# Chapter 17
# Nuclear Fuel Complex—A Five Decade Success Story of Indian Nuclear Power Program

**Komal Kapoor and Dinesh Srivastava**

**Abstract** Nuclear Fuel Complex (NFC), Hyderabad was conceived as a pivotal industrial arm of the Department of Atomic Energy (DAE) in the late 60s with a mandate to fuel the nuclear power program of India and came into existence in 1972 as major industrial arm of DAE. This article traces its inception, growth, achievements and ambitious plans to support all strategic sectors.

**Keywords** NFC · Nuclear materials · Zircaloys · Steam generator tubes · Quality Assurance · Fuel production

## 17.1 Relevance of Nuclear Power

Owing to ever-growing demand for electricity, due to the increase in population and industrial requirements, several forms of electricity generation have been explored. They include coal-based thermal power, hydroelectric, gas-based power, renewable sources (solar and wind), nuclear power and their contributions are shown in Fig. 17.1.

However, the availability and accessibility of quality coal and long term consequences in terms of environmental effects and ecological changes are important points to be considered in running these plants. In view of the recent global concerns about environmental effects of coal-based power production, there is a renewed effort to find suitable alternatives to coal-based power production. Even though hydroelectric power stations account for about 12% of power production, they are restricted to certain geographical locations adjacent to rivers or waterfalls. Similarly,

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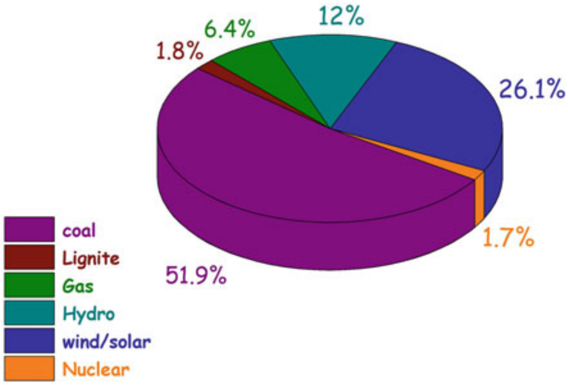


**Fig. 17.1** Distribution of the installed power generation capacity of 393.389 GW in India as of Sept 30, 2021, as per Ministry of Power, Government of India

power stations using renewable sources (wind and solar) are also restricted to certain geographical locations and thus not able to cater to the requirements across the length and breadth of the country.

In view of these points and due to several advantages such as providing clean energy, sustainable power generation and availability of reliable power in all climatic conditions and geographical locations, nuclear power has become a promising and competitive source for generation of power. Given the huge resources of Thorium, India can rely on long term power sustainability through nuclear power, along with other energy sources.

## 17.2 Dr. Homi J. Bhabha—Father of the Three-Stage Nuclear Power Program in India

In view of the advantages as cited above, Dr. Homi Jehangir Bhabha sowed the seeds for nuclear energy in India in the year 1944 and conceived the idea of a Three Stage Indian Nuclear Program. Subsequently the Tata Institute of Fundamental Research (TIFR) was founded in 1945. TIFR was the backbone for the formation of Atomic Energy Commission (AEC) in 1948, followed by the formation of Department of Atomic Energy (DAE) in 1954. The pace of establishment of nuclear power had been hastened in the country after setting up of Nuclear Power Corporation of India Limited (NPCIL).

Nuclear fission of an unstable heavy atom is the genesis for nuclear power generation. U235, Pu 239 and U233 are the various isotopes used in nuclear fission reactions and therefore, one of these isotopes-based fuel with an appropriate coolant and moderator is used in nuclear power reactors. The three-stage Nuclear Power Program as envisaged by Dr. Bhabha was adopted by India and is shown in Fig. 17.2. The Three stages Indian Nuclear Power Program incorporates closed fuel cycle and thorium utilization as the main stay for sustained growth.

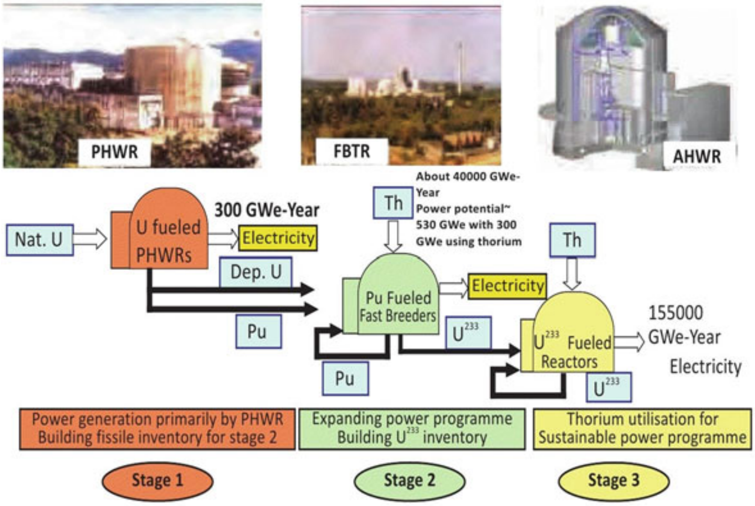


**Fig. 17.2** Three stage Indian nuclear power programme adopted by India

This 3-stage Indian Nuclear Power Program involves the use of Pressurized Heavy Water Reactors (PHWRs) with natural Uranium containing small amounts of U235 as fuel and $D_2O$ as coolant and also as a moderator in the 1st stage. Pressurized heavy water exchanges its heat with normal water and the steam thus generated is sent to a turbine to produce electricity. Plutonium-239 is extracted by reprocessing the spent fuel from 1st stage. In 2nd stage, this Pu239 will be used as input fuel for Fast Breeder Reactors (FBRs). Fertile isotope Th232 surrounds the fast reactor fuel core in FBR and the fertile thorium gets converted into fissionable U233 upon neutron absorption. And, as envisaged in 3rd stage Advanced Heavy Water Reactors (AHWRs) with U233 as fuel is to be adopted for power generation. The vast resources of Thorium in India can establish the sustainability of the three-stage nuclear power program adopted for energy security of the country for a long time. Pressurized heavy water reactors (PHWRs) are the major contributors to the nuclear power generation in India.

## 17.3 Birth of Nuclear Fuel Complex

Nuclear Fuel Complex (NFC), Hyderabad was conceived by Dr Bhabha as a pivotal industrial arm of Department of Atomic Energy (DAE) in the late 60s with a mandate to fuel the nuclear power program of Govt. of India and came into existence in 1972 as major industrial arm of DAE. The survey of land selection for establishing NFC site was personally supervised by Dr. H. J. Bhabha himself in 1965.

Being a premier industrial unit of DAE, Nuclear Fuel Complex (NFC) is engaged in manufacturing and supply of fuel sub-assemblies and other reactor core components with very stringent specifications to India's Pressurized Heavy Water Reactors (PHWR), Boiling Water Reactors (BWR) and Fast Breeder Reactors (FBR) operated by NPCIL. As an ISO 9000, 14,000 & 45,000 certified organization, NFC adheres to all three ISO standards during manufacturing & supply processes. Natural $UO_2$ and enriched $UO_2$ in the form of pellets are being used as fuel in PHWR & BWR respectively and MOX/MC as fuel for FBR. Whereas core components include zirconium-based alloys (Zircaloys) such as Zr-4 alloy and Zr-2 alloy as fuel-clad materials for PHWR & BWR respectively and Stainless Steel for FBR. The Zr–Nb alloy is being used for pressure tube manufacturing.

The production of nuclear-grade materials with acceptable quality involves mastery of many diverse technologies in the fields of mechanical, chemical and metallurgical processes. Successful and cost-effective production is a team effort involving, mechanical, chemical, metallurgical, fabricator engineers and quality control personnel. Over these years, NFC has evolved as a bright example for the successful transfer of technology from lab scale to large scale production. This would have not been realized without the contribution of strong work force that is there behind every achievement of NFC.

With comprehensive nuclear fuel manufacturing cycle under its belt, NFC is the only organization in the world to have the capabilities to process uranium and zirconium streams from ore to core, all under one roof.

## 17.4 Timeline of Milestones

After conceptualization of NFC during 1960s, a pilot plant was established in 1961 to produce nuclear-grade natural $UO_2$ powder and pellets and the half core of first PHWR (RAPS-I) was fabricated at AFD, Trombay. The rich experience gained during this time has enabled DAE to embark upon commercial production of nuclear fuel and Nuclear Fuel Complex (NFC) has come into existence with a production capacity of 100 Te of PHWR fuel and 24 Te of BWR fuel in 1972 at Hyderabad. The first 19-element PHWR fuel bundle with wire-wrapped spacers was produced in NFC on 8th June 1973 with the available indigenous technologies and assistance from Russia & Canada.

It is appropriate to recollect the past when it took almost 21 years for NFC to produce the first one lakh fuel bundles and next four lakh fuel bundles could be produced in the next 20 years time. Thus it took 40 years to manufacture the first 5 lakh fuel bundles. However, NFC is now able to manufacture one lakh bundles in a year. This has been possible only with the adaptation & implementation of innovative and break-through technologies into manufacturing and inspection & testing methodologies. Every production plant in NFC has progressively increased their plant capacities by incorporating state-of-the-art automation into their process and quality control systems.

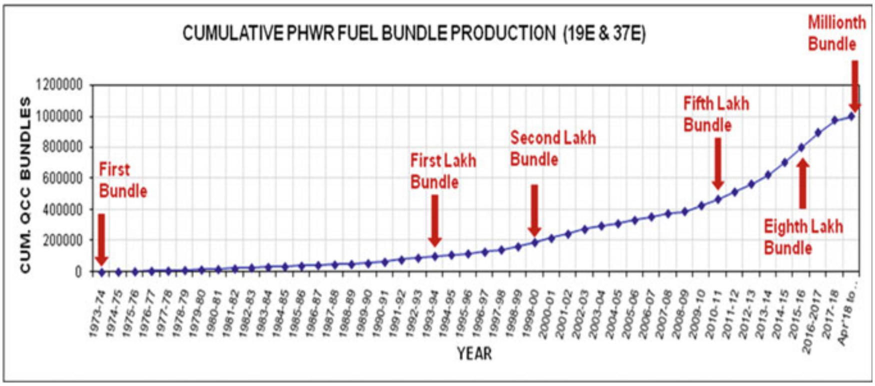


**Fig. 17.3** Cumulative PHWR fuel bundle production

Capacity expansion of zirconium sponge production was already achieved in the year 2009 at Zirconium Complex (ZC), Pazhayakayal, Tamil Nadu. A new green field project called as Nuclear Fuel Complex-Kota (NFC-K) is being set-up at Rawthbhatta, Rajasthan as a fuel production facility to augment the additional requirements of India's Nuclear Power Program. Today the emphasis is being made on production with consistent quality and safety with the inclusion of concept of clean & green environment.

