Energy Security for India
- A Challenge to Materials Scientists and Technologists*

I feel honoured to have been elected as the President of The Indian Institute of Metals, a position held by several pioneers and doyens. I express my sincere thanks and gratitude to the Council and all the members, for the faith and confidence reposed in me. It gives me immense pleasure to extend warm greetings to every member of the Indian Institute of Metals. I would like to thank and pay my respects to all the founder members of the institute and the past presidents and their esteemed councils who have nurtured this institute from infancy in 1946 to its current stature of unprecedented glory. It is their determination, dedication, vision and hard work that have enabled IIM to be recognized as one of the premier institutes in materials science and technology, catering to the needs of its members engaged in multifaceted activities related to minerals, metallurgy and materials.

Several new initiatives need to be taken by the Institute to accelerate the India 2020 march and to ensure professional growth of our members in all sectors, be it academic, research or industry. These initiatives also need to be in tune with the changing scenario of liberalization and globalization. It is in this context that I would like to present some strategies planned for the development of the Institute and the growth of materials science, engineering and technology during the tenure of my Presidentship. The Institute, at this juncture, has an unprecedented responsibility to nurture young professionals and contribute to Human Resource Development. It is important to involve undergraduate and post graduate students in metallurgy and allied disciplines in science and engineering in the universities and the engineering colleges, in the IIM activities at an early stage and impart knowledge through vocational certification courses; workshops and orientation courses in personality and career development and promote leadership skills by encouraging them to organize activities of the student affiliate chapters.

There are also equally compelling reasons to forge a more vibrant and active collaboration of industries with academic and research institutes. Apart from organizing continuing education

programmes designed to the interest of specific industries, a discussion forum will also be initiated in the redesigned web site of IIM. The transactions of The Indian Institute of Metals have become a truly international quality journal of Minerals, Metals and Materials engineering and is attracting a large number of researchers from India and abroad to contribute their original research and valued review papers. We have also embarked on changing the outlook of Metal News with the incorporation of a large number of information items of interest to the members pertaining to different disciplines of the Institute. Our associate membership examinations have been enjoying good patronage and we can popularize metallurgical education among students from an early stage by promoting technical and scientific books of high standards, related to metallurgical and materials science and technology. In this context, it is a matter of pride that Tata Steel under the guidance of Shri.B. Muthuraman, Chairman, Ferrous Division of IIM, have published an informative book 'Ferrum Hunters' which has served as an excellent cradle of knowledge for the young school students. This book, written by Dr. A.K. Das and Prof. H. S. Ray, has enthused and sparked interest in the young students to learn about iron and steel. It is gratifying to note that this book would be translated into several regional languages, which would instill interest in students from all regions of the country. A technical and scientific books committee would be established in IIM to coordinate the activities related to the publication of technical books, on priority basis.

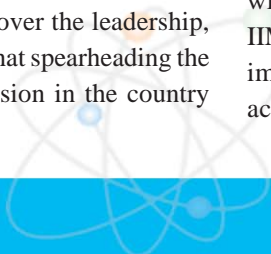Having taken over the leadership, I come to realize that spearheading the metallurgy profession in the country is a unique and pleasant responsibility. Industries by and large are governed by the policies framed by Government through its network of ministries. It is very important to see that The Indian Institute of Metals plays a key role by providing guidance and technical inputs in policy making through the establishment of fruitful interactions with Scientific Advisors and administrators of various ministries. Our interactions with ministries would enable the formulation of a suitable technology roadmap for the growth of the country.

> In recent years, India has witnessed tremendous growth prospects in the component manufacturing industry sector. It is anticipated that the R&D in manufacturing industries would also get the much needed encouragement

During my interaction with several IIM members over the last thirty years, I realized that there are many members keenly interested in contributing to the robust growth of the Institute. My strategy therefore is to encourage more members, especially, young and promising professionals, to participate in IIM activities. IIM should emerge as a powerful organisation reflecting the strong voice of the professionals. I urge all our members to respond positively towards enhancing and widening the scope of our activities. IIM should also be proactive and make impact in wider circles of industry, academia, research institutes and in Government. To make IIM voice heard and respected, we need members who would come forward and participate enthusiastically in various activities. There is enormous scope for every member to grow and contribute to the advancement of the institute, irrespective of their age and location in the country. More importantly, all of us face the challenge to demonstrate our versatility in advancing the activities of IIM and achieve leadership in the world stage. It is time that IIM is viewed with more respect and as a vehicle for growth of the profession internationally. With the active co-operation of all the members, IIM will no doubt, become an effective first-stop resource for technical knowledge, education and professional development within the next few years. In order to have positive and long-term impact of IIM in the minerals, metallurgy and materials community, we would like to establish and maintain a strong, creative and well-considered strategic direction and road map. Based on this direction, our committees in the institute shall develop programmes that cater to the needs of the scientific, academic and professional engineering communities.

In recent years, India has witnessed tremendous growth prospects in the component manufacturing industry sector. It is anticipated that the R&D in manufacturing industries would also get the much needed encouragement and it will contribute significantly towards enhancing the competitive edge of component manufacturers. In the current environment, Institute-Industry interaction has a crucial role to play in harnessing Indian Industry's competitiveness to match global standards of quality and reliability. Discussion meetings on this subject would herald opening up of newer

vistas of cooperation and synergy between the industry, academic and research institutes. IIM would take the initiative to organize the symposia on Industry-Institute interactions on broad fronts of emerging materials technologies, processing and products. Besides industries, funding agencies such as Technology Information Forecasting and Assessment Council, National Research and Development Corporation, Confederation of Indian Indusry and Department of Science and Technology would also be involved in these meetings to discuss their role and the modality of funding the research activities oriented towards developing global competitiveness of small and medium scale industries. We shall have technical meetings by Chapters on the topics of interest to the industries in the region.

The Indian Institute of Metals, I am very sure, can play a crucial role in our country's efforts to become a 'developed' nation – a dream cherished by billions of Indians. It is my firm conviction that development of human resources, female literacy, health care, infrastructure and energy are the important areas of priority. Today, I would like to focus on energy, as self-sufficiency in energy is linked to our growth i.e., GDP and country's advancement in various spheres. It is indeed an astonishing fact that two billion people in our mother Earth have no access to modern energy ! In India, the energy production level must be stepped up to 1350 Gigawatts by 2050, for ensuring high quality of life, sustainable and robust economic growth. It is heartening to note that energy policy is emerging as a national priority and inputs from specialists of various disciplines are being brought in to meet the challenges posed by high

demand for energy and environmental acceptability. This is a formidable task and a huge agenda. Definitely, mature professional organisations like The Indian Institute of Metals can play a crucial role in our march towards ensuring long term energy security,

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since materials are pivotal to the success of various energy systems.

We have come a long way from the days of our ancestors; the only source of energy they had was a log of wood. Today, we have identified a myriad of energy sources from fossil fuels to nuclear fusion. But our demands on energy due to changes in our life styles have also increased. According to the International Energy Agency figures, the global demand on energy would increase by 60% by 2030. However, the challenge for India is much larger as it would be reqired to enhance every available option for achieving self sufficiency in energy by 2050. This important and ambitious goal of ensuring energy security can be achieved only through synergistic interaction amongst different sections of the society: the politicians, bureaucrats, private entrepreneurs, technocrats and the scientists.

The key to self sufficiency in the energy sector depends not only on the resources, but on many other factors : generation, distribution, efficiency in usage, reduction of losses in transmission and storage. The development of environmentally acceptable technologies is imperative for public acceptance of high power systems. Higher fuel prices and emphasis on 'return on capital' are the two major considerations that demand construction of plants, capable of running with minimal maintenance over extended lifetimes. Simultaneously, there is a need to reduce particulate and pollutant emissions and eliminate generation of greenhouse gases. Transmission systems must be reconfigured to operate in a more distributed fashion; high energy density storage devices should be developed. All these stages need innovative inputs from both science and engineering disciplines. There has been a remarkable success of the aerospace and information sectors in the last few decades, owing to launching of innovative materials. The directionally solidified and single crystal blades of nickel-based superalloys, high oxidation resistant and thermal barrier coatings and ceramic components for the hot gas path are being successfully used in the gas turbines. These achievements motivate the materials scientists to evaluate our role in the energy sector, which has had a longer lifetime than the two mentioned above. How shall we accelerate our country's march towards self-sustainability with respect to energy?

The first principle is that every source of energy needs to be exploited, with adequate attention to the commercial viability and environmental aspects. Radically new developments in both engineering and materials

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technology are called for towards meeting these demands. All the advanced energy concepts require advanced materials and manufacturing technologies. The design engineers, materials scientists, alloy producers, component manufacturers, plant builders and plant operators should be brought together, reflecting the need to match material properties and component behaviour. The role of advanced materials/processes, which is most relevant to the family of materials scientists is discussed below, with respect to fossil fuel, nuclear power and renewable energy sources.

> The issue to be addressed is as follows: is it possible to produce 'smart' fossil power ? Can one introduce the concept of distributed energy systems with micro-turbines (< 500 kWe)? Such evolutionary and revolutionary solutions are possible if and only if scientists come up with novel materials

Based on today's projections, it appears that fossil fuels would continue to dominate the energy scenario in the coming decades. Hence, there is a compelling need to increase the efficiency of power plants : increase operating temperatures, extend the lifetime of plants, reduce downtime, introduce provision to switch between coal, gas and oil and most importantly reduce emission levels. Burning of fossil fuels releases unacceptable amounts of oxides of carbon, sulphur and nitrogen. Some of

these lead to the risk of global climate change. Global warming, ozone depletion, green house effects and disastrous flooding are the factors, which common man is concerned with, today. These changes are also known to endanger life conditions on earth, including that of human species.

The issue to be addressed is as follows: is it possible to produce 'smart' fossil power ? Can one introduce the concept of distributed energy systems with micro-turbines (< 500 kWe)? Such evolutionary and revolutionary solutions are possible if and only if scientists come up with novel materials.

Capabilities of current ferritic steam turbine steels must be enhanced, alternative materials assessed, and the performance and life assurance issues related to use of coatings addressed. Will conventional steel be replaced by marginally better steels or even the quantum steels? or will they be completely replaced by radically new materials? The advanced new materials should be capable of withstanding higher temperatures and corrosive environments of power generation systems such as coal gasifiers, turbines, combustors and fuel cells. Gas turbine materials face an additional problem of erosion.

The profitable commercialisation of microturbines depends heavily on the development of reliable oxide ceramic components for the combustor, monolithic silicon nitride ceramic components for the radial flow rotors and environmental barrier coatings of tantalum oxide to protect the rotors.

Iron aluminides are being used for increasing the oxidation and sulphidation resistance. In applications requiring high temperature creep strength, oxide

dispersion strengthening is being explored. A new generation of corrosion resistant high temperature alloys is being developed for components in advanced fossil energy combustion and conversion systems.

The structural ceramics for high temperature applications like fiber-reinforced silicon carbide need development of mechanically strong fiber-matrix interfaces that are resistant to oxidation.

The acceptance of fossil power is strongly related to the long term environmental issues. The development of fuel cells has opened up vistas to the new energy-saving technology, with high efficiency and less pollution. Several types of fuel cell technologies are being developed for possible commercial use: Alkaline Fuel Cell (AFC), Phosphoric Acid Fuel Cell (PAFC), Solid Oxide Fuel Cell (SOFC) and Molten Carbonate Fuel Cell (MCFC). The AFC is expensive and susceptible for contamination. The PAFC has long warm-up time and has potential for use only in small stationary power generation systems. Hence, these two fuel cells developed around 1960's are not found suitable for large scale production and commercialization.

