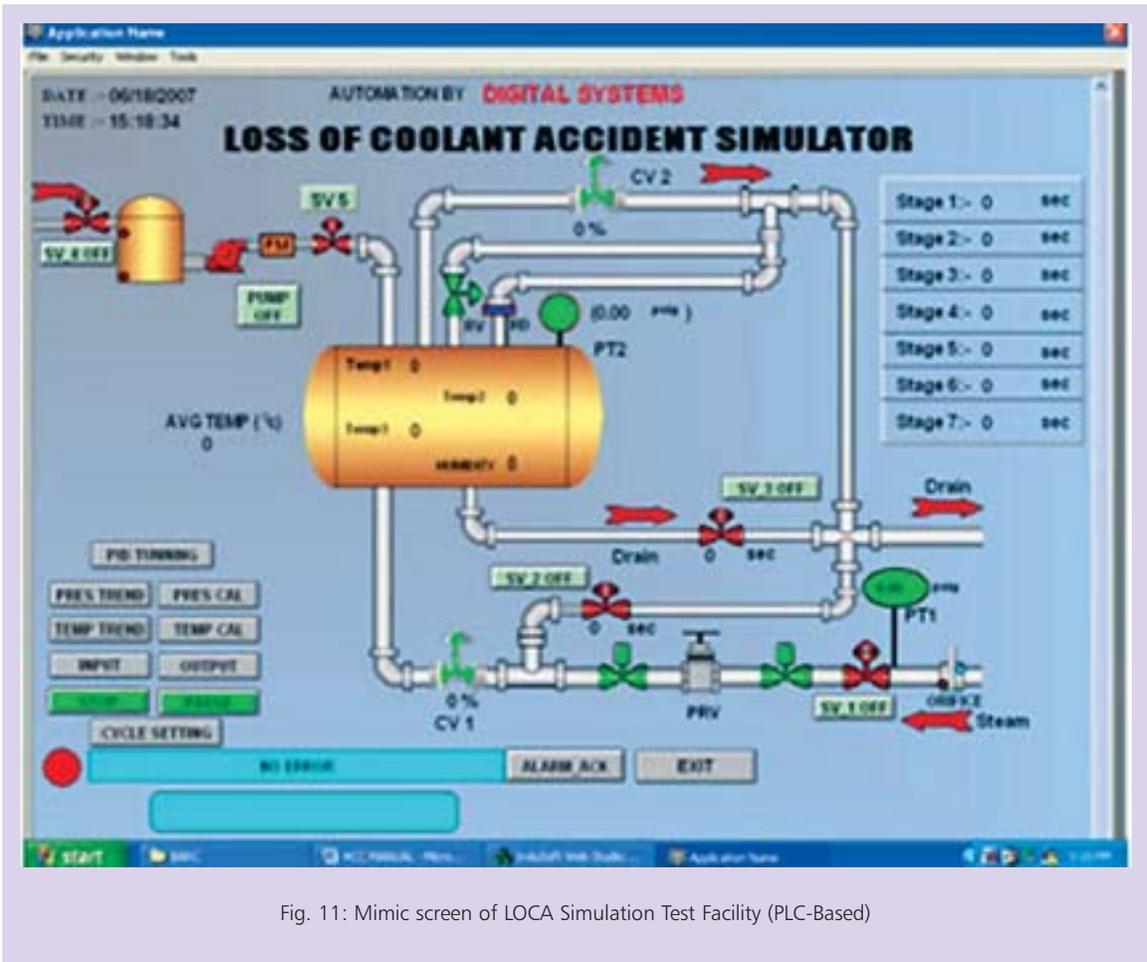
Fig. 11: Mimic screen of LOCA Simulation Test Facility (PLC-Based)

test profile is shown in Fig.12. Maximum steam temperature and pressure achievable in the LOCA chamber are 150°C and 3.4kg(g) (50 psig) respectively. Provision has been made for on-line measurement of performance parameters of the items being tested inside the LOCA chamber. Humidity Generation and control inside the LOCA simulation test facility is also possible to expose the items to the controlled humidity level inside the LOCA chamber. LOCA test facility is useful for testing small components (volume of the chamber is 1 m^3). For testing larger components like Primary Heat Transport pump motors, a larger facility has been set up at Electrical Research & Development Association (ERDA), Vadodara under BRNS Project. These facilities are constantly being used by various users mainly DAE units. Services are being provided to upcoming and operating Nuclear Power Stations regularly in the areas such as (i) Standardisation of new engineering hardware and their procurement, (ii) Estimation of residual life, (iii) Failure analysis and reliability improvement and (iv) Import substitution.

Augmentation of Test and Measurement Facilities for Ageing Studies

Measurement of performance parameters of components and equipments is also very important
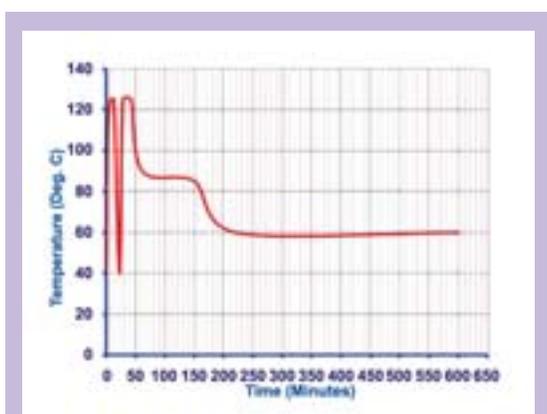
Fig. 12: Typical temperature profile for experiment

activity associated in ageing research studies to judge whether item is ready to perform its intended function under prevailing conditions.

Nuclear Power Plants (NPPs) contain myriads of electrical cables (insulated with some form of polymeric insulation) of various sizes and voltage ratings. Failure of cables is primarily due to the hardening and embrittlement of the insulation resulting in the formation of micro cracks, loss of dielectric strength and high leakage currents. Percentage elongations-at-break (E-at-B) are derived from measurements by tensile tests on cable insulation materials to establish the qualified life. Monitoring cable degradation by measuring E-at-B is in many cases not feasible. Correlation study of the E-at-B with the physical/chemical deterioration of the insulation and jacket materials is an important element and it helps in predicting the cables life. E-at B is generally correlated with Oxidation Induction Time (OIT), weight loss in thermogravimetric analysis and Indenter Modulus (IM).

As explained above, E-at-B and Tensile Strength are basic parameters for prediction of life of cables. Tensile test is performed in accordance with ASTM-D2633-82, using a Universal Testing Machine (UTM) equipped with pneumatic grips and having an extensometer clamped to the sample. Special tensile specimens (dumbbells for larger cables or cylinders for smaller cables) of the insulation or jacket materials without the copper conductor are used for these tests. These tests are destructive, and therefore, many samples are required if tests are conducted regularly.