During its 50 years of journey, NFC has attained complete self-reliance in the manufacture & supply of fuel and core components for PHWRs and BWRs operating in the country. In this process, it has achieved the following important milestones during PHWR fuel bundle production and the cumulative PHWR fuel bundle production is shown in Fig. 17.3.

To sum up, the successful journey that NFC made during the last 50 years of its existence towards technological excellence from technology denial regime can be described in decade wise as below:

*1970–1980: Acquiring Knowledge and 1st mile stone*

- India forayed into the domain of PHWRs and NFC was established at Hyderabad with a capacity to manufacture 100 TPY of PHWR fuel.
- Plants were constructed and critical machinery was imported from Canada & Russia.
- It was all new for scientists and engineers to produce Uranium and Zirconium on industrial scale.
- Acclimatization of the processes and machinery of U & Zr production technologies.
- First 19-element PHWR fuel bundle with wire-wrapped spacers in 1973.

| | |
|---|---|
| Inception of NFC | June, 1972 |
| First Bundle Production | June, 1973 |
| First Lakh Bundle Production | January, 1994 |
| Fifth Lakh Bundle Production | December, 2011 |
| Millionth Bundle Production | September, 2018 |

*1980–1990: Understanding the existing processes and introducing new ones*

- The equipment and processes were either replaced or modified to make them suitable to Indian raw materials
- Indigenization of processes has helped in scaling up the manufacture of Nuclear Fuel to 180 TPY
- Welded split spacer design of PHWR fuel sub-assembly
- Graphite coating of clad tubes
- The processes still remained manual and laborious, where Uranium is seen moving from one process step to next process step.

*1990–2000: Developing Applications and 2nd milestone*

- The decade was significant for NFC as it had to cater to the new PHWR fuel requirements for Kaiga and Kakrapara plants besides meeting the fuel requirement of operating reactors at Kalpakkam and Rawatbhatta.
- This extra demand for fuel had thrown a serious challenge due to huge gap between demand and supply.
- Processes were modified suitably and scaled-up equipment was procured, installed & commissioned successfully to accommodate the newer demands.
- The accumulated raw materials and rejects to the tune of 500MT were successfully processed and converted into finished fuel.
- Manufacturing of First one lakh fuel bundle was completed in 1994.

*2000–2010: Decade of Innovations*

- During this decade, NFC implemented many process innovations and indigenized process equipment across all operations.
- Manufacturing technology for extremely thin-walled tubing was established and Seamless Calandria tubes were produced for two 540 MWe PHWRs at Tarapur.
- Chamfered, double dish pellets and admixed lubrication.
- Empty tube welding, curved bearing pad.
- 37-element fuel bundle.
- Triple melting of end-plug ingot.
- NFC concentrated on the development of the engineering industry for its futuristic innovative requirements with respect to various reactor components, accessories for fuel assemblies and advanced automatic equipment.

*2010–Till Date: Decade of Technological Revolution and significant milestones*

- NFC has significantly exceeded its designed capacities by implementing Automation in fabrication and inspection.
- Flexible manufacturing systems have been developed for simultaneous processing of different input materials like Magnesium diuranate (MDU), HTUP, uranium ore concentrate (UOC) and sodium diuranate (SDU).
- An innovative process of direct reduction of ammonium diuranate (ADU) to $UO_2$.
- Introduction of new route of double radial forging and single pass pilgering for manufacturing Pressure Tubes.
- Technology was developed to manufacture U-bend Alloy 800 tubing in 30-m straight length for Steam Generators of 700 MWe PHWRs.
- Established new manufacturing processes for seamless tubes in circular, square, hexagonal cross sections, Double clad tubes, multi-clad varieties for different types of power reactors.
- Standardization of $UO_2$ powder characteristics for short sintering cycles.
- Manufacturing of 300MT of NG Zirconium sponge at ZC, Pazhayakayal.
- NFC has achieved the world's highest production of 1512 MT of PHWR fuel during 2016–17.
- Manufacturing of the first one millionth PHWR fuel bundle in 2018.

## 17.5 Production Activities in NFC

Nuclear grade natural Uranium Dioxide ($UO_2$) pellets are produced at NFC by converting a variety of raw materials using a well-established conversion process comprising different stages like dissolution, solvent extraction, precipitation, calcination & reduction to get $UO_2$ powder. Subsequently, pellet fabrication is accomplished through granulation, pre-compaction and high temperature sintering of $UO_2$ powder. The resultant $UO_2$ pellets are then qualified for physical integrity and chemical purity for encapsulating them into zirconium alloy fuel tubes for fabricating the fuel sub-assemblies. The three types of fuel sub-assemblies (bundles) fabricated in NFC are 19 Element bundle for 220MWe PHWRs (16.5kg weight), 37 Element bundle for 540/700 MWe PHWRs (23.8 kg weight) and $6 \times 6$ BWR bundle for 160 MWe BWRs (230 kg weight) and are shown in Fig. 17.4.

The desired specifications are achieved by having strict control on material manufacturing process. Control on manufacturing process can be achieved through monitoring the quality of materials taking part in the process and also with a strict vigil on process conditions. Chemical Quality Control (CQC) of raw materials, process intermediates and final products will ensure the desired quality of final products and thus, it becomes an integral part of QA/QC program. As an independent department, Quality Assurance (QA) group ensures the quality at intermediate stages and final stage of production to ensure the compliance to the requirements of the customer. Safety and Environment Protection are also ensured with the designated departments during entire manufacturing process.

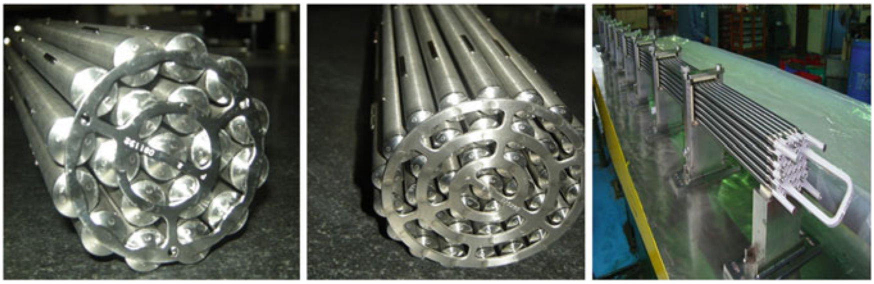

**Fig. 17.4** The three types of fuel sub-assemblies (bundles) fabricated in NFC **a** 19-element bundle for 220 MWe PHWR, **b** 37-element bundle for 540 and 700 MWe PHWR, and **c** 6 × 6 BWR bundle for 160 MWe BW

Besides this, NFC also manufactures different reactor components using special alloys including special steels for strategic application and also produces high purity materials of 5N & 6N purity for electronic & tool applications. Apart from principle customer NPCIL, the list also includes DRDO, ISRO, HAL, BHAVINI, IGCAR, BARC, RRCAT, etc.

The diversified production activities of NFC for nuclear and non-nuclear applications are summarized in Fig. 17.5.

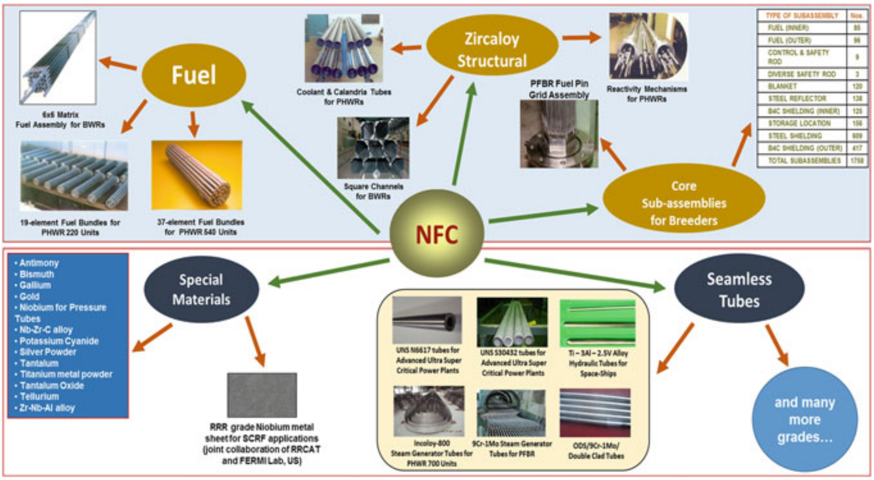


**Fig. 17.5** Diversified production activities of NFC

## 17.6 Contributors to the Success of NFC

The success of NFC is the success of its production facilities and the technically strong & skilled team of workforce. They are engaged in manufacturing of nuclear fuel, in-core and out-of-core structural, special tubes and special materials backed up by a strong quality monitoring group to ensure the quality of the materials produced. Safety group is functioning to take care of the safety of all operations. The activities of individual production plants at NFC are described below.

### *17.6.1 Nuclear Fuel Manufacturing Plants*

Nuclear Fuel manufacturing is very critical and plays a vital role in nuclear fuel cycle. The stringent chemical, physical and metallurgical requirements of nuclear fuel need to be engineered into the nuclear fuel during manufacturing. The physical characteristics also need to be engineered based on the operation conditions of the nuclear fuels which are quite harsh and also vary from reactor to reactor. The nuclear fuels during their operation are subjected to high-temperature operating conditions, high neutron flux environment which leads to physical and metallurgical changes.

Nuclear fuel is made for three types of nuclear power reactors, namely Pressurised Heavy Water Reactor (PHWR), Boiling Water Reactor (BWR) and Fast Breeder Reactor (FBR).

*PHWR Fuel Assemblies:* Natural uranium dioxide (Nat.$UO_2$) is the fuel for PHWRs and is obtained from different raw materials like Magnesium Di-Uranate (MDU), Sodium Di-Uranate (SDU) or Uranium Ore Concentrate (UOC). MDU/SDU concentrate is obtained from the indigenously milled uranium mines at Jaduguda, Jharkhand/Tummalapalli, AP and supplied by Uranium Corporation of India Limited (UCIL) and UOC is imported from different countries. MDU/SDU/UOC is subjected to dissolution followed by solvent extraction and subsequently precipitation of uranyl nitrate with ammonia to get Ammonium Di-Uranate (ADU). A further step of controlled heat treatment of calcination of ADU gives Uranium dioxide ($UO_2$) powder. The $UO_2$ powder is then processed to high-density cylindrical pellets by various operations like pre-compaction, final compaction and sintering at high temperature (1700 °C) in reducing atmosphere. The sintered $UO_2$ pellets are then centre-less ground to desired dimensions.

