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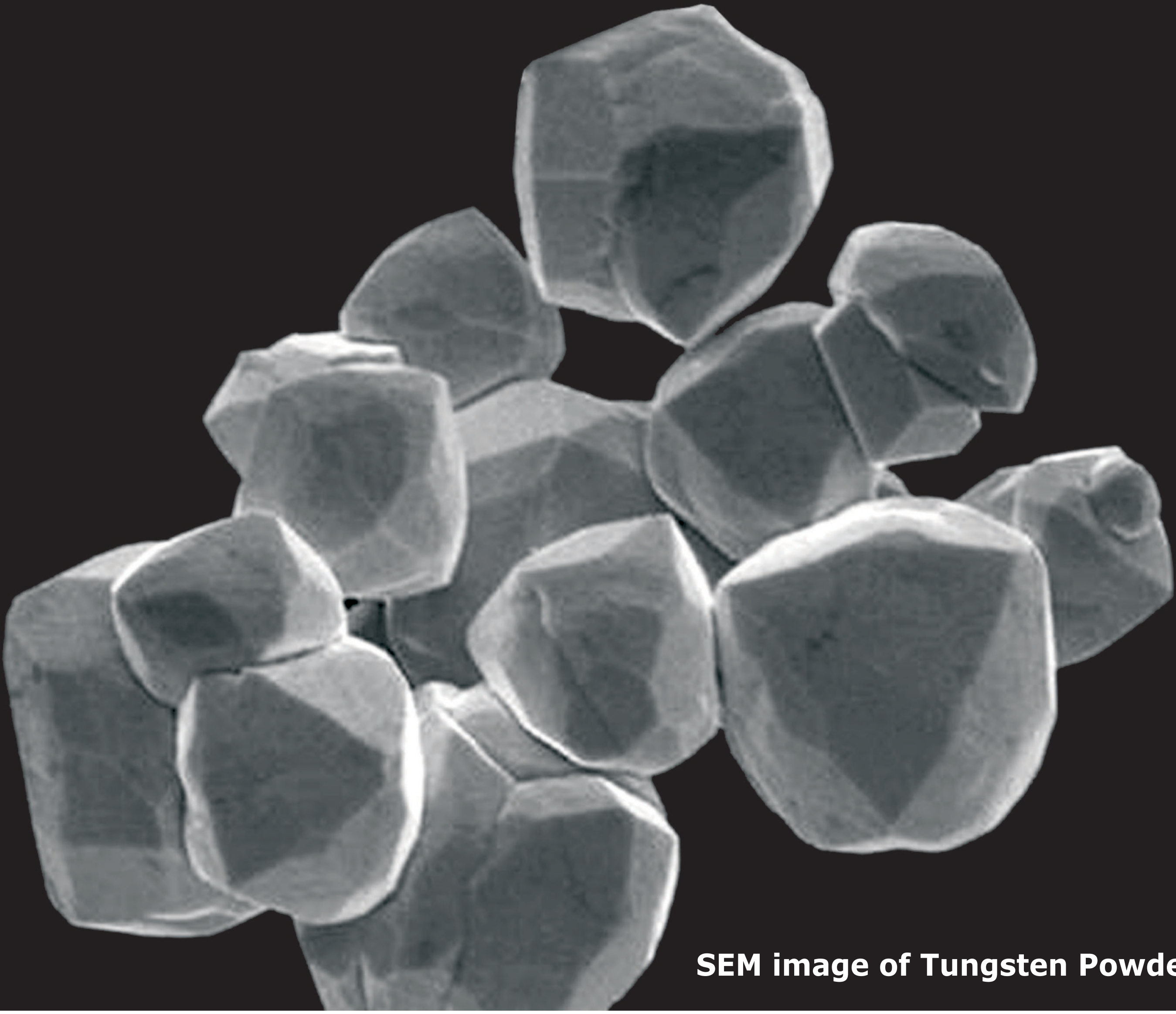

SEM image of Tungsten Powder

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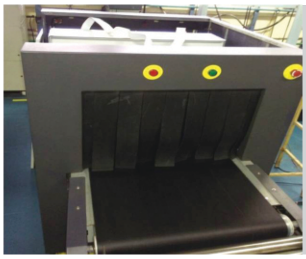

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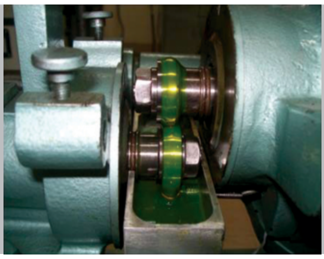

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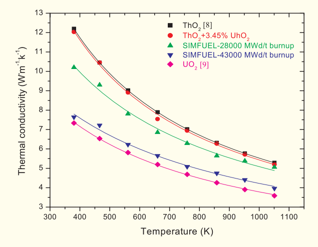

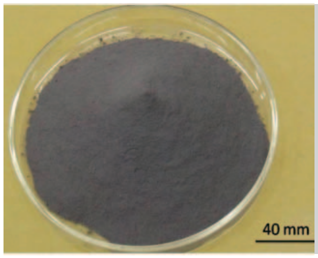

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Automated Powder Processing, Pelletisation and Inspection System For AHWR Type Fuel Pellets

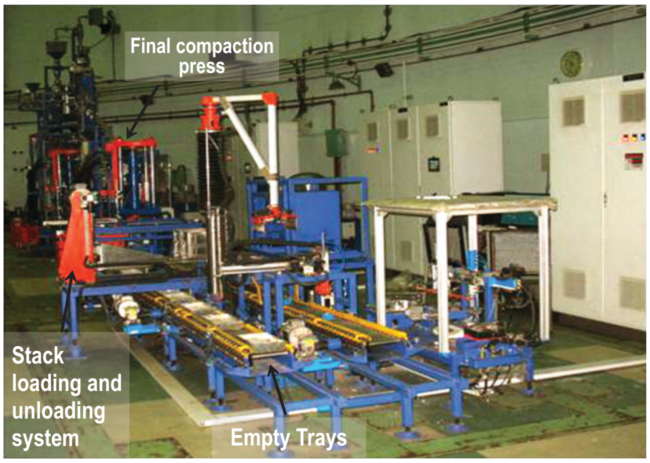
R.K. Mittal and R.S. Prasad
Engineering Design & Development Division, Multidisciplinary Research Group
K.M. Danny and Sudhir Mishra
Radiometallurgy Division, Nuclear Fuels Group

Development and fabrication of (Th-U^{233}) O$_2$ fuel inside hot cell for Advance Heavy Water Reactor is an important step in realization of India's three stage nuclear power program. The associated high gamma activity demands high level of automation and remote handling inside hot cell to reduce man-rem. Engineering Design & Development Division and Radiometallurgy Division developed mock- up facility for automation and remotisation of (Th-U^{233}) O$_2$ fuel fabrication and commissioned in CIRUS, BARC. Fabrication of Nuclear fuels inside hot cell becomes very difficult. With only master slave manipulators as the handling aid, automation of all fuel fabrication processes is highly desirable. In order to gain sufficient experience in fully automated fuel fabrication, mock–up facility has been designed, installed and commissioned. Surrogate powders like Alumina and Zirconia are being used for mock-up trials.

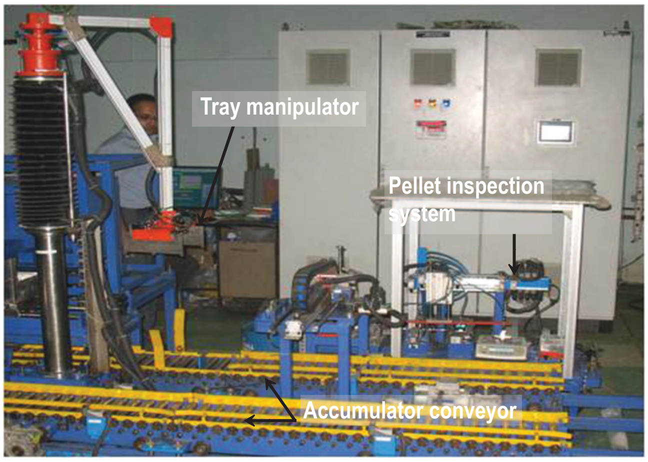
Installation, commissioning and operation of any equipment inside hot cell must address constraints such as limitation of space, compactness of the system, ease of maintenance and operation. Many innovative schemes and systems have been incorporated, which not only address these constraints but also help in reducing process time ensure operational convenience and ease of maintaining these systems.

The facility consists of a series of interconnected cells. Some important major equipment includes (a) automated powder transfer and handling system. (b) automatic dosing system (for powder and other additives). (c) gravity discharge. (d) hydraulic presses with automated tool changing. (e) pick & place and tray indexing set-up for green pellets. (f) conveyors for transfer of trays. (g) stack preparation station. (h) loading/unloading to/from sintering furnace. (i) pellet inspection set-up. All these operations will be performed in simulated hot cells remotely.

This facility has a centralized control facility and all the operations can be controlled through single computer having SCADA software. Communication between SCADA software, different Human Machine Interfaces (HMI) and drives is through Ethernet. The system is having Auto as well as Manual mode of operation. Individual cell operations can be controlled through the respective HMI's or the centralized PC. Each and every component can be controlled independently of others in manual as well as auto mode.

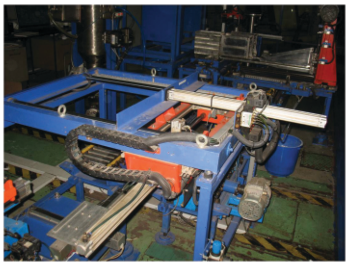


Full scale Pellet Production Facility



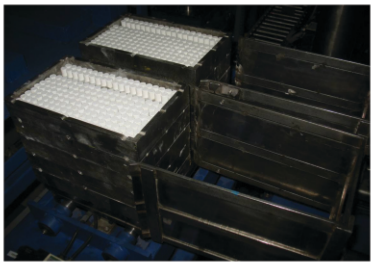
Tray Manipulator and Pellet Inspection Facility

Pressing of pellets



Tray handling unit

Lloaded tray on conveyor



5x2 trays in Stack

Dr. M.R. SRINIVASAN
Member, Atomic Energy Commission

Green Energy Options for Sustainable Development

My attention was drawn to a report in The Hindu of August 1, 2015 (Coimbatore Edition) on fuel utilisation issue recently by the National Sample Survey Office (NSSO). Highlights of this report are

a) Two thirds of the rural households rely on firewood for cooking.

b) Two thirds of the urban households use LPG for cooking.

c) 14% of urban households (including half of the poorest 20%) still rely on firewood.

d) Use of LPG in rural households has gone up from 2%, two decades ago to 15% in 2011-12.

e) In North Indian States, Cow dung cake is a major fuel for cooking in a third of the households in UP and Punjab, a quarter in Haryana and a fifth in Bihar.

f) A fourth of the rural households still rely on kerosene for lighting - Rural households in A.P., Punjab, Tamil Nadu and Kerala used electricity for Lighting but in UP only 40% rural households had electricity.

My memory went back to the Presidential address of Dr. Homi Bhabha to the first U. N. Conference on Peaceful Uses of Atomic Energy held in Geneva in August 1955 (nearly sixty years ago). Assisted by Shri Sohrab Patuck of the Tata Administrative Service, Bhabha drew attention to the fact that India's major fuels then were firewood and cow dung. The combined contribution of coal and oil was overshadowed by the traditional fuels. Bhabha drew attention to the dangers of deforestation, which indeed has happened and the loss of organic nutrients to the soil through burning of cow dung.

It has come to me as a surprise that we are using in absolute terms more firewood and more cow dung cake as cooking fuel now than we did in 1950's! A second point that emerges is that the substantial additional fuel to the Indian economy by way of locally produced coal or imported petroleum has largely been used by the urbanised sections of society and those that are employed by organised industry. There is no doubt that some part of the energy has gone to increase food production for irrigation pumping, fertilizer and pesticide production and of course to transporting food articles from the farm to the urban consumer. The consequence of this situation is the continuing poverty and deprivation of large sections of the rural population (excluding the large land holders). I will now go back to discussing the more limited commercial energy issues. But we must not overlook the large rural energy problem.

In broad terms, India's consumption of commercial energy is roughly half from coal and half from petroleum. Coal production in India is about 600 million tonnes and we import about a hundred million tonnes of coal composed both of coking and power grade coal. So for as petroleum is concerned, we reached 70% self reliance in the 1980's or so, but now we depend close to 75% on imports as domestic production has not seen any dramatic increase. So far as natural gas production is concerned, India remains a minor player. Last year a substantial power generation capacity based on gas remained non operational due to non-availability of gas. We do import some LNG but until last year when oil prices were high, landed LNG cost was US $10/mbtu and hence was an expensive fuel. It is unfortunate India has so far not succeeded in obtaining piped natural gas from Iran, Central Asia or Myanmar, Indonesian and Malaysian natural gas got cornered by Japan and Thailand in the 1990’s to be supplied as LNG at the then prevailing low prices. Unless something changes dramatically, India is not able to take advantage of a gas based energy revolution. Even with regard to shale gas, India's potential is not high, currently confined to Cambay basin, Krishna, Godavari, Damodar and Cauvery. There are risks of polluting water bodies and water itself becoming a scarce commodity, shale gas development may not be welcome. On one ground shale gas scores compared to coal mining, in being more benign on the land than the latter. Our present Coal Minister has said that India's coal production would be ramped upto a billion tonnes per annum over the next some years. However given the fact that much of our coal seams are in the remaining forested areas of the country, whether such large scale mining is possible remains an open question.

On a long term basis, India's coal consumption has increased at about 5% per annum and petroleum consumption at about 7% per annum. Unless some other primary fuel is available as a substitute, these growth rates may continue if Indian economy were to grow at 7% or more in the coming years. Looking at the electric power sector, we may note that starting with a base of a mere 2GW in 1950, installed capacity now is about 250 GW. Looked at in isolation, the 125 fold growth in 65 years may appear good. China in the same time span has gone up from 2GW to about 850 GW! If we are serious about *Make in India* and about building essential infrastructure of high speed trains, steel plants, cement plants and so forth, a rapid increase in power generating capacity is a must.

In the five decades after India's independence, the growth in electricity, coal and petroleum sectors was due to the dominant role of the public sector enterprises in the respective fields. However the ills of the large public sector behemoths - like overstaffing, high labour welfare costs, lack of accountability, corruption, political interference and unsatisfactory service to the public at large resulted in opening up the energy sector to greater involvement of the private sector. It is too early to say whether expected benefits have accrued to the country as a result of the entry of the private sector in the energy field. The addition to power capacity by private players is still quite slow. Entry of private sector into coal mining has got mired into the controversy regarding mining leases. In the natural gas sector, the great expectation about large amounts of gas coming out of the Krishna Godavari basin, at affordable costs, has not been realised. The hope held among certain energy economists that the 2003 Electricity Act and other initiatives taken around then that competition would promote lower prices for energy services, has not been realised.

We will now discuss the electricity sector in greater detail, as this is a field I am more familiar with. For a long time now, electric power is sold across the country at a rate that is about one rupee less (per kWh) than it costs to produce. Sometimes the differential is more so as we produce more kWhs, we have a higher loss, which shows up in the books of the electricity boards (or their successors, the distribution companies). In the tariff fixation, there is a complex scheme of subsidies - free power to agriculture, various levels of subsidies to domestic users, industry users paying more than full cost plus fair profit and so forth. All these ills were there prior to the Electricity Act of 2003, and they continue to be there. If a unit of electricity results in GDP growth that is substantial, then we could accept the aggregate loss of the electric supply system as just another element of tax. However, the snag is that the non-electricity user (and there are many in India) also has to carry the burden of loss on sale of electricity. But the political system has come in the way of rational pricing of electricity supply in the past and appears to continue to do so in future also. This tariff policy is a big deterrent for creating internal resources to sustain a healthy growth of the electric supply system. In a recent case a private power producer was forced to seek a revision in the cost of power due a levy imposed by the government of the country from which coal was sourced. Unless we have a power sector in good economic health, we can hardly expect to have a healthy growing economy.

In the first couple of decades after independence, the emphasis was on building hydro-electric power stations as part of multipurpose river valley projects. From the 1970's onwards building coal based power stations was taken up actively. Now coal and gas based generation dominates the field with hydro making only small gains as it is facing opposition from environmentalists. Wind energy has made good progress. I have personally seen large wind energy farms near Kudankulam (Kanyakumari) and Coimbatore in Tamilnadu and in Chitradurga in Karnataka. India made an early entry into nuclear power with our first atomic power station going operational in 1969. This station at Tarapur was imported from the USA and uses low enriched uranium as fuel. This power station has completed forty five years of safe operation and supplies power at less than one rupee per kWh ! Lewis Strauses, an early Chairman of the US Atomic Energy Commission had made a claim that in his grandson's time, nuclear electricity would be too cheap to meter ! This was before any nuclear power station had been built. I shall discuss later the experience on cost of nuclear power from our more recent stations.

Our experience with the US on Tarapur has been a mixed one. The station was built in five and a half years - something of a record for nuclear power stations. It was financed by a low interest long term loan. But getting fuel from the US on a timely basis was a huge problem. After India had its first nuclear test in 1974, US supplies of fuel became erratic from 1980 onwards, France agreed to supply fuel for Tarapur. However US companies were prevented from supplying spares or technical information after 1974. India had to stand on its own in solving various technical problems and sourcing from within India all spare parts and replacement components.

Our second nuclear power station in Rajasthan was built with cooperation from Canada. The two reactors of this station use natural uranium as fuel and heavy water as moderator. The Canadian Technology was emerging and so it took longer to build these reactors. In addition, localisation of supply of components and equipment was taken up seriously in order to lay the foundations of a self-reliant nuclear industry. The first unit of the Rajasthan station went into operation in 1972 but hardly operated for a little more than a decade, when there was a problem with a major nuclear component (called end shield). In the meantime, work had commenced on the second unit. But with the Pokhran test of 1974, Canada discontinued cooperation with India. India completed the second unit at Rajasthan in 1980 on its own and began to operate it in a reliable and safe manner, incorporating all the lessons learnt on the first unit. The remotely operated *on load* refuelling machines were a particular challenge and our engineers and technicians began to operate them successfully. It is this feature that enables natural uranium to be used as fuel.

Dr. Bhabha died in the Mont Blanc air crash in January, 1966 and before his untimely death, he convinced the Government of India that the third nuclear power station, to be built at Kalpakkam, Tamil Nadu would be designed and executed as a fully Indian venture. It was my good fortune that Dr. Sarabhai (who succeeded) Dr. Bhabha as Chairman, AEC posted me as the Chief Project Engineer, Madras Atomic Power Project (MAPS). Developing all round industrial capability to make all the components and materials was a tough proposition. In the meantime, India refused to join the Nuclear Non-Proliferation Treaty that the US, USSR and UK had launched in 1970. In 1974, India went ahead with the Pokhran I test. The US and its allies in North America, Europe and elsewhere embargoed supply to India of equipment or materials destined for nuclear use. When Madras unit I was made operational in July 1983, India joined a select band of countries that could design and build nuclear power plants on their own namely USA, USSR, UK, France, Canada and Japan.

Following successful completion of MAPS, India took up building nuclear power units at Narora, Kakrapura, Rajasthan expansion and Kaiga. India had now entered an industrial phase of nuclear power plant building, with very little inputs from outside the country. From the 1990's onwards, our nuclear power units turned in very good performance, remaining on line continuously for very long periods. In May 1998, India conducted the Pokhran II series of nuclear tests, in view of adverse geopolitical developments in the region. Pakistan also conducted its tests before the end of May 1998. Thus both India and Pakistan became overt nuclear weapon states and along with Israel, all outside the NPT.

Predictably, the US expressed its unhappiness about India's actions and Indo - US relations went through a brief period of chill. However by the early years of the new century, US began to explore how to accommodate a *de facto* nuclear state India, in the global scheme of things. There were marathon meetings between Strobe Talbott of US and Jaswant Singh of India at many places around the world. However it was left to President George Bush and Prime Minister Manmohan Singh to reach an agreement to work towards a nuclear rapprochement on July 18, 2005. Given the complexity of the issues involved, the Indo - US cooperation agreement was signed in September 2008, after the IAEA had concluded a special protocol with India and the nuclear supplier's group issued its consent on civil nuclear cooperation with India. Agreements were signed with France and Russia also in 2008. In more recent times, similar agreements have been signed by India with UK, Kazakhstan, Canada and others. Following these agreements, India is now accessing uranium from some of these countries.

Although India made an early start in harnessing nuclear energy, the growth of nuclear power capacity has been modest. A principal reason was the embargoes that were placed on India for nuclear imports. India built reactors on its own but they were of about 230mw capacity. The two 540 mw reactors were built in the period 2000-2010. During this period, we had also embarked on the Kudankulam project with Russian collaboration to build 2X1000 MW light water reactors, using low enriched uranium. So when the July 18, 2005 agreement between US and India was reached, there was expectation that a number of large sized nuclear power units would be built in the next decade or so. In fact the US received a broad letter of intent that India would procure nuclear power plants of about 10,000 MW capacity, subject to the cost of power from these units being competitive with power from alternate sources in the concerned region.

India and France had an ongoing dialogue to build six reactors with an output of 1600 MW each, at a site in Maharashtra, at Jaitapur near Ratnagiri. Similarly Russia was very keen to supply more 1000 MW VVER reactors, similar to the ones under construction at Kudankulam. On the Indian side, our parliament passed civil nuclear liability law in 2010. In the law adopted by India, there is a specific provision that there would be a right of recourse against a supplier in the event of a wilful neglect or a latent or patent defect. Industry practice world over has been that the operator is solely liable and the supplier is indemnified. Given the background of the Bhopal tragedy, lawmakers in India did not want to allow the suppliers to go scot free under all circumstances. The US nuclear suppliers especially were not prepared to accept the Indian law and pressed India for amending it to their satisfaction. India has recently provided an insurance mechanism to the supplier to cover this risk.

The Fukushima accident of March 2011 had a big impact on the revival of nuclear power worldwide. It is now clear that the tragedy could have been avoided if Tokyo Electric Power Company had installed emergency diesel generators at a height above the maximum flood level of the site. It is no doubt true that the earthquake was a very strong one and the accompanying tsunami was unprecedented. A big weakness that was revealed was that the Japanese regulators were lax in performing their functions and the utility itself negligent in ensuring plant safety under conditions that were predicted by some of the Japanese seismologists and engineers. Fukushima resulted in delaying startup of Kudankulam unit by nearly two years due to local opposition. Germany which had a very good track record in operating nuclear power units has announced retiring progressively its operating nuclear power units. However, the US, France, Russia, China, Korea and India believe that nuclear power is safe and an important part of their energy mix.

Our discussions with France on the European Pressurised Reactor (EPR) got drawn out due to internal review in France of safety of nuclear power units under beyond design basis accidents. When India and France embarked on discussion of cost of power from EPRs built in India, projected costs were substantially higher than costs anticipated by India. Early in 2015, following discussions between Prime Minister Narendra Modi and President Francois Hollande, the French nuclear power plant builder Areva is engaged on discussions with Larsen and Toubro and other Indian industries to reduce construction costs by a higher level of localization. Results of this exercise are awaited.

The Nuclear Power Corporation of India (NPCIL) is in discussions with Westinghouse of USA, who is building four reactors of their AP-1000 series in the US. At present safety documentation is being made available for review by the Indian Atomic Energy Regulatory Board. Initial indicative costs appear much higher than Indian expectations. With regard to General Electric of US, the discussions are even more in a preliminary stage. Unless a meeting ground is reached with US nuclear power plant builders in the next year or so, the 2005 agreement would have conferred *Nuclear Respectability* on India but not given any *Nuclear Kilowatt hours*!

