PHWR FUEL EXPERIENCE IN INDIA

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ABSTRACT

Production of 19-element zircaloy clad natural uranium oxide fuel bundles for Pressurised Heavy Water Reactors (PHWR) of 220 MWe type in India is being carried out at Nuclear Fuel Complex (NFC) at Hyderabad since June, 1973. During the last 26 years, more than 1,75,000 fuel bundles have been fabricated and supplied by NFC to Nuclear Power Corporation of India Limited (NPCIL) for use in PHWR 220 units. In the financial year 1998-99 (April 1998 - March 1999), NFC produced 20,157 fuel bundles (306 tons), which is the highest annual production since the inception of NFC. For the year 1999-2000, a production target of 23,500 fuel bundles (around 350 tons) has been set, of which nearly 175 tons have been fabricated till the middle of September 1999. In the last few years, at NFC, efforts are being made to augment safety, fuel quality, automation and productivity. The in-pile performance of PHWR fuel produced in NFC has improved progressively over the years. By the end of the year 2000, twelve PHWR 220 MWe would be operational in India for which the fuel and the zircaloy structurals would continue to be fabricated at NFC. In parallel, a new project has been initiated for fabrication of 37-element zircaloy 4 clad natural uranium oxide fuel bundles for the forthcoming twin units of PHWR 500 MWe at Tarapur Atomic Power Station (TAPS - 3 & 4).

1.0 INTRODUCTION

Nuclear Power is an inevitable energy option for India in the next millenium. The raw materials for nuclear power programme, namely, uranium and thorium occur disproportionately in India. According to the recent reports **(1,2)** of the Atomic Minerals Directorate of Exploration and Research (AMD), the proven reserves of uranium, thorium and zirconium in India are 92,000 tons U_3O_8, 5,90,000 tons ThO_2 and 18 million tons zircon respectively. For judicious utilisation of limited uranium but vast thorium resources, the Department of Atomic Energy (DAE) in India is pursuing a three stage nuclear power programme, with a closed fuel cycle, linking natural uranium-fuelled Pressurised Heavy Water Reactors (PHWR) in the first stage with mixed uranium (depleted) plutonium-fuelled Liquid Metal Cooled Fast Breeder Reactors (LMFBR) with thorium blanket in the second stage. The U^{233} produced in LMFBRs would be used in the third stage in Advanced Heavy Water Reactors (AHWR), which would be operated on self sustaining Th^{232}-U^{233} fuel cycle.

During the last three decades, India has achieved self-reliance in the front and back ends of the nuclear fuel cycle. These include:

- Exploration and Mining of uranium and thorium.
- Production of nuclear grade, sinterable UO_2 powder from low grade uranium ores and Production of high density UO_2 fuel pellets.
- Production of nuclear grade ThO_2 powder starting from monazite sand and Fabrication of high density ThO_2 pellets.
- Production of hafnium-free nuclear grade zirconium sponge from zircon sand and Fabrication of zirconium alloy ingots and components.
- Production of zirconium alloy clad natural uranium oxide fuel bundles for PHWRs.
- Production of zirconium alloy clad thoria assemblies for neutron flux flattening in the initial core of PHWRs during start up.
- Reprocessing of spent UO_2 fuel from PHWRs for recovery of plutonium and depleted uranium.
- Reprocessing of thoria bundles from PHWRs for recovery of U^{233}.
- Fabrication of zirconium alloy clad mixed uranium plutonium oxide (MOX) fuel for water-cooled reactors and stainless steel (type 316) clad, mixed uranium plutonium monocarbide (MC) fuel for LMFBR.
- Treatment and management of radioactive wastes.

2.0 PHWR PROGRAMME

PHWR is the backbone of the nuclear power programme in India. Presently, eight PHWR units of capacity 220 MWe each (a few units have been derated) are in operation contributing 1520 MWe. Four more PHWR 220 units would be connected to the grid before the turn of the century, two each at Kaiga Atomic Power Station and Rajasthan Atomic Power Station (RAPS - 3 & 4). Construction activities of two units of PHWR 500 MWe have started at Tarapur Atomic Power Station (TAPS 3 & 4) in October 1998. DAE has set a target of installing 20,000 MWe nuclear power by the year 2020 in which there would be 14 units of PHWR 220 and 12 units of PHWR 500 **(3)**.

3.0 MINING, EXPLORATION AND CONCENTRATION OF 'U' ORE

Presently, three underground uranium mines at Jaduguda, Bhatin and Narwapahar in the Singhbhum District of Bihar State in the eastern part of India are in operation. These three deposits contain low grade ores with uranium in the range of 0.04 to 0.06% only. The uranium exploration activities have been enhanced in other parts of the country. During 1998-99, in Gulbarga district of Karnataka State, bore-wells in Gogi have intercepted high grade (upto 1% U_3O_8) uranium mineralisation associated with brecciated limestone of Bhima basin. Extensive radiometric and magnetic surveys are also under way in Cuddapah basin in Andhra

Pradesh State at Lambapur and Banaganapalli. Additional uranium reserves were confirmed at Wahkyn in Meghalaya State. In-situ leaching technology has been initiated in the sand stone deposits of Domiasiat in Meghalaya State.

