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Founder and Architect of the Indian Atomic Energy Programme

Inside

From the Director's Desk

Challenges in Providing Robust Design and Technology for Prototype Fast Breeder Reactor

India is targeting to reach at least the per capita energy consumption of the present world average (2200 kWh/a) by 2030 from the current value of 660 kWh/a. Accordingly, the current generation capacity of about 140 GWe is to be raised to about 600 GWe by 2030. Further, to limit the cumulative energy import during the next fifty years to about 30%, the electricity availability is to be increased by about ten times in the next fifty years. Such a high demand for energy growth with the limited resources, high fluctuations in natural gas prices and environmental considerations make nuclear energy as the inevitable option for the country. To fulfill the objectives of providing sustainable clean energy, Homi Bhabha had envisaged a three stage programme much before the realization of the importance of nuclear power as sustainable energy option and clean energy was visualized by the world. Under this, the potential of water reactors (about 10 GWe capacity) in the first stage, fast reactors (about 42,200 GWe-yr) in the second phase and use of thorium (155,000 GWe-yr) in the third stage would be exploited. Today the water reactor programme has reached its maturity and we are operating seventeen water reactors with very high capacity factors. The fast reactor programme, started under the second stage, has been progressing steadily in the country for the last forty years in the mission mode. Strong science based R&D executed in multidisciplinary domains and extensive collaborations with academic and R&D institutions and public support have helped realizing successful operation of Fast Breeder Test Reactor for twenty three years. Construction of 500 MWe Prototype Fast Breeder Reactor is progressing well and is targeting for commission in 2011. Further, our success would lead to meeting the aspirations of world FBR community to realize their own long term targets. To reach the status of what we are now, we have met many challenges and I highlight below a few challenges which we have faced to achieve robust design and technology of PFBR.

PFBR design addresses all the possible failure modes comprehensively, giving due considerations to the operating experiences of about three hundred ninety reactor years. High temperature design for long reliable operation of components operating at temperatures around 820 K for design life of forty years, design of mechanisms and rotating equipment operating in sodium & argon cover gas space, handling the sodium leaks and sodium water reactions in the steam generators,

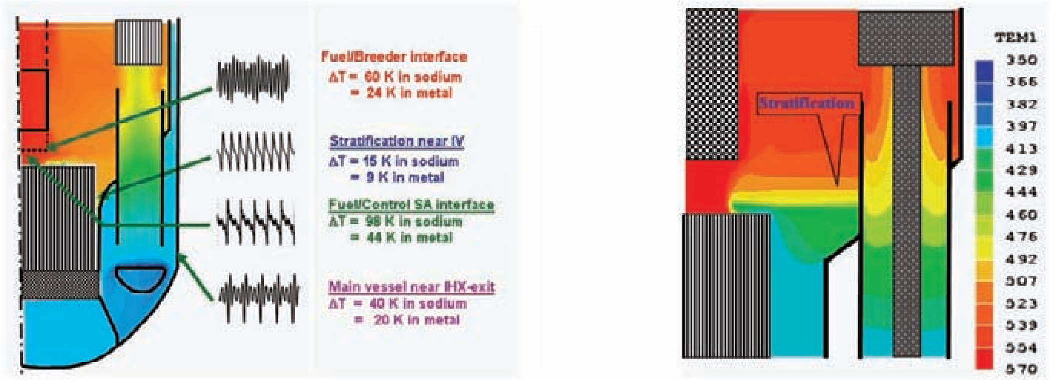

Figure 1: Numerical simulations of thermal striping and thermal stratifications in sodium pools

seismic analysis of interconnected buildings resting on the common base raft, seismic design of thin walled vessels, pumps and absorber rod mechanisms and in-service inspection of reactor internals within sodium are a few challenging issues addressed in the design. These apart, the development of high performance materials in particular for the core structures, viz. clad and wrappers, to operate under high temperature, sodium, irradiation environments, non-metallic materials (special high density concrete, elastomers, ceramics, cables, etc.), operating at high temperatures and radiation environments and special sensors for sodium applications (detection of water leaks in steam generator, sodium leaks, purity measurements, level detectors), sodium chemistry, understanding of sodium aerosol behaviour, sodium fire and sodium water reactions, are the complex domains which have been mastered with strong scientific knowledge base.

Understanding fully the quantum of R&D involved and available resources, it has been planned well ahead to effectively use the expertise available in-house and elsewhere in the country. First of all, the PFBR design has been originally conceived with the desire of using well established technology to the maximum extent possible with idea of keeping R&D requirements to the minimum. In spite of this, introduction of a few first of its kind technologies is considered to be inevitable for PFBR, which is quite understandable, in the context as PFBR is first in the generation of large number of reactors to be built in 21st century. Even though, the items under this category are not many, the required R&D activities, to put them confidently in to the reactor, were worked out to be quite large. I would like to highlight a few challenging analytical studies: viz. complex pool hydraulics studies to understand and provide design solutions for the thermal striping and thermal stratifications within the main vessel, seismic analysis of nuclear island inter-connected buildings (NICB) along with the mechanical components, buckling investigation of thin shells under dynamic forces exerted during seismic events and high rate straining on main vessel due to fast transient fluid-structure interaction under postulated core disruptive accident conditions (Figures 1-3). The analytical results were validated through elaborate experimental programme, a few of them are truly international benchmarks.

Another important domain which decides the success of Prototype Fast Breeder Reactor is the manufacturing technology. The majority of components in a pool type SFR are thin walled

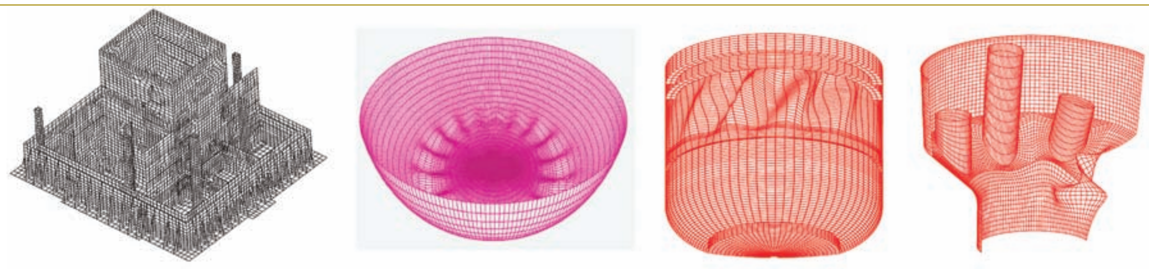

Figure 2: Finite element models of nuclear island inter-connected buildings and vessels for investigations of buckling under seismic forces

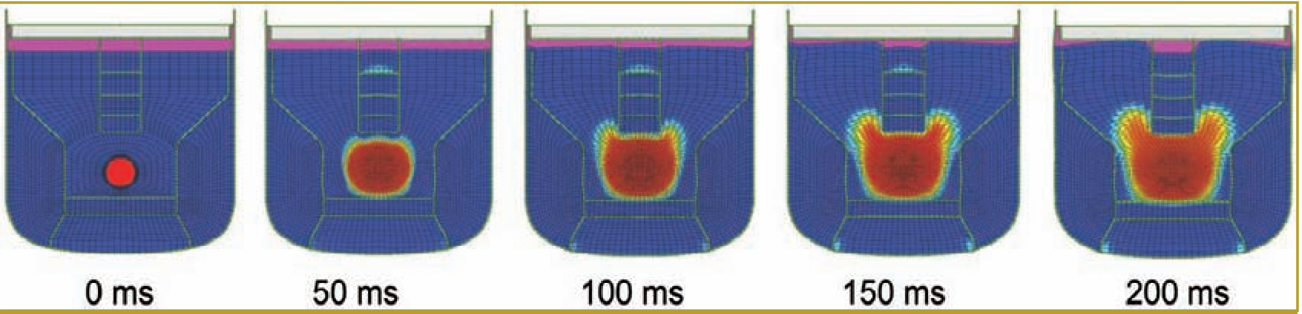

Figure 3 : Numerical simulation of molten core bubble expansion under core disruptive accident

large diameter shell structures. High dimensional stability is required during operation as well as under earthquake conditions. The structure should have high potential to absorb energy which relies on the high ductility of weldments apart from inherent ductility of steel, in case of severe accidents. The major manufacturing challenges of these structures are: the basic plates should not have any defects such as laminations, for which high quality control is essential, large lengths of welds while integration of individual petals, stringent control on the manufacturing deviations, high quality welds with low residual stress to be achieved without any heat treatment. Manufacture of thin vessels, such as main vessel, safety vessel, thermal baffles and inner vessel have been completed successfully (Figure 4). High quality welds have been achieved with insignificant weld repairs, cold forming limiting to < 10% and close form tolerances of ± 12 mm (≤ 0.2% of radius) are the major achievements. These are possible by adopting stringent dimensional control at petal level, innovative weld fit up methods, and proper sequence methodology, state-of-art techniques for inspection and quality control, numerical simulations of forming and welding procedures, innovative mockup trials, lessons learnt from feed back experiences of various industries and elaborate technology development exercises.

Austenitic stainless steel plate type insulations are provided in the form of panels around the safety vessel, to reduce the heat transfer to reactor vault.