The finished $UO_2$ pellets are encapsulated in thin-walled Zircaloy tubes, both ends of which are sealed by resistance welding. Appendages such as spacers and bearing pads are resistance welded on these elements and 19 or 37 such elements of specified configuration are assembled together by welding them on to end plates at either end to form 19-element fuel assembly designed for 220 MWe reactors and 37-element fuel assembly designed for 540 and 700 MWe reactors.

*BWR Fuel Assemblies:* Cylindrical $UO_2$ pellets of varying enrichments and chemical compositions imported from other countries are encapsulated in thin-walled tubes of zirconium alloy, both ends of which are sealed by TIG welding. Elements with varying compositions are placed in a specified configuration such as 6 × 6 array along with spacer grids, stainless steel tie plates, zirconium alloy spacers and flow nozzles to form 6 × 6 nuclear fuel assemblies for BWRs.

*Fast Breeder Reactor (FBR) Fuels:* NFC is also responsible for fabrication of core sub-assemblies for Indian Fast Breeder Reactors deployed under 2nd stage of Indian Nuclear Power Program. The facility at NFC presently caters to the requirements of core sub-assemblies for two reactors namely 13 MW(e) Fast Breeder Test Reactor (FBTR) and 500 MW(e) Prototype Fast Breeder Reactor (PFBR).

NFC fabricated all the core sub-assemblies such as Fuel, Blanket, Nickel Reflector, Carrier and Special Assemblies for its initial core of FBTR in the beginning. Since then it is also engaged in continuously supplying annual requirements of Fuel and special sub-assemblies of FBTR. A typical FBTR fuel sub-assembly consists of 511 intricately machined components of 35 different types.

The Core sub-assemblies are hexagonal in shape with very thin wall special grade Stainless Steel (SS) tubes (circular and hexagonal) and precision SS components. These were fabricated with in-house developed know-how and equipment/fixtures built with indigenous capabilities. Pelletisation of the thorium oxide ($ThO_2$) has been carried out for the first time on a large scale that involved considerable ingenuity and effort.

The fabrication of various FBTR core sub-assemblies involves unique operations like button forming and chrome plating on hexagonal tubes, crimping on clad tubes, bead forming on spacer wires, helical wire wrapping on pins, etc. These operations are executed on special-purpose machines which were also developed indigenously. The fabrication of FBTR fuel involves substantially high radioactivity, which in turn increases complications in manufacturing. Deploying radiation protection lead shields at various process workstation help to overcome these challenges.

NFC fabricated and supplied core sub-assemblies like Fuel, Blanket, Control & Safety Rod, Diverse Safety Rod, Reflector, Inner Boron Carbide Shielding, Diluent, Purger, Source and Instrumented Central Sub-assemblies for initial core of PFBR. A typical PFBR Fuel sub-assembly consists of 1541 intricately machined components of more than 35 different types. Also, it involved the supply of about 60,000 crimped tubes and 2.5 Lakhs precision fuel pin components fabricated in-house/ outsourced meeting the stringent specifications involving Quality Assurance team of NFC and Quality Surveillance team of NPCIL/BHAVINI. The Core sub-assemblies are hexagonal in shape and are 4.5 m long. The fabrication processes of most of the machining components were developed and outsourced due to bulk quantity requirements. The various equipment, fixtures and radiation shields were developed indigenously for unique operations like Spacer Wire Bead Forming, Wire Wrapping, Automatic TIG Welding, Button Forming, Robotic fuel pin assembly, etc. NFC has also developed Automatic autogenous TIG welding technique for welding of very thin-walled Fuel clad tubes and Hexagonal wrappers. The complexity of fuel sub-assemblies involves handling and manufacturing of substantially high radioactive fuel pins, which were overcome by deploying special automation techniques and (composite) radiation shields for protection against gamma and neutron radiation as per regulatory requirements and safety standards. In addition to this, a special fuel assembly shop/facility has been established close to reactor site at Kalpakkam.

NFC is also involved in planning and setting up of nuclear fuel fabrication facilities for fabrication of various types of pins and sub-assemblies required for annual reloads of PFBR and FBRs. Fabrication of Fuel for FBTR & PFBR using In-house/indigenous made equipment and fixture is an example of India's self-reliance and Make in India policy of GoI.

### 17.6.2 Reactor Grade Zirconium Metal Production Plant

Reactor Grade (RG) Zirconium metal (RG Zr metal) is produced by limiting critical impurity element Hafnium (Hf) making it suitable for nuclear applications.

Zircon sand is the raw material for production of Zirconium metal. It comprises of Zirconium Silicate containing 67% Zirconium with about 2% Hafnium. Hafnium being a neutron absorber element (due to its high neutron absorption cross-section), its removal is an essential step in the nuclear metallurgy of Zirconium. The permissible limit for Hafnium is very less in Zirconium. The first step of removal of Silica involves the treatment of zircon with Caustic Soda. The resulting frit is washed with water to remove water-soluble Sodium Silicate. Then Zirconium and Hafnium are brought into solution with Nitric Acid. The separation of Zirconium from Hafnium and other impurities is achieved by solvent extraction using Tri-n-Butyl Phosphate (TBP) in Kerosene as the solvent. Zirconium is preferentially extracted into the organic phase leaving Hafnium and other impurities in aqueous phase. The Zirconium-laden organic is then stripped to recover pure Zirconium in aqueous solution. Zirconium Hydroxide is precipitated from the pure solution using Ammonia and the Hydroxide is filtered, washed, dried and calcined in a rotary kiln to obtain pure Zirconium Oxide. The oxide is hammer milled to fine powder.

Hafnium-free Zirconium Oxide is converted to Zirconium Tetrachloride ($ZrCl_4$) intermediate through chlorination operation in static bed reactors. Zirconium Tetrachloride is then reduced to Zirconium through magnesio-thermic reduction (Kroll's reduction) operation. The reduced mass of Zirconium after mechanical separation of $MgCl_2$ by-product is subjected to pyro-vacuum distillation operation for removal of entrapped Mg and $MgCl_2$ to get pure Zirconium metal.

### 17.6.3 Fuel Cladding and Assembly Components Production Plants

Chemically qualified Zirconium sponge is converted into different types of zirconium alloys after addition of required quantity of alloying elements and melting. Zirconium metal and the alloying elements are compacted in hydraulic presses to

**Table 17.1** Composition of various Zircoloys

| Zirconium alloy type | Alloying elements (Weight %) | | | | |
|---|---|---|---|---|---|
| | Sn | Fe | Cr | Ni | Zr |
| Zircaloy-1 | 2.5 | – | – | – | Balance |
| Zircaloy-2 | 1.5 | 0.12 | 0.1 | 0.05 | Balance |
| Zircaloy-3 | 0.25 | 0.25 | – | – | Balance |
| Zircaloy-4 | 1.5 | 0.22 | 0.1 | – | Balance |

obtain compacts/briquettes. These compacts are welded to each other by electron beam welding under vacuum to obtain a long cylindrical electrode. These electrodes are melted multiple times by consumable electrode in vacuum arc re-melting furnace in water-cooled copper crucibles, with intermediate stage machining for obtaining final ingots. The composition of different Zircaloys is given in Table 17.1.

Zircaloy ingots are subjected to 1st stage of extrusion, machining and cutting. After making a hollow billet, it is subjected to beta-quenching, machining and 2nd stage extrusion in order to obtain a hollow blank. This hollow blank is stress relieved in vacuum and passed on for multi-stage pilgering with intermediate vacuum annealing. Tube finishing operations like straightening, grinding, cutting, etc. are also performed to obtain the requisite stringent quality.

For this purpose, NFC possesses state-of-the-art fabrication facilities such as extrusion & piercing press, cold rolling mills, vacuum annealing furnaces, special surface finishing and treatment equipment are available to achieve the desired mechanical and metallurgical properties of cladding tubes.

Fuel tubes are assembled together with components, like End plates, End Caps, Bearing Pads & Spacer Pads, to form a fuel bundle. Bars required for manufacturing end plugs are produced by cold rotary swaging operation of the extruded bars in different passes with intermediate vacuum annealing, final straightening and centerless grinding to required sizes. As the end plug acts as the first sealing of fission products, the produced bars undergo rigorous quality checks. Similarly, Zircaloy Ingot is extruded to slabs which are then rolled to sheets. Bearing pads and spacer pads are punched out of these sheets. These components are made out of either Zircaloy-2 (for BWRs) or Zircaloy-4(for PHWRs). For these, NFC is equipped with mechanical presses, Automatic Vibratory finishing system, centre lathe machines, automated machining centres, etc.

### *17.6.4 Nuclear Reactor Core Component Production Plants*

Seamless tubes of different sizes are being manufactured using alloys of Zirconium, titanium and special-grade stainless steels. Pressure Tubes (Zr-2.5wt% Nb alloy), Calandria Tubes (Zircaloy-4) and Garter Spring (Zr-2.5wt% Nb-0.5wt% Cu alloy) are the critical core structural of Pressurised Heavy Water Reactors (PHWRs). Square

Channels (Zircaloy-4) are used in Boiling Water Reactor (BWRs) and Hexcans (SS316/ D9 alloy) are used in Fast Breeder Reactors (FBR).

Manufacturing process routes for these critical cores structural are successfully developed and continue to be supplied to all the PHWRs, BWRs and FBRs.

Also, the manufacturing process route for reactor control assemblies required for PHWRs is successfully developed and continues to be supplied to all the PHWRs. These assemblies are designed for reactor power monitoring, control mechanisms and shut down. These are made of zirconium alloys and require high precision, reliable components and high quality tubes before welding. The manufacturing processes use hot extrusion, forging, pilgering, drawing of various sizes of tubes and punching, machining of components. These assemblies use a combination of electron beam welding, TIG welding and resistance welding and have stringent quality specifications for soundness of welds and accurate dimensional control.

For this purpose, advanced welding and machining facilities such as electron beam welding equipment, specialized TIG welding machines, CNC machines, pilger mills, precision roll joint machines, vacuum heat treatment furnaces, special surface finishing and treatment equipment are available in NFC.

