An Integrated Approach for Safer, Productive and Reliable PHWR fuel manufacturing at NFC

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Abstract: India has been pursuing three-stage nuclear power programme and has developed comprehensive capabilities in all aspects of nuclear power and fuel cycle and is now recognized as a country with advanced nuclear technologies in the comity of nations. The first stage of Pressurized Heavy Water Reactors (PHWRs) based on natural uranium has reached a state of maturity. In view of civilian nuclear safeguards agreement with NSG and IAEA, Nuclear Power Reactors in India and associated fuel manufacturing facilities at Nuclear Fuel Complex (NFC) are grouped into IAEA safeguarded and out-of-safeguarded facilities. The civilian nuclear energy generation has to be accelerated for achieving energy security for the country. NFC has pioneered manufacturing technologies of UO2 fuel, fuel clad and structural components for the PHWRs 220, 540 and PHWR700. Nearly 20 GWe of nuclear energy generation is being planned through PHWR route. Several technological improvements that were carried out recently in the production lines are the key to achieve higher productivity and safety. NFC has also been pursuing capacity augmentation by adding newer equipment in the existing facility and setting up new plants both for uranium production as well as zirconium production.

Flexible manufacturing systems consisting of automatic workstations and robots were introduced in the 19 and 37 element PHWR fuel assembly lines. Various safety measures were introduced right from design stage for improving radiological safety for workmen. State-of-art equipment were designed, developed and commissioned for reduction/ elimination of fatigue-oriented operations.

In addition to natural uranium oxide fuel, NFC has also successfully manufactured virgin slightly enriched uranium (SEU) fuel and reprocessed depleted uranium fuels which were irradiated in the operating PHWRs.

The paper brings out NFC's role in Indian nuclear power program and its manufacturing capabilities for types of PHWR fuel, zircaloy structural and the recent advances made in the production line.

1.0 Introduction

Nuclear Fuel Complex (NFC) is the sole fuel manufacturing facility in India that caters uranium di-oxide (UO_2) fuel to all the water cooled power reactors operating in the country. By adopting self-reliant indigenous technology, NFC has fast grown to an international standard fuel manufacturing company and presently manufacturing over 800MT natural uranium di-oxide fuel annually that caters to the eighteen operating PHWRs. In line with the growth plan of nuclear power in India through induction of 700MWe PHWRs, NFC has been augmenting the production capacity for production of UO_2 powder, UO_2 pellet and fuel assembly to produce about 950MT PHWR fuel annually.

NFC's fuel customer the Nuclear Power Corporation of India Limited (NPCIL) is presently operating 21 nuclear power reactors with an installed capacity of 5780 MW in the country. The reactor fleet comprises of two BWRs, eighteen PHWRs and one 1000MWe capacity PWR that has already attained criticality. Currently it has four 700MW capacity PHWRs under various stages of construction. NPCIL has achieved about 379 reactor years of experience in safe operation of nuclear power plants. Highest ever nuclear power gross generation of 32863 MUs was achieved in the year 2012-13.

As a part of development of advanced fuels for PHWRs, an SEU fuel design has been developed. About fifty such bundles were fabricated by NFC and tested in-pile in one of the PHWRs. The bundles have successfully completed their irradiation. The maximum burn up achieved is approx. 25000 MWd/TeU.

Closed fuel cycle involving reprocessing of PHWR spent fuel has been adopted by India that supports fast breeder reactor program in the country. NFC has pioneered fabrication of reprocessed depleted uranium fuel used for flux flattening during initial start up. The reprocessed fuel containing approx.0.6%U235 has also been judiciously used in the PHWRs for contributing to power generation. Dry processing of higher uranium oxides to uranium di-oxide powder, controlled material handling with local shielding, additional dust containment measures, etc. were innovated for controlling the radiological hazards associated with the reprocessed uranium. Hundreds of reprocessed depleted uranium (RU) fuel bundles were fabricated by NFC, which were loaded in different 220 MWe and 540 MWe PHWRs.

Production line of pellet and assembly produces both 19 element fuel and 37 element fuel for 220MWe and 540MWe PHWRs respectively. Mechanization efforts have been implemented for handling of powder and pellets. Flexible manufacturing systems comprising of automatic work stations and robots were introduced in the19 and 37element PHWR fuel assembly lines. State of the art equipments were designed, developed and commissioned for reduction/ elimination of operators' fatigue.

In view of civilian nuclear safeguards agreement with NSG and IAEA, nuclear power reactors and associated fuel manufacturing facilities at NFC are grouped into (i) IAEA safeguarded and (ii) out of IAEA safeguarded facilities. The IAEA safeguarded facilities comply with IAEA material identification and uranium material accounting requirements. Though Uranium Ore Concentrate (UOC) and a part quantity of sintered UO2 pellets are being imported for the safeguarded facility, the entire UOC raw material for out of safeguard facility is received from the Indian source in the form of MDU and other concentrate forms.