Figure 4: Components manufactured under technology development

Figure 5: Manufacturing various internal components of PFBR

As these type of insulations are not commercially available, the same have been designed and fabricated indigenously using 0.1mm thick sheets stacked to form panels. Dimples are provided to ensure precise spacing between the sheets. The manufacture and assembly of the panels were completed overcoming several challenges in view of thin sheets forming, requirement of uniform emissivity, uniform spacing, formation of dimples without cracks, complicated assembly sequences over the safety vessel. Innovative experiments were carried out to confirm compliance of thermal and seismic design requirements.

There are a few components which call for challenging machining techniques. The grid plate tops the list. In fact, for FBTR, the grid plate is the only component which has been imported. Machining of large diameter plates and shell assembly to the specified tight tolerances on dimensions to satisfactorily meet all the critical functional requirements of the component, nozzle welding with thick intermediate shell without distortion, achieving sound and crack free hard facing on the large diameter (6.7 meter) annular tracks in bottom plate of grid plate and also in the inner surface of sleeves with nickel based cobalt free hard facing material, heat treatment of large austenitic stainless steel parts at 1320 K with controlled rates of cooling and heating, assembly of a large number of parts (~14900) meeting the important requirements on verticality of sleeve assemblies (Ø0.1 mm) and handling without introducing any sagging due to self weight are the challenges in the manufacturing technology (Figure 5). The confidence is raised through elaborate technology development exercises.

Success of Sodium Cooled Fast Reactor depends upon the successful operation of mechanisms operating in sodium. The primary sodium pumps, absorber rod drive mechanisms, fuel handling systems are the important mechanisms operating in sodium. These components which are partially immersed in high temperature primary sodium, have parts which are required to work in liquid sodium and mixture of argon-sodium vapour. There are long slender mechanisms in these components with stringent concentricity between top and bottom ends, to be achieved by machining, assembly and welding. Reliable operation should be ensured even with the misalignment between the absorber subassemblies and the drive mechanisms, caused due to manufacturing tolerances, deflection of supports and thermal & irradiation bowing. The components are manufactured with several precision machined and fabricated parts with close tolerances to accomplish the requisite safety functions.

Worldwide Sodium Fast Reactor experiences clearly indicate that the steam generators generally decide the plant load factor. The critical aspects in this component are the choice of materials and the kind of welds between tube to tubesheets. The state of art material, modified 9Cr-1Mo steel with tight control on chemistry is chosen. The overall length of about 25 meter with around 550 tubes makes the fabrication process very complex. By adopting in-bore welding, tube-to-tube sheet joints are carried out with stringent acceptance standards on dimensions and weld quality without any lack of penetration & fusion, cracks, undercuts and unacceptable porosities. The maximum weld thinning is less than the permissible value of <0.2 mm. The welding technology has been matured based on elaborate technology development exercises and many trials.

The in-service inspection (ISI) equipment to monitor the welds on the main vessel and safety vessel and also an ISI system to monitor as well as repair the tube to tubesheet welds of steam generator have been developed with indigenous efforts. The most challenging items in the system are the mechanisms and seals that should operate reliably within the inter-space between main vessel and safety vessel at 420K under mild radioactive environment. These are sophisticated components to perform the inspections within very narrow spaces. The area to be scanned is very large which needs to be completed within shortest possible time, since it has bearing on the load factor of the plant. The mechanisms are fully computer controlled for remote operations, developed on the basis of intelligent algorithms extensively validated based on numerical simulations and elaborate manufacturing technology development methodologies.

The construction of Sodium cooled Fast Reactor also involves many challenges in civil engineering design and technology. For the first time, the concept of interconnected buildings has been adopted in PFBR. The main vessel and safety vessel are supported independently on the inner and outer walls of reactor vault which is quite complex structure and called for extensive R&D in the design validation as well as mockup trials for ensuring constructability. The nuclear island consists of eight buildings including reactor containment buildings which are interconnected and resting on six meter thick common base raft. This has been designed to achieve compact layout giving due considerations for maintenance and safety. Many innovative construction methodologies have been followed to proceed with civil construction and mechanical components erection concurrently.

In the successful manufacturing of PFBR components, the leading Indian industries such as L&T (Hazira, Powai, Ranoli), BHEL, Walchand Nagar Industries Limited (WIL), Godrej, MTAR Hyderabad, Kirloskar Brothers Limited (KBL), Gammon India Limited, are involved. Since several industries are involved (Figure 6), the dimensional tolerance requirements at various interfaces have been clearly identified and being resolved successfully adopting robust mechanisms (formation of taskforces, for example). The confidence on long delivery components such as main vessel, inner vessel, absorber rod drive mechanisms and steam generators on the quality and time schedule has been raised, through

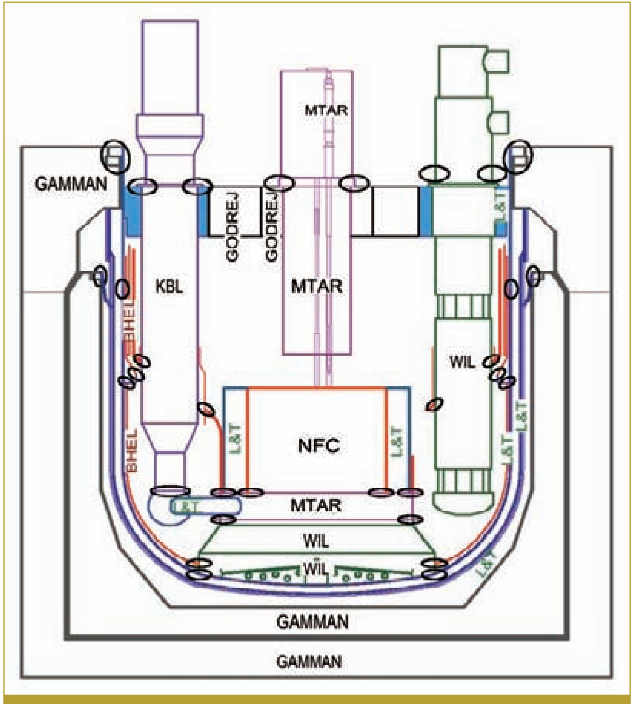

Figure 6: Industries involved in manufacture of PFBR components

Figure 7: Successful erection of safety vessel on the inner wall of reactor vault in June 2008

extensive manufacturing technology development exercises and a few components which have been manufactured through the technology development exercises.

Transportation of thin shell structures from the site assembly to the support locations is another challenging activity in the construction. Erection of very large dimension and slender components with stringent dimensional accuracies (a typical tolerance to be achieved on horizontality over fifteen meters is less than ± 1 mm) is the most challenging task. This has been achieved by envisaging and analysing all possible problems apriory and subsequently establishing systematic solution techniques with extensive mockup trials, in close co-ordination with IGCAR, BHAVINI and industries.

Our technology development has been completely backed up by extensive R&D and science. Hence our technology should be a success and PFBR project will be completed in time with strict adherence to quality, which definitely gives high pride to the nation. This has been demonstrated by the successful erection of safety vessel along with delicate thermal insulation panels on the inner wall of reactor vault.

We made a conscious effort to utilize the expertise available in the academic and research institutions in addition to the industry for realizing the goals of our indigenous mission programme. A robust mechanism has been established for effectively implementing the collaborative research projects. The interaction with academic and research institutes also includes participation of students to pursue postgraduate research at our Centre. To enrich the collaborative efforts further vocational training courses and workshops have been organized with focused themes. The contributions have been both from the eminent faculty members and enthusiastic students and some of the contributions have been outstanding. Outsourcing R&D through collaborations has also helped in generating critical inputs and development of several centers of excellence. Technology development exercises have paved the way for incorporating up-to-date manufacturing and inspection technologies for manufacture of large and precision engineered components. The benefits of the close IGCAR-academia-research-industry interactions will go substantially beyond nuclear energy and have a wider dimension of societal relevance.

While acknowledging our own achievements, we have to remember that, still we have a tough way to travel to realize our ultimate target of becoming a global leader in this technology. To give the confidence towards this, we have set certain benchmarks, namely establishing techno-economic viability through sodium cooled fast reactors with mixed oxide fuel and closed design for long life (100 years), significant reduction of capital cost and fuel cycle cost (200 GWd/t burnup), metallic fuel with high breeding to achieve doubling time less than ten years and construction of series of large size reactors (1000 MWe) with co-located fuel cycle adopting mega park concept and exploitation of thorium resources through FBRs. This is the great opportunity for us to enhance our efforts in multifold dimensions.

Baldev Raj

(Baldev Raj)
Director, IGCAR

Cover Gas Purification System (CGPS) Pilot Plant

PFBR is a pool type fast breeder reactor and argon is used as a cover gas above the free level of sodium. In case of failure of any fuel pin, the fission gases would come out of the clad and will pass through the sodium to the cover gas. The presence of fission gases in the cover gas would raise the activity level. Since absolute leak tightness of the cover gas could not be ensured, it is likely that the activity will get into the reactor containment building. In addition, there would be an increase in the amount of radioactivity being discharged through the stack, although it would still be lower than permissible. However, in accordance with the principle of ALARA (as low as reasonably achievable) and to ensure minimum release, it has been decided to treat the cover gas to remove the radioactive fission gases.