The SOFC and MCFC are best suited for large stationary power generation. These fuel cells operate in the range 600 – 1000°C necessitating concentrated efforts on the development of variety of advanced materials. Solid Oxide Fuel Cells have existed for more than a century since Nernst described ionic conduction in Yttria stabilised Zirconia in 1897. However, the developments have been mainly limited by the availability of specialised materials for the heat exchangers, fuel processors, sensors and controls. The compulsion to

develop efficient and less polluting power drives the development of these materials. Selection of the fuel cell materials has become more focused with anodes based mainly on nickel/ Yttiria stabilized zirconia cermets. For interconnects, development of ferritic steels has been emphasized for 800°C operation, especially with pervoskite coatings to protect cathode contact. Balance of plant materials has also been advancing; glass sealants have been developed for stacking the cells together: more economical heat exchangers and fuel processors are available; a high quality thermal insulation is being used. The conclusion is that the development of materials for SOFCs is attaining some maturity. Today, the main efforts required are to demonstrate the longevity and reliability of the materials in many components of gas turbine hybrids, and in systems such as automotive auxiliary power units, stationary combined heat and power plants in buildings and larger pressurized SOFC gas turbine hybrids. In the development of SOFC materials, studies of reactions at electrode/ electrolyte interfaces in fuel cells to overcome long term aging of the interfaces under high DC current loads is assuming importance. Emerging concepts include gas separations using Electrical Swing Adsorption (ESA) on carbon fiber composite molecular sieves. ESA appears to be a promising alternative to current pressure swing adsorption methods.

2005, declared as the World Year of Physics takes one's thoughts to the beginning of the previous century – a Golden era for the Physicists, studded with many marvellous discoveries. The world's most remembered link between mass and energy, proposed by Albert Einstein, has promised to transform our economy and environment with plentiful and clean energy – either by fusing light nuclei as in the sun i.e., fusion or by breaking heavy, unstable nuclei i.e., fission.

We have travelled a long way from the discovery of the basic process to its commercialisation. Today, there are around 440 nuclear reactors based on fission, which are totally 'green' i.e., no harmful environmental release. However, if nuclear power is to completely replace fossil power, it would require 2000 large 1000 megawatt reactors !!! – an impossible task even from the point of view of fuel availability. However, nuclear energy could quickly become the 'safe' mainstay of the grid. Nuclear reactors already provide 20% of power in the US and 75% in France. In the present scheme of planning, 25% of India's power in 2030 would be met by the nuclear power.

India's power strategy is based on the present status of implementation of the Three Stage Nuclear Power Programme that has been the key-driver, propelling the activities of the Department of Atomic Energy in the five decades of its existence. The commercial viability of first stage, namely thermal nuclear reactors has already been established. India's nuclear programme, in each of its phases owes its success amongst others to the multi-faceted mission oriented materials research programme. The Nuclear Fuel Complex, Hyderabad indeed was based on the intense materials research programme on Zirconium and its alloys at BARC, Mumbai.

The commissioning of Fast Breeder Test Reactor (FBTR) - the flagship of Indira Gandhi Centre for Atomic Research, in October, 1985, marked the birth of the second stage of India's nuclear programme. Again, in this stage also, materials research has been to a good extent, responsible for its success. The confidence to proceed with carbide fuel, for the first time in the world, was gained from the expertise on the thermodynamics of various fuels. The use of liquid metal(sodium) cooled fast breeder

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reactors for energy production poses a challenge to the metallurgists and the designers on development of suitable structural and cladding materials. The materials inside the reactor core have to withstand intense neutron irradiation and high temperatures. These hostile environments introduce materials problems unique to fast reactors, like void swelling, creep and embrittlement which determine the permissible life of core components. For economic viability, the target burn-up required for FBRs is large, more than 20 atom% of heavy metal (~ 200,000 MWd/t) and this can be achieved only by the availability of materials resistant to void swelling, irradiation creep and irradiation embrittlement, as well as satisfying high temperature mechanical properties. The residence time of fuel sub-assembly and hence the achievable fuel burn-up is limited by either void swelling of the hexagonal

sheath material or creep strength of the clad. Since fuel cycle cost is strongly the linked with burn-up, development of materials resistant to void swelling and irradiation embrittlement is very important and a challenging task. In FBRs, ferritic and martensitic steels are contemplated for use as possible structural and/or fuel cladding and other in-core component applications. Ferritic steels, HT9 and Mod.9Cr1Mo are of interest because they display low swelling compared to conventional austenitic stainless steels 304 and 316 when irradiated. However, the irradiation hardening in these steels affects their toughness and fatigue properties. The embrittlement effect in these steels is reflected through the increase in ductile-brittle transition temperature and reduction in upper shelf energy. Development of ferritic steel compositions, which are less prone to irradiation hardening effects is urgently needed and it is a great challenge to alloy designers.

Oxide dispersion strengthened ferritic steels (ODS) show the potential to be used as cladding material in FBRs with the ability of operating temperatures beyond 650°C. The major problem that hindered their widespread application is the anisotropy of mechanical properties owing to the processing procedures. These alloys show bamboo-like grain structure and a strong deformation texture which are responsible for their anisotropic mechanical properties, especially an inferior biaxial creep –rupture strength. Research and development programmes are needed to produce equi-axed structure and to explore new alloy compositions. There are other problems with ODS steels besides anisotropy. At present, there is no information on the production of thick-walled parts or large-diameter tubing. Fabrication processes for these

materials for heavy sections still need to be established, and this includes the problem of joining these materials. Therefore, even if the anisotropy problems are solved, much research and development is required for establishing the commercial acceptance of ODS steels for structural applications.

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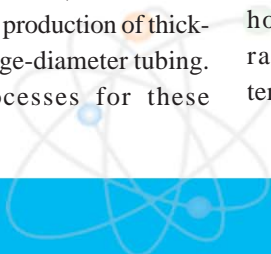
Presently the main goal is to reduce the cost of nuclear power. This can be acheived by increasing the lifetime of the reactor itself from 60 to 100 years, development of life assessment techniques, increase in the residence-time of fuel in the reactor core, increase of burn up of the fuel, reducing the cost of fuel cycle and if needed even changing the fuel for better performance.

The continuous changes in the core component materials from 316 stainless steel to ferritics are the result of an intense materials research programme. In most of the leading materials research programmes, modelling studies are essential to predict materials behaviour under hostile environments like high radiation field, high pressure, temperature, wherein it is not always

possible to perform experiments. Presently, methods to overcome embrittlement problem in radiation resistant steels are being attempted by grain boundary engineering employing advanced state-of-the-art characterisation techniques.

The beginning of construction of a commercial, 500 MWe Fast Breeder Reactor at Kalpakkam based on the experience of FBTR needed maturity, not only in the materials aspects, but also in the development of the required technology, which has been successfully carried out. Fast Breeder Reactor (FBR) components are larger in size than FBTR. Design features of many components are entirely different from that of our previous experience. There was a compulsion to establish newer procedures of fabrication, transport, assembly at site, inspection procedures, methods to ensure reliability of operation for the present design life and possibility of extending the plant life, all of which have been carried out successfully, as a part of technology development. In this process, a number of Indian manufacturers were involved to develop special toolings and to create infrastructure required for the manufacture of FBR components. All leading manufacturers have now set up separate fabrication shops for nuclear components and have specially trained manpower to meet stringent specifications of the nuclear industry.

Like nuclear fission, controlled nuclear fusion could generate electricity without producing air pollution. Thermonuclear fusion is the energy source for the Sun and the stars. For equal amounts of fuel, the energy from fusion is about one million times greater than that from fossil fuels. For such fusion reactions to proceed at high enough rates to be

practical, the fusion fuels (heavy hydrogen) must be heated to temperatures of about 100 million degrees Celisius. Two ways are being pursued to contain the fusion fuel at the required temperature and density: magnetic confinement and inertial confinement. In magnetic confinements, intense magnetic fields confine low-density plasma at high temperatures. In inertial confinement fusion, lasers or accelerators compress extremely small pellets to the very high densities and temperatures. Research on inertial fusion, in which plasma is confined by laser-driven energy fields rather than by magnetic fields is moving along exciting directions. The pursuit of fusion energy is an endeavor, rich in scientific and technological challenges, with the potential to yield tremendous benefits to energy security, economic competitiveness, and international stability. Although tremendous strides have been made over the past decade, scientific questions still remain. The spontaneous formation of a thick insulating surface by the fusion plasma, where the temperatures drops from 40 million degrees to a few thousand, is yet to be understood. The biggest technological challenge for magnetic confinement of plasma in fusion reactors is developing advanced materials that can survive the harsh environment of high temperature and radiation. Efforts are required to replace steel with materials such as vanadium and ceramics, or find ways to protect the first wall of the fusion reactor. Modelling of the magnetic process is particularly difficult because length scales must range from a few millimeters to meters and time scales from millionths of a second to a few hours.

Extensive research and development efforts have provided high impetus to the growth of power industry based on renewable resources. Consequently, there have been continuous evolution in various aspects of renewable energy that include:

- wind, wave, tidal, hydro and geothermal power

- solar power: thermal and photovoltaic

- materials issues relevant to biomass and biotechnology

In wind turbines, for example, materials issues relate to production of large rotating structures at the limits of tensile strength, the need to resist

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the irregular loading and environmental attack characteristic of offshore operation. The success of mere thirty wind turbines providing power to 25,000 households in Costa Rica supported by the Dutch Government is a good example of the utility of wind power. There are a large number of wind mills operating in Thirunelveli-Kanyakumari districts of Tamil Nadu providing power to thousands of households, under

private enterprise. Corrosion and erosion are significant problems for wave,tidal, hydro and geothermal plants and are particularly severe for plants burning biomass or biosynthesised fuels.

In a sense, solar energy is an ideal energy source, especially for tropical countries like India where it is abundantly available; it is 100% renewable and poses no problem in terms of pollution, greenhouse gas generation or security of the energy resource. Photovoltaic solar cells, which directly convert sunlight into electricity, are made of semiconducting materials. These photovoltaic cells provide power for a wide range of applications: at the lower end of the spectrum consumables like watches, calculators and the like can be used with these cells, while at the higher end, power is supplied to light houses and electrical grids. Despite these, the commercial advantages of solar power are not commensurate with the magnitude of the efforts put in. But as has been stated earlier, every source of power needs to be exploited for meeting the growing demand. In this context, development of materials for solar power assumes importance.

The workhorse for harnessing solar power since 1954 is photovoltaic cell made of different forms of silicon. The removal of impurities and defects in the silicon is of critical importance, and is addressed with techniques such as surface passivation with hydrogen and gettering off the impurities out of surface. The purity of the solar-grade silicon feedstock and its availability at an affordable cost are the main problems the industry faces.

Innovations in this field continue: thin film photovoltaic cells use layers of semiconductor materials, only a few micrometers thick and coated on to an

inexpensive backing such as glass, flexible plastic, or stainless steel. Semiconductor materials for use in thin films include amorphous silicon, copper indium diselenide, and cadmium telluride. Other breakthroughs in the area of solar cells include development of Group III-V semiconductors like Gallium Arsenide, 'band gap engineering' by alloying and high efficiency multi junction devices.

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A variety of advanced approaches to develop solar cells are under investigation. Dye-sensitized solar cells use a dye impregnated layer of titanium dioxide to generate voltage. Titanium dioxide is relatively inexpensive. Other advances include polymer (or plastic) solar cells which may include large carbon molecules and photoelectrochemical cells that produce hydrogen directly from water in the presence of sunlight.

The efficiency of energy systems is generally discussed with much attention to the generation part and much less on transmission and storage though these two factors play a crucial role in the economics and efficiency of power production. Even in apparently mature areas, materials issues continue to be relevant, for example, in the competition between aluminium and copper in transmission lines. Some of the breakthroughs, though not yet commercialised, relate to development of superconducting materials. The capacity of superconducting materials to handle large amounts of current with no resistance and extremely low energy losses can be applied to electric devices such as motors and generators, and to electricity transmission in power lines.

Are there research activities exploring efficient methods of transmission of power? Will high-temperature superconductor cables, with capacity to carry three to five times more power than conventional utility cables, replace today's transmission lines? Such issues are the main challenges to the material scientists, whose innovations would prove very beneficial to future generations.

Storage is important for managing fluctuations in demand and supply; systems capable of storing large amounts of energy at high densities are required. The proposed hydrogen economy will require a hydrogen generation, transmission and storage infrastructure that will be dependent on materials-led developments.