In addition, NFC has contributed to various developmental programs of DAE such as Compact High Temperature Reactor, Upgraded APSARA Reactor through advanced machining and welding of exotic materials.

### *17.6.5 Stainless Steel and Special Alloy Tubes Production Plants*

These are exclusive facilities for development & manufacturing the seamless tubes using various advanced grades of Stainless Steels & Special alloys, Nickel-based super alloys, Iron-based super alloy, Titanium alloys, Maraging steels for Nuclear, Space and Defence strategic applications. They house state-of-the-art manufacturing facilities like Cold rolling mills (Pilger mills), Tube straightening mills of different capacities & sizes, Draw-bench, Heat treatment facilities like Bright Annealing furnace, Vacuum Annealing furnace, Roller Hearth (LPG fired) Annealing furnace, Chemical operations like De-glassing, Pickling, Passivation, Alkaline degreasing, Solvent degreasing and Inspection facilities like Ultrasonic, Eddy Current & Hydrostatic Pressure Testing.

Manufacturing starts with forged & machined cylindrical billets which are hot extruded to hollow blanks. Extruded blanks undergo series of thermo mechanical processing to achieve desired properties. Finished tubes are subjected to various Inspection & Tests as per customer requirements. NFC has played a pivotal role in indigenous development & manufacturing of these products as import substitute and is an excellent example for Make in India policy.

### *17.6.6 Special Materials Plant*

Nuclear Fuel Complex is also the country's premier facility engaged in the manufacture of a variety of high purity materials (5N/6N) and they find numerous applications in Electronics, Defence, Nuclear Industries, Scientific & industrial research organizations, institutions of higher learning and even in general engineering industry.

High purity materials such as antimony, bismuth, cadmium, selenium, tellurium, gallium, phosphorous oxy chloride, antimony trioxide, gold, gold potassium cyanide (GPC) and silver are produced. In addition, tantalum pentoxide, tantalum metal and reactor grade niobium metal in the forms of rod, sheet and crucibles are also produced. The high purity materials are used in semiconductor technology for the synthesis of compound semiconductors, and as dopants, diffusants, solders, etc. Tantalum is used in a variety of high temperature and corrosive atmosphere applications. Tool grade tantalum pentoxide finds its application in tool industry. Reactor grade niobium is used in nuclear industry for alloying of zirconium to produce special ZrNb alloys. NFC has produced Residual Resistance Ratio (RRR) grade niobium metal for use in super conductivity (SC) applications. Advanced alloys such as NbTi, NiTi, NbZrC, have been developed by electron beam melting route.

The production of these materials involves a variety of highly sophisticated equipment, advanced techniques, clean working environment and specialized technical skills. The gamut of operations include Hydrometallurgy, Pyro-metallurgy, Electrolytic processes, Solvent extraction, special distillations, zone refining, Electron beam refining, etc. Rigorous quality control is exercised at all stages of production to achieve quality and reliability of products. The availability of wealth of talent, advanced equipment and state-of-art of technology, backed up by excellent quality assurance processes ensures the quality of products. The characterization of high purity materials and intermediates using specialized analytical techniques such as AAS, ICP-OES, XRFS, UV–Vis Spectrophotmeter, IGF-based gas analyzers and Classical chemical methods are being done.

Further, NFC has transferred developed technologies to prospective entrepreneurs and they include technology for the production of Magnesium granules, Zirconium metal power, production of high purity materials such as Phosphorous Oxychloride, Indium, Sodium Iodide, Gallium, Gold, Silver, Capacitor grade tantalum powder and Tantalum anodes, etc.

A new production plant is being set-up in collaboration with ISRO for the production of niobium for exclusive usage in Indian Space programme.

### *17.6.7 Quality Assurance Group*

Quality is important in any field of human endeavour, more so in a critical, high-tech area such as nuclear power plants where the costs of failure are extremely high with respect to material loss and also from the societal angle. The demands thus made on the Quality Assurance (QA) programs in DAE in general and NFC in particular, are on an altogether different level compared to those in other industries. NFC is unique in its integrated approach to the manufacture of a variety of finished products from ore to core through employing rigorous Inspection, QA and Non-destructive Evaluation (NDE) on an industrial scale. Because of these demands, NDE in NFC has, through years of experience, attained a high level of maturity. The high standards of the products manufactured at NFC are highlighted by their excellent real-time performance. NFC is striving to achieve Six Sigma strategy as a part of continual improvement in its operations, products and services through technological excellence and well structured QA program.

The exacting performance required by the nuclear fuel and hardware in the Power Reactor demands fulfilling stringent quality requirements of each product's specifications. NFC adopts well-structured quality assurance program. The goal is realized by employing a set of sophisticated equipment and techniques with qualified manpower. The State-of-Art NDE facilities, Centralized Analytical Quality Control Laboratory, Metallurgical & Mechanical testing and Advanced Material Characterization Laboratory carry out the testing, analysis and measurement in order to ensure process control and product compliance to specifications. Periodic reviews and brain storming are conducted to improve recoveries.

The sophisticated non-destructive evaluation facilities developed and techniques established which include ultrasonic test, eddy current test, X-ray radiography, dye-penetrate test, mass spectrometric leak detection and automated machine vision systems. Precision dimensional measurement systems and automatic physical measurement facilities cater to the in-house needs for measurement and qualification of products. An array of analytical techniques like Inductively Coupled Plasma Atomic Emission Spectrometry, Atomic Absorption Spectrometry, X-ray Fluorescence Spectrometry, Mass Spectrometry, Gas and Ion Chromatography, Laser Photometry are employed for analysis of raw materials, intermediates and final products.

A number of online measurement and control equipment have been introduced all along the processes and production lines. The Advanced Material Characterization Lab is equipped with several sophisticated characterization instruments viz. TEM, SEM-EBSD, XRD, Dilatometer, X-ray residual stress analyzer for studying metallurgical characteristics like microstructure, texture, dislocation density, re-crystallization behaviour, crystallography, nano-feature characterization, residual stress analysis etc. These facilities help in developing a variety of products and advanced alloys.

The emergence of several Quality Circles bears testimony to the fact that each and every employee working in their area is concerned and dedicated towards improving quality. Every year, the month of November is observed as Quality Month. As part of Quality Month Celebration, several lectures by eminent speakers and competitions like quiz, slogan and essay writing are conducted to create Quality Awareness among the employees.

NFC has over the past five decades earned a justifiable pride place in DAE as a reputed, reliable, quality-conscious supplier of critical inputs to the nuclear power program in India.

### 17.6.8 Safety Engineering Division

NFC gives utmost importance to the safety of workers, environmental protection and prevention of accidents/incidents at field level. It is regulated by Atomic Energy Regulatory Board (AERB). For taking care of overall safety aspects, to achieve the objectives of safety and co-ordinate with various plants, Safety Engineering Division (SED) was formed in the initial years of NFC. SED coordinates with AERB on regular basis for implementation of Factories Act, 1948 and Atomic Energy Factories Rules, 1996 and other statutes.

### 17.6.9 Environment Protection

While fulfilling the mandate of supplying the nuclear fuels and nuclear reactor components to Nuclear Power Program and support to strategic program of India, NFC gives utmost importance to protect environment by way of proper handling and disposal of by-products and effluents. A dedicated Effluent Management section comprising of expert chemical engineers is working towards this goal. The section is responsible for safe & prompt disposal of various process effluents generated from the various activities at NFC to firms authorized by Telangana State Pollution Control Board (TSPCB). Also, various reports are sent to statutory authorities viz. TSPCB, Atomic Energy Regulatory Board, Ministry of Environment and Forest & Climate Change. Items viz. Used oil, Spent resin, Boiler soot, Used polyurethane sponge plugs, Thermocol, etc. which were posing a significant safety/fire hazard are also disposed properly.

### 17.6.10 Zirconium Complex, Tamil Nadu (a Unit of NFC, Hyderabad)

In order to meet the additional requirements of production of zirconium metal, Zirconium Complex (ZC) was conceived in 2001 as a green-field project at Pazhayakayal, Tuticorin, Tamil Nadu. The complex was commissioned in November 2009 to produce Zirconium Oxide and Zirconium Sponge to meet the enhanced demand. During the last 13 years, the production capacity of the Plant has gradually increased and the rated capacity was achieved in FY2014–15.

**Table 17.2** Expansion of nuclear power in India

| Reactor type | No. of units | Capacity (MWe) |
|---|---|---|
| PHWRs | 40 | 19,860 |
| LWRs | 34 | 39,820 |
| FBRs | 9 | 4,500 |
| Total | 83 | 64,180 |

Use of zirconium and its alloys for nuclear applications requires stringent monitoring of quality of raw materials, chemicals and intermediate process streams/ products. A Materials Testing Laboratory is set up for analysis of samples using state-of-the-art analytical instruments for process control and quality control of products.

Zirconium Complex was certified for Quality Management System as per ISO-9001:2015 by Bureau of Indian Standards on 15th May 2018. Continuous efforts towards improvement/development of production processes are being made for higher productivity, better recovery, lesser consumption of chemicals and reduction of effluents. With these efforts, ZC is achieving newer heights and excelling at fulfilling the mandate of the Department of Atomic Energy.

Zirconium Complex has future plans of setting up of Magnesium Recycling Technology Development & Demonstration Facility and capacity augmentation of zirconium sponge production to meet the future demand commensurate with the nuclear power programme and the ground works in this direction have been already initiated. Further to this, a plan of action has been worked-out to enhance Zr production to 1300 TPY through capacity expansion at Zirconium Complex, Pazhayakayal in two phases.

Based on the ambitious plan of generating 60 GWe of nuclear energy by the year 2050, about 20 GWe is proposed to be generated through PHWRs and the remaining through LWRs and FBRs as shown in Table 17.2.

Accordingly, PHWR design has been successfully scaled up to higher capacities of 540 MWe (TAPS 3 & 4) and 16 numbers of 700 MWe. Towards this, presently 4 nos. of 700 MWe PHWRs are under advanced stages of completion at Rajasthan (RAPS 7 & 8) and Kakrapara (KAPP 3 & 4). Further, Government has accorded administrative approval and financial sanction for construction of 12,700 MWe PHWRs. This expansion in nuclear power program requires additional annual supply of 2000 MT of Fuel, Structural for 2–3 Reactors, Reactivity Mechanisms for 2–3 Reactors and supply of 40 Sets of steam generator (SG) Tubes. In view of this, NFC has geared up to meet these additional requirements and accordingly set up the following facilities.