Activated charcoal has been used for adsorbing the fission gases in a number of liquid metal cooled fast breeder reactors. It is well known that the dynamic adsorption coefficient is higher at cryogenic temperatures vis-a-vis ambient and hence, for adsorption of fission gases at cryogenic temperatures, less amount of activated charcoal would be required enabling the plant to be easily accommodated in reactor containment building. To aid in the design of the cover gas purification system for PFBR, a pilot plant has been set up to study the different operating parameters that would influence dynamic adsorption coefficient.

Experiments at various temperatures from ambient (303 K) to cryogenic (130 K) were conducted in cover gas purification system pilot plant shown in Figure 1. The system consists mainly of gaseous argon tank, diaphragm compressor (DC), exchanger-economiser (contained in cold box-1), liquid nitrogen bath (contained in cold box-2), adsorption column containing activated charcoal (contained in Cold Box-3), sample injection facility and online gas chromatograph (OLGC) for analysing the samples. The liquid nitrogen bath is used to cool the recirculating argon, which in turn cools the adsorber bed. Three liquid nitrogen storage tanks are available for the storage of liquid nitrogen.

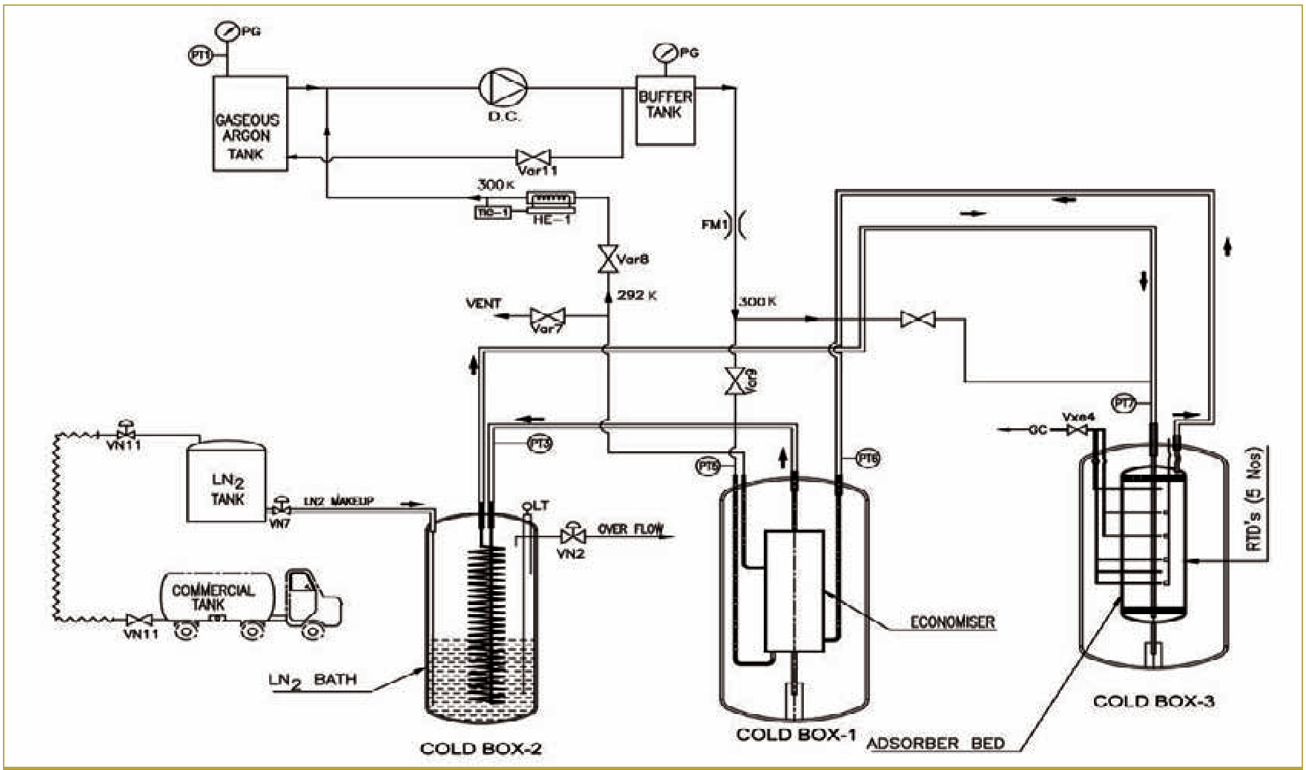

Figure 1: Flow diagram of cover gas purification system pilot plant

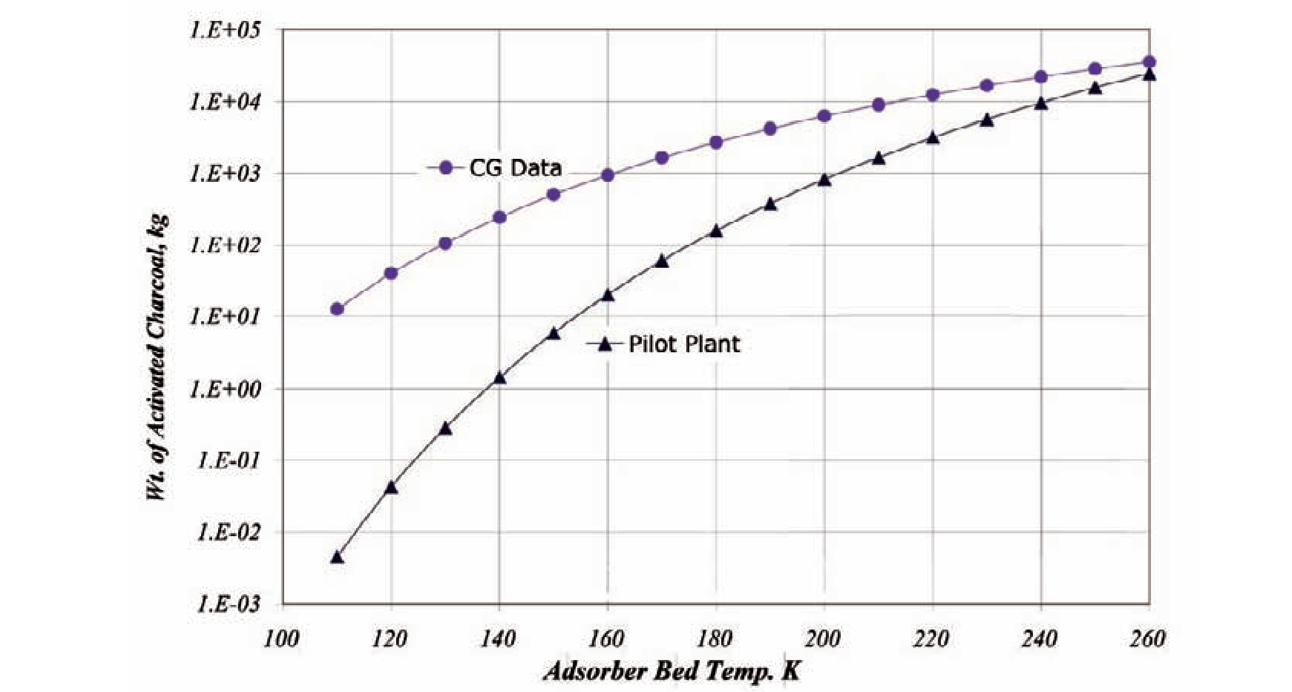

Figure 2: Weight of activated charcoal required for PFBR

The required temperature in the adsorber bed is achieved by maintaining the pressure and level in liquid nitrogen bath (cold box-2). The required flow rate was achieved by throttling the diaphragm compressor by-pass valve. After achieving the required flow rate and temperature in the system, argon containing 1% xenon was injected into the main flow of argon and an online gas chromatograph was used to monitor the xenon concentration at the outlet of the adsorption column bed. Once xenon was detected at the outlet, the re-circulation mode was switched over to once through mode to remove xenon from the system. The total volume of argon passed through the adsorption column between the injection time and breakthrough time of xenon as detected by online gas chromatograph is used for the dynamic adsorption coefficient calculations. The argon was continuously vented outside the building in the once through mode till the analysis of sample by online gas chromatograph showed no xenon concentration. To conserve the carrier gas (argon), after the xenon was detected in the last sample line, the temperature of the bed was raised to ambient by removing the liquid nitrogen in cold box-2 and nitrogen gas was used to flush out the remnant xenon. The bed and other systems were then purged using argon to ensure that all the nitrogen was replaced and the unit was ready for the next experiment.

Experiments to determine the dynamic adsorption coefficient of indigenous activated charcoal were carried out from ambient temperature to 130 K and the data used to compute the amount of charcoal required to obtain a decontamination factor of 104 as shown in Figure 2. This Figure also shows the charcoal amounts required as computed by extrapolating the laboratory scale experiments between 258 K and 313 K conducted earlier in Chemistry Group. The dynamic adsorption coefficient values obtained in both experiments at near ambient temperatures agree within experimental error. However, the steep increase in dynamic adsorption coefficient with decreasing temperature expected based on laboratory scale experiments between 258 K and 313 K is not observed during the pilot plant experiments

Based on the experimental data obtained from the pilot plant, design of the PFBR adsorber bed was carried out. This is the only system planned to be operated in PFBR at cryogenic temperatures. The experience with the operation of pilot plant has given confidence to the design of a similar system for PFBR.