Government policy strongly influences R&D in energy generation and channelises the direction of research. However, industry's R&D investment decisions, and the balance of this spending between various technologies, depend on more subtle readings of the economic climate, the rules of the energy market and perceptions of how these will change in the future. The present atmosphere is most conducive for ensuring energy security to all. In the international scenario, there is a strong drive to ensure energy to all the countries; within our country there is a cherished "dream" to become a powerful nation. India should not only become 'developed' in the conventional definition of the term, but more importantly, mature into a nation with sensitivity to the needs of all sections of our society and provide good quality of living standards at an affordable cost. It is we, the 'Materials scientists and technologists', who have to rise to the occasion and fulfill the dreams of all our fellowmen.

I urge each member of The Indian Institute of Metals to contribute significantly towards improving the life style of our fellowmen. I have no doubt in my mind that long term energy security would certainly be achieved within the chosen time targets and we all can, then, feel legitimately proud of having contributed towards this remarkable achievement.

(Baldev Raj)

Challenges in Design and Development of Diverse Safety Rod and its drive mechanism for PFBR

Operational control of nuclear power reactors is normally achieved by the movement of neutron absorbing material in or out of the core region. Additional neutron absorbers are normally arranged to be held out of the core region but can be inserted rapidly into the core on demand. These are normally called safety rods.

In Fast Breeder Test Reactor (FBTR), there is only one type of control rod, which is used for both control and shutdown purposes. However for the present generation reactors, IAEA and AERB safety guidelines insist on two independent fast acting Diverse Shutdown Systems. A shutdown system comprises of sensors, logic circuits and drive mechanisms besides neutron absorbing rods. The description of the design and developmental efforts of the absorber rods and drive mechanism of the second shutdown system of Prototype Fast Breeder Reactor (PFBR), which are designed to be diverse from those of the first system, is the subject of this article.

Based on literature survey, various concepts like liquid absorber, gas expansion module, absorbers actuated by hydraulic means *etc* were studied with a view to assess their merits and limitations. After analyzing the various design options, the basic concept of using high temperature electromagnet (EM) for holding the absorber rod, scram release by EM and resetting by mechanical means was chosen for critical study and development.

In PFBR, the second shutdown system has three-absorber rods namely the Diverse Safety Rods (DSR) and the respective drive mechanisms are called as Diverse Safety Rod Drive Mechanisms (DSRDM). The DSRDM mainly consists of two parts, *viz*., upper part and lower part. The lower part is partially immersed in the hot pool of sodium. The upper part is enclosed in the mechanism box of the control plug and the specified temperature of operation for the components in the upper part is fixed as 80 °C.

The DSRs are held outside the active core region by an EM that is at the lower end of the mobile assembly of the DSRDM. The mobile assembly is coupled to the nut of the roller screw-nut mechanism. The Motor drive sub-assembly rotates the screw in either direction to raise or lower the mobile assembly. When the EM holds the DSR, it translates up or down based on the direction of rotation of the motor. On receiving the SCRAM signal, the EM de-energizes and drops the DSR, which falls into the sodium, under gravity. The DSR gets decelerated due to the damping action of sodium in the dashpot after traveling a certain free-fall distance. The schematic arrangement of the DSRDM and DSR are shown in Fig.1.

There is no comprehensive design code, which covers all the design aspects of the mechanisms. Hence considerable efforts have been made to investigate the various design requirements and to arrive at suitable engineering solutions. The design requirement in two of the important subsystems namely, EM of DSRDM and dashpot of DSR are explained below as typical case studies.

Electromagnet

The major points that weigh in the design of the EM are as follows:

- Material selection to operate in high temperature sodium environment.
- Configuration to achieve leak tightness.
- Maximising load carrying capacity.
- Ability to take misalignment between EM bottom end and DSR sheath top end.
- Minimising thermal stresses.
- Avoiding risk of self-welding between armature of DSR and EM.

These challenges were all successfully met, thanks to an intensive collaborative R&D on various issues. Fig 2 shows the design of EM that satisfies all the above requirements.

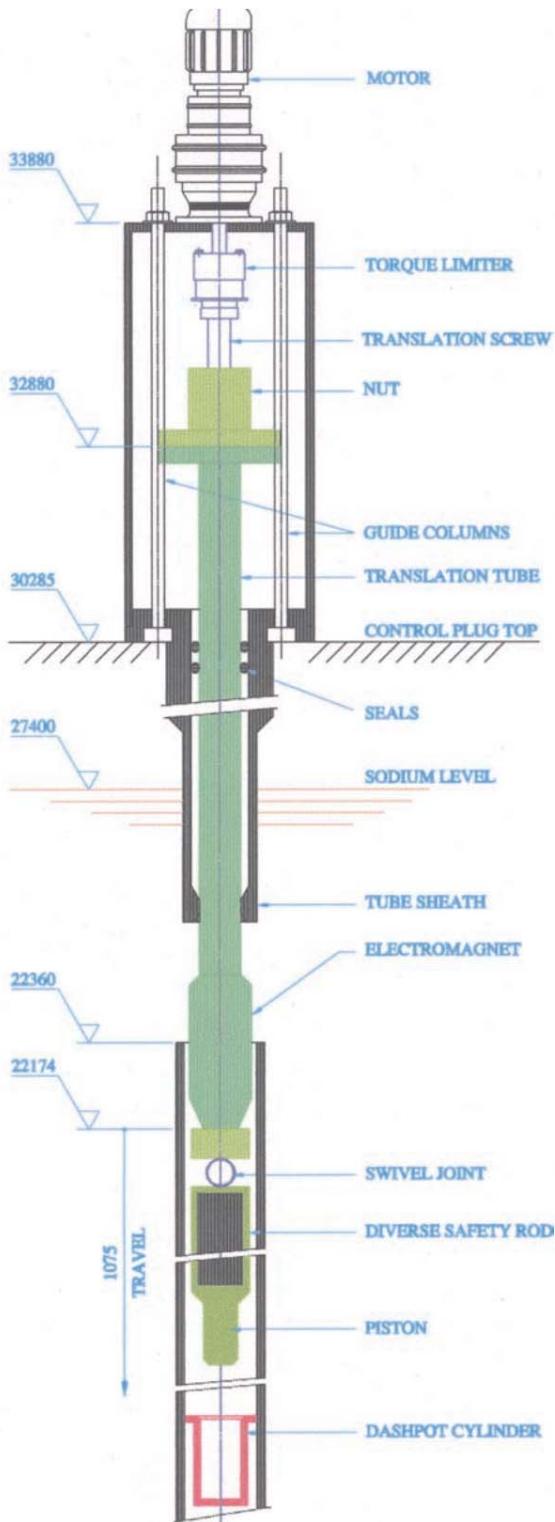| **Salient Dimensions/Features of DSRDM**		
❖ Lower Part		
• Maximum diameter	:	248 mm
• Length	:	10,683 mm
❖ Upper Part		
• Maximum diameter	:	250 mm
• Length	:	2795 mm
❖ Length of Integrated Assembly	:	12,241 mm
❖ Number of		
• Fabricated/Machined Items:	:	82
• Proprietary Items	:	90
❖ Weight of		
• Mobile Assembly	:	1500 N
• Diverse Safety Rod	:	476 N
❖ Materials		
• Iron, AISI 316LN, RNiCr-B, Al.Bronze, Carbon Steel, Alloy Steel, Viton etc.		

Fig. 1 : Schematic Arrangement of DSR and DSRDM

Fig. 2 : Electromagnet assembly

Soft iron is chosen as the material for the inner and outer cores of EM. The material of the armature of the DSR is *2.25 Cr - 1 Mo steel*. These materials are readily available from indigenous sources. The outer surface is chrome plated to reduce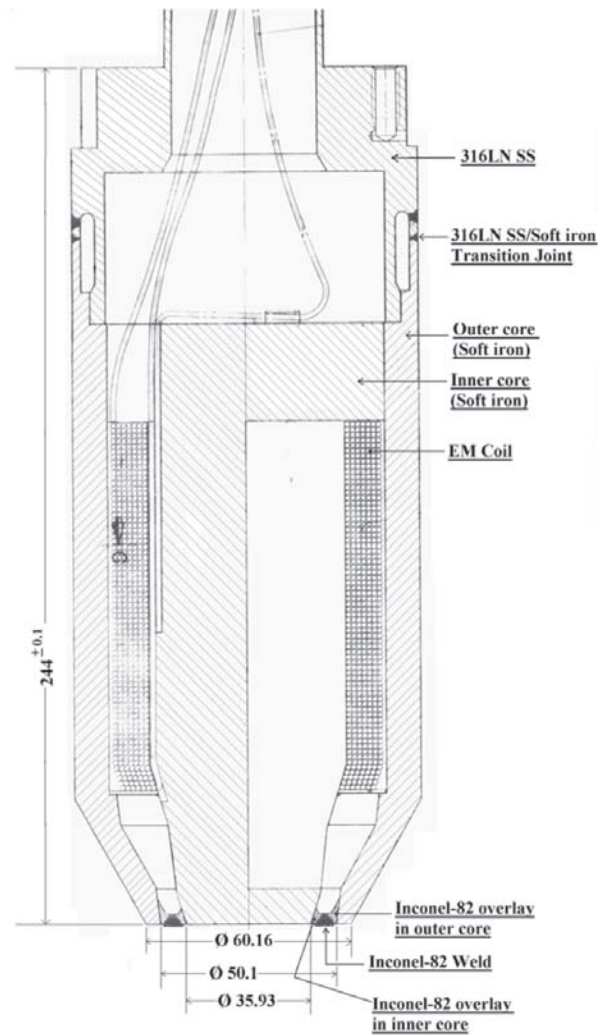 wear and self-welding during the course of rubbing with the sheath of the DSR. The inside of EM is sealed from the sodium to achieve the required response time and to prevent the exposure of EM coil to sodium. Adequate leak tightness is achieved by welding the bottom ends of inner and outer cores with inconel 82 filler. This filler is non-magnetic and thus prevents flux leakage between inner and outer cores. A projection of 0.1 mm is maintained below the cores in the filler region to avoid direct contact of the armature of the DSR with the cores. This is to reduce the response time as well as risk of self-welding. The inner core is left free at the top end to allow free expansion with respect to the outer core.

Design decisions have been verified by extensive testing of EM at room temperature, in a furnace and in sodium. Specimens of the same material combination are also tested separately to verify the performance against self-welding. Experiments are planned to verify the design against thermal shocks.

Dashpot

The important points to be considered in the design of dashpot are as follows:

Table 1: List of experiments for DSRDM & DSR

S.No	Name of the experiment	Objective
1	Testing of Electromagnet of DSRDM in air, furnace and in sodium	To measure load Carrying capacity with respect to current at various temperatures and response time. To verify the endurance against thermal shocks.
2	Testing of dashpot of DSR in water	Functional testing and to measure deceleration and pressure with respect to time.
3	Testing of DSR in water loop	To measure the pressure drops in various positions of mobile DSR. To measure the free fall time vs flow. To measure the flow split between mobile DSR & bypass flow in the annulus between mobile DSR & stationary sheath. To measure the hydraulic lifting force. To verify the performance against flow induced vibrations.
4	Testing of specimens for Self welding possibility between armature & EM of DSRDM	To prove that there is no self-welding risk between the armature and Electromagnet for the chosen combination of materials under the given stress and temperatures in sodium.
5	Testing of prototype DSRDM & DSR in air/water and in sodium	Integral testing of the system for Functional verification at various temperatures & Endurance testing
6	Development of eddy current position sensor for drop time measurement	Laboratory scale testing to study the physical and engineering feasibility and then integral testing with the system.
7	Development of acoustic detection capability.	Laboratory scale testing to study the physical and engineering feasibility and then integral testing with the system.
8	Testing of DSRDM and DSR under seismic conditions	To ensure the insert ability and to measure the drop time

- Material for dashpot piston and cylinder that have to operate at high temperature in the environment of very high neutron fluence and in sodium.
- Suitable configuration of piston and cylinder that give smooth deceleration to the mobile DSR
- Ability to take misalignment between the mobile DSR and its sheath
- Manufacturability

Fig.3 shows the design of dashpot that has met all the design requirements. Modified 9 Cr- 1 Mo is the material chosen for both piston and cylinder, mainly from the consideration of resistance to swelling. A minimum radial gap of 0.3 mm is ensured between the piston and cylinder to take care of relative thermal expansion and swelling, The entire outer surface of the piston and the top end of cylinder are hard faced with RNiCr-B to avoid deformation at the time of the entry of piston into the cylinder during fast drops. The piston is suitably profiled to give smooth deceleration. Extensive testing in water has yielded very encouraging results. Sodium testing is under progress.
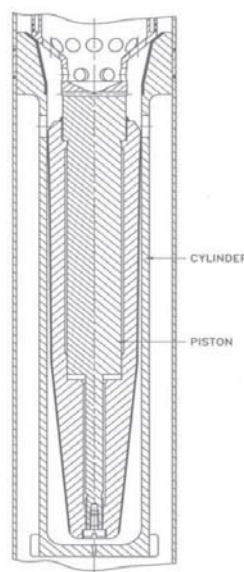

Fig 3 : Dashpot Assembly

Design validation

The DSRDM and DSR are one of the subsystems that ensure safety of the reactor. Hence extensive plans were made to test and validate the design. The table gives the summary of the experiments and their objectives.

