FABRICATION, QUALITY ASSURANCE & PERFORMANCE OF PHWR FUEL IN INDIA

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ABSTRACT

Pressurised Heavy Water Reactor (PHWR) is the backbone of the indigenous nuclear power programme in India. The Nuclear Fuel Complex (NFC) at Hyderabad is responsible for manufacturing zircaloy 4 clad natural uranium oxide fuel for the PHWRs in India, using magnesium-di-uranate concentrate from Uranium Corporation of India Limited (UCIL) and zircon sand from Indian Rare Earths Limited (IREL) as starting material. In the last two consecutive financial years (April-March), 1999-2000 and 2000-2001, the annual production of PHWR 220 fuel bundles at NFC exceeded 26,000 and the fuel for the initial cores of Kaiga 1&2 and RAPS 3&4 were delivered. In September 2000, NFC crossed a major milestone with the manufacturing of the 200,000th fuel bundle. NFC received the ISO-9002 certificate for quality management system from M/s. TUV, India in December 2000. The uninterrupted and timely supply and high quality of fuel from NFC for the 12 operating 12 PHWR units paved the way for the Nuclear Power Corporation of India Limited (NPCIL) to achieve more than 80% average plant load factor (PLF) in 1999-2000 and 2000-2001, keeping the I-131 activity in coolant channels way below the permissible limits. Several modifications in the fuel fabrication flowsheet, equipment and process parameters and quality control steps have led to significant reduction of radioactive aerosol, increase in productivity, minimisation of rejects and improvement in fuel quality.

1.0 INTRODUCTION

Out of the six nuclear power reactors that went into commercial operation all over the world in the year 2000, four are Pressurised Heavy Water Reactors (PHWRs), popularly known as CANDU, which are located in India. These reactors, namely, Kaiga 2, RAPS 3, Kaiga 1 and RAPS 4 are of the PHWR 220 type and were connected to the grid in March, June, October and December 2000 respectively. Presently, there are 12 operating PHWRs in India with a total installed capacity of 2400 MWe as shown in Table 1. The construction activities of two PHWR 500 units at Tarapur (TAPP 3&4) are progressing rapidly. These are the fore runners in the series of PHWR 500 MWe units, which would be constructed in India in the coming years. Excavation work of two more PHWR 220 units has started at Kaiga (Kaiga 3&4) in March 2001. NPCIL is planning to construct four PHWR 500 units at Rajasthan (RAPP 5-8) and two additional PHWR 220 units at Kaiga (Kaiga 5&6). By the year 2020, sixteen PHWR 220 and twelve PHWR 500 units are likely to be operational in India with a total installed capacity of 9280 MWe.

Figure 1 shows the map of India, indicating the locations of the activities in the front-end of the PHWR fuel cycle. Presently, the Uranium Corporation of India Limited (UCIL) is operating three underground mines at Jaduguda, Narwapahar and Bhatin in the Singhbhum District of Jharkhand State and preparations are underway to open a fourth mine at Turamdih in Singhbhum.

In the uranium concentration plant of UCIL at Jaduguda, the ores are crushed, milled and subjected to sulphuric acid leaching followed by purification by the ion-exchange process and precipitation of uranium concentrate in the form of magnesium di-uranate (MDU), popularly known as yellow cake, which contains around 70% U_3O_8. Apart from Singhbhum District, the Atomic Minerals Directorate of Exploration and Research (AMD) have confirmed uranium deposits of nearly 13,000 tons (of U_3O_8) in the Cretaceous sedimentary basin at Meghalaya State and in the last two years significant uranium intercepts have been met in the Proterozoic basins at Cuddapah and Bhima in Andhra Pradesh and Karnataka States respectively (1). In addition, uranium deposits have also been discovered in Albitite zones at Aravallis in Rajasthan State. Techno-commercial feasibility and environmental studies are underway as part of the pre-mining activities in these locations.

India has abundant reserves of zircon in the beach sands of the coastal States of Kerala, Tamil Nadu and Orissa, which are exploited by the Indian Rare Earths Limited (IREL). Nuclear Fuel Complex (NFC) at Hyderabad is responsible for manufacturing zircaloy clad natural uranium oxide fuel bundles for PHWRs, using magnesium di-uranate from UCIL and zircon sand from the IREL plants at Chavara and Manavalakurichi as starting materials.