(Reported by B. Muralidharan and colleagues)*
**Collaborative work between colleagues of FRTG & CG*

A Parallel Cluster Supercomputer at IGCAR

A multi-purpose parallel high-performance computing cluster has been built using state-of-the-art components at Computer Division, IGCAR to cater to the diverse computational requirements of the users. With significant improvements in the performance of PC Servers and networking devices, building high performance computing cluster using the commodity-off-the shelf components is an economical approach to achieve supercomputing capabilities.

Cluster Configuration

The parallel super computing cluster comprises of 128 compute nodes and a management node interconnected by high-performance infiniband and gigabit networks. Each cluster node is powered by dual-processor, quad-core 64-bit latest Intel Xeon processor with the clock speed of 3.16 GHz. The cluster has 1024 processor cores with one terra byte of distributed memory.

The management/master node is the head node of the cluster which is used for cluster administration and providing user interface for job submission and management. The compute nodes are the cluster nodes where the users' jobs actually run. They are highly optimized to execute the parallel codes of the users. In addition, a console server is configured for hardware management of all compute nodes.

Interconnect Networks

To exploit the full potential of the high performance computing cluster with increased processor speeds, it is essential to have high-performance interconnects between cluster nodes. Infiniband architecture is an industry standard, channel-based, switched fabric, interconnect architecture for servers. It provides very high bandwidth and low latency for communication and better scalability to large number of nodes. It uses low-level remote direct memory access (RDMA) protocol to reduce the application latency and processor overhead.

This cluster system has three interconnect networks. The primary network meant for inter-processor communication (IPC) is based on the Infiniband architecture. The Infiniband switch supports upto 144 DDR 4X ports each with speed of 20 Gbps. The Administration network meant for cluster management and monitoring is based on 1Gbps Gigabit Ethernet. The Management network meant for hardware remote management and console access of nodes using intelligent platform management interface is based on gigabit ethernet. IPMI provides

Figure 1: 1024 Core high performance computing cluster at IGCAR

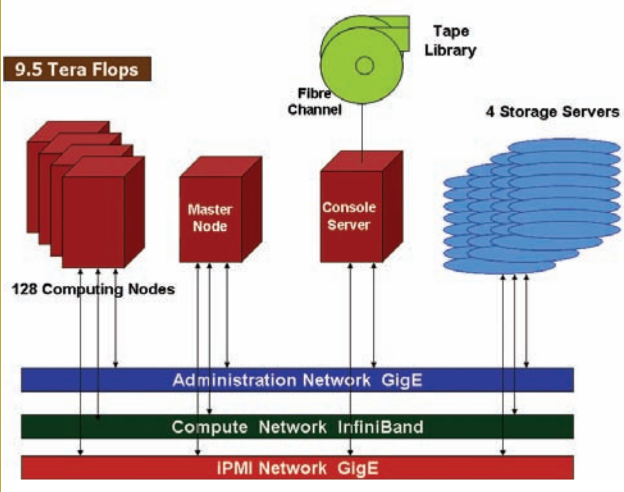

Figure 2 : Architecture of high performance computing cluster

remote access, monitoring, and control functions for hardware without using keyboard video monitor switches and complex wiring.

Storage System

The cluster has four storage nodes each with 6 terra byte of disk capacity. The storage nodes are based on dual-core Intel Xeon Processor and redundant array of inexpensive discs (level 5) is configured on each node to overcome single-disk failures. GlusterFS, a scalable clustered file system is configured to unify the disk storage across the four storage bricks over Infiniband interconnect giving an aggregated raw capacity of 24 TB. Also GlusterFS has been configured with NUFA scheduler to aggregate all local disks in the compute nodes into one large storage disk of 20TB capacity to give the local node more priority for file creation over other nodes during job execution.

Automated Tape Library

To meet the large data backup requirements of the cluster storage, an automated tape library has been installed with 4 LTO-Gen3 drives and 48 media slots to backup up to 38.4 TB of compressed data using 800 GB LTO-3 Tapes. A backup server is setup and programmed to take periodic backups of the user data.

Gluster HPC Software suite

Advanced cluster distribution software (Gluster) designed for massive scalability and performance has been installed and configured for building and managing this high-performance computing cluster. It provides a clustering development platform comprising OS provisioner, parallel MPI libraries, compilers, resource and job managers, distributed cluster monitoring tools etc to give clients a unified system view of the massively parallel cluster.

Performance Benchmarking

The performance of the cluster is measured in terms of number of floating-point operations per second (GigaFLOPS/TeraFLOPS). The industry-standard high-performance linpack (HPL) is used to evaluate the parallel cluster performance. A sustained performance of 9.5 TFLOPS is achieved after fine tuning various system factors and benchmarking parameters.

Intelligent Power Management and Cooling

Intelligent power distribution units (IPDUs) have been installed with advanced console server to enable remote power control and real-time current monitoring of cluster nodes using web user interface. The twin-noded cluster systems in 1 unit form factor are compactly housed in five 42 unit racks with efficient cooling arrangement made through precision air-conditioning (PAC) system.

Applications

This parallel supercomputing cluster is designed to meet the large-scale numerical computing requirements of IGCAR Scientists and Engineers. High computing intensive scientific applications in the areas of computational molecular dynamics, material modeling, reactor core calculations and safety analysis, weather modeling and engineering applications in the area of finite element analysis, computational fluid dynamics can effectively make use of the cluster to vastly reduce their run times. The system has been successfully commissioned and is being used extensively.

(Reported by S. Rajeswari and colleagues, Computer Division, EIG)

Young Officer's FORUM

Bloom of *Trichodesmium erythraeum* and its impact on water quality and plankton community structure in the coastal waters of Kalpakkam

Shri Ajit Kumar Mohanty obtained his Masters degree in Marine Sciences (Marine Biology) from Department of Marine Sciences, Berhampur University, Orissa in 2004. He joined as JRF in an IGCAR-ANNA UNIVERSITY collaborative project in 2005. He has published seventeen national and international journal papers, two book chapters and has presented nine papers in conferences. He joined IGCAR as Scientific Officer (SO/C) in August 2008 and presently working on coastal ecology in Environmental and Industrial Safety Section, Safety Group.

Phytoplankton, the unicellular microscopic form of plant, is the dominant floral component in the marine environment. They contain the pigments of various kinds that enable them to carry on photosynthesis and thus giving them the identification of plant. These highly successful photosynthetic microscopic plants, responsible for ~90% of the primary production in the oceans and ~40% of the global primary production, undergoes seasonal population explosions called phytoplankton blooms. Of the 5,000 known phytoplankters only about 300 species are bloom forming (when their concentration exceeds 5×10^5 cells l^{-1}) out of which about 80 species forms the harmful algal bloom (HAB). The bloom phenomenon that contains toxins or having negative impacts is generally termed as "Harmful Algal Bloom" (HAB). This spectacular natural phenomenon is generally known as 'red tide' or 'green tide' or 'brown tide' according to the phytoplankton species involved. During this process of rapid phytoplankton proliferation various toxic compounds are released as extra cellular products which can kill the higher organisms like zooplankton, shellfishes, fishes, birds, marine mammals and human that feed upon them either directly or indirectly. Toxins released could affect the central nervous system causing temporary or permanent memory loss, paralysis etc. while some of the toxins affect the respiratory system causing suffocation, malfunctioning of lungs etc. There is an increase in frequency of phytoplankton bloom appearances in the coastal environment in recent times, believed to be due to alteration of coastal habitats caused by anthropogenic influences particularly eutrophication (increase in nutrient content).

Trichodesmium erythraeum, a marine cyano-bacterium, is an important nitrogen-fixer in the sea. It is one of the common bloom-forming species found in tropical and sub-tropical waters, particularly in the eastern tropical Pacific and Arabian Sea, contributing > 30% of algal blooms of the world. Estimated global nitrogen fixation by *Trichodesmium* bloom (~ 42 Tg N yr^{-1}) and during non-bloom conditions (~ 20 Tg N yr^{-1}) suggests that it is likely to be the dominant organism in the global ocean nitrogen budget. *Trichodesmium* normally occurs in macroscopic bundles or colonies and blooms formed by them are often extremely patchy. The patchy spatial distribution of plankton blooms is usually connected to the physical variability of the water body.

Blooming of phytoplankton particularly by *Trichodesmium* (cyanobacteria) generally occurs during February to May (pre-monsoon) in the coastal waters adjoining India. Reports in literature showed frequent occurrence of *Trichodesmium* blooms in Indian waters, however, it occurred more frequently in the west coast as compared to east coast. Equipped with buoyancy regulating gas vesicles and nitrogen fixation enzymes, *Trichodesmium* is regarded as an organism well adapted to stratified, oligotrophic conditions. Thus, *Trichodesmium* abundance should be high in boundary currents and decrease towards the coast where nitrogenous nutrients become more available. To the best of our knowledge from all the available reports on *Trichodesmium* bloom from east and west coast of India, they have been observed far away from the coast (> 30 km). This appears to be the first report of *Trichodesmium* bloom which was sighted near the coast ~ 500m inside the sea at

Kalpakkam coastal waters. During a regular coastal water monitoring program, a prominent discolouration of the surface water was noticed in the coastal waters of Kalpakkam on 19th February 2008. The bloom was very dense and created yellowish-green coloured streaks (Figure 1a) of about 4 to 5m width and 10-20m long. The entire bloom extended to several kilometers long along the coast. The phytoplankton responsible for discolouration was identified as *Trichodesmium erythraeum* (Figure 1b & 1c). Though, bloom of *Noctiluca scintillans* and *Asterionella glacialis* have been observed in the coastal waters of Kalpakkam, there has been no report of bloom by *Trichodesmium erythraeum.* This prompted us to closely monitor the coastal waters with respect to chemical and biological characteristics during the bloom period. The acumen in investigating *Trichodesmium* bloom appearance and distribution stems from the recent report about its harmful nature to coastal fish and shellfish fauna having social and economical connotations. Surface water samples were collected twice daily (between 9 to 10 AM and 4 to 5 PM during the bloom period (19th to 23rd February), whereas, during pre- and post-bloom periods samples were collected weekly in the morning hours.

