INDIAN NUCLEAR SOCIETY NEWS

INDIAN NUCLEAR SOCIETY
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Indian Nuclear Society's
International Conference

INSIC-2023

Nuclear For Clean Energy Transition

December 12-15, 2023
DAE Convention Centre, Anushaktinagar Mumbai - 400094, India

TECHNOLOGIES FOR
NEW INDIA@75

QUARTERLY BULLETIN OF
INDIAN NUCLEAR SOCIETY

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FROM THE EDITOR'S DESK

My Dear Fellow INS-Members,

Greetings. The INS International Conference, INSIC-2023 is just round the corner, with the theme, 'Nuclear for Clean Energy Transition'. More details of the Conference to be held from December 12 -15, at the DAE Convention Centre in Anushaktinagar, Mumbai is in this issue immediately after this Editorial.

The INSIC-2023 Team is working very hard to make this Conference a scientific, technical and an intellectual stimulus to be aware of the consequences of unbridled global warming and how Nuclear Energy is essential to thwart the Global Warming nemesis.

Nuclear Reactors to produce clean and sustainable energy is a must. Building and commissioning of Nuclear Reactors in their various avatars, including the small modular reactors (SMR) are required asap-mode. SMR was the theme of the previous issue of INS News.

This issue of INS News has articles on the next generation energy systems, manufacture of steam generation tubes that are used in nuclear reactors using special alloys, and a spin-off of nuclear research, viz., electron beam accelerators for use in industry and for societal benefit. These articles are comprehensive and written by very senior scientists in the field.

A one-day workshop/symposium INS Public Outreach Programme on Nuclear Energy for Heath, Environment and Development (INS-NEHED23) was held in collaboration with BHU-IIT, Varanasi on October 14, 2023, covering a wide range of nuclear-related subjects. It was well attended. Highlights of the programme are included in this issue.

Coming back to the context of the INSIC-2023, it will be very appropriate to bring to your notice that the IAEA will release three booklets that will coincide with the COP28 at Dubai. They are free to download from the link given and will be of interest to all.

1. Nuclear Energy and Climate Change: Questions and Answers on Progress, Challenges and Opportunities https://iaea.us6.list-manage.com/track/click?u=958dfcbed8f359a6db0bb9c87&id=a2541dea50&e=da5b91eacf
2. Nuclear Energy in Climate Resilient Power Systems https://iaea.us6.list-manage.com/track/click?u=958dfcbed8f359a6db0bb9c87&id=d3228ea687&e=da5b91eacf
3. Nuclear Energy in Mitigation Pathways to Net Zero https://iaea.us6.list-manage.com/track/click?u=958dfcbed8f359a6db0bb9c87&id=d3228ea687&e=da5b91eacf

Hope you have all registered for the INSIC-2023 and will come to make the Conference a grand success.

M.G.R. Rajan

ABOUT INSIC-2023 CONFERENCE

Nuclear energy is an inevitable choice to achieve deep decarbonisation,since it is the largest source of base load power with minimum carbon footprint. This energy transition is crit al t to mi ate the climate change and to limit the rise in the global average temperature to 1.5C^0. Sustainable scenario for year 2050 envisages three-to four-fold increase in nuclear power generationwhich along with other clean energy sources can achieve net zero emission target leading to a sustainable energy future.

INSIC-2023 aims to bring together global experts from industry, R&D organisations and a ademia to deliberate on the dirrectionsor decarbonisasation with nuclear as an essential oundaation of this transition.

The conference will mainly consist of invited talks by experts and industry leaders, contributory posters, panel discussions and industrial exhibition.

ABOUT INDIAN NUCLEAR SOCIETY

Indian Nuclear Society (INS) is a registered society of nuclear professionals and boasts membership of over 5000 life members and 70 corporate members. It was established in 1988 with an aim to promote and efffectely y utilise Nuclear Science and Technologies for the benefit of society while maintaining international s fety standards.

Since 1989, INS has been organizing its Annual Conferences on the topics of current interest in nuclear science and technology. INS holds seminars, webinars, and poster competition designed for outreach programs. It brings out a quarterly newsletter highlighting the research and development in Nuclear Science & Technology in India.

INS website is enriched with information about various topics of nuclear science and engineering in the form of recorded lectures series in simple language and presentationmade especially for common man desirous to know about nuclear. INS has also conducted joint programs with international nuclear societies in the past.

NUCLEAR POWER CORPORATION OF INDIA LIMITED (NPCIL)

Nuclear Power Corporation of India Limited (NPCIL) is a Public Sector Enterprise under the administrative control of the Department of Atomic Energy (DAE), Government of India.

NPCIL is responsible for design, construction, commissioning and operation of nu clear power reactors. NPCIL is presently operating 23 commercial nuclear power reactors with an installed capacity of 7480 MW. The reactor fleet comprises two Boiling Water Reactors (BWRs), 19 Pressurised Heavy Water Reactors (PHWRs) including one 100 MW PHWR at Rajasthan (owned by DAE, Government of India) and two VVER reactors of 1000 MW capacity each. Kakrapar Atomic Power Project (KAPP) Unit 3, the first indigenous 700 MWe PHWR of the country, commenced commercial operation on June 30, 2023.

NPCIL is implementing a large expansion program to address the energy security of the country & the climate change goals. NPCIL has 9 more reactors under co nstruction with a total capacity of 7500 MW. Pre-project activities at new sites, which were accorded 'in principle' approval by the Government of India, have been initiated to enable early launch of projects at these sites. Being a responsible corporate body, NPCIL conducts several activities benefitting the society under its Corporate Social Responsibility (CSR) and implements several projects related to Sustainable Development.

NPCIL - FUELLING A POWERFUL FUTURE

At COP-26, India announced to the world
5 commitments or 'amrit tatva' that India would meet to tackle climate change-related issues.

Commitment 1: By 2030, India will increase its non-fossil capacity to 500 GW.

Commitment 2: By 2030, India will fulfil 50 per cent of its energy requirements with renewable energy.

Commitment 3: India will reduce one billion tonne of the total projected carbon emission between now and 2030.

Commitment 4: By 2030, India will reduce its economy's carbon intensity to less than 45%.

Commitment 5: India will achieve the target of net zero emissions by 2070.

TOPICS OF THE CONFERENCE

- Road to net zero emission and the **energy mix** for the future
- Growth of Generati n III and III+ nuclear reactors - accelerated **growth and cost** reduction
- **Advanced nuclear reactors: SMR**, HTGCR, MSBR etc
- **Life extension** and management of aging nuclear reactors
- **Nuclear hydrogen**
- **Emerging** technologies in support of nuclear power deployment, security and safety
- **Regulatory** framework and challenges for emerging nuclear technologies
- **Industry** preparedness and particip ation
- **Policies and public** acceptance of nuclear energy

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Development, Manufacturing, Inspection, Testing and supply of Alloy 800 (UNS N08800) Steam Generator Tubes for 700 MW(e) PHWRs

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1.0 Introduction:

Alloy-800 (UNSN08800) is used in the Nuclear Steam Generators as tube material for its inherent properties including Stress Corrosion Cracking resistance and high temperature strength. The tubes of Alloy-800 are very well suited for Condenser and Heat-exchangers applications. In Nuclear Power Plants it resists carburising environment in primary circuit due to ^{14}C produced by (n,α) reaction from ^{17}O in the coolant water and by (n,p) reaction of ^{14}N present as an impurity in Zircaloy clad and Fuel. Thus this material is preferred over conventional Austenitic Stainless Steel grades (ASS) in Nuclear Power plants. Unlike ASS, this material is resistant to Stress Corrosion Cracking (SCC). The material is well studied with respect to its corrosion, mechanical properties and creep properties. Tubes for Steam Generators are required in U bend form with external surface shot peened to further strengthen resistance to SCC. Finished tubes are in cold worked condition for improved strength (mechanical properties).

Tube fabrication starts with hot extrusion of mother hollows from forged and machined round billets followed by multiple cold reduction steps with combination of pilgering and drawing. Each cold reduction step (except final drawing) is followed by mill-Annealing, which typically consists of passing tube lengths through a furnace on a travelling belt at temperatures high enough to recrystallize the material and dissolve all the carbides (~1000°C). Final size of tubes is cold worked through drawing process with optimum cold work to achieve enhanced Mechanical properties (YS & UTS) along with specified ductility. Chemical composition of the Alloy-800 used in the SG tubes for the Nuclear Power Plants is modified by controlled addition of Ti for stabilization (Table-1). Alloy-800 Nuclear Grade (NG) as compared to the standard ASTM grade specification has lower Carbon content to minimize sensitization, an increased stabilization ratio (Ti/C: ≥12, Ti/(C+N): ≥ 8, N: ≥ 0.03), and marginally increased Chromium and Nickel contents to achieve a higher resistance to pitting and Trans-Granular Stress Corrosion Cracking (TGSCC). Alloy-800 (NG) also has higher resistance to caustic induced SCC and it is almost immune to Pure Water SCC (PWSCC).

Element	Specification	Typical
C	0.03 max	0.028
Si	0.3-0.7	0.68
Mn	0.40-1.0	0.90
P	0.015max	<0.01
S	0.015max	0.001
Co	Aim for 0.015	0.005
Al	0.15 to 0.45	0.3
Ti	0.6 max	0.45
N	0.03 max	0.0095
Cu	0.075 max	0.005
Cr	20-23	22.8
Ni	32-35	34.3
Fe	Remainder	Remainder
Ti/C	12 min	16
Ti/(C+N)	8 min	12
(N+P)	0.045 max	0.0195

Table1: Chemical composition of the

Ternary phase diagram at 400°C for Fe-Cr-Ni is given in Fig. 1 which shows Alloy 800 and series of other alloys containing varying Ni and Cr content. Alloy 800 is a γ solution strengthened alloy which is designed for corrosion resistance under severe environment. The γ-phase consist

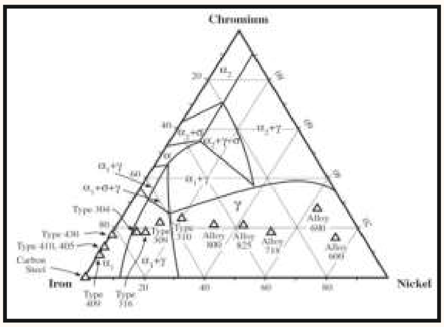


Fig. 1 Ternary phase diagram showing the Fe-Cr-Ni and Fe-Cr alloys, Alloys of interest to steam generators superimposed on Fe-Cr-Ni ternary diagram for 400°C [9]

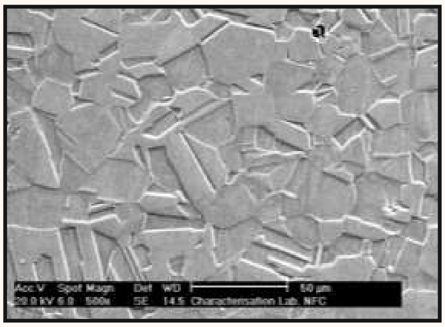


Fig.2: Microstructure of solutionised Alloy-800 showing single phase austenitic structure and absence of any intermetallic precipitates.

primarily of small coherent precipitates embedded in FCC matrix. The precipitates, denoted as γ', have an L12 crystal structure based on the Ni_3Al ordered compound which are solutionised in the final annealing. Fig.2 shows the as-solutionised material with absence of any precipitate after annealing. The finished tubes are cold worked to a small extent to increase the Tensile properties. There is no change in the microstructure during this cold working i.e. drawing. Higher carbon content requires a higher mill-annealing temperature to dissolve all the carbides. Undissolved Inter granular carbides are undesirable because they provide nucleation sites for the dissolved carbides and prevent precipitation of the carbides on the grain boundaries and, therefore, prevent appropriate grain boundary carbide coverage. The mill-annealing temperature controls the material yield strength and in turn the residual stresses.

2.0 Indigenous Development

Alloy-800 tubes are one of the most critical tubes in the Nuclear Power plant. These tubes with lengths up to 26m are required in U bend and shot peened surface condition for the 700 MWe PHWR Steam Generators (SGs) under construction by NPCIL. Alloy-800 is used in the Nuclear Steam Generators as tube material for its inherent stress corrosion, creep and high temperature strength properties. Erstwhile these tubes for all the earlier reactors were imported. The challenging task of indigenous development and supply of these critical tubes on par with international quality standards was taken up at NFC, Hyderabad. The development of these tubes began with a pilot order from NPCIL for Alloy-800 U bend tubes for 700 MWe PHWRs covering all the bend radii required for fabrication of the Steam Generator. This was followed by a bulk order from M/s. L&T for 8 sets of SG tubes (~20,000 tubes) and 3 sets (~7500 tubes) from BHEL. Presently, manufacturing of tubes for 40 sets of SGs for NPCIL under Fleet mode (10x700 Mwe PHWRs) is in progress.

Specification requirements w.r.t. dimensions, chemical composition, mechanical, metallurgical, corrosion properties, residual stress, etc. are stringent to avoid any failure during service. Finished U bend tubes having 19 mm OD x 1.1 mm wall thickness and length up to 26m are formed into wide range of bend radii (total 72) starting from 91 to 1014mm, with one bend radius at every 13mm interval. Specifications for U bend tubes are stringent with respect to tolerance on bend radius, leg spacing (2R), ovality & out-of-roundness in the bend region. Further, the finished tubes after U-bending are subjected to Hydrostatic pressure testing (250 bar) followed by Glass bead shot peening on entire external surface, on bend region as well as on both straight legs to induce residual compressive stresses up to a minimum depth of 0.12 mm. The finished tubes before bending are tested with stringent reference standards in Eddy Current with 0.8 mm dia. through holes instead of ASTM specification of 1.5 mm dia. and Ultrasonic Testing with 100µm depth, 1.5 mm length, saw tooth notch with 60^{o} angle. Also, finished tubes required with enhanced yield strength and low corrosion rate are tested for IGC as per ASTM G-28 and SCC as per G-36.

3.0 Manufacturing Process of Alloy-800 Steam Generator Tubes :

The development of process route was divided in two stages, Ist to manufacture straight tubes of length up to 27 m meeting all the stringent requirement of dimensions, chemical composition, mechanical properties, corrosion properties, NDE, etc and IInd stage of development of two new processes namely ‘U bending’ and ‘Glass bead shot peening’. These facilities were not existing prior to taking up this important work.

3.1 Manufacture of long straight tubes:

The specifications for procurement of raw material in the form of forged and solution annealed rounds were arrived at considering the variables during thermo-mechanical processing and final product specifications. Thermo-mechanical processing consists of hot extrusion followed by cold working which include a combination of pilgering and drawing with intermediate and final heat-treatment. The forged rounds were procured after conducting requisite checks for its soundness, inclusion rating, carbide precipitation, grain size, chemical composition, etc.