Thermal analysis on microsamples of cables is mainly non-destructive and is linked to the level of antioxidants present in the polymeric materials. Ageing of cable materials is evaluated by measuring the period of time before a small sample of insulation experiences rapid oxidation when subjected to a constant elevated temperature in an oxygen atmosphere. OIT measurements on artificially aged

specimens are useful to formulate life estimation criteria based correlation with E-at-B values. OIT is carried out using Differential Scanning Calorimeter (DSC) shown in Fig.14. A correlation of E-at-B with OIT has been established for some I&C cables[10].

Ageing affects both the steady state (calibration) and dynamic (response time) performance of sensors (i.e. Resistance Temperature Detectors (RTD), Thermocouples and Pressure Transmitters, solenoid valves, Pressure Switches etc.). Multifunction calibrator (Fig.16), designed by RSD, is being used for calibrating and monitoring the performance parameters of various process instruments during

thermal & radiation ageing studies and LOCA simulation testing of the equipments. One of the important features of this setup is to simulate transmitter input and measure transmitter output.

Apart from above test facilities, various test and measuring instruments are also available in Ageing Research Laboratory in RSD, Hall No. 3. Some of them are; Fully Automatic Capacitance and Dissipation Factor (C&TanDelta) Measuring instrument, Fully Automatic AC Dielectric Breakdown Tester, Insulation Resistance Tester,

Fig. 13: Universal Testing Machine


Fig. 15: DSC thermogram and illustration of DIT Measure


Fig. 14: Differential scanning calorimeter

Fig. 16: Multifunction calibrator pneumatic & hydraulic test pumps and pressure gauges regulators and Indicators along with Mimic Panel
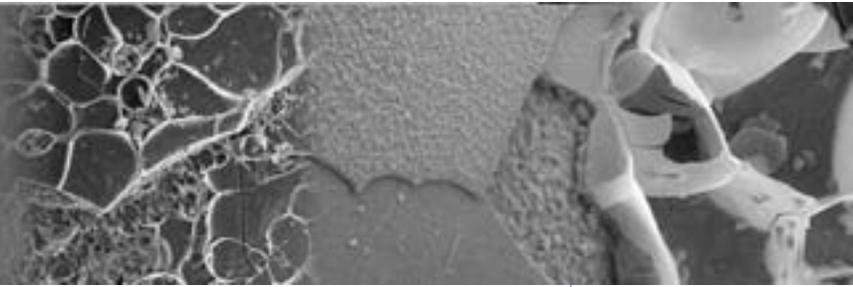
Pneumatic Press Cutting Machine. In addition, instruments like Time Domain Reflectometer for diagnosing cable faults are being procured under XI plan.

Challenges Ahead

In recent years, Nuclear Power Plants have seen a sudden increase in the deployment of digital systems for instrumentation & control functions. This is seen in new NPPs as well as in older plants (replacement of previous analog systems). This analog-to-digital preference is largely driven by the fact that (1) digital systems offer better performance and additional features compared to analog systems, and (2) analog replacement parts are becoming increasingly difficult to obtain. While digital technology has the capability to improve operational performance, the introduction of this technology opened up new challenges for the treatment of these systems in Probabilistic Safety Assessment (PSA). In particular, these challenges include (1) rapid changes in technology used in digital systems (2) new failure modes associated with digital technology; (3) modeling of software and (4) handling the interaction of hardware and software failures.

Traditionally, hardware failures are evaluated using MILSTD 217 F (N2) and its upgrades. But the rapid change in technology and improvements force technologists to look for alternate techniques in the absence of operating experience data. Recently Physics of Failure models are extended to these semiconductor devices, focusing much on the degradation mechanisms and precipitating them through suitable tests. Physics of Failure models looks into modeling the degradation mechanisms possible depending on material of construction, use environment, etc. and using this information in estimating the failure rate. Research is in progress, in Reactor Safety Division, to develop the Physics of Failure models for various degradation mechanisms.

Similarly, modeling of software reliability is a crucial task, and reliability community has still not come to consensus on the standardization of approach to be used. Extensive verification and validation is carried out on software, which qualitatively assures its quality. However, PSA needs a quantitative estimate of software reliability. Applying reliability growth models is one of the techniques for software reliability quantification, which was in practice for software having some failure experience information. However, this approach cannot be extended to new software and more ever it doesn't give any credit to the software development process. Recent trend is to account for software development process, quality standards used, software engineering principles adopted etc. in reliability prediction. This has resulted in harnessing the strength of software engineering metrics for reliability prediction. Research is underway in identifying the critical quality metrics that have bearing on reliability prediction and employing them for estimating reliability. This is also pursued under XIth plan project at Reactor Safety Division.

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70th National Workshop on "Radiochemistry and Applications of Radioisotopes": a report

The 70th BRNS-IANCAS National Workshop on Radiochemistry and Applications of Radioisotopes was jointly organized by the Indian Association of Nuclear Chemists and Allied Scientists (IANCAS) and the Department of Chemistry, Yogi Vemana University, Kadapa, during 17-25 August, 2009. The inaugural function was held on 17th August, 2009, which was presided over by honorable Vice Chancellor of Y.V. University, Prof. A. Ramachandra Reddy. Dr. V. Venugopal, President, IANCAS and Director, Radiochemistry and Isotope Group, BARC inaugurated the Workshop. Dr. P.V. Nagendra Kumar, Academic Consultant, Department of Chemistry, welcomed the resource persons, participants, faculty members and students. Dr. A.G. Damu, Head, Dept. of Chemistry, Y.V. University and Convener of the Workshop gave a brief account of the activities of the Chemistry Department. Dr. A.V.R. Reddy, Secretary, IANCAS and Head, Analytical Chemistry Division, BARC talked on the aims and objectives of IANCAS and its activities in developing partnerships with academic institutions. Dr. Veena Sagar, Treasurer, IANCAS and coordinator of the Workshop, described the technical programme. In his presidential remarks, Prof. A. Ramachandra Reddy said, that such Workshops will be useful for creating an atmosphere backed by high quality science, for taking up new challenges and also motivating young students to take up science as a career. Dr. V. Venugopal, in his keynote address gave an "Overview of Atomic Energy Programme" and emphasized the need for energy in general and nuclear energy in particular. He said that nuclear energy is a clean form of energy and economically viable. Apart from expanding the energy base, radioisotopes and radiation find applications that benefit society. Dr. Subramanyam Sarma, Assistant Professor, Department of Chemistry, Y.V. University proposed vote of thanks.

Inaugural Session: (left to right) Dr. V. Venugopal, Prof. A. Ramachandra Reddy, Dr. A.V.R. Reddy and Dr. Veena Sagar

The Workshop programme consisted of lectures in the morning sessions and laboratory experiments in the evening sessions. A total of 50 delegates participated in the Workshop. They were provided with two IANCAS books, (1) Fundamentals of Radiochemistry and (2) Experiments in Radiochemistry. 12 lectures covering various aspects of Radiochemistry and applications of isotopes were delivered. Two special lectures on (1) Mining of uranium ores and application of nuclear techniques for minerals and (2) Radioisotopes in biotechnology were included. Six experiments on the use of radiation detectors, use of sealed sources and separation of radioisotopes from uranium and thorium were conducted.