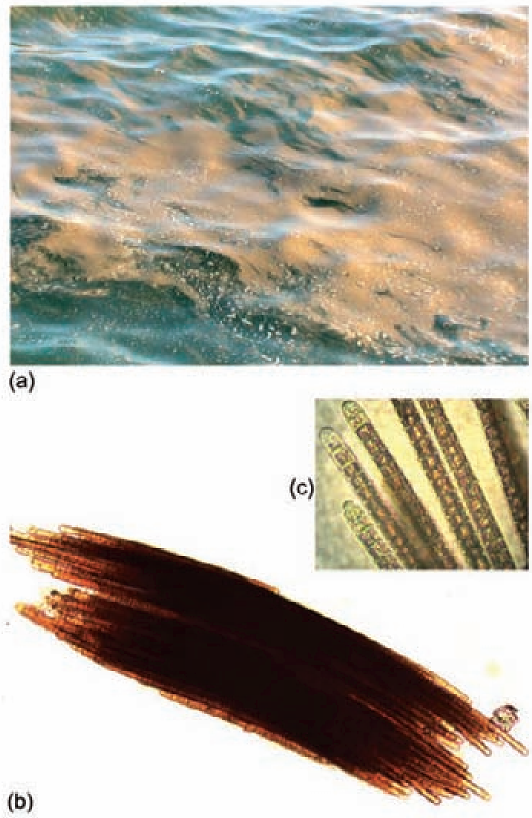

Figure 1: Discolouration of coastal water of Kalpakkam by Trichodesmium erythraeum bloom patches (a); Bundles formed by trichomes (c); magnified view of trichome (b)

Hydrography

Values of pH did not show much variation and ranged from 8.0-8.2. It did not show any correlation to bloom appearance and remained almost stable during pre-bloom, bloom and post-bloom periods. The surface water temperature ranged from 27.2-32.6 °C. Comparatively high temperature was noticed during the afternoon collections. Temperature has long been recognized as an important factor that controls *Trichodesmium* abundance. Cyanobacteria require relatively high temperature for its optimum growth compared to other phytoplankton. The bloom was more predominant during afternoon period (31.2-32.6 °C) when the temperature was relatively high as compared to morning period (28.4-28.7 °C), signifying the positive role of temperature in blooming of this species.

Salinity values ranged from 31.58-33.18 psu. Stable salinity condition close to typical value of 32 psu and above is known to support the growth and abundance of *Trichodesmium*. It is well known that the cyanobacterium is a stenohaline form with optimum growth at > 33 psu and can't survive in low salinities. Dissolved oxygen (DO) concentration ranged from 6.2 - 8.1 mg l^{-1} (Figure 2). The lowest and the highest dissolved oxygen concentration was observed during the post-bloom and bloom period respectively. Marginally high dissolved oxygen content was noticed during the bloom compared to the pre- and post-bloom period. This could be due to photosynthetic release of oxygen by the dense algal biomass. As expected relatively low dissolved oxygen values were observed during the post-peak bloom period, indicating that some of the cells are in decaying stage.

Nutrients

Nitrate is considered to be the most stable nitrogenous nutrient responsible for the metabolism and growth of phytoplankters. It ranged from 0.17 – 6.79 μmol l^{-1}, the highest value being observed during the pre-bloom period and the lowest during the bloom (Figure 2). Relatively low nitrate levels, continuous patches with yellowish green colour and increased primary production (as reflected in chlorophyll-a values) coinciding with peak bloom period sufficiently indicated that the bloom was in growth phase. Reduction in nitrate concentration during *Trichodesmium* bloom has also been reported earlier. However, ammonia values were significantly high during the bloom, especially on the day of highest cell density, compared to the pre- and post bloom observations (Figure 2), which ranged from 0.22-284.36 μmol l^{-1}. This could be ascribed to the diazotrophic nature of *Trichodesmium*, which has the ability to produce ammonium through the process of nitrogen fixation. As a result of the above process, the total nitrogen (TN) was also very high (392.80 μmol l^{-1}) on the peak bloom day (Figure 2). Surprisingly, perusal of a plethora of literature available from Indian coasts revealed that ammonia concentration during *Trichodesmium* bloom has rarely been estimated or reported. During the present observation, in spite of prevalence of very high ammonia content, there was no fish mortality which could be due to persistence of the bloom for a short period and possibility of its drifting away from the shore. Had it continued for extended period its social and economical connotations would have been colossal.

Phosphate levels ranged from 0.09 μmol l^{-1} (pre-bloom) to 1.51 μmol l^{-1} (bloom) (Figure 2). An abrupt increase in phosphate content was encountered on the day of highest cell density compared to the rest. This could be due to the extracellular release and decomposition of plankton. Moreover, bacterial liberation of phosphate from dead organisms could also be responsible for enhanced levels of phosphate during blooms. Total phosphorus (TP) values also showed a similar trend to that of phosphate and ranged from 0.14-2.83 μmol l^{-1} (Figure 2). Silicate values ranged from 7.58–16.28 μmol l^{-1} and remained almost stable during the study period indicating its non-utilization by this species.

Phytoplankton community structure

Results showed that the bloom constituted both individual trichomes and colonial forms although the later dominated to the extent of 80-90%. Generally the trichome length varied from 300-1200 μm. Unlike the west coast of India, wherein phytoplankton bloom is generally observed during the beginning of southwest monsoon period (May-September),

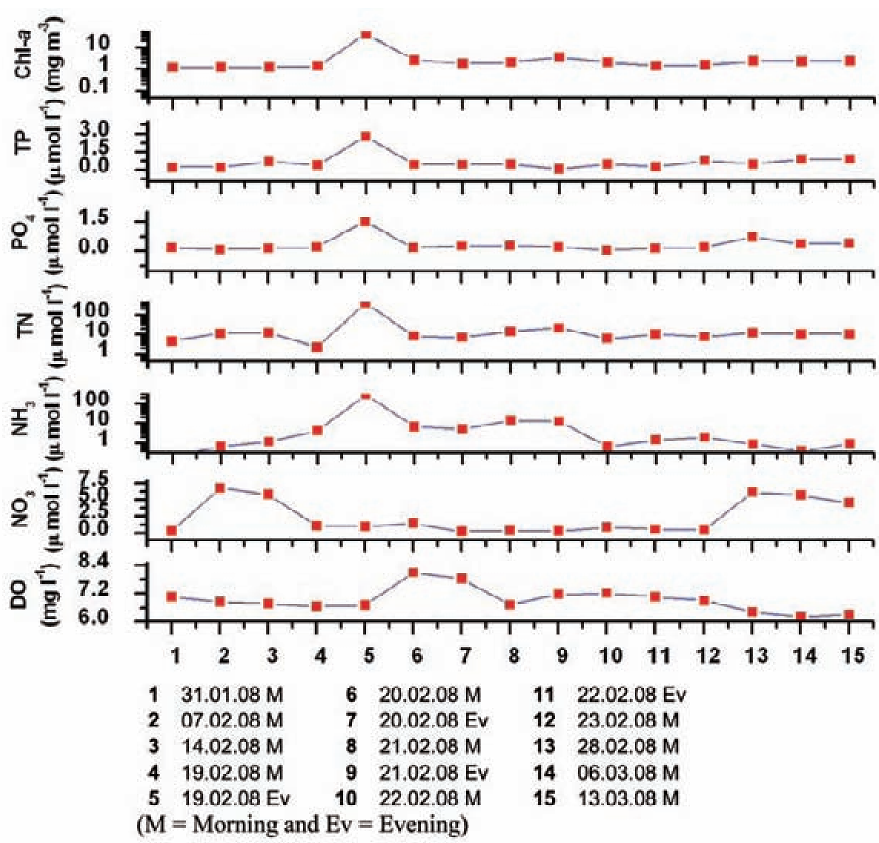

Figure 2: Variations in physico-chemical properties and Chlorophyll-a in the coastal waters of Kalpakkam during appearance of Trichodesmium erythraeum bloom

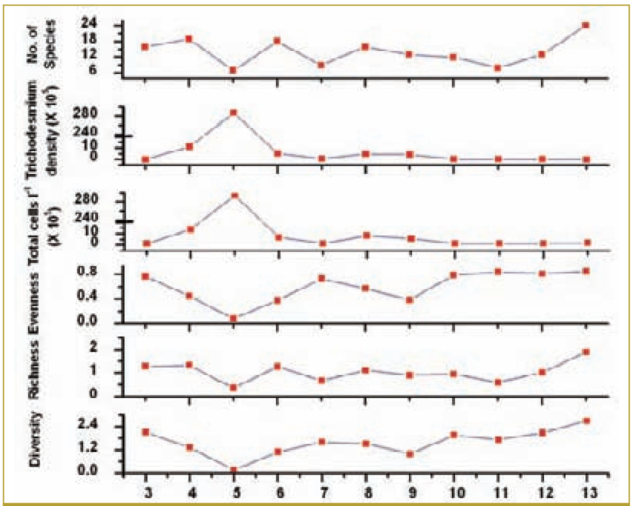

Figure 3: Variations in phytoplankton community structure and diversity indices during the bloom

the present bloom was observed during the end of north east monsoon period. The present observation coincided with the transition period during which the coastal water current was about to change from southerly to northerly direction. This is the lull period during which the lowest magnitude of current is observed at this location. Blooms have been known to be conspicuous in calm conditions, which assist the trichomes to form dense rafts on the surface of the sea as has been observed during this study.