The Uranium Corporation of India Limited (UCIL), a public sector undertaking (PSU) under DAE, is responsible for the production of magnesium-di-uranate (MDU) concentrate from uranium ore. The Jaduguda mill of UCIL processes about 2000 tons of ore per day from which around 200 tons of uranium, in the form of MDU or yellow cake, are produced annually. The ore is crushed and milled and subjected to sulphuric acid leaching followed by ion exchange refining and precipitation of MDU. The MDU contains about 70% U_3O_8, which is sent to Nuclear Fuel Complex (NFC) at Hyderabad for further purification and production of high density UO_2 fuel pellets by the classical "powder metallurgy" route.

4.0 PHWR FUEL DEMAND AND PRODUCTION IN INDIA:

From its inception in the year 1971, NFC has produced more than 2600 metric tonnes of natural uranium oxide fuel for the PHWR 220 units, operated and maintained by NPCIL. During the year 1998-99, NFC has produced 20,157 fuel bundles (306 tons), which is the highest annual fuel production since the inception of NFC. Thus, the fuel requirement of eight operating PHWRs and the two forthcoming PHWR 220 units at Kaiga (Kaiga 2) and Rawatbhata (RAPS 3) has been met. The annual production of natural UO_2 fuel bundles for PHWRs during the last few years in NFC is shown in Figure **1**. Kaiga 2 has attained criticality on September 24, 1999 and RAPS 3 would attain the same by the end of 1999. The annual production of natural UO_2 fuel bundles for the year 1999-2000 is likely to cross 23,500 (350 tons) and meet the reload fuel requirements of operating stations and also the fuel needed for the initial cores of the two forthcoming PHWR 220 reactors at Kaiga (Kaiga 1) and Rawatbhata (RAPS 4). Kaiga 1 and RAPS 4 are likely to be commissioned by the third quarter of the year 2000. In order to cater to the fuel demand for PHWR 220 and PHWR 500 units in India, NFC has drawn up the fuel manufacturing schedules, which is indicated in Figure **2**.

4.1 Fabrication of zircaloy-4 cladding tubes and components:

Zircaloy-4 cladding tubes, end plugs, bearing and spacer pads for the PHWR fuel elements and end plates for the 19-element fuel bundles are produced in NFC, starting with zircon sand. Figure **3** summarises the essential steps followed in NFC for the production of nuclear pure, hafnium-free zirconium sponge from zircon sand. The zircon sand is leached with NaOH for removal of silica. Next, the hafnium is removed by solvent extraction process using tributyl phosphate (TBP). Hf-free ZrO_2 powder is subjected to carbothermic chlorination to form $ZrCl_4$, which is subjected to magnesio-thermic reduction, employing the Kroll's process for production of nuclear pure zirconium sponge. During the year 1998-99, NFC produced 165 tonnes of reactor grade zirconium sponge, which is the highest annual production of zirconium sponge since the inception of NFC. A new zirconium sponge plant would be constructed by March 2001 at NFC. Demonstration trials are underway for electrolysis of

$MgCl_2$ (reaction product of Kroll's process) for recovery and recycling of magnesium and chlorine.

The zirconium sponge is alloyed with tin, iron, chromium and oxygen and subjected to double-melting in a vacuum-arc-furnace using consumable electrode. The ingots are hot-extruded and subjected to pilgering, rolling and swaging with intermediate vacuum annealing to obtain thin-walled zircaloy-4 tubes, sheets and bars respectively. The process flow sheet followed in NFC for the production of zircaloy-4 cladding tubes, sheets and rods needed for PHWR fuel assemblies, is summarized in Figure **4**. The fuel cladding tubes are coated with graphite on the inner surface.

4.2 Production of UO_2 fuel pellets and fuel bundles at NFC:

The process flowsheet followed in NFC for fabrication of PHWR 220 fuel is summarised in Figure 5. At NFC, the as-received MDU from UCIL is converted into nuclear pure ammonium-di-uranate (ADU) by the wet chemical route, involving dissolution of MDU in nitric acid, purification of uranium solution by solvent extraction (using tributyl phosphate) followed by precipitation of ADU by addition of ammonium hydroxide. The ADU is subjected to controlled calcination in air, followed by hydrogen reduction and stabilisation to obtain sinterable grade UO_2 powder of desirable specific surface area, particle size, and oxygen to uranium ratio(**4**). The high density UO_2 fuel pellets for the PHWR units are manufactured by the classical cold-pelletisation of UO_2 powder in multi-punch hydraulic presses followed by high temperature sintering in reducing atmosphere (**5**). Finally, the fuel bundles are manufactured by employing specialised resistance welding, machining and assembling operations. A special mention may be made here regarding attachment of appendages to fuel element by resistance welding techniques, which is unique to Indian fuel and found to be cost-effective, eco-friendly and technically superior to conventional beryllium brazing.

The New Uranium Oxide Fuel Plant (NUOFP) for production of additional quantities of UO_2 powder and sintered UO_2 pellets and New Uranium Fuel Assembly Plant (NUFAP) for the manufacture of fuel bundles have been commissioned at NFC in 1998. The production activities in these plants are now in full swing.