Alloy-800 is having poor hot workability because of its low thermal conductivity due to presence of γ′ precipitates such as Ni_3Al, $Ni_3(Ti, Al)$ and carbides precipitates such as TiC and $Cr_{23}C_6$. The presence of the precipitates in Alloy-800 and relatively higher grain size in as received forged billet are responsible for its relatively higher elevated temperature strength and hence characteristically difficult to extrude. Extrusion parameters such as temperature, strain rate, lubrication and container preheating temperature were optimized to successfully produce mother blanks from these rounds.

To meet the final stringent Ultrasonic testing requirement, extruded blanks were subjected to extensive conditioning on internal as well as external surface. Internal surface was conditioned by means of honing and external surface through machining. Such conditioned blanks were ultrasonically qualified for its soundness and taken up for further processing by cold pilgered in three stages to the pre-final size, followed by final drawing with controlled cold work to meet the enhanced Yield strength specifications. The intermediate cold work process parameters such as area reduction, lubrication, tooling design and heat treatment parameter such as soaking time, temperature and atmosphere were optimized in order to achieve consistent quality of tubes with close control on dimensions, surface finish, corrosion properties, (IGC rate < 0.6mm/Yr) and SCC resistance. The final cold work imparted through drawing was established successfully to achieve enhanced yield strength. With this development, plant has achieved recovery of around 80%.

3.2 Development of U bending process:

The finished straight tubes tested and accepted in all aspects such as ECT, UT, dimensions, ID boroscopy etc having length up to 27 m are required to be bent to 72 different radii varying from 91 to 1014 mm. This was performed on a special purpose bending machine having innovative tooling concept of both individual bending dies and inverted truncated cone type dies. These inverted truncated cone type dies have a special feature of achieving continuously adjustable bend radius by varying plane of bend to achieve the desired bend radius. Thus, a single cone die caters to several bend radii thereby reducing tool change over time and more importantly saving in terms of tool inventory. The machine also has a feature of bending tube with or without mandrel. The machine is designed to impart bending angle up to 230^0 with a provision of imparting pre-bending of 10-15^0 bending angle to accommodate higher spring back, specially while bending higher bend radii to achieve bend angle of 180^0. The process parameters for bending such as angle, radius of bend were optimized to carry out bending of all 72 different radii meeting the stringent dimensional specifications like tolerance on bend radii ($\pm$0.75 mm), ovality (<5%), out of roundness (<6%), wall thinning , etc.

3.3 Development of Glass Bead Shot peening process :

Fig-3. Glass Bead Shot Peening m/c

Finished tubes after U bending are subjected to Glass Bead shot peening to induce residual compressive stress on the external surface up to a depth of 0.12 mm (min), to impart improved resistance against SCC while limiting the external surface finish within 3.3μ Ra as per the specifications. This was a new process inducted into the production line. A special purpose automated Glass Bead shot peening machine (Fig-3) was developed indigenously, having 3 sets of nozzle assemblies housing 3 nozzles placed at 120^o configuration (Fig-3a) for uniform blasting over entire external surface covering bend region and both straight legs of U bend tubes of 72 different radii (91 to 1014 mm CLR). The process parameters such as Glass bead media i.e. 'C' Grade (Fig-3b), blasting pressure, linear speed, etc. were optimized

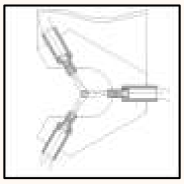


Fig-3a. Nozzle configuration

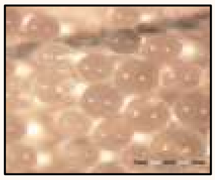


Fig-3b. Glass Bead media

and established through extensive performance tests involving measurement of residual stress pattern of shot peened tubes across section as against the operating parameters, using X-ray diffraction technique. With the optimized parameters, tubes of various bend radii were shot peened consistently meeting all the specification requirements of residual compressive stress up to desired depth, while maintaining the surface finish within the specified limits.

3.4 Inspection & Testing of tubes

During the development of the process flow sheet, several trials were carried out for meeting the quality requirement. While establishing the processes, array of inspection, testing techniques were developed, essential inspection and testing equipment were designed, developed and commissioned successfully, to achieve the quality requirements and match the production capacities. Following is a brief description of the inspection and testing carried out for meeting the stringent specifications.

a) UT of OD machined & ID honed tubes:

In order to improve the acceptance (%) i.e. the ratio of number of tubes accepted against tested in UT at the finished stage, several experimental process studies were carried out. The typical defects observed in the final stage were traced back to be originating from the extruded material. Standards for ultrasonic testing for extruded tubes after OD machining & ID honing stage were established. Regular feed-back to production regarding material to be removed from OD and ID of extruded hollows was given by analyzing the defects intercepted by UT. The feed-back process along with the extensive analysis of UT defects in the extruded hollows resulted in improvement of acceptance in UT from 50% in the initial lots to 85% in the subsequent lots after its successful implementation.

b) Ultrasonic testing of tubes:

Fig-4. High speed Ultrasonic testing m/c.

A high-speed UT system with advanced testing features was needed for carrying out Ultrasonic testing in the final stage, in order to meet the production rate. Existing equipment for UT at NFC was capable of testing at low speeds i.e 1 m/min, limiting the testing capacity. To overcome the limitation, specifications of high speed system were evolved and new system was procured. The advanced UT system could be developed through extensive interactions and feedback with the equipment manufacturer (Fig-4). This system was installed, successfully commissioned and established for testing of Alloy-800 tubes at higher speeds (4-5 m/min) which could be achieved through several modifications as compared to the existing system at NFC.

c) Eddy current testing of Tubes :

Against the conventional 1.5 mm dia through hole as the reference standard, a stringent standard with size of 0.8mm dia hole was required as per customer specification. An automatic tube handling system with defect marking for long length tubes was used for testing. This Eddy current unit with specially developed sensing coil and tube handling system was developed indigenously and installed for testing of SG tubes.

d) Pressure testing of U bend tubes :

A new automated Hydrostatic Pressure Testing system for U bend tubes with combined end cutting after pressure testing was developed indigenously and was commissioned (Fig-5) for testing of tubes at 250 bar pressure using DM water of low conductivity as per specifications.

Fig 6. U bending over Conical dies

Fig-5. Pressure testing Unit

e) Bending Qualification :

Qualification of bending involves extensive testing of minimum radius bend formed over Ring dies & Cone dies (Fig-6) including dimensional measurement i.e. bend radius, leg spacing (2R), flatness, outer diameter, wall thickness, Hydrostatic Pressure Testing (HPT), Liquid Penetrant Test (LPT), ball pass test, visual Examination of internal surface, Surface finish, wall thinning, ovality, out of roundness, optical illustration & hardness in the bend region. Bulk manufacturing can only be commenced after successful qualification of Bending process as per specifications. Dimensional parameters including bend radius, leg spacing ovality, out of roundness are checked at regular interval during production as a part of Process Control.

f) Special purpose out-of-roundness measuring unit:

Measurement of out-of-roundness is required for all the tubes with bend radius ranging from 91 to 1014 mm. The measurement needs to be carried out at different sections in the bend portion, to verify extent of distortion during the forming operation. A Non-destructive roundness measurement unit (Fig-7) especially designed at NFC was successfully qualified and adopted for measurement of out-of-roundness (limit < 6%) which is a critical parameter for the U bend tubes.

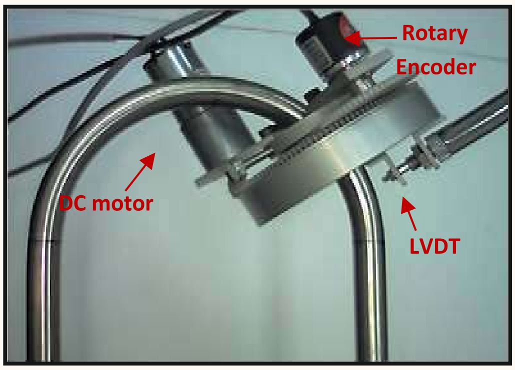
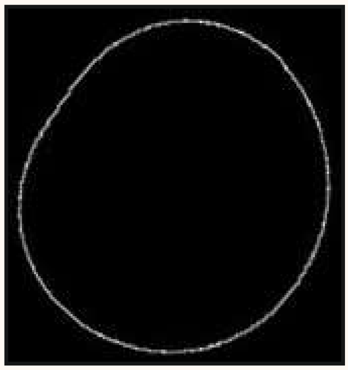


Fig-7. Out of roundness measurement gauge for U bend tube

Profile in section of bend region as seen in a section in Metallograph



Profile at bend region as generated by the gauge

g) Shot Bead Peening qualification:

As per specification for the peened surface quality, compressive stresses, have to be present up to a minimum depth of 0.12 mm from tube outside surface, both in the straight and bent portions of the tube. Stress profiles of the shot peened samples with set of blasting parameters were analyzed at the OD (outside of the bend) and ID (inside of the bend) as a function of depth for the U bend region. Optimum blasting pressure and linear speeds were established after multiple experimental trails, to consistently achieve the required compressive stresses in the bend region as well as the straight legs.

h) Measurement of residual stress profiles:

Fig-8. XRF Stress Measuring Unit

Establishing the depth of residual stress induced through shot peening over the external tube surface, requires generating profile of residual stress in the tube along the depth from OD. A new method using X-Ray diffraction (Fig-8) was developed to evaluate the residual stresses along the thickness. The profile of stress was measured by carrying out successive removal of layers from the OD surface using electro polishing technique. This method was used to qualify the shot bead peening operation as well as for regular measurement of Stress in the Production lots.

i) Dimensional inspection of U bend tubes using gauge block: In order to measure the dimensions of the U bend tubes e.g. radius, leg spacing, leg length difference, etc. a special purpose gauge block, suitable for all 72 radius ranging from 91 to 1014 mm was designed and commissioned at NFC.

Fig-9. Surface Plate Gauge Block for U bend tubes

j) Straightness measurement on surface plate (13m long):

One of the critical requirements of the U bend tubes is straightness measurement. This requires a very long surface plate with precise alignment along the length. A Granite surface plate (Fig-9) with 8 precisely crafted blocks, aligned over 13m length was developed indigenously and installed with an accuracy of 50 microns over the entire length for measuring the straightness of the U Bend tube.

k) Visual examination using boroscopy:

Each tube with length of nearly 26 meters was examined by ID boroscopy. Special purpose long length ID video-scope was used to examine the ID surface of the tubes (Fig-10) at high magnification (10X).

Fig-10. Boroscopy of 26m long tubes

l) Metallurgical, Corrosion, Mechanical and Chemical tests:

Stress corrosion testing in boiling liquid $MgCl_2$ is one of the most crucial test for this material. This test was carried out on the U bend tube to certify its resistance against stress corrosion cracking. Product Chemical analysis, Metallography, grain size, IGC, SCC and tensile testing at room (RT) as well as elevated temperatures (HT @350oC) were carried out for these tubes as required in the specification.

3.5 Storage, checking & Packing of U-bend tubes

Packing is one of the most critical operations in case of SG tubes, as total 2489 Nos of tubes covering 72 different bend radii (91 to 1014 mm CLR) required for one set of Steam Generator are to be packed in 89 rows with alternate odd

Fig-11. U Bend Storage Racks

Fig-12. Layout check fixture

Fig-13. Even & Odd row packed

(91,117,143….1001mm) & even (104,130,156….1014) radii series configuration, distributed into 13 boxes as per the sequence of tube insertion during final assembly for fabrication of Steam Generator. Tubes are manufactured radius wise i.e. total quantity for each bend radius for full set at a time. Tubes cleared in all respects including QS are stacked radius wise in specially fabricated U bend storage racks (Fig-11). During packing, tubes of required radii from the storage racks are taken out row by row, thoroughly cleaned and placed on to layout checking fixture (Fig-12) with supports placed at specified distances for simulating the assembly condition, as per Grid baffle position of the SG. Each tubes is internally sealed at two locations from each end (100 mm & 300 mm from both the open ends) using special threaded halogen free plastic ID plugs. Both the open ends are closed with a halogen free plastic end cap. This is followed by polythene tube sleeving over the entire length and final heat sealing at both ends. Sealed tubes are then placed in structurally reinforced plywood box in alternate even and odd radii layers (Fig-13) with grooved foam spacers between each layer at regular interval along the length of the box. Thus the triangular pitch required for assembly of the Steam generator is maintained during packing. Total, 2489 tubes packed in 13 boxes along with necessary documentation after obtaining QS clearance & Shipping Release is supplied to the fabricator for further assembly of the SG.

4.0 Conclusion

With the above developmental works, NFC has established complete set up for manufacturing of Steam Generator tubes for Nuclear applications and has successfully manufactured and delivered 32500 U Bend tubes for total 13 sets of Steam Generators. Manufacturing of 3rd set against 40 set order for Fleet mode PHWRs is under progress. This has led NFC to become the fourth manufacturing unit in the world having capability to manufacture Steam Generator tubes for Nuclear application.

Physics of Next Generation Energy Systems – An Overview

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Abstract

Nuclear energy will have to be the mainstay in today's green economy scenario. It will be prudent to develop mix of different innovative and revolutionary reactors as well as enhanced efficiency of current day reactor systems.

India has successfully deployed Pressurised Heavy Water reactors (PHWR) with indigenous design and achieved functional maturity. Following a well-defined path of the three-stage programme, India plans to multiply its capacity generation with addition of different types of reactor systems based on different requirements. Physics design will have to play a major role in these new energy systems which will have to cater to diverse objectives. Advanced Heavy Water Reactor (AHWR) and Molten Salt Reactor (MSR) utilising thorium, Small Modular Reactors (SMR) using enriched uranium and Accelerator driven systems (ADS) for fissile material production are some of the reactors which have the potential to cater to India's energy needs. The physics design of each of these energy systems is different and challenging and has evolved from our deep insight and understanding. For example, the AHWR design was developed with evolutionary and revolutionary features with respect to self-sustenance in the bred fissile species U-233 and achieving inherent safety feature of negative coolant void coefficient conducive to heat removal through natural circulation. The molten salt reactor is governed by proper material selection and simulations for fuel dynamics. The challenge in SMR is achieving an integral configuration of all sub systems and a small core with longer cycle lengths. The sub-critical multiplication in ADS and its coupling with accelerator will have another dimension in design, safety, and operation.

These advanced reactor designs have been subjected to high level of validation. Advanced fuels have been qualified in research facilities. Passive and inherent safety has been demonstrated with experiments. This talk will give an overview of the current developments in these thermal reactors of tomorrow and the self-reliance achieved in the designing these systems.

1.0 Introduction

Advanced energy systems are characterised with respect to enhanced fuel utilization, efficient heat removal, improved safety, and competitive economics [1]. Use of advanced fuel or new type of fuels should ensure that fuel utilisation be as high as possible and waste requires to be minimised. Enhanced fuel utilisation implies high burnup or higher cycle energy which tends to the selection of fuels that can retain the fission products or fission gasses and having a better matrix where the fuel can perform well under prolonged burnups. Fuel designs will also be required to perform and stay intact even under extreme transients or runaway situation so that the radiological impact is minimal. This requirement has led to development of improved cladding material for housing the fuel meat [2].