Kudankulam unit I is presently under its first refueling cycle. Unit II is in the startup mode. Russia has agreed to supply units III and IV. Units I and II have a power cost of Rs.4/kWh. Units III and IV have a capital cost of Rs.20 crores per MW and this will result in a power cost of Rs.6.5/kWh in 2021-22. Russia has agreed to supply more reactors; there is space for the fifth and sixth units at Kudankulam. Another site would have to be identified for additional VVER units.

NPCIL has designed its own 700 MW PHWR unit and four of them are under construction, two each at Kakrapara (units III and IV) and at Rajasthan (units VII and VIII). Recently, Government of India has sanctioned construction of two 700MW PHWR at a site in Haryana. The cost per MW is Rs 15 crores and the cost of power is likely to be Rs 6.5/kWh in 2021-22 period.

I was recently at Kaiga, near Karwar where four reactors of 225MW (PHWR) were in operation. The first two units were operating at 100% power and units III and IV at well above 100%. Reactors at Kaiga have operated for over 300 days continuously; they have exceeded 400 days on a number of occasions. One of the Kaiga reactors crossed 500 days, highest for any reactor in India then. The record among Indian reactors is RAPS V which was on line for 765 days continuously (the second highest in the world). Kaiga is supplying power at Rs 3/kWh. It is one of the most beautiful nuclear power stations anywhere in the world.

If we have to accelerate our nuclear power capacity, we must build more 700MW PHWRs (Immediately two more will be built at Kaiga) - this can be achieved by committing to some 8 or 10 units at one time so that industry can batch produce the components and reduce the manufacturing period. Construction could be taken up at two or three sites. A similar strategy should be adopted by taking up eight or ten 1000 MW VVER at more than one site, and with a high degree of localization of equipment supply. Discussions with France and US should continue but action on more PHWRs and VVERs should not be delayed any further.

In the early years of this century, the strategic planning group of the Department of Atomic Energy made a projection of the likely demand for electricity in the time horizon up to 2052. This study revealed that the installed capacity may have to go up to 1250 to 1350 GW by 2052, allowing for some 5000 kwh/capita. Of this the nuclear component was estimated to be between 275-300 GW. Since then we have seen dramatic increase in lighting efficiency through the use of LEDs and motor efficiencies in the industry through a variety of innovations. Similarly energy efficiency in steel, cement and other industries has improved substantially. We may therefore project a lower per capita consumption of 3000 kwh. So the capacity required by 2052 would be a more realistic 750-810 GW. Even taking the lower figure of 750G, we may need a nuclear capacity of 275 GW. Fossil fuels (coal and gas) may contribute 275GW and 200 GW could come from renewable and hydro.

During 2005-2008 when we were discussing the Indo -US nuclear agreement, I had suggested that India needed some 30 to 50 GW of nuclear capacity in the first stage using natural and low enriched uranium. This of course was an interim target. The 2050 target of 275 GW of nuclear power may consist of some 125 GW of natural uranium and low enriched uranium reactors, 100 GW of fast breeder reactors and 75 GW of thorium based and other advanced systems. Therefore we need to develop our own PWR which along with our own PHWR could contribute significantly to the first stage 125 GW of nuclear power. Our BARC-NPCIL has completed the design of 900 MW Indian Pressurised Water Reactor, which should be taken up for execution at the earliest.

The Prototype Fast Breeder Reactor of 500 MW at Kalpakkam is about to be started up in the next few months. Two Fast Breeder Reactors of 600 MW are planned at Kalpakkam to follow the PFBR. The FBRs will use the plutonium in the spent fuel of the first stage reactors. The rate of induction of FBRs will depend on the rate at which plutonium is available. We also have a design of a 300 MW Advanced Heavy Water Reactor (AHWR) which would demonstrate the feasibility of using thorium as a fuel. Again this project needs to be taken up for execution soon. India has a limited amount of natural uranium. We can in the new regime, post 2008 agreements, import both natural and enriched uranium from overseas. The plutonium from spent fuel using both local and imported uranium can fuel a large number of fast reactors. As we reach the stage of using thorium, we shall depend more and more on locally produced thorium.

There is a resolve in the country to push renewable energy as fast as possible. We are using 1.25 MW and 2.5 MW wind turbines at many places. We should also explore offshore wind turbine complexes use say 16 x 5 MW units. We are making a start on large scale solar energy harnessing. A recent project for Tamilnadu mentions a cost of Rs. 7/kWh. If we take into account the subsidy element, the real cost will be about Rs. 9/kWh. While this may be acceptable for a promotional project, large scale induction of solar and wind energy would depend on sharp reduction in costs over the next few years. Recently the Minister of State for Power, Coal and New and Renewable Energy stated that the target for renewable energy for 2022 would be 175 GW (up from 30 GW at present). Unless costs come down, the subsidy burden would become excessive.

Although Indian industry has grown quite well in supplying the needs of the energy sector, there are significant gaps. One such is the field of high quality heavy forgings. To fill this gap, NPCIL and L&T have jointly set up an integrated forge plant at Hazira. Apart from the big stuff, we need local manufacturers to make high quality valve actuators, limit switches, micro switches, sensors and so forth.

With regard to R&D support to energy industries, we have institutions such as the Central Fuel Research Institute, Central Power Research Institute, Indian Institute of Petroleum, Central Electronic Lab, Semiconductor Complex, R&D Labs of DAE and so forth. Yet we have difficulty in resolving problems such as turbine-generator vibrations, in a prompt manner. While BHEL has set up manufacturing capabilities of international standards, they have to do more in mastering the basic technologies embedded in their products. Strong networking with academic institutions on a continuing basis is necessary to create centers for stress analysis, vibrations, creep, fatigue, high temperature behavior, corrosion and so forth.

In the area of renewable energy, namely wind and solar, there is an opportunity for Indian Science and Technology to make original contributions and we must encourage our researchers in every way possible. Across the whole spectrum of energy technologies our goal should be not only to make in India but to make in India using Indian designs and Indian Technology.

Concluding Remarks:

India is located some distance above the equator and well below the latitudes that experience severe winters, except along the Himalayas. So it is not a land that needs large amounts of energy for space heating. We are increasingly resorting to air conditioning in our cities and towns, as we are forced to live in apartments rather than individual bungalows. Much of India is well endowed with solar energy. Even if it were possible to expand harvesting of solar energy in a massive way, we need other forms of reliable and continuous sources of energy to support an industrialised society that will assure a reasonable quality of life to the large population of the country. Lee Kwan Yu, the builder of modern Singapore stated in his 2005 Nehru Memorial Lecture.

"*Since the industrial revolution, no country has become a major economy without becoming an industrial power*"

We must shed our lurking suspicion of modern technology and accept it whole heartedly and master it. For this to happen we must develop nuclear and solar energy actively, using fossil fuels as a bridge to get there. In the longer term, we may also be able to harness thermo nuclear (or fusion) energy or indeed the energy in the hot rocks, below the surface of the earth.

Action points on the Energy Issue

1. Do not burn cow dung as fuel. Build large number of bio gas (or bio-methanation) plants to return nutrients to soil and produce gas for cooking (milk coops and dairyco help ?).
2. Shift rural domestic fuel from fire wood and dung cake to Gobar Gas, Coke briquettes, kerosene and LPG.
3. All new coal fired power plants to use supercritical and ultra supercritical boilers to get higher efficiency. Follow developments in the coal gasification combined cycle designs to achieve still higher efficiency.
4. Replacement of all lighting systems to LED. Motor efficiency improvements across all users.
5. Implement mass transport systems in all cities. Encourage electric cars and buses, especially in urban areas.
6. While present day motor cars are more efficient than earlier designs, revolutionary designs using materials and structures as used in space vehicles could give much higher fuel efficiency.
7. Develop lower cost higher efficiency solar photo voltaics and wind generators.
8. Pursue energy saving across the entire chain of electricity production, transmission and distribution, using new technologies from the IT industry.
9. Pursue actively the nuclear options of first, second and third stages with highest emphasis on Indian design, Indian manufacture and Indian technology.
10. Intensify search for hydrocarbons on land and offshore, acquire assets abroad; lay down pipelines overland or offshore to source from friendly countries. Also acquire overseas coal and uranium assets wherever feasible.
11. Develop designs for a practical solar cooker (present designs are OK for rice, dal & veg). Roti is the problem. Can a PV with inductive heating do the job?
12. Pursue basic research on production of H_2 using solar energy (Prof. CNR Rao himself is doing this kind of work).
13. Scientists and Technologists must spread message about the relevance of their work for societal benefit. Opponents of any tech venture are experts at communication. Our S&T personnel are poor interlocutors.
14. Ajit Doval (NSA) said this in Mumbai recently (4/8/15) "*National strength is based on national will and national will depends on what the nation thinks. The Indian media has its own compulsions much like I have my own. But we denigrate all the time. We should spread positivity and optimism and build a healthy nation together*".

Dr. M.R. Srinivasan played a key role in the advancement of Pressurised Heavy Water Reactor (PHWR) technology. Early in his career, Dr. Srinivasan worked with Dr. Homi Bhabha in the development of Apsara reactor. He served as the Chairman of Atomic Energy Commission and Secretary, Department of Atomic Energy. Dr. Srinivasan has been a senior advisor at the International Atomic Energy Agency during 1990-92 and the founder member of World Association of Nuclear Operators. In recognition of his immense contributions, Dr. Srinivasan was conferred Padma Vibhushan (2015), Padma Bhushan (1990) and Padma Shri (1984) by the Indian government.

Indigenous Development of Dual Energy X-ray Baggage Scanning System

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Development of X-ray detectors, front end and signal processing electronics have been carried out for the production of X-ray baggage scanning systems in India under collaboration with BEL-Pune and BEL-Bangalore. The machine has been qualified for imaging performance as per the required standards. Overview of this development is presented.

Introduction

Detection of threatening objects and materials using X-ray line scan images is important part for security inspection. In X-ray Baggage Inspection Systems (XBIS), line scan images of objects are obtained by measuring the transmitted X-rays through the objects using pixelated detectors. A standard dual energy machine comprises of about 640 pixels each of high energy (HE) and low energy (LE) detectors to generate two images. Depending on the atomic number of the material, the low energy detectors and high energy detectors give different contrast and information about the nature of objects can be obtained. The XBIS also needs to qualify certain criteria in terms of spatial resolution, wire resolution in air, contrast for thin objects, penetration through thick objects, and discrimination between inorganic and organic materials.

Scintillator coupled photodiode detectors are used for generation of line scan images in XBIS. The availability of technology for pixelated X-ray detectors which are the most important and critical part of the XBIS system was the bottle neck for commercial production of such systems in India. Therefore, technology development of such detectors was undertaken by Electronics Division, BARC [1-2]. Using the detector technology developed, the indigenous development of XBIS was carried out under a MOU between Electronics Division-BARC, BEL-Bangalore and BEL-Pune. Electronics Division, BARC provided the technical details such as design of X-ray detectors and fabrication process, design of front end and data acqusition electronics and software for data acquisition. Based on these details, detectors and required electronics were fabricated by BEL, Bangalore. BEL, Pune carried out overall integration along with baggage motion system, X-ray tube, control electronics and imaging software. The XBIS has been qualified for imaging using test objects. The significance of this development rests on the fact that the pixelated X-ray detectors required for XBIS are for the first time made in India. The capability to make such detectors in India for XBIS has paved the way for commercial production of such systems.

XBIS description

The XBIS consists of a system PC with USB interface for the data acquisition electronics, and front end electronics integrated with detector cards. Each front end electronics card has HE (64 pixels) and LE detectors (64 pixels). The front end electronics cards are serially connected for data transfer to data acquisition electronics card. The cards are housed in a L shaped mechanical housing and are arranged such that X-rays are incident at 90^0 to the detectors. The object under inspection is placed on a conveyor belt inside a tunnel and is moved at a specific speed to acquire line scan images which are processed and are displayed on the PC. The description of various sub systems of the XBIS is given in the following subsections.

Development of X-ray detectors

The detector system of XBIS needs to be compact, have high sensitivity, good uniformity and low cross-talk. Also it needs to be modular for enabling required coverage in the imaging system as per the size. Considering these requirements, scintillator coupled silicon photodiodes are the best choice for imaging applications. The basic detection element is formed by pixelated scintillators coupled to low-noise linear array silicon photodiodes. Considering high attenuation coefficient for X-rays, ease in machining to make small pixels, non-hygroscopic nature, compatibility for use with photodiode and better photon yield, Cesium Iodide (CsI) is the best choice as scintillator for XBIS. The absorption length of scintillator is decided by the maximum energy of X-rays. Trade-off between resolution and contrast is used to optimize the width and height of pixels. The XBIS detectors were designed for 140 keV X-ray source energy. Monte Carlo simulations were carried out by Electronics Division, BARC to study generation of X-rays in the source and their deposition in the scintillator. Based on this study, various parameters for the photodiodes and scintillator were finalized. The simulated X-ray spectrum generated by 140 keV e-beam on a tungsten target is polychromatic with higher intensity of low energy photons. The average energy of photons is about 68 keV. By using a copper filter between LE and HE detectors, the average energy of incident photons on HE detectors is shifted to the higher side to about 100 keV. The theoretically estimated energy deposition for various thickness of CsI scintillator was obtained for X-rays from a 140 keV X-ray source . Better than 95 % energy is deposited for CsI thickness higher than 4 mm. For incorporating flexibility to use the same detectors for higher X-ray energy XBIS, which is required for check-in baggage screening, scintillator thickness was optimized.

The X-ray detectors are fabricated as linear arrays of 16 pixel each. The fabrication of linear array photodiodes was done by BEL-Bangalore. The fabrication process details and mask design for the photodiodes were provided by Electronics Division, BARC. The photodiode arrays were coupled to scintillator of two different thickness to realize HE and LE detectors. The fabricated detectors are shown in Fig.1. During the development, the HE and LE detectors were characterized by Electronics Division, BARC using 140 keV X-rays at IT&IS, IAD, BARC to validate their performance. The charge generated in photodiodes due to X-rays was measured using a 16 channels current to voltage converter or using an electrometer for different tube current and voltage settings. After successful performance tests, the production of X-ray detectors and their assembly with readout electronics was carried out.

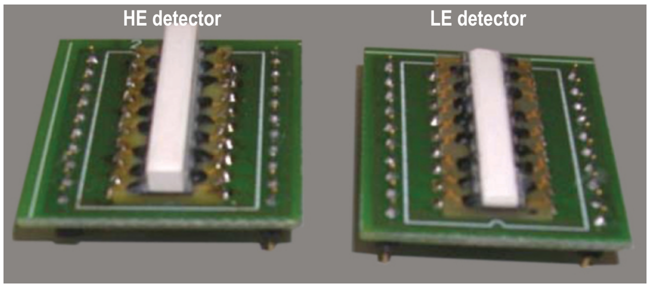

Fig. 1: HE detector and LE detector

Front end and data acquisition electronics

The front end detector card with X-ray detectors integrated with front end electronics is shown in Fig.2. Each board has 64 pixels of LE detectors stacked above the 64 pixel HE detectors and front end electronics for 128 channels. The front end electronics employs charge integrators with programmable gain to convert the detector charge to voltage. Programmable gain makes the system more versatile for different settings of X-ray source. The output signal is digitized using 16 bit ADCs. The front end electronics has been implemented using low power, high precision off the shelf components (ICs) with 32 channels per IC for keeping low costs. The amplification and digitization are done inside the IC. The detector boards are serially connected in a daisy chain and serial data from all cards (640 channels of LE and 640 channels of HE) is acquired using a data acquisition card. The data acquisition card uses a FPGA for setting various data acquisition parameters and rearrangement of data for generating HE and LE raw images. The fabrication and assembly of front end detector and data acquisition cards (ten detector cards and one data acquisition card per XBIS) was carried out by BEL-Bangalore as per the design details provided by BARC. The performance of complete detector card along with detectors and data acquisition card was validated by Electronics Division, BARC using the 140 keV X-ray source at IAD, BARC prior to integration in XBIS.

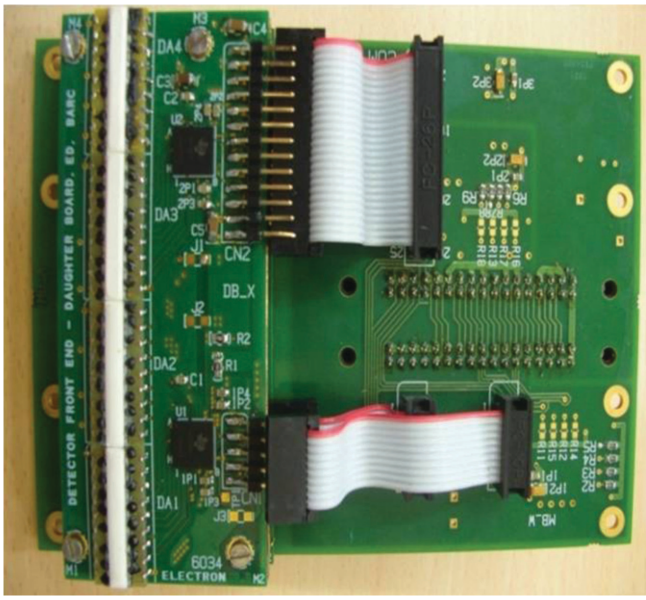

Fig. 2: Detector Card

Mechanical assembly of XBIS

The complete design and fabrication and integration of mechanical sub systems such as mechanical housing for the 60x40 tunnel, conveyor belt assembly for baggage, mounting arm for detector boards, X-ray tube arrangements, primary and secondary collimators and control electronics were carried out by BEL, Pune. The mechanical design was done to utmost accuracy so that the detectors and collimators are perfectly aligned and are at the required angle with respect to the source. Fig. 3 shows the assembled cards in the L shaped detector arm. The detector arm is suitably shielded to prevent leakage of X-rays. The picture of integrated XBIS is shown in Fig. 4.

Qualification of XBIS

The qualification of integrated XBIS was carried out jointly by Electronics Division, BARC, BEL-Pune and BEL-Bangalore. The XBIS was qualified for various functional tests and using standard test piece (STP) for evaluating imaging performance. The STP was made for assessing the image performance as per European Civil Aviation Conference

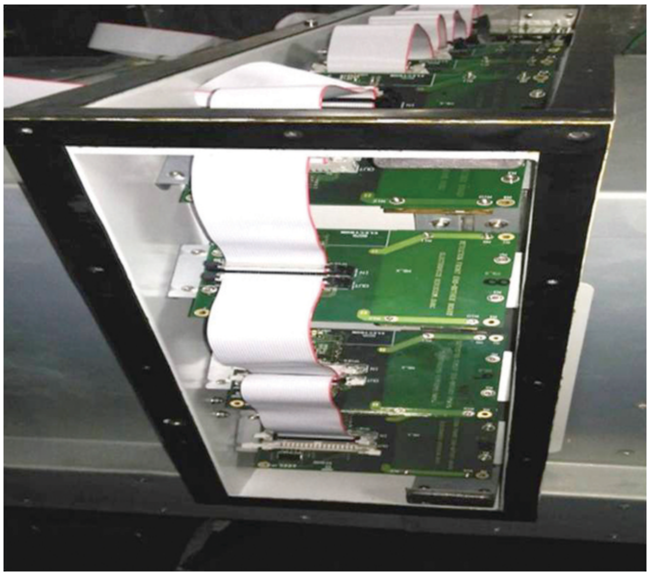

Fig. 3: L shaped detector arm with detector cards

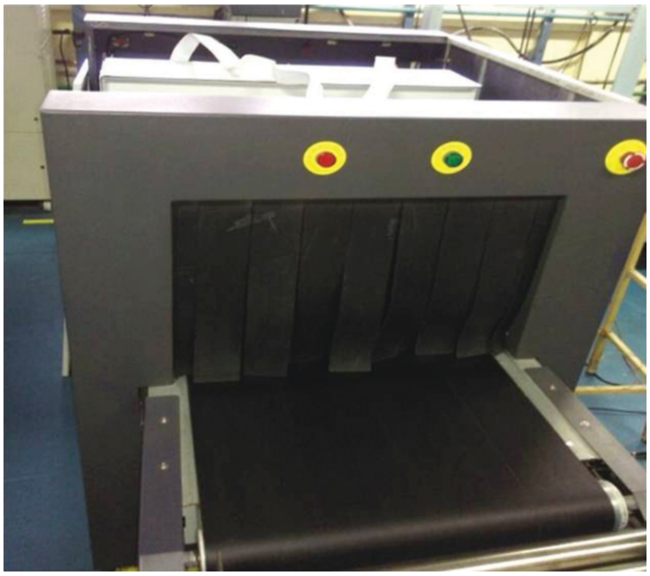

Fig. 4: Integrated XBIS

(ECAC) standard. The functional tests were performed to measure linearity of HE and LE detector signals with X-ray dose. The LE detector signals for increasing X-ray tube currents are shown in Fig. 5(a). The linearity of detector signal with dose was checked for each pixels (Fig. 5(b)). Similarly, the increase of HE detector signals for increasing X-ray tube currents and linearity of detector signal with dose was verified for each pixels of HE detectors.

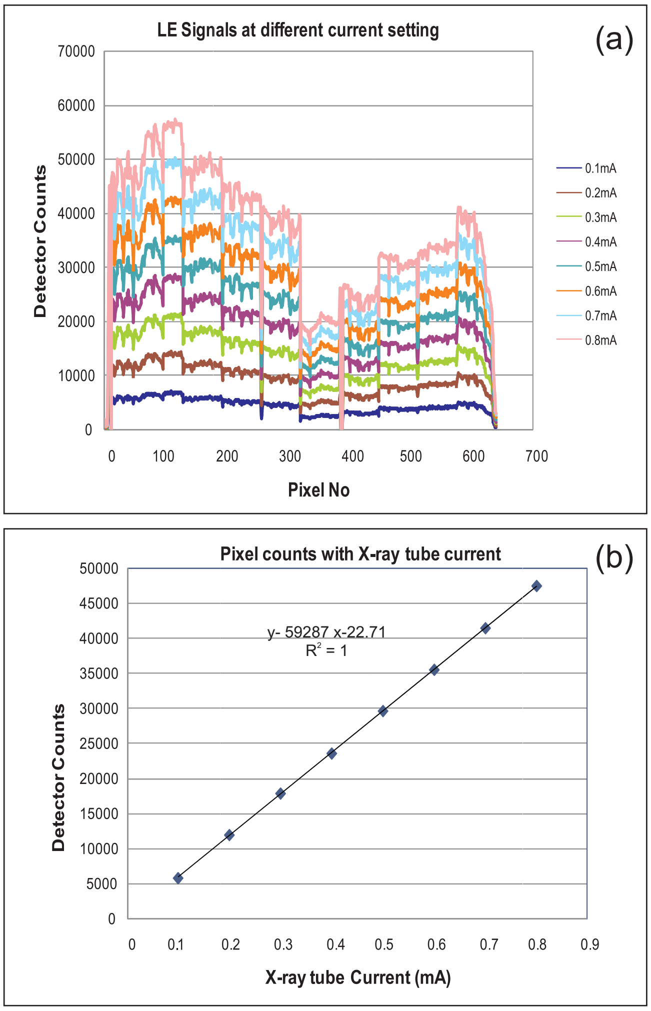

Fig. 5: (a) Variation of LE detector signal with X-ray tube current, (b) Linearity of detector signal with X-ray tube current.