The design and developmental activities for DSRDM and DSR, which are one of the most important and totally indigenous subsystems of PFBR have been done with utmost care. The activities have yielded encouraging results and have enhanced the confidence that operation of DSRDM and DSR in the reactor would be trouble free and the intended functions would be fully met. The experience has enriched the 'In-house knowledge' in design, testing R&D related to materials, instrumentation and other issues related to the operation of the mechanisms in sodium.

(R.Vijayashree, P.Chellapandi and S.C.Chetal, Reactor Engineering Group) **11**

Production of enriched elemental boron from enriched boric acid

Compounds of boron containing ^{10}B are used as neutron absorbers in the nuclear industry. In fast reactors, boron carbide is used as a control rod material. Boron carbide containing boron enriched in ^{10}B isotope will be used in the control rods of the first Indian Prototype Fast Breeder Reactor (PFBR).

The carbothermic reduction of boric acid or its anhydride is used presently in the large scale commercial production of boron carbide. In this process, a significant quantity of boron is lost during the reduction and subsequent process steps. An alternate process which does not involve significant loss of boron would be more suitable for the production of enriched boron carbide from boric acid (enriched in ^{10}B). Such a scheme was developed by the Materials Processing Division (MPD), Bhabha Atomic Research Centre not only to minimize the loss of precious enriched boron, but also to enable its recovery from the process wastes. This scheme involves the following steps; i) conversion of boric acid into potassium fluoroborate, ii) production of boron from potassium fluoroborate through fused salt electrolysis, iii) purification of the cathode deposit by "acid-leaching", iv) production of boron carbide by direct reaction of the elements and v) consolidation of the boron carbide powder. The loss of boron is minimal in this route. In order to generate the fundamental engineering data required for building a facility for the production of elemental boron (steps (i) to (iii)) based on the above scheme and to standardize and optimize the process parameters, a "demonstration facility" was established and is currently being operated at the Chemistry Group (CG) at IGCAR.

The process flow-sheets developed at CG, IGCAR for the production of elemental boron from boric acid are shown in Fig.1 and 2. In the first step, boric acid containing ^{10}B (from boron enrichment plant) would be converted to potassium fluoroborate, KBF_4 by reacting it with hydrofluoric acid, followed by the addition of KOH. The KBF_4 precipitate would then be filtered, washed and dried. Subsequently boron would be obtained by electrolyzing a molten mixture containing 18 wt % KBF_4, 12 wt % KF and 70 wt % KCl at 800°C. The elemental boron which is obtained, as a cathode deposit is separated from the electrode, cleaned with water, leached with hydrochloric acid and dried.
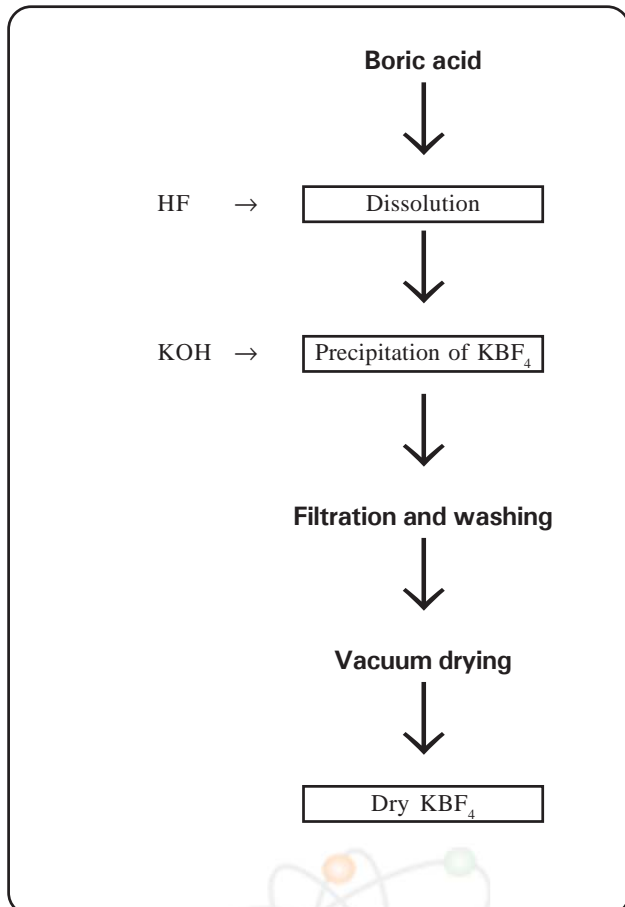
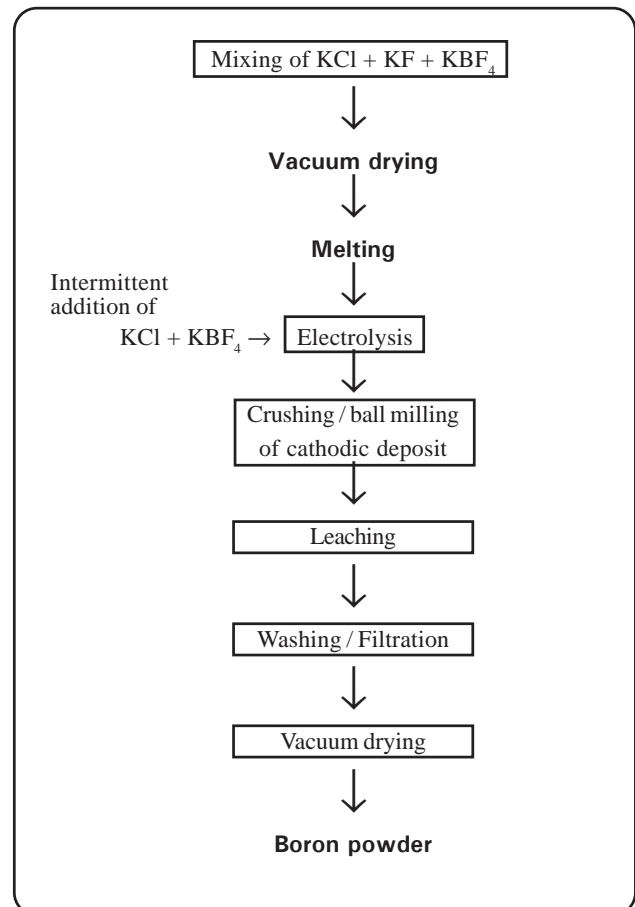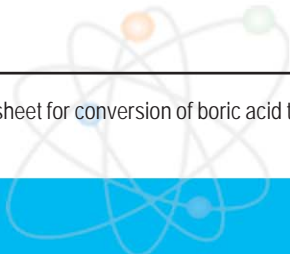Fig. 1 : Flow sheet for conversion of boric acid to KBF_4

Fig. 2 : Flow sheet for conversion of KBF_4 to boron

BORON ELECTROWINNING ASSEMBLY

(+) CATHODE

1. Inconel vessel
2. Mild steel cruciform cathode
3. Protective graphite cup
4. Molten salt
5. Nickel cathode shaft
6. Graphite crucible
7. Graphite sleeve
8. Nickel liner
9. Argon inlet
10. Cooling water inlet
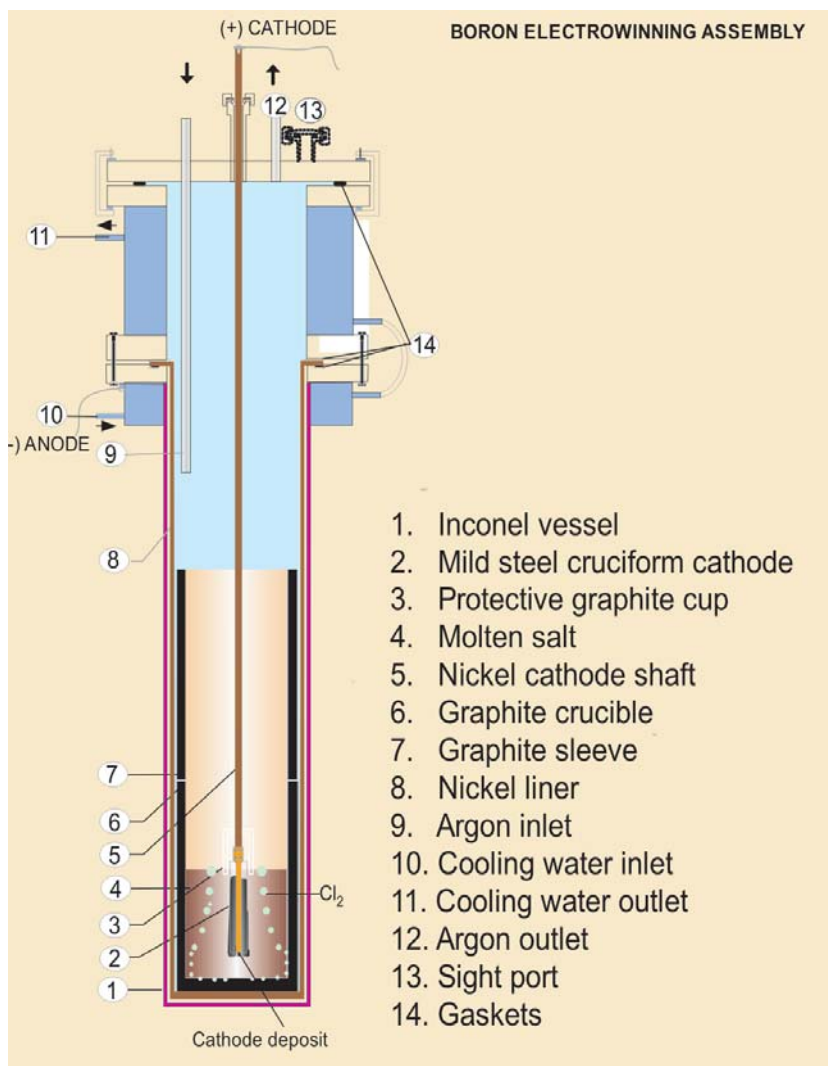11. Cooling water outlet
12. Argon outlet
13. Sight port
14. Gaskets

Cathode deposit

Fig. 3 : The electrowinning set-up

Fig 4. Enriched elemental boron deposit

A diagram of the electrowinning set-up is given in Fig. 3. In a typical electrowinning experiment, about 12 kg of KCl, 8 kg of KBF_4 and 5 kg of KF salts were first pre-dried under IR lamps followed by vacuum drying to bring down the moisture level in the salt.

These dried salts were then mixed in appropriate proportions and loaded into a high density graphite crucible of 300 mm diameter and 400 mm height. This graphite crucible along with the salt mixture was then placed inside the electrolytic cell made of inconel (Fig. 3). The salt mixture was again dried in vacuum in order to bring down the level of residual moisture present in the salt mixture. After melting this mixture at 800 to 850°C, pre-electrolysis was carried out to remove some of the impurities present in the molten salt. Electrolysis was then carried out at 800°C. Boron was deposited on the mild steel cathode and chlorine gas was liberated at the anode. The boron deposit thus obtained was removed from the cathode, crushed, milled and leached with hot water to remove the residual salts from the deposit. This deposit was further leached with boiling HCl in order to remove the iron impurity. The product thus obtained was then washed with water, dried and stored under argon. Fig.4 shows a photograph of the electrodeposited boron.