In order to design reactors with higher efficiency, better coolants have been used in addition to light water such as super critical water coolant or liquid metal coolant where the heat removal aspects are superior and thermal margins can be enhanced. Operation at high temperatures will require other coolants like lead or lead-bismuth. The properties of super critical water can be exploited even to achieve good breeding in the fuel by tuning the neutron spectrum [3].

One of the design goals of advanced reactors is ultimate safety. This can be achieved by using passive safety means and inherently safe features such as reactivity and temperature feedbacks. Ultimate safety can be achieved when on any perceived initiating event, all the feedbacks act in such a way to mitigate the event and bring the reactor back to safe conditions. Advanced reactors also aim towards having a minimum or no exclusion zone which requires detailed modelling of the radioactive source term and at the same time design systems so that core damage frequency is at least one order less than that in the current generation reactors. After the Fukushima accident, protection mechanisms are required to be built in so that there is cooling provided for an extended period in order to protect the core and its internals [4].

A most important factor is how economic will be the generating costs of these advanced reactors especially when multiple barriers of safety are engineered. Enhanced fuel utilisation can reduce the fuel requirement costs and enhanced safety could also limit long trips or outages. A competitive fuel cycle is required to be evolved. With reprocessing and recycling the fuel economics can be improved. However, the end goal of ultimate safety will be the deciding factor for new reactor designs rather than economics.

2.0 Drivers for advanced energy systems

Ever since the eight decades of design and operation fission reactors several categorisations of reactors have been made. However, the IAEA has been consolidating guidelines for new builds and has come out with a comprehensive categorisation of old as well current and new reactor designs in its GEN-IV forum [5]. All the above objectives mentioned earlier have been very clearly articulated in the GEN-IV forum. Though Gen-IV principles are well known and several reports are available in open literature, the salient features of the GEN-IV systems are bought out here for brevity. The design objectives elucidated are like mentioned earlier are use fuel more efficiently, reduce waste production, high levels of safety, proliferation resistant cycles and economically competitive.

Towards this perspective, six reactor technologies were chosen for further research and development,
namely, Gas-cooled Fast Reactor (GFR), Lead-cooled Fast Reactor (LFR), Molten Salt Reactor (MSR), Supercritical Water-cooled Reactor (SCWR), Sodium-cooled Fast Reactor (SFR) and Very High Temperature Reactor (VHTR). Also, with nuclear share having to increase manifold in a very short span in achieving carbon neutrality, small reactors are being considered to replace plants based on fossil fuels.

The advanced reactors will be more complex and will be required to have a multi-dimensional approach to achieve all the design goals. So, diverse designs are required which cater to big reactors for energy production, smaller ones for non-power applications like, Hydrogen generation, waste incineration, district heating and compact power packs for remote areas. Small nuclear reactors are already deployed for strategic applications like submarines and are also required as ice breakers and for nuclear fuel powered space vehicles.

The approach can either be evolutionary or revolutionary. Evolutionary designs are already proven and can be deployed in a short duration as they will have small gestation periods. Revolutionary designs will require extensive experimentation to qualify fuel, fuel cycle and safety processes. They are governed by material challenges, scaling up and new regulatory requirements. These will be required to be addressed carefully and so may be ready for deployment only after several years.

Physics will play a major role in all these new designs. This paper will bring out some of the efforts made towards enhanced fuel utilisation and safety aspects of advanced reactor systems being designed in BARC [6]. This article will cover the physics features of Advanced Heavy Water Reactor (AHWR), Indian Pressurised Water Reactor (IPWR) and the indigenous designs of high temperature reactors (HTR), Molten salt reactor (MSR), Small Modular Reactor (SMR) including some design improvements in existing Pressurised Heavy Water Reactor (PHWR) with the emphasis on design goals discussed above.

2.1 Fuel utilisation

Fuel utilisation is best compared using a parameter equivalent mined uranium required per TWhr(e). This will be useful in comparing reactors of different power capacities on the same footing i.e. equivalent energy generated. In Table 1, the fuel utilisation of a few light water and heavy water reactors are compared [7]. PHWRs have higher conversion factor and require less mined uranium to achieve the equivalent energy. Since LWRs require enriched uranium, energy or work is spent in enriching the fuel too, but longer residence time results in lower annual inventory requirement. This estimate also implies that PHWRs of higher power would be a good option but these reactors would require a larger land footprint. LWRs of larger cycle length would have enhanced fuel utilisation. The challenge is then to design reactors that are good converters of the fertile species to fissile species or near breeder. In AHWR, attempt has been made to operate on Th-U233 cycle achieving a near breeding in the bred fissile isotope U-233 [8]. Advanced LWRs also have gone for two-year cycle lengths by using burnable absorbers in the fuel and improving the clad material [9]. Closed fuel cycle option further increases the energy potential of the mined uranium.

Table 1 Comparison of fuel utilisation in thermal reactors

Reactor Type	Power Electric / Thermal / Fission (MW)	Feed enrichment in equilibrium cycle (%)	Discharge Burnup GWd/Te	Cycle length for refuelling	Equivalent mined uranium* Te/TWhr(e)
BWR	1330 / 3990 / 4070	~2.4	22.0	24 months	25.0
PWR	1280 / 3800 / 3900	~3.3	33.0	12 months	23.38
VVER	1000 / 3000 / 3150	~3.92	43.0	295 days	22.26
PHWR-220	220/ 750 / 802	0.71	6.7	On power	22.67
PHWR-540	540 / 1760 / 1830	0.71	7.0	On power	20.17
PHWR-700	700 / 2190 / 2310	0.71	7.0	On power	19.64
AHWR-300	300 / 920 / 980	3.25	38.0	On power	21.42

2.2 Enhanced safety requirements

The design objective is to achieve higher level of safety than the existing reactors. This can be achieved in design by incorporating multiple systems and using passive features. Plant design should include multiple barriers for containing radioactivity, robust design to perform under safety limits and to achieve ultimate safety by diverse principles. Core safety is governed by inherent negative feedbacks, quick detection or on-line monitoring for process parameters and redundancy in achieving defense-in-depth. For example, in AHWR the inherent negative void coefficient mitigates any power excursion under normal operating conditions, axial gradation of fuel enrichment leads to bottom peaked heat flux distribution and thereby better thermal margins. AHWR core has been designed to have decay heat removal by passive means through isolation condensers and prolonged heat removal capability by core submergence. A typical scenario is shown in Figure 1 where the external reactivity addition for credible reactivity transients is arrested by inherent negative feedbacks which is desirable feature of advanced reactors [10]. In Figure 2, the results of safety analysis for AHWR showing clad surface temperature with core damage frequency for all anticipated operational occurrences (AOO) and the design and beyond design basis events are shown to

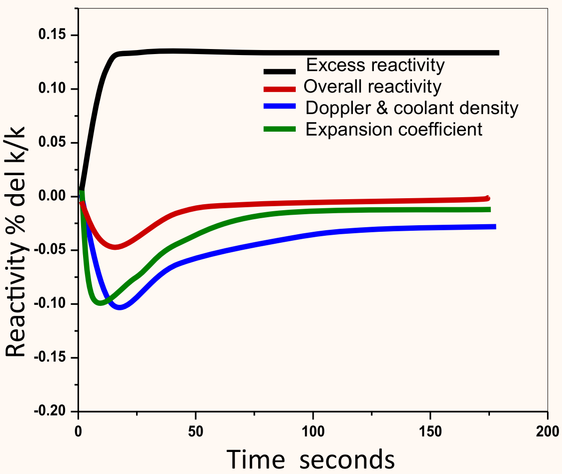


Figure 1 : Transient behaviour in advanced reactors with feedbacks - Inherent Safety

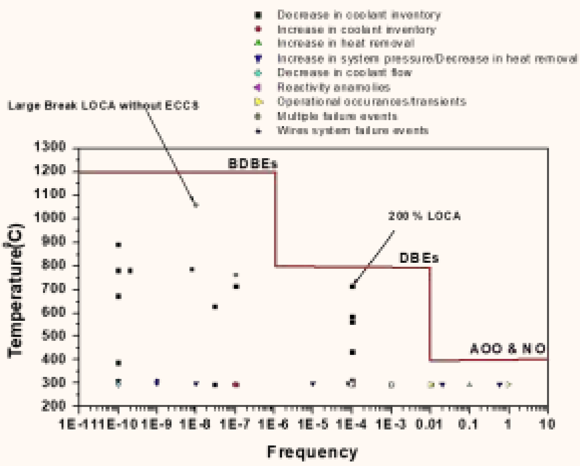


Figure 2 : AHWR Safety analysis : Clad surface temperature for different types of accidents

illustrate the higher levels of safety achieved by design [11].

In AHWR, the Passive Poison Injection System (PPIS) is designed to actuate when the system pressure exceeds limiting conditions, is an example of engineered safety system for beyond design basis events. Gravity driven water pool is engineered to provide long term cooling. The containment design is improved to contain the radioactivity release under all anticipated conditions. Some advanced reactors also have core catchers for containing the radioactivity released from core melt accidents.

2.3 Radiological safety

In the previous sections it was shown that the in advanced reactors, in any worst accidental scenario, core damage frequency is minimised and estimated to be at least one order lower than the current day reactors. With respect to radiological impact, the new reactor designs aim to reduce the exclusion zone and prove that even in beyond design basis accidents, the radioactivity release will be limited within the plant boundary. Other systems are also engineered to mitigate the radioactivity release. Rigorous deterministic and probabilistic safety studies are required to be done with realistic approach and less conservatism to establish these enhanced safety goals.

3.0 Salient features of some advanced energy system being designed at BARC

Several new reactors are being designed by BARC and are at different stages of progress. AHWR has been designed with the aim of thorium utilisation and as a demonstration reactor for the entire thorium fuel cycle. It has both evolutionary and revolutionary features and a notch higher with respect to safety compared to the currently operating PHWRs. Indian Pressurised Water Reactor (IPWR) is being designed to extract more energy from indigenous uranium. Molten Salt reactors (MSR) also being designed to exploit the features of thorium fuel efficiently through online processing. High temperature reactors (HTR) are being designed to utilise the process heat for potential application such as hydrogen generation. Accelerator Driven Subcritical Systems (ADSS) are being designed for fissile material generation, minor actinide incineration or transmutation. In the article, the physic features of the above-mentioned reactors will be presented.

3.1 Advanced Heavy Water Reactor - Salient features

The Advanced Heavy Water Reactor (AHWR) of India has been designed to produce 300 MWe with boiling light water as coolant and heavy water as moderator and utilises thorium [12]. The fuel cycle is based on the conversion of naturally available thorium into fissile U-233, which will then undergo fission *in-situ* to generate energy. The uranium in the spent fuel will be reprocessed and recycled back into the reactor. AHWR uses a small amount of plutonium as external fissile feed, but most of its energy output comes from thorium-U233 fuel. The design has stressed on enhanced safety and reactor is provided with several passive safety features such as negative coefficient of coolant void reactivity, heat removal through natural circulation of coolant and passive containment cooling for decay heat removal.

The fuel design is governed by fertile-to-fissile conversion, efficient burning of plutonium and heat removal aspects. It was a challenge to design the fuel cluster to achieve self-sustenance in the bred U-233, to optimise the radial and axial power distribution to be conducive to heat removal through natural convection. Achieving negative void coefficient in a pressure tube system with combination of heavy water and boiling light water required tuning of the neutron spectrum. These have been achieved by differential fissile contents and using a harder thermal spectrum to achieve effective resonance captures.

The equilibrium core design has a very low excess reactivity thereby minimizing the reactivity swings and enhancing the safety. A low power density (compared to other heavy water reactors) of about 4 kW/l ensures higher margins during operational transients. The control rod withdrawal speeds are also lower, which minimizes the effect on control rod related reactivity insertions. Two independent and functionally diverse fast acting shutdown systems provide a significant safety margin. In addition, the reactor regulating system continuously monitors and controls local and global power. An added safety feature is provision of ECCS inside the fuel cluster.

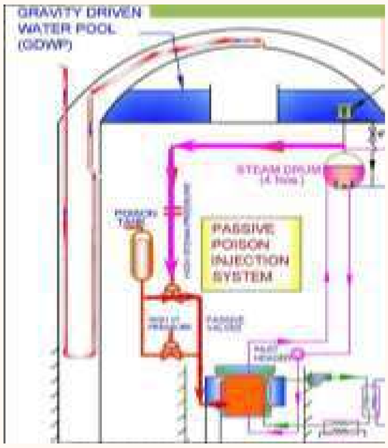
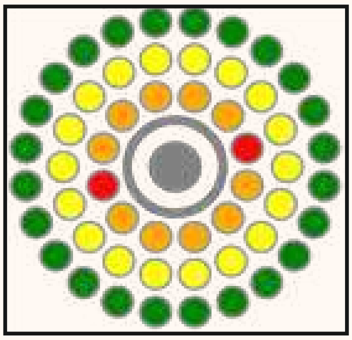


Figure 3: Passive shut down capability in AHWR with passive poison injection

A schematic of the primary heat transport circuit illustrating the passive shutdown capability of AHWR is shown in Figure 3. The core power distribution is also required to be as flat as possible to facilitate natural circualtion. This feature restricts the power producded in a channel and therefore the core size and the global power is optimised to 750 MWth. The optimised cluster is shown in Figure 4a. The equilibrium core layout and core flux distribtuion is shown in Fugures 4b and 4c. The neutronics and the thermal hydraulics is strongly coupled and safety analysis has been perfomed using coupled simualitons to arrive at a desired power distribtuion [13]. Detailed experimental studeis were done in one-to-one thermal facility to demonstarte natural circulation.