For manufacturing zircaloy-4 clad UO_2 fuel element and fuel bundles, great emphasis has been given towards automation and development of indigenous equipment. Presently, several such equipment are in operation for graphite coating, resistance welding of end plugs, spacers and bearing pads, cleaning of fuel elements and manufacturing of fuel bundles.

4.3 Production of Thoria Bundles:

Any long term nuclear power programme in India has to be based on judicious utilisation of vast thorium resources in thermal and fast reactors. In order to build up a data base on the fabrication, in-pile performance and reprocessing of thoria, a decision was taken to introduce thoria bundles, in a modest way, during initial start up of PHWRs for neutron flux flattening.

For fabrication of ThO_2 bundle, MgO-doped (MgO as 'sintering aid') sinterable grade ThO_2 powder is obtained from Indian Rare Earths Ltd. (IRE) as starting material. High density thoria pellets are fabricated in the Nuclear Fuels Group at Bhabha Atomic Research Centre (BARC), Mumbai by cold-pelletisation and sintering. At NFC, thoria pellets are stacked and encapsulated in zircaloy-4 cladding tube.

From Kakrapar Atomic Power Station (KAPS) onwards, zircaloy clad ThO_2 bundles are being used in place of depleted UO_2. The 19-element ThO_2 bundles are similar to the natural UO_2 fuel bundles. The in-pile performance of ThO_2 bundles have been satisfactory in NAPS 2, in the two units of Kakrapara Atomic Power Station (KAPS 1 & 2) and in Rajasthan Atomic Power Station (RAPS 2 re-started after coolant channel replacement). Hence, ThO_2 bundles are being used in Kaiga 2 and RAPS 3 and would also be used in all forthcoming PHWR units in India.

4.4 Quality Control of PHWR fuel at NFC:

From the inception of nuclear fuel fabrication programme at NFC, a lot of emphasis has been laid for quality control procedures, including delivery checks of raw materials, qualifying equipment and plant personnel, evaluation of process intermediates and final products, and systematic documentation. The major quality checks are as follows:

• UO_2 Powder	Specific surface area, particle size distribution, oxygen to uranium atom ratio, chemical purity and sinterability.
• UO_2 Pellets	Dimensions, density, microstructure, surface integrity and chemical purity (emphasis on 'H' and equivalent boron contents).
• Zircaloy-4 Cladding Tubes	Dimensions, flaw evaluation, (ultrasonic and eddy current testing) mechanical properties, microstructure & texture (including hydride orientation, 'f_n' ratio, phase content and grain size), and chemical purity.
• Graphite Coating on Zircaloy-4 Cladding Tubes	Coating thickness and adherence.

• Zircaloy-4 clad Fuel Element with Appendages	UO_2 stack length and weight, Integrity (He-leak & ultrasonic testing of welds) weld metallography (for qualification), weld strength of appendages.
• Fuel Bundle	Visual examination, dimensional checks, 'He'-leak testing, weld strength of end plate (for qualification), surface contamination, weight.

Recently, a programme for obtaining ISO 9002 certification has been initiated at NFC and the certificate is likely to be obtained by the middle of the year 2000.

5.0 PHWR FUEL PERFORMANCE:

The Nuclear Power Corporation of India Limited (NPCIL) is responsible for the design, construction and operation of nuclear power stations in India. During the period from April 1998 to March 1999, the gross generation of electricity from the eight operating PHWRs and the two Boiling Water Reactors (BWR 160 MWe) have been 12,000 million kilowatt hour units. The average capacity factors of these reactors have been 75%. The capacity factor has been 88%, 89% and 91% respectively for RAPS 2, NAPS 1 & 2, KAPS 1 & 2 during the period from April 1999 - June 1999 **(6)**. The eight PHWR units in India have so far achieved more than 15,000 full power days of operation. More than 1,75,000 natural uranium oxide fuel bundles fabricated by NFC have been loaded in these reactors so far. The overall fuel failure rate has been less than 0.087% in the year 1997-98 and practically zero during 1998-99. The I-131 activity in coolant channels in all the stations has been less than 2.0 μ Ci/liter. The average discharge burn-up for the PHWR fuel in India is in the range of 6150 MWd/Te 'U' and 7100 MWd/Te 'U' and the maximum discharge fuel burn up has been 15,200 MWd/Te 'U'.

6.0 DEVELOPMENTAL ACTIVITIES:

The research and development back up for the PHWR programme in India is provided by BARC. The thrust in the fuel fabrication programme of NFC has been to continuously improve the safety of the plants, quality of the product, productivity and reduction in fuel fabrication cost. For this, the following programmes are underway:

- A spray drier has been installed in NUOFP in order to obtain dust-free and free-flowing ADU and minimise radioactive aerosol. In the old uranium oxide plant, turbo drier is in use;