For evaluating imaging performance of XBIS, the STP was moved with a standard speed (0.2 m/sec) and images were acquired at 140 keV, 0.6 mA settings of X-ray source. The raw data obtained from detectors was processed by the software developed by BEL for image enhancement and noise reduction. The software also incorporated coloring of image objects in accordance with international standards for classification of materials in organic, inorganic low and high Z metal, non penetrating materials. The STP used for qualification of XBIS is shown in Fig. 6. The different test objects shown are (A) – Stainless steel (SS) strips of incremental thickness, (B) SS wedge of different steps, (C) Copper plate with slits in X/Y directions, (D) Salt and sugar, (E) Wire of different diameters in air and, (F) Wires behind aluminium plates of different thicknesses. Raw images

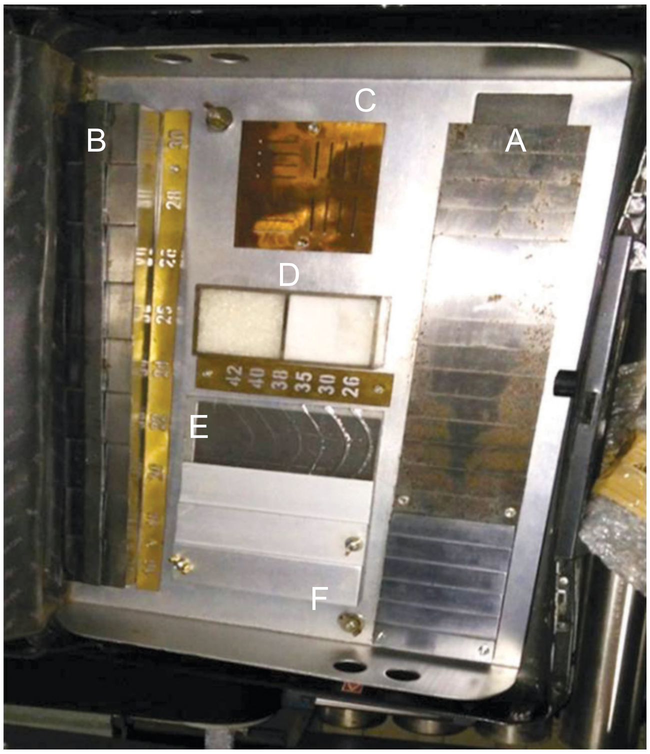

Fig. 6: STP comprising different objects.

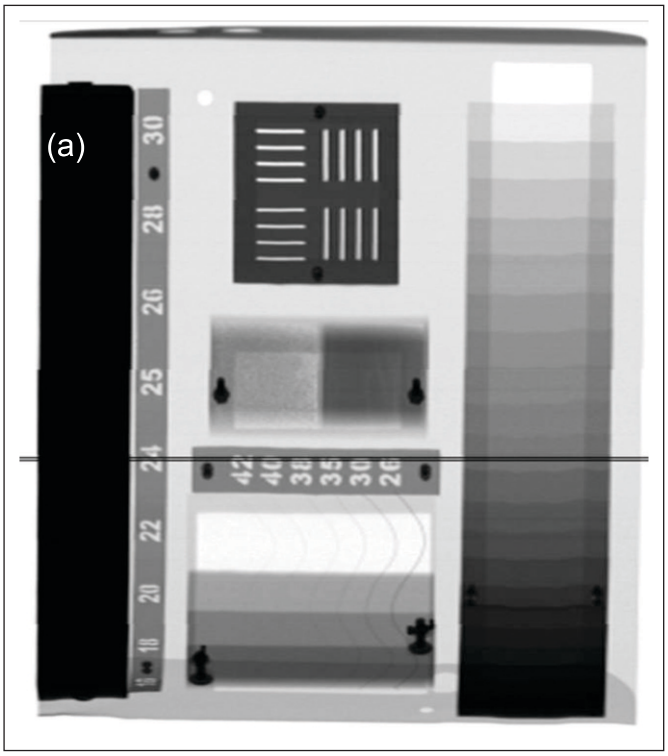

Fig. 7(a): LE raw image of STP

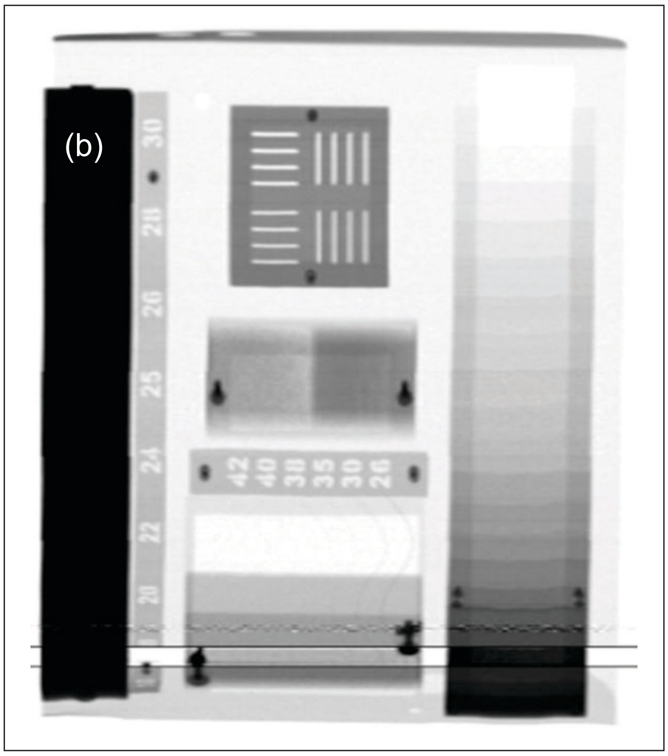

Fig. 7(b): HE raw image of STP

obtained with the LE and HE detectors are shown in Fig.7 (a) and (b) respectively. The processed image with color information added as per the classification of objects is shown in Fig. 8. Based on the imaging of STP, the XBIS has been qualified for i) 42 SWG wire resolution in air and behind aluminium plate of thickness 5/16 inch, ii) spatial resolution of 1 mm in X and Y direction, iii) 0.1 mm steel thickness penetration in thin materials, iv) discrimination between organic and inorganic materials, v) Penetration through 24 mm SS wedge.

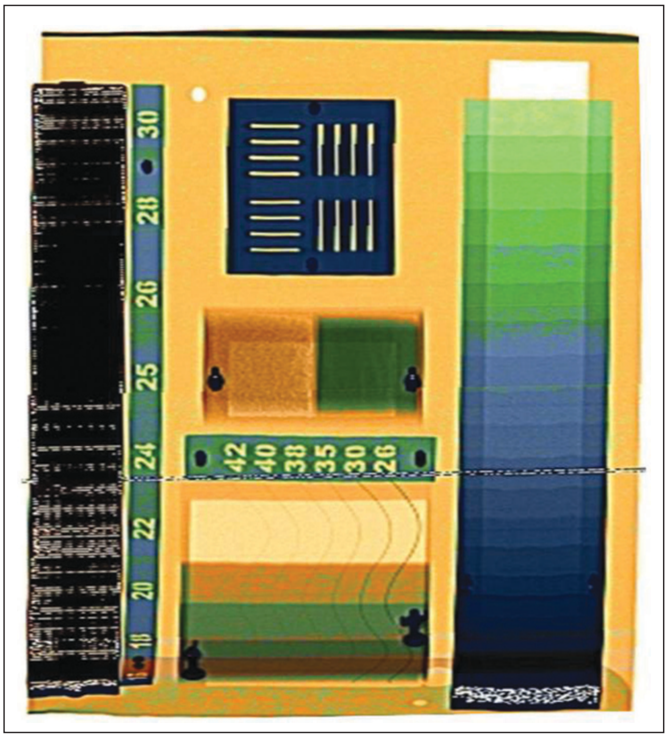

Fig. 8: Colored image showing different classification of materials.

Summary

Capability for industrial production of XBIS has been developed under MOU between Electronics Division-BARC, BEL-Pune and BEL-Bangalore. The acquired image by the XBIS meets required criteria as per international standards.

Acknowledgements

Authors are thankful to Shri Y.S. Mayya, Director, E&IG for the encouragement and support in carrying out this work. Authors acknowledge the support of Dr. Umesh Kumar, IT&IS, IAD for providing X-ray source facility for characterization of detectors and electronics.

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Article

Development and Applications of Thin Layer Activation Analysis Technique for Monitoring Wear and Corrosion Processes

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Thin layer activation (TLA) analysis technique is used for monitoring wear and corrosion phenomena in a number of industrial equipments. This technique can be used in several industries, such as, automotive industry, oil industry, chemical industry, railway, refrigeration systems and other process instrumentation. TLA allows both offline and on-line monitoring of the loss of matter from a critical surface, by wear, erosion and corrosion. The technique offers high sensitivity by estimating surface loss of material in the range of nanometer to hundreds of micrometer. This technique is based on the production of a radioisotope on the surface of a material by a charged particle induced nuclear reaction, followed by an estimation of the loss of the activity which is a measure of the surface loss of materials. Present article describes development and applications of TLA technique at Isotope and Radiation Applications Division for monitoring wear and corrosion of different grade steel components.

Introduction

Wear and corrosion phenomena involve degradation of materials from surfaces of metallic and non-metallic components. The reliability of industrial equipments, transportation systems and other machine parts can be significantly influenced by wear/corrosion. The need of suitable technique for monitoring wear/corrosion is based on three main factors, i.e., economics, safety and energy conservation. Wear/corrosion of industrial components causes economic losses to the industry; it can compromise the safety of operating equipment by causing failure of parts. Wear/ corrosion monitoring can help in designing engineered surfaces, thereby increasing the working life of components, thus saving large sums of money and leading to conservation of material, energy and the environment. The conventional techniques such as gravimetric, micrometry, profilography, replica method etc. are used for wear and corrosion measurements in industry but these techniques have poor accuracy, low sensitivity, cumbersome to use as the component need to be dismantled or removed for each measurement and cannot be applied in all situations due to non-accessibility. Thin layer activation (TLA) analysis is a highly sensitive nuclear technique used for monitoring wear and corrosion phenomena employing radioactive tracer [1-5]. In this technique gamma emitting radioisotopes are introduced in-situ and distributed in a small area on the surface of interest of an engineering component. The radioisotopes are removed from the surface along with the base element of the sample during the wear/ corrosion process. The material loss can be monitored either by monitoring the remaining radioactivity on the sample or by measuring the removed radioactivity from the sample using specific radioactive counting equipment. The surface labeling of a component with radiotracer is accomplished by irradiating the component with a suitable particle beam in a particle accelerator. Generally the major isotope present in the sample becomes radioactive by undergoing nuclear reaction as a result of high energy particle bombardment from the accelerator. The radioisotopes are distributed in the range 3-4 mm on the surface of the irradiated sample and to a depth of few micrometers (less than 500 micrometer). The amount of radioactive nuclide generated is very small, typically 1 atom in 10^{10} in activated zone. Since only a thin surface layer of the specimen is activated, the activity levels involved in this technique are much lower than would be the case with bulk activation by neutron irradiation. The activity levels of a few micro curie is sufficient for TLA applications, hence elaborate radioactive handling procedures are not required. TLA technique has a number of advantages over other conventional techniques, such as, high sensitivity in monitoring slow degradation process, offline as well as online measurement, simultaneous measurement of surface degradation of several components in the same machine, working with relatively low level of activity and quicker compared to conventional methods. Due to these advantages, TLA technique is considered as a versatile technique for monitoring wear, corrosion and erosion processes in several industrial components, in research and other engineering applications.

Principle of the TLA technique

When an ion beam of suitable energy is bombarded on the surface of interest of a machine part, it generates a thin layer of gamma emitting radioactive isotopes from surface to a certain depth. The depth to which the material can be activated is dependent on both the energy and angle of incident of the ion beam. The amount of activity induced is controlled by the ion beam intensity and the activation duration. The radioisotope labeled component is then remounted in the machine, which undergoes wear/corrosion. When the material undergoes wear/corrosion, there will be a loss of the base material and proportionately there will be a loss of radionuclide from the surface of the material. The loss of radionuclide is then monitored by using a suitable gamma radiation detector during the course of the experiment. The loss of radionuclide is then converted to the amount of the material loss from the surface during the wear/corrosion by the help of stacked foil calibration.

Ion beam irradiation

The choice of the bombarding particle and its energy is dependent on the desired product radionuclide, the depth of activation required in the specimen surface, and the possibility of producing other undesirable radionuclide in the target material. For TLA applications charged particle accelerators, such as, cyclotron, pelletron, are used in the medium energy range (5-30 MeV). Generally the ion beam of light charged particles, such as, p, d, ^{3}He and ^{4}He are used to generate product radionuclide in TLA technique. Also, sometimes radioactivity is induced with heavy ions to enhance the sensitivity of the technique. The irradiation set up is designed according to the sample shape and size. The duration of irradiation is decided by estimating the amount of activity required, in other words taking into account the duration of wear/corrosion experiment. Large components are irradiated by external beam at atmospheric air pressure because of their sizes, but small components can be irradiated inside the vacuum line. The specific activity as a function of depth within the material produced by the charged particle bombardment depends on the energy loss rate of the particle and the reaction cross-section for production of the respective radionuclide. It may also be controlled by varying the angle of incidence of the particle beam to the target surface.

Determination of experimental yield curve

The yield of a radioisotope at different depth from the surface is experimentally obtained by irradiating a stack of thin metal foils with the ion beam of suitable energy and beam current. Then the radioactivity of individual foils is measured by using a high pure germanium (HPGe) gamma spectrometer. The counts obtained from the spectrometer are converted to activity (Bq) by the help of a standard source having same energy as the product radioisotope. The activity per unit beam current per unit thickness per unit time of irradiation is plotted against the depth at which the foil is located to obtain the yield curve. The yield curve of ^{56}Co radioisotope produced by nuclear reaction ^{56}Fe (p,x)^{56}Co in stacked foil irradiation of pure iron metal foils is shown in Fig. 1. The integral area under the yield curve represents the total yield of the product radioisotope in a thick target of the same metal under similar irradiation condition.

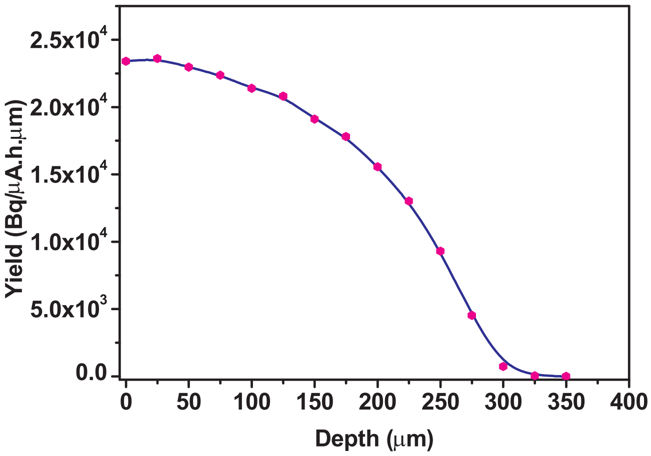

Fig. 1: Yield curve obtained from radioactivity measurement of ^{56}Co radioisotope generated in stacked Fe-foils

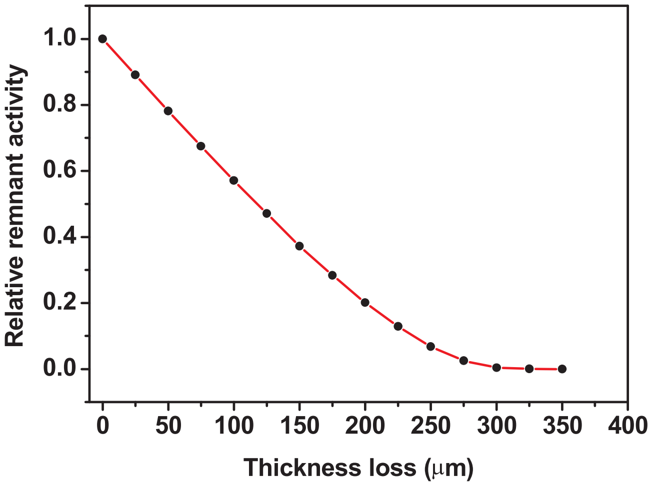

Fig. 2: Calibration curve obtained from radioactivity measurement of ^{56}Co radioisotope generated in stacked Fe-foils

Determination of experimental calibration curve

In actual experiment, the loss in radioactivity of material of interest is measured as a function of wear/corrosion time. There is a need to correlate the loss of radioactivity to material degradation as a consequence of wear/corrosion in order to determine the wear/corrosion process. For this purpose depth profiling is carried out by irradiating a stack of few thin foils (15-20 numbers) of known thickness and made up of same material as the actual sample under similar irradiation conditions. The radioactivity of the stacked foils is measured by removing one by one foil from the top (beam facing) by using gamma spectrometer, which is known as remnant activity. The relative remnant activity (A/A_0) is calculated by dividing each measured counts (A) by initial counts (A_0). The calibration curve is obtained from the plot of remnant activity versus thickness removed. Figure 2 shows a calibration curve obtained by irradiating a stack of fifteen iron foils (Fe foils), each having thickness 0.025 mm with 13 MeV proton beam having 200 nA current for four hours. The counts obtained in an actual experiment are correlated with the calibration curve and the corresponding equivalent thickness loss is derived.

Case studies

Two case studies have been carried out to demonstrate the application of TLA technique to estimate the wear and corrosion processes. These are discussed in the following sections.

Application of TLA technique for measurement of wear using tribometer setup

Wear of the surfaces is never a desirable process as this reduces the useful life of the machine elements and also degrades the performance of the machinery. The wear process can be prolonged by efficient selection of lubricant for a given application. In the present investigation the TLA technique has been used to measure wear rate of disc gears made up of EN31 steel in lubricated condition. Materials made up of EN-31 alloy steel are most extensively used in automotive industry. Four different types of heavy duty gear lubricants have been tested for their anti-wear behavior. The objective of the study was to access the performance of different lubricants by measuring the wear rate of disc gears by TLA technique.

Disc gears made up of EN 31 steel (1.5 Wt% C, 0.52 wt% Mn, 0.22 wt% Si, 1.3 wt% Cr, 0.05 wt% S and 0.05 wt% P and 96.36 wt% Fe) were irradiated with 13 MeV proton beam using BARC-TIFR Pelletron accelerator facility, Mumbai. The disc gears were irradiated for 4 hours each by proton beam having beam current of 200 nA. The nuclear reaction involved in this study is ^{56}Fe(p,n)^{56}Co. For this nuclear reaction the cross section value is maximum for 13 MeV proton energy, hence irradiation has been carried out at this energy. The product ^{56}Co has a half life of 77.3 days and gamma energies 847 KeV (100%) and 1238 KeV (67 %). The wear experiments were conducted on an Amsler twin-disc tribometer. The disc gear was mounted in the tribometer with the activated zone located at the contact point, as shown in Fig. 3. The tribometer simulates the running of an engine by moving the two discs under lubricated condition. Four different lubricants of SAE 80W90 grades (TR-1, TR-2, TR-3, TR-4) were procured from the local Indian market and tested. The wear damage of the gear in presence of each lubricant has been measured by periodically measuring the loss in radioactivity within the disc gear during the course of the wear testing. The calibration curve was generated by stack iron foil irradiation as mentioned in section 2.3. Throughout the experiment the count rate was measured from area of 847 KeV photopeak. The activity of irradiated discs were measured on an HPGe gamma spectrometer using Mn-54 standard source and was found to be in the range 2.1-2.2 MBq (57-60 μCi).

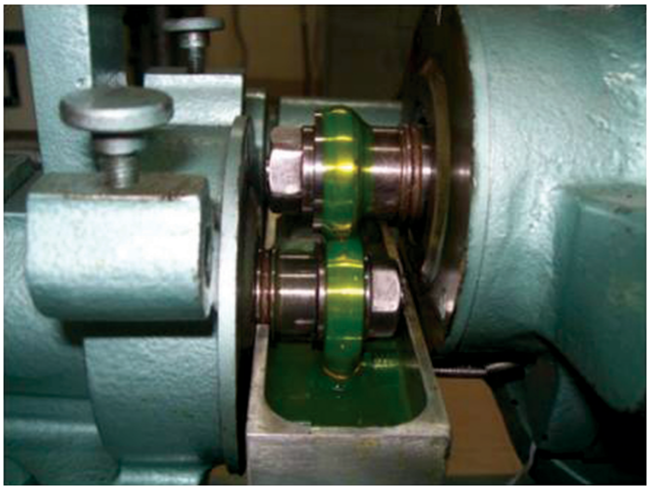

Fig. 3: Mounting of irradiated disc at the upper position in tribometer set up under lubricated condition

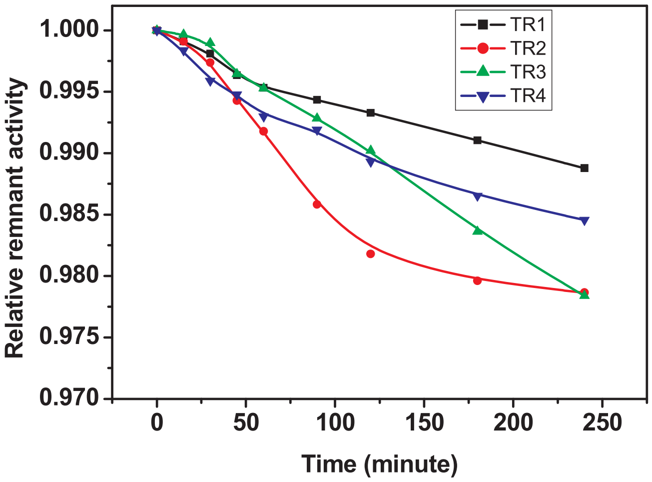

Fig. 4a: Relative remnant activity versus time plot for TR1-TR4 at 30 KgF load and 200 rpm speed

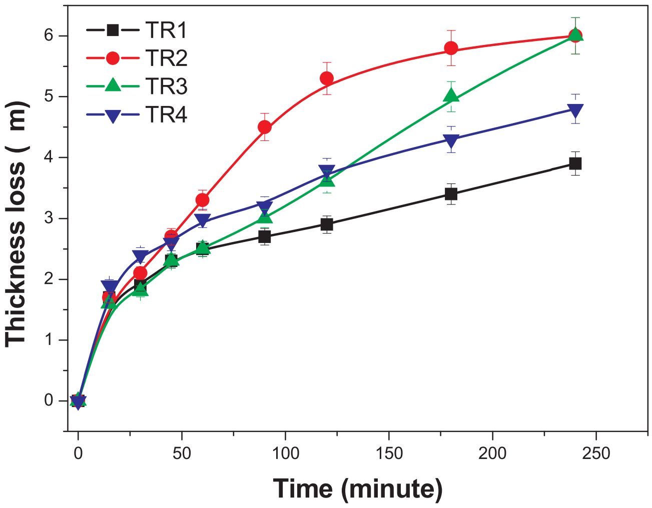

Fig. 4b: Equivalent thickness loss versus time plot for TR1-TR4 at 30 KgF load and 200 rpm speed

The counting of the disc gears in all the experiments were performed using a 50 mm gamma ray NaI(Tl) scintillation detector assembled with multichannel analyzer. The counts obtained at different time during the wear test were first converted to relative remnant activity by dividing it with the initial counts. The plot of relative remnant activity versus time is shown in Fig. 4a. Thickness loss corresponding to the relative remnant activity values is derived by the help of the calibration curve (relative remnant activity versus thickness loss) shown in Fig. 2. E.g. in Fig. 4a, TR-4 curve, let's consider any two values of relative remnant activity, i.e., 1 and 0.986. The corresponding thickness loss values, known as equivalent thickness loss obtained from the calibration curve (Fig. 2) are 0 and 4.3 µm, respectively. In this technique, the equivalent thickness loss is represented per unit area for measuring wear rate. By knowing the density of a component material, the equivalent thickness loss can be converted to equivalent mass loss of the component. The wear rate is obtained by dividing time duration of the wear test with the corresponding thickness loss.