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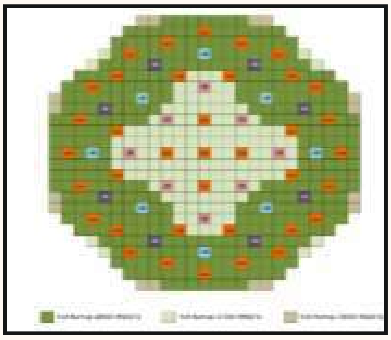

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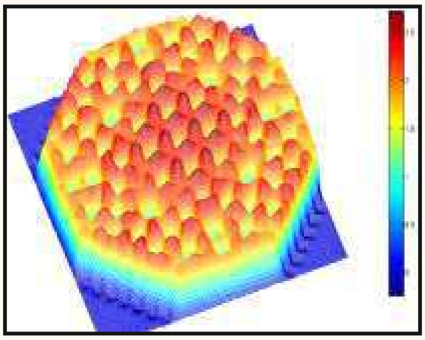

(4c)

Figure 4a: Optimised AHWR equilibrium ore fuel cluster; Figure 4b: Equilibrium core layout of AHWR; Figure 4c: Flat core power distribution conducive to heat removal through natural circulation

Several experiments have been performed in the AHWR critical facility to qualify the integral and differential parameters of thorium-based fuel such as neuron

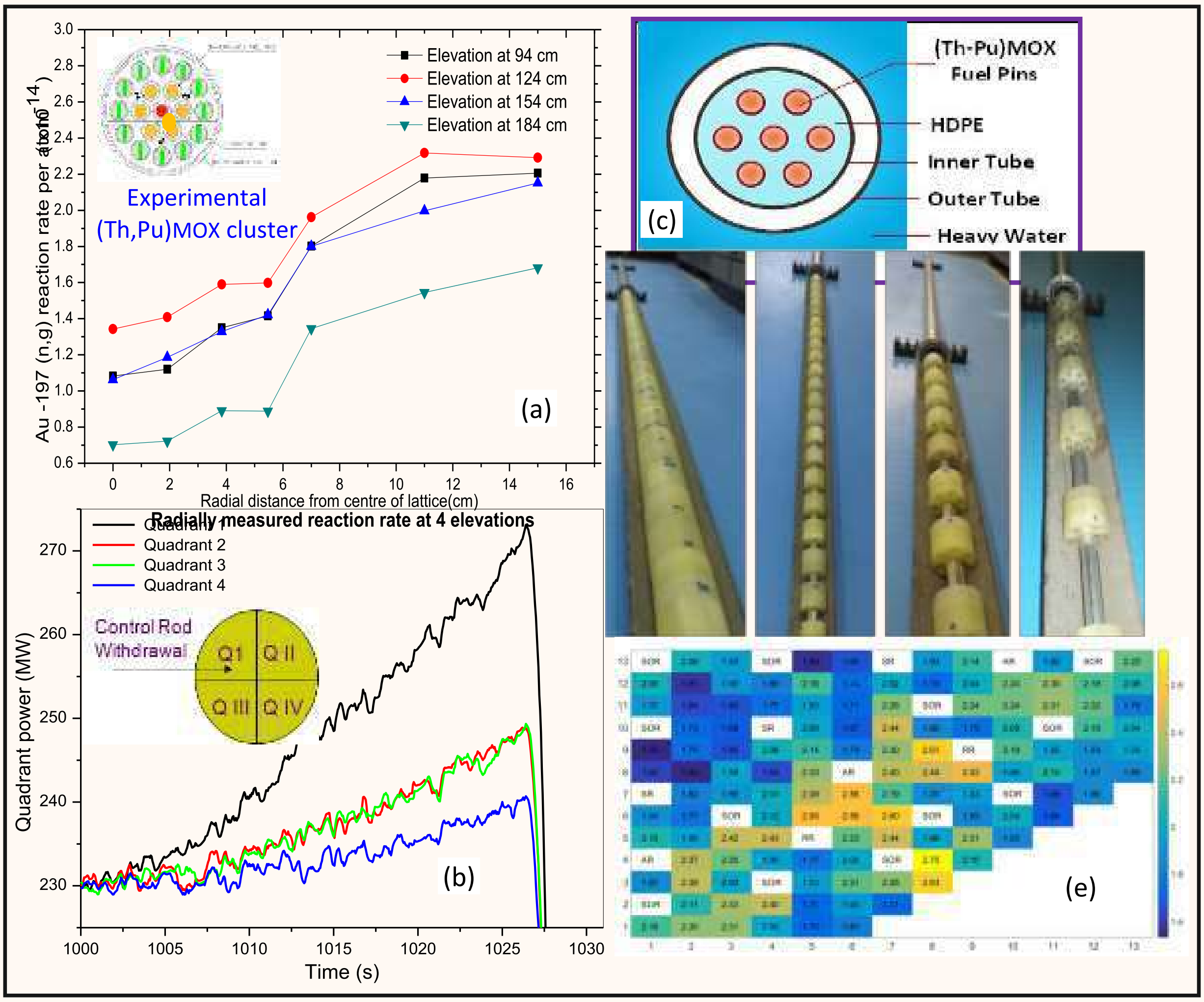

Figure 5a: Radial power distribution in experimental (Th-Pu)MOX cluster); Figure 5b: Coupled neutronic and thermal hydraulic analysis for LORA in AHWR using PFROMISIN ; Figure 5c and 5d: Experimental arrangement for coolant void worth measurement; Figure 5e: Neutronics and thermal hydraulics iterated power distribution

spectrum, radial and axial peaking factors inside the fuel cluster, coolant void worth.

Results of experimentation for physics safety features and development of adnanced computational tools is presented in Figures 5a through 5e. AHWR design is an example of how to approach towards safety and demonstrate the advanced features through experimentation.

3.2 Physics features of IPWR

IPWR core is designed to produce 900 MW(e) using enriched uranium with a competitive fuel cycle as per the current LWR standards. An average enrichment of 4.22% is used to obtain a discharge burnup ~46 GWD/T in a hexagonal core arrangement [14]. Gadolinium is used as the integral burnable absorber admixed with fuel to suppress the initial excess reactivity and achieve longer cycle lengths. The equilibrium cycle length of 410 days is achieved by three batch fuelling. As in most PWRs, the core excess reactivity is managed by soluble boron in moderator and rod cluster control in the fuel assembly. All the reactivity coefficients have been designed to be negative during any operating regime. The optimised fuel assembly of the equilibrium core loading is shown in Figure 6a and the core layout with the radial reflector and core barrel is shown in Figure 6b.

The physics challenges are to minimise in the initial soluble boron concentration so that the coolant temperature coefficient is remains negative and achieve optimum peaking factor both in the fuel assembly and over the entire core. Another important feature in LWRs is to minimise the fluence seen by the reactor pressure vessel and to this end the power distribution of the core is managed with both out-in and in-out fuel shuffling and providing a good reflector region.

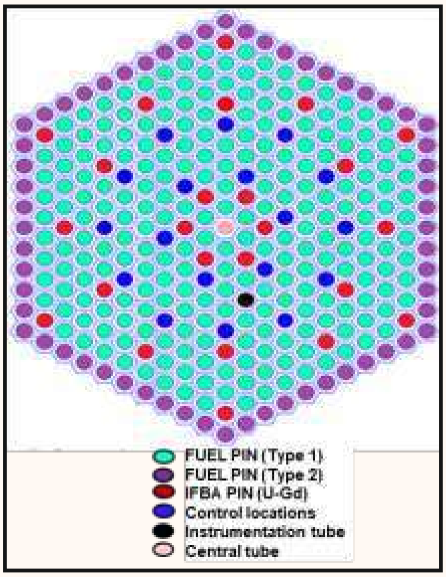

Figure 6a : Profiled fuel assembly of IPWR for equilibrium core loading

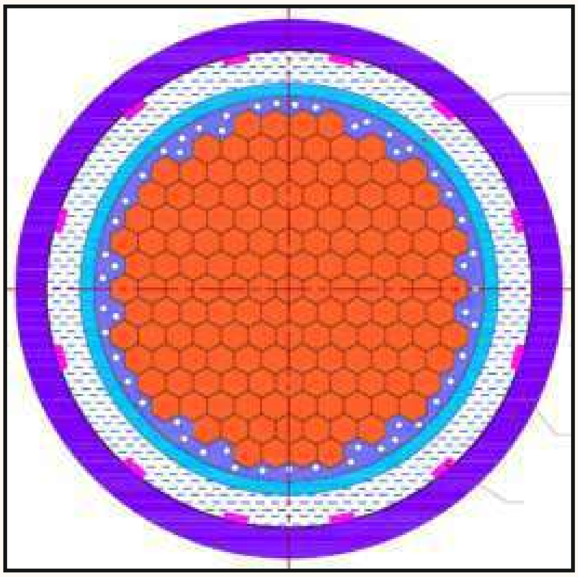

Figure 6b : Layout of the IPWR core

3.3 Physics challenges of High Temperature Reactor (HTR)

A preliminary physics design of compact high temperature reactor has been done with the main aim of using it as a power source in remote regions [15]. Other designs, namely the innovative high temperature reactor (IHTR) is being pursued where the operating temperatures are high enough to generate hydrogen from chemical processes. These reactors use TRISO coated fuel particles and moderated with BeO. Physics studies have been performed for CHTR with Th-233U or HEU fuelled, Lead Bismuth Eutectic (LBE) cooled, vertical prismatic type reactor rated for 100 kWth power. The CHTR core requires about 2.7 kgs of U233 and 5.8 kgs of thorium for a core life of 15 years [16]. The physics challenge is to maintain the core reactivity for such long-life cores. IHTR is being configured as a pebble bed reactor where each pebble has about 1,50,000 TRISO particles and these pebbles float in a lead coolant or Pb-Bi eutectic coolant. The challenge here is to model these highly heterogenous fuel-moderator combinations which require new methods.

3.4 Design features of Indian Molten Salt Breeder Reactor (IMSBR)

It has been shown in the Molten Salt Reactor Experiment (MSRE) at ORNL that fluorides of Lithium, Beryllium and uranium in a molten configuration can be successfully deployed as efficient fuel [17]. If the fuel is based on thorium-U233 cycle, the Pa-233 produced can be effectively converted to U-233 outside the core. It is prudent to exploit the 27-day radioactive decay half-life of Pa-233 and design online fuel processing, where a fraction of the volume of fuel can be removed from the core and allowed to decay and later pumped back into the core. The salient feature of this type of core is that the fuel and coolant are admixed together in a molten configuration and the operating temperatures are to be kept such that the fluid is always maintained in molten sate. The feed and bleed process of the fuel from the core can be easily adjusted in this type of liquid fuel by pumping to maintain excess reactivity of the core. The physics of these type of reactors is complicated, where the refuelling must be constantly governed and the delayed neutrons are distributed inside and outside the core causes concern [18].

3.5 Accelerator Driven Subcritical systems (ADSS)

ADSS can be used as an advanced energy system for transmutation. ADSS usually consists of a high energy proton accelerator, a spallation target, which produces neutrons and a surrounding sub-critical core which uses these neutrons for effective transmutation for conversion. The energy amplification that can be achieved with high power accelerators has been well proved. A 1 GeV proton can produce about 20-30 spallation neutrons and the beam energy required to produce 1 neutron will be about 40 MeV. If the subcriticality in the core is maintained at 0.98 and working out the fission energy generated per neutron and after applying the thermal to electricity conversion efficiency it can be

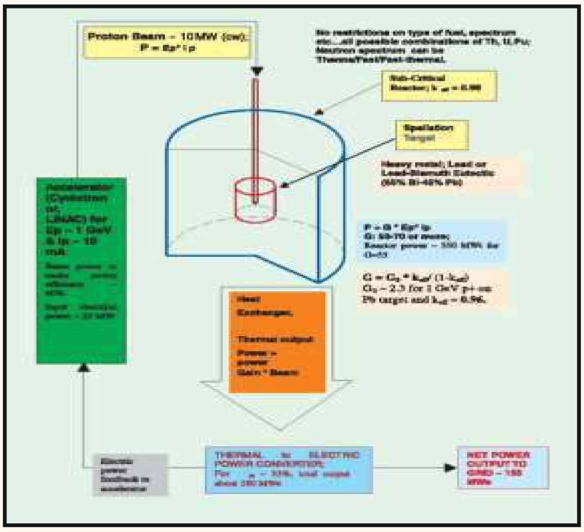

Figure 7 : Energy amplification in typical ADSS

shown that the net energy of about 1.3 GeV can be generated [19]. The subcritical core can be designed as per the objective of either minor actinide incineration or fertile -to -fissile conversion. The ADSS can be safely operated as the sub-critical core which will not lead to any runaway situation. The accelerator and beam dynamics are required to be designed for optimum performance. The energy amplification is explained in the schematic of a typical ADSS system in Figure 7.

BARC is engaged in designing thorium based sub-critical core with accelerators of optimum energy for demonstration of subcritical multiplication and fissile U-233 production. Thermal and fast neutron spectrum reactor core are being explored [20].

Apart from the design challenges of the accelerator itself, the modelling of sub critical multiplication is usually performed using a Monte Carlo approach and this requires extensive benchmarking and experimentation validation.

4.0 A few advanced reactors of the world

A few advanced reactors being conceptualised elsewhere in the world with varying design objectives is presented in this section.

Small Modular Reactors (SMRs) of the capacity from 30 MWe to about 300 MWe are being developed for augmenting the nuclear share in the energy mix [21]. The light water based PWR type SMRs are perceived as an ideal candidate to replace coal fired plants. The modular design aids in easy fabrication or factory assembled pressure vessel and easily transported to any plant site. The small core, small less than about 2.0 m in diameter, puts a lot of challenge on the core power distribution and heat removal. The core reactivity and fuel management require to be addressed in a more rigorous way than currently operating reactors. If the radioactivity release in limited to the plant boundary itself, these reactors can be located even in populated zones and has higher level of radiological safety. The enhanced safety objective requires a stricter control that all the feedbacks are to be negative and manifest as fast as possible. The general schematic of an SMR is shown in Figure 8 [22]. Several countries are looking at different designs of SMRs for power production, strategic as well as non-power applications.

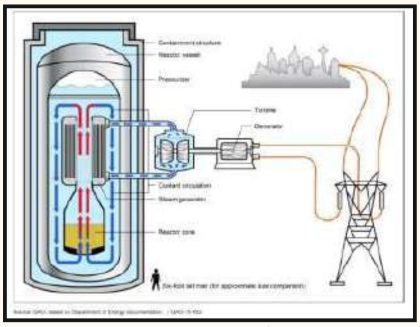

Figure 8 : Illustration of a light water small modular nuclear reactor (SMR)

Advanced PWRs: The next generation PWRs are designed with a competitive fuel utilisation features namely longer cycle lengths and high burnups. Conceptual designs based on thorium fuel with HEU or reactor grade plutonium have been developed for high burnup cycles.

Another interesting concept is the CANDLE reactor with very long-life cores, where the fuel burnup is controlled by the burning rate with optimised fissile contents and unique fuel management [22]. TERRAPOWER's Travelling wave reactor is another breed and burn design where the burnup is high over targeted zones and fissile conversion is achieved *in situ.* The burnup is affected as a wave by using directional reshuffling into less burnt fissile regions [23]. In block-type high temperature gas-cooled reactors (HTGRs) with thorium fuel, by simply increasing the core height, the reactor life can be elongated.

AECL is researching the thorium fuel cycle application to Enhanced CANDU 6 and ACR-1000 reactors with 5% Pu in the closed fuel cycle option. The driver fuel required for starting off is progressively replaced with recycled U-233, so that on reaching equilibrium, 80% of the energy comes from thorium. The design has the flexibility of using initial fuel as LEU, Recycle Uranium (RU), 235U or Pu. Plutonium recycle is being considered as an option for reducing the waste and this can be best adopted by mixing it with thorium [25].