### *17.6.11 NFC-Kota, Rawatbhata, Rajasthan*

A new fuel fabrication facility is being set up (NFC-Kota) at Rawatbhata near Kota, Rajasthan. This green field project is established with plant capacity of 500 TPY

PHWR fuel fabrication and 65 TPY fuel cladding fabrication. The capacity of fuel cladding fabrication will be further augmented by 100 TPY. NFC-K project envisaged to establish 37 element fuel bundle manufacturing facility to cater to fuel requirement of up-coming 4 Nos: of 700 MWe PHWRs. The project is in an advanced stage of completion and is expected to take-up the production shortly.

## 17.7 Experiences in Indigenous PHWR Fuel Manufacturing

With its expertise in multi-faceted technical areas, NFC has become mature, self-sufficient in manufacturing technology of nuclear fuel fabrication and structural materials. The lean grade ores from mines with varying geology, leaching methodology & concentration and ores with diverse composition with wide variety of impurities pose several challenges in achieving consistent $UO_2$ powder quality & $UO_2$ pellet sinterability. This has thrown a challenge to NFC in meeting the enhanced fuel fabrication requirements to meet energy demands. However, after conducting several lab scale/pilot scale experimental studies and with thorough understanding of the results from these studies, NFC has overcome the technological challenges and successfully demonstrated large scale production of consistent quality fuel pellets from the raw materials of various chemical forms received from indigenous sources.

Introduction of many innovative state-of-art technologies for various processes, equipment mechanization and automation led to ergonomic advantages for the plants. Continual analysis and optimization of the process parameters resulted in improvement of overall process recovery with higher productivity, environmental and radiological safety.

The primary mandate entrusted to NFC could be successfully met with the adaptation of technology up-gradation, introducing automation and capacity augmentation. The following paragraphs highlight some of those achievements.

### *17.7.1 Innovative Technologies/Technological Breakthroughs in Fuel Manufacturing*

#### 17.7.1.1 Automation in NFC

Fuel fabrication involves large no. of chemical, metallurgical & mechanical processes and involves handling of very large no. of intricate components with intensive inspection at every stage of manufacturing/fabrication. Also, ‘Zero Failure’ target requires reliability, reproducibility and precision across all stages of production & inspection involving raw materials, intermediate stages and final products.

Automation is the key and essential to achieving these goals. Apart from this, automation benefits in safe handling of radioactive & hazardous materials on large scale and thereby reducing the radiation exposure to working personnel and air born activity levels. Elimination of manual operations with automation will enhance the safety in operations through remote/centralized controls & provision of alarms/ safety inter-locks. Additionally, it economizes the process by minimizing the failure rates & manpower requirements, especially to meet the high demands of production. Automation further improves the digitization and documentation processes.

#### 17.7.1.2 Developments in UO2 Powder Production

Sinterability and physical integrity of $UO_2$ pellet is largely dependent on the physical characteristics of the $UO_2$ powder, which in turn is closely related to powder process parameters, such as dissolution temperature, organic/aqueous (O/A) ratio, uranium concentration, free acidity of uranyl nitrate solution, precipitation temperature, flow rate of the precipitant and temperature profile during heat treatment of the intermediates. It has been observed qualitatively that the effective filtration of uranyl nitrate extract before precipitation, plays a crucial role in achieving defect-free $UO_2$ pellets by filtering out various solid insoluble impurities.

For production of $UO_2$ powder with required characteristics that are acceptable in fuel pellet production coping up with varying impurity levels in raw materials, various process improvements and parameter optimizations have been carried out at various stages of $UO_2$ powder production process as detailed below.

*Increase in dissolution temperature of raw material:* A raise of 10°C in raw material dissolution temperature from the existing condition has ensured the complete conversion of dissolved organics and soluble silica present in the raw material.

*Change of Uranyl Nitrate feed in Slurry Extractor:* Introduction of Uranyl Nitrate Feed (UNF) to the Slurry Extractor at 3rd stage in place of 1st stage has reduced the aqueous entrainment in Uranyl Nitrate extract, which also decreased the tendency of formation of emulsions in subsequent stripping operation.

*Increase in Uranyl Nitrate Feed concentration.* The feed concentration has been increased by 75 gpl from the existing concentration to decrease the aqueous entrainment in the Uranyl Nitrate Pure Solution (UNPS) extract which is required to have better phase separation during solvent extraction process.

*Introduction of Vapour Ammonia during precipitation* The vapour ammonia precipitation of UNPS was introduced in place of liquid ammonium hydroxide solution to get ammonium diuranate (ADU) powder with desired size & morphology. Also, time of precipitation was reduced and minimized the liquid effluent generation as well.

*Increase in % TBP in solvent extraction process:* It is necessary to increase extract saturation to reduce the impurities in the extract and it was achieved by increasing the percentage of Tri Butyl Phosphate (TBP) by 3% from the existing condition during extraction. This has resulted in increase of U concentration in the extract by 10 gpl which is equivalent to an increase of extract saturation from 90 to 95%.

*Introduction of modified baffle in Calcination furnace:* For homogeneous mixing and complete conversion of ADU to $U_3O_8$, heat transfer simulation studies were carried out by modeling the calcination and reduction operations involved in the powder production. Accordingly, the baffle plates of calcination & reduction furnaces were suitably modified and a unique design of baffle cage as shown in Fig. 17.6 was introduced in the rotary furnaces for calcination, reduction and stabilization operations. This has resulted in increased powder lifting and heat transfer to the powder. After the modification, there was a remarkable decrease in calcination temperature (by about 20°C) with the required powder quality consistently due to the cascading effect realised with the provision of lifters.

*Modification in AU Precipitation:* The powder morphology has been customized by optimization of critical parameters like Ammonia Flow rate, UNPS concentration and Precipitation Temperature, terminal pH. Using the optimized parameter, the batch precipitation time has been reduced and resulting in more chemically active AU powder. Furthermore, the $UO_2$ powder produced from this AU powder has resulted in reduction in the temperature of subsequent calcination operation and played a pivotal role in reduction of sintering cycle.

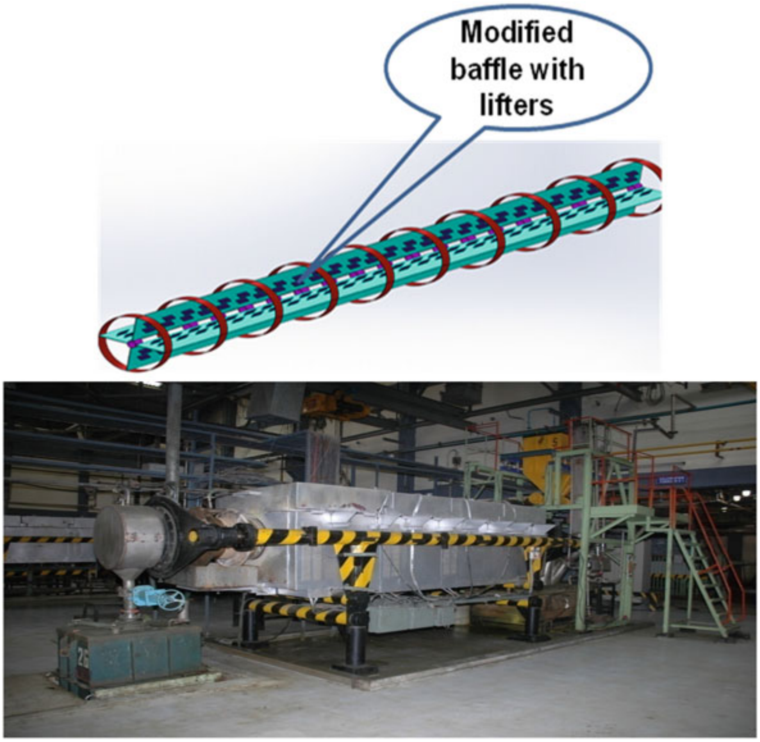


**Fig. 17.6** Unique design of baffle cage for rotary furnaces and the picture of calcination furnace

*Modifications in Stripping Operation.* The Port and the Mechanical Coalescers were modified to increase the stripping efficiency by 100%. The port modifications (before and after) and Mechanical Coalescers are shown below in Fig. 17.7a–d respectively.

The several process modifications carried-out in $UO_2$ powder production along with benefits obtained so in the plant are summarized in the following Table 17.3.

Automation in $UO_2$ Powder Production In order to have reliability in process with safety interlocks and reproducible quality in $UO_2$ power production, automation in powder production has been introduced. They include

(i) Automated operations through PLC-Based SCADA
(ii) Automated Radioactive Slurry Transfer System

The automation has resulted in an increase in recovery to around 99% (one of the highest recovery worldwide), 20% reduction in process variability, 40% reduction


**Fig. 17.7** **a**, **b** Port modifications, **c** mechanical coalescer (MS), **d** MS placed in mixer settler

**Table 17.3** Process modifications in $UO_2$ powder production and capacity increase

| Sl. no | Process | Capacity increase (%) | Technological advancements |
|---|---|---|---|
| 1 | Dissolution | 100 | (a) Oxidative dissolution<br>(b) Automated process control |
| 2 | Slurry extraction | 100 | (a) High Conc<br>(b) High flow rate feed<br>(c) Increase in TBP Conc<br>(d) Hydrodynamic modifications |
| 3 | Stripping | 100 | (a) Mechanical coalescers<br>(b) Port modifications |
| 4 | Precipitation | 50 | Change of AU morphology |
| 5 | Filtration | 85 | (a) Automated vacuum receivers<br>(b) Powder chute modification |
| 6 | Drying | 70 | (a) Additional heaters<br>(b) Thermal insulation |
| 7 | Calcination & reduction | 60 | Furnace internal modification |

in man shifts, 55% reduction in average air activity with the complete elimination of manual operations.

There has been more than tenfold increase in the production of $UO_2$ powder using the existing infrastructure after the process modifications.

#### 17.7.1.3 Developments in $UO_2$ Pellet and Fuel Bundle Fabrication

*Development of Advanced 3-D blending machine* Powder blending is one of the important process steps where $UO_2$ granules of various size distribution and powder lubricant are mixed homogeneously before undergoing pellet fabrication in final compaction press. An advanced 3-D blending machine was designed and developed indigenously to ensure homogeneity in mixing of $UO_2$ powder with lubricant. This has reduced the powder blending time drastically from 30 min to about 4 min and helped in lowering the variations in green pellet density by five times. The 3D Blending Machine as shown in Fig. 17.8 has replaced the existing carbouy rolling machine.