- One of the rotary furnaces so far used for air-calcination of ADU to obtain UO_3 is being modified to carry out simultaneously calcination of ADU, reduction of UO_3 and stabilization of UO_2 in one step;
- For minimising radioactive aerosol and energy cost, the Sol-Gel Microsphere Pelletisation - Low Temperature Oxidative Sintering (SGMP-LTS) process **(7,8)** is being implemented on a pilot plant scale at BARC. The SGMP-LTS process is dust-free, avoids generation and handling of radioactive aerosol, facilitates automation in pellet production and minimises the fuel pellet fabrication cost by employing low temperature (~ 1200^0 C), short duration (1 hour) sintering in oxidative atmosphere. Ammonia internal gelation process using hexamethylene tetramine (HMTA) as ammonia generator and silicon oil at 90°C as gelation bath have been used to obtain dust-free and free-flowing hydrated gel-microspheres, which after controlled calcination produce soft and porous UO_2 microspheres which could be directly pelletised. A low temperature pusher type continuous sintering furnace has been indigenously manufactured and installed in BARC. This furnace has a densification zone and reduction zone with a nitrogen curtain in between. The sintering of the UO_2 pellets take place in the densification zone which is maintained at an atmosphere of nitrogen and air mixture containing less than 1000 ppm oxygen. The reduction zone consists of nitrogen and hydrogen mixture for controlling the stoichiometry of UO_2 pellets after densification. The UO_2 pellets fabricated in this indigenous furnace are of high density (> 96% T.D.) and contain uniformly distributed, closed, spherical pores in the ideal diameter range of 2 to 5 microns.
- Trials are underway for direct and dry conversion of sintered UO_2 pellets, which conform to all chemical specification but are rejected due to surface defects or density mismatch, to sinterable UO_2 powder by controlled oxidation and reduction;
- Hot vacuum (~ 300°C) degasing of UO_2 pellets prior to encapsulation would minimise moisture and other hydrogen bearing impurities in pellets, which in turn would avoid internal hydriding of fuel elements;
- 100% ultrasonic testing of the weld region of resistance welded fuel element is being introduced in order to intercept any weld defect and also to phase out the destructive metallography technique for evaluating set up and process welds in each shift;
- A new sequence of fuel element and fuel bundle fabrication is being developed. The present practice is to load sintered UO_2 pellets in graphite coated fuel cladding tube, close both ends of the tubes by resistance welding and then to attach spacers and bearing pads on fuel elements by resistance welding. In this method, it is very difficult to salvage sintered pellets from rejected fuel element. In addition, the pellets inside the fuel element may chip because of several handling steps after encapsulation. In order to resolve this problem, demonstration trials are underway to weld (resistance welding) bearing and spacer pads on graphite coated fuel cladding tube and use these tubes for loading and encapsulation of UO_2 pellet stacks. Figure 6 depicts a pictorial sequence of the existing and proposed process steps for assembling fuel bundles. Initial trials have yielded very encouraging results.

7.0 ACKNOWLEDGEMENT:

The present paper is a compilation of fuel fabrication activities at different plants of NFC. The author is grateful to all his colleagues in NFC and other DAE units associated with PHWR fuel programme and would like to thank, in particular, Mr. R.N. Jayaraj, Manager, Ceramic Fuel Fabrication Plant and Mr. B.Laxminarayana, Manager, Fuel Quality Assurance of NFC.

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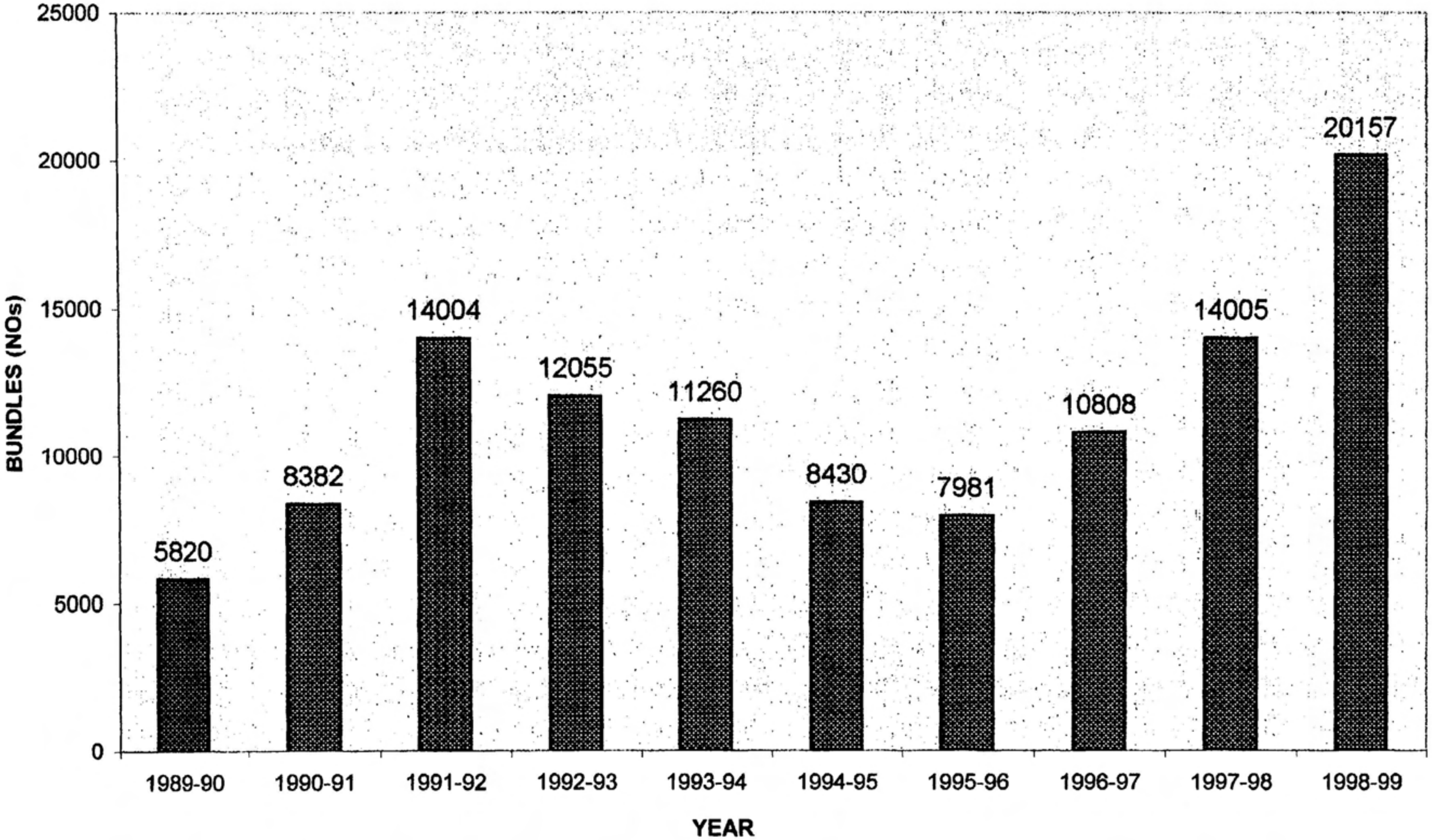