Phytoplankton community showed a distinct variation in its qualitative as well as quantitative characteristics. In total sixty nine species of phytoplankton were identified which comprised of sixty two diatoms, five dinoflagellates, one silicoflagellatte and the cyanobacteria, *Trichodesmium erythraeum*. The population density of phytoplankters ranged from 1.23×10^5 and 2.94×10^7 cells l^{-1} (Figure 3) showing more than two order increase during the peak bloom period. The lowest cell density was observed during post-bloom period. Surprisingly, *Trichodesmium* was found only during the bloom period from 19^{th} to 23^{rd} February 2008 and was totally absent during the pre- and post-bloom period. Contribution of *Trichodesmium* to the total cell count ranged from 7.79 % (1.10×10^4 cells l^{-1}) to 97.01 % (2.88×10^7 cells l^{-1}). It is known that *Trichodesmium* is more abundant in subsurface layers (20-30 m) as compared to surface water. Though, the present bloom was observed in coastal waters with much lower depth (~ 8 meter), however, bottom samples (~7m) did not indicate its presence. The observed density of *Trichodesmium* was found to be the highest, reported to date from Indian waters.

Community structure of phytoplankton showed that the number of species on a single observation varied between seven species (on the day of highest cell count) and twenty four during the post-bloom period. As expected relatively less number of species were found during the bloom as compared to pre- and post-bloom periods. Interestingly, number of species were relatively less during the afternoon collections on all the occasions as compared to the morning collections. This again strengthened the theory that phytoplankton such as *Trichodesmium erythraeum,* which can tolerate relatively high amount of irradiance remained during afternoon as compared to other species.

A distinct variation in all the three diversity indices was noticed during the study period (Figure 3). Relatively high values of all the indices during the pre- and post-bloom periods showed that the phytoplankton community was floristically rich during these periods. A significant decrease in diversity indices during peak bloom period could be attributed to the dominance of *Trichodesmium*.

Photosynthetic pigment

Chlorophyll-a, the chief photosynthetic pigment of autotrophs, showed wide variations and ranged from 1.21-42.15 mg/m^{-3} (Figure 3). Highest concentration coincided with the highest cell density. The peak value of this pigment was about twenty times higher than the normal values, an indicative of blooming situation.

Appearance of *Trichodesmium erythraeum,* an unusual phenomenon in the neritic region (coastal waters of Kalpakkam) points to the need for continuous monitoring coastal ecosystem on long-term basis to comprehend the cause of bloom appearance and its ecological significance.

(Reported by Shri Ajit Kumar Mohanty and colleagues
Environmental and Industrial Safety Section
Safety Group)

Young Researcher's FORUM

Experimental Investigation of Defects and Diffusion During Silicidation in Metal-Silicon Systems

Dr. S. Abhaya completed her M.Sc (Physics) degree from Department of Nuclear Physics, University of Madras, Chennai in 2000. She had then joined IGCAR as a research fellow and carried out her doctoral studies during 2001-2006 and obtained her Ph.D degree in 2007 from University of Madras. She was selected for the K.S Krishnan Research fellowship in the year 2007 and posted at IGCAR. Upon successful completion of the fellowship, she joined in January 2009 as Scientific Officer (SO/D) in Materials Science Group, IGCAR. She has received best poster award for one of her conference papers.

Metal silicides are formed as a result of chemical reaction between metal and silicon atoms across the interface in a metal-silicon system. The advent of metal silicides in silicon technology has paved way for reliable ohmic contacts, Schottky barriers, which have potential applications in smaller and efficient electronic devices. Since metal silicide formation is basically driven by the diffusion of metal or silicon or both across the interface, point defects are injected at the interface. Thus, there is a complex interplay between defects and diffusion in the formation of metal silicides and the application of various experimental techniques can provide comprehensive information on these aspects. Detailed experimental studies have been carried out on a variety of metal/silicon thin films systems and the present article highlights the salient results obtained in Pd/Si system.

Palladium was electron beam evaporated on to silicon substrate to form Pd(100 nm)/Si thin film junction and annealed in the temperature range of 300- 1070 K. Figure 1 shows the glancing incidence X-ray diffraction (GIXRD) spectra of Pd/Si samples at selected annealing temperatures. Only pure palladium peaks are observed for initial annealing temperatures and beyond 570 K, Pd_2Si peaks alone are seen and no other silicide is observed. Thus, in the temperature range of 570-1070 K, only Pd_2Si phase is present.

Rutherford backscattering spectrometry (RBS) measurements were carried out on these samples and thickness, composition of the over-layer and the elemental concentration profiles were deduced from

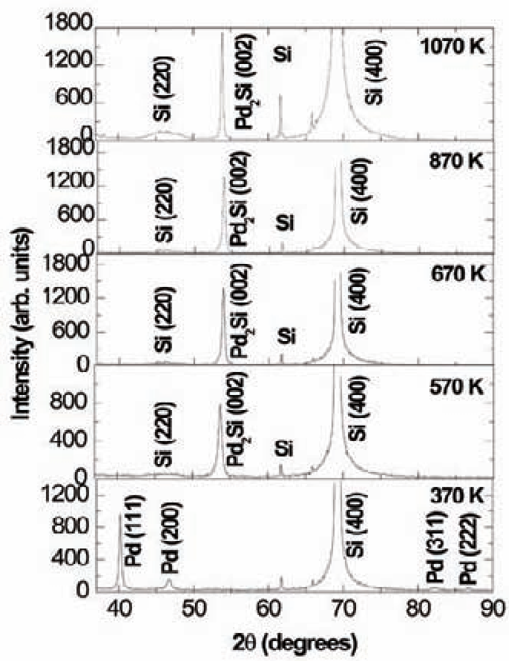

Figure 1: GIXRD spectra of Pd/Si at selected annealing temperatures

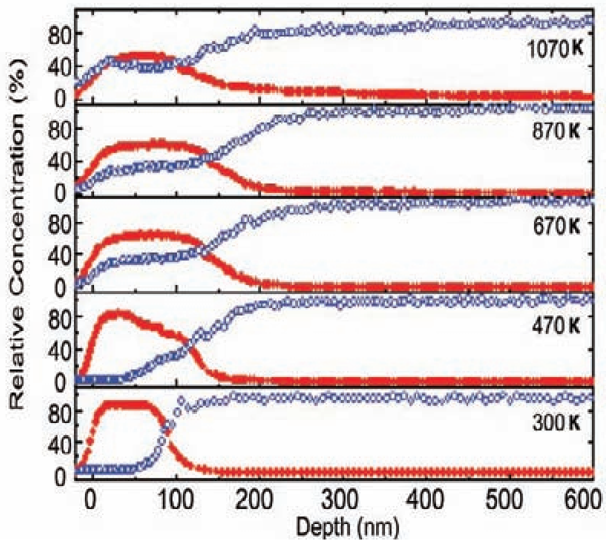

Figure 2: Relative concentration profiles of Pd (red circles) and Si (blue circles) at selected annealing temperatures deduced from RBS results

the backscattering spectra, as shown in Figure 2. At 300 K, the palladium concentration is 100 at% and that of silicon is 0 at% up to about 100 nm implying that the Pd/Si interface is located at ~100 nm. At 470 K, while there is no silicide phase formation, there is noticeable interfacial mixing. The interface has shifted to higher depth values with the silicon profile going deep into palladium profile suggesting that silicon is the faster diffusing species and is responsible for Pd_2Si formation. Between 570 K and 870 K, the relative concentration of palladium and silicon is maintained as per the stoichiometric values of palladium and silicon in Pd_2Si. The thickness of the Pd_2Si layer is deduced to be ~165 nm. Beyond 1070 K, the concentration is higher than the stoichiometric value of silicon in Pd_2Si. Since Pd_2Si is the only phase present, the increase in silicon concentration is attributed to the presence of silicon enriched Pd_2Si. The enrichment is due to silicon diffusing from the substrate region to the silicide region.

Since silicon segregation on top-surface is to be confirmed, surface sensitive auger electron spectroscopy (AES) measurements were carried out on these samples. Differential Auger spectra were recorded for all the annealing temperatures. Figure 3 shows the relative concentrations of palladium and silicon deduced from the differential Auger spectrum as a function of annealing temperature.