*Integrated Blending & Granule Transfer System and Rotary Compaction Press.* A newly designed Integrated Blending & Granule Transfer System (Fig. 17.9a) and Rotary Press (Fig. 17.9b) for Final Compaction of $UO_2$ powder was introduced to reduce density variation in green pellets by 50% and for two-fold increase in the productivity. Also, consistent Sintered Density and reduction in handling defects like chips (reduced by 3%) was achieved by using these systems.

*Development of automatic pellet stacking machine.* An industrial scale image processing-based automatic pellet stacking machine has been developed successfully for the first time in NFC. The machine is based on vision technique where the image of un-stacked pellets row is captured and is processed to find individual pellet length and its position. An advanced algorithm is developed for selection of pellets from row being stacked and buffer to obtain required stack length (480.68 + 0.00/−1.60 mm). A robot is used for interchange of pellets as decided by the algorithm. After stacking, stacked row is verified for stack length by Linear Variable Differential Transformer

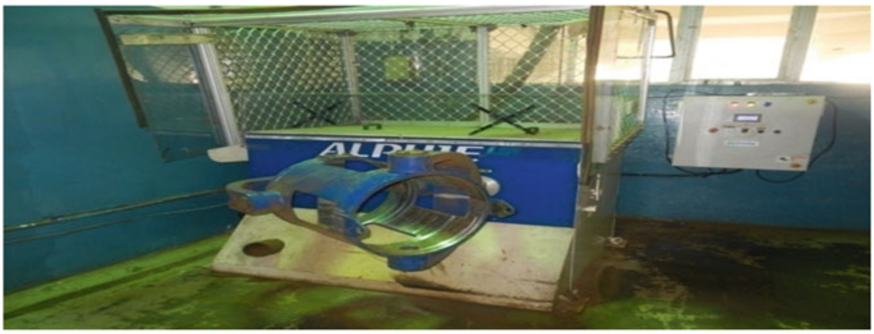

**Fig. 17.8** 3D blending machine


**Fig. 17.9** **a** Integrated blending & granule transfer system. **b** Rotary compaction press

(LVDT). Machine speed is equivalent to an operator speed. This auto pellet stacking machine as shown in Fig. 17.10 provides great ergonomic advantages by eliminating dependence on skilled operator for stacking and it also minimizes radiation exposure to the working personnel.

**Fig. 17.10** Automatic pellet stacking machine

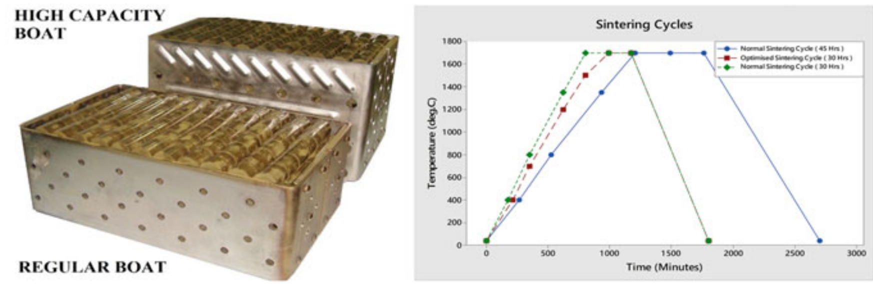


**Fig. 17.11** High capacity molybdenum boat with MLR material and modified sintering profile

*Design & Development of High Capacity Molybdenum Boat with MLR Material.* Existing Molybdenum sintering boat design was modified with MLR (Molybdenum-lanthanum oxide recrystallized) grade material for improved sintering quality, thermal life and capacity. The innovative corrugation design at free surfaces has resulted in better heat transfer and sintering. With modified boat, both capacity per boat and thermal fatigue life of the boat has increased by 50%. The modified boat is shown in Fig. 17.11.

*Modified Sintering Profile.* A multistep heating profile has been developed after in-depth analysis of the $UO_2$ powder morphology. The pushing interval has been reduced, resulting in reduction of $UO_2$ sintering cycle time by almost 50%. Furnace throughput also increased by 40%. This temperature profile is being used in regular production activities. The modified sintering profile is shown in Fig. 17.11.

With these modifications, the overall sintering output has doubled during regular production.

*Automated Green Pellet Charging System.* The system is being used for automatic transfer of $UO_2$ green pellets into Mo boats and the developed PLC-based Pellet Charging System has been integrated with Compaction press. It works on vacuum pick and place concept. Elimination of manpower for boat preparation and minimizing radiation exposure to operator, elimination of chipping defects at green stage due to zero manual handling, increase in visual recovery by 3% are among the advantages. It is shown in Fig. 17.12a.

**Fig. 17.12** **a** Automated Green Pellet charging system. **b** Sintered Pellet discharging system

*Automated Sintered Pellet Discharging System.* The system is being used for automatic discharge of sintered UO2 pellets from Mo boats into SS rod trays for inspection and grinding. Vision-based SCARA Robot processes the image from Area Scan Camera and analyses the position of the pellets to place on SS trays. Elimination of manpower and minimizing radiation exposure to operator, minimizing of chipping defects are among the advantages. It is shown in Fig. 17.12b.

#### 17.7.1.4 Automated Appendage Welding

*Integrated Spacer & Bearing Pad Welding Unit*. This automatic PLC-based control system as shown in Fig. 17.13 is involved in handling, loading & un-loading of fuel-clad tubes and feeding of spacer & bearing pad along with pick & place for positioning of appendages. It can do 1800 appendages welding per shift per machine.

*Integrated End Cap Welding & Machining (IECWM) Unit*. Introduction of IECWM unit has eliminated manual handling of fuel element/tube and there-by reducing Radiation Exposure to operating personnel and improving overall safety. It can do 120 elements per hour of production which almost an increase of 150% from exiting production and with a recovery of 99%. The unit operations are shown in Fig. 17.14a–d.

*Robotic End Plate Welding Machine for 37 Element PHWR Fuel Bundle.* This facility has been established for fabrication of 37 Element PHWR Fuel bundles meant for forthcoming 700 MWe PHWRs. Annually 65,000 PHWR Fuel Bundles are being produced in this facility. Consistent Bundle Recovery of around 99% was achieved with a reduction of 15% in mandays. It has given an improvement of 20%

**Fig. 17.13** Integrated spacer & bearing pad welding unit

**Fig. 17.14** Integrated end cap welding and machining unit. **a** Tube machining, **b** End cap feeding, **c** End cap welding, **d** Element machining

productivity/person, 10% improvement in machine availability. There was significant reduction in operator fatigue. It is shown in Fig. 17.15.

#### 17.7.1.5 Automated Radioactive Material Handling Machines

In order to improve Radiological Safety for occupational personnel, several state-of-the-art machines are introduced into regular plant operations involving radioactive materials. The introduction of such automated machines has resulted in reduction of Occupational Dose by 40%, Average Air Activity was reduced by 5% and samples above DAC were reduced by a factor of 2. They include Automatic Boat Transfer

**Fig. 17.15** Robotic end plate welding machine for 37 element PHWR fuel bundle

using an Autonomous Guided Vehicle (AGV), Automatic Pellet Feeding to centre less grinding (CG) machine and Automatic Pellet Loading System.

#### 17.7.1.6 Automation in Fuel Bundle Inspection

With an aim to increase productivity along with reduction in radiation exposure and also to reduce operator fatigue, the following automation systems have been introduced in fuel bundle inspection. They include Automatic Sintered Pellet Density Measurement System, Automated Ultrasonic testing (UT) for End Cap Welded Elements of PHWR Fuel Element, Integrated Helium Leak Test (HLT) and UT System for Fuel Elements and Automated Fuel Bundle Inspection System.

*Automatic Sintered Pellet Density Measurement System.* It works on Archimedes' principle for measuring the density of sintered $UO_2$ pellets (immersion technique) and uses SCADA with data logger system. The advantages include density measurement being independent of shape—dishing accounted (error in measurement due to discontinuity in pellet geometry is eliminated), elimination of manpower there-by reduction in radiation exposure and significant increase in through-put.

*Automated UT for End Cap Welded Elements of PHWR Fuel Element*. Fuel bundles are manufactured to high quality standards following stringent quality control program fulfilling the customer requirements. Manufacturing of PHWR fuel assemblies involves fabrication of clad tubes by pilgering process, resistance welding of different appendages on to the clad tubes, graphite coating on ID & baking of clad tubes, encapsulating of fuel within clad tubes by resistance butt welding of end caps and final assembly of fuel elements into fuel bundles by end plate welding.

Out of all the processes involved in the fabrication of PHWR fuel assemblies, end cap welding process is considered to be the most critical, as it hermetically seals the nuclear fuel inside the clad tube and plays a major role in controlling the fuel failures. Hence the quality of end cap weld joints is being monitored to high level of in-house developed standards of metallography and ultrasonic testing for evaluation of integrity of weld joints.

An automatic Ultrasonic Testing (UT) system was developed at NFC for 100% UT of end cap weld joints for ensuring their quality, replacing the random-based manual UT system. Automation of UT process eliminates human error, reducing the operator effort and time. The system is completely automated to meet the mass scale production requirements.

Automatic UT system as shown in Fig. 17.16 uses an immersion type pulse echo shear wave technique with a 20 MHz spherically focused probes. Individual fuel elements are picked from the element loading tray and immersed in a water bath. Probes move automatically near to the end cap weld regions and are indexed automatically with a pitch of 75μ over a sampling length of 900μ. No operator intervention is required as the UT probes are automatically indexed and moved near to end cap weld joints. The fuel element is rotated slowly for full circumferential scanning of the weld joints simultaneously. PC-based defect detection system is used for recording the signals and defective elements are identified automatically. The system has a repeatability of ±3% of FSH, three times faster than manual scanning and takes 30–40s per element for scanning and analysis.

This in-house developed integrated system has eliminated separate Helium Leak Test (HLT) operation and made it possible to have 100% ultrasonic testing (UT) (from earlier 25% UT sample check) along with HLT operation. This has resulted in an increase of manpower by 100%. Using this system already more than 30 Lakh welds are tested. The system is shown in Fig. 17.17.