FIG.1 : PHWR FUEL BUNDLE PRODUCTION AT NFC

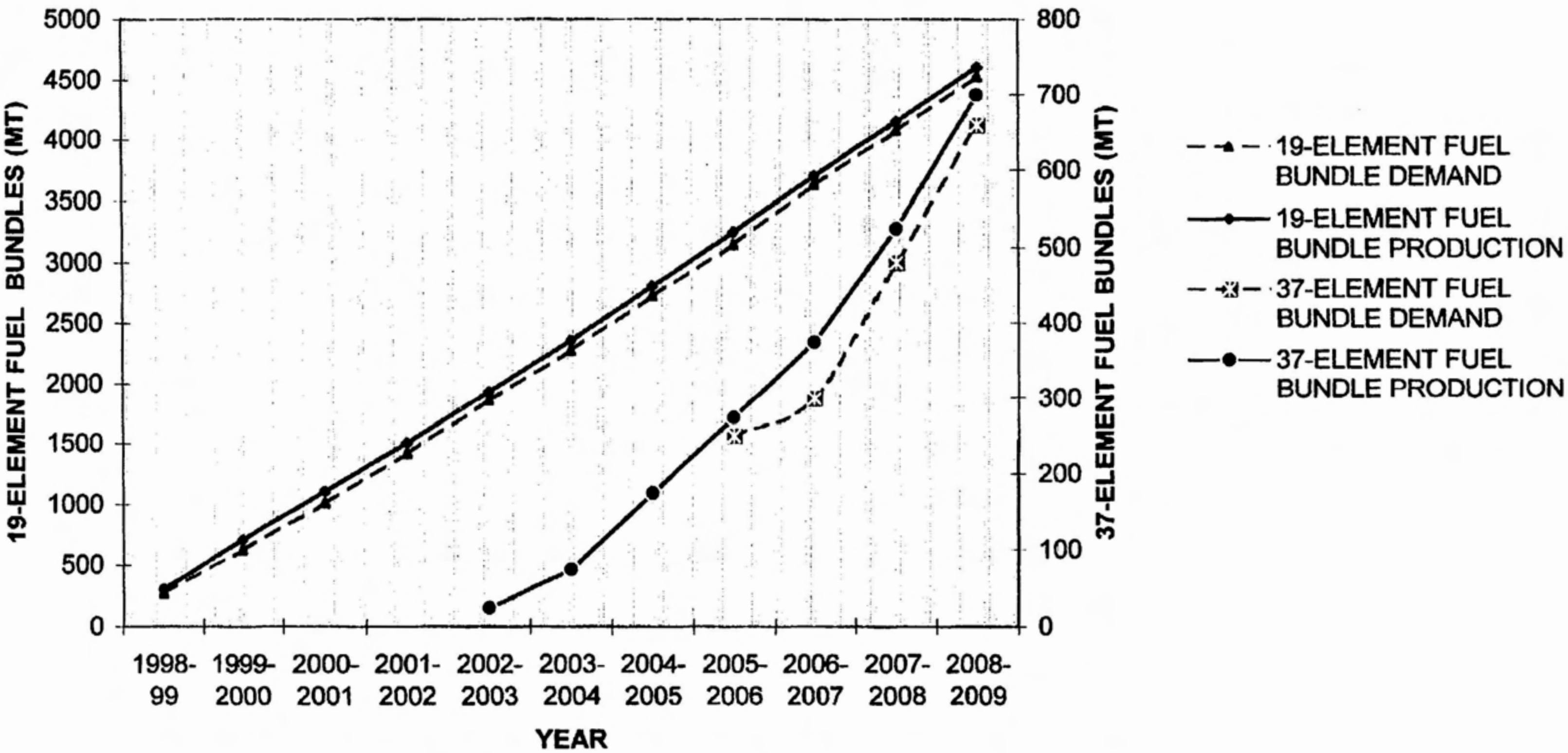

FIG.2: CUMULATIVE DEMAND AND PRODUCTION OF PHWR-220 MWe AND PHWR-500 MWe FUELS IN INDIA