Summary

This article gives an overview of the physics challenges involved in advanced reactor designs. A few reactors being developed by BARC have been described. The choice of the reactor or fuel cycle will depend on each country's energy needs. The emphasis being on enhanced safety and fuel utilisation, the new designs will require to be validated and benchmarked with scaled down demonstration reactors or experimentation in research reactors in ambient temperatures and neutron spectrum. Efforts are on in BARC to demonstrate safety in advanced reactors both through experimentation and advanced theoretical modelling. On the fuel cycle, it is important to irradiate these new types o fuel and perform post irradiation examinations to qualify the design.
In order to move towards carbon neutrality, the energy share from nuclear will have to increase manifold and will require to build many new reactors in a comparatively shorter period.

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Evolution of Indigenous Electron Beam Accelerator Technology in BARC from Nuclear to Societal Applications

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Indian Nuclear Society has been instrumental in making Indian Nuclear technological development popular and relevant over decades. Department of Atomic Energy has nurtured multiple verticals for strong indigenous base for all associated technology. Electron beam technology is also one such domain which is started since 1960s. Started with electron beam welding for the need to build many critical components for reactor to avoid oxidation of refractory materials during welding, this technology has grown significantly in terms of capability, performance and automation from 25kV to 80kV and 2kW to 12kW for welding and 2x150kW for electron beam melting machine has been demonstrated jointly with NFC.

In order to get intense power, pulsed electron beam accelerator has been initiated in 1970s for fusion program to study relativistic electron beam (REB) for many aspects of plasma, beam plasma interactions, and conversion into Flash X-rays and microwaves for electromagnetic interference efficacy. From components till system level it has been designed, developed and demonstrated from 10s of MW to 10s GW electrical power producing 1MV Flash X-rays and 1GW microwave power in BARC. It included development of many topologies of high voltage generation, switching, pulse forming network and high power diagnosis. These technologies are required to get utilised mostly for nuclear program or in-house application to make system rugged and reliable.

Using this expertise of electron beam, high voltage and pulsed power technology, an industrial electron accelerator program was taken up to produce machine based radiation facility which can complement radioisotope based application with inherent safety features. Radiation technology is well established since last 65 years for food preservation, delay in ripening, and inhibition of sprouting, seed mutation and Non-Destructive Testing (NDT). It is also used for medical sterilisation to tele-cancer therapy.

Evolution of Industrial accelerator started with first electron accelerator developed in 1998 at BRIT campus rated for 500kV,20mA. It is based on LaB6 based thermionic emission of electron beam followed by cock-roft multiplier configuration for high voltage column, thereafter electromagnetic coil for beam stirring, scanning over Titanium foil before it comes out from vacuum to air. Each and every system was made for the first time and accomplished from concept to realisation within five years (1993-98) and got demonstrated by that time

Priminister Shri Atal Bihari Bajpayee as shown in Fig.1.

Fig.1 First Indigenous 500kV DC Accelerator inaugurated by PM A.B.Bajpayee, Aug.,1998 (from CC Auditorium, BARC,Mumbai)

This beam is utilised for surface irradiation of textile, rubber tiles for many studies and analysis. This vertical accelerator has self-shielded Lead barrier, so could be made in bay area with conveyor belt below ground surface to take advantage of ground shielding. It had limited application but gave confidence to proceed with next level of development to meet industry scale requirements at par with commercially available accelerators i.e. 10MeV RF accelerator and 1-3MeV DC Accelerators in Electron Beam Centre, Navi Mumbai. A dedicated building is constructed to in-house these facility along with all auxiliaries of sub system development labs, shielded area for radiation hall and conveyor system for regular operation. It required immense coordination between BARC-SAMEER-DCSEM and CIDCO to realise this facility to cater for upcoming societal benefits. Finally Building was inaugurated by Chairman Dr.Anil Kakodkar on July 22,2004 as shown in Fig.2.

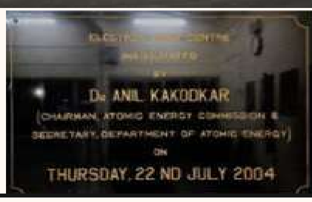


Fig.2 EBC building inauguration by Dr.Anil Kakodkar, Chairman, AEC and secretary,DAE in presence of Dr.N.Venkatramani,Director, BTDG and Dr.R.C.Sethi, Project Manager,EBC

In order to develop RF accelerator each and every sub-system has been taken as per given schematic in fig. 3. It has a few critical components like RF cavity 2856 MHz design (beam dynamics based design) and development (precision ±4micron, machining of Oxygen free high purity Copper Cavities, high vacuum brazing, stage wise characterisation-bead pull method) and HV-High frequency Klystron modulator providing flat top pulses, Pulsed electron gun (LaB6 cathode), and associated electromagnetics for beam focussing, stirring, scanning over 100x1500mmm Titanium window.

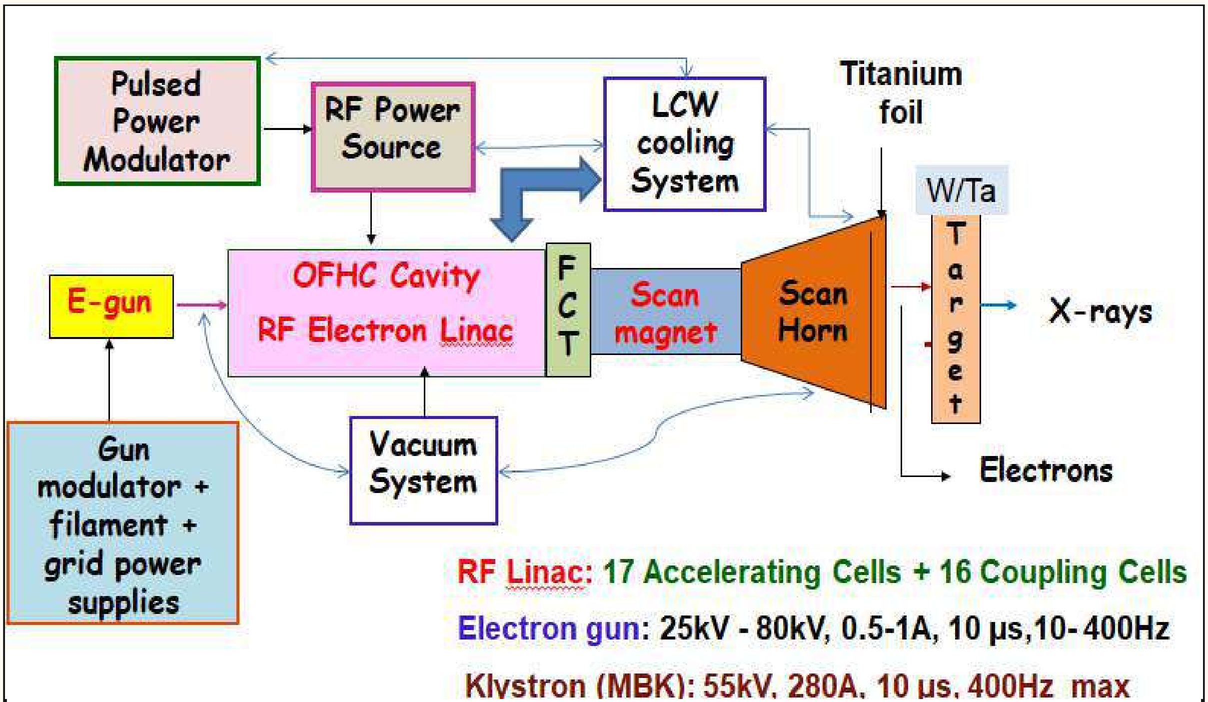


Fig.3 Schematic Block diagram of RF Linear Accelerator

Making scan horn to take care of these beam scanning without getting heated and holding vacuum for beam path many safety interlocks and sensors were incorporated learning search and scram method to close all entries to irradiation zone before starting the beam. An electromagnetic analyser was also built measure the beam energy before scan horn.

First 10MeV, RF Linear accelerator (LINAC) is commissioned in two floors, at first floor Linac was there from gun, cavity,vacuum, RF setup till beam optics) and in ground floor scan horn along with conveyor system are commissioned. After assembly EMI/EMC ssues were also resolved. This system is inaugurated by that time Priminister Shri Manmohan Singh, in 2008 as given in Fig.4.

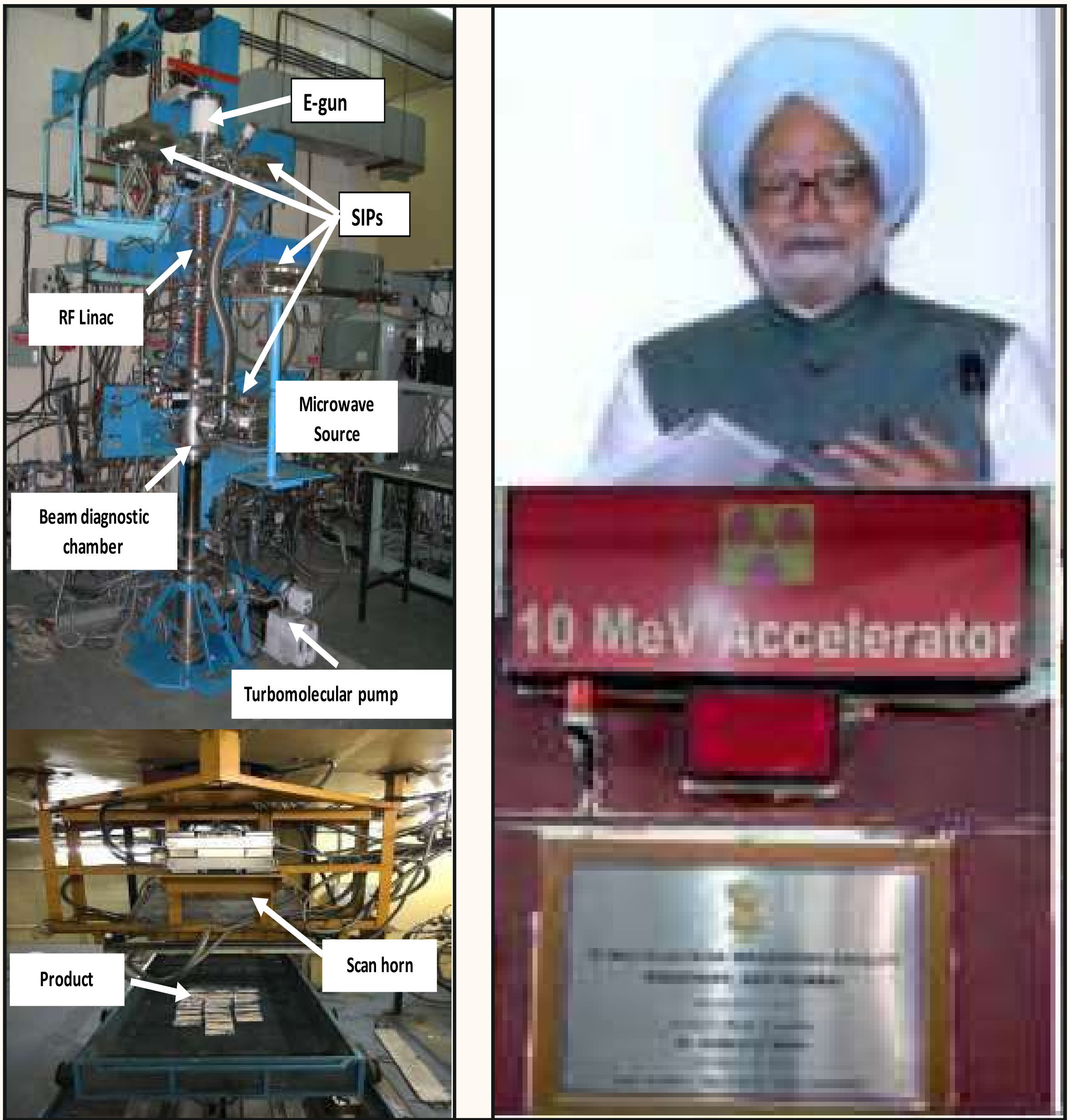


Fig.4 First Indigenous 10MeV RF e-LINAC inaugurated by PM Manmohan Singh, 2008 [For food, Agricultural and Industrial Application]

This facility is continuously being used by BARC scientists along with many prestigious institutes like ISRO, ICT, BTRA,VSI, BHEL, and industries for diverse applications. One more compact horizontal 9MeV, 1kW RF accelerator is developed and deployed at Electronics Corporation of India *ECIL) in Hyderabad for commercialisation. Recently it has been added with a newly designed Beryllium based neutron target to provide facility for n-radiography. Fig.5 illustrates the LINAC and target with n-radiography results showing water level inside a steel glass.

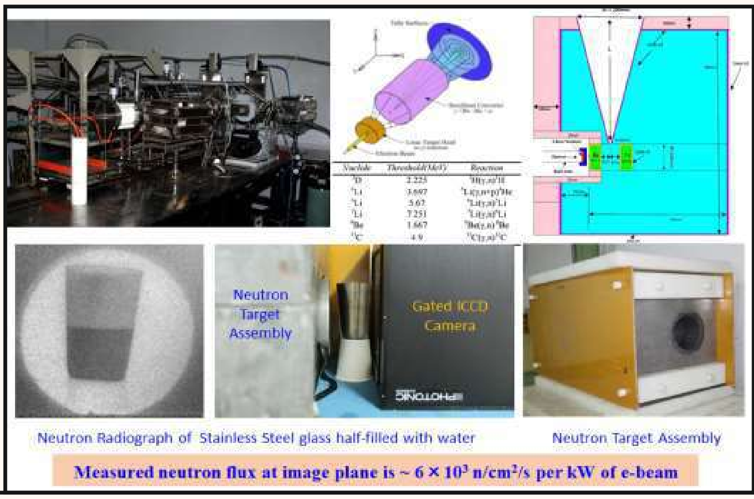


Fig.5 Horizontal 9MeV LINAC at ECIL, Hyderabad, for NDT and n–radiography results

This facility is kept below 10MeV to avoid neutron generation for electron beam and X-rays irradiation and NDT application. For n-radiography it can be appended to 15MeV also.

In continuation of DC accelerator development, different topology for HV multiplication is adopted for 3MV DC accelerator viz. Dynamatron type arrangements in which lumped capacitors are replaced with geometrical configuration of electrodes. It is designed and developed with fast recovery diodes and current limiting inductor assemblies. Typical sub-system of DC accelerator is illustrated in Fig.6. A Litz wire based high frequency (100kHz) transformer is developed for the first time with indigenous 100kHz oscillator. It has used 6m tall pressure vessel to use Nitrogen upto 8kg/cm2 pressure. Inside chamber there is arrangements for e-gun power supply using ripple of HV column at 1-3MV, inside HV dome. Beam is made to move through drift tube in vacuum around which guard rings are there for voltage equalisation.