*Development of Automatic Fuel Bundle Inspection system.* For ease and quality in manufacturing of PHWR fuel bundles, a Robot aided end plate welding station and a Supervisory Control And Data Acquisition (SCADA)-based automated bundle inspection system were developed in-house. After the end plate welding operation is complete, the Robot handles the fuel assembly and places on a conveyor for inspection

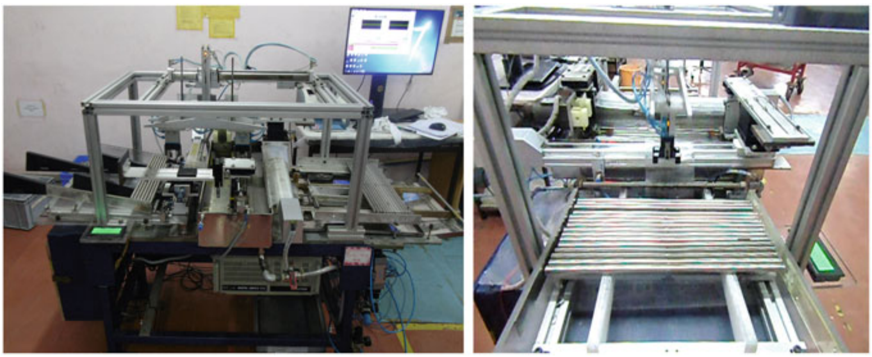

**Fig. 17.16** Automated ultrasonic inspection system for end cap weld joints

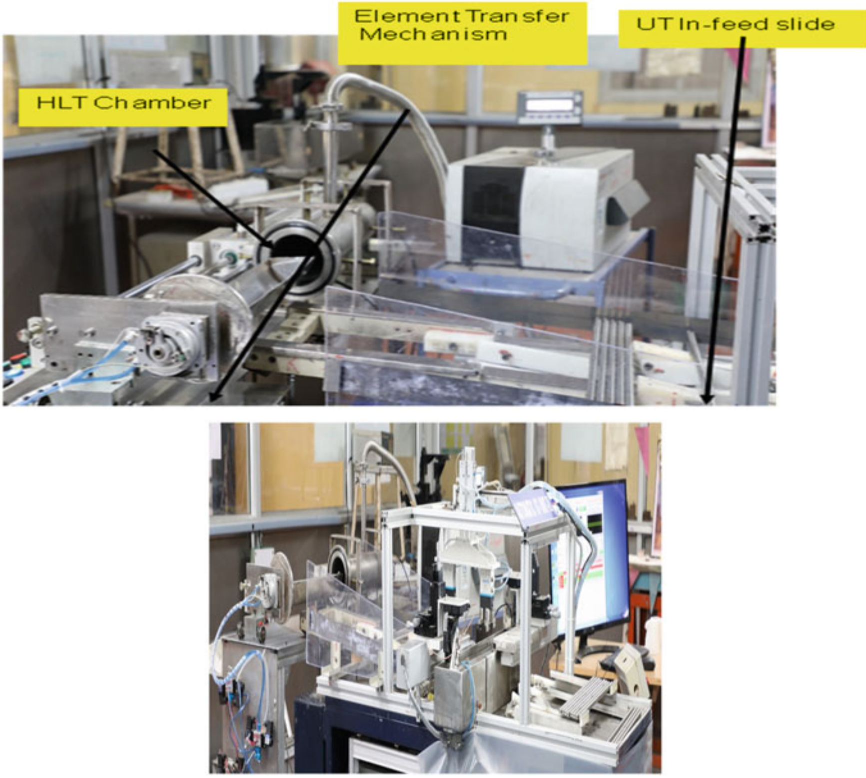


**Fig. 17.17** Integrated HLT and UT system for fuel elements

activities. The inspection system performs a series of inspection activities such as back filling, Helium leak testing, bundle diameter gauging, weight measurement, etc., reducing human fatigue and thereby increasing productivity by 50%. In Automated Fuel Bundle Inspection system as shown in Fig. 17.18, the fuel bundles are placed in Helium chambers kept at 6 $kg/cm^2$ for about 30 min, then excess helium is air washed and passed through Helium leak detection chamber. Subsequent to HLT (Helium Leak Test), the bundles are sent through gauging and dimensional testing stations followed by final visual inspection. All the operations are controlled by a computer-based SCADA system and inspection data is logged on to a computer.

*Automated System for UO2 Pellet Visual Inspection*. Prior to loading them into empty fuel tubes, UO2 pellets are subjected to 100% visual inspection for defects like cracks, end capping, end chips, pits as shown in Fig. 17.19. Introduction of automated visual inspection system has reduced the subjectivity-related errors due to manual operations. Further, it has minimized the exposure to radioactivity during inspection.


**Fig. 17.18** Automatic fuel bundle inspection system


**Fig. 17.19** Automated visual inspection of UO2 pellets

#### 17.7.1.7 Advanced QA Systems for Improving PHWR Bundle Quality

*Vision-Based Tube Inspection System (VBTIS).* An automatic vision-based tube and end cap inspection system has been introduced in the production line. The system is designed to identify and separate tubes having variations beyond the specified limits with respect to Tube diameter, Scratches, Dents, Pits on the outer surface, End chamfer, etc. This is shown in Fig. 17.20a.


**Fig. 17.20** **a** Vision-based tube inspection system, **b** Laser marking of bundle numbers on end plates, **c** Metallic Jig for PHWR bundle fabrication

**Fig. 17.21** 1500kg Zr-metal produced and Facility for its production

*Laser Marking of Bundle Numbers on End Plates (LMBNEP).* Laser marking machine introduced for marking identification number on PHWR end plate has drastically improved readability, repeatability, accuracy. Marking cycle takes <7 s. This is shown in Fig. 17.20b.

*Metallic Jig for PHWR Bundle Fabrication (MJPHWRBF).* Implementation of metallic jigs instead of Perspex jigs at end plate welding of both 19 and 37 Element bundles has increased life of jigs (3000 Bundles/pair against 150 Bundles/pair). This is shown in Fig. 17.20c.

Using these automated systems in UO2 pellet production, inspection and fuel bundle fabrication, there is a tenfold jump in production activities during the last ten years.

#### 17.7.1.8 Developments in Zirconium Sponge Metal Production

Technology Demonstration Unit has been successfully commissioned at Zirconium Complex, Pazhayakayal, Tuticorin, Tamil Nadu for the production of 1500 kg batch against regular batch size of 950 kg for the first time. Several batches are produced through this process. Efforts have been made to reduce the production cycle time and to meet the additional requirements of sponge metal. The chemical analysis of the 1500 kg Zr sponge batches produced is meeting the technical specification. Higher productivity, improved purity, energy savings and improved recovery by 2% are the advantages. Figure 17.21 shows the production facility with a picture of typical batch produced.

#### 17.7.1.9 Developments in Structural Components Production

*Development of Novel Route for Production of Pressure Tubes.* After successful completion of trials for fabrication of Zr-2.5%Nb Pressure Tubes (PT), a novel modified route based on double radial forging, single stage extrusion and single pass pilgering route was taken up for their production of industrial scale. During the extrusion, high extrusion ratio of >10 is used to obtain favourable crystallographic texture. This crystallographic texture has primarily basal pole orientation (0002) in the transverse (circumferential) direction. During further single-stage pilgering, there is no modification of this transverse texture. Such a texture is favourable for creep properties of the tube, which is one of the main life limitation properties for this structural material.

#### 17.7.1.10 Quality Improvement in PT Through Modified Route

*Metallurgical Improvements*

- Introduction of two stage radial forging has led to coarser overall grain size and more uniformity in properties along the length of the tubes
- Higher extrusion ratio results in more favorable aspect ratio of alpha grains and higher fT i.e. stronger transverse basal pole texture compared to older route (0.65–0.70 in new route versus 0.5–0.6 in old route)
- Single pass pilgering has eliminated the requirement of intermediate annealing, thus ensuring more continuous beta phase network along the grain boundaries of alpha grains Increasing the Q factor from ~2 to 4 has changed the hydride orientation from mixed to predominantly transverse.

*Visual Improvements*

- Modification of autoclave carriage has resulted in significant reduction in jerks and vibration encountered by the tubes during loading, unloading and autoclave operation thus marks created by autoclave carriage on tube surface have been practically eliminated
- The customer has given a note of approval about these steps taken to improve the visual quality of the tubes.

*Dimensional Improvements.* Modification in pilgering pass schedule and fine-tuning of tooling profiles has resulted in significantly better dimensional control with the DCRs for dimensional deviations getting reduced from ~84% (341 tubes out of 403 tubes) for RAPP 8 to 20% (67 tubes out of 326 tubes) for KAPS II.

*Advancements in Grinding & Honing.* Modification in Honing machine: Increase in stroke length of honing machine to 7.5 m to carry out honing in single stroke. Advantages of OD grinding are confirmation of Blank Wt., UT Status before Pilgering, minimizing of reworks in Final Tube stage. Where-as minimized reworks in final pilgered tubes, better compliance towards stringent dimensional requirements in final tube, improved efficiency & recovery are the advantages of ID conditioning. The operations are shown in Fig. 17.22.

*Advancements in Packing of Pressure Tubes.* In view of its criticality and cost of production, it is equally important to dispatch the pressure tubes to reactor sites in the most secured manner so that they can be introduced into reactor without any re-works. Figure 17.23 shows the modified packing for dispatch of Pressure Tubes

**Fig. 17.22** Grinding & honing operations in PT production

to Reactor sites. This simple modification has resulted in reduction of re-works and thereby savings to NFC.

*QA improvements in PT/CT*. Laser-based OD Measurement for Pressure Tubes was introduced for digital data acquisition in place of Thermal Strip Chart prints, for digital output in place of manual measurements and Automatic Logging of WT values at every 400 mm interval.

*Development of new design for Garter Spring Manufacturing*. A new design of Corrugated Girdle wire has been introduced in place of Plain Wire for manufacturing the Garter Springs. The new design has the ability to accommodate up to 6% creep expansion of pressure tubes and good sensitivity in detection of garter spring location. Figure 17.24 shows typical pictures of garter springs.