2.0 FUEL FABRICATION

The manufacturing of PHWR 220 fuel bundles at NFC is carried out at Uranium Oxide Plant (UOP), Ceramic Fuel Fabrication Plant (CFFP), New Uranium Oxide Fabrication Plant (NUOFP) and New Uranium Fuel Assembly Plant (NUFAP). UOP and CFFP are in operation since the inception of NFC in the early 1970s. The NUOFP and NUFAP went into commercial operation in 1999.

The fabrication processes followed at NFC for manufacturing zircaloy hardwares, UO_2 pellets and PHWR fuel bundles have been described in details in the proceedings of the 6th International Conference on CANDU Fuel (2). Figure 2 summarises the major process steps followed at NFC for production of PHWR fuel bundles. At UOP and NUOFP, the yellow cake (Magnesium di-uranate - MDU) received from UCIL or uranium oxide scrap in the form of rejected sintered pellets, green pellets and sludges from centerless grinding units are dissolved in nitric acid followed by purification by solvent extraction and precipitation by ammonia to obtain pure ammonium di-uranate (ADU). The ADU is subjected to controlled calcination, reduction and stabilisation to obtain sinterable grade UO_2 powder of desirable specific surface area, particle size and oxygen to metal ratio. At CFFP and NUOFP, the UO_2 powder is converted to free-flowing granules by either precompaction-granulation or roll compaction-granulation and compacted to green pellets in double acting hydraulic presses utilising multiple die punch sets. The pellets are loaded in molybdenum charge carriers and sintered in pusher type continuous sintering furnaces at around 1700^0 C in cracked ammonia. The sintered pellets are ground and inspected in terms of dimension, density and visual defects. The accepted pellets are stacked and loaded into thin walled zircaloy 4 (Zr-4) cladding tubes. At CFFP and NUFAP, the cladding tubes containing the pellets are hermetically sealed with end plugs using resistance welding technique. Next, zircaloy 4 spacer and bearing pads are resistance welded on the fuel pins and finally 19 such fuel pins with appendages are clustered to form a fuel bundle for PHWR 220 MWe unit. However, recently a few hundred fuel bundles have been manufactured by employing an improved technique **(3)** in which bearing and spacer pad appendages are resistance-welded on zircaloy 4 cladding tubes prior to UO_2 pellet loading.

Figure 3 shows the annual production of PHWR fuel at NFC during the last five years. In the last two consecutive financial years (April-March), 1999-2000 and 2000-2001, the annual production of PHWR 220 fuel bundles at NFC exceeded 26,000 and the fuel for the initial cores of Kaiga 1&2 and RAPS 3&4 were delivered. The cumulative production of PHWR 220 fuel bundles at NFC, since its inception in the early 1970s, crossed the 200,000th mark in September 2000. Each 19-element PHWR fuel bundle contains around 15 kg uranium oxide and generates 650,000 units (kWh) of electricity.

During the last 2 years, great emphasis has been given to radiological safety, improvement in fuel quality, minimisation of rejects and recycling of uranium oxide scrap. The major modifications in the plant and process flowsheet include:

i) containment of equipment and improvement in the ventilation system in the UO_2 powder area,
ii) adapting simple and effective technique for large scale recycling of green and sintered UO_2 scrap
iii) introduction of a spray drier unit in NUOFP for obtaining nearly free-flowing ADU powder,
iv) introduction of roll compaction-granulation process for improved productivity of free-flowing UO_2 granules and admixing solid lubricant to UO_2 granules,
v) change over to tungsten carbide dies and cryogenic-treated die steel punches for UO_2 pellet compaction,
vi) switching over to chamfered pellets and
vii) optimisation of UO_2 pellet loading in molybdenum charge carriers and sintering cycle

All these factors yielded very rich dividends by way of higher productivity, lower specific energy consumption, enhanced grinding recovery and minimum down time of equipment, which led to significant reduction in fuel fabrication cost.

The 19-element fuel bundles manufactured by the modified route, utilising zircaloy 4 tubes with spacer and bearing pad appendages welded prior to pellet loading and encapsulation, were introduced on a trial basis in Madras Atomic Power Station (MAPS) and Kakrapar Atomic Power Station (KAPS), where their performance has been satisfactory.