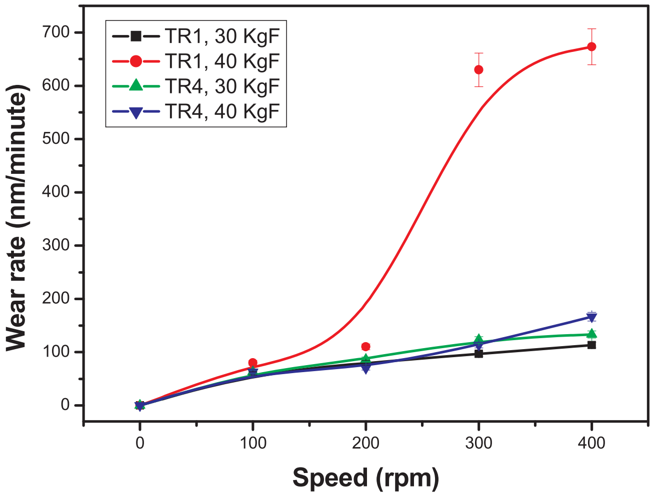

Fig. 5: Wear rate vs speed plot for TR1 and TR4 at different loads

Several factors, such as load, speed (rpm) and temperature can influence the wear process of the gear, thereby can affect the performance of the lubricant. The equivalent thickness loss of disc gear due to wear was monitored for four hours applying 30 KgF load and at 200 rpm speed with each lubricant and the result is shown in Fig. 4b. It was observed that, initially there is no significant difference in the wear rate in all the four cases, whereas after 50 minutes of wear time, the wear rate is least in the case of TR1. This implies, out of four lubricants, TR1 has good anti -wear property for 30 KgF load and 200 rpm speed. Figure 5 shows the variation in wear rate with speed for the discs lubricated with TR1 and TR4 at different loads. It has been observed that the wear loss is almost steady for both the loads and also for high rpm, in case of TR4. This suggests, TR4 has the best anti-wear performance behavior for all the load and speeds considered.

Application of TLA technique for monitoring corrosion in stainless steels

Corrosion in petroleum refinery is caused by various factors, such as, corrosive material present in the crude oil, temperature and pressure. In oil refining processes chloride ion (Cl^{-}) is present, which originates from crude oil, catalyst and cooling water. Iron base alloys like stainless steel are prone to corrosion in presence of dissolved chloride ions. A laboratory study has been carried out to estimate the corrosion behavior of stainless steel 316 L (SS 316L) in presence of chloride ion. Rectangular shape test coupon of SS 316L (17.26 Wt% Cr, 12.16 wt% Ni 2.57 wt% Mo, 1.75 wt% Mn, 0.26 wt% Cu and 66 wt% Fe) was used for the corrosion study. Since the major element present in the coupon is Fe, the coupon was labeled with small amount of radioactivity in the similar manner as mentioned in section 3.1. The nuclear reaction and the gamma energy peaks are also same as in case of the sample used for wear testing. Hence, the radioactivity counting, calculation of reduced remnant activity and equivalent thickness loss were done similar to as mentioned in section 3.1. The γ ray activity of the activated coupon was measured using an HPGe spectrometer, which was calibrated using ^{54}Mn standard source. The activity of the coupon was found to be 2.2 MBq (60 µCi).

The corrosion measurements were performed in a 500 ml capacity closed bottle. The test coupon was immersed in 200 ml acid solution by means of a nylon thread. At suitable intervals the coupon was removed from the acid solution and washed with an aqueous solution of 20g NaOH, 20 g Zn granules in 100 ml water under boiling condition for 30-40 minutes. The final washing of the coupon was performed in double distilled water followed by acetone. Then the coupon was dried under ambient condition and the radioactivity

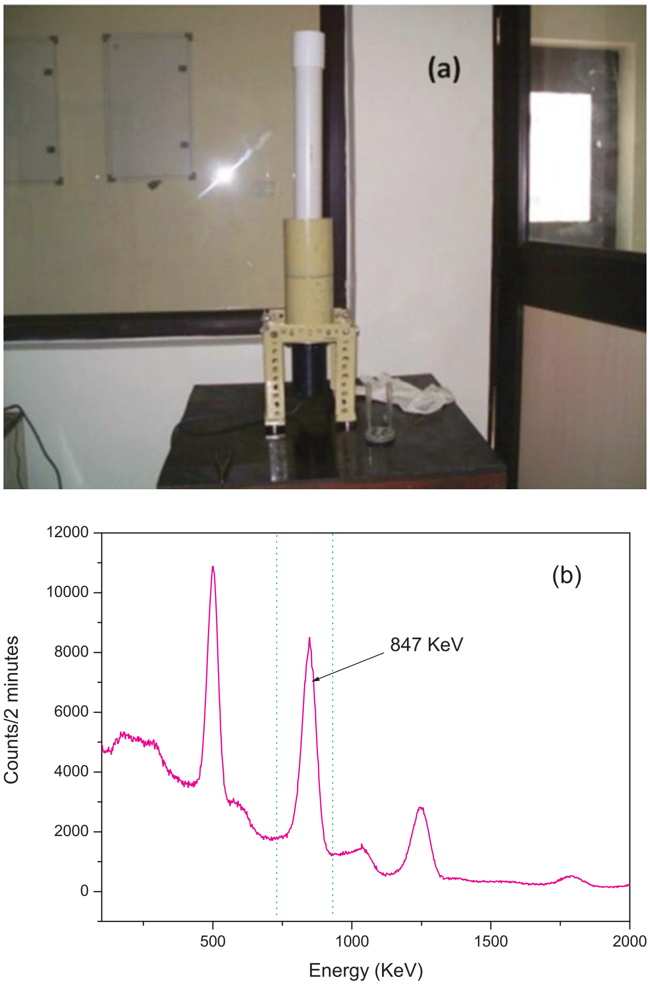

Fig. 6: (a) Radioactivity counting set up consisting of a NaI (Tl) detector, (b) corresponding gamma spectrum

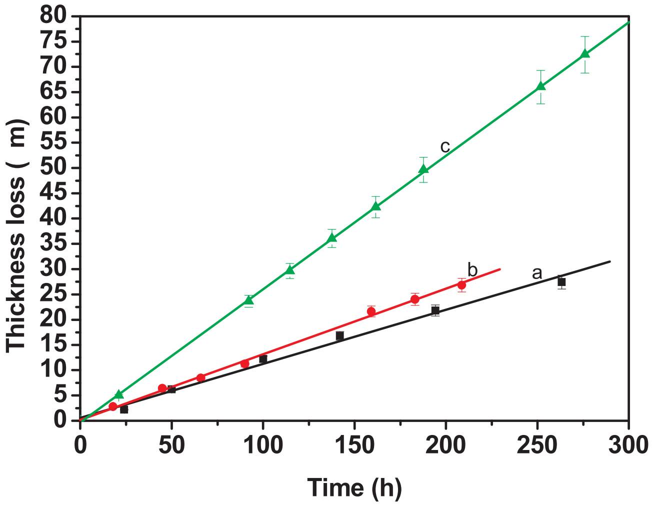

Fig. 7: Effect of HCL concentration on corrosion rate for (a) 0.5, (b) 1, (c) 3 mol dm^{-3} HCl

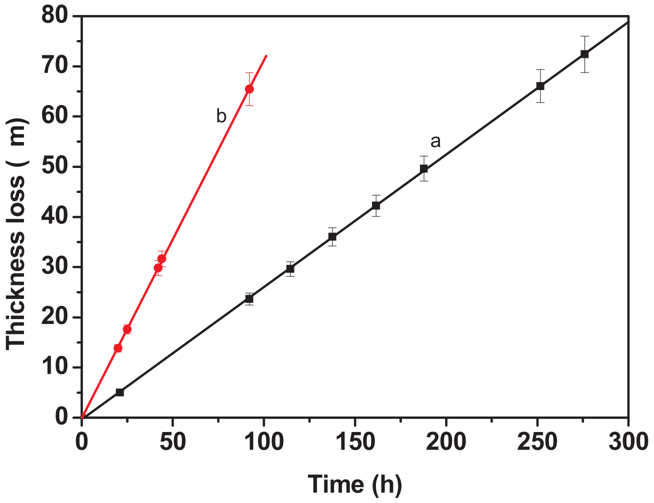

Fig. 8: Corrosion rate for SS 316L coupon in 3.0 M HCl at (a) 25 ^{0}C, (b) 40 ^{0}C

counting was done on a NaI(Tl) detector system as shown in Fig. 6. From the counts, the relative remnant activity and the equivalent thickness loss were calculated. The corrosion rate was obtained from the slope of thickness loss versus time plot.

It was observed that the corrosion rate of SS 316L in 0.53 mol dm^{-3} HCl varies from 106 nm/h263 nm/h and corrosion rate increases with increase in acid concentration as shown in Fig. 7. The effect of temperature on corrosion rate was studied for 3 mol dm^{-3} HCl and the result is shown in Fig. 8. The corrosion rate was measured to be 713 nm/h at 40 ^{0}C, which is higher than that found at room temperature. Hence the corrosion rate is accelerated with increase in temperature.

Radiological safety aspects

After the completion of irradiation, the radioactive components were cooled for few days to allow the decay of short lived radioisotopes, if any. After cooling the components were transported from BARC-TIFR Pelletron facility to radiotracer laboratory, IRAD, BARC in type approved lead containers with prior approval of BARC Safety Council. After necessary measurements, the radioactive components were transported to the experimental site (IIP, Dehradun) with prior approval of Atomic Energy Regulatory Board (AERB), Mumbai. At IIP, Dehradun, the wear/ corrosion rate measurements were carried out in a laboratories approved by AERB. The experiments were carried out by trained and authorized personnel of IRAD, BARC and IIP, Dehradun. The radioactive waste generated was stored in a suitable container and placed in an isolated room to allow the activity to decay. The activity in the components and in the waste generated was so small that it did not pose any radiation hazard to the personnel. The general guidelines for safe handling of radioisotopes issued by International Commission on Radiological Protection (ICRP) and AERB were followed during the investigations.

Conclusions

The thin layer activation analysis technique is used in the industrial research and development in the developed and the developing countries. This technique helps to increase the lifetime and reliability of various machines, installations and technological processes. The TLA technique has been developed and standardized in Isotope and Radiation Applications Division and applied for monitoring laboratory scale wear and corrosion processes. The sample irradiation, calibration procedure, testing and measurement conditions were optimized. The future perspective is to familiarize TLA technique to Indian industries, so that they can make use of this technique for solving industrial wear and corrosion problems and to make end users aware of its safety and its benefits.

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Conducted and Radiated Emission Tests for Fault Tolerant Power Distribution System ECPS-100 Developed for PHWR700MW C&I

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Electronics devices when designed to meet specific requirements, the designers do not generally envisage the amount of electromagnetic interference that this particular device may give as power line conducted noise and radiated noise. After the product is developed, the quantification of the same is carried out in certified EMI-EMC set-up to get these figures of conducted emissions (CE) and radiated emissions (RE), and its mitigation as per limits of the chosen standard. In the latest embodiment of Fault Tolerant Power Distribution System ECPS™ (Electronics Corporation Power Supply) developed for NPCIL (PHWR700MW plant) we carried out CE and RE tests and quantified the spectrum obtained for CE and RE, and mitigated them as per CISPR22 standards. In this short article we bring out the CE and RE results of the latest product ECPS, done at EMI-EMC Centre of ECIL Hyderabad.

Introduction:

The power supply to run all electronics systems for Control and Instrumentation (C&I) of Nuclear Power Plants are one of the most important components to enhance overall plant performance, [3], [6]. This aspect was realized by BARC, and thus from very basic the design which aimed for a rugged fault tolerant hot-pluggable, load sharing power supply was conceived and then engineered by ECIL and utilized in very large numbers in Nuclear Reactor Protection and Control Systems, for NPCIL plants, [1], [2], [4]. These are modular Switched Mode Power Supplies (SMPS) are termed as 'Fault Tolerant Power Distribution System' (FTPDS). These are configured as M+N system, what we term as SMPS M+N configuration. The number M will cater total load, and number N are redundant units and all M+N sharing the load equally. Say our load is 185W, to cater that we use two (M) units of 100W and one (N) unit of 100W as redundant. Thus failure of one unit will not interrupt the load current. This configuration is therefore enhancing plant reliability and availability. This FTPDS (SMPS M+N) is Trade-Marked product [5] [8], [9] as ECPS™XX; like ECPS SM60 indicating 60W modules, ECPS SM100 indicating 100W modules. The latest embodiments [2], [8], [9] for NPCIL-PHWR700MW plant, is ECPS SM100 with two variants the first one is with DC-DC (input 220V DC), and second one is with AC-DC (input 230V AC and this one having added circuits with boost convertor for Power Factor Correction (PFC) and Total Harmonic Distortion (THD) controls). For both embodiments output is regulated DC voltages of 5V, 12V, 15V, 24V. In this article we will report the conducted (CE) and radiated emission (RE) tests conducted on the latest embodiments. The CE and RE qualifications are must, so that they are qualified for usage in C&I systems. The CE and RE levels give the figure of electronic noise that is generating from this device; to be under acceptable limits; so that it is not detrimental to other electronics equipments sharing the power line or at near proximity [7]. Presently about 10,000 numbers of ECPS100 are being fabricated for NPCIL-PHWR700MW. The detailed test results are kept in CAD NPP, ECIL-Hyderabad.

Product Embodiments:

The first phase is called ECPS-I, where basic inherent load sharing was demonstrated. This product was well utilized in very large numbers by ECIL for NPCIL power plant control and instrumentation systems from Kaiga-1 & 2 to PHWR-500 TAPP 3 & 4; and then to Kaiga 3 & 4 and RAPP 5 & 6.

Few of these were employed in up-gradation of C&I for-Dhruva reactor, NAPP 1&2, KAPP 1&2, and MAPP 1&2. The second phase called ECPS-II had forced share daisy chain circuit to forcefully and equally share the load current, despite wide difference in individual voltage setting of each module. This circuit modification now has been retrofitted in older plants also-by doing site modification in earlier ECPS-I. Various stages of product development since 1993 at BARC and ECIL are depicted in Fig. 1. Based on feedback from all users the third generation advancement of the earlier models (embodiments) was taken up in mid-2006. This new product [8], [9] is complete, (1) with two front panel displays (for unit voltage and unit current), (2) with reduction in width, (3) with

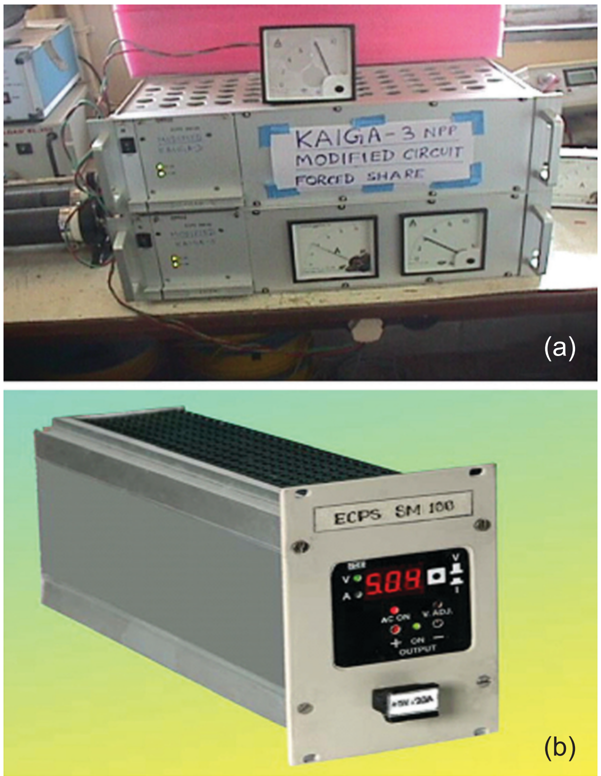

Fig. 1: Various stages of product development since 1993 (*a*) Modification with forced third wire connectivity for current sharing on ECPS; (*b*) The prototype of final embodiment of ECPS

inclusion of forced third wire current sharing circuit, (4) with voltage adjustment in front-panel, (5) with in built circuits to have good input Power Factor Correction (PFC) & Total Harmonic Distortion (THD) Control-as per IEC1000-3-2 Standard. This is new-product for NPCIL PHWR-700MW reactor C&I systems. In this embodiment only 100Watt (width 16T) with two models DC-DC and AC-DC; are fabricated; for output 5V, 15V, 24V.

About Electromagnetic Emissions and its need for control and regulation:

The term conducted emissions refer to physical phenomena which enables electromagnetic energy being created in an electronic device and gets coupled to its input power cords (AC or DC). The reason that conducted emissions need to be controlled or mitigated is: (i) Electromagnetic (EM) energy that is coupled to a device power cord can finds its path to the

Fig.2: Latest embodiment of ECPS SM100 fourteen of them sharing the load

entire power distribution net-work of C&I system that the electronic device is connected to. (ii) This EM energy coupled to the power wiring uses the larger net-work (i.e. the power wiring itself) to 'radiate' more than this particular device itself. As a result the other electronic devices and systems can receive the electromagnetic interference through a radiated path (or much less frequently via a direct electrical connection). The frequency range where conducted emissions are controlled or regulated is typically lower than the frequency range where radiated emissions are regulated.

The conducted emissions (CE) are regulated by FCC over frequency range of 450 KHz to 30 MHz, and CISPR22 conducted emission (CE) limit extends from 150 KHz to 30 MHz. Here measurements are done with CISPR22 standard [7]. The radiated emissions RE is recorded at 10m distance at frequency range 30 MHz to 1000 MHz. The Conducted Emission (CE) measurements recorded in terms of voltage (as dB micro-volts) via impedance Stabilizing Network (LISN) are common mode currents in power wires connected to earth (body) wire. Radiated emissions are measured by RF receiver as field strength in dB micro-volts / meter. Both the emission spectra are recorded on Spectrum Analyzer, and are shown in Fig. 5.

Source of Emissions:

Since about late eighties, the C&I systems in Nuclear Power Plants have started using the Switched mode Power Supplies (SMPS). The first of SMPS was used in Dhruva Research Reactor (ECCS: Emergency Core Cooling System) in 1986, then for Research Reactor-Kamini (Reactor Regulation System), 1988 and then in KAPP Plant (PDCS: Programmable Digital Comparator System) 1990. The reason that SMPS are inherently larger contributors to conducted and radiated Emissions i.e. CE and RE than the linear regulated supplies is due to the power MOSFET transitioning at the switching frequency. The switching frequency (80K Hz-for the latest embodiment of ECPS) and its harmonics are well within the frequency band regulated for conducted emissions. Electromagnetic energy at this frequency and its harmonics gets coupled back onto the power cord (AC or DC) of the electronic device. In the latest embodiment of ECPS that we tested, the configuration is prone to CE problems because the switching element is on the primary side of the main power transfer transformer, where it creates the interference that couple directly to the input power cords. Thus the energy that is coupled to the power cord is much higher in amplitude than if the MOSFET switch is on the secondary side of the transformer, where it would be switching a stepped down voltage. A very good power supply line filter is needed for these SMPS to mitigate the emissions. These power line filters are provided in the design of individual ECPS as well as placed on power-mother boards.

Prior to year 2002, the CE standards set by FCC and by CISPR were different. In 2002 the FCC changed the CE standard to match CISPR standard. The frequency range in the previous version of FCC in CE tests was 450 KHZ to 30 MHz, while frequency range of CISPER is 150 KHz-30MHZ for CE tests. But higher/lower range for specific (special) standard is allowed, where special Line Impedance Stabilized Network (LISN) is required. The standard LISN to measure CE as per CISPR is basically a High Pass filter for the measuring equipment with 50 Ohm input resistance. These standard LISN provides 50 Ohms (2% tolerance) impedance at frequencies greater than 100 KHz, and impedance rolls off at lower frequency. At 80Kz our fundamental frequency the LISN impedance is about 20 Ohms.

Fig. 3 gives a general SMPS configuration of buck converter. The Fig. 3 show the leakage capacitors marked as C_{Stray}, provide coupling impedance at high frequency for leakage current path. The P N E lines represent input Positive Negative and Earth Lines of power cord respectively. The earth line of the

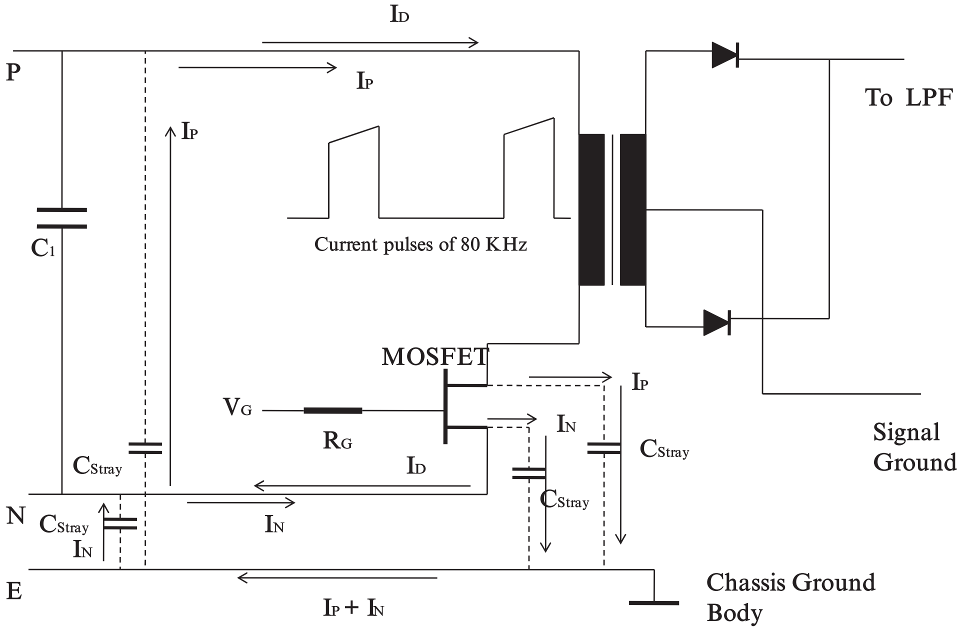

Fig. 3: A representative figure of SMPS and leakage current

power cord is connected to the Chassis Ground (Body) of the ECPS. For DC-DC models the primary of transformer sees a 220V DC voltage (between P and N), and for AC-DC model the boosted DC (about 390V) is provided by another pre-boost (AC-DC) switched convertor (switching at 100 KHz in the latest embodiment of ECPS) for PFC and THD control. This new circuit has helped to make (Power-Factor) PF as 0.99 from, with THD of 0.8 while the earlier embodiments had PF as 0.55 with THD more than 1.1. The P and N in case of AC-DC are corresponding to Phase and Neutral lines. The boosted switched convertor is placed after P and N and then DC Voltage of 390V goes to the same Switcher circuit as shown in Fig. 3. However, this is representative figure to give the idea of leakage current (I_P , I_N in figure-3) that is the source of emission.