The valedictory function was held on 25th August, 2009. Prof. A. Ramachandra Reddy and Mr. B. K. Sen, Vice President, IANCAS and Head, Product Development Division, BARC gave away the certificates to the participants. Two instruments namely G. M. counter and NaI(Tl) gamma scintillation detector-based gamma spectrometer along with the sealed sources, were handed over by Mr. B.K. Sen to Prof. A. Ramachandra Reddy. The instruments will be kept with the Chemistry Department and Dr. A.G. Damu, Head Dept. of Chemistry was given the responsibility of the instruments and the radioactive sealed sources. He assured that the instruments would used for research as well as for lab experiments by Post Graduate students.

Forthcoming Conference

2nd International Conference on Reliability, Safety and Hazard – 2010 (Risk-based Technology & Physics-of-Failure Methods)

The above conference is being organized by BARC, CALCE, University of Maryland, USA International Inst. of Info. Technology, Pune, India and will be held at Vashi, Navi Mumbai, from 14-16 Dec., 2010.

The objective of this conference is to provide a forum for technical discussions on recent developments in the area of risk-based approach and role of physics-of-failure methods in decision making.

The conference invites research and technical papers of high quality, bringing out the original contributions, for presentation in the conference proceedings. It is proposed to publish a book containing the papers presented in the conference.

Application areas include: Nuclear Power Plants & Research Reactors, Chemical and Processing Plants, Aerospace and Navigation Systems, Infrastructural, Software Systems, Health Care Systems, Transport and Monitoring Systems, Nuclear Facilities, Structural Systems, Electronics & Communication Systems.

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Bhabhatron-II Teletherapy Unit Inaugurated at Can Tho Oncology Hospital, Vietnam

During the IAEA General Conference (2006), our Prime Minister Dr. Manmohan Singh offered a new indigenously developed Telecobalt unit Bhabhatron to the International Atomic Energy Agency (IAEA) to support the Programme of Action for Cancer Therapy (PACT) Initiative of the Agency. Subsequently, a tripartite agreement was signed between India, Vietnam and the IAEA in 2007 to install the machine at Can Tho Oncology Hospital. However, the unavailability of a shielded room required for this type of machine, resulted in delay in the shipment of the unit. Finally, the machine was commissioned in December 2009. The high capacity cobalt-60 radioactive source was provided by the Board of Radiation and Isotope Technology (BRIT). The commissioning was done by M/s. Panacea Medical Technologies Pvt. Ltd., Bengaluru. The unit was inaugurated on 28th April, 2010, by His Excellency Lal T. Muana, Indian Ambassador to Vietnam. Eminent doctors from Vietnam and neighbouring countries, representatives from the IAEA, attended the inaugural function.

Manjit Singh, Director, Design Manufacturing & Automation Group, BARC, speaking on the occasion.

(From L-R): Dr. H. Q. Thang (Director, Can Tho Oncology Hospital),
H. E. Lal T. Muana, Manjit Singh and Dr. Werner Burkart

At the inauguration ceremony, Dr. Werner Burkart, Deputy Director General, Dept. of Nuclear Sciences and Applications, IAEA, expressed his deep appreciation to the Government of India for the donation.

Can Tho is the largest city in the Mekong Delta, with a population of over one million, previously had no radiotherapy facility for the treatment of cancer patients.

The Bhabhatron unit commissioned at Can Tho Oncology Hospital will now make radiotherapy accessible to nearly 20 million people living in the region.

BRNS Theme Meeting on "Environmental Baseline Studies for Nuclear Installations"

The Health, Safety and Environment Group of BARC, organized a two-day theme meeting on Environmental Baseline Studies for Nuclear Installations during Feb 11-12, 2010. The theme meeting was attended by more than 100 experts including those from the Ministry of Environment and Forest, Atomic Energy Regulatory Board, Nuclear Power Corporation of India Limited, Heavy Water Board, Indian Rare Earths Limited, Nuclear Fuel Complex, Uranium Corporation of India Limited, Atomic Minerals Directorate for Exploration and Research and Indira Gandhi Centre for Atomic Research. Welcoming the experts, Mr. V. D. Puranik, Head, Environmental Assessment Division said, that environmental surveillance programme for nuclear activities in our country was started at a time when environmental data was either sparse or non existent for most of the locations. The care and concern for environment shown by nuclear industry slowly permeated to other industrial activities and today it is mandatory to have baseline studies in different components of environment, for an environmental management plan for any proposed industrial activity. In his introductory address, Mr. H. S. Kushwaha, Director, Health, Safety and Environment Group stressed the need for baseline studies, considering it as an important aspect in environmental assessment. He further elaborated that nuclear industries conduct two types of EIA studies, viz. rapid EIA for clearing site from

Release of Protocol booklets by Dr. Anil Kakodkar

government/regulatory authorities and comprehensive EIA for baseline studies. For a meaningful baseline survey, emphasis is being given to a standard protocol accepted by the regulatory agencies of the country. Dr. Anil Kakodkar, former Chairman, Atomic Energy Commission and Homi Bhabha Chair Professor, stressed the need to develop skilled human resources at university level, in order to contribute baseline studies to be carried out around proposed nuclear sites. Dr. Anil Kakodkar released the current series of five protocols published by the Health, Safety and Environment Group and developed by experts in the field covering sampling, analysis and statistical interpretation of data. The five protocols are:

1. Protocol for Conducting Pre-Operational Environmental Surveillance around Nuclear Facilities
2. Protocol on Hydrogeological Characterization and Groundwater Modeling for Nuclear Facility Sites
3. Protocol for Baseline Study on Demographic Pattern and Health Profile around the Proposed Nuclear Facilities
4. Protocol for Assessment of Radiological Risk to Non Human Biota
5. Protocol for Survey of Flora and Fauna.

He hoped that this will also ensure transparency in activities related to the environmental aspects of all the nuclear facilities in the country, so as to comply with the requirements of regulatory bodies.

Dr. R. M. Tripathi, Head, RPS(NF), Environmental Assessment Division thanked the academicians and officials from regulatory agencies including Ministry of Environment and Forest (MoEF), key persons involved in development of the protocols and invited speakers, for participating in this theme meeting covering various environmental aspects related to ongoing and proposed nuclear facilities of the country. Dr. S. K. Jha coordinated the technical programme of the theme meeting.