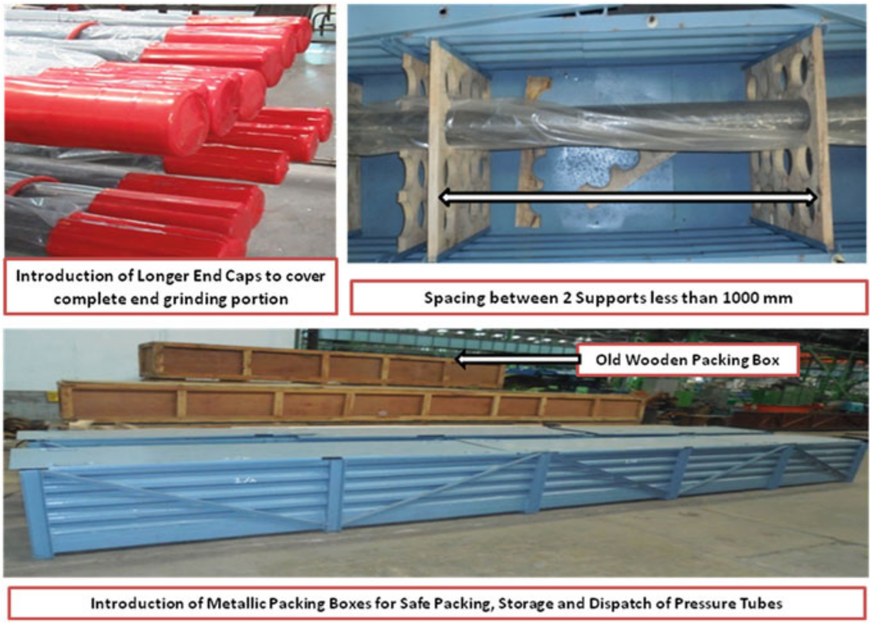


**Fig. 17.23** Packing for dispatch of pressure tubes to reactor sites

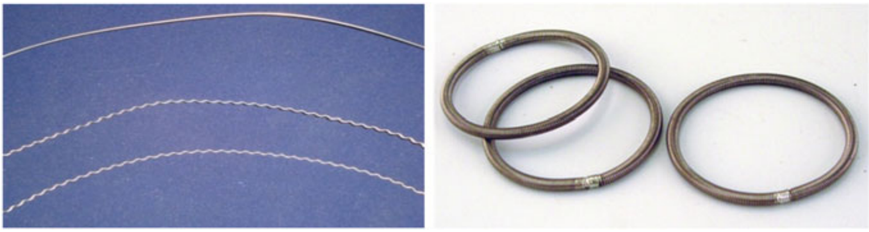

**Fig. 17.24** Garter Springs made with corrugated girdle wire

**Fig. 17.25** Incoloy-800 U bend SG tubes

## *17.7.2 'Atmanirbharta'—A Make in India Initiative*

### 17.7.2.1 Steam Generator Tubes for PHWR

NFC successfully manufactured Incoloy-800 U bend steam generator (SG) tubes first time in India. The production of 30-m-long Incoloy-800 U bend tubes is a technological challenge to any engineer and NFC could do it successfully and delivered 8 sets for RAPS 7 & 8, KAPS 3 & 4 reactors. In view of very high demand, a dedicated facility has been established to double the production capacity to 6 sets per year. It generates significant revenue to NFC. It has opened an opportunity to NFC to become potential supplier of U bend SG tubes in International market. A typical picture of these tubes is shown in Fig. 17.25.

### 17.7.2.2 Indigenous EB Melting Furnace

In view of restricted technology, a successful effort was made in NFC to built indigenous electron beam melting furnace. The indigenously built EB Melting Furnace is used in melting and purification of refractory & reactive metals and alloys for strategic applications in Nuclear, Space, Defence fields. The efforts have resulted in huge revenue savings for the department and eliminated the dependency on external agencies for the maintenance of the furnace. The EB Furnace was built for the first time in India using indigenously available resources and in the process, India has become 4th country in the world to have such a facility. The facility was inaugurated by the President of India in 2018 as shown in Fig. 17.26 and since then being used for different purpose.


**Fig. 17.26** Indigenously built EB melting furnace and inauguration by President of India

#### 17.7.2.3 Manufacturing of Special Tubes

Several special grade steel tubes have been manufactured for special & strategic applications for first time in India as import substitutes such as Incoloy-800 U bend SG tubes, Zr-1% Nb tubes, Titan-24/11 tubes, SuperNi 42, Inconel 690/600, Alloy 617 etc. Some of them are shown in the following paragraphs.

Titanium Tubes Manufacturing: Zirconium and Titanium have similar metallurgical characteristics and processing routes (Extrusion, Pilgering, Heat Treatment, etc.). NFC with its vast experience of manufacturing Zircaloy tubes is well equipped to take up bulk manufacturing Ti-alloy tubes as import substitutes. Over the years, various Titanium alloy products like Titan-24 Tubes for Strategic Nuclear application, Ti-half alloy Truss rod Tubes for PSLV & GSLV, Ti half alloy Hydraulic Tubing for Light Combat Aircraft (LCA) have been developed. It is planned to augment capacity through an exclusive facility.

SuperNi-42 Tubes: These tubes as shown in Fig. 17.27 are of small diameter, extremely thin-walled and have stringent specifications with respect to dimensional tolerances and metallurgical properties. After initial trials for indigenous development in collaboration with BARC Mumbai, the manufacturing route was established for bulk production. The process consists of production through 10 stages of thermo mechanical processing followed by final finishing operations & stringent quality checks of mechanical testing, ultrasonic testing, dimensional & visual inspection. Optimization of the process was done using the experience gained on thermo mechanical processing on this special alloy, to achieve significantly improved recovery and productivity. It is planned to augment capacity through an exclusive facility.

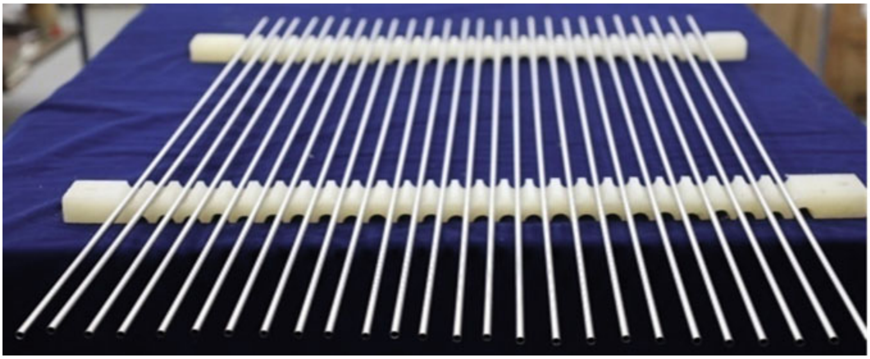

**Fig. 17.27** Typical picture of SuperNi 42 tubes

#### 17.7.2.4 Other Developmental Works Carried Out in NFC

With its structured and well-established manufacturing process under its belt, NFC continuously made technological improvements to refine the processes. Some of them are as follows.

- NFC demonstrated the production of 1500 MTe of natural uranium fuel (world's highest-ever production).
- Manufactured and supplied 19/37 element Natural Uranium Fuel bundles for all the PHWRs and Enriched Uranium Fuel Assemblies of $6 \times 6$ types to BWRs. For the first time, 37 element fuel bundles with modified bearing pad design was made for the initial core requirement of India's 1st 700MWe PHWR at KAPS-3.
- In-house development of Auto Ring gauging for PHWR fuel bundles, a mandatory requirement prior to loading of bundles in to reactor core.
- Development of automated vision-based inspection system for surface examination and dimensional measurement of fuel bundle appendages viz. Bearing and Spacer pads to increase through-put with reliability.
- Development of High corrosion resistant SS-304L pipes for Fast Reactor Fuel Cycle Facility (FRFCF).
- Development and manufacturing of D9 Fuel Clad Tubes and Pure Nickel Tubes for Prototype Fast Breeder Reactor (PFBR).
- Development of Alloy 617 tubes for Advance Ultra Super Critical (AUSC) power plant.
- Development of and supply of Zr-1%Nb alloy tubes for strategic applications.
- Development and manufacturing of RRR Grade Niobium sheets for fabrication of Super Conducting cavities.

## 17.8 Association with NPCIL

As NFC enters golden year of its existence and it is a matter of privilege to recollect the fruitful association with Nuclear Power Corporation of India Limited (NPCIL), its principal customer who are responsible to operate nuclear power reactors in India. The association dates back to 1974 soon after Canada's withdrawal from cooperating India in PHWR program due to Pokhran-1 restrictions. Since then NFC has come long way in supporting NPCIL starting from 220 MWe at NAPS to 540 MWe at TAPS to present indigenous variant of 700 MWe at KAPS.

### *17.8.1 Role of NFC in First Criticality of KAPP*

It is a happy and momentous occasion to DAE, especially NPCIL Team on achieving the 'First Criticality' of 3rd Unit of Kakarpar Atomic Power Project (KAPP-3) on 22–07–2020 at 09.36 AM. Indeed, it is a proud moment to all of us to see a congratulatory message from Shri Narendra Modi, The Prime Minister of India saying 'development of indigenous reactor as shining example of Make in India and a trailblazer for many such achievements'.

It is interesting to note that KAPP-3 finds a special place in Indian Nuclear Power Program as India's First 700 MWe and biggest indigenously developed variant of Pressurized Heavy Water Reactor (PHWR). Operationalisation of India's first 700 MWe reactor marks significant scale-up in design and economies of existing 540 MWe reactor without significant design changes and also addressing the important issue of excess thermal margin. It is also important to note that the milestone moment has come ahead of its original schedule. Thanks to coordinated efforts of many related agencies including NFC. This has given a tremendous boost and confidence to DAE to handle & ensure the successful completion of such mega projects. Thus, KAPP-3 has become the backbone to new fleet of 10 such reactors sanctioned by government in 2017. This will help DAE in ramp-up the nuclear power capacity to 22,480 MWe from existing 6780 MWe by 2031, where 700 MWe reactors find a lion share.

Nuclear Fuel Complex (NFC) has played an important & substantial role in this achievement through the timely supply of several reactor-core components to this indigenous variant and directly contributing to the government stand of self-reliance. The core components include 125T of natural uranium fuel, 392 channels of pressure tubes, 1568 numbers of garter springs, 30 m length of 'U-bend' Incoloy800 steam generator tubes, 96 numbers of reactivity mechanism assemblies. Therefore were challenges in executing this time bound assignment and but, were successfully met by NFC with untiring and commendable efforts of its employees. The technological solutions to these challenges were developed and seamlessly implemented. For example, development of two pass forging route with single pass pillgering in place of extrusion route was carried out to produce 6 m long pressure tubes with better stability and uniform mechanical properties under reactor conditions. Similarly, blank machining, ID honing and OD turning operations were introduced during fuel clad manufacturing process to reduce wall variations in clad thickness and also to obtain better recovery in UT pass. The design of garter springs was also changed to corrugated & welded spring to improve integrity of griddle wire under dynamic flow of coolant and improved testing capability during ISI.

## 17.9 Summary

One can confidently say that NFC always sets a new benchmark in *N*ever *F*ails in its *C*ommitments attitude and continue to play a significant role in all NPCIL's ambitious future expansion programs and delivering the requirements of other departments like DRDO, ISRO as well.

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