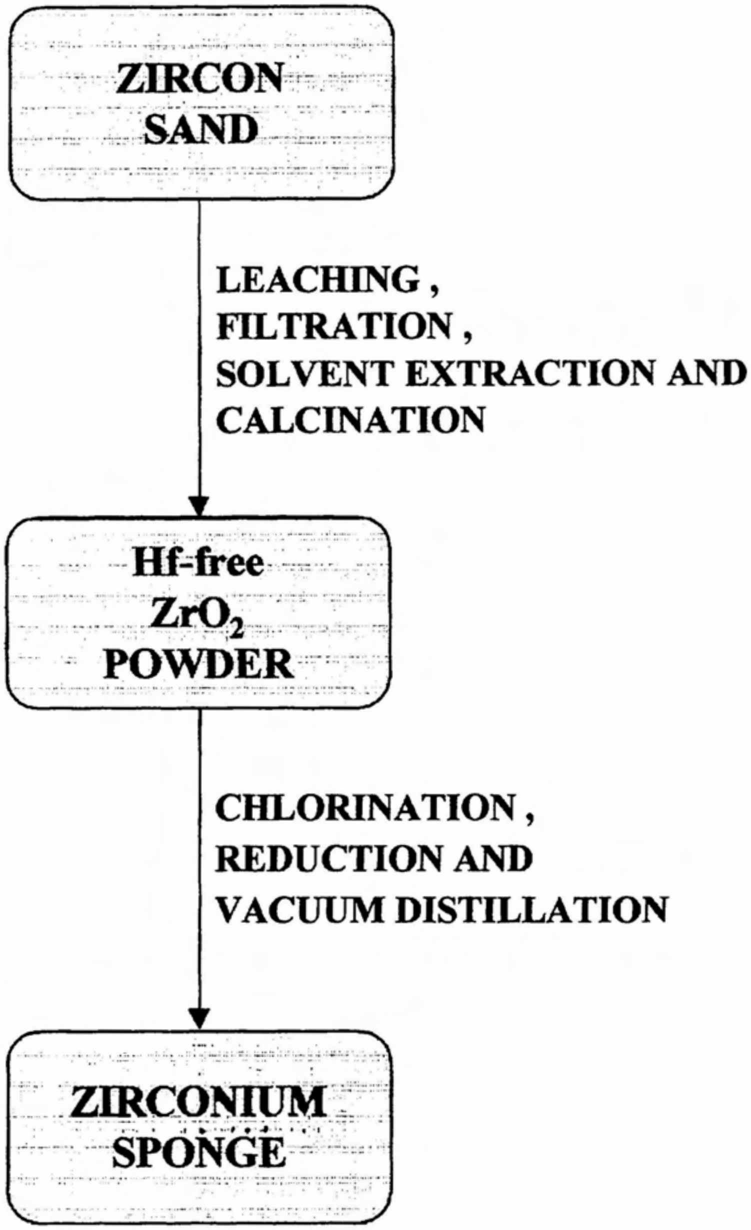

FIG.3: PROCESS STEPS FOLLOWED IN NFC FOR THE PRODUCTION OF NUCLEAR GRADE ZIRCONIUM SPONGE FROM ZIRCON SAND

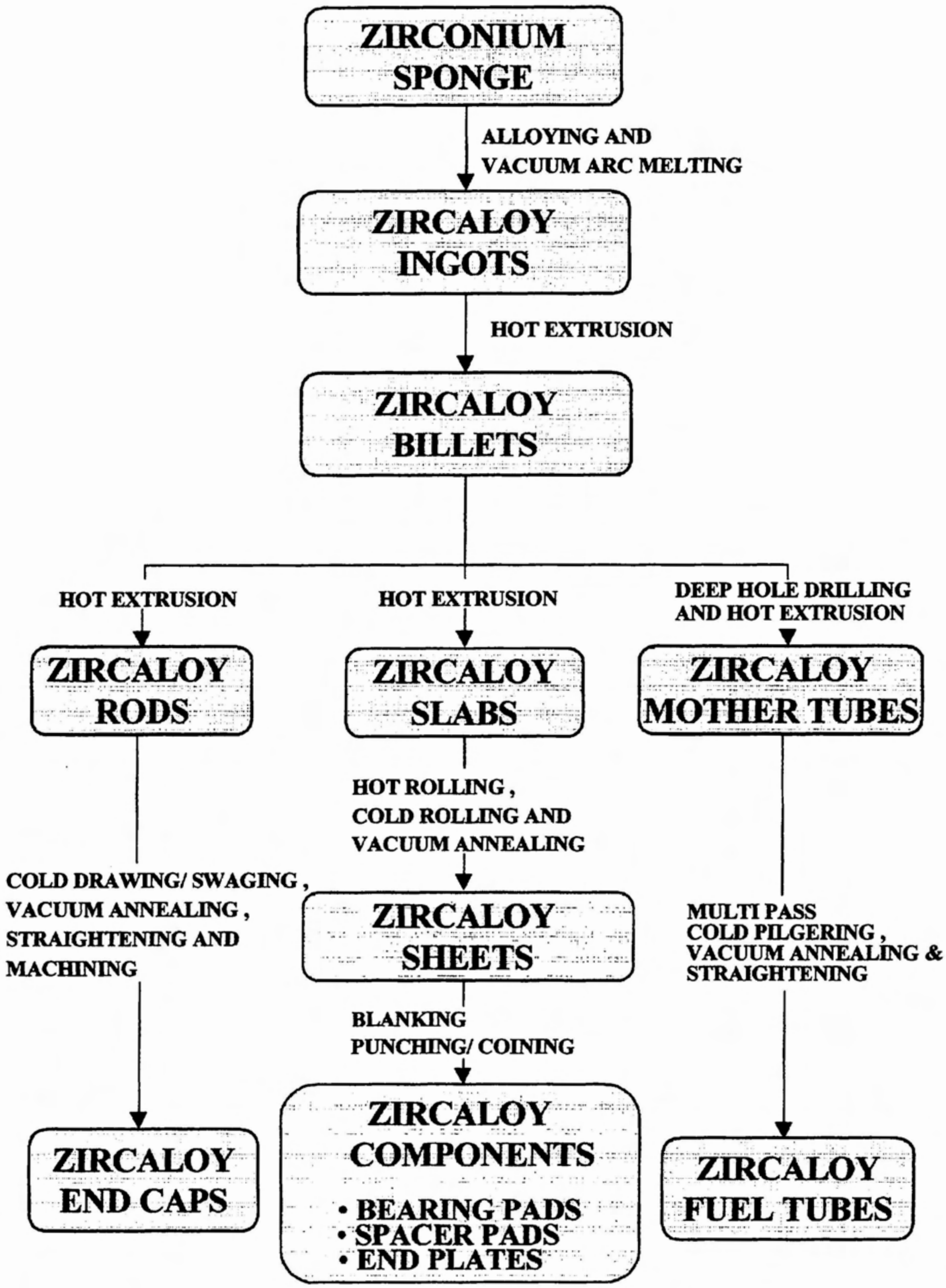