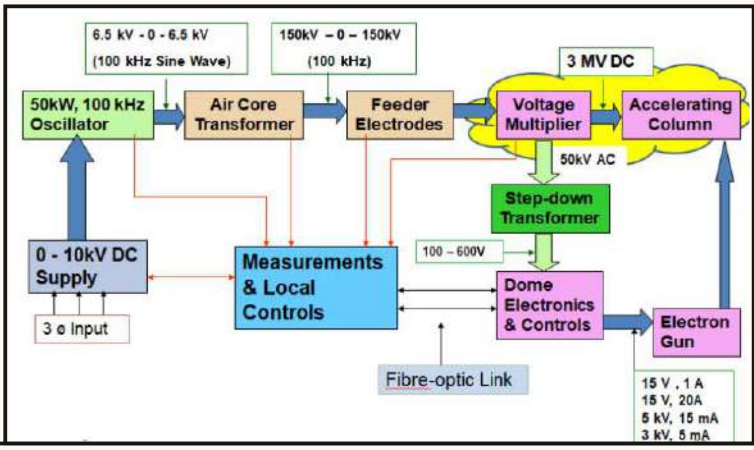
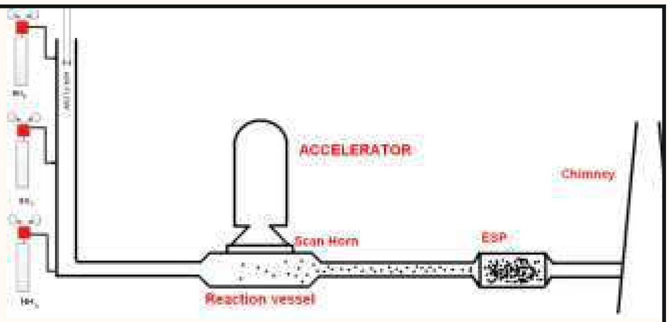


Fig.6 Block diagram of typical Dynamatron Type DC accelerator

This system is demonstrated for simulated flue gas irradiation by e-beam in presence of moisture and ammonia. The schematic is shown about simulation of gas thereafter sending through beam zone as indicated below in Fig.7.

Fig.7 Simulated flue gas facility at EBC



- 1 MeV, 3mA beam parameters and 450m^3/hr flow rate of simulated gas
- NOx is reduced from 20 ppm to 0.4 ppm
- At 450m^3/hr flow rate of simulated gas, SOx reduced from 100ppm to 60ppm
- Amonium-sulphate and Amonium-nitrate are collected in bag filter

The schematic is shown about simulation of gas thereafter sending through beam zone. Generation of OH(-) radicals facilitated to remove SOx and NOx simultaneously. It was inaugurated by That time Honourable President Shri Pranab Mukherjee on 2013 from CC Auditorium remotely as shown in Fig.8.

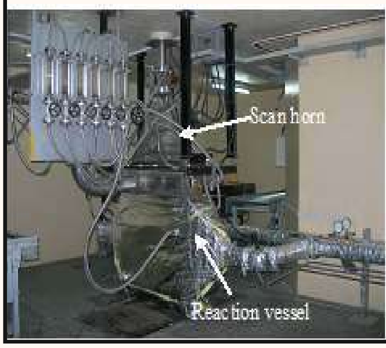


Fig.8 DC 3MV accelerator used for Flue has clean-up from SOx and NOx Inaugrated by President Pranab Mukherjee, Nov.15,2013

This work was done in collaboration with BHEL team. There after also many more applications were demonstrated like Rubber tiles treatment for SBC, degradation of solar panels with age for ISRO, paint curing, and wrinkle free rayon for industries. For water treatment , 0.7-1.5MeV DC accelerators are used, hence a few experiments are conducted for waste water treatment. In textile industries, removing Dye is very difficult and complex chemicals are hazardous for land and water bodies, hence making them biodegradable is the task. After many experiments in simulated dye water, parameters are optimised thereafter actual textie water was brought from Surat industries, and demonstrated for 10,000 litre at 1MeV,10kW operation with 1MLD throughput capacity. It was inaugurated by Honourable President Shri Ramnath Kovind, in 2018 as shown in Fig.9

Fig.9 DC Accelerator at 1MV,10kW for Textile/Dye water clean-up at 1MLD Inaugurated by President Ramnath Kovind, May15,2018

This facility is being upgraded to 1MV,100kW for 2MLD capacity. The system is being used for various type of waste water to reduce COD and BOD. Sample Tannery water is also treated and it was found that Chromium -6 could be converted into Chromium-3, under irradiation with controlled parameters. Thereafter, an MoU has been signed between BARC and Natioal Mission of Clean ganga (NMCG) for deployment of this facility at CET,Unnao site for waste water treatment.

National Border Security needs full body cargo scanner is imported, hence an indigenous solution is needed from LINAC till image processing. Thus amuti group task is taken up within BARC and portal type 6MeV RF LNAC based is developed with semiconductor detector arrays and indigenous software to show the images. In this facility LINAC produced beam is converted into x-rays and suitably collimated with required dose stability. Gun and other components were properly aligned, tested separately for vibration movement before installation to do required changes at design level. This facility is qualified as per ANSI 42.46 as shown in Fig.10

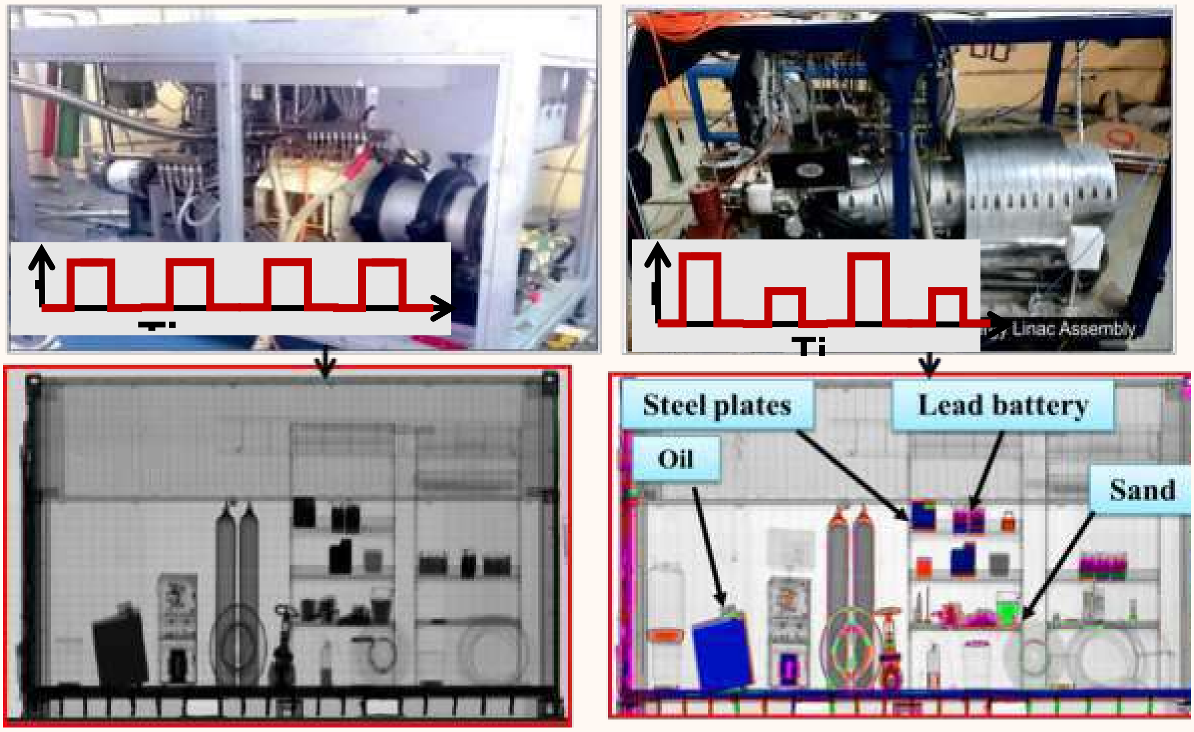


Fig.10 Portal type 6 MeV LINAC and Dual Energy 6/4 MeV based Cargo Scanner

This LINAC was operated at 4MeV-6MeV; meeting all the criteria as required for any imported system during Factory Acceptance Test (FAT) as per global standards. In order to increase the throughput (trucks/hr) and material discrimination capability interlaced dual energy is required and next development has been taken up. In 2021 it has been first qualified in electron beam centre then installed within BARC site to show full scale Indigenous Cargo Scanner (ICS) in gantry mode and qualified ANSI 42.46, IEC62523 as indicated in Fig.11

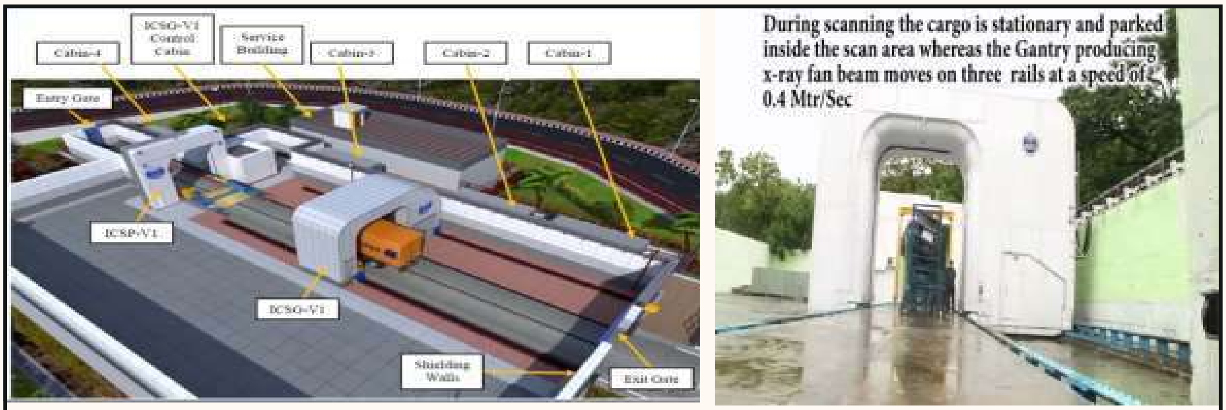


Fig.11 Gantry Type Dual Energy Linac based Cargo Scanner

After making so many accelerators, Transfer of Technology (ToT) has been taken up, and with all available resources documents were compiled and many companies were given ToT on non exclusive basis. It was also felt , if there will be many accelerators there should be accelerator simulator for new operators and refresh skill. hence, first time industrial accelerator operator training simulator has been developed for DC Accelerator, RF LINAC and ICS operation with in house engineers of EBC, a s shown in Fig.12.

Fig.12 Accelerator simulator For Operator's Training
Inaugurated on Feb.9, 2021

Electron beam accelerator s used by BARC has been developed along with many radiation processing for food, agriculture, environment and industries. In EBC, 10MeV, 3kW, RF LINAC is continuously is being used by multiple users from industries, researchers and academia. To go for high power beam, it was analysed, RF cavity needs some change in thermal management. Thus a table top compact 10MeV,5kW RF LINAC is developed Fig.12.

Fig.12 Photograph of X-band 6MeV LINAC Test setup

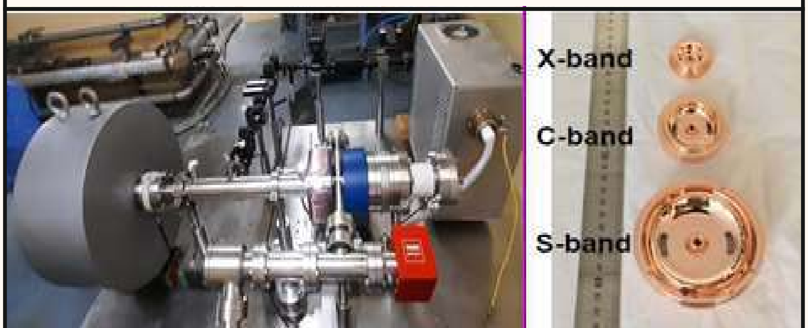


Fig.13Photograph of X-band 6MeV LINAC for medical application

To make LINAC compact for medical applications X-band 6MeV is designed, developed and beam operation is in progress to meet stability criteria as shown in Fig.13. In Amril kaal it is envisaged that 30-50MeV LINAC will be developed for RIB generation and n-ToF applications.

Conclusion

Electron Beam Centre, Beam technology Development Group [BTDG] has developed many types DC- RF electron accelerators and radiation processing as well. The complete know how of this technology has been transferred on non inclusive basis to many industries as per DAE norms. A few MoU is also under progress for field trials under inter-ministry collaboration. Electron Beam Centre, accelerators operational for multi-disciplinary process development. This centre is regularly used as educational visit for students, faculty, farmers and industries for awareness. R&D Program are being continued for X-band medical LINAC and 30MeV LNAC for RIB studies. Development so far can be commercialised by Industry partners with BARC handholding on technology till export potential.

Acknowledgment

Author expresses her sincere gratitude to Director BARC, Chairman, AEC and Secretary, Department of Atomic Energy for continuous support this indigenous technology from design, development, demonstration to deployment. Thanks are also extended to all BTDG colleagues, superannuated seniors, collaborators of BARC, R&D institutes and Industries for making this technology matured enough to get deployed.

Appendix:1. Typical electron energy and dose required for various applications and cost

Applications	Energy (MeV)	Dose (kGy)
Food Preservation	5-10	0.5-1.0
Disinfesting of Grain	1	**0.5-1.0**
Fungi, bacterial control	1-10	1.5-3.5
Sterilization of Medical Prods	**1-10**	≥25
Grafting monomers	0.3-10	**20-50**
Crosslinking of polymers	2-10	**50-350**
Degrading polymers	2-10	**50-1000**
Curing of Coatings on wood	**0.15-0.5**	**20-500**
Cargo scanning, radiography	Up to 6	1-6
Purification of Exhaust Gases	0.5-1.5	10-15
Cancer treatments	4-18	Few Gy (approx..)