The specifications of the elemental boron powder to be used for the production of boron carbide pellets for reactor applications and the typical chemical assay of the elemental boron produced at CG, IGCAR are given in Table 1. A large number of production campaigns were carried out to standardize the process parameters in order to obtain elemental boron that meets all the technical specifications. The chemical purity, specific surface area, distribution of sizes among the particles and X-ray crystallite size of these boron powders were investigated. Analytical methods were standardized, and in cases that were not available, developed for the characterization of starting materials, process intermediates and the final product involved in the boron production process. The morphology of these deposits was examined using scanning electron microscopy, while the

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Table1

Specifications for the elemental boron and the typical chemical array of boron produced at CG, IGCAR

Element	Specification (Wt %)	Processed boron (Wt %)
Boron	94 % minimum	97
Carbon + Oxygen	4 % maximum	2
Iron	1 % maximum	0.5
Aluminium + Magnesium + Silicon + Calcium	0.9 %	0.7
Fluoride	0.1 % maximum	0.025
Chloride	0.1 % maximum	0.025

chemical state of the matrix as well as the impurity phases present in them were established using X-ray photoelectron spectroscopy (XPS). The ease of oxidation of these powders in air was investigated using differential thermal analysis coupled with thermogravimetry. The characteristics of the electrodeposited boron as well as the processed boron studied by these techniques helped to optimize the process parameters.

Comparing the technical specification for elemental boron and the chemical assay of processed boron produced at CG, IGCAR (Table 1) it is concluded that the processes which are currently being employed are capable of producing elemental boron powder that conforms to the specifications. It was established that elemental boron powder with a purity of 95-98 % (meeting all the technical specifications as control rod material in a fast reactor) could be produced using the above process. It was also demonstrated that the above process can be employed for the large-scale production of elemental boron through the electrowinning process.

After standardizing the production methodology by producing natural elemental boron from boric acid, enriched elemental boron is being produced from enriched boric acid from the Separations Technology and Hydraulics Division.
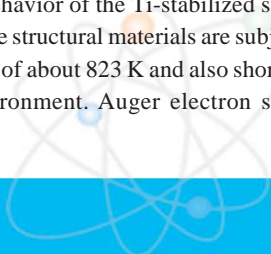
*(Reported by
S. Anthonysamy, Convener,
Task Force on Elemental Boron
Production, Chemistry Group)*

Surface segregation of minor alloying elements in Ti-modified stainless steel (D9) studied by Auger electron spectroscopy

Ti-modified 15Cr-15Ni-2.2Mo stainless steel, D9, is the material chosen for the structural applications in the Prototype Fast Breeder Reactor(PFBR). Optimum amount of minor alloying elements and proper thermo-mechanical treatments are known to improve and enhance the resistance to irradiation induced void swelling. Among various precipitates formed in Ti-modified stainless steels. The carbide and phosphide (MC and M_2P) are the most preferred ones due to the fact that they form in nanometer size and are distributed throughout the bulk. MC precipitate formation is also known to remove carbon and suppress $M_{23}C_6$ precipitation at grain boundaries, which are detrimental by way of embrittlement and intergranular cracking. Segregation of alloying elements to surface and grain boundaries is important in arriving at a proper understanding of the high temperature behavior of the Ti-stabilized stainless steel type D9 alloys for reactor applications, as these structural materials are subjected to prolonged exposure at elevated service temperature of about 823 K and also short time transients to higher temperatures in the reactor environment. Auger electron spectroscopy is one of the tools used

extensively for the surface segregation studies. In this work, surface segregation of alloying elements in Ti-modified stainless steel, D9, upon thermal annealing, has been studied using Auger electron spectroscopy (AES) with specific emphasis on the influence of thermomechanical treatments on surface segregation.

The iron based D9 alloy (Ti/C=6) having the composition with Ni (15.068 wt%), Cr (15.051 wt%), Mo (2.248 wt%), Mn (1.509 wt%), Si (0.505 wt%), Ti (0.315 wt%), C (0.05 wt%), Ta + Nb (0.02 wt%), Co (0.015 wt%), P (0.011 wt%), S (0.0025 wt%), B (0.001 wt%) and N (66wt.ppm) was prepared in the Metallurgy and Materials Group. These samples were solution annealed at 1340 K for 30 minutes, subsequently held at 1470 K for 5 minutes and finally furnace cooled. The average grain size is 20 µm. One set of samples were cold rolled to 20% thickness reduction to study the
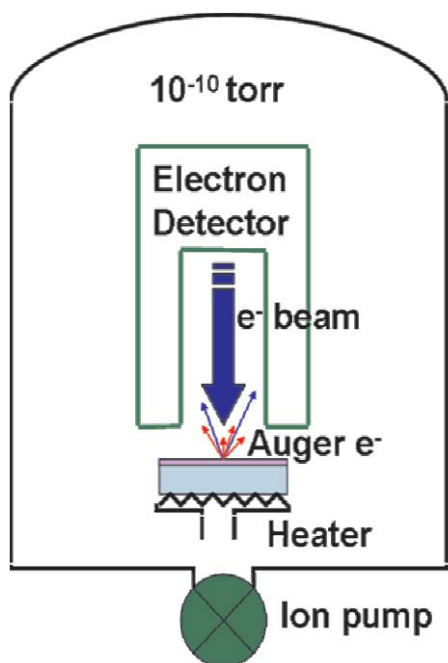
Fig. 1 Schematic diagram of the experimental arrangement. The sample is bombarded with a primary electron beam (from an electron gun) to generate Auger electrons from the sample surface (emanating from the top ~ 5 nm layer), which are detected using an electron detector/analyzer. The sample is heated with a resistive heating assembly. The sample assembly is inside an UHV chamber evacuated to 10^{-10} torr using an ion pump.

effect of cold work induced segregation behavior. Chemical composition of segregated elements was monitored using Auger electron spectroscopic measurements, as a function of isochronal annealing temperature between 300 and 1000 K for both solution annealed and cold-worked samples. Figure 1 shows the schematic arrangement of the experimental arrangement. As received samples were sputtered with 3 keV Ar^+ ions for 10 minutes so as to remove the surface contamination. Since annealing treatments were done in the same chamber without breaking vacuum, subsequent measurements were done without additional sputtering. In order to verify the surface segregation effects, samples were sputtered after the final annealing step at 973K with 3keV Ar^+ ions for 10 minutes.

Figure 2 compares the raw differential Auger spectra for 20 % cold-worked D9 alloy with a Ti/C ratio of 6 in (a) as received and sputtered condition (b) after 973 K annealing and (c) sputtered with 3 keV Ar^+ ions for 10 min after final annealing. As seen from figure 2(a), the major constituents viz. Fe, Cr, Ni, and Mo are clearly seen along with Si, N and Ti. Carbon and oxygen were found to be present in all the samples under most of the annealing conditions. After annealing at the final temperature of 973 K (fig. 2(b)), sulphur, nitrogen and

titanium are prominently seen along with phosphorous. It is also noticeable that due to minor element segregation, the intensity of the major Fe peaks have been reduced. After this measurement, the sample was sputtered and this spectirum is shown in fig. 2 (c). As can be seen, the surface segregation of S, P, N and Ti is clearly confirmed by the disappearance of S and P along with drastic reduction of N and Ti, after sputtering. The silicon line is seen only after sputtering. These observations are qualitatively similar for the solution annealed sample also.

Figure 3 compares intensities of various segregated elements for solution annealed and cold worked samples after final annealing at 973 K. Normalisation of individual elemental peak heights has been done with respect to the Fe (703 eV) peak height. As seen from Fig 3, Sulphur is the most dominating surface segregating species along with Cr, N, Ni and Ti at 973 K, agreeing with previous segregation studies in steels. However, the striking feature is the observation of high surface segregation of Ti along with C and N for the cold worked sample. It can be seen that the extent of surface segregation of these elements in the solution annealed sample is appreciably less.
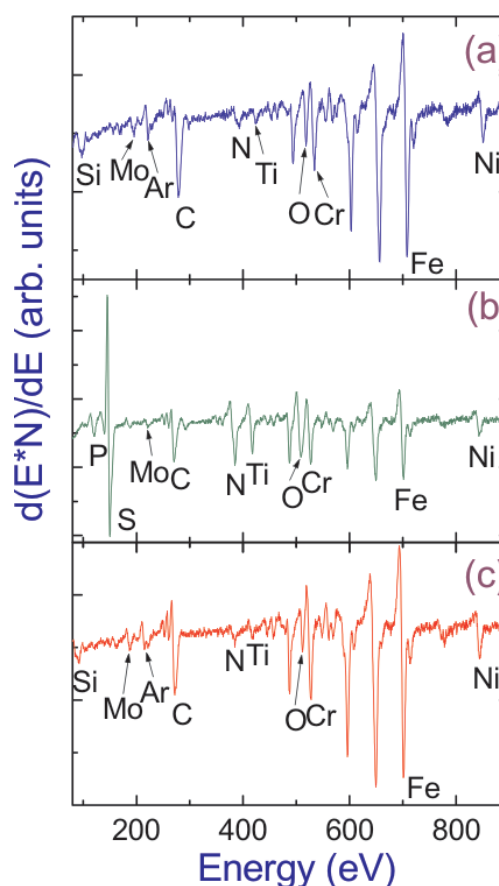

Fig. 2 Auger electron spectra of 20 % cold-worked sample with Ti/C ratio of 6 after (a) as-received and sputtered (b) annealing at 973 K and (c) sputter cleaning after 973 K anneal. In this experiment, each element gives rise to characteristic Auger electron peak and the respective elements are marked in the figure. The peak due to argon arises due to sputtering argon gas used in the surface-cleaning process. After annealing at the final temperature of 973 K (fig. (b)), sulphur, nitrogen and titanium are prominently seen along with phosphorous. Upon removing the top surface layer by sputtering (fig (c)), the dominant features (fig. (a)) are restored, confirming the surface segregation behavior.
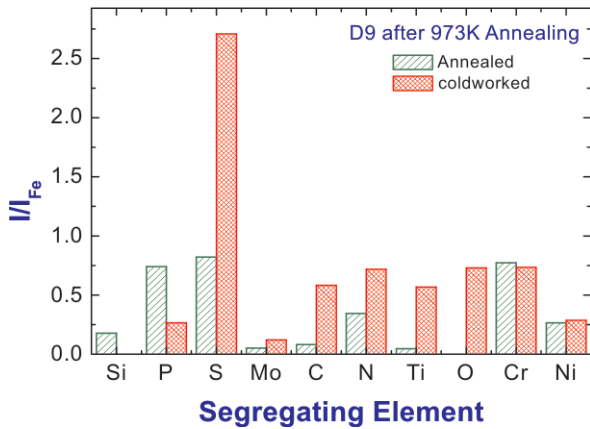
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Fig. 3 Variation of normalized Auger peak heights for various elements for solution annealed and cold worked D9 samples after annealing at 973 K. The peak heights of each element have been normalized with that of pure Fe peak, for comparing the behavior of annealed and cold-worked samples.

Figure 4 shows the variation of normalized peak heights of Ti, C and N as a function of annealing temperature in annealed and cold worked samples. As seen from figure 4(a), Ti segregation in solution annealed D9 almost remains constant, except for small peaking around 870 K. On the other hand, the cold worked sample shows a sharp increase in Ti segregation above 800 K. Surface content of carbon is seen to decrease with increasing temperature for solution annealed D9, while it increases with annealing temperature above 800 K in the cold worked sample, as shown in figure 4(b). Nitrogen segregation in annealed sample shows a clear peak around 850 K and falls thereafter, as seen in fig. 4(c). On the other hand, the cold worked sample shows a sharp increase beyond 800 K. Sulphur segregation increases above 850 K in both annealed and cold worked samples. This behaviour is consistent with the site competition between N and S. Sulphur, having higher segregation enthalpy, ultimately dominates over N segregation above 850 K in the solution annealed sample.