The pulsed current has DC component plus all harmonics. The DC component does not leak through, only the pulsating current harmonics leaks to the E-wire. In the figure-3, the dotted lines represent the leakage current path via stray capacitors; in reality these are distributed capacitor which couples the harmonics of the pulsating currents to the earth (E) line. This generates common mode current components namely I_P and I_N , with $I_P + I_N$ current flowing in the E-wire; which is the cause of emission.

Measurements:

The CE tests (as per CISPR 22) are done via utilizing Line Impedance Stabilized Network (LISN) connected to P and N leads of the ECPS (individual case as well as shared case). The voltage spectrum corresponding to CE current is (in dB micro-volts)—measured across 50 ohm impedance on spectrum analyser i.e. i.e. $V_p = (I_P)$ (50 Ohm), and $V_N = (I_N)$ (50 Ohm). The set up is shown in figure-4, and record of spectrum V_P is shown in Fig. 5.

For RE tests two sets of antenna are used. First we recorded the radiated emission for 30MHz to 230MHz, with Bi-Conical antenna kept at 10m from ECPS bin in an-echoic chamber, shown in Fig. 6, and then we use log-periodic dipole antenna system to record the RE from frequency 230 MHz to 1000 MHz, shown in Fig. 7.

Observations:

After placement of filters at rear side on mother-board-which houses the ECPS; and shielding the internal cable at the power ON/OFF switch, for the DC-DC ECPS and the AC-DC ECPS, the maximum value 3-4 dB micro-volts was observed in CE tests. This value is much less than the lower limit CE i.e. 60 dB micro-volts, in the range of 150 KHz-30 MHz spectral range (defined by [7]). This corresponds to V_P and V_N of

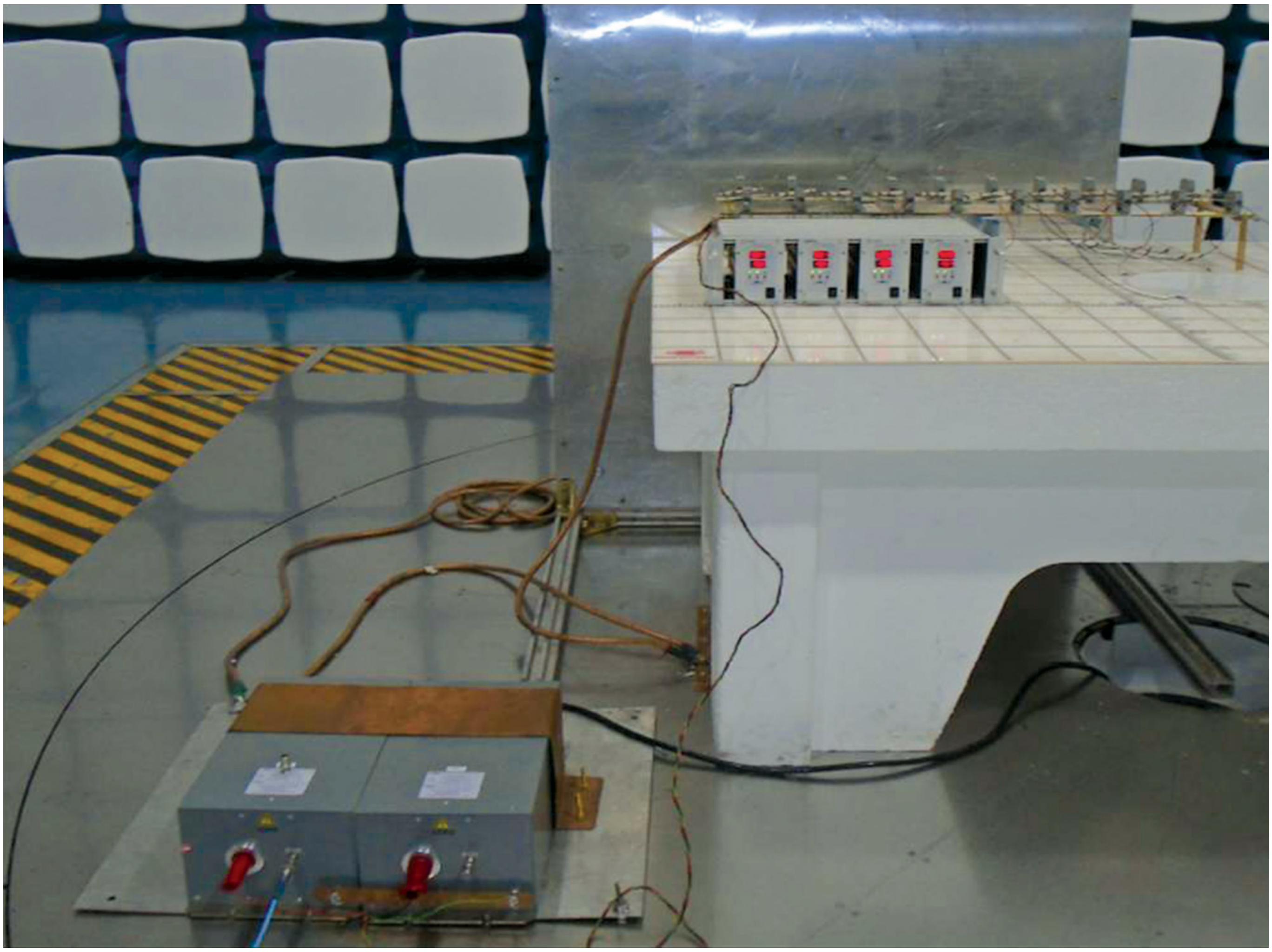

Fig. 4: The CE test set-up with LISN connected to input power cord of ECPS bin containing four ECPS SM100

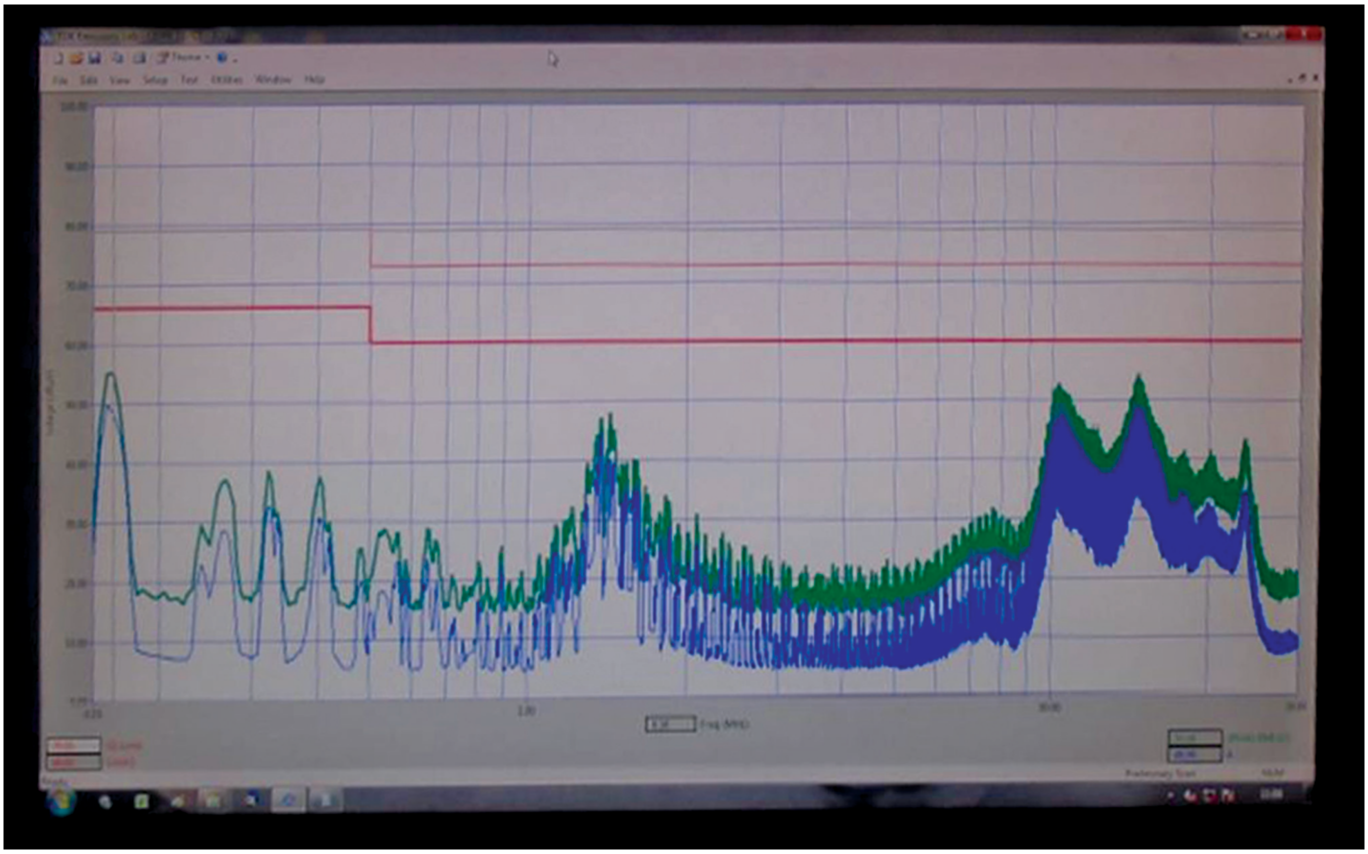

Fig. 5: Spectrum obtained in CE Tests from 150 KHz to 30 MHz, with limit lines for CISPR22 case

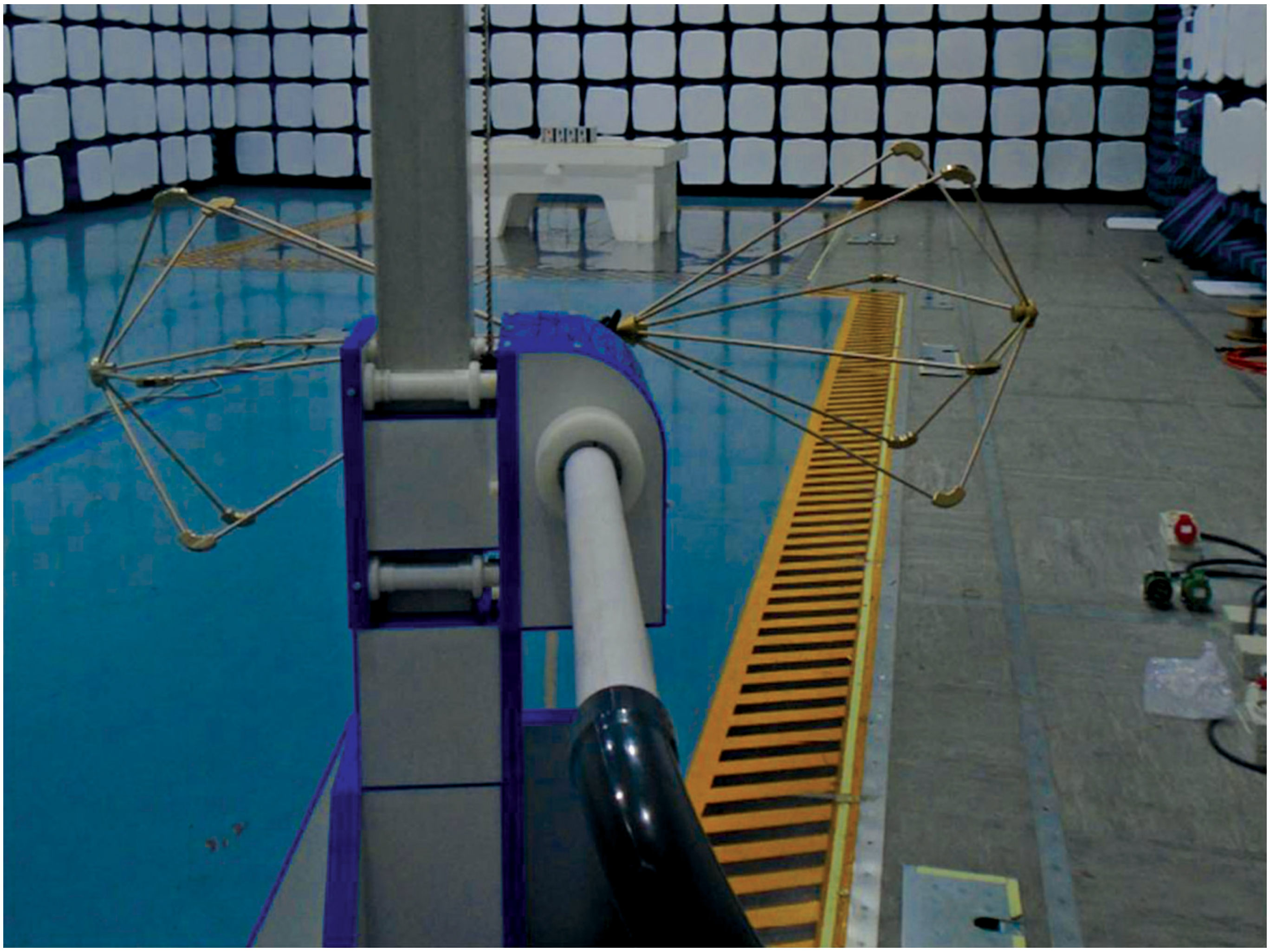

Fig-6: Antenna at 10m for RE measurement in range 30 MHz to 230 MHz

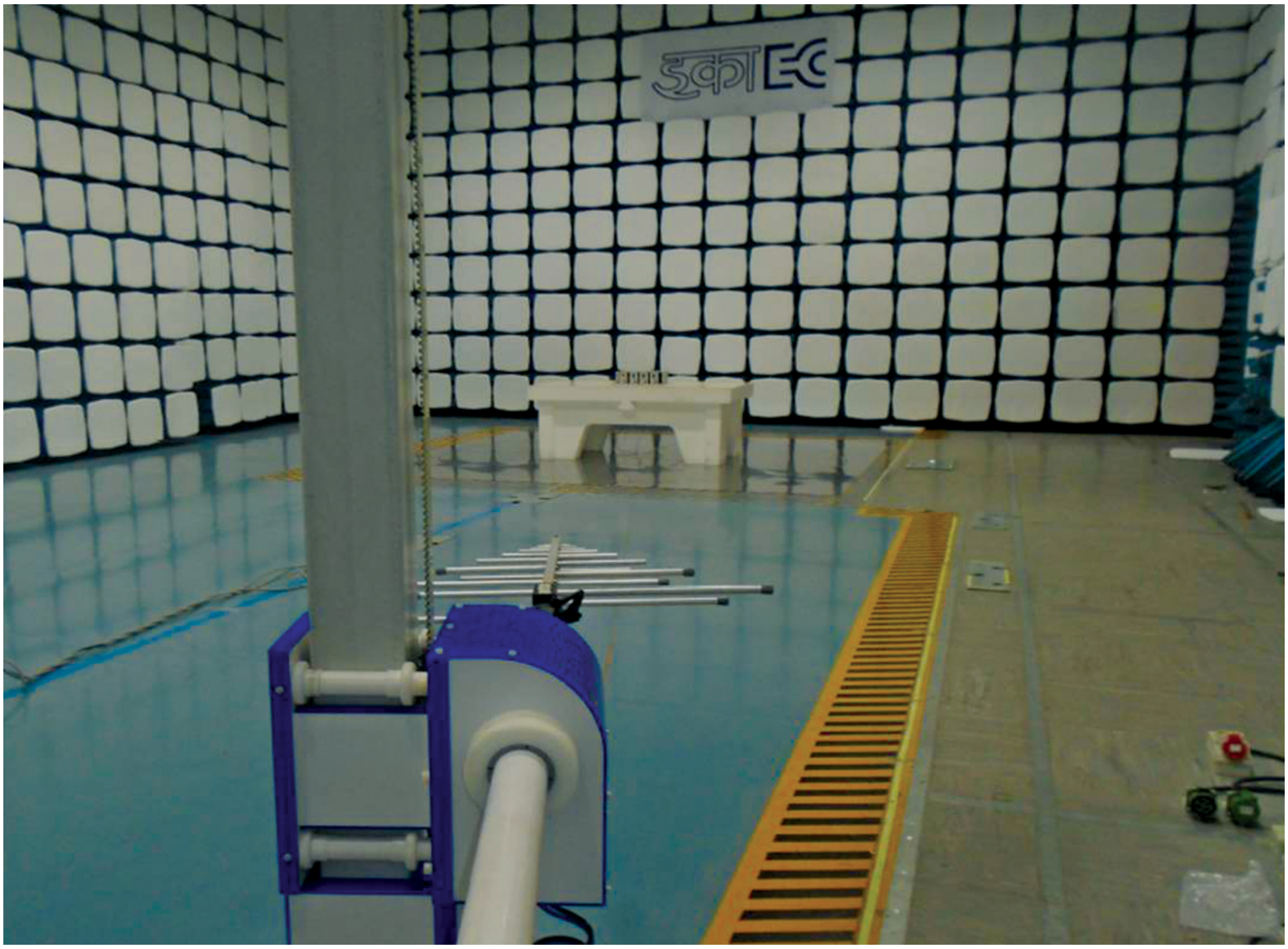

Fig. 7: Antenna at 10m for RE measurement in range 230 M Hz to 1000 M Hz.

less than 1 mV that amounts to leakage currents I_P and I_N less than 20 micro-amperes.

After placement of the ECPS units inside shielded bins, then insertion of ferrite beads placed on long wires connected to load; twisting the load wires; and shielding the internal cable at the ON/OFF switch, RE measurements done on the DC-DC ECPS and AC-DC ECPS showed; 2 dB micro-volt / meter. The maximum value, observed is, lesser than the lower limit of RE i.e. 37 dB micro-volts / meter, (=20 log (E /1 micro-volt per meter) in the range of 230-1000 M Hz spectral range. This corresponds to electric field of lesser than about 71 micro-volts / meter comes from $E = 10^{(37/20)} = 71$ micro-volts / meter. In actual we still expect lesser dB micro-volts / meter, as the system will be inside RF shielded Instrument Racks (IR) in the Nuclear Plant sites.

As required by BHEL same experiment was conducted again as per CISPR11. The DC-DC model of ECPS cleared the limit for CE test by 4 dB micro-volt and AC-DC model cleared the CE limit by 7 dB micro-volt margin. Further in order to record the RE from the rear side of ECPS where we have load wires connections, it is observed at RE tests both the models crossed the limit at antenna height of 2m. This test was done on unshielded system; actually the entire assembly at site is housed inside shielded instrument rack-that will reduce the RE from rear side of the ECPS assembly.

Interpretations of observed spectrum

A Pulse Width Modulated signal (PWM) signal can be considered to be sum of an infinite amount of sine and cosine waves of varying amplitude and frequency. We can obtain expressions for the amplitudes of these waves by computing the Fourier series for signal. In essence the original signal here denoted by $v(t)$,with time period T_p = 2L is expressed as

$$v(t) = \frac{a_0}{2} + \sum_{n=1}^{\infty} a_n \cos\left(\frac{n\pi t}{L}\right) + \sum_{n=1}^{\infty} \sin\left(\frac{n\pi t}{L}\right)$$

where

$$a_0 = \frac{1}{L}\int_{-L}^{L} v(t)\mathrm{d}t$$

$$a_n = \frac{1}{L}\int_{-L}^{L} v(t)\cos\left(\frac{n\pi t}{L}\right)\mathrm{d}t$$

$$n = 1, 2, \ldots\ b_n = \frac{1}{L}\int_{-L}^{L} v(t)\sin\left(\frac{n\pi t}{L}\right)\mathrm{d}t,\ n = 1, 2, \ldots$$

For simplicity take L=1; and define the PWM signal, with duty cycle D as $v(t)$=0 for-1<t<-D, $v(t)=V$ for-$D<t<D$ and again $v(t)$=0 for$D<t<1$. We get the amplitudes as $a_0 = 2VD$, $a_n = \frac{2V}{n\pi}\sin(n\pi D)$ and $b_n=0$. We note that with duty cycle D=50% we will have only fundamental, and other odd harmonics, plus DC. For PWM signal of D<50% we will have DC component fundamental plus all harmonic components; with decreasing amplitude. The fundamental in DC-DC model of ECPS is 80KHz and in AC-DC model of ECPS two fundamental frequencies 80KHz and 100KKz (due to extra Boost Convertor employed for PFC and THD controls).

The PWM is thus having multi-frequency components, and here Inter-Modulation Noise at several frequencies due to beats appears in CE and RE measurements. Inter-Modulation Noise is due to concept of Inter-Modulation Distortion (IMD). The Inter-Modulation (IM) product at frequencies f_{IM} are generated by two ore more signals at frequencies $f_1, f_2, f_3; \ldots$ The relation between f_{IM} and these f_1, f_2, f_3 is expressed as $f_{IM} = |m_1 f_1 + m_2 f_2 + \ldots|$, with $m_j = 0, \pm 1, \pm 2, \ldots$ The order of IM product is given as $n=m_1+m_2+\ldots$ This means that the frequency of second order IM product Im_2 with $n=2$, $m_1=m_2=1$ results in $f_{IM} = |f_1 \pm f_2|$.

The third order IM_3($n=3, m_1=2m_2=1$) gives $f_{IM} = |2f_1 \pm f_2|$ or $f_{IM} = |2f_2 \pm f_1|$ i.e. with $m_1=1$ and $m_2=2$.

In our experiments we observed odd and even harmonic components and various other spectral lines-and sometimes with increasing amplitude at a particular frequency range. We note that first of all we are having in our system a square wave (of basic frequency 80 K Hz, in DC-DC model) with Duty-cycle less than 50%, at full load. For CISPR CE-RE, recording is from 150 KHz onwards. Thus we are supposed to get infinite numbers of harmonics (as per Fourier series) as-DC, first harmonic (80KHz), second harmonic (160KHz), third harmonic (240Kz) fourth harmonic (320 KHz) … 8MHz, 16Mz, 24MHz, (32Mz)…; and so on. Because we restricted our record from 150 KHz to 30 MHz, we are not seeing the first harmonic components. Not only one sees these components, but also one observes addition and subtraction of the components, as described in Inter-Modulation Noise.

For the AC-DC model, apart from the infinite frequencies due to 80 KHz, we also have 100 KHz as basic frequency for pre-boosted DC-DC circuit for PFC and THD control. Therefore we are also recording 200 KHz, 300 KHz, 400 KHz…….10MHz, 20MHz, 30 MHz….in addition to the frequencies listed ones for DC-DC model. Here the 100KHz component is getting added and subtracted and we are also getting 180KHz, 260KHz, 340KHz, ….16MHz+100KHz, 16MHz-100KHz, 24MHz+100KHz, 24MHz-100KHz,…. 20MHz+100KHz, 20MHz-100KHz,…… Here also at higher decades showing continuous spectral lines (Fig. 5); due to Inter-Modulation Noise as described above.

For CE recording, we are measuring the 'leaked' current components, I_P and I_N, from P-leads and N-leads respectively to the Earth- (E-leads); at the Spectrum Analyzer, via LISN. We are therefore measuring $V_P = (I_P)$ (50 Ohms), and $V_N = (I_N)$ (50 Ohms) through LISN (at 50 Ohm terminal impedance). The stray-capacitors (C_{stray} that is always present), at higher frequency band is presenting a very-very low impedance path to those high Fourier components; plus all components that are generated via Inter Modulation Noise Thus we are observing at these frequency ranges higher amplitude of V_P and V_N (in dB micro-volts), due to increased leakage currents (I_P and I_N) at those higher frequencies and due to IMD; as explained above.