DAE-BRNS Symposium on Emerging Trends in Separation Science and Technology (SESTEC-2010): a report

The DAE-BRNS Symposium on "Emerging Trends in Separation Science and Technology (SESTEC-2010)" was held in the Vikram Sarabhai Auditorium of the Indira Gandhi Centre for Atomic Research (IGCAR), Kalpakkam, during March 1-4, 2010. Dr. T.G. Srinivasan, Chairman LOC, SESTEC-2010 and Head, FCD, IGCAR welcomed the delegates. Dr. V.K. Manchanda, Convenor, SESTEC-2010 and Head, Radiochemistry Division, BARC outlined the programme of the Symposium and acknowledged the overwhelming response received from delegates within the country as well as from overseas. Prof. G.D. Yadav, Director, Institute of Chemical Technology (ICT), Mumbai in his inaugural address, highlighted the importance of forging alliances between academia and research institutes for national benefit. Dr. V. Venugopal, Director, Radiochemistry and Isotope (RC&I) Group, BARC highlighted the important role of separation science in the nuclear fuel cycle. Mr. S.C. Chetal, Director, Reactor Engineering Group, IGCAR in his Presidential address emphasized the challenges in

At the inaugural function from left to right are: Dr. T.G. Srinivasan (Head, Fuel Chemistry Division, IGCAR & Chairman-LOC, SESTEC-2010, Mr. S.C. Chetal, Director, Reactor Engineering Group, IGCAR, Prof. G.D. Yadav, Director, ICT, Mumbai, Dr. V. Venugopal, Director, RC&I Group, BARC, Dr. V.K. Manchanda, Head, Radiochemistry Division, BARC & Convenor, SESTEC-2010, Dr. P.N. Pathak, Secretary, SESTEC-2010

the area of separation science and technology for the fast reactor fuel cycle. Dr. P.N. Pathak, Secretary, SESTEC-2010 proposed the vote of thanks.

DAE-BRNS sponsored SESTEC symposium series was conceived in 2004 to provide a platform to researchers for exchanging ideas and emerging trends in the area of Separation Science & Technology. In a short span of 6 years, this symposium has gained importance and is now recognized as a major event in the area of Separation Science & Technology in the country. Special volumes of "*Desalination*" based on contributions at SESTEC-2006 (Vol. 232, 2008) and of '*Desalination and Water Treatment*' (Vol. 12, 2009) based on contributions at SESTEC-2008 have been published. It is heartening to note that 227 contributory papers (17 Oral and 210 Poster presentations) in SESTEC-2010 were authored by scientists from 5 National Laboratories and 16 academic institutions apart from various DAE units. The invited speakers (31 including 16 from overseas) in SESTEC-2010 were outstanding scientists/ technologists and represented 11 countries. Approximately seventy-five delegates from BARC participated in the Symposium. All the posters were rapporteured by young scientists.

Apart from solvent extraction and ion exchange, a wide range of topics related to separation science and technology were covered. It included: design, synthesis and characterization of solvents and resins, design and development of separation equipments, separation science and technology in the nuclear fuel cycle, emerging separation technologies, electrochemical and pyrochemical separations, treatment of industrial effluents, isotope separations, membrane science and technology, radiochemical separations, and water treatment and recycling. There was a very lively interaction between the young scholars and the experts during Poster sessions.

Mr. A.L.N. Rao, Chief Executive, Heavy Water Board, Mumbai delivered an evening special public lecture on "*Difficult Separations – Heavy Water Board's Four Decade Journey*" on March 1, 2010.

In the concluding session, a panel discussion was conducted where Dr. P.R. Vasudeva Rao, Director, Chemistry Group, IGCAR, Dr. G.D. Jarvinen, Los Alamos National Laboratory, USA, Prof. G. Cote, ENSCP - Chimie ParisTech, France, Mr. S.K. Ghosh, Director, Chemical Engineering Group and Dr. V.K. Manchanda, Convenor SESTEC-2010 participated. All the speakers provided their perspective about SESTEC-2010 and on the future directions of separation science and technology. The prizes for best Oral and Poster presentations were also distributed by Association of Separation Scientists & Technologists (ASSET). A feed back session was arranged to seek suggestions for future programmes.

Fire Safety Training Programme for Fire Squad Members in Central Complex (CC) Building

The Ministry of Urban Development GoI, has issued general instructions to prevent fire incidents in all Government buildings. In order to prevent fire incidents, several measures have been suggested, which include conducting fire emergency drills frequently in Government buildings. As a part of this exercise, a one-day Training programme on Fire Safety was organized on 26th March 2010, by the Fire Services Section, to familiarize the fire squad members of the Central Complex building, with fire fighting operations/methods. More than100 personnel participated in the programme. Mr. R. P. Raju, Convener of the Task Force for conducting fire drill in the CC building welcomed the speakers, invitees and participants of the training programme and briefed them about the necessity of conducting such training programmes and the action plan of the task force for conducting emergency exercises in Central Complex. Mr. N. D. Sharma, Controller, BARC in his inaugural address to participants of the training programme shared his views on fire safety and the role and responsibility of the occupants in keeping the building safe.

Mr. A.K. Tandle, Chief Fire Officer emphasized in his lecture that fire emergency/evacuation exercise should be carried out as per the regulations of the National Building Code Part IV, to prepare the occupants to evacuate the building in an orderly and systematic manner in case of a fire emergency. He also insisted that fire emergency plan should be developed based on hazards and needs of the building/organization.

Mr. R. S. Agrahari, Dy. Chief Fire Officer delivered a detailed lecture on 'Fire Safety Aspects' describing the first-aid fire fighting equipment and their usage and general fire precautions to be taken, to ensure fire safety in the buildings and also particularly in high rise buildings.

Mr. K. P. S. Pillai, Member-Secretary of the Local Safety Committee for CC building gave vote of thanks.

A separate Live fire fighting demonstration session was also organized using different types of fire extinguishers and fire hydrants with different types of water spraying nozzles.

Inaugural address by Mr. N. D. Sharma, Controller, BARC.
On the dais (L-R): Mr. R. S. Agrahari, Dy. Chief Fire Officer, Mr. K. P. S. Pillai, Member-Secretary of the Local Safety Committee for CC building, Mr. A.K. Tandle, Chief Fire Officer

National Technology Day at BARC: a report

The National Technology Day was celebrated at the Central Complex Auditorium in BARC on the 11th of May 2010.

The Chief Guest for the morning session of the function was Prof. A.B. Pandit from the Institute of Chemical Technology, Matunga, Mumbai. Dr. R.B. Grover, Director, Knowledge Management Group welcomed the speaker and introduced him. While introducing him, he highlighted the fact that in today's knowledge-driven economy, an individual who imparts knowledge successfully is an asset to the nation. Dr. Grover also informed the audience that Prof. Pandit has received the **ICT Best Teacher Award** on 10 occasions in the last 15 years.