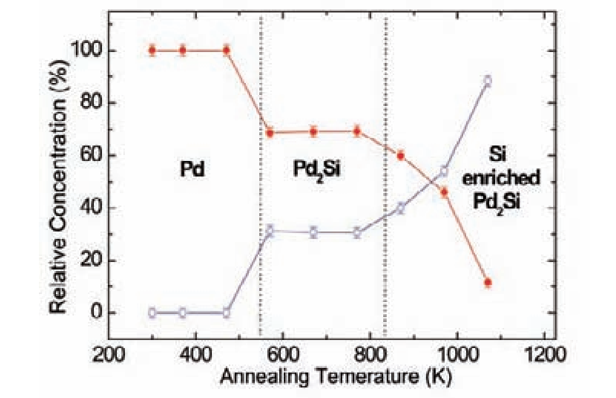

Figure 3: AES deduced relative surface concentrations of Pd (red circles) and Si (blue circles) as a function of annealing temperature

From 300 to 470 K, only palladium is observed. At 570 K, the relative concentration of palladium is ~70 at% and that of silicon is ~30 at% corresponding to stoichiometric values of palladium and silicon in Pd_2Si, which is attributed to Pd_2Si formation. The concentration of palladium and silicon remains unchanged up to 870 K indicating the presence of Pd_2Si phase alone. Beyond 870 K, the relative concentration of silicon increases above the stoichiometric value of silicon in Pd_2Si. Since GIXRD measurement confirms that Pd_2Si phase is the only phase present, the increase in silicon concentration is only due to segregation of silicon on Pd_2Si surface consequent to diffusion of silicon from substrate region to Pd_2Si region.

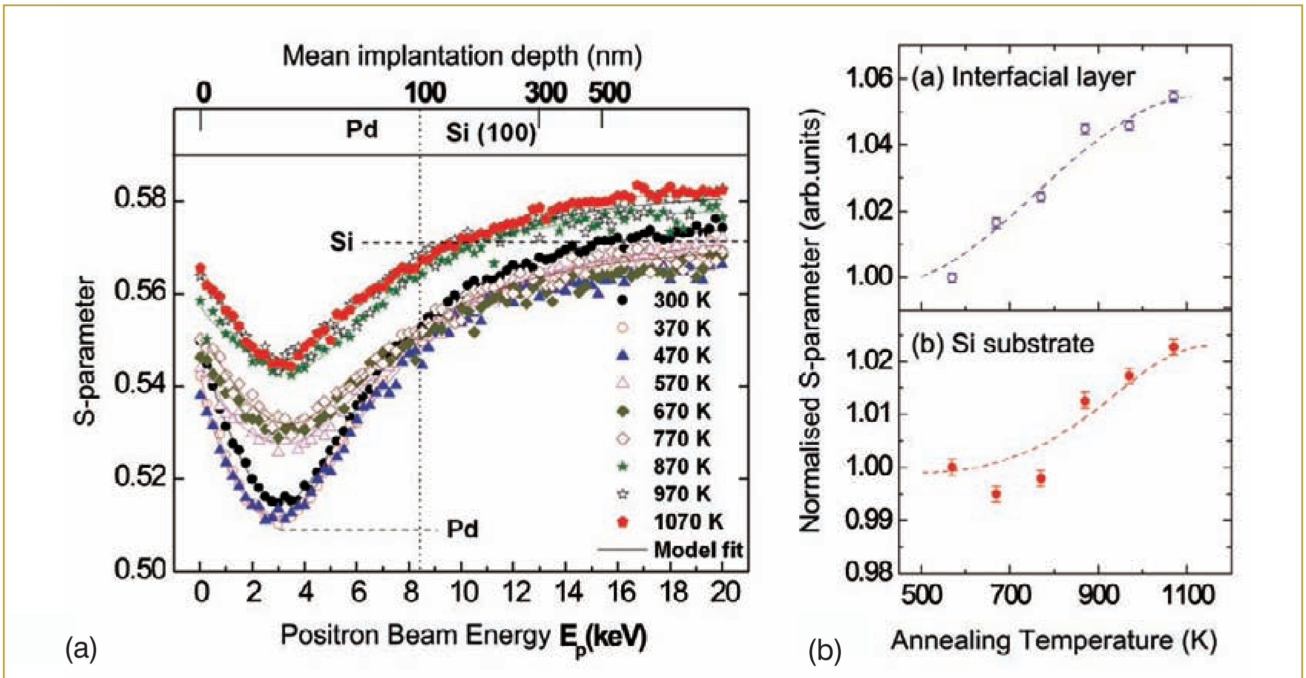

Figure 4: Variation of S versus. E_p curves for Pd/Si samples annealed at various temperatures (shown on left). The vertical dashed line shows the location of the original Pd/Si interface. S-parameter values of bulk Pd and Si samples are shown by horizontal dashed lines. Normalized S-parameter (shown on right) of (i) Interfacial layer and (ii) Si substrate at E_p = 8.8 keV and 20 keV respectively. The dashed lines through the data points are a guide to the eye.

Since, silicon is fast diffusing into palladium region to form the silicide, there should be production of vacancy-defects at the interface and in silicon substrate regions. So as to investigate the presence of vacancy-defects, depth-resolved positron beam measurements have been carried out. From these measurements, a defect-sensitive S-parameter has been deduced. Corresponding to the occurrence of vacancy-defects, S-parameter increases at those depth regions. Figure 4 shows the experimental S versus E_p curves for Pd/Si samples. The minimum value of the S-parameter around 3 keV is attributed to positron annihilation in palladium over-layer and the saturation S-parameter value at higher positron energies is attributed to positron annihilation in Si substrate. At 570 K where palladium silicide (Pd_2Si) is formed as shown by GIXRD studies, the S-parameter of the overlayer increases. This shows the sensitivity of the technique to phase transformations. Beyond 870 K, there is a sudden increase in S vs. E_p curve i.e., the S-parameter values corresponding to surface, palladium over-layer, Pd/Si interface and silicon substrate are higher and stay constant up to 1070 K. In light of the above AES result, the observed change in S-parameter of the over-layer beyond 870 K is attributed to the presence of silicon enriched Pd_2Si region.

So as to bring out the evidence for presence of vacancy defects across the interface and the silicon regions, the normalized S-parameter values corresponding to the interface and the silicon region have been plotted as a function of annealing temperature as shown in Figure 4. The normalization for the interface and the substrate have been done with respect to the corresponding VEPFIT deduced S-parameter values at 570 K, which is the formation temperature of Pd_2Si. It is seen that the normalized S-parameter value corresponding to the interface gradually increases with annealing temperature and reaches a value of 1.055 ± 0.0015 by 1070 K. Normalized S-parameter value corresponding to the silicon substrate region stays at $\sim$ 1.00 up to about 770 K and increases to 1.0227 ± 0.0015 by 1070 K. The normalized S-parameter value above 1.00 indicates the existence of vacancy defects. To estimate the size of the vacancy defects generated at the interface, the present S-parameter values (Figure 4) were compared with that of ab-initio calculations of S-parameters in crystalline silicon. It is seen that the normalized S-parameter in the range of 1.022 –1.045 is attributed to the presence of divacancies.

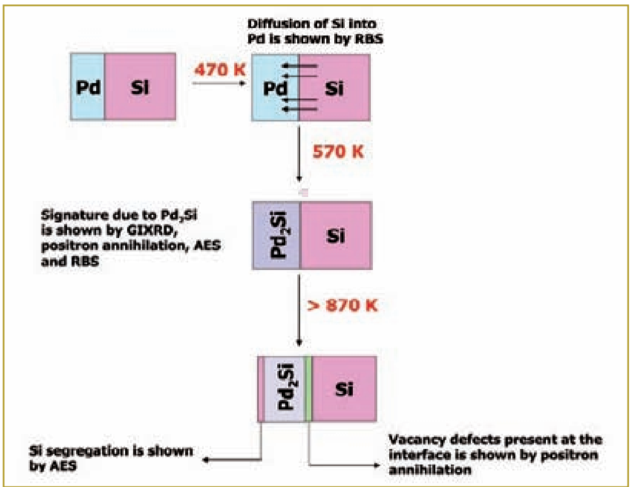

Figure 5: Schematic of the Pd/Si system at various temperature stages

The larger S-parameter values at the interfacial region than at the substrate region are ascribed to the presence of larger concentration of divacancies than in the silicon substrate region. In view of their high mobility, divacancies produced at the interface, diffuse into silicon region beyond 870 K. This is the first direct experimental evidence towards production of divacancies due to enhanced silicon diffusion from silicon region to Pd_2Si region beyond 870 K and the diffusion of these defects from interface to substrate region at higher annealing temperatures.

Figure 5 summarizes the results obtained in Pd/Si system as a consequence of thermal annealing. During the formation of Pd_2Si, silicon is the fast diffusing species and this is confirmed by the RBS concentration profiles of palladium and silicon which shows tailing of silicon into palladium across the interface. At 570 K, Pd_2Si phase is formed. This phase transformation is picked up by positron annihilation measurements which show an increase in S-parameter corresponding to the over-layer. GIXRD, RBS and AES measurements also show signatures due to formation of Pd_2Si at this temperature. Beyond 870 K, while positron annihilation measurements show signatures of production of vacancy defects across Pd_2Si/Si interface consequent to enhanced diffusion of silicon from substrate to silicide, AES shows segregation of silicon on Pd_2Si surface. The present experimental studies clearly bring out the importance of using complementary techniques to obtain a comprehensive picture on the silicidation behavior of metal-silicon systems.