Conclusions:

In this short note we presented the brief result of Electro Magnetic Interference Tests done for a developed new product ECPS100 to be used in NPCIL-PHWR700MW, as per CISPR22 standard. Here we comment that if we want to do CE, RE tests as per say some special standards or MIL –STD, then accordingly measurements will also be different for different ranges of frequencies. The mitigation methods of use EMI filtering shielding etc used here may be stringent for the other standards. So those solutions need be different. Also packing the developed circuit onto a different PCB, with different enclosure, and internal wiring and assembly will give different results.

Acknowledgements:

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Simfuel - Near Unirradiated Analogue of High Burn-up Nuclear Fuel

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Simulated fuel based on ThO_2-3.5% UO_2 corresponding to 28000 and 43000 MWd/t burn-up and simulated fuel based on UO_2 corresponding to 7000 MWd/t burn-up were fabricated by powder metallurgical route by adding high purity oxides such as SrO, Y_2O_3, ZrO_2, MoO_3, $BaCO_3$, La_2O_3, CeO_2, Nd_2O_3, RuO_2, Rh_2O_3, Pd, Cs_2CO_3, Pr_6O_{11} and Sm_2O_3 to ThO_2 and UO_2 powders in desired quantities which simulate the fission products. Thermophysical properties e.g. thermal diffusivity/conductivity, thermal expansion and specific heat of fabricated samples were studied.

Introduction

The purpose of the *SIM*ulated high burn-up nuclear *FUEL* (SIMFUEL) is to replicate the chemical state of the solid fission products generated in irradiated fuel. SIMFUEL is a synthetic nuclear fuel like UO_2 or ThO_2 containing additions of Sr, Y, Zr, Mo, Ru, Rh, Pd, Ba, La, Ce, Nd etc. in proportions intended to be analogous to spent fuel with various burn-ups. SIMFUEL helps in estimating the extent of degradation in the thermo-physical and mechanical properties of the fuel due to the presence of fission products. The use of SIMFUEL has a number of advantages compared to irradiated fuel.

An in-depth knowledge about the fuel material and its behaviour under various conditions is crucial to ensure the safe operation of nuclear power plants. However experiments with irradiated materials are difficult and very costly. The thermo physical properties data from irradiated fuel are very limited, due to the difficulties associated with the high-radiation fields, and

a. non-availability of intact (free of cracks), well-characterized specimens required for measurements.

b. non-availability of instruments required for characterization inside hot cell.

c. difficulty in determining the influence of the various parameters from the few data available from irradiated fuel.

SIMFUEL provides a convenient way to investigate intrinsic properties of a fuel. Because gases and volatiles are not added, the microstructure does not contain the bubbles observed in irradiated fuel. Microstructure of SIMFUEL also does not contain cracks that are observed in irradiated fuel. The other advantages of SIMFUEL are:

- The absence of radioactivity permits easy and reliable measurements.
- The intrinsic properties of the material are measured. This is useful for modelers. The effects of porosity and gas bubbles are accounted for in the codes.
- The microstructure of SIMFUEL is well characterized.
- It is difficult to obtain sufficiently large samples of irradiated high burn-up fuel for accurate thermal diffusivity or conductivity measurements.

However, SIMFUEL does not replicate features such as grain-boundary segregation of volatile and semi-volatile elements, nor does it replicate radial variations in microstructure and distribution of fission products within a fuel pellet.

The behaviour of nuclear fuel during irradiation is largely dependent on its physico-chemical properties and their change with temperature and burn-up. Accurate representations of thermophysical properties like thermal conductivity, thermal expansion and specific heat under relevant temperature and neutron fluence conditions are necessary for evaluating reactor performance under normal operation and accidental conditions. Irradiation in nuclear fuel results in the formation of fission products which exist mostly as four different groups:

a) elements dissolved in matrix (Sr, Zr, Nb, Y, La, Ce, Pr, Nd, Pm, Sm)

b) metallic precipitates : Mo, Tc, Ru, Rh, Pd, Ag, Cd, In, Sb, Te

c) oxide precipitates : Rb, Cs, Ba, Zr, Nb, Mo, Te

d) volatile elements Kr, Xe, Br, I, etc.

Their chemical state in oxide fuels is governed by oxygen potentials present during irradiation. The presence of these phases, the formation of fission gas bubbles, the change of oxygen-to-metal ratio (O/M) and restructuring result in the change in thermophysical and thermomechanical properties of the fuel with burn-up.

In this study, thermophysical properties e.g. thermal diffusivity/ conductivity, thermal expansion and specific heat of the following samples were studied:

1. ThO_2-3.5% UO_2 and simulated fuel based on ThO_2-3.5% UO_2 corresponding to 28000 and 43000 MWd/t burn-up.
2. UO_2 and simulated fuel based on UO_2 corresponding to 7000 MWd/t burn-up.

Sample fabrication

SIMFUELs corresponding to an average burn-up of 28000 and 43000 MWd/t were fabricated by powder metallurgical route by adding high purity (>99.9%) oxides such as SrO, Y_2O_3, ZrO_2, MoO_3, $BaCO_3$, La_2O_3, CeO_2, Nd_2O_3, RuO_2, Rh_2O_3, Pd, Cs_2CO_3, Pr_6O_{11} and Sm_2O_3 to ThO_2 and UO_2 powders in desired quantities which simulate the fission products. The SIMFUEL compositions used is this study are shown in Table 1 was based on the ORIGEN-2 CODE[1]. Wet mixing of powders in ethanol medium was carried out to achieve a homogeneous mixing of the powders. Fabrication flow sheet is given in Fig. 1. Similarly simulated fuel based on UO_2 corresponding to 7000 MWd/t burn-up were fabricated by adding SrO, Y_2O_3, ZrO_2, MoO_3, $BaCO_3$, La_2O_3, CeO_2, Nd_2O_3, RuO_2, Rh_2O_3 and PdO, to UO_2 powders in desired quantities[2].

Thermophysical properties

Thermal expansion

The coefficient of thermal expansion (CTE) values are needed to calculate stresses occurring in the fuel and cladding with change in temperature. If the thermal expansion varies considerably between the fuel and cladding, stresses will be accumulated during the thermal cycling. Thermal expansion behavior of polycrystalline samples of ThO_2-3.45%UO_2 and SIMFUEL has been investigated from room temperature to 1823 K using a high temperature dilatometer. The percentage linear thermal expansion obtained for these compositions are shown in Fig. 2. The dilatometer was calibrated with Tungsten, NBS SRM (Standard Reference Material) 737. Temperature calibration of the dilatometer was checked using uranium metal sample, whose phase transformation temperatures are well known.

Bakker et al.[3] observed ideal solution behavior for ThO_2-UO_2 from vapour pressure measurement at high temperature and concluded that thermal expansion of the solid solutions $(Th_{1-y}U_y)O_2$ where $0 \leq y \leq 1$, could be reasonably approximated at various temperatures by taking linear interpolated expansion data of ThO_2 and UO_2 as per their weight fraction. The percentage linear thermal expansion data of ThO_2-4% UO_2, thus calculated by taking linear interpolated expansion data of ThO_2 and UO_2 as per their weight fraction, is also shown in Fig. 2. It was observed to be in close agreement with data obtained for composition ThO_2-3.45%UO_2. Reported data[4] of ThO_2 is also included in Fig. 2 for comparison.

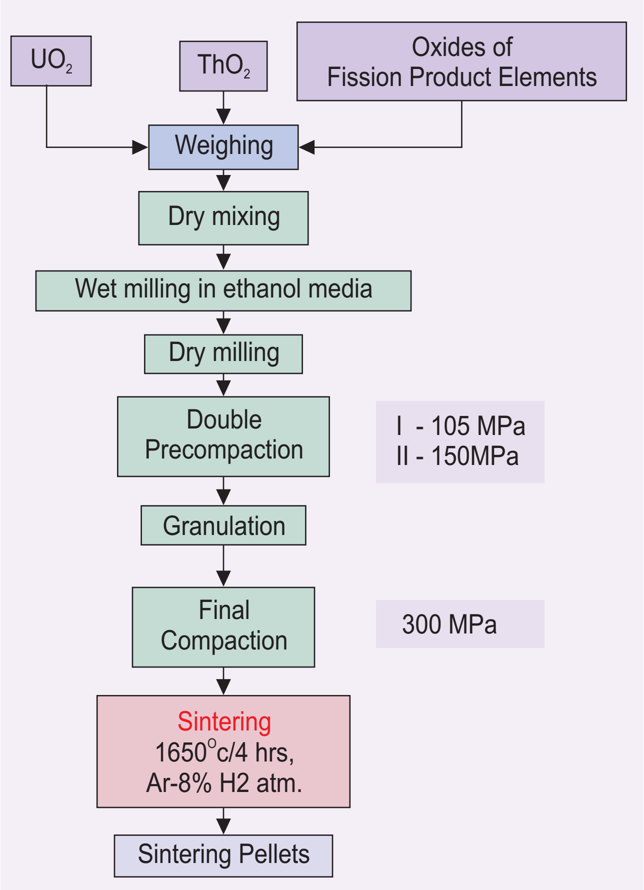

Fig. 1: SIMFUEL pellet fabrication flow chart

Table 1: Compositional detail of SIMFUELs based on ORIGEN CODE

Sr. No	Composition (wt%)	SIMFUEL based on ThO_2-3.45% UO_2 28000 MWd/t burn-up	SIMFUEL based on ThO_2-3.45% UO_2 43000 MWd/t burn-up	SIMFUEL based on UO_2 7000 MWd/t burn-up
1	ThO_2	95.0800	93.9526	-
2	UO_2	2.5592	2.3956	99.38
3	ZrO_2	0.4450	0.6916	0.108
4	MoO_3	0.3254	0.5052	0.102
5	Nd_2O_3	0.3218	0.5192	0.086
6	CeO_2	0.2612	0.3970	0.088
7	Cs_2CO_3	0.2572	0.3792	-
8	$BaCO_3$	0.1442	0.2378	0.044
9	SrO	0.1332	0.1992	0.026
10	Pr_6O_{11}	0.1120	0.1658	-
11	La_2O_3	0.1060	0.1586	0.032
12	RuO_2	0.1022	0.1628	0.076
13	Y_2O_3	0.0760	0.1162	0.014
14	Sm_2O_3	0.0442	0.0698	-
15	Rh_2O_3	0.0162	0.0198	0.012
16	Pd	0.0160	0.0300	0.028*
Total fission products in percentage		**2.3606**	**3.6522**	**0.6**

*PdO

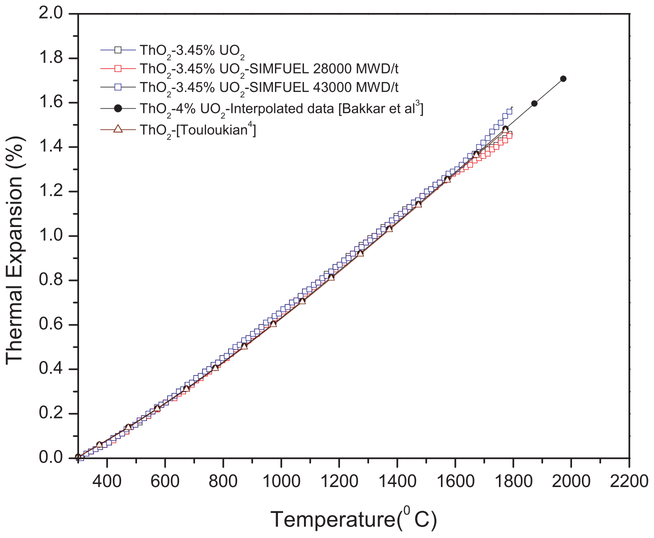

Fig. 2: Thermal expansion vs. temperature plot for ThO_2-3.45% UO_2 and SIMFUELs

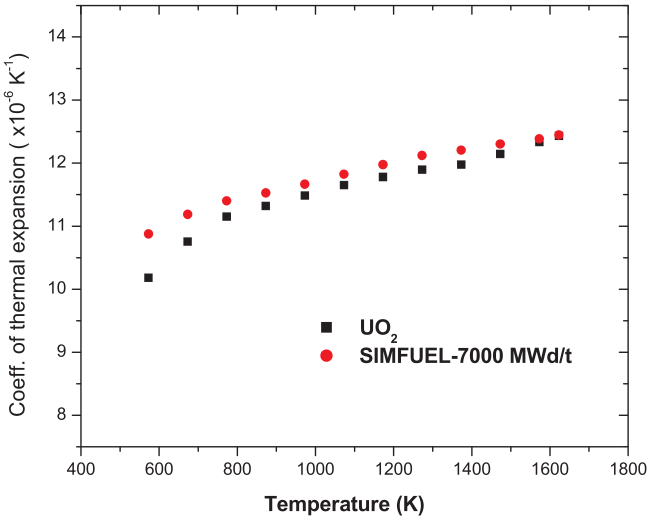

Fig. 3: Coefficient of thermal expansion vs. temperature

Thermal expansion value of any material depends on temperature (T) as follows:

$$(\Delta L/L_0)_T \times 100 = A + BT + CT^2 + DT^3 \qquad (1)$$

where, $(\Delta L/L_0)_T \times 100$ is percentage thermal expansion value and A, B, C and D are constants. When the temperature changes by ΔT, the change in length ΔL is proportional to ΔT and the original length L_0,

$$\Delta L = \alpha \times L_0 \times \Delta T , \qquad (2)$$

where, this proportionality constant, α is called the 'coefficient of linear thermal expansion' (CLTE) or simply 'coefficient of thermal expansion' (CTE).

The percentage thermal expansion data for various materials taken up in this study was fitted with third degree polynomial equation and the least squares fitted expressions for all the materials are given below (validity: $300 \leqslant T \leqslant 1773$).

For ThO_2-3.45% UO_2:

$$\left(\frac{\Delta L}{L_0}\right)\times 100\ (\%) = -0.03067 + 7.52366\times 10^{-4}.(T/K) + 3.70585\times 10^{-7}.(T/K)^2 - 1.40197\times 10^{-10}.(T/K)^3 \qquad (3)$$

For ThO_2-3.45% UO_2SIMFUEL (28000 MWd/t):

$$\left(\frac{\Delta L}{L_0}\right)\times 100\ (\%) = -0.02833 + 7.33999\times 10^{-4}.(T/K) + 3.67885\times 10^{-7}.(T/K)^2 - 1.29092\times 10^{-10}.(T/K)^3 \qquad (4)$$

For ThO_2-3.45% UO_2SIMFUEL (43000 MWd/t):

$$\left(\frac{\Delta L}{L_0}\right)\times 100\ (\%) = -0.03376 + 7.95589\times 10^{-4}.(T/K) + 2.84347\times 10^{-7}.(T/K)^2 - 9.65375\times 10^{-11}.(T/K)^3 \qquad (5)$$

Table 2: Co-efficient of thermal expansion values for ThO_2-3.45%UO_2 and SIMFUELs

		Coefficient of Thermal Expansion (CTE) $\times 10^{-6}$ (1/K)		
Sr. No	Temperature Range (°C)	ThO_2-3.45% UO_2	SIMFUEL based on ThO_2-3.45% UO_2	
			28000 MWd/t burn-up	43000 MWd/t burn-up
1	300-373	6.85	6.85	6.85
2	300-473	7.51	7.51	7.51
3	300-573	8.06	8.06	8.43
4	300-673	8.58	8.31	8.58
5	300-773	8.88	8.88	8.88
6	300-873	9.08	9.08	9.25
7	300-973	9.36	9.21	9.36
8	300-1073	9.57	9.44	9.57
9	300-1173	9.62	9.62	9.62
10	300-1273	9.76	9.76	9.76
11	300-1373	9.88	9.79	9.88
12	300-1473	9.89	9.89	9.89
13	300-1573	9.98	9.90	9.98
14	300-1673	9.91	9.76	10.05
15	300-1773	9.78	9.70	10.45

The co-efficient of thermal expansion values for ThO_2-3.45%UO_2 and SIMFUELs, calculated as per to equation (2) in various temperature ranges are given in Table 2.

Coefficient of thermal expansion data for UO_2 based simulated fuel, determined using dilatometer, was also plotted against temperature in Fig 3. It was found that coefficient of linear thermal expansion of UO_2 based simulated fuel is higher than UO_2.

The average coefficients of linear thermal expansion of ThO_2-3.45 wt.% UO_2 and simulated fuel corresponding to 28000 and 43000 MWd/t burn-up fuel using dilatometer, over a temperature range of 300 to 1773 K, were found to be 9.78×10^{-6}, 9.70×10^{-6} and 10.45×10^{-6} K^{-1}, respectively. It can be seen that there is a systematic increase in the average thermal expansion coefficient of simulated fuel with burn-up compared to virgin fuel (ThO_2-3.45 wt.% UO_2 or UO_2) and this is related to the higher thermal expansion coefficient of dissolved rare earth oxides and lower melting point of SIMFUEL matrix.

The uncertainty in the values of $\Delta L/L_0$ may arise from three factors, namely accuracy in temperature measurement (i.e. the accuracy of the thermocouple), accuracy in LVDT and the accuracy in the digital micrometer for the measurement of the initial length of the sample (L_0). The thermocouple used in the present study was W-3% Re & W-25% Re. having an accuracy of ± 13 degree in the temperature range of 300K - 699 K and ± 1% in the temperature range of 700 K – 2023 K. The LVDT of the dilatometer is capable of measuring a length change of ± 0.1 µm. The digital micrometer used for initial length measurement has an accuracy of ± 1 µm. The uncertainty (maximum) in the above values of $\Delta L/L_0$ estimated by taking into account all the three above mentioned possible errors was found to be ± 5 %, in the temperature range from 300 K – 1773 K for both ThO_2-UO_2 , UO_2 and SIMFUELs.

Specific heat

Heat capacity data are needed to convert thermal diffusivity to thermal conductivity data and the later is in turn used as an input for computer codes that model fuel performance. Heat capacity measurements were carried out using a heat flux type differential scanning calorimeter. The temperature calibration of the calorimeter was carried out in the present study by the phase transition temperature of National Institute of Standards and Technology (NIST) reference materials (mercury: T_{fus} = 234.316 K; gallium: T_{fus} = 302.914 K; indium: T_{fus} = 429.748 K; tin T_{fus} = 505.078 K; lead: T_{fus} = 600.600 K) and AR grade samples (n-pentane: T_{fus} = 140.490; cyclohexane: T_{fus} = 280.1 K, T_{trs} = 190.0 K; deionised water: T_{fus} = 273.160 K; potassium nitrate: T_{fus} = 400.850 K; silver sulfate: T_{fus} = 703.150 K; potassium sulfate: T_{fus} = 856.150 K). Heat calibration of the calorimeter was carried out from the enthalpies of transition of these reference materials. For the determination of heat capacity, NIST synthetic sapphire (SRM 720) in the powder form was used as the reference material. Heat capacity of the oxide was determined in two different temperature ranges: (i) 128 T(K) 299 and (ii) 305 T(K) 845. The classical three-step method in the continuous heating mode was followed in this study to measure the specific heat in the first temperature range i.e. from 128 K to 299 K. Heat flow as a function of temperature was measured at a heating rate of 5 K min^{-1} with high purity helium as a carrier gas with a flow rate of 2 dm^3 h^{-1}. In order to determine heat capacity in the step-heating mode in the second temperature range from 305 K to 845 K, three sets of experiments were carried out in argon atmosphere at a heating rate of 5 K min^{-1} and a gas flow rate of 2 dm^3 h^{-1}. All three sets of experiment were performed under identical experimental conditions viz. heating rate, carrier gas flow rate, delay time and temperature range. About 300-350 mg of the sample was used for the heat capacity measurements. The heat capacity of the sample under investigation was calculated by a simple comparison of the heat flow rates in the three runs.

The specific heat capacity values of ThO_2-3.45% UO_2 and the two compositions of simulated fuel corresponding to 28000 and 43000 MWd/t burn-up were obtained in two different temperature ranges: (i) 128 T(K) 299 and (ii) 305 T(K) 845. Their specific heat capacity values obtained were plotted against temperature and are depicted in Fig. 4.

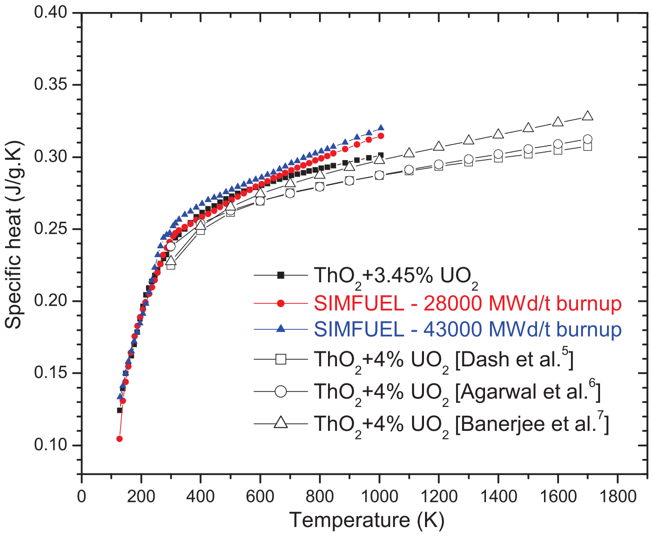

Fig. 4: Specific heat vs. temperature for ThO_2-3.45%UO_2 and SIMFUEL

In this figure, the specific heat capacity of ThO_2-3.45% UO_2 has been compared with the heat capacity of ThO_2-4% UO_2 reported in the literature [5,6,7] and shows a close match. The heat capacity data of the simulated fuel are found to be slightly higher than those for ThO_2-3.45% UO_2 as shown in Fig. 4. The values of specific heat capacity in the higher temperature range, of the three compositions of thoria-urania solid solutions taken up in this study, are best fitted into the following polynomial expression by the least squares method and are given below:

For ThO_2-3.45wt% UO_2:

$$C_p / (Jg^{-1}K^{-1}) = 0.27015 + 3.455\times10^{-5}(T/K) - 3.78\times10^{3} / (T/K)^2 \quad (6)$$

For ThO_2-3.45% UO_2 SIMFUEL (28000 MWd/t):

$$C_p \,/\, (\mathrm{Jg^{-1}K^{-1}}) = 0.2354 + 8.169\times10^{-5}(T/\mathrm{K}) - 1.5\times10^{3} \,/\, (T/\mathrm{K})^2 \qquad (7)$$

For ThO_2-3.45% UO_2 SIMFUEL (43000 MWd/t):

$$C_p \,/\, (\mathrm{Jg^{-1}K^{-1}}) = 0.2447 + 7.63\times10^{-5}(T/\mathrm{K}) - 1.4149\times10^{3} \,/\, (T/\mathrm{K})^2 \qquad (8)$$

Thermal diffusivity

Thermal diffusivity and conductivity are important parameter to understand the performance of the fuel pins under irradiation. The changes in thermal conductivity occur during irradiation by the formation of fission-gas bubbles, build-up of fission products, and by the change of oxygen-to-metal ratio (O/M). Hence the knowledge of thermal conductivity is needed to evaluate its thermal performance. The thermal diffusivity measurements on SIMFUELS were carried out using laser flash method. The thermal diffusivity data was verified with standard reference materials (Graphite, SRM-8426) and was found to be within accuracy of ±5% with the reported values. Figures 5 and 6 show the variation of thermal diffusivity with temperature for ThO_2-3.45% UO_2 and UO_2 based simulated fuels, respectively. It is found that thermal diffusivity of SIMFUEL is lower than virgin fuel and decreases with increase in temperature and burn-up.