The growth of PHWRs in the country as shown in Fig.1 has been possible due to the matching growth of production of PHWR fuel at NFC.

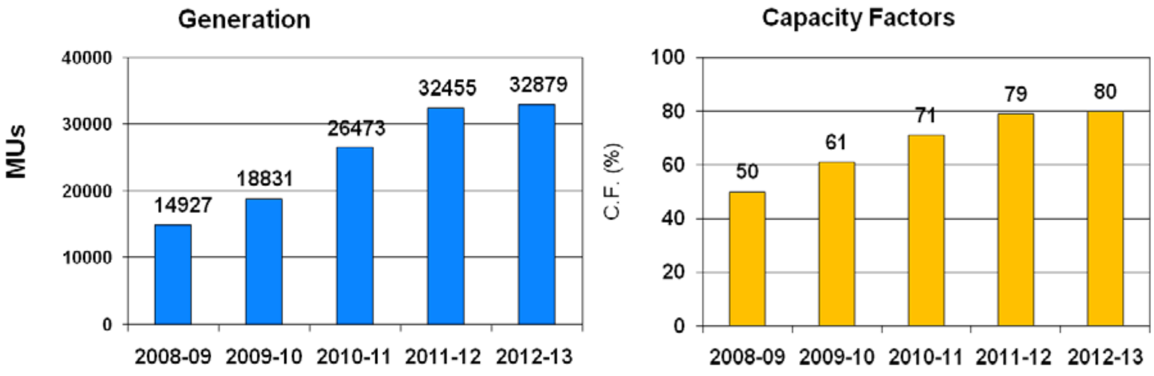

Fig.1: Overall performance of the operating PHWRs

2.0 Need to Increase the Production Capacity

Considering the fuel requirements of the forthcoming 700MWe units also, NFC is working towards raising the capacity further and marching towards achieving a total production capacity of about 1500 TPY which includes setting up of one more unit of NFC with a capacity of 500 TPY. The capacity requirements towards PHWRs would be further increasing in future as projected in Table-1.

Indian Nuclear Power Generation Through PHWRs (Present & Future)				
Category	Capacity (MWe)			Uranium Requirement (TPY)
	Present	Future	Total	
PHWRs				
Safeguarded (Imported)	1620	8380	10000	2000
Un-Safeguarded	2840	7160	10000	2000

Table-1 Future requirement of fuel for PHWRs

Towards this, NFC has already established a new zirconium sponge production facility that produces 250TPY zirconium sponge. In addition, activities for manufacturing fuel and core structural are also being firmed up for additional PHWR 700 MWe units, which are scheduled to be online by 2020. During 2020s, NFC would be engaged in manufacturing annually around 50,000 numbers of 19-element fuel bundles for PHWR 220 Units and around 67,000 numbers of 37-element fuel bundles for PHWR 540/700 Units.

In addition, various reactor core structurals like Coolant Channels, Calandria Tubes, Reactivity Mechanisms, Garter Springs for PHWRs and Square Channels for BWRs are also manufactured at the Complex. NFC is self sufficient in manufacturing zirconium alloy products right from production of zirconium oxide powder, zirconium sponge and melting of alloy ingots. The production capacity of the zircaloy structural components has also been augmented accordingly. In addition, NFC has recently placed on record its unique capability in manufacturing steam generator tubes for PHWR700.

While all these activities form part of the First Stage of Nuclear Power Programme in India, NFC has also been engaged in the manufacture of Core Sub-assemblies and components for the Fast Breeder Reactors. NFC is thus playing a dominant role in the second stage of the nuclear power program in India.

3.0 Fuel Fabrication

3.1 Manufacturing of natural uranium oxide PHWR fuel and recent improvements

The Uranium ore concentrate is chemically processed through ammonium di-uranate (ADU) precipitate route to produce nuclear grade purity sinterable UO_2 powder. The nuclear grade UO_2 powder is further processed to high-density fuel pellets through pre-compaction, granulation, final compaction, high temperature sintering and centerless grinding operations. The zircaloy-4 clad tubes are machined, degreased and then welded with spacer pads and bearing pads (appendages). The appendage welded tubes are coated with graphite on the inner surface of the tubes and baked under vacuum. Stacked high density pellets are loaded into these tubes. The loaded tubes are hermetically sealed by welding end caps to make fuel elements. A number of such elements are assembled in specific configuration and welded together at either ends with end plates to form a fuel bundle. The PHWR fuel bundles consist of either 19-elements or 37-elements depending whether they are for 220 MWe units or 540 MWe units respectively. The configuration of the fuel bundle remains the same for 540 MWe and 700 MWe. The finished fuel bundles after stringent quality checks are packed in thermocole and transported to various reactor sites through standard containers.