(Reported by Dr. S. Abhaya, Materials Physics Division, Materials Science Group)

Conference/Meeting Highlights

IAEA consultancy meetings

May 25-29, 2009

Two IAEA Consultancy meetings were held at IGCAR, Kalpakkam during May 25-29, 2009. One meeting chaired by Shri H.S. Kamath, Director, Nuclear Fuels Group, BARC reviewed the document on "Status and tends of uranium plutonium mixed oxide, carbide, nitride and metallic fuels for sodium cooled fast reactors- fabrication, properties and irradiation behaviour" and the one chaired by Dr. P.R. Vasudeva Rao, Director, Chemistry, Metallurgy and Materials Groups, IGCAR reviewed the document on " Back end of the Fast Reactor Fuel Cycle: Status and Perspectives". Dr. H.P. Nawada, Section Officer, Nuclear Fuel Cycle Section, IAEA was the Scientific Secretary for the two meetings. The participants of the meetings included Dr. Michel Masson, CEA, France , Dr. Mikhail Kormilitsyn, RIAR, Russia and Dr. Tomozo Koyama, JAEA, Japan (experts for the document on back end fuel cycle) and Dr. Ho Jin Ryu, Korea (expert for the document on nuclear fuel fabrication), besides many specialists in these areas from BARC and IGCAR. The review and finalization of the documents in the meetings involved intense discussions on the current status of the developments in these areas and thus the meetings provided a valuable platform for the scientists of DAE to exchange their views with international experts in addition to the contribution to the document.

Shri S.C. Chetal Director, REG, Dr. P.R. Vasudeva Rao Director, CG & MMG and Dr. P. Chellapandi, Director, SG with other participants at IAEA Consultancy meeting

DAE-BRNS Theme Meeting on Materials for Fast Breeder and Fusion Reactor Applications

June 26, 2009

A one day Theme Meeting on "Materials for Fast Breeder and Fusion Reactor Applications" was organized jointly by Indira Gandhi Centre for Atomic Research, Indian Institute Metals - Kalpakkam Chapter, and Board of Research in Nuclear Sciences on June 26, 2009 at Convention Centre, Anupuram, as part of the birth centenary celebrations of Dr. Homi Bhabha, father of India's nuclear power programme. Dr. Baldev Raj, Director, IGCAR inaugurated the theme meeting and emphasized the importance of synergy among various institutions in the country in the fission and fusion reactor research programs. Dr. P. R. Vasudev Rao, Director, Chemistry, Metallurgy and Materials Group spoke about the genesis of the theme meeting. The key note lecture on "Development, Characterization and Performance of Sodium Cooled Fast Breeder Reactor and Fusion Reactor Materials" was delivered by Dr. K. Bhanu Sankara Rao, Associate Director, MDCG and Head, Mechanical Metallurgy Division. The theme meeting was conducted in three technical sessions devoted to a) Design, Selection and Production Materials for FBRs b) Mechanical Behaviour of Structural Materials and c) Materials for Fusion Reactor Systems. About 60 outstation delegates and 90 delegates from IGCAR participated in the technical deliberations. Leading experts from IGCAR, MIDHANI, Nuclear Fuel Complex, International Advanced Research Centre for Powder Metallurgy and New Materials, Defense Metallurgical Research Laboratory, Institute for Plasma Research and BARC presented invited papers.

Dr. Baldev Raj, Director, IGCAR with other dignitaries during the inauguration

Visit of Dignitaries

A team from Great Lakes Institute of Management, Manamai Village, Kancheepuram District visited the Centre on 22 June, 2009 to hold discussions with Dr. Baldev Raj, Distinguished Scientist and Director, IGCAR and other senior colleagues of the Centre. The team comprised of Prof. S. Sriram, Executive Director, Prof. T.N. Swaminathan, Director, External relations, Prof. R.S. Veeravalli, Director, Corporate Initiatives and Executive MBA, Prof. M.J. Xavier, Director, Dr. Krishna Ram, Placement Director, Shri V. Sankaran, Director, and Shri S. Prabhakar. Dr. Baldev Raj, Director, IGCAR, Shri S.C. Chetal, Director, REG, Dr. P. Swaminathan, Director, EIG, Shri K. Manoharan, Deputy Director, GSO, Dr. A. Vijaya, Medical Superintendent, DAE Hospital and Dr. M. Sai Baba, Head, S&HRPS & SIRD were the participants from IGCAR. Shri Prabhat Kumar, Project Director, BHAVINI also participated in the meeting. The deliberations started with the introductory remarks by Dr.Baldev Raj, Director, IGCAR, who gave his perspectives on possible areas of cooperation between IGCAR and Great lakes Institute towards envisaging the development of neighbourhood. Prof. Sriram and Prof. Veeravalli also made presentations. The team visited Fast Breeder Test Reactor.

Team from Great Lakes Institute of Management with Dr.Baldev Raj, Director, IGCAR

Forthcoming Meetings / Conferences

Workshop on Nuclear Power Plant Life Management (Won-PLiM 2009)

October 6-9, 2009

As a part of the birth centenary celebrations of Homi Jehangir Bhabha, a Workshop on Nuclear Power Plant Life Management (Won-PLiM 2009) is being organized by IGCAR, Kalapkkam, during October 6-9, 2009. The main objective of the meeting is to bring together scientists, engineers and managers working in the interdisciplinary science and technology of PLiM programmes of NPPs, enabling exchange of technical knowledge and sharing of experience.

Scope

During Won-PLiM 2009, eminent experts from France, Hungary, India, Switzerland and USA would speak and share their experience on various aspects of PLiM of NPPs including

- Ageing management, in-service inspection, risk analysis, life prediction, refurbishment and life extension
- Life extension of PHWR, BWR, PWR and sodium cooled FBRs
- International scenario and practice on life management of NPPs
- Classification of components for ageing management
- Ageing management of metallic materials, long term properties, damage mechanism, fracture mechanics, mitigation strategies, new materials, materials modeling
- Ageing management of non-metallic structures and components including concrete
- Ageing management of cables and instrumentation
- Issues related to safety upgradation and redundancy
- Regulatory guidelines and licensing renewal procedures
- Waste storage and disposal during extended periods of plant life
- Economics of nuclear plant life management
- Public acceptance
- International cooperation in research and development programmes

Participation

Participation of engineers, scientists and managers from nuclear installations, research organisations, regulatory agencies, engineering industry and academic institutes associated with nuclear programme is solicited. Deadline for registration of participants for attending Won-PLiM 2009 is July 31, 2009.

Address for Correspondence

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Forthcoming Meetings / Conferences

8th International Conference on Barkhausen Noise and Micromagnetic Testing (ICBM8)
February 11-12, 2010
and
Pre-Conference Workshop on Materials Characterization using NDE Techniques
February 10, 2010

8th International Conference on Barkhausen Noise and Micromagnetic Testing (ICBM8) will be held at Indira Gandhi Centre for Atomic Research (IGCAR), Kalpakkam, India during February 11-12, 2010. The previous conferences were held in 1998 at Hannover (Germany), 1999 at Newcastle upon Tyne (UK), 2001 at Tampere (Finland), 2003 at Brescia (Italy), 2005 at Petten (The Netherlands) and 2007 at Valenciennes (France). The seventh ICBM will be held in July 15-16, 2009 in Aachen, Germany.

Scope

Assessment of microstructures both during manufacturing and during service life is important for ensuring reliable and safe performance of engineering components. Non Destructive Evaluation (NDE) parameters derived from B-H loops, magnetic and acoustic Barkhausen noise techniques are sensitive to changes in microstructures and stress distributions and can provide information almost obtainable by microscopy. These techniques are nowadays becoming inevitable tools for materials scientists for characterisation of microstructures and residual stresses. Magnetic Barkhausen Noise (MBN) and micromagnetic testing find extensive applications in aerospace, nuclear, defence, marine, transport and power industries as a quality control tool and also for remnant life assessment and life extension. MBN and micromagnetic techniques are gaining acceptability in industries and several advances are taking place in this fascinating field. The objective of ICBM8 is to bring together scientists and engineers working in MBN and micromagnetic NDE area to exchange technical knowledge & experience, to forge collaborations and to interact with peers.

Participation from research organisations, engineering industry and academic institutes is invited. The conference language is english. It is planned to organize several technical sessions in which contributed papers as well as invited talks by leading international experts from various countries will be presented. The scope of ICBM8 includes all topics in MBN and micromagnetic NDE including

- Microstructural characterization
- Residual stress measurements
- Damage assessment
- Industrial applications including quality control and inservice performance assessment
- Instrumentation and sensor development
- Theoretical modelling and data processing

Important Dates

Submission of abstracts	August 30, 2009
Intimation of acceptance of abstracts	September 15, 2009
Submission of full-text of papers	November 30, 2009
Deadline for registration	December 15, 2009
Advertisements in Souvenir	December 15, 2009

Address for Correspondence

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Awards & Honours

Dr. Baldev Raj has been selected as Vice-President, International Institute of Welding.

He has been appointed as Adjunct Professor and Honorary Consular General, Department of Electrical and Computer Engineering, Michigan State University, USA.

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