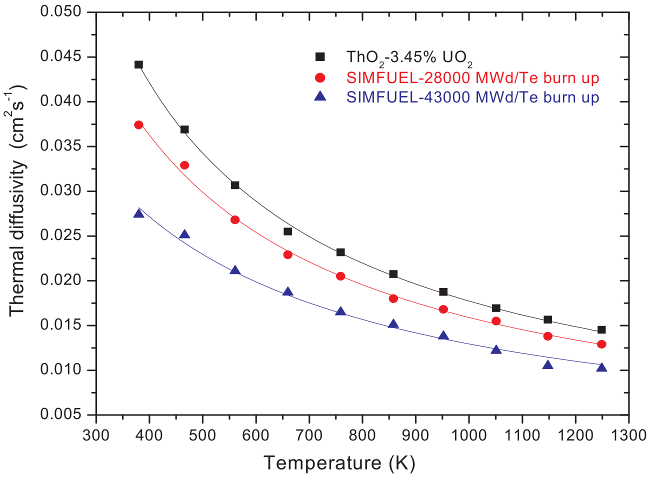

Fig. 5: Thermal diffusivity vs. temperature for ThO_2-3.45%UO_2 and SIMFUEL at 28000 and 43000 MWd/t burn-up.

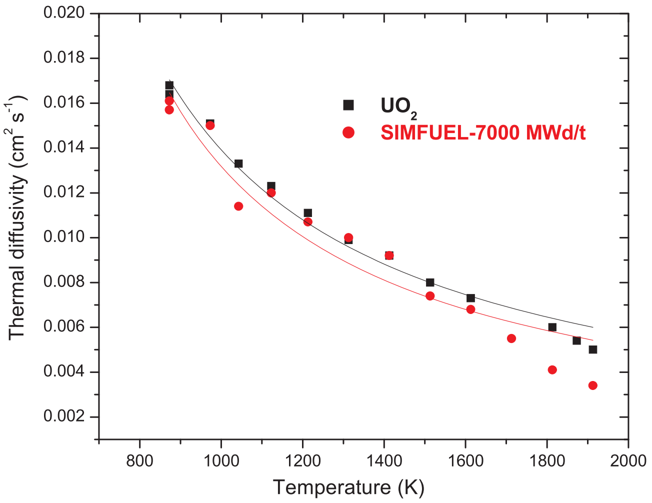

Fig. 6: Thermal diffusivity vs. temperature for UO_2 and SIMFUEL at 7000 MWd/t burn-up

Thermal conductivity

Thermal conductivity of fuels is an important parameter which determines the maximum allowable power rating of the reactor fuel. The thermal conductivities of ThO_2-3.45% UO_2 and SIMFUEL pellets were derived from the measured values of thermal diffusivity by using the relation:

$$\lambda = \alpha \times \rho \times C_p \qquad (9)$$

where, λ is the thermal conductivity, α the thermal diffusivity, ρ the density of the material and C_p its specific heat at constant pressure. The thermal conductivity data could be expressed in the following form applicable for insulators and dielectric solids.

$$k = \frac{1}{A_0 + B_0 \times T} \qquad (10)$$

where, 'A_0' and 'B_0' are constants. The parameter 'A_0' represents the influence of phonon scattering by lattice imperfections and 'B_0' describes the influence of phonon-phonon scattering.

Parameters A_0 and B_0 are 0.02169 and 1.61915×10^{-4} for ThO_2-3.45wt% UO_2 , 0.04048 and 1.5396×10^{-4} for ThO_2-3.45% UO_2 for SIMFUEL (28000 MWd/t) and 0.05861 and 1.80184×10^{-4} For ThO_2-3.45% UO_2 SIMFUEL (43000 MWd/t)

Fig. 7 shows the thermal conductivity of ThO_2-3.45% UO_2 and SIMFUEL as a function of temperature in the temperature range 380 K to 1050 K. Thermal conductivity data of pure ThO_2[8] and UO_2[9] are also shown in the same figure for comparison. The values of ThO_2-3.45% UO_2 and SIMFUELs lie in between that of ThO_2 and UO_2. Fig. 8 shows the variation of thermal conductivity of simulated fuel based on UO_2 with temperature.

It was observed that thermal conductivity of the SIMFUEL is lower than that of virgin fuel and both decreases with increase

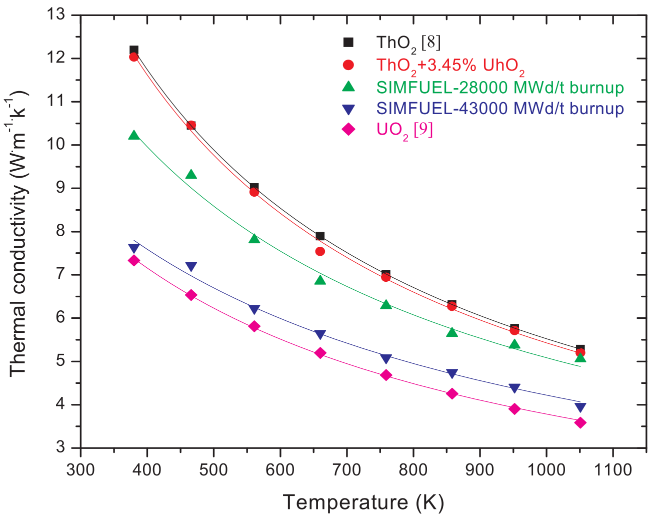

Fig. 7: Thermal conductivity vs. temperature for SIMFUELs. For comparison literature data of ThO_2 and UO_2 are also shown.

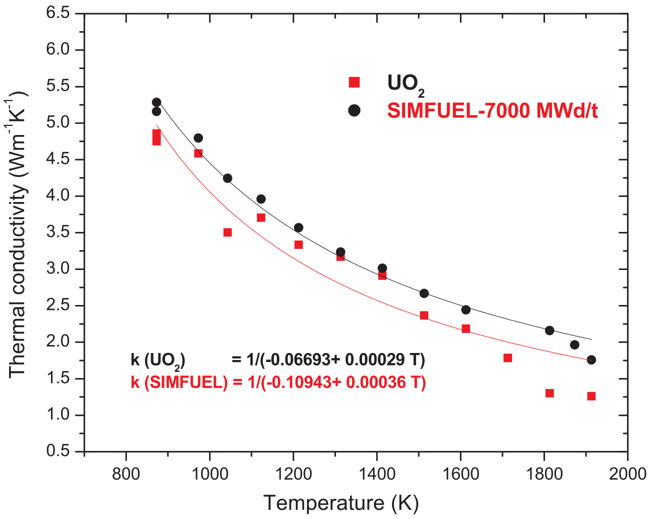

Fig. 8: Thermal conductivity of PHWR simulated fuel vs. temperature

in temperature. The decrease could be attributed to the presence of impurities which acts as scattering centers for inharmonic phonon scattering.

Conclusions

SIMFUEL attempts to replicate the chemical state of the solid fission products generated in irradiated fuel so that detailed experiments can be undertaken, without encountering intense radiation field, to estimate the extent of degradation in the thermo-physical and mechanical properties of the fuel due to the presence of fission products. The following conclusions can be drawn from the present investigation:

- Simulated fuel has a slightly higher thermal expansion as compared to virgin fuel. The higher expansion of SIMFUELs may be related to the higher thermal expansion coefficient of dissolved rare earth oxides and lower melting point of SIMFUEL matrix.
- Specific heat of SIMFUEL was found to be slightly higher than ThO_2-3.45% UO_2.
- Thermal diffusivity and thermal conductivity of simulated fuel decreases with temperature and burn-up. Decrease in thermal conductivity could be attributed to the presence of impurity scattering centers for inharmonic phonon scattering.

Acknowledgement

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Demonstration of Production of Tungsten Metal Powder and its Consolidation into Shapes

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Materials Group

Tungsten is a strategically important metal used as plasma facing component in fusion reactors, radiation shields in cancer therapy machines, ammunition in defence applications, high speed cutting tools etc. The primary resources or minerals occurring in India contain a very low value (0.25-0.5 wt. %) of tungsten. Mineral beneficiation processes involving crushing, grinding, primary and secondary gravity separation, floatation are essential to produce the ore-concentrate suitable for further processing up to the preparation of the intermediate ammonium para-tungstate (APT). APT was further converted to tungsten tri-oxide (WO_3). Hydrogen reduction of WO_3 producing high purity W metal powder was demonstrated in large scale batches. Densification of W powder was further studied using vacuum hot pressing at 1950°C, and high density W metal plates of 5 mm thickness and 60 mm diameter were produced. The products obtained at every stage were systematically characterized using X-Ray diffraction (XRD), scanning electron microscope (SEM), energy dispersive spectroscopy (EDS) and electron backscattered diffraction (EBSD) techniques.

Keywords: Tungsten, Hydrogen reduction, Hot pressing, Radiation shields

Introduction

Tungsten possesses high melting point (3410°C), high density (19.26 g/cc) and superior mechanical strength at high temperature. Tungsten metal is therefore being used as plasma facing components for instance diverter plates of fusion reactor (ITER), and as ammunition materials in military applications. Tungsten based heavy alloys such as W-Ni-Fe and W-Ni-Cu possess distinguished properties combined with their ability to absorb radiation as well as their outstanding mechanical properties and machinability. These are the ideal materials for a wide range of applications, such as in aerospace, the automotive industry, medical engineering and the construction industry. Different shapes of W-Cu alloys are used as gamma radiation shielding in the cancer therapy machines such as Bhabhatron. Tungsten is also used in cutting tools (cemented carbide tools), high speed steels and different grades of steels such as ferritic martensitic steels etc. Tungsten is therefore a strategically important metal for India.

However, all the ore deposits of tungsten present in India are of low grade compared to world resources. In India, the major deposits of tungsten are (i) Degana, comprising of four distinct types, namely, quartz vein, eluvial, phyllite and granite, (ii) Balda, (iii) Khobna-Kuhi-Agargoan, (iv) Burugubanda-Tapaskonda, (v) Scheelite-bearing gold ores of Kolar and Hutti, and (vi) Madurai [1].Total reserves of tungsten in the country are 50.22 M.T. [2]. However, the available grades of ores analyse between 0.04 to 0.5% WO_3 and most of the grade falls below 0.1% WO_3 [1]. The concentrate for commercial use generally needs 60-70% WO_3 requiring an enrichment of WO_3 between 300 to 1600 times. Even after such enrichment by physical beneficiation methods, the end product does not meet the desired specification in terms of purity and grade, because most of the tungsten minerals are found to be intimately mixed with undesirable elements like tin, molybdenum, phosphorus, arsenic, sulphur and other base metals. As regards processing, it has been found more profitable to produce low grade concentrates with higher recovery of tungsten from the lean ores. When such low grade concentrate is converted to an intermediate product such as ammonium paratungstate (APT), better plant economy results [1]. Therefore, an appropriate technology involving conversion of low grade concentrate to APT by aqueous processing is being developed to suit the Indian conditions, where, by and large deposits are of low grade in nature. In the present paper, a techno-economic scheme for processing of low grade tungsten ores as well as secondary resources is addressed. Hydrogen reduction of WO_3 has been demonstrated in kg scale batches. Pure tungsten metal powder produced by hydrogen reduction was further characterized using XRD and SEM. Finally, the fabrication of tungsten shapes was done using vacuum hot pressing, and the consolidated product was characterized using various techniques.

Processing of low grade wolframite concentrate

In India, tungsten minerals-wolframite and scheelite occur in many places but in very low concentration. One of the largest deposits of wolframite, located at Degana, Nagaur district of Rajasthan. Wolframite is the main tungsten mineral associated with other minerals like quartz, mica, feldspar, sulfide and topaz. Physical beneficiation treatment comprises crushing, grinding, primary and secondary gravity separation, floatation yields two types of concentrates-one assaying 7-30% and the other about 65% WO_3 [1]. The concentrate with higher values of WO_3 is amenable to further economical recovery of tungsten. The flow sheet for low-grade wolframite concentrate was developed earlier at BARC [3] with the objective of recovery of tungsten and other valuable associates.

Processing of secondary resources

In the manufacture of cemented carbide tools, besides main ingredients WC and the binder Co, various other carbides such as NbC, TaC and TiC etc. are incorporated, in varying proportions either individually or in different combination to attain specific combination of metallurgical properties. WC tools scrap is another indigenous source of tungsten. Recycling of cemented carbide tools scrap aimed at recovery of W and Co metals, generates residue sludge containing substantial quantities of W, Co, Nb and Ta. WC scrap and corresponding sludge, generated on recycling of scrap for recovery of W and Co therefore differ in chemistry from batch to batch. Flow sheets for processing of different types of carbide sludge were developed at BARC [4].

Recovery of pure tungsten tri-oxide (WO_3)

Once the tungsten values are brought into solution, it is then subjected to purification. Purification is accomplished by first, converting the entire W into hexavalent state using an oxidant such as HNO_3/$NaNO_3$ and then adjusting the pH of the solution to alkaline range of 10.5-11 in order to cause precipitation of silica, alumina and iron. The clarified solution after filtration is then purified by three different routes namely (1) precipitation as synthetic scheelite, (2) recrystallisation as ammonium paratungstate (APT) and (3) carbon adsorption and desorption. Finally, WO_3 is obtained by calcination of APT. High purity WO_3 required for conversion to W metal powder is produced from APT.

Preparation of W by hydrogen reduction of WO_3 in kg scale

Tungsten metal powder was produced by hydrogen reduction of tungsten tri-oxide at 900-1000°C. Hydrogen reduction of WO_3 to metallic tungsten takes place in number of steps:

$$WO_3 \rightarrow WO_{2.9} \rightarrow WO_{2.72} \rightarrow WO_2 \rightarrow W \qquad (1)$$

The overall reaction is

$$WO_3\,(s) + 3H_2\,(g) \rightarrow W\,(s) + 3H_2O\,(g) \qquad (2)$$

Thermogravimetic (TG) studies were conducted for hydrogen reduction of WO_3 is presented in Fig. 1. Thermogravimetic analysis (TGA) plot shown in Fig. 1 clearly indicates the stepwise reduction of WO_3 to pure W.

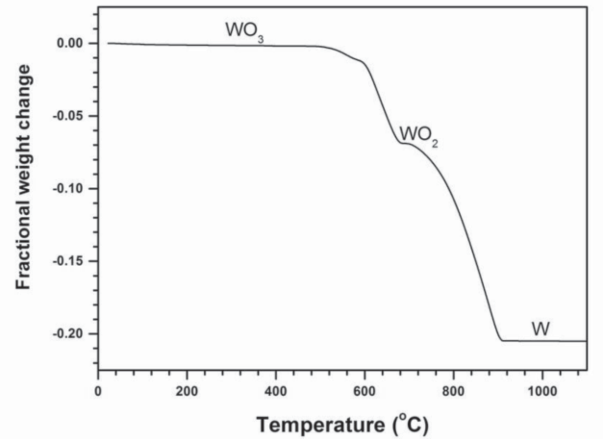

Fig. 1: TG plot for hydrogen reduction of tungsten tri-oxide

The hydrogen reduction reactions are reversible in nature and their course is determined by the equilibrium constants:

$$Kp = \frac{P_{H2O}}{PH_2} \qquad (3)$$

Where, P_{H2O} is the equilibrium partial pressure of water vapour and P_{H2} the equilibrium partial pressure of hydrogen.

The stability of oxides and tungsten was predicted with reduction temperature and moisture content of the flowing gas [5].

Preparation of pure W from WO_3 by hydrogen reduction was carried out using a static bed in tubular type resistance heating furnaces. Initially, the hydrogen reduction was carried out in 50 g scale, and the parameters of the reduction process were optimized. Subsequently, a larger scale reduction facility was designed and fabricated in-house. The parameters of hydrogen reduction such as temperature, hydrogen flow rate, time, powder bed thickness are optimised systematically to achieve 100% yield of hydrogen reduction of WO_3. Fig. 2 represents the pure W metal powder produced after hydrogen reduction of 1 kg of WO_3. The as-reduced powder was further characterized using SEM and XRD.

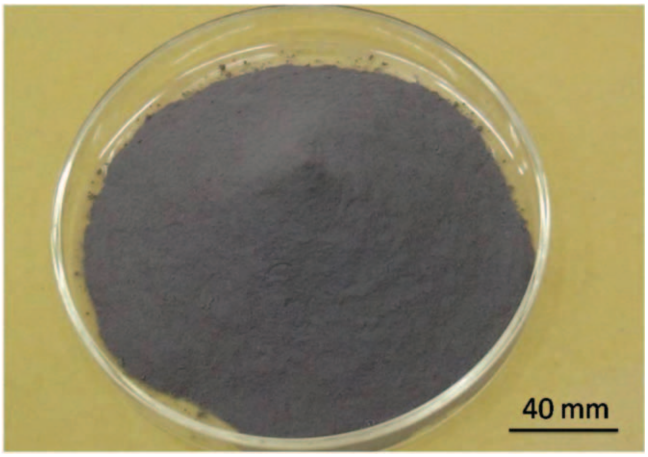

Fig. 2: Tungsten metal powder produced by hydrogen reduction of 1 kg of WO_3

The SEM image (Fig. 3) of the W metal powder was captured. The average particle size of individual W powder varied between 5 to 10 μm.

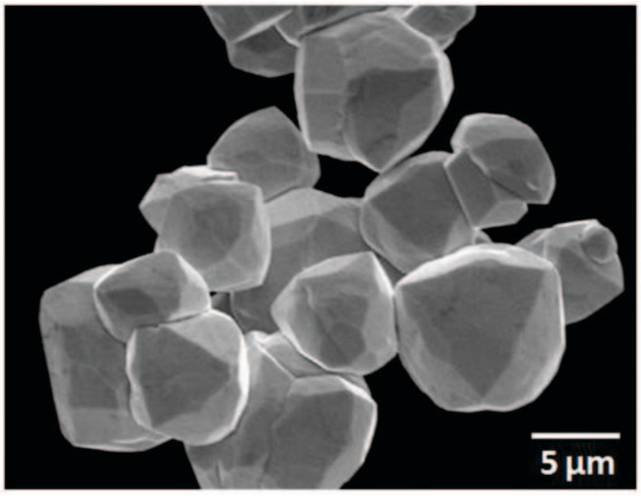

Fig. 3: SEM image showing the individual W powder produced by hydrogen reduction

XRD analysis (Fig. 4) confirmed the formation of only W phase in the product powder.

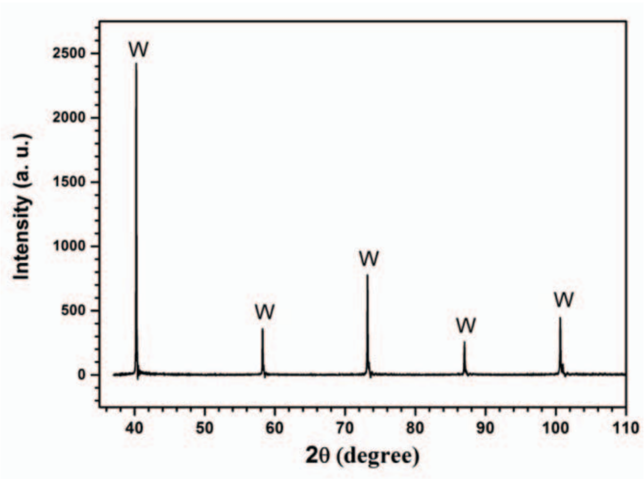

Fig. 4: XRD plots for hydrogen reduced WO$_3$ indicating the formation of W phase

Consolidation of W powder into shapes

Due to higher melting temperature, the consolidation of tungsten into high density products is a challenging task. In the current investigation, the vacuum hot pressing technique was adopted to study the densification behaviour of pure W. The powder prepared by hydrogen reduction was filled in a graphite die and hot pressing was done using graphite plunger at 1950°C for 2 h by applying the progressive load up to 50 ton. The density of the hot pressed W was found to be about 18.2 g/cc. Applying optimized processing parameters, the W shapes of 60mm diameter and 5 mm thickness (Fig. 5a) were produced by hot pressing. Fig. 5(b) shows a 40 mm × 40 mm × 4 mm plate prepared from hot-pressed plate after EDM cutting and subsequent machining.

The as-consolidated tungsten was characterized with respect to hardness measurement, and microstructural analysis using SEM and EBSD. The average Vickers hardness of the hot-pressed W was found to be 305 HV at 500 g load. For EBSD studies, the samples were cut from the hot-pressed plates using EDM and polished up to 0.5 μm diamond finish followed by electrolytic polishing using 2% NaOH aqueous solution. Figs. 6 and 7 represents the EBSD maps obtained from the EP surface of the samples taken respectively from the

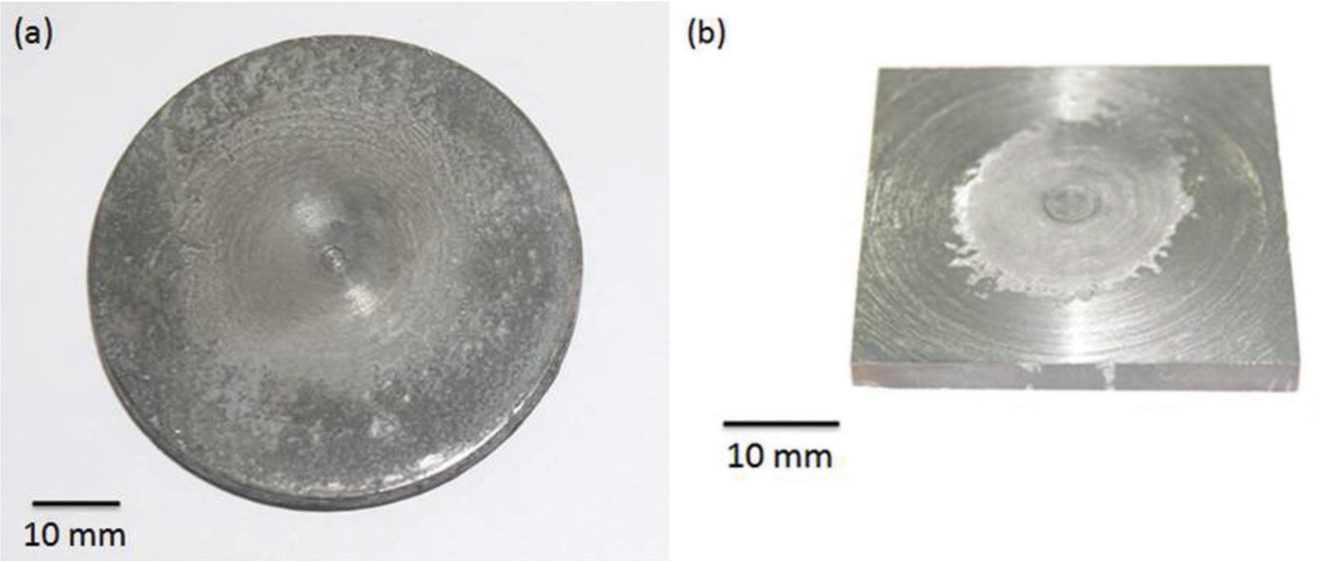

Fig. 5: Tungsten plates; (a) as hot-pressed, and (b) machined after EDM cutting

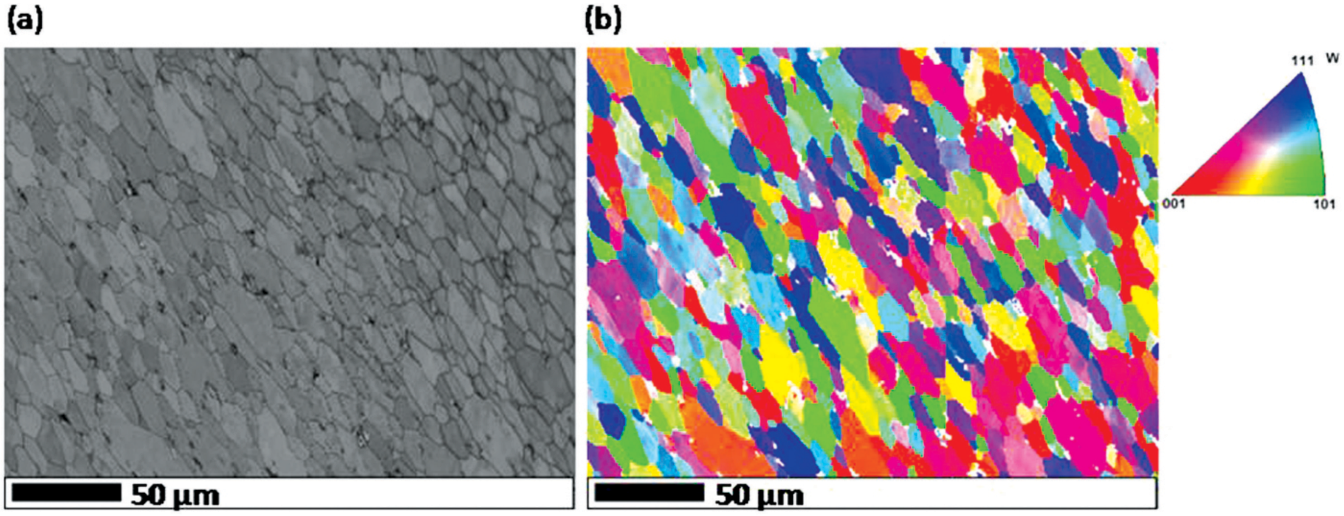

Fig. 6: EBSD maps showing the microstructure of the surface perpendicular to the loading direction of the hot pressed (at 1950°C) W; (a) band contrast image and (b) inverse pole figure map (inset-legends of IPF)