Recently several improvements have been made in production processes and equipment. A few such achievements are briefly mentioned below:

Towards automation of the potentially health hazardous processes, SCADA (Supervisory Control And Data Acquisition) System has been implemented for wet operations with necessary interlocks and alarms. The processes like UOC dissolution, solvent extraction, ADU precipitation and handling of hazardous chemicals like acids, TBP, etc. are carried out remotely and safely through this SCADA system. A typical SCADA user interface process screen for dissolution is shown in Fig. 2.

A mechanized granule transfer system is conceived, developed, fabricated and successfully commissioned at the pelletizing plant. In this system, a SS container is held, tilted and granules from it are transferred into the press hopper in a semi-automatic mode. Introduction of this system led to elimination of intermediate container and reduction in air borne activity.

Automatic charging of green pellets in to the sintering boats has been indigenously developed and integrated with the pellet compacting press. The system converts vertically compacted pellets into a horizontal array which are picked automatically and placed layer by layer inside the sintering boat (Fig. 3).

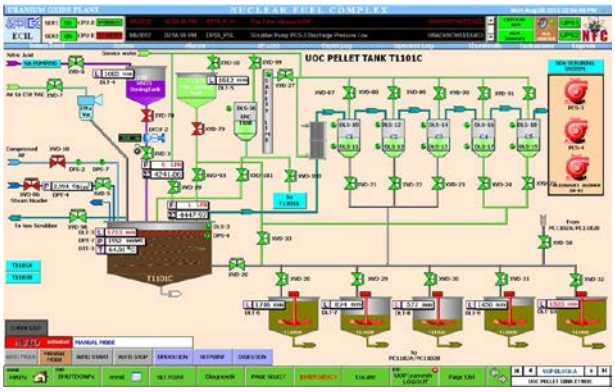

Fig.2: Typical SCADA User Interface for Dissolution

Fig.3: Mechanized pellet charging system

A fully computerized automated Pellet Density Measurement System based on immersion technique has been developed and has been put to regular use for measuring density of sintered UO_2 at pellets for qualification check of every sintered boat. It can handle both 19 & 37 Element pellets. The system has reduced the overall cycle time of density evaluation (Fig. 4). NFC has also recently developed a state-of- the art automatic pellet visual inspection system that has been inducted in the production line. The system works on high resolution automatic imaging and sorts out the visual defective pellets from the stacks of pellets (Fig. 5).

Fig.4: Auto density check system

Fig.5: Automatic pellet visual inspection system

In the assembly plant, integration of two numbers of end plate welding stations with an industrial Robot has minimized manual handling and brought a considerable increase in productivity (Fig. 6). TCE (Tri Chloro Ethylene) which was being used for degreasing elements and bundles being a toxic material has been replaced with a biodegradable alkaline degreaser as a part of the Environmental Management Programme of NFC.

An automated PHWR Fuel Bundle Inspection System was introduced for enhancing the reliability of bundle testing. Similarly an automated machine vision system has been developed to carry out visual inspection of PHWR fuel pellets, which has resulted in reduction of operator fatigue and man-power (Fig. 7).

Fig.6: Industrial robot at endplate welding

Fig.7: Automatic bundle inspection system

3.2 Manufacturing and in-pile performance of SEU Bundles

With a view to improve the effective utilisation of uranium and to increase the average Burn-up of PHWR fuel, NFC has manufactured and supplied Slightly Enriched Uranium (SEU) in the range of 0.9% to 1.1% U-235 isotopic content. The pellet fabrication processes like compaction and sintering were optimised and standardised for achieving the required density of pellets. These SEU bundles were test irradiated and analysed by NPCIL. The maximum and average burn-up of these SEU bundles are approx. 24770 MWD/TeU and 19466 MWD/TeU respectively.

During the irradiation campaign of SEU bundles, not a single SEU bundle is failed. Again the wet sniffing result of the discharged SEU bundles indicates that there was no fuel failure. So the performance of the SEU bundles is quite satisfactory. Out of 51 SEU loaded into the reactor core, so far 47 bundles were discharged from core.

For all the channels loaded with SEU bundles, the difference in estimated increase in Channel Outlet Temperature (COT) and the observed increase in COT was within the acceptable error band. The variation of continuous DN count rate during refueling, recycling and discharge of the SEU bundles were monitored. The percentage change in initial and final DN count rate during refueling and recycling were almost within 10%.