Prof. Pandit gave a presentation on 'R&D Knowledge Sharing and Technology – Some Random Thoughts'. In his talk, he referred to a large number of research papers published in national and international journals by Indian scientific community and commented on the lack of their transformation into technologies. He analyzed the reasons and also reviewed a successful model which was being followed by ICT and DAE, for implementation of the scientific knowledge developed through a variety of targeted projects with known deliverables. He further discussed specific successful case studies.

The Department of Atomic Energy felicitates Scientists and Engineers of its various units, who have carried out in meritorious research work, by awarding them with the Homi Bhabha Science & Technology Awards. The nine distinguished awardees, who were given the awards in 2009, delivered lectures on the topics of their research, during the afternoon session. Three parallel sessions were organized. One session was held at the Briefing Room, CC Auditorium, where Dr. Tulsi Mukherjee, Director, Chemistry Group chaired the session. He was assisted by Mr. R.K. Sharma, Head, Media Relations & Public Awareness Section, SIRD. The second session was held at the Computer Centre Auditorium, where Mr. R.K. Patil, Associate Director (C) E&IG chaired the session. He was assisted by Mr. Manoj Singh, SIRD and the third parallel session was held at 'D' Block Auditorium, Mod Labs, where Dr. V.K. Handu, Head, TPPED chaired the session. He was assisted by Dr. K. Bhanumurthy, Head, SIRD.

Chief Guest of the function,
Prof. A.B. Pandit from the Institute of
Chemical Technology, Matunga, Mumbai.

Welcome address by Dr. R.B. Grover, Director,
Knowledge Management Group

Following presentation were made in the three sessions:

Mr. N. Sivaraman, Chemistry Group, Indira Gandhi Centre for Atomic Research (IGCAR) on *'High Performance Separations of lanthanides & actinides'*; Dr. Haridas Pal, Radiation & Photochemistry Division, Chemistry Group on *'Tuning Photochemical Properties using Supramolecular Approach & Possible Applications';* Dr. P.K. Pujari, Radio Chemistry Division, Radiochemistry & Isotope Group, BARC on *'Positron Spectroscopy: Nanostructures to large engineering materials'*; Dr. Alok Chakrabarti, RIB Group, Variable Energy Cyclotron Centre (VECC) on *'RIB Development at VECC-goals and achievements'*; Dr. Subhashish Mazmumdar's lecture was presented by Dr. Debasis Sen, Solid State Physics Division, Physics Group, BARC on 'Theoretical aspects of Small Angle Neutron Scattering and Small Angle X-ray Scattering', Dr. S.M. Yusuf, Solid State Physics Division, Physics Group, BARC on 'Functional Magnetic Materials: Magnetic Properties and Possible Applications'. Mr. A. Rama Rao, Reactor Engineering Division, Reactor Design & Development Group, BARC on 'Vibration as a Diagnostic Tool for Health Monitoring of Machines, Structures & Equipments'; Dr. A.K. Sinha, Centre for Design & Manufacture, BARC on 'Design & Development of Instruments

Mr. N. Sivaraman, Chemistry Group,
Indira Gandhi Centre for Atomic Research (IGCAR)
delivering the presentation

Dr. P.K. Pujari, RCD, RC&IG being felicitated by
Dr. T. Mukherjee, Director, CG

Dr. Haridas Pal, Radiation & Photochemistry Division,
Chemistry Group delivering the presentation.

Dr. Alok Chakrabarti, RIB Group,
Variable Energy Cyclotron Centre (VECC)
delivering the talk.

Dr. S.M. Yusuf, Solid State Physics Division,
Physics Group, BARC delivering the presentation.

Dr. A.K. Sinha, CDM being felicitated by
Mr. R.K. Patil, AD, E&IG

Dr. Subhashish Mazmumdar's lecture
was presented by Dr. Debasis Sen,
Solid State Physics Division, Physics Group, BARC

Mr. Rajesh Kalmady being felicitated by
Mr. R.K. Patil, AD, E&IG

for Synchrotron Beam lines Applications and Sub-Reflector Positioning Mechanism of DSM Antenna' for Chandrayaan-1; Mr. Rajesh Kalmady, Computer Division, Electronics & Instrumentation Group, BARC on 'Developments in High performance computing and grid computing in BARC'.

All the nine lectures were well received by the audience. The speakers tried to use simple informal language and gave their presentations in a lucid manner.

Dr. A. Rama Rao, RED being felicitated by
Mr. R.K. Patil, AD, E&IG

Nuclear Energy for National Development: a report

Public awareness programmes on nuclear Energy, were conducted in Varanasi on March 24th and 25th, 2010. The programmes were conducted in Banaras Hindu University for Faculty of Science students, Institute of Information Technology students and the students of Institute of Agricultural Sciences. Dr. R. Chidambaram, Principal Scientific Adviser to the Government of India was the Chief Guest and he inaugurated the programme. He also gave a keynote address on 'Nuclear Energy & Climate Change'. Faculty from BARC included Dr. K. Bhanumurthy, Head SIRD who spoke on 'the Role of Nuclear Power in National Power Programme. Dr. J.G. Manjayya, NABTD on 'Application of Nuclear Energy in Agriculture Biology', Mr. S.K. Singh, HRDD on 'Career Opportunities in the Department of Atomic Energy and the Homi Bhabha National Institute' and Mr. R.K. Sharma, Head, MR&PAS on 'Radioisotopes in Healthcare and BARC Technologies – Societal Impact'. Over 400 students and faculty members attended the seminar. Their enthusiasm was evident from the fact that the auditorium was jam-packed. Their strings of questions were responded to.

Seated in the centre Dr. R. Chidambaram. To his right are Mr. R.K. Sharma, SIRD, BARC, Mr. S.K. Singh, HRDD, BARC, Dr. J.G. Manjayya, NA&BTD, BARC, Prof. Rajesh Singh, BHU. To his left are Prof. B.D. Singh, Rector, BHU, Prof. Shiv Raj Singh, Director, Institute of Agricultural Sciences, BHU, Prof. S.C. Lakhotia, Dean, Faculty of Science, BHU, Prof. Virendra Singh, Dean, Institute of Technology, BHU.

Dr. R. Chidambaram with the group of Essay Competition winners

The jam-packed auditorium with the students seated on the steps too!

Scientists – Farmers' meet at Rajiv Gandhi South Campus, BHU, Barkacha. Dr. K. Bhanumurthy, Head, SIRD seated in the centre. To his right are Mr. S.K. Singh, HRDD, BARC, Dr. J.G. Manjayya, NA&BTD, BARC, Prof. Rajesh Singh, BHU. To his left are Prof. Onkar Singh, OSD, BHU & Mr. R.K. Sharma, SIRD, BARC.

The second programme was held on the Rajiv Gandhi South Campus, Barkacha for the students of the Institute of Technology. The programme was inaugurated by Dr. K. Bhanumurthy, Head, SIRD. A special programme for farmers and NGOs was also organized at Barkacha. The programme was very useful to the farmers and they appreciated the efforts of BARC Scientists in the area of Nuclear Agriculture.