The concomitant increase of Ti, C, and N segregation above 800 K (in Fig. 4) in the cold worked sample can be understood in light of the TiC(N) precipitation in these type of alloys. It is well established that nanometer size TiC(N) precipitation occurs above 800 K throughout the bulk in Ti-modified alloys. Our earlier positron annihilation studies on cold-worked D9 alloy with Ti/C ratio of 6 also revealed a sharp increase in positron trapping at nanometer size titanium-carbide precipitates above 800 K. These nucleated TiC precipitates subsequently impede the dislocation movement, resulting in sluggish growth kinetics. Rapid growth of TiC precipitates was finally observed to occur along with the grain growth during recrystallisation at temperatures above
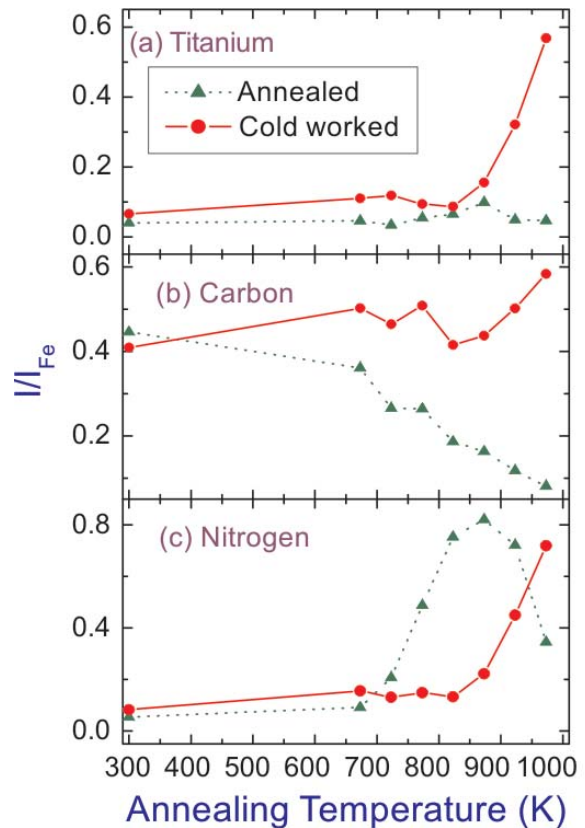

Fig. 4 Variation of normalized peak heights of Ti, C and N as a function of annealing temperature in solution annealed and cold worked samples. This data had been deduced from a series of measurements carried out on annealed and cold-worked samples at various annealing temperatures.

1100 K. In light of above observations, the co-segregation of Ti, C and N in cold worked samples is attributed to the complex interplay between solute-dislocation binding as well as impeded diffusion and annihilation of dislocations at temperatures above 800 K.

In conclusion, the surface segregation behavior of minor elements such S, C, N and Ti in D9 sample, subjected to elevated temperature aging has been investigated using Auger Electron Spectroscopy. Prior cold-work was found to be considerably influencing the segregation behavior. Sulphur was the dominant segregating species at high temperatures. Ti and N were found to co-segregate along with carbon upon cold working. This co-segregation was associated with the nano-scale TiC(N) precipitation in D9 alloy. Further studies are planned to understand this surface segregation behavior upon sodium exposure.

(R. Rajaraman, P. Gopalan and
G. Amarendra, Materials Science Division)

Pressure Transient Consequences on the Main Steam System during Turbine-generator Trip and Plant - Grid Disconnection Events

Chetan Verma
DOB: 12.05.80

Chetan Verma obtained his B.Tech (Chemical Engineering) from the Institute of Technology, BHU in 2002 and M.Tech (Chemical Engineering) from IIT-Kanpur in 2004. He joined the BARC Training School through DGFS-2002 and joined IGCAR as Scientific Officer (SO/C) in September 2004.

A Turbine-Generator (TG) trip event and plant grid disconnection event (leading to lower load operation), in a power plant, leads to rapid pressure buildup and steam hammer in the Main Steam System (MSS), which is a cause of concern for the integrity of the SG tubes and MSS. As per the current estimation on the frequency of various Design Basis Events (DBE), these are category 2 events with expected occurrence of 381 times in the plant life of PFBR. Therefore, a pressure transient analysis code **TARANG** has been developed to study the MSS pressure transients.

The PFBR MSS is provided with a turbine bypass system (TBS) and Atmospheric Steam Discharge System (ASDS) to mitigate the consequences of pressure rise due to these events and safety relief valves as the ultimate line of defence. In order to keep the main condenser cost low, only 60 % steam is bypassed and dumped into the condenser after two stages of depressurisation and desuper-heating through turbine bypass valves (TBV). Therefore, an additional Atmospheric Steam Discharge Valve (ASDV) has been provided which can expel up to 40 % of the rated steam flow in the atmosphere. In order to improve the availability of the plant, the turbine bypass system has been implemented as two 50 % parallel systems rather then one 100 % system. The simplified schematic flow sheet of MSS including the ASDV and turbine bypass with Auxiliary Steam Header (ASH) in between two TBV is shown in Fig.1. Another important characteristic of PFBR, which has a bearing on the pressure transients in the MSS, is the fact that the steam generators (SG) are of once through, integrated units (without any boiler drum as in conventional fossil power plants) which significantly reduces the severity of this event. Due to the rapidness of the event, a detailed analysis is required to understand the transient behavior of the MSS.

A one - dimensional compressible fluid flow in a horizontal pipe with rigid walls is considered for development of *the TARANG* code. Method of Characteristics (MOC) is used to solve the governing equations of mass, momentum and energy balance and interfaced with other process models. Inlet is considered at the SG outlet with Boiler Feed Pump (BFP) as pressure source, and SG and High Pressure Heaters (HPH) as pressure loss elements. Outlets are considered at the Turbine Governor Valve (TGV), ASDV and condenser.

TBVs are considered to be a combination of depressurizing and desuperheating valves with spray water mechanism. Due to the large pressure drop across the TBV, flow through them becomes choked. It has been considered that the TBV desuperheats the steam up
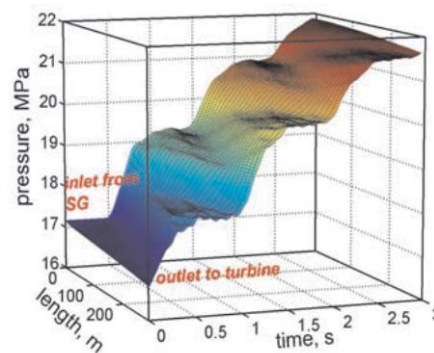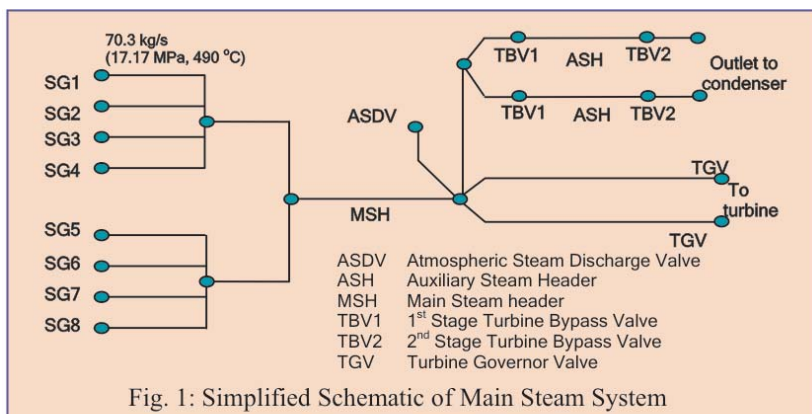

Fig. 1: Simplified Schematic of Main Steam System

Fig. 2 Pressure profile in MSS: without control action by TBV and ASDV

Table 1: Various Cases Analysed for the Parametric Analyses of TG Trip Event

Case No.	TBV1		TBV2		ASDV	
	stroke time, s	actuation by	stroke time, s	actuation by	stroke time, s	actuation by
1	1	17.5 *	1	17.5*	0.5	17.7*
2	1	17.3*	1	17.3*	0.5	17.5*
3	1	TG trip signal	1	TG trip signal	0.5	17.3*
4	1	,,	1	,,	0.5	TG trip signal
5	1	,,	1	,,	1	,,
6	1	,,	1.1	,,	0.5	,,
7	1	,,	1.5	,,	0.5	,,

* Pressure (MPa), measurement at MSH outlet

Table 2: Maximum Pressure reached during various cases

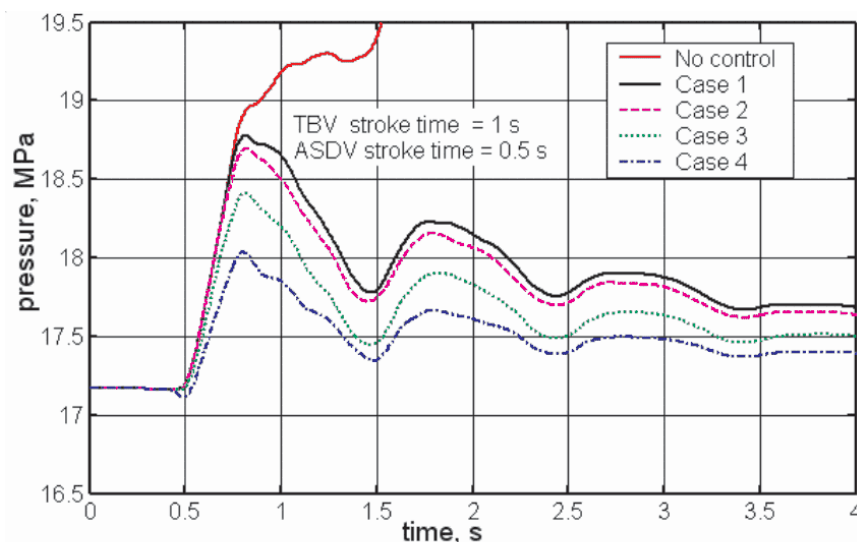| Case No.	Maximum Pressure (MPa)	
	SG outlet	ASH
1.	18.78	3.44
2.	18.70	3.44
3.	18.41	3.38
4.	18.04	3.33
5.	18.28	3.38
6.	18.04	3.55

Fig.3: Pressure Variation at SG Outlet

to the desired condition almost instantaneously. A process model for the desuperheating portion is required only to evaluate the effects of insufficient or failure of cooling water flow, which is not included in the scope of this study. The valve constants are determined based on the required flow capacity (60 % for TBV and 40 % for ASDV) at normal operating conditions (at higher pressures more steam will be relieved).

The TG trip event is simulated by assuming that the outlet boundary condition flow through the turbine end of the computational model reduces linearly to zero in 0.3 s. The resulting pressure transients at various points in the MSS are obtained. The pressure profile in the MSS without any control action by the TBV and ASDV is shown in Fig 2. The design requirements of when the ASDV and TBV should start opening and with what speed they have to get fully opened, characterized by their 'stroke-time' are evaluated in this study. Table 1 shows the various cases analysed and Table 2 shows the maximum pressure reached at the SG outlet and in the ASH for these cases.

Due to the actuation of TBV and ASDV, steam starts flowing through them. A reduced pressure wave propagates into the MSS, which checks the increase in the pressure at various parts of the MSS and pressure continues to reduce in a periodic manner. Fig.3 shows the comparative pressure variation at the SG outlet for the cases considered. When the TBV and ASDV opened, based on a high-pressure signal (case 1), the SG outlet end pressure reaches a maximum of 18.78 MPa. When both these valves are opened simultaneously along with the TG trip command (case 4), it is seen that the maximum pressures reached is ~ 18 MPa. From Table 2 it is also seen that ASH pressure (Case 4, 6 and 7) is very sensitive to difference in stroke - times of TBV1 and TBV2.

This evolution of maximum pressure with respect to different design parameters provide vital inputs for the design and operation of the MSS in PFBR.