FIG.4: PROCESS FLOW SHEET FOLLOWED IN NFC FOR THE PRODUCTION OF ZIRCALOY-4 FUEL TUBES AND COMPONENTS

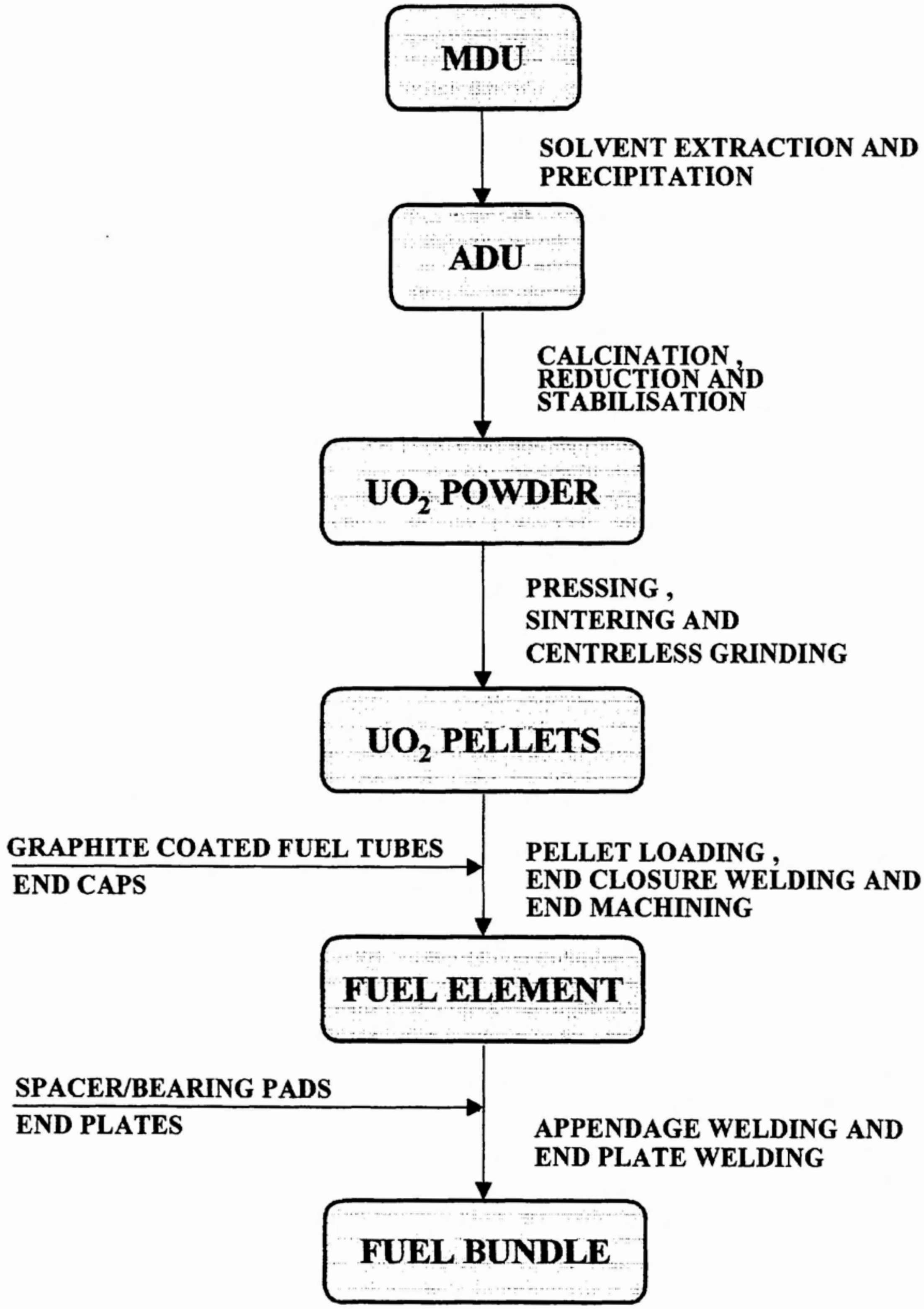