3.3 Manufacturing and in-pile performance of Reprocessed Depleted Uranium Bundles

Depleted uranium oxide fuel having fissile content of about 0.6%U^{235} and about 0.3% U^{235} was fabricated at NFC for 19 element as well as 37 element fuel and was utilized for flux flattening in PHWRs and generation of power. High decontamination factors were employed during reprocessing of the spent fuel to maintain Plutonium content less than 0.2ppm and fission products less than 0.1micro Ci/gm. RU from PHWR spent fuel bears a typical isotopic content as shown in Table.2

	Natural Uranium	PHWR RU
U232	None	Ppb
U234	0.006%	0.0044%
U235	0.71%	0.28%
U236	None	0.0691%
U238	99.284%	99.6% .

Table 2: Typical isotopic composition of PHWR RU fuel

NFC has processed this material from higher oxides through dry conversion to UO2. Requisite controls were followed for confining the material during dry processing by increasing the negative pressure inside the enclosure, increasing the ventilation air-changes in the process plant, using local shielding at the pellet handling. Safety demonstration was required to obtain the appropriate authorizations. The material is processed in campaigns with all aspects of monitoring and control.

Reactor physics and safety studies were carried out and regulatory permissions were obtained prior to loading in the reactor. The major use of the reprocessed depleted uranium has been done as a part of the initial charge fuel for flux flattening. About 350 to 2000number of bundles were used in each new reactor.

3.4 Production of Zirconium alloy products

Fuel tubes are produced from hot extruded blanks by multiple cold working process (pilgering) followed by annealing. Finishing operations like straightening, sandblasting, polishing and cleaning are carried out on the final tubes before they are subjected to ultrasonic testing. The tubes are cut to length and supplied to assembly plants. In addition to the supply of tubes for PHWRs & BWRs, various special types of tubes in different sizes are fabricated for strategic applications. The annealing and pickling activities were managed in a planned way to cater to the requirements of multiple products such as Fuel Tubes (19 & 37 element PHWR, BWR & AHWR), Pressure Tubes, Calandria Tubes, Garter Springs, Reactivity Mechanism Tubes, Rods, Sheet Products and other special & developmental products etc. This is a challenging job as all these products are to be processed simultaneously. The trend of increasing production of fuel tubes is shown in Fig. 8.

Fig.8: Increasing capacity of fuel tube production

Radial Forging and extrusion of Zr-2.5%Nb Pressure Tube on production scale for 700MWe PHWR: After successful developmental trials in previous years for fabrication of Zr-2.5Nb pressure tube based on radial forging route, a systematic campaign was undertaken on production scale to produce limited number of pressure tube with repeatable mechanical and metallurgical properties. Radial forging of two ingots of 550 mm Ø followed by blank extrusion to 119mm OD X 6 mm WT were successfully carried out. A total of 24 blanks were produced for manufacturing of CWSR pressure tube by successfully maintaining the radial forging parameters and extrusion parameters such as forging temperature, soaking time, radial forging strain rate, reduction ratio per pass, extrusion ram speed and temperature as established during the developmental trials (Figs. 9 through 11). All these tubes were characterized in terms of metallurgical and mechanical properties such as texture and aspect ratio of the alpha phase, tensile strength. Results have indicated the presence of higher F_t, higher (F_t-F_r) values and longer alpha grains with requisite mechanical strength specified for 700MWe PHWRs in all the pressure tubes consistently on repeatable basis.

Fig. 9: 520 mm Ø Arc Melted and Machined Zr-2.5%Nb Ingots

Fig. 10: Radial Forged Zr-2.5%Nb Ingots

Fig. 11: As Extruded (119mm OD X 6mm Wt) Zr-2.5%Nb blanks

4.0 Conclusions

Nuclear Fuel Complex that manufactures UO_2 Fuel and Zircaloy structural components plays a pivotal role in the growth of PHWRs derived nuclear power in India. The Complex manufactures and supplies entire PHWR fuel and Zircaloy structurals produced right from the processing of Ore Concentrate to the finished products. NFC has manufactured advanced fuels like SEU and Reprocessed Uranium fuel that were successfully utilized in the Indian PHWRs. Capacity upgradation and safe operations were achieved through incorporation of process modifications and mechanizations in the production lines. NFC is working towards a totally automated production facility with capacity enhancements matching with the requirements of .

5.0 Acknowledgements

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6.0 References

1) Internal report of NPCIL on performance of SEU Bundles in Indian PHWR.
2) Bhardwaj S.A., **Design, development and performance of advanced fuels in PHWRs**, International Conference on Characterisation and Quality Control of Nuclear Fuels (CQCNF-2012), Hyderabad, India, February 27–29, 2012.
3) Nageswar Rao G. et al., **Fuel Related Operational Experience in Indian Power Reactors**, International Conference on Characterisation and Quality Control of Nuclear Fuels (CQCNF-2012), Hyderabad, India, February 27–29, 2012.
4) Bhardwaj S.A. et al., **Advances in PHWR Fuel Technology**, second International Conference on Advances in Nuclear Materials (ANM-2011), Mumbai, India, February 9–11, 2011.