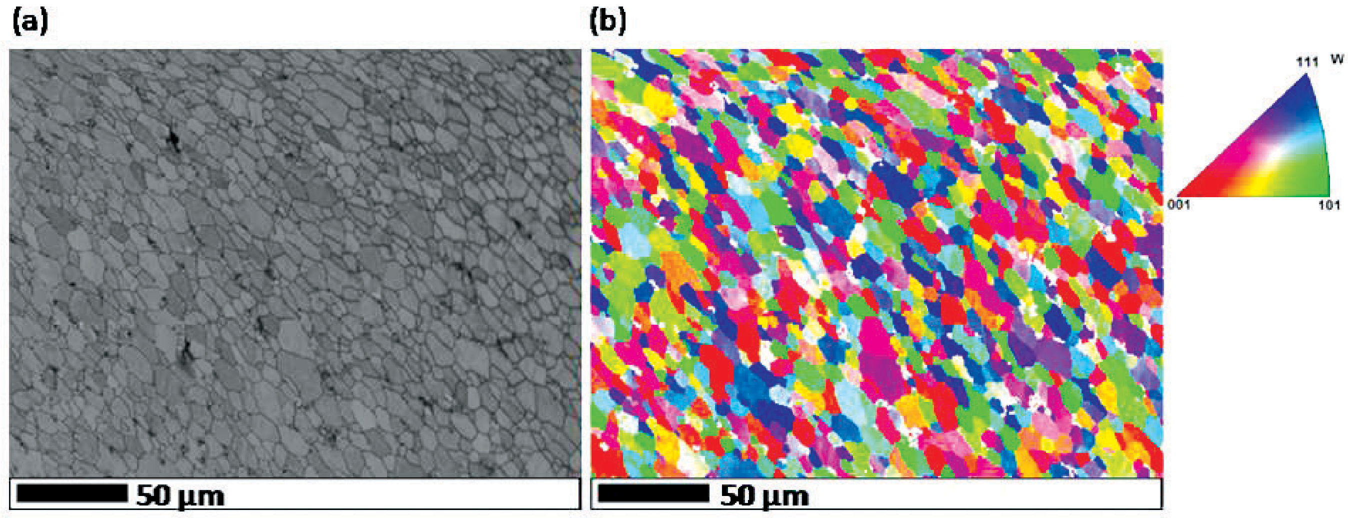

Fig. 7: EBSD maps showing the microstructure of the surface parallel to the loading direction of the hot pressed (at 1950°C) W; (a) band contrast image and (b) inverse pole figure map (inset-legends of IPF)

directions perpendicular and parallel to the applied load during hot pressing. Polycrystalline tungsten has been formed, and the average grain size is about 10-15 µm (Fig. 6) in perpendicular direction and 6-8 µm (Fig. 7) in the direction of parallel to the applied load. The microstructure of the hot pressed W consisted of recrystallized grains and the orientations of the grains are found to be random (Figs. 6b and 7b).

Summary

Hydrogen reduction of tungsten tri-oxide in kilogram scale batches was successfully demonstrated. Pure tungsten metal powder of particle size about 5-10 µm was produced. Densification behaviour of tungsten powder was studied, and high density tungsten metal plates of 5mm thickness were successfully fabricated by vacuum hot pressing at 1950°C. Further work will be continued to produce tungsten tri-oxide from low grade scheelite-bearing gold ores of Hutti and Kolar. This technology is now available from BARC for large scale production of W powder.

Fabrication of different shapes of W based alloys (W-Cu and W-Ni-Fe) required for Bhabhatron is currently being taken up at BARC.

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A Report of the 32nd Training Course on "Basic Radiological Safety and Regulatory Measures for Nuclear Facilities, organised by BARC Safety Council Secretariat

BARC Safety Council Secretariat (BSCS) conducts a series of short-term training courses on "Basic Radiological Safety and Regulatory Measures for Nuclear Facilities" for the staff of BARC, to impart general awareness on radiological safety, industrial safety and regulatory requirements. The 32nd Training Course was conducted at HPD Auditorium, CT&CRS, Anushaktinagar during September 26-29, 2016.

In the inauguration of the training programme on September 26, 2016, Shri K.Jayarajan, Head, BSCS welcomed the dignitaries and participants. Shri Y.K.Taly, Chairman, BARC Safety Council introduced the syllabus and its relevance. Chief Guest of the function, Shri R.J.Patel, Former Director, RD&DG and RRF emphasised on the safety aspects and the necessity of adherence to the regulatory codes, guides and procedures. The Guest of Honour Shri A.B.Mukherjee, AD, RPG and key note speaker Shri S. Bhattacharya, AD, RG talked about the importance of training in implementation of ALARA (As Low As Reasonably Achievable) programme in research and power reactors. The Course Director, Shri R.P.Hans, BSCS proposed the vote of thanks.

Participants of the training programme, along with Shri S.Bhattacharya; Shri Y.K.Taly; Shri R.P. Hans; Shri R.J.Patel; Shri A.B.Mukherjee; and Shri K.Jayarajan and invitees.

Forty participants from Reactor Group(RG); Reactor Project Group(RPG); Reactor Design & Development Group (RD&DG); Design, Manufacture and Automation Group (DM&AG) and Accelerator Control Division (ACnD) attended the course. The course was carried out through classroom lectures and video display. Site visits to Plutonium Plant (PP) and fire demonstration by fire officer were also arranged for the participants. Faculty members include, experts from Radiation Safety Systems Division, Radiological Physics & Advisory Division, Medical Division, Industrial Hygiene & Safety Section, Fire Services Section and Chemical Engineering Division, in addition to the officers from BSCS. The training programme covered radiation protection programme in reactor operation; dosimetry and dose control; radiation detection and measurement; environmental radiation monitoring around nuclear facilities; occupational health care and management of internal contamination; preparedness and response for nuclear and radiological emergencies; biological effects of radiation; safety culture and regulatory framework for BARC. A written test was conducted at the end of the course.

Certificates were distributed to all participants during valedictory function held on September 29, 2016. The function was graced by Dr.D.N. Badodkar, AD, DM&AG; Shri Y.K.Taly, Chairman, BSC; Shri A. Rama Rao, AD, RD&DG; Shri P.M.Gandhi, Head, FRD; Shri K. Jayarajan, Head, BSCS and Shri R.P.Hans. Feedback on the training programme was taken from the participants for improving the future training programmes. The training programme was well appreciated by all the participants.

Theme Meeting on Operational Experience of Helium Liquefiers, 19th October 2016 at TSH, BARC

Research equipment operating at extremely low temperatures are quite common these days. Dr. S C Gadkari, Head TPD, pointed out in his opening address that scientific institutes find it advantageous to operate helium liquefiers onsite where many equipment need liquid helium or cooling capacities beyond few watts at T 4.2 K are required. Dr. N.K. Sahoo, Associate Director, Physics Group gave an overview of applications of liquid Helium in his presidential address. Mr. S. K Gupta, President, Indian Vacuum Society and Head TTCD described past association of Indian Vacuum Society in organizing meetings on cryogenics. Dr V C Sahni, Former Director, Raja Ramanna Centre for Advanced Technology, Indore and Director, Physics Group, BARC in his keynote address highlighted the association of Physics Group with different types and capacities of liquefiers since early eighties. He expounded on the importance of current projects critically dependent on Liquid Helium.

Technical Physics Division (TPD), BARC has been operating helium liquefiers for two decades and Cryo- Technology Division (CrTD), BARC has recently succeeded in making an indigenous liquefier (see the brief communication in this issue). Liquefiers are complicated machines needing skill and experience which are specific to its operation. The deployment and operation of Helium Liquefiers varies with institutes according to specific applications and site specific requirements. Therefore it is important to share techniques and valuable operating experience among community engaged in this activity. With this aim, TPD organized the theme meeting on operational experience of helium liquefiers where participants from many institutes such as IIT Bombay, Tata Institute of Fundamental Research, Mumbai, Inter University Accelerator Centre (IUAC), New Delhi and UGC-DAE CSR, Indore in addition to TPD and CrTD from BARC discussed their requirements, type and capacities of liquefiers and shared acquired wisdom for successful operation.

Prof. C V Tomy from IIT Mumbai has discussed how swelling of the fiber piston due to moisture absorption caused serious interruption of their reciprocating expander based liquefier and emphasized the periodic examination and maintenance of the machine. IUAC uses the machine in liquefier cum refrigerator mode with major application in the operation of Nb-superconducting cavities for heavy ion accelerator. These cavities use liquid helium for cool down and refrigeration (closed loop) mode during operation. Sh. Anup Choudhury presented the requirement of specific cool-down rate to minimize impurity gas absorption by Nb. Mr. M. R. Singh, TPD, presented general safety measures for low temperature laboratories, the regulatory processes for operation of equipment needing liquid helium and special safety measures required for large volume storage of cryogens.

In the afternoon session Mr. M.P. Saravanan discussed the experience of UGC-DAE CSR, Indore with numerous nitrogen and helium liquefiers of different capacities. Mr. A.A. Shinde talked on Helium refrigerator being used for superconducting lead cavities for ion accelerator at TIFR. He told about the onsite upgradation of refrigerator capacity and the intricacies of simultaneous control of valves on the feed and return lines of cryogen. Mr. Mukesh Goyal, CrTD, BARC gave a historical perspective of the success story of the indigenous efforts in developing the turbo expanders, liquefier and external purifier. This led to discussion about the type, sizes, speed, capacities and variation in deployment of turbo-expanders in liquefier process cycle.

The meeting was well attended and appreciated by all including users of cryogen, particularly the discussion on safety aspects. The organizers thanked BRNS-DAE for providing financial support for theme meeting and also appreciated IVS for lending its name to the occasion.

NPCIL takes home BARC-developed water filter

A Memorandum of Understanding (MoU) was inked with the Nuclear Power Corporation of India Limited (NPCIL) on 26th July 2016 for distribution of BARC-developed 'off-line domestic water filters with silver nano ultra filtration' technology at NPCIL's projects/stations for its Corporate Social Responsibility (CSR) programme.

DAE Technologies Display and Dissemination Facility (DTDDF)

Under the 12th Five Year Plan BARC setting up DAE Technologies Display and Dissemination Facility (DTDDF) centers for showcasing the department's indigenous technologies. The project aims to promote and enhance scientific temper among village communities by exhibiting products useful to them directly and to conduct various training programmes to rural households living in the proximity of DAE facilities.

BARC inks Memoranda of Understanding (MoU) with the following institutes for setting up DTDDF centres

- School of Agricultural Sciences and Rural Development (SASRD) Medziphema campus, Nagaland, on June 22, 2016.
- Raipur Institute of Technology, Raipur, Chhattisgarh on June 24, 2016.
- SJC Institute of Technology, Chikkaballapura, Karnataka, on June 28, 2016.
- Anubose Institute of Technology (ABIT), Telangana, on July 7, 2016.
- SLBS Engineering College, Jodhpur, Rajasthan, on July 13, 2016.

Highlights of 12th ISEAC-DM-2016

The Twelfth ISEAC Discussion Meet on Electrochemistry and its Applications (12th ISEAC-DM-2016) was conducted at the Grand Banquet Hall of the Acres Club, Chembur, Mumbai, India during December 7-8, 2016. About 50 delegates from different parts of India, including 9 invited speakers from overseas and 4 invited speakers from India, participated in the Discussion Meet. The event was supported and partially sponsored by Board of Research in Nuclear Sciences (BRNS) of the Department of Atomic Energy (DAE), International Society of Electrochemistry (ISE) and Bioelectrochemical Society (BES). The scientific program of the Discussion Meet comprised of invited talks, posters and oral presentations by research scholars and other researchers. A special session to clarify some fundamental concepts in electrochemistry was also organized for the students, who are pursuing PhD degrees.

The Discussion Meet was inaugurated by Prof. B. S. Tomar, Director, Radiochemistry and Isotope Group, BARC. He highlighted the role of electrochemistry in nuclear material accounting for determination of uranium and plutonium in various matrices and about the scope of studies on the speciation of various actinides by electrochemical techniques. He also released the bound volume of 12th ISEAC-DM-2016 containing extended abstracts of all the invited talks and contributory papers. Prof. Pradeep K. Pujari, Head, Radiochemistry Division, BARC was a distinguished guest at the inaugural function. Prof. Suresh K. Aggarwal, President ISEAC and Chairman of the Organising Committee of 12th ISEAC-DM-2016 welcomed all the delegates. He summarized the growth of ISEAC and stressed the multi-disciplinary character of electrochemistry. He encouraged the Indian delegates to exploit the high sensitivity of Differential Electrochemical Mass Spectrometry (DEMS) to unravel the mechanism of various electrochemical reactions. Prof. Aggarwal also appealed to the Indian delegates to join ISE as Annual Members so that ISEAC could play an important role in the ISE activities. Dr. Saurav K. Guin, Secretary ISEAC from Fuel Chemistry Division, BARC presented a vote of thanks.

The 13 invited talks were presented in five technical sessions. These included talks by Prof. Fritz Scholz, Prof. Rudolf Holze and Dr. Jeyabharathi Chinnaya from Germany; Prof. Bernhard Gollas from Austria; Dr. Dev Chidambaram and Dr. (Ms) Vidhya Chakrapani from USA; Dr. (Ms.) Mega Kar from Australia; Dr. Giovanni Landi from Italy; Dr. (Ms.) Bhavana Deore from NRC, Canada; and Dr. Subir Kumar Ghoash (BARC), Dr. Ashis K. Satapati (BARC), Dr. Bhaskar R. Sathe (Aurangabad), and Dr. Nagaraj P. Shetti (Hubali) from within India. The oral presentations were made by research scholars and the posters were displayed throughout the entire duration of the event. The participants evinced a keen interest in the Un-conference Session. There was also an exhibition stall arranged by M/s Ranga Techno Impex Pvt. Ltd. (www.rangasgroup.com) from Chennai, and another stall by ISEAC displaying the hard bound Volumes of the previous ISEAC events.

The Valedictory Session was conducted by Prof. S.K. Aggarwal, and Dr. Saurav K. Guin (Secretary), Mr. Arvind Ambolikar (Treasurer). He appealed to the delegates to act as ambassadors of ISEAC and requested them to motivate their colleagues interested in electrochemistry, to join ISEAC as well as ISE as members. He also appealed to all the ISEAC members to regularly visit the ISEAC website to know the latest about the activities of ISEAC.

Technology Transfers

During April-July 2016, the Bhabha Atomic Research Centre (BARC) has transferred ten technologies to various industries and also established Technology Display and Dissemination Facilities (DTDDF) across five states in collaboration with various technical and educational institutions in the country. Full details are provided below:

“Fluoride Detection Kit for Ground Water (FDK)” Technology was transferred to M/s MAX Chemicals (India), Indore, (Madhya Pradesh) on April 1st, 2016

This technology was developed by BARC's National Centre for Compositional Characterization of Materials (CCCM), Hyderabad. This field-kit has been devised for a quick and easy estimation of fluoride levels in groundwater for establishing its suitability for drinking needs. The testing procedure is quite simple. Just add a specified amount of fluoride detection (FDK) reagent to water sample and identify the color developed. The color develops instantaneously and the distinction can be made with the naked eye. Water sample can immediately be categorized as safe, marginal or unsafe for drinking from fluoride point of view. Generally, this kit can be an excellent tool for individual and community level identification of safe groundwater sources. Importantly, the cost incurred per analysis works out to be nominal.

“Handheld 12-Channel Tele ECG Instrument” was transferred to M/s Star Automation, Puducherry on April 27th, 2016

The Electronics Division, BARC, has developed a Handheld 12-Channel Tele-ECG Instrument that operates with the help of a mobile phone and the available Bluetooth feature. The instrument records all the 12-leads of ECG simultaneously and displays the same on the mobile screen. After complete recording, the report is generated in the form of an image, which can be transferred to the lab technician's mobile through Multimedia Messaging Service (MMS) or any other file sharing apps. The device is ideally suited for rural healthcare. Across hospitals in metros, this machine can be operated using a laptop/desktop and the report can be shared on Local Area Network (LAN). The final ECG report in standard graphical format can be generated on a blank A4 size paper.

“High Salt Rejecting Composite Polyamide Reverse Osmosis (RO) Membrane For Desalination” and “DIP-N-DRINK Membrane Pouch” technologies were transferred to M/s Permionics Pvt. Ltd., Vadodara, (Gujarat) on June 8th, 2016

“High Salt Rejecting Composite Polyamide Reverse Osmosis (RO) Membrane For Desalination” Technology was developed by Membrane Development Section, Chemical Engineering Group (ChEG), BARC. Reverse osmosis (RO) is an efficient and an increasingly common solution for providing safe drinking water from saline water sources. The thin film-based composite polyamide membranes with high salt rejection characteristics are capable of removing more than 97% salinity from saline water besides removing most of the dissolved contaminants with high level of reproducibility from highly saline water with levels up to 35000 ppm salinity (seen in sea water). The Thin-Film Composite (TFC) membranes in spiral module can be applied for desalination of highly saline water and sea water (in two stages), water reuse (in pharma /biotech, waste water, electrocoating, food and beverage industries) and radioactive waste treatment. The membrane prepared in this process has potential bigger industrial applications

“DIP-N-DRINK Membrane Pouch” technology was developed by Membrane Development Section, ChEG, BARC. The Membrane Pouch is based on Osmosis process to get sterile drinkable solution from biologically contaminated water especially during disaster conditions like flood, cyclones, tsunami and earthquakes. It is also useful for concentration of high-value-low-volume product in food, pharmaceutical, chemical industries. It can also be used in Oral Rehydration Therapy in villages and remote locations.

“kVp Meter and Exposure Timer” Technology was transferred to M/s General medical Equipments, Noida, UP on June 29th, 2016

The “kVp Meter & Exposure Timer” provides a convenient and fast method of measuring the effective kilo Peak Voltage (kVp) and exposure time of Diagnostic X-ray machines. It follows a non-invasive method, wherein the ratio of response of X-ray detectors located under filters of different thickness is correlated for the measurement of kVp.

The instrument has several features, including automatic reset before new measurement, distance independent operation between Detector unit and X-ray target, measurement of kVp and exposure time in a single exposure and user friendly 16 digits and two line alphanumeric Liquid Crystal (LC) display. The instrument is light weight and is calibrated in standard X-ray machines, which are in turn calibrated with a standard potential divider method.

"Ambient prolonged storable meal for natural calamities and other targets" Technology was transferred to M/s. Cheftalk Food and Hospitality Services Pvt. Ltd. Mumbai on June 30th, 2016.

The BARC-developed Ambient prolonged storable meal for natural calamities and other targets deals with the development and optimization of a product called stuffed baked food (SBF). It was conceptualized on an ethnic product called 'Litti' or 'Bati', which is predominantly used as a regular food preparation in north India. The developed product is ambient storable up to 8 months and can be used to meet food needs of victims of natural calamities. It can also be used by defense personnel, for school lunch programme, and by space scientists. The extended shelf life of this product under ambient conditions is achieved by employing vacuum packing and gamma irradiation.

Radiation processing of food is a well-known technology based on application of physical energy where no chemical preservatives are involved and does not increase the temperature of the food. It has been approved by various international and national organizations to ensure 'Food Security & Safety'.

"On-Line Domestic Water Purifier Based on Ultrafiltration Polysulfone Membrane" technology was transferred to M/s. R. D. Aquatech, Mysuru (Karnataka) on June 30th, 2016.

The On-line domestic water purifier" technology has been developed by Desalination Division, BARC. The device is based on polysulfone ultrafiltration membrane coated on a unique cylindrical configuration. The device on connecting to domestic water source purifies running water from micro organisms, color, odour, suspended solids and organics. It is very effective in removing bacteria to the extent of > 99.99% (4 log scale) and also removes complete turbidity to produce crystal clear water. This device does not need electricity or addition of any chemicals. It is almost maintenance-free except for occasional cleaning of suspended solids which deposit on membrane surface and this does not take more than few minutes. It produces about 40 liters of pure water per day at about 5 psig head pressure and works in the range of 5 psig to 35 psig head pressure. The device completely filters out dead bacteria from the final filtered water.

"Solar Energy Driven Portable Domestic Brackish Water Reverse Osmosis (BWRO)" technology was transferred to M/s Surya Water Treatment Systems, Sangli (Maharashtra), on July 12th 2016.

The "Solar Energy Driven Portable Domestic Brackish Water Reverse Osmosis (BWRO)" technology has been developed by Desalination Division, BARC.

This technology is based on solar photovoltaic (PV) system. It has an inbuilt capacity of 10 litres per hour (lph) and can desalinate contaminated water having salinity ranging from 1000-3000 ppm (mg/lit) and provide drinking water of salinity in the range of 50-300 ppm. The processed water is free from toxic elements, pathogens & turbidity. It is best suited for remote areas where electricity is not available and in locations where there is no stable voltage supply. Further, it can also be useful in urban areas. As it is portable, it will be of great help for people stationed in desert areas, especially in case of defense personnel. Importantly, it doesn't require external source of power and is an off-grid standalone system.

"Production of Turmeric-based Nutraceutical – Turbovita" Technology was transferred to M/s Veena Industries, Nagpur on 28th July, 2016

The product was developed by Radiation & Photochemistry Division (RPCD), BARC, under a Technology Incubation understanding. After successful completion of incubation, the technology was transferred to Incubatee M/s Veena Industries, Nagpur.

Globally, there is a huge demand for turmeric/curcumin based supplements and nutritional products. Presently, these are not widely available in India. With growing health consciousness among the people, this nutraceutical can provide the beneficial effect of curcumin for patients undergoing treatment for chronic diseases like diabetes and arthritis. It also can reduce the physiological_troubles associated with long-term exercise.

Central Complex at BARC

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