3.0 QUALITY ASSURANCE

There has been a continuous effort to improve the quality of fuel. In December 2000, NFC received the ISO-9002 Certificate from M/s. TUV, India based on the quality management system.

Close interaction of fuel fabrication and quality assurance teams resulted in improved efficiency in all the plants. In the uranium oxide powder production plants, it was possible to achieve significant improvement in the quality of UO_2 powder in terms of optimum specific surface area, particle size and oxygen to uranium ratio. As a result, the percentage acceptability of the UO_2 powder batches, based on sinterability test, reached impressive figures of 97.17% and 99.49% in 1999-2000 and 2000-2001 respectively. It was also possible to bring down the average hydrogen content in sintered pellets in the range of 0.15 to 0.16 ppm and average hydrogen in graphite coated zircaloy 4 tubes less than 18 ppm.

For quality assurance of fuel elements and assemblies, new techniques were introduced for better reliability and repeatability. One such step is the introduction of dimension measurement system based on image analysis technique for evaluating fuel tubes, end plugs and spacer and bearing pads. It was possible to minimise significantly the rejections due to weld defects by employing a novel ultrasonic testing (UT) technique (4) of welds as a non-destructive process control tool, using a point focussed spherical probe of 30 MHz. The UT signals could be easily resolved and specific weld defects like non-fusion line, weld spark, sheath folding, etc. and their locations could be identified quickly, without the need for machining the weld up-set. The method utilises an incident beam at an angle of 27^0, focussed at weld up-set (outside) as a reference point. Thus, the dependence on destructive metallography for evaluation of process and set-up welds is eliminated. The rejection level of fuel elements due to welding defects, based on the results of the helium leak testing, could be kept as low as 0.003%.

4.0 PERFORMANCE

The uninterrupted and timely supply and high quality of fuel from NFC paved the way for the Nuclear Power Corporation of India Limited (NPCIL) to operate the 12 PHWR units with an average plant load factor of 80% during the last two years. Thus, NPCIL could generate 10,300 million units and 14,300 million units (kWh) of electricity during 1999-2000 and 2000-2001 respectively. These are the highest figures of NPCIL since its inception and accounted for nearly 3% of the total annual electricity produced in India. The average I-131 activity, a measure of fuel behaviour in the reactors, has been reasonably low (less than 5 micro curie per litre). The average discharge burn-up of fuel in the past two years was in the range of 7,000 MWd/t, which is higher than the average design burn-up of 6,700 MWd/t.

5.0 LOOKING FORWARD

- The three decades of experience in industrial scale manufacturing of 19-element PHWR 220 fuel bundles, utilising indigenous resources of uranium and zirconium, has instilled enough confidence to set-up a state-of-the-art facility at NFC utilising indigenous equipment for manufacturing 37-element fuel bundles for the forthcoming PHWR 500 units. The main objective is to manufacture high quality fuel economically, while ensuring high radiological safety standards.

- The recent trend in PHWR fuel development all over the world has been to enhance the average burn-up by a factor of 2 to 3 from the present level of 6,700 MWd/t. For this, efforts are underway to introduce advanced fuels like slightly enriched uranium (SEU) or recycled uranium (REU) oxide, $(U,Pu)O_2$, $(Th,Pu)O_2$ and $(Th,U^{233})O_2$ containing 1 to 2% 'fissile' material. For this, there is a need to develop a suitable, dust-free advanced process, amenable to automisation and remotisation, for manufacturing high-density oxide or mixed oxide fuel pellets in order to minimise radioactive aerosol and exposure of plant personnel to radiation.

- High radiological safety, development of cost effective processes in nuclear fuel cycle, "secured automated fuel fabrication" routes, methods for real time accounting of nuclear materials, a 6 sigma quality culture in fuel production and achieving nearly zero fuel failure in reactors are some of the major objectives of PHWR fuel technology in India in coming years.