FIG.5: PROCESS FLOW SHEET FOLLOWED IN NFC FOR PHWR FUEL PRODUCTION

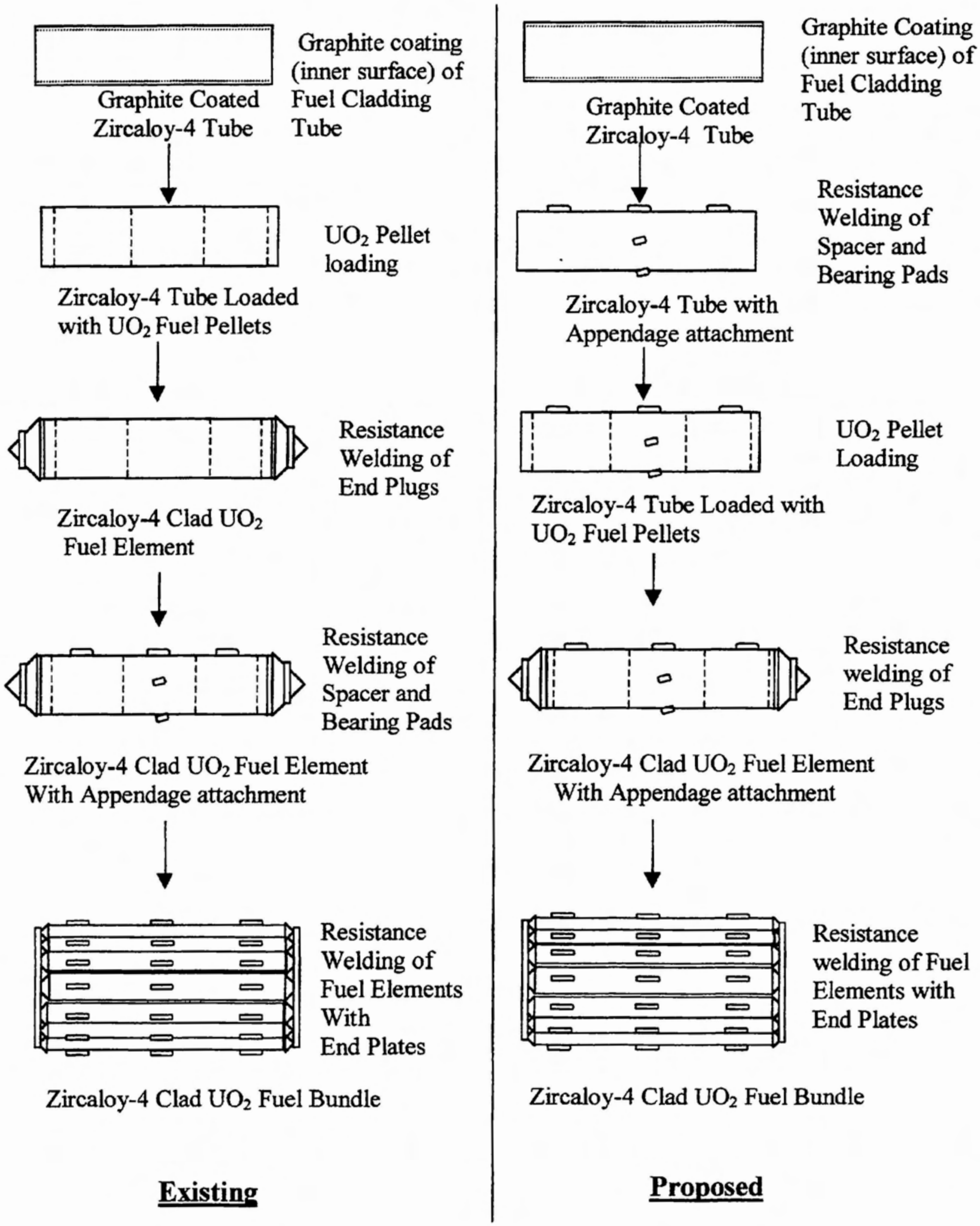

FIG.6 : PICTORIAL SEQUENCE OF ASSEMBLY OPERATIONS FOR PHWR FUEL BUNDLE PRODUCTION