The programme involved broader student involvement in the form of essay competition and prizes were also distributed. Both the programmes at Varanasi were well received and interaction with the students helped in clarifying queries related to Nuclear Power, Careers in BARC and technologies for rural development.

Both the programmes were organized with co-ordination from Director, Institute of IT, Director, Institute of Agricultural Sciences, Prof. S.C. Lakhotia, Dean, Faculty of Sciences, BHU and Prof. Rajesh Singh, Chairman, Press, Publication & Publicity Cell, BHU.

Report on '' THERMOWORK 2010 ''

The DAE – BRNS Workshop on Computational Thermodynamics and Phase Diagram Calculations (THERMOWORK 2010) was held at the Homi Bhabha Centre for Science (HBCSE) Education, Mankhurd, Mumbai during March 3-4, 2010.

There was overwhelming response to the workshop from all over India. But due to limitation of class room facilities, where hired laptops had to be installed, the number was restricted to about 50 participants. The participants were from BARC, IGCAR and NML, Jamshedpur.

Dr. T. Mukherjee, Director, Chemistry Group, BARC, welcomed the participants of the workshop and highlighted the importance of computational thermodynamics and the activities in BARC in this

area. Dr. H.C. Pradhan, Director, HBCSE spoke about the activities of the Centre and the relevance of such educational activity being held at HBCSE. Dr. D. Das, Head, Chemistry Division, BARC, highlighted the salient features of the workshop and indicated how this kind of hands-on workshops are more beneficial to the participants.

The workshop was inaugurated by Dr. Srikumar Banerjee, Chaiman, AEC. In his inaugural address, Dr. Banerjee elaborated the various computational methods used by thermochemists. He described in detail, about the importance of phase diagram calculations, for computational thermodynamics, as thermochemical data for metastable phases can only be evaluated by computational methods. Dr. Banerjee cited several examples where

A view of the class room with Prof. Pelton explaining the capabilities of the FACTSAGE Software for
phase diagram calculations and evaluations of various chemical equilibria.
The participants are able to carry on the computations on their laptops simultaneously

computational thermodynamics and phase diagram calculations, have been extremely useful in designing and evaluating materials for specific purposes. He highlighted the example of the role played by thermodynamic calculations, in the development of the unique mixed carbide fuels, its contribution to the out-of-pile studies on Mark I carbide fuel fabricated by BARC scientists for FBTR. He also pointed out that computational thermodynamics will have a greater role to play in the coming years, as the Department of Atomic Energy is taking on the challenging tasks pertaining to PFBR, AHWR, CHTR fuel development etc. and workshops of this kind will definitely encourage scientists to take on those challenges.

FactSage is one of the largest fully integrated database computing systems for thermochemical calculations, involving multiphase and multicomponent equilibria. Professor Arthur D. Pelton, CRCT, Ecole Polytechnique Montreal, Canada, who is one of the original developers of FactSage, gave comprehensive lecture demonstrations on this software for two days.

The salient features of the workshop were:

- The software and databases were demonstrated in real time, along with case studies of advanced applications.
- The FactSage software and all databases were temporarily installed on the participants laptops'.
- Instruction manuals with extensive annotated input/output examples were provided for all the participants.

Forthcoming Conference
21st International Conference on Structural Mechanics in Reactor Technology (SMiRT 21)

The Homi Bhabha National Institute will host the above conference at the India Habitat Centre, New Delhi, India, from November 6-11, 2011. This conference, the 21st in the series will aim to cover all professional, practical and technical issues, related to Structural Mechanics in Reactor Technology. The topics covered would be

- Mechanics of Materials
- Fracture Mechanics and Structural Integrity
- Applied Computations, Simulation and Animation
- Characterization of Loads.
- Modeling,Testing and Response Analysis of Structures, Systems and Components
- Design and Construction Issues
- Safety, Reliability, Risk and Margins
- Issues Related to Operations, Inspection and Maintenance
- Waste Management, Fuel Cycle Facilities and Decommissioning
- Challenges of New Reactors

Important Dates

- **December 2010 -** Deadline for abstract submission
- **March 2011 -** Planning session and General Assembly
- **April 2011 -** Notification of abstract acceptance and paper submission
- **September 2011 -** Deadline for paper submission
- **November 2011 -** SmiRT 21 Conference

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Safe Drinking Water: Water Purification Technologies developed at BARC

Availability of safe drinking water is a major concern for the people as well as the government. BARC has contributed towards this goal, by developing and transferring to industry, the following water purification technologies:

"Membrane Assisted Defluoridation Process for Safe Drinking Water" technology: This process consists of two steps. The first is sorption of fluoride on activated alumina (Al_2O_3). This is the prevailing practice for Defluoridation. The second step involves separation of secondary contaminants like aluminium, micro-organisms etc., using indigenously developed UF membrane device. The process provides safe drinking water, free from fluoride, aluminium and micro-organisms. It can be adopted at both domestic and community levels, with/without the use of electricity.

This technology was transferred to:

a) M/s LTEK Systems, Nagpur on 21st January, 2010

Photograph after signing the technology transfer agreement with M/s Rupali Industries, Mumbai.
Seen from left to right are Mr. V. K. Upadhyay, TT&CD, Dr. A. K. Ghosh, DD, Dr. S. Prabhakar, Head, STS, DD,
Dr. P. K. Tewari, Head, DD, Mr. Rahul Repale, Mr. Ramdas Repale,
Ms. Rupali Repale, from M/s Rupali Industries, Dr. R. C. Bindal, DD, Mr. A. M. Patankar, Head, TT&CD,
Mr. B. K. Pathak, Head IPMS, TT&CD, Ms. S. S. Murudkar, TT&CD.

b) M/s Rupali Industries, Mumbai on 24th February , 2010

c) M/s Ajay Industrial Corporation Ltd., Delhi on 26th February, 2010.

"Arsenic Removal from Drinking Water Ultra Filtration Membrane Assisted Process" technology: This process also consists of two steps. The first step is sorption of arsenic species on *in situ* generated sorbent, through addition of two preformed reagents and second is separation of this arsenic containing sludge, using indigenously developed UF membrane device. The process is adaptable at both domestic and community levels. It can remove arsenic contamination from ground/surface water having concentrations of 500 ppb or more, to less than 10 ppb.

This technology was transferred to M/s LTEK Systems, Nagpur on 21st January , 2010.