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TABLE 1: OPERATING PRESSURISED HEAVY WATER REACTORS IN INDIA

Plant	Capacity	Date of Commercial Operation
Rajasthan Atomic Power Station (RAPS), Rawatbhatta		
RAPS – 1	**100 MWe**	**16th December 1973**
RAPS – 2	**200 MWe**	**1st April 1981**
RAPS – 3	**220 MWe**	**1st June 2000**
RAPS – 4	**220 MWe**	**23rd December 2000**
Madras Atomic Power Station (MAPS) Kalpakkam		
MAPS – 1	**170 MWe**	**27th January 1984**
MAPS – 2	**170 MWe**	**21st March 1986**
Narora Atomic Power Station (NAPS)		
NAPS – 1	**220 MWe**	**1st January 1991**
NAPS – 2	**220 MWe**	**1st July 1992**
Kakrapara Atomic Power Station (KAPS)		
KAPS – 1	**220 MWe**	**6th May 1993**
KAPS – 2	**220 MWe**	**1st Sept. 1995**
Kaiga Atomic Power Station		
Kaiga – 1	**220 MWe**	**16th November 2000**
Kaiga – 2	**220 MWe**	**16th March 2000**
Total	**2400 MWe**	

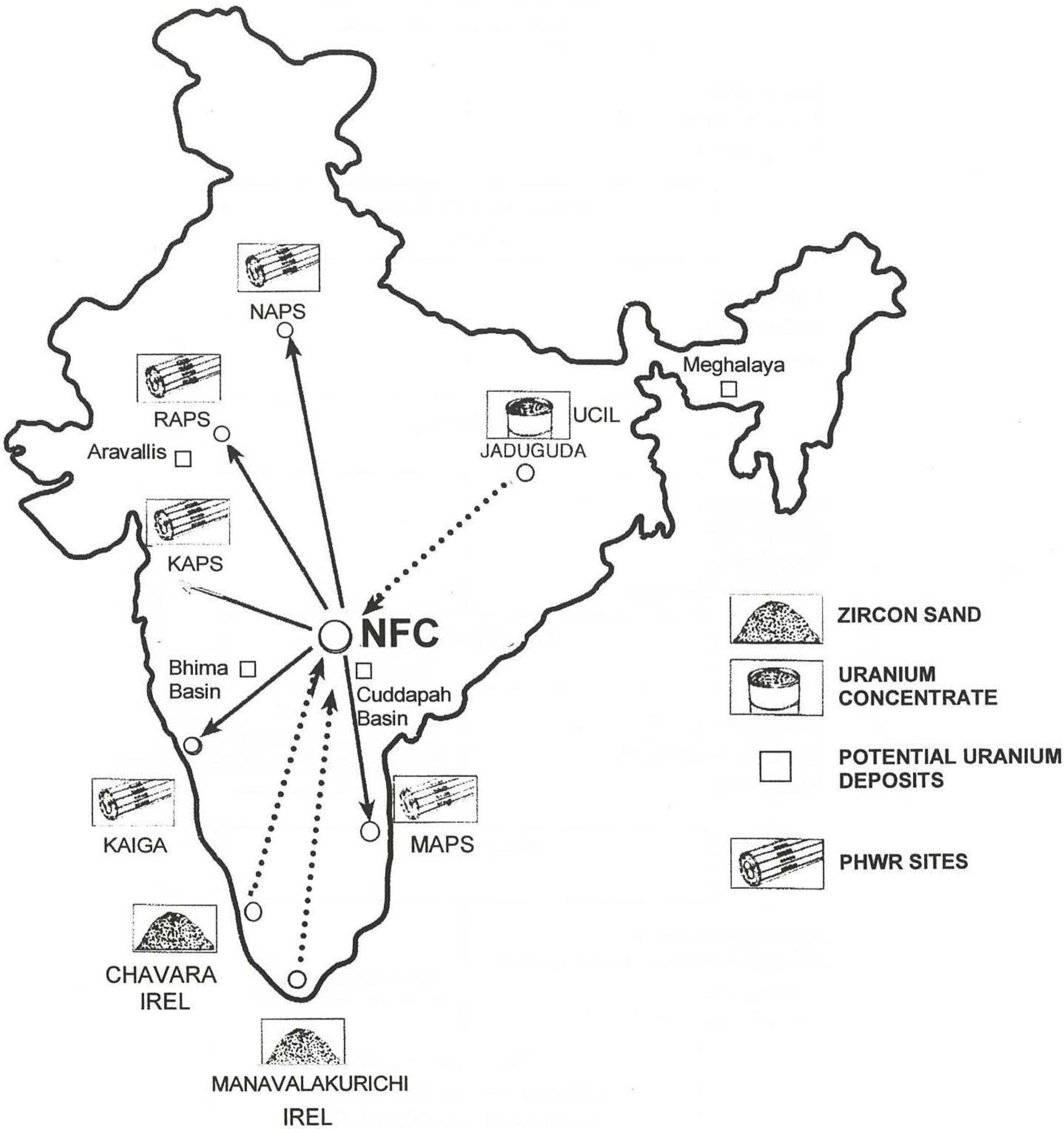

FIG 1: PHWR FUEL CYCLE ACTIVITIES IN INDIA

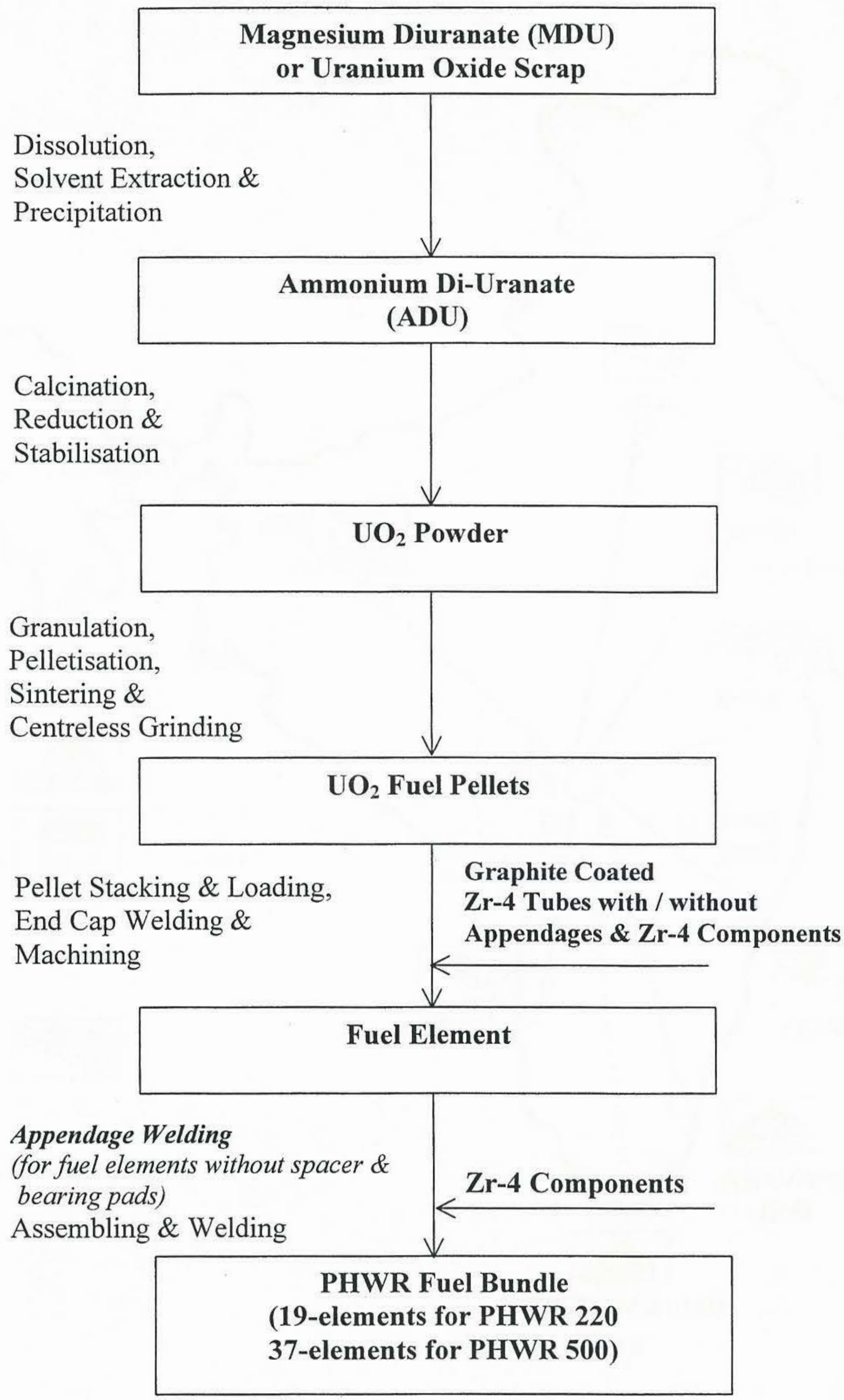

FIG 2: FLOWSHEET FOR MANUFACTURING PHWR FUEL BUNDLES AT NFC

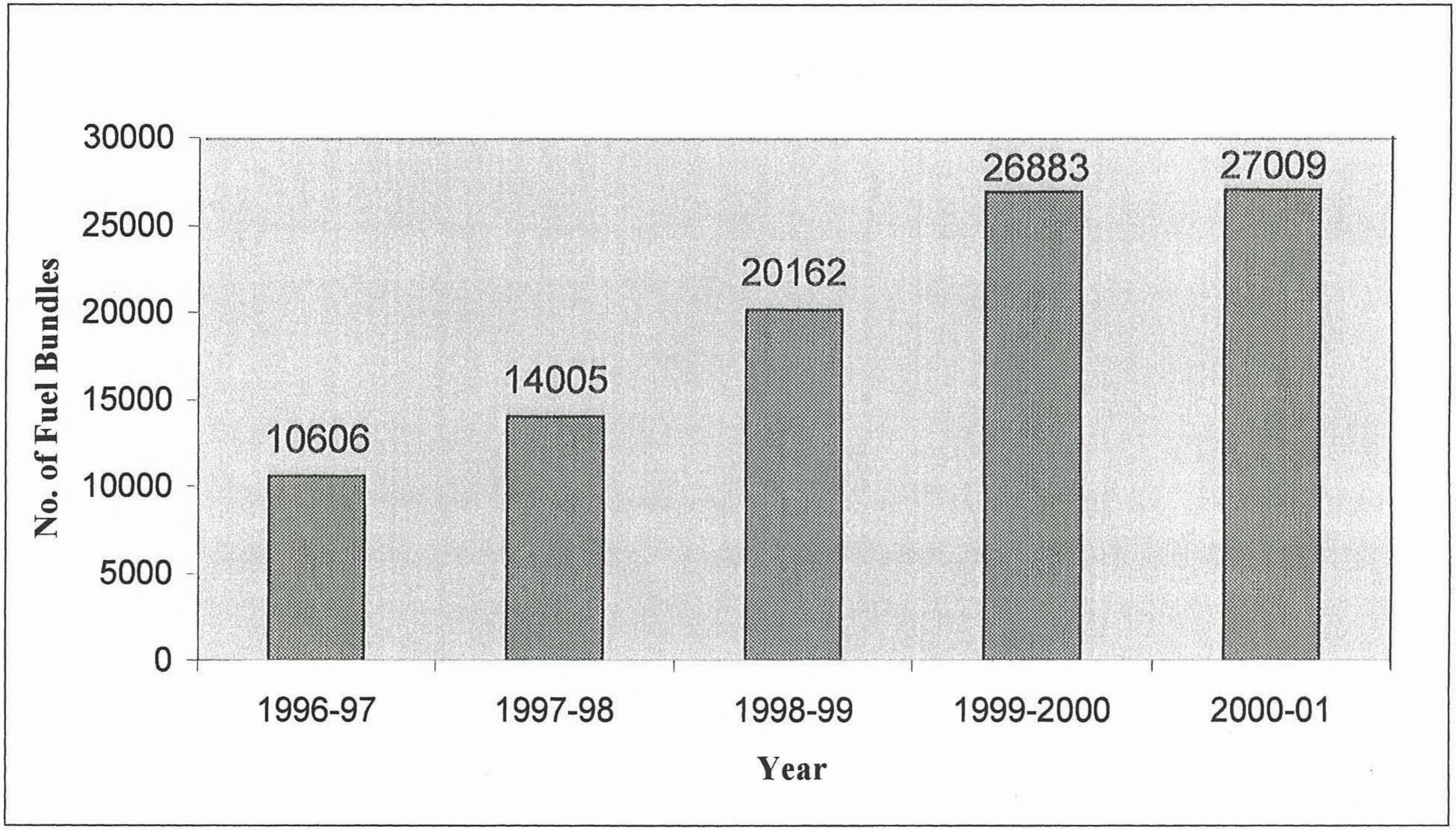

FIG 3: PRODUCTION OF ZIRCALOY 4 CLAD 19-ELEMENT PHWR FUEL BUNDLES AT NFC