Present Throughput capacity of EBC facility:

Application	Dose (kGy)	Through put
Food items (Onion, potato, mango etc.)	0.1 – 1.0	50 tons / h
Food product (spices, onion powder etc.)	10 - 14	0.6 tons / h
Medical product	25	0.25 tons / h
Polyethelene O-ring	300	20000 Nos. / h
Power diode irradiation	4	12000 dio / h

COST/ECONOMICS:

(i) 10 MeV, EB Mode costs Rs. 0.37 per kg (Onion)
(ii) 10 MeV, EB Mode costs Rs. 4.0 per kg (Spices)
(iii) Typical Dye Waste Water Treatment 16 Rs/kiloliter

Appendix:2- Dose limits Approved by government of India

भारत का राजपत्र
The Gazette of India

EXTRAORDINARY

PART III—Section 4

PUBLISHED BY AUTHORITY

NEW DELHI, FRIDAY, AUGUST 26, 2016/BHADRA 4, 1938

MINISTRY OF HEALTH AND FAMILY WELFARE

(Food Safety and Standards Authority of India)

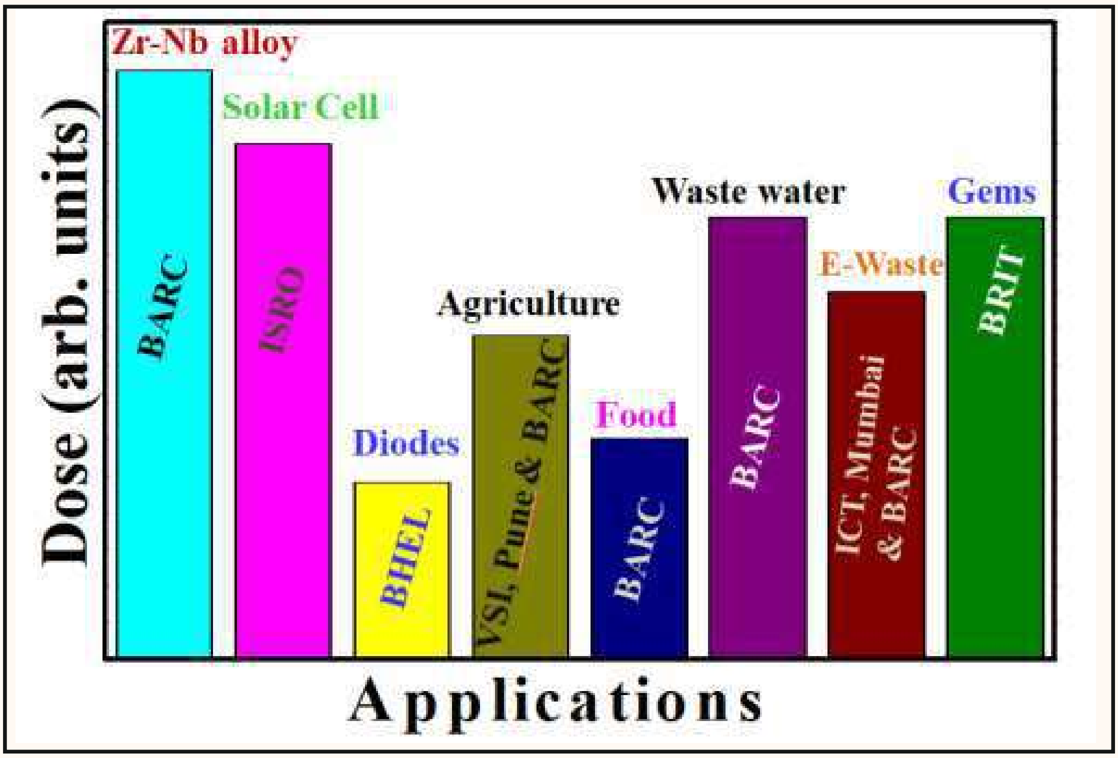
NOTIFICATION

New Delhi, the 23rd August, 2016

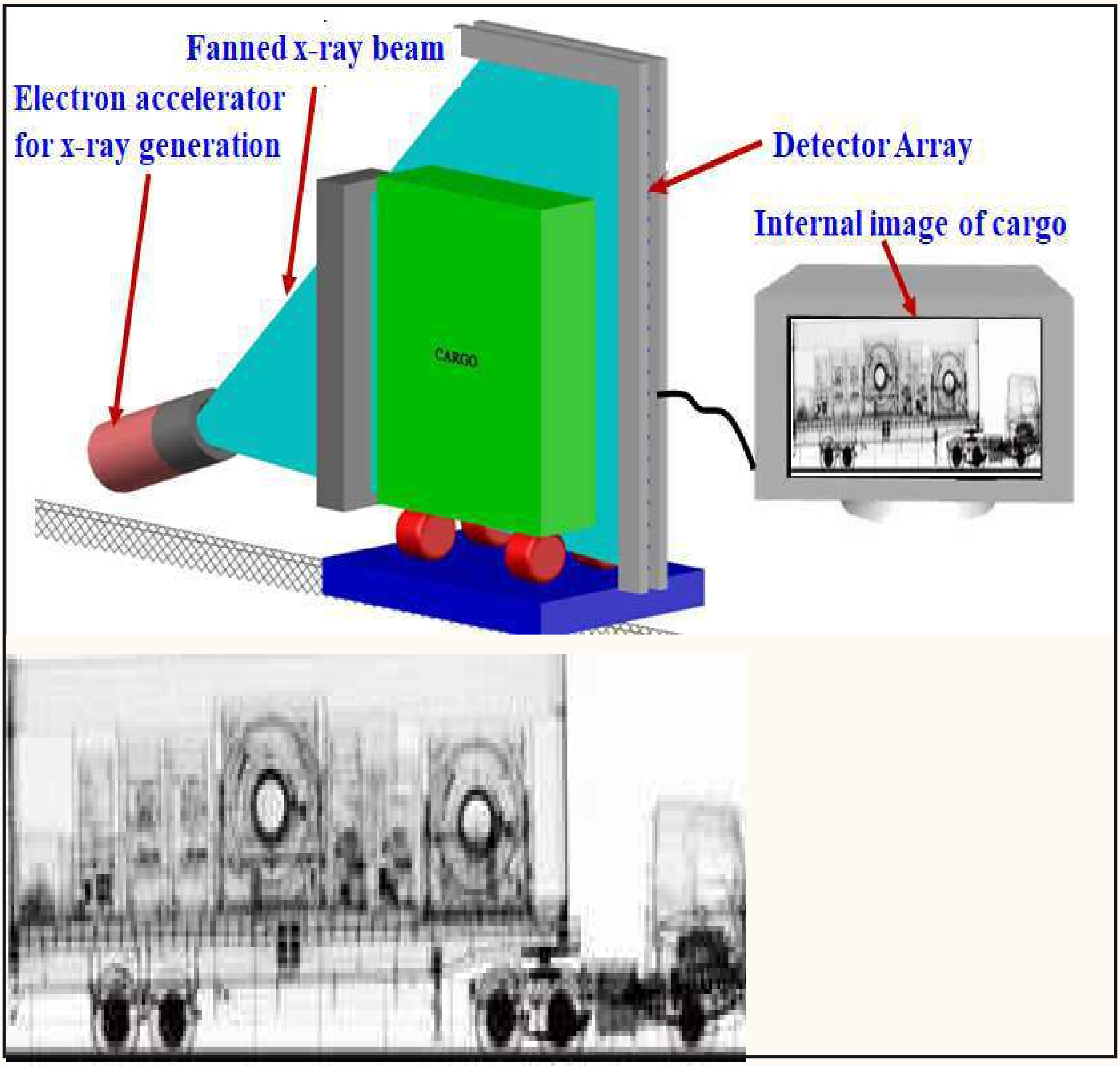
Table 1: Classes of Food Products and Dose Limits for Radiation Processing

Class	Food	Purpose	Dose Limit kGy (kilo Gray)	
			Minimum	Maximum
1	2	3	4	5
Class 1	Bulbs, stem and root tubers and rhizomes	Inhibit sprouting	0.02	0.2
Class 2	Fresh fruits and vegetables (other than Class 1)	Delay ripening	0.2	1.0
		Insect disinfestation	0.2	1.0
		Shelf -life extension	1.0	2.5
		Quarantine application	0.1	1.0
Class 3	Cereals and their milled products, pulses and their milled products, nuts, oil seeds, dried fruits and their products	Insect disinfestation	0.25	1.0
		Reduction of microbial load	1.5	5.0
Class 4	Fish, aquaculture, seafood and their products (fresh or frozen) and crustaceans	Elimination of pathogenic micro organisms	1.0	7.0
		Shelf -life extension	1.0	3.0
		Control of human parasites	0.3	2.0
Class 5	Meat and meat products including poultry (fresh and frozen) and eggs	Elimination of pathogenic microorganisms	1.0	7.0
		Shelf -life extension	1.0	3.0
		Control of human parasites	0.3	2.0
Class 6	Dry vegetables, seasonings, spices, condiments, dry herbs and their products, tea, coffee, cocoa and plant products	Microbial decontamination	6.0	14.0
		Insect disinfestation	0.3	1.0
Class 7	Dried foods of animal origin and their products	Insect disinfestation	0.3	1.0
		Control of moulds	1.0	3.0
		Elimination of pathogenic micro organisms	2.0	7.0
Class 8	Ethnic foods, military rations, space foods, ready-to-eat, ready-to-cook/minimally processed foods.	Quarantine application	0.25	1.0
		Reduction of microbial load	2.0	10.0
		Sterilization	5.0	25.0

Appendix-3 Utilisation of Indigenous Accelerator for developing Radiation processing



Appendix-4 Typical LINAC based cargo scanner



It can be used (i) for misdeclaration,

(ii) Suspicion generation based on density/texture differences

(iii) To stop Human/weapon trafficking

NO X-rays source can detect narcotics or explosive that needs special detectors based on NAA or GC etc.

Book Review: Nuclear Fuel Cycle

B.S.Tomar[1] and P.R.Vasudeva Rao[2]
[1]Former, Director RC&IG, BARC and Institute Chair Professor, HBNI
[2]Former, Director IGCAR and Former, Vice Chancellor, HBNI

The book on Nuclear Fuel Cycle, edited by B.S.Tomar, P.R.Vasudeva Rao, S.B.Roy, Jose Panakkal, Kanwar Raj and A.N.Nandakumar, under the auspices of Homi Bhabha National Institute and published by Springer recently, has been written keeping in mind the students coming out of Universities after their graduation / post-graduation and who wish to join the nuclear industry or engage in R&D in areas related to nuclear fuel cycle. The book will also be useful to those practicing nuclear science and engineering and engaged in different nuclear fuel cycle activities. The present article gives an overview of the book for the benefit of the members of Indian Nuclear Society in particular and the members of science and engineering disciplines in general. The foreword of the book has been written by Dr. Anil Kakodkar, Chancellor, Homi Bhabha National Institute and Former Chairman Atomic Energy Commission.

Chapter-1: This chapter begins with a brief introduction to the nuclear fuel cycle, followed by description of what is meant by front end and back end of the fuel cycle. The chapter also describes different categories of nuclear fuel cycles based on the strategies for reuse of the fuel in open and closed fuel cycles and their impact on nuclear waste management. Finally the chapter provides glimpses of the prevailing international scenario on nuclear fuel cycle.

Chapter-2: This chapter gives a detailed account of the exploration, mining, milling and processing of uranium. The various methods employed to explore uranium ore deposits are described, which include remote sensing, radioactivity measurement, gravity, electrical and magnetic methods. This is followed by different types of mining methodologies, viz., open pit mining, solution mining, and underground mining. The different types of methodologies of leaching in terms of the operational mode are described in detail, such as, atmospheric leaching, autoclave leaching, in-situ leaching, pug cure leaching, heap leaching. The chapter also describes the various methodologies which are being used for separation of isotopes of uranium, mainly, fissile (^{235}U) and fertile (^{238}U) isotopes.

Chapter-3: This chapter gives a detailed description of the fabrication methodologies for different types of fuels, viz., ceramic fuels (which include, oxides, mixed oxides, non-oxide fuels) and metallic fuels. The flowsheets for fabrication of UO_2 fuel bundles are described in detail. Similar processes for fabrication of mixed oxide fuels (MOX), based on oxides of (U, Pu), (Th, U) have been described. Fabrication of non-oxide fuels, such as, metallic alloy fuels, mixed carbide and mixed nitride, and fabrication of dispersion fuels of different types, viz., metal-metal (METMET) fuels, ceramic-metal (CERMET) fuels, ceramic-ceramic (CERER) fuels, have also been described. Lastly, the advances in fuel fabrication methodologies, particularly in fabricating accident tolerant fuel assemblies, and automation in fuel fabrication have been touched upon briefly.

Chapter-4: This chapter deals with the stringent quality control checks on fuel fabrication at various stages. Physical quality control techniques employed to qualify the final fuel element, including characteristics of the powder used in fuel fabrication, physical inspection of the fuel pellets, and measurement of density, linear mass, dimensions and surface defect have been described. The metallography of the fabricated fuel has been described in detail, followed by radiography testing which provides information about the discontinuities such as cracks or voids in the fuel. Further the chapter describes various chemical quality control measures employed for the qualification of the fuel, including the measurement of heavy element (uranium, plutonium, etc.) content, isotopic composition, phase analysis, oxygen to metal ratio, etc., and also various techniques employed for assay of trace elements. Other tests, such as, total gas analysis, dissolution test, weld chemistry test and cover gas analysis have also been touched briefly.

Chapter-5: This chapter describes the thermo-physical and thermo-chemical properties of the nuclear fuels, including the phase equilibria of the various nuclear fuel materials. The chapter discusses various allotropes of uranium, plutonium, zirconium and the phase equilibria in the binary systems, viz., U-Pu, U-Zr, Pu-Zr, U-Al, U-Si, etc., as well as the ternary systems U-Pu-Zr among the metallic fuels. Among the oxide fuels, phase equilibria in various systems, namely, U-O, Pu-O as well as U-Pu-O, and U-Th-O systems have been described in detail. Similar phase equilibria have been described in the case of carbide and nitride fuels based on U and Pu as well as their ternary systems. The solubility of critical impurities such as oxygen in fast reactor fuels (carbides, nitrides) have also been discussed briefly. The second part of the chapter, deals with the thermophysical properties of nuclear fuels, viz., thermal conductivity, thermal expansion, heat capacity of fuels, their vaporization characteristics and the thermochemical aspects of the fuels as well as fission

products. O/M oxidation states, alloy phases, etc. with regard to metallic as well as ceramic fuels have been described.

Chapter-6: This chapter deals with the examination of the fuel post irradiation in the reactor. The chapters begin with a description of various types of Post-Irradiation Examination (PIE), namely, on-line inspection, pool-side inspection, and inspection in hot cells. This is followed by a brief description of the types of inspections carried out on irradiated solid nuclear fuels for assessing fuel swelling, irradiation growth, in-pile densification, fission gas release behaviour, microstructural changes as well as redistribution of fuel constituents and fission products. A brief description of irradiation effects on fuel cladding has also been added. This is followed by various non-destructive testing techniques for PIE, which include, visual examination, leak testing, profilometry, gamma scanning and gamma spectrometry, eddy current testing, ultrasonic testing and radiography. Destructive techniques of PIE include, fission gas release measurement and analysis, microscopic examination, autoradiography, burn-up estimation, etc. As PIE is mostly done in hot cells, radiological safety and shielding are of paramount importance. This aspect is also adequately covered in this chapter.