"Back Washable Spiral Ultra Filtration Technology for Domestic and Industrial Water Purification" technology: It consists of a Backwashable spiral ultrafiltration (UF) membrane element. Polysulphone membrane sheets are wound in spiral configuration. The unit can produce crystal clear water with respect to microorganisms, suspended solids and colloids. The special feature is the backwashability of the UF element, to restore

Photograph after signing the technology transfer agreement with M/s LTEK Systems, Nagpur.
Seen from right to left are Dr. D. Das, Head, ChD, Dr. S. R. Bharadwaj, Head, FCM&C Section, ChD,
Dr. A. D. Belapurkar, Ex. BARC, Dr. T. Mukherjee, Dir. Chemistry Group, Dr. C. L. Lakhotia, M/s LTEK,
Mr. Rahul Dhabu, M/s LTEK, Mr. V. K. Upadhyay, Mr.. S.S. Kulkarni,
Mr. B. K. Pathak Ms. S.S. Murudkar from TT&CD.

its stabilized pure water flux. These units can be used for domestic as well as industrial purposes.

This technology was transferred to M/s LTEK Systems, Nagpur on January 21st, 2010.

"On-line domestic water purifier, based on ultrafiltration polysulfone membrane" technology: This device is based on polysulfone type of ultrafiltration membrane, which is coated on a cylindrical configuration. It is very effective as it removes bacteria to the extent of > 99.99% (4 log scale) and removes complete turbidity and produces crystal clear water. This device does not need electricity or addition of any chemical. It is almost maintenance-free, except for occasional cleaning of suspended solids which deposit on the membrane surface and this does not take more than a few minutes. It produces about 40 liters of pure water per day at about 5 psig head and works from 5 psig to 35 psig.

This technology has earlier been transferred to 18 parties. Recently this has been transferred to:

a)   M/s. Aurangabad Food Industries, Aurangabad on 24th December, 2009.
b)   M/s Fontek Corporation, Navi Mumbai on 19th March, 2010.

The four technologies discussed above were developed by the Desalination Division.

"Domestic Water Purification Device based on photocatalysis using Solar Light" technology: The technology was developed by the Chemistry Division. This Domestic water purification device is based on photocatalytic disinfection of water, with non-toxic, reusable TiO_2 photocatalyst using solar light. A prefilter like polypropylene candle or asbestos container with polypropylene cloth filter and activated charcoal removes suspended particles and dissolved organics from water. The free radicals generated by the photocatalyst kills microbial contamination. The device does not require electricity or chemicals. The device purifies water in batch mode.

This technology was transferred to:

a)   M/s LTEK Systems, Nagpur on 21st January, 2010.
b)   M/s Ajay Industrial Corporation Ltd., Delhi on 26th February, 2010.

The Technology Transfer and Collaboration Division coordinated all the activities related to the transfer of these technologies.

Theme Meeting and Round Robin Exercise on Pushover Test on Prototype RCC Structure: a report

Earlier, the Reactor Safety Division (RSD), BARC along with Central Power Research Institute (CPRI) Bangalore conducted a round robin exercise and theme meeting on pushover test on prototype Reinforced Concrete structure on 01/05/2008 and 02/05/2008 at CPRI Bangalore. The structure tested was a replica of a substructure of an existing office building at BARC. At the outset, Dr. G.R. Reddy, BARC introduced all the participants about the requirement and objectives behind the exercise. Mr. Akanshu Sharma, BARC provided the details of designs and was followed by Dr. Ramesh Babu and Mr. M.N. Gundu Rao of CPRI to give information on construction and instrumentation aspects. This was followed by presentations by participants of the theme meeting namely BARC, NPCIL, DCS&EM, AERB, IIT Bombay, IIT Delhi, IIT Madras, IIT Roorkee, IIT Guwahati, NITK Surathkal, CPRI Bangalore, SERC Chennai, Thapar Institute of Technology Patiyala and Tyagarajar College of Engineering.

The theme meeting was followed by the experiment, which was inaugurated by Chairman, Atomic Energy Commission along with Director, BARC and Director-General, CPRI. The structure was tested till failure. Fig. 1 shows the structure being tested at the tower testing facility at CPRI Bangalore.

This structure was then repaired and retrofitted using Fiber Reinforced Polymer Composites (FRPC). Again, a two-day theme meeting on 24-25 March, 2010 was conducted where Dr. Ramesh Babu, CPRI gave the welcome address and Dr. G.R. Reddy, BARC briefed all the participants about the exercise. Researchers, working in the field of pushover analysis and repairs and retrofitting of RCC structures participated in the exercise. The institutes/

Fig. 1: Testing of original structure

organizations who participated in the second phase of the exercise included, BARC, NPCIL, DCS&EM, IIT Bombay, IISc Bangalore, CPRI Bangalore, SERC Chennai, Thapar Institute of Technology Patiyala, UVCE Bangalore, IIIT Hyderabad, SIT Tumkur and PSN College of Engineering Tirunelveli, Sardar Patel College of Engineering, Mumbai. Binyas Contech Pvt. Ltd., Bangalore and R&M International, Mumbai provided the necessary support for repair and retrofitting of the structure. On the next day, the structure was tested till failure. Fig. 2 shows the retrofitted structure being tested at CPRI Bangalore. Fig. 3 shows the theme meeting in progress and the participants taking part in the experiment.

Fig. 2: Testing of retrofitted structure

In-Situ Free Vibration Test

In order to evaluate the fundamental frequency of the structure in the two directions, before commencing the pushover test, a free vibration test was conducted for the retrofitted structure. Highly sensitive accelerometers were placed at different floors to pick up the vibration signal generated by the blow of a hammer. Fast Fourier Transform (FFT) of the signal gave the information on the fundamental frequency of the structure.

Experimental Results

The pushover curves as obtained for as built and retrofitted structure are shown in Figs. 4 and 5 respectively. The curves were plotted till large damage occurred at various locations and no significant lateral load resistance remained in the structure.

Fig. 3: Theme meeting and experiment under progress
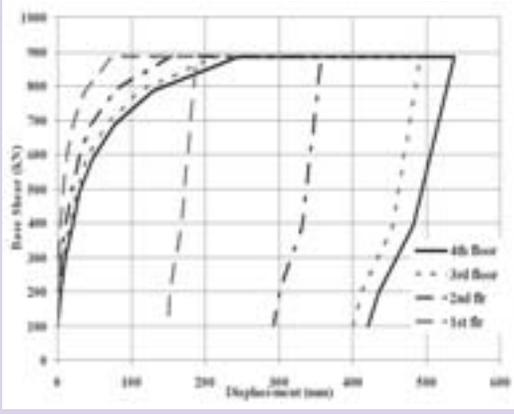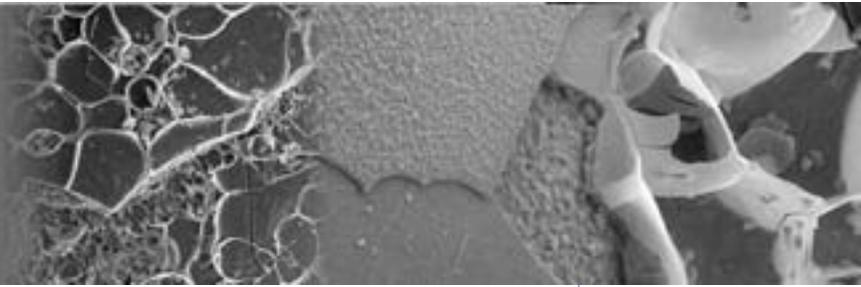
Fig. 4: Pushover curve for original structure
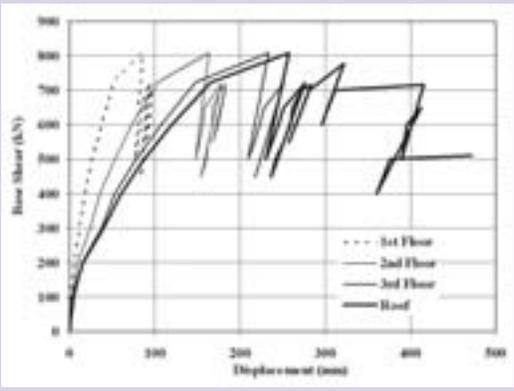
Fig. 5: Pushover curve for retrofitted structure