Chetan Verma and colleagues,
Mechanics and Hydraulics Division,
Reactor Engineering Group

Acoustic Emission Technique - A Non-destructive tool to Monitor Stress Corrosion Cracking

Ms. Anita Toppo
DOB: 16.09.75

Ms. Anita Toppo *obtained her M.Sc. Degree (Chemistry) from University of Pune in 1998. She has initially worked in the Department of Explosives, Nagpur during 1999-2001. She joined IGCAR directly as Scientific Officer (SO/C) in February 2001.*

Materials degrade during service due to their interaction with their environment and due to the effects of high service temperatures. The processes include intergranular corrosion, stress corrosion cracking (SCC), corrosion fatigue (CF), pitting corrosion, thinning, creep and fatigue damage. Hence, periodic inspections of structural materials and components of nuclear plants by non-destructive techniques (NDT) are very important to detect and evaluate their degradation. Most of the NDT techniques are used off-line during shut down periods, and, hence, can be both time consuming and expensive. However, the need to reduce economic losses and safety impact due to corrosion have necessitated the use of NDT techniques for on-line monitoring of corrosion in plants. The stringent inspection regulations necessitate the use of more advanced and reliable on-line NDT

methods for assessing structural integrity of parts, specifically to detect the damage at its initiation stage; in other words, much before the defects are detected by conventional NDT techniques. The acoustic emission (AE) technique presents the most viable tool for on-line corrosion monitoring of corrosion. AE has been developed as a non-destructive evaluation technique for structural integrity monitoring and for leakage detection in pressure systems, in addition to being a useful tool for materials research. The AE phenomenon is the result of transient elastic wave propagation generated by a rapid release of energy within a material due to changes in local stress and strain fields.

Corrosion processes are highly amenable to detection and characterisation by the AE technique. Some of the processes during corrosion, such as dissolution of metal and film formation do

not emit detectable AE, while some other processes such as film cracking, gas evolution, hydrogen migration, plastic zone formation, discontinuous cracking during SCC and hydrogen cracking produce AE, since all these processes strain the lattice. In corrosion processes that occur without application of stress, detection and monitoring of corrosion is due to evolution of hydrogen, formation of hydrogen bubbles and their motion on the specimen surface. Fig. 1 shows a representative map on relative AE amplitude distribution of microprocesses that may operate in connection with SCC or corrosion fatigue. It is observed that AE generated by several of these microprocesses occur at amplitude levels comparable with those for hydrogen gas evolution.

In our experimental programme, compact tension (CT) specimens of AISI type 316LN stainless steel (SS) were subjected to SCC testing in 45% $MgCl_2$ solution at 413 K in the range of stress intensity factors of 13-26 $MPa.m^{0.5}$ using the constant load testing method. The tests were carried out at 413 K to eliminate boiling of the environment. Since the specimen was immersed in a corrosive environment, the AE probe could not be placed on it. Instead, a wave guide was welded on to the specimen and the AE
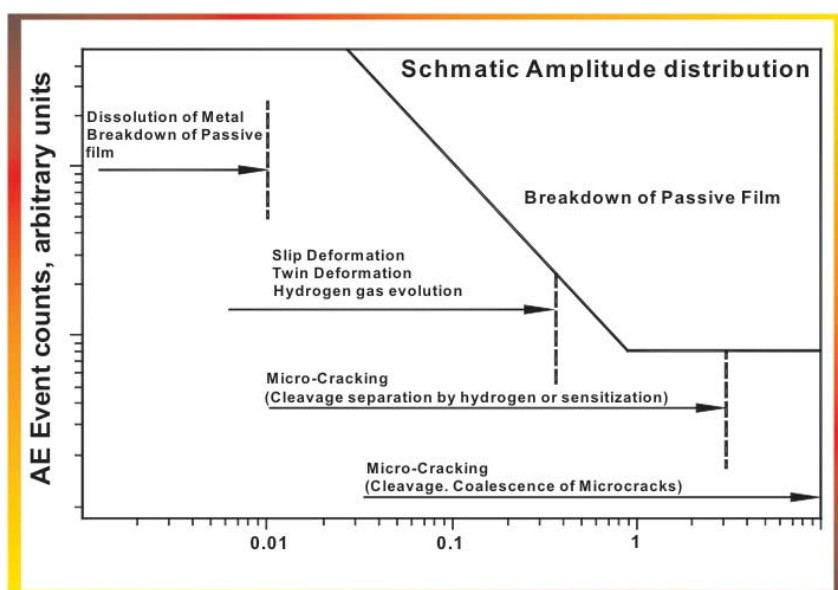

Fig. 1: Various AE sources during SCC or corrosion fatigue processes and their energy levels drawn on amplitude distribution
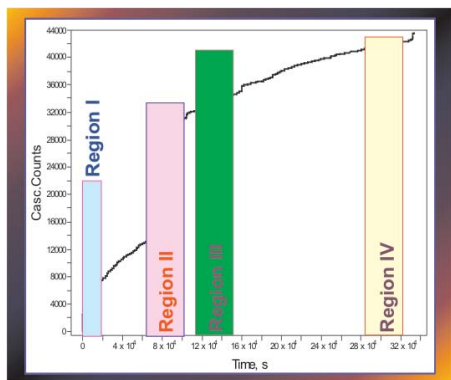
Fig. 2: Variation of AE counts with time during SCC
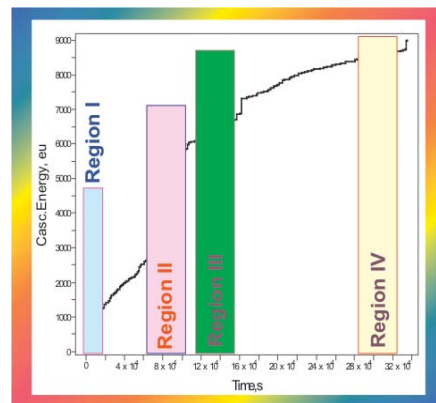of type 316LN SS in 45% $MgCl_2$ solution at 413 K

Fig. 3: Dependence of AE energy on time during SCC
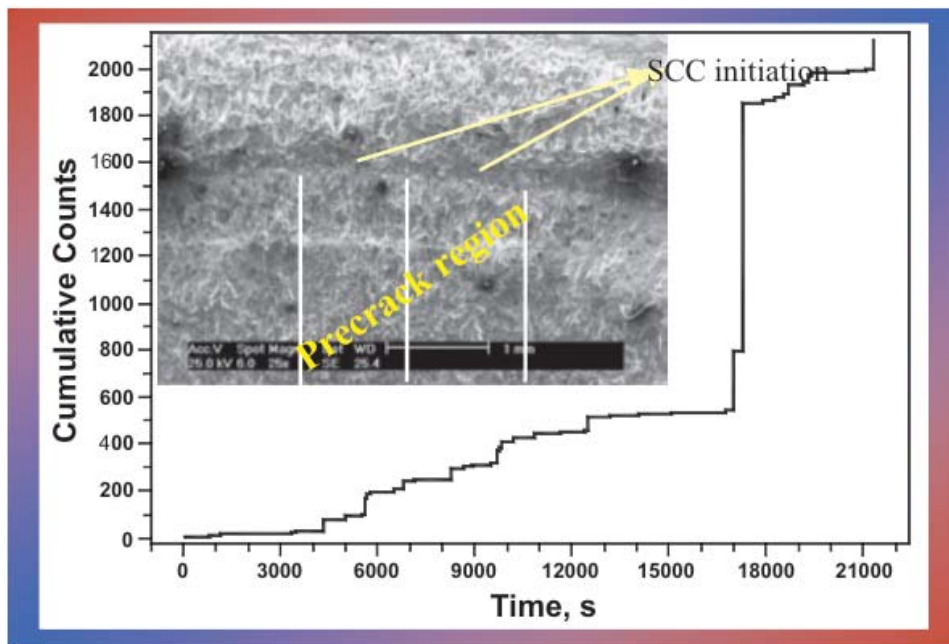of type 316LN SS in 45% $MgCl_2$ solution at 413 K

Fig. 4: Burst in AE counts and energy corresponds to SCC initiation

signals generated during the test were monitored with respect to time using a Vallen Systeme AMS3 system with a broad band frequency sensor.

The average SCC crack growth rate in the plateau region is 2.33 x 10^{-8} m/s in the K_I range of 13-26 MPa.$m^{0.5}$. Figs. 2 and 3 show variation of AE counts and energy with time. Both AE counts and energy emitted during the SCC of type 316LN SS increased with time. A sudden burst in AE counts and energy was observed at the same time during the SCC tests. The cause of this sudden burst of AE counts and energy

was investigated in another set of experiments, by stopping the SCC test some time after such a burst in AE counts and energy was observed. The CT specimens were then pulled to failure and the fracture surface observed. The fractograph superimposed in Fig. 4 shows the presence of a narrow region of SCC (dark region in the fractograph) between regions of precrack and ductile failure. This confirmed that the burst of AE counts and energy corresponded to SCC initiation.

During the SCC test, AE with amplitudes of 27.6, 31.2, 33.6, 35.8, 37.2,

39.8, 40.9, 41.6, 42.5, 44 and 46.5 dB with different counts, energy and rise times occurred. The observed AE activity (Figs. 2 and 3) was studied in detail for better understanding of the SCC phenomenon in four different regimes of the test viz. at the start of the test (Region I), during SCC initiation (Region II), during the early stages of SCC crack growth (Region III) and during later stages of crack growth (Region IV). Fig. 5 shows the amplitude of AE signals as a function of time during the various stages of the SCC test. Initial hydrogen evolution ceased before crack
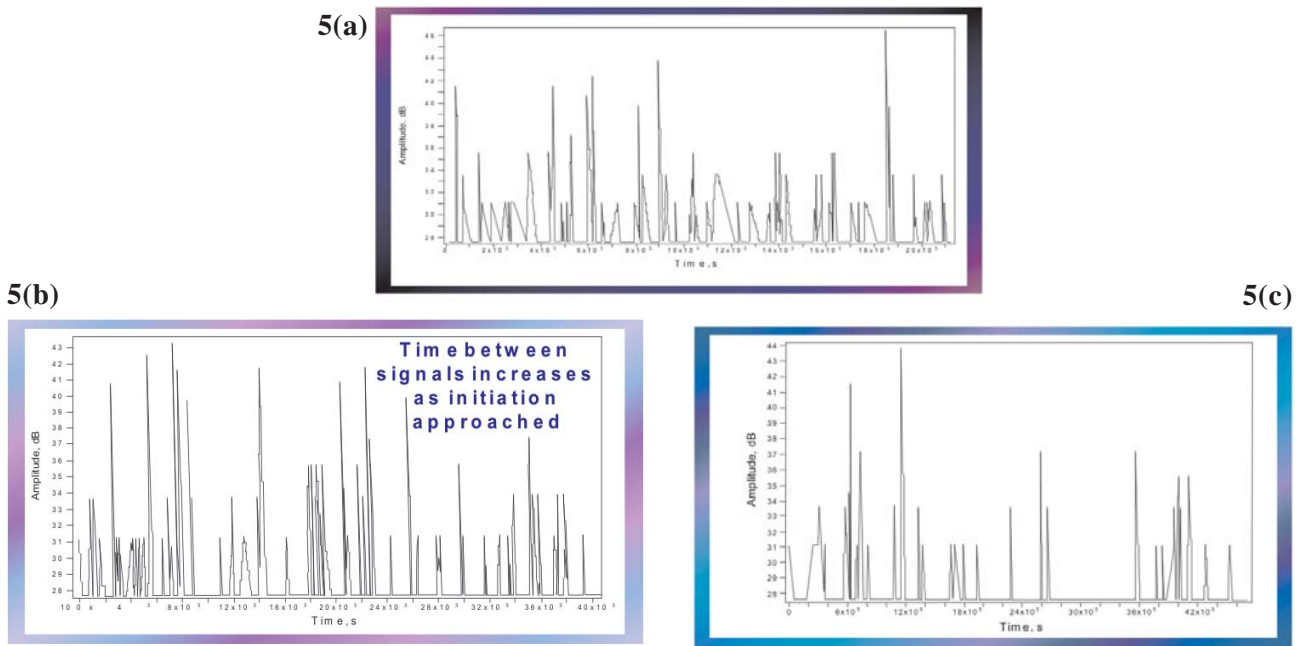
5(a)