Chapter-7: This chapter on nuclear fuel reprocessing begins with a brief description and the need for nuclear fuel reprocessing as well as its role in closing the nuclear fuel cycle. After ~~a~~ describing the aqueous chemistry of actinides, the authors have given historical development of the reprocessing of U-Pu based fuels including different separation methods, e.g., precipitation, solvent extraction, etc. Engineering aspects of the different solvent extraction equipment are described. Subsequently a more detailed description of the well-known PUREX process has been covered. The chemistry of some of the fission products, such as Ruthenium, Zirconium and Technetium, which add to the complexity of the process, has been described. The chapter also touches upon the reprocessing of thorium based fuels including its historical significance. The chapter also deals with the unique features in reprocessing of fast reactor fuel and various challenges in the process due to high fuel burn up and high content of noble metals. Lastly the non-aqueous reprocessing of future molten salt fuel as a part of advanced fuel cycles has been touched up on in the conceptual form.

Chapter-8: This chapter on radioactive waste management begins with the objective and basic philosophy of radioactive waste management. The classification of the radioactive wastes into low level waste (LLW), intermediate level waste (ILW) and high level waste (HLW) is explained in detail. This is followed by a description of the basic steps in radioactive waste management, from segregation and pre-treatment to final storage/disposal. Detailed methodologies for management of various types of waste have been described. A section has been devoted for describing the recovery of useful radioisotopes such as ^{137}Cs, ^{90}Sr and ^{106}Ru from HLLW. The separation of minor actinides present in the HLW has also been described. Significant details of the processes involved in the vitrification of the HLW, namely matrix design, glass formation and the studies towards its chemical durability as well as the engineering aspects of the various melters are given in the chapter. The processes for management of gaseous and solid radioactive wastes have also been described in detail. Lastly the different types of disposal facilities for solid wastes, namely, near-surface as well as deep geological disposal facilities have been described in detail. The important topic of deep geological repository and the associated aspects, such as, criteria for the site selection, the host rock, and its performance assessment have been described.

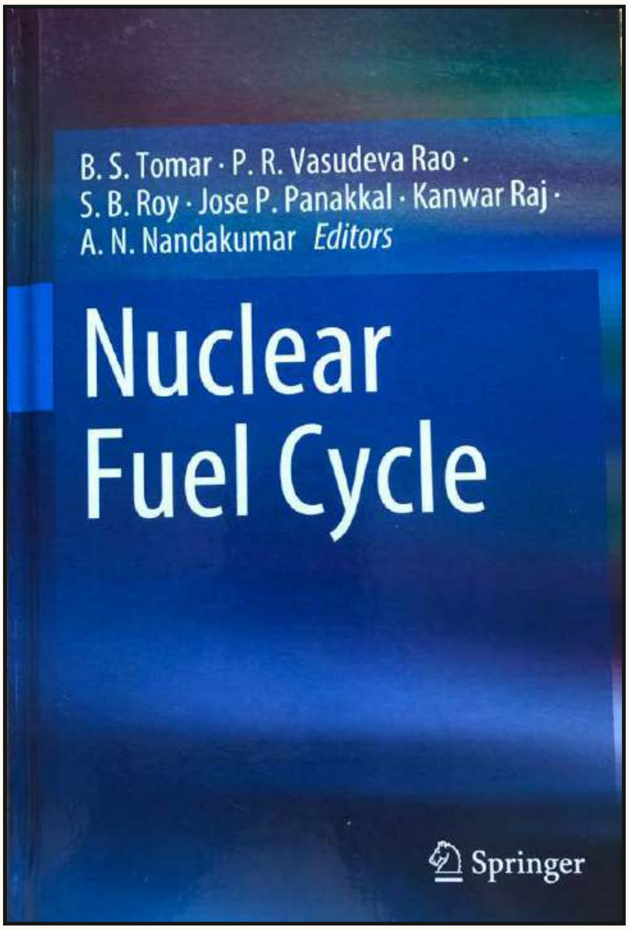
Chapter-9: This chapter deals with the nuclear material accounting and control (NUMAC), which is an important component of nuclear safeguards. After a brief description of requirement of nuclear safeguards, the different nuclear materials and their critical mass, the basic concepts behind the nuclear material accounting are explained. The different types of facilities, such as item handling and bulk handling facilities from NUMAC perspective have been described. This is followed by explanation of the different terms in NUMAC, and the reporting system. Fundamentals of statistical aspects in nuclear material accounting and statistical treatment of uncertainties associated with MUF (Material Unaccounted For) have been described. Destructive and non-destructive methods for taking physical inventory and verification of nuclear materials have been described along with the international target values for the uncertainties. The chapter ends with a brief description of the measurement control programs required for monitoring and controlling the quality of measurements of special nuclear materials as well as the techniques for containment and surveillance of the nuclear material under safeguards.

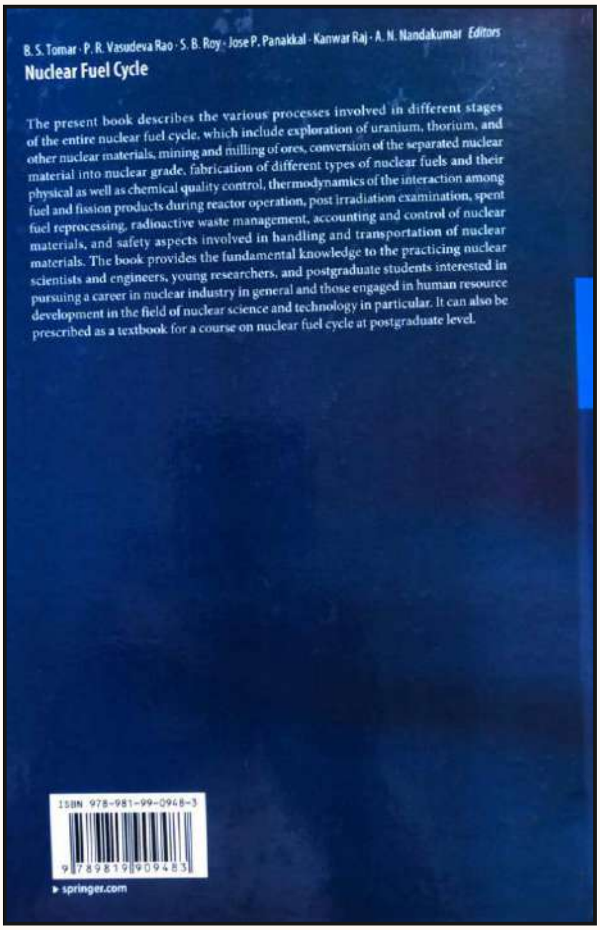
Chapter-10: The chapter on transport and storage of nuclear materials gives the information about the radiological safety measures to be taken into account during the transport of radioactive materials. The chapter begins with introduction to transport of nuclear materials, relevant to the front as well as back end of the nuclear fuel cycle. The philosophy behind the radiation protection of the public as well as the personnel responsible for the transport as well as built in inherent safety against radiological risks while transporting radioactive materials are described. The chapter also describes the different types of packaging used for transport of different radioactive materials, viz., excepted packages, industrial package, Type A, B and C packages as well as packages containing fissile materials. This is followed by different tests for the packages to withstand the normal as well as accidental conditions during transport. Finally a brief description of the emergency response in case of any untoward event has been covered.

Chapter-11: This chapter provides fundamental knowledge about the radiation and radiation protection while handling with radioactive materials. The chapter is divided into two parts. Part-I begins with description of units of radioactivity, radiation exposure and radiation absorbed dose and equivalent dose. A brief discussion on biological effects of radiation is followed by principles of radiation protection. Part-II deals with the application of the principles of radiation protection in nuclear facilities with a detailed description of how radiological facilities are divided into different zones depending upon the radiation levels and quantity of radioactive materials. Special safety requirements considered in different nuclear facilities have also been described.

It is significant to note that the ~~book~~ chapters in the book have been written by experts chosen from various units of DAE, both serving and retired. The expertise of the authors has ensured that current developments are covered adequately and at the same time, a broad perspective of the entire subject is brought out. To ensure the accuracy of content and adequacy of coverage, the book chapters went through independent review by experts. The Editorial Board has put in its best efforts to ensure that the technical content is at a level suitable for the intended readership and a balance is maintained between different chapters.

The book is available in e-book is well as hardcopy format from Amazon as well as directly from Springer.





Do You Know?

In India we talk of energy security in terms of nuclear fuel! It is not realised by many that Uranium material used in U.S. nuclear power reactors is largely imported because it's cheaper to buy from other countries. In 2022, 95% of the uranium purchased by U.S. nuclear power plant operators originated in other countries. USA imports 41% of share of world uranium and China's share of imports is 52% . Together they gobble 93 percent of world uranium!

Dr. M.R. Iyer

Highlights: One day workshop INS Public Outreach Programme on Nuclear Energy for Heath, Environment and Development (INS-NEHED23)

The INS-NEHED23 workshop was organized by INS Mumbai in association with IIT (BHU) and BHU at IIT (BHU) on October 14, 2023 The workshop was hosted by IIT(BHU) and co-hosted by BHU and the speakers were from INS, IIT (BHU) and BHU. It provided a comprehensive overview of the benefits, challenges, and future prospects of nuclear energy as a sustainable and reliable power source. Throughout the session, participants engaged in meaningful discussions and exchanged valuable insights.

Key Takeaways:

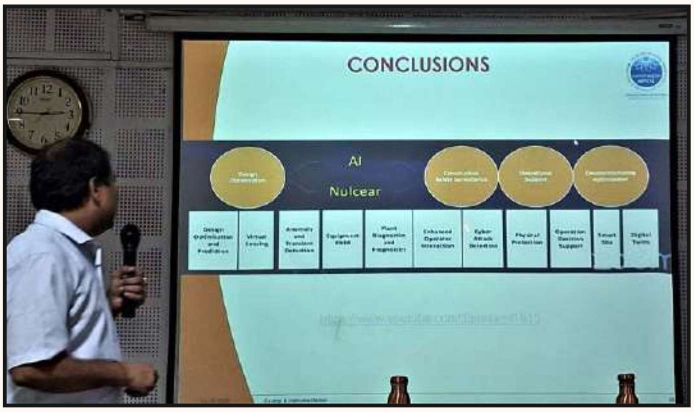
1. Nuclear Energy for sustainable development: Nuclear Science and Technology help countries to reduce poverty and hunger, generate electricity, manage water resources, treat diseases such as cancer and respond climate change – and much more.
2. Safety and Regulations: Safety remains a crucial consideration in the deployment and operation of nuclear power plants. The workshop emphasized the importance of stringent regulations, robust safety protocols, and continuous monitoring to ensure the well-being of both the environment and surrounding communities.
3. Carbon Reduction: Nuclear energy emerged as a vital tool in combating climate change. Its ability to generate large amounts of electricity with minimal greenhouse gas emissions makes it a crucial component of any low-carbon energy portfolio.
4. Artificial Intelligence (AI) Applications in Nuclear Energy: Nuclear power provides a reliable and consistent energy source, reducing dependence on fossil fuels and enhancing energy security. Its capacity to generate power continuously, regardless of external factors such as weather conditions, contributes to grid stability. The exponential growth of AI technology in recent decades has resulted in new opportunities and challenges in terms of improving the safety and economics of nuclear power plants. Potential AI applications include equipment prognostics, reactor design optimization, more precise reactor autonomous control and operation, nuclear safety analysis and accident management.
5. Nuclear Waste Management: Effective and safe disposal of nuclear waste is a key concern. The workshop explored advanced waste management techniques, such as reprocessing and deep geological repositories, and emphasized the importance of ongoing research and development in this field.
6. Technology and Innovation: The workshop highlighted the role of technological advancements in enhancing nuclear energy's safety, efficiency, and cost-effectiveness. From next-generation reactors to advanced fuel cycles, innovation is instrumental in shaping the future of nuclear power.

Moving Forward:

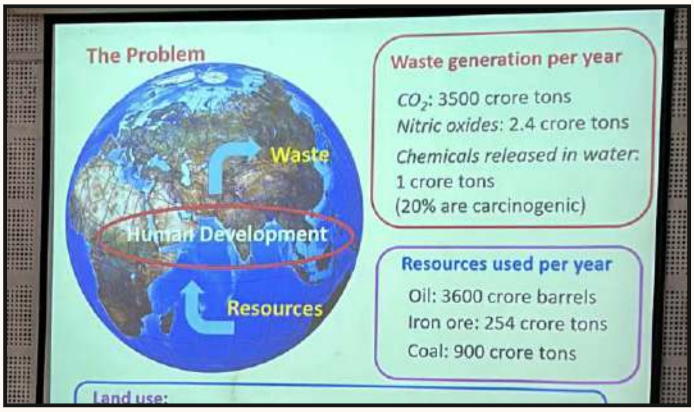
The workshop provided a platform for stakeholders to collaborate, share experiences, and exchange best practices. To capitalize on the potential of nuclear energy, continued investment in research and development, public education, and policy support were identified as key areas of focus. The workshop also encouraged the participants to work on the related areas and offered them to join INS to keep them updates in the related technology. INS also looks forward to start a INS-Chapter in Varanasi, after realizing the enthusiasm of the participants.

In conclusion, the nuclear energy workshop served as an enlightening and productive forum to explore the various facets of nuclear energy. By fostering dialogue and encouraging collaboration, participants created a foundation for harnessing the benefits of nuclear power while addressing concerns and challenges. The insights gained from this workshop will undoubtedly shape future discussions and decisions regarding the integration of nuclear energy into our sustainable energy mix.

Inauguration of INS-NEHED 23



Artificial Intelligence in Nuclear Safety



A slide from
Prof. BN Jagatap's talk

Shri S. Malhotra
delivering his talk

Dr Tyagi, BHU
delivering his talk on Neutrons

INS-Seminar

An INS-seminar was arranged on 16-09-2023 on 'Nuclear Hydrogen Towards Quest for Net Zero' by Shri K. T. Shenoy, Director, Chemical Engineering Group, BARC, Mumbai, at AERB Auditorium, Niyamak Bhawan-A, Anushaktinagar, Mumbai.

Highlights:

Hydrogen is increasingly seen as a key component of future energy systems if it can be made without carbon dioxide emissions. It is being increasingly used as a transport fuel, despite the need for high-pressure containment. Hydrogen also has future application as industrial-scale replacement for coke in steelmaking and other metallurgical processes.

Nuclear energy can be used to produce hydrogen in several ways: Cold electrolysis of water, using off-peak capacity, Low-temperature steam electrolysis, using heat and electricity from nuclear reactors, and

High-temperature steam electrolysis, using heat and electricity from nuclear reactors

A single 1,000-megawatt nuclear reactor could produce more than 150,000 tonnes of hydrogen each year. Just ten nuclear reactors could provide about 1.5 million tonnes annually, which is 15 percent of current hydrogen produced in the United States2.

Left: Prof BN Jagatap, President INS introducing Shri KT Shenoy, who is delivering his talk (Right)

Audience at the Seminar

Shri KT Shenoy being felicitated by Dr. Rama Rao (left) and Dr. S. Gangotra (right)

The views and opinions expressed by the authors may not necessarily be that of INS.
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