As seen from the plots, the original structure could resist a peak base shear of around 900 kN. During the test, the structure displayed various failure modes and at the end of the test, the structure could not resist any significant lateral load. However, the structure after being repaired and retrofitted with the FRPC could be restored up to almost 90% of its original state and the retrofitted structure could resist a peak base shear of around 800 kN. Till date, almost all the tests on FRPC retrofitting have been conducted at component level or small scale structural level. The results of this test could therefore very well prove the efficacy of the retrofit system using FRPC.

Failure Patterns

A few failure patterns of the as built and retrofitted structure are shown in Figures below. Fig. 6 shows typical beam failures observed in the test. The beams displayed various flexural and flexural-shear cracks. Spalling of concrete can be observed on the tension face of the beams.

Fig. 7 show typical joint failures observed in the structure.

Fig. 6: Failure of beams of as built and retrofitted structure

Fig. 7: Joint failures of as built and retrofitted structure

The structure could successfully pushed back to original geometric position, repaired and retrofitted with FRPC to get the original capacity of the structure. After retrofitting, the failures were modified, first in terms of non-spalling of concrete due to good confinement provided by FRPC and second, the failure modes and locations also got shifted from joints to the beams and columns.

Comparing the experimental results with pre- and post- test analysis provided vital information regarding the modeling aspects. It was observed that considering only flexural failure modes for beams and columns, as is generally done in analysis and design, may not be sufficient to provide correct picture, and the results may be on unconservative side. In order to make predictions in close agreement with the real behavior, it is required to incorporate all the possible failure modes in the analysis such as flexural, shear, axial and torsion modes along with suitable interactions. Also, nonlinear modeling of the joints has to be considered to obtain the true behavior of the structure.

Observations and Discussions

Pushover test on a full scale prototype structure was conducted as round robin exercise where participants from various institutes from India participated in the theme meeting and the experiment. The failure patterns observed clearly displayed the vulnerability of RC buildings with non-conforming detailing to fail in undesirable failure mechanisms such as joint shear failures, bond failures etc. In addition to that, many failures like beam flexure, column compression-flexure, column tension-flexure, beam torsion etc. were displayed in the experiment.

Failure modes and test results of retrofitted structure revealed that while performing retrofitting design, one needs to understand the behavior of the structure in both linear as well as nonlinear range by analysis. Identify the change in the failure modes and locations and if required the retrofitting scheme has to be appropriately modified. Thus, the retrofitting design is an iterative procedure. Another very important aspect of repair and retrofitting is the workmanship. Surface preparation by removal of old loose concrete, pouring of new concrete and its bonding with old concrete, rounding off sharp corners etc are few important aspects. Also, proper care should be taken to bond the FRP sheets and laminates to the original structure

BARC Scientists Honoured

Name of the Scientist:		**B.K.Shah, Outstanding Scientist & Head, Quality Assurance Division**
Award	:	National NDT Award 2009 for 'International Recognition'
Awarded by	:	Indian Society for Non-Destructive Testing (ISNT) at the National Seminar (NDE 2009) held at Tiruchirapalli, Tamilnadu, during Dec.10-12, 2009.

Name of the Scientist	:	**Prof. (Dr.) Jai Pal Mittal, Raja Ramanna Fellow, BARC**
Award	:	Prof. Meghnad Saha Distinguished Fellowship
Awarded by	:	The National Academy of Sciences, India.

Name of the Scientists	:	**Nivedita P. Khairnar and H.S.Misra, Molecular Biology Division**
Title of the Paper	:	**"Characterization of an X family DNA polymerase of a radiation resistant bacterium, *Deinococcus radiodurans* for its role in radioresistance and as a short patch base excision repair enzyme"**
Award	:	Best Research Paper Award
Presented at	:	"35th Annual Conference of Environmental Mutagen Society of India (EMSI) and International Symposium on Mutagens & Genetic Diversity for Health & Agriculture", held at Punjab University, Chandigarh, during March 12-14, 2010.

Name of the Scientist	:	**N.L. Misra, Fuel Chemistry Division**
Honour	:	Appointed as Member of the Editorial Advisory Board for the journal *X-ray spectrometry*, published by John Wiley & Sons Ltd., UK.

Name of the Scientists	:	**B.N. Mohanty, R. Gaikwad, V.R. Sonar, S. Raul, D.K. Das, A. Prakash, Md. Afzal and J.P. Panakkal, Advanced Fuel Fabrication Facility**
Title of the Paper	:	Feasibility study of phosphorus determination in $(Th-U)O_2$ sample using different types of solvents for the extraction of phosphomolybdic acid.
Award	:	Best Poster Award
Presented at	:	"SECTEC-2010" held at the Indira Gandhi Centre for Atomic Research, Kalpakkam, Tamilnadu, during March 12-14, 2010.

Name of the Scientists	:	**Ramani Venugopalan and D. Sathiyamoorthy, Powder Metallurgy Division and A.K.Tyagi, Chemistry Division**
Title of the Paper	:	"Development of Carbon-Carbon Composite: Its Characterisation' and Irradiation Studies"
Award	:	Best Paper Award
Presented at	:	First Asian Carbon conference (FACC 2009) held at India Habitat Centre, New Delhi, India, during November 25 -27, 2009.

Name of the Scientist	:	**Mr. Kamal Sharma, Reactor Safety Division**
Title of the papers & Awards	:	"Element Free Galerkin method for Crack Analysis" Best Paper Award "Application of FEM & ANN for Ball Indentation Testing Simulation" Best Oral Presentation Award
Awarded at	:	International Conference of Recent Advances in Mechanical Engineering (ICRAME-2010) held at N. I. University, Tamilnadu, during April 7-9, 2010.

The Pond near North Gate