5(b)

5(c)

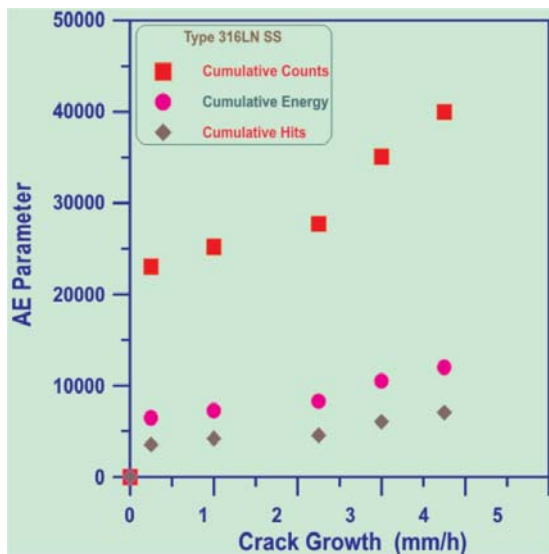Fig. 5: AE amplitude distribution during the SCC tests

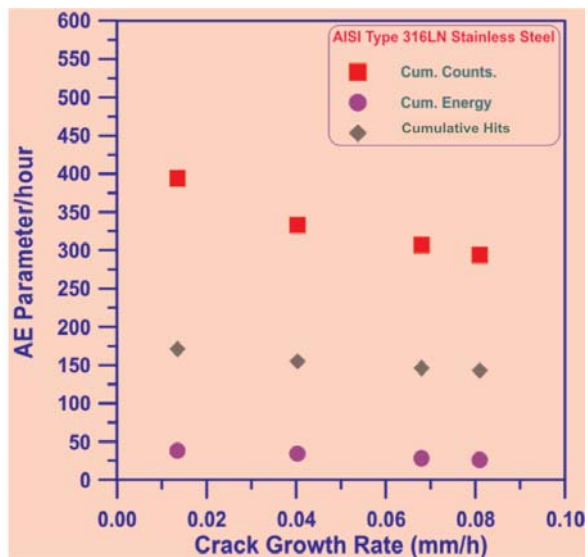Fig.6: AE parameters increase with crack length

Fig. 7: Rate of AE parameters decrease with increasing crack growth rate

initiation occurred. During initiation, the time gap between AE signals increased. This time gap increased further with increasing crack growth (Fig. 5a,b and c). During the start of the test, low amplitude (< 39.8 dB) AE events were more than the high amplitude (> 39.8 dB) AE events. However, as initiation was approached, a reduction in the larger amplitude signals was observed and the small amplitude AE events were found to have more counts and more energy and possessed a wider range of rise times than at the start of the test. This signified that the production of low amplitude AE events with higher counts and energies caused the initiation of SCC. In the early stages of crack growth, the AE counts and energy dropped significantly. During later stages of crack growth, low amplitude AE signals were found to dominate and the counts and energy of high amplitude AE dropped considerably as compared to early stages of crack growth.

AE during crack growth

In the present work, maximum AE signals were found to occur at 31.2 dB. Hydrogen gas evolution had ceased much before initiation as soon as an

environmental-compatible passive film was formed. Hence, based on literature, it could be inferred that in the absence of hydrogen evolution, the AE signals during SCC propagation corresponded to plastic deformation or to ductile tearing of ligaments between two adjacent planes. Studies carried out in NDED, IGCAR, showed that no AE occurred during the post necking period of the ductile failure of austenitic SS during tensile testing. This ruled out ductile tearing to be the source of AE. However, AE due to dislocation motion during plastic deformation between yield stress and ultimate tensile strength was reported. To confirm that the AE signals were due to plastic deformation, a CT specimen was loaded at a K_I value equal to 15 MPa.m$^{0.5}$ in air, and the AE signals recorded for about 16,000 seconds. It was seen that the AE signals due to plastic deformation of the precrack tip had rise times of $< 120\,\mu s$, with maximum emissions occurring between 31 to 34 dB. Comparison of this result with the AE results during SCC confirmed plastic deformation to be the major source of AE.

On correlating the AE data with the SCC crack length and crack growth rate showed that the AE counts and energy increased with increasing crack length (Fig. 6). However, when the same parameters were normalised against the time for crack growth, the rate of AE counts and energy decreased with increasing crack growth rate (Fig. 7). This was explained based on triaxial state of stress ahead of the crack-tip, which causes plastic deformation and blunts the crack. Larger the crack length, higher is the value of K_I. This results in greater stress triaxiality leading to larger plastic zone ahead of and, hence, greater blunting of the crack tip. Larger plastic zone would imply that longer times would be required for the crack to resharpen for further crack propagation to occur. This explains the larger time gaps between two AE events during later stages of crack growth and the reduced AE rate with increasing crack growth rate. It was inferred that AE was emitted during formation of plastic zone. The time period between two AE events corresponded to the period of material dissolution that caused crack growth. The absence of hydrogen evolution during SCC initiation and growth implied that cracking did not occur by hydrogen embrittlement and that the dissolution mechanism caused the cracking. Thus, it was observed that discontinuous or burst type AE can occur not only during hydrogen embrittlement but also during dissolution controlled SCC.

(Anita Toppo and colleagues, Corrosion Science & Technology Division, Metallurgy & Materials Group)

CONFERENCE HIGHLIGHTS

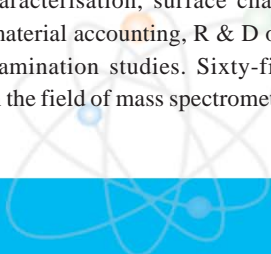# Application of Mass Spectrometry in the Nuclear Fuel Cycle

December 21-23, 2005

A theme meeting on "Application of mass spectrometry in the nuclear fuel cycle" was organised under the auspices of BRNS and Indira Gandhi Centre for Atomic Research during December 21-23, 2005. This meeting was held in the SRI guest house in Anupuram. Dr.Baldev Raj, Director, Indira Gandhi Centre for Atomic Research inaugurated the meeting. Dr.P.R.Vasudeva Rao, Director, Chemistry Group welcomed the gathering. Dr.C.K.Mathews and Dr.H.C.Jain delivered plenary lectures highlighting their experiences of working with mass spectrometry.

The meeting was conducted in six sessions encompassing 14 talks. Specialists from the various units of DAE delivered lectures which provided a broad overview of the recent trends in mass spectrometry. The areas covered were the applications of mass spectrometry to isotope and enrichment studies, trace and ultra-trace elemental characterisation, surface characterisation of materials, nuclear material accounting, R & D of fuel cycle and post-irradiation examination studies. Sixty-five researchers, pursuing research in the field of mass spectrometry, from various units of DAE such as BARC, IGCAR, HWB and RMP and also from academic institutions such as Pondicherry University, IIT (Chennai) and NGRI(Hyderabad) participated in the theme meeting.

The meeting concluded with a panel discussion on "Indigenous Development, Inter-comparison experiments and Potential areas of application of MS" which was chaired by Dr.V.Venugopal, Director, RC & I Group, BARC. The panel discussion resulted in suggestions on greater utilisation of indigenous mass spectrometers, sharing of knowledge database and expertise amongst the users to lower the downtime of the equipment, conducting round-robin inter-lab comparison experiments and evolving reliable standards, sampling and protocols. A working group with members from various units of DAE would be formed towards meeting these objectives.

(Reported by M. Sai Baba, Chemistry Group)

ISO 9001: 2000 Certification of IGCAR

In the pursuit of excellence by any organisation, a Quality Management System is essential for achieving continual improvement in the quality of products and processes. ISO 9001:2000 helps in establishing a Quality Management System that is practised globally by organizations engaged in manufacturing, services, and R&D activities. At IGCAR, we are engaged in state of the art testing and research activities related to the fast reactor development programme. Laboratories of various Divisions under Metallurgy Group, Electronics and Instrumentation Group, Chemical Group, Safety

Team of qualified IGCAR internal auditors (ISO 9001:2000) along with MECON

Group and Engineering Services Group are presently undergoing the ISO 9001 certification process. These laboratories are in the Mechanical Metallurgy Division, Materials Technology Division, Non-destructive Evaluation Division, Corrosion Science and Technology Division, Computer Division, Electronics and Instrumentation Division, Quality Assurance Division, Mechanical and Hydraulics Division, Fuel Chemistry Division, Materials Chemistry Division, Chemical Instrumentation and Facilities Division, Safety Engineering Division, Radiological Safety Division, Medical Division (Hospital laboratories) and Physical Metallurgy Section. MECON, a Government of India undertaking, is the consultant for the ISO certification process.

The Apex Quality Manual (AQM) of IGCAR provides an overall guidance for establishing and practising the Quality Policy and Quality Management System (QMS). Periodic internal audit is a fundamental requirement to ensure success of the QMS. For its implementation, 21 officers from the respective Divisions/ Section were given comprehensive training for 2 days by MECON during May 2-3, 2005. Senior Managers from MECON led by Shri. G.V. Aruna, Deputy General Manager, conducted the training programme. The programme involved lectures, group discussions, practicals and a written test. All the 21 participants passed the certification test and were declared eligible to conduct internal audits of IGCAR. Certificates were distributed to the auditors on Dec. 12, 2005 by Shri S.C. Chetal, Director, Reactor Engineering Group. Shri Chetal emphasised the need for acquiring ISO certification even for a quality conscious organisation such as IGCAR, and indicated the challenges in sustaining the Quality Management System.

The ISO 9001:2000 certification audit of IGCAR laboratories has now been completed. BVQI, one of the world leaders in ISO certification, was chosen as the certification agency. BVQI conducted the external audit in two phases. In the first phase, the audit of documents - Apex Quality Manual and Divisional Quality Manuals- was carried out. In the second phase, all the 13 laboratories, including Hospital Laboratories, were audited for 3 days during March 6-8, 2006. All the laboratories were found to meet the requirements of ISO 9001:2000 Quality Management System. BVQI has now recommended all the 13 IGCAR laboratories for ISO 9001:2000 certification.

(S.L Mannan, Chairman, Management Review Committee
and M.D. Mathew, Management Representative for
ISO 9001 Certification, Metallurgy & Materials Group)

Fast Reactor Fuel Safety

February 27-28, 2006

The second CEA – IGCAR technical seminar on Fast Reactor Safety was held at IGCAR, Kalpakkam during February 27-28, 2006. The theme of the seminar was on "Fuel Safety". Fuel Burn-up Aspects, Fuel – Sodium Compatibility as well as Design Safety Limits were discussed in the Seminar by Indian as well as French participants. The Indian presentations covered the FBTR operating experience as well as the design of PFBR fuel from the point of view of fuel safety. The French presentations covered the operating experience in Phenix as well as Superphenix reactors. The French delegates visited the PFBR site, FBTR and also a few other facilities at IGCAR, and participated in a brief function to celebrate 20 years of successful operation of FBTR. The seminar concluded with the identification of major areas for future collaboration.

Indo-French technical seminar in progress – Seen in the photo are the delegates of the Indian delegation, led by Dr Baldev Raj, Director, IGCAR and the French delegation led by Dr Patrick Ledermann, Deputy Director, Nuclear Energy Division, CEA, France.

IAEA Technical Meetings

March 1-3, 2006

IGCAR hosted two IAEA meetings at Kalpakkam during March 1-3, 2006. These are - IAEA Technical Meeting on "Fuel Failure and Failed Fuel Detection Systems for Fast Reactors" and Third Technical Meeting of Scientific and Technical Committee of the Joint Study on "An Innovative Nuclear Energy System based on a Closed Nuclear Fuel Cycle with Fast Reactors" (CNFC-FR). The meetings involved the participation of experts from France, China, Japan, Korea, Russia and Spain, besides India. The Joint Study on CNFC-FR, which is a part of the IAEA International Project on Innovative Nuclear reactors and Fuel Cycles (INPRO), is chaired by India.

Joint session of the two IAEA meetings in progress - Mr. Akira Omoto, Director, Division of Nuclear Power, Department of Nuclear Energy, IAEA is seen to the right of Dr Baldev Raj, Director, IGCAR