AN OVERVIEW OF PHWR FUEL IN INDIA

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ABSTRACT

Pressurised Heavy Water Reactor (PHWR) is the first stage and the backbone of the nuclear power programme in India. Presently, twelve PHWR 220 MWe type units are in operation and two units of PHWR 540 MWe & four units of PHWR 220 are in different stages of construction. Design and development activities are underway for further augmenting the capacity of PHWR 540 to 680 MWe. Eight such reactors have been planned by Nuclear Power Corporation of India Limited (NPCIL).

The exploration and mining activities of uranium has been significantly enhanced by Atomic Minerals Directorate for Exploration and Research (AMD) and Uranium Corporation of India Limited (UCIL) respectively and a new underground mine has been opened in Turamdih in Jharkhand State. Nuclear Fuel Complex (NFC) has, so far, manufactured some 280,000 zirconium alloy clad natural uranium oxide fuel bundles and some 4,600 depleted and some 300 thorium oxide assemblies. These fuel bundles and assemblies are of the 19-element type. NFC has recently initiated the fabrication activity of 37-element fuel bundles for the 2 forthcoming PHWR 540 units of the Tarapur Atomic Power Project (TAPP 3&4). In recent years, NFC has introduced several modifications in the manufacturing and quality control processes, which have significantly improved the productivity, recovery and quality of PHWR fuel and in turn its performance in reactors. Large-scale introduction of depleted uranium oxide bundles has been planned not only for the initial core for neutron flux flattening but also for the subsequent equilibrium cores. As part of Pu recycling programme, 50 numbers of MOX-7 test fuel bundles have been manufactured by Bhabha Atomic Research Centre (BARC) in collaboration with NFC for irradiation-testing in one of the PHWR 220 units of Kakarapar Atomic Power Station.

1.0 INTRODUCTION

India occupies only 2% of the world's land mass but with 1.1 billion people has 16% of the world's population. The total installed electric power in the country is in the range of 130,000 MWe (including captive power plants). However, because of the large population, the per capita consumption of electricity is in the range of 600 kWh per year only, which is nearly 4 times lower than the world average and some 15 times lower when compared to the OECD countries. For improving the per capita consumption of electricity, apart from initiating several measures to control the population growth, a programme of installing approximately 10,000 MWe electric

power every year has been launched in order to bring the total installed electric power in the country in the range of 300,000 MWe by the year 2020. 'Nuclear Fission Energy' is one of the viable and sustainable sources of primary energy to meet the ever-increasing demand of electricity at a price affordable to the common man without degrading the environment in terms of greenhouse gas (and in turn global warming) and acid rains. Presently, 14 nuclear power reactors are in operation with total installed capacity of 2720 MWe, which is only some 2.5% of the total installed electric power in the country. The Department of Atomic Energy (DAE) has set a target of installing 20,000 MWe nuclear power by the year 2020 of which water-cooled thermal reactors would account for more than 18,000 MWe as shown in Table 1. The electricity generated from nuclear power reactors in India has progressively increased from 11,174 million units (kWh) in 1998-99 to 19,242 million units in 2002-03 as shown in Figure 1.

Pressurised Heavy Water Reactor (PHWR), popularly known as CANDU all over the world, and its fuel cycle is the backbone and the first stage of the indigenous nuclear power programme in India. The three-stage programme, linking the fuel cycles of PHWR and Liquid Metal-cooled Fast Breeder Reactor (LMFBR) and thorium-based advanced thermal reactors, is aimed at judicious utilization of modest uranium but vast thorium resources. For a viable long-term nuclear power programme in India, LMFBRs are essential. The PHWRs in the first stage would not only generate electricity but also produce sufficient plutonium for launching a large LMFBR programme, which would breed U^{233} from thorium blankets.

The first CANDU reactor in India, the Unit 1 of the Rajasthan Atomic Power Station (RAPS 1), was constructed and commissioned in collaboration with Canada and went into commercial operation on December 16, 1973. RAPS 1 was the forerunner of the 220 MWe type PHWRs. Thereafter, India has been pursuing a self-reliant PHWR programme. Presently, 12 PHWR 220 type units are in operation and 4 are under construction. The second unit of Rajasthan Atomic Power Station (RAPS 2) and Madras Atomic Power Station (MAPS 2) have undergone en-masse coolant channel replacement and are operating satisfactorily. In general, there has been progressive improvement in the 'capacity factor' of all the PHWR units in India as shown in Figure 2. Last year, one of the PHWR 220 units of Kakrapar Atomic Power Station operated with a plant load factor of 98% and reached the highest position among all the operating PHWRs in the world. Two PHWR 540 units are under construction as part of Tarapur Atomic Power Project (TAPP 3&4). These two reactors would be the first in the series of PHWR 500 type units in India. Design and development activities are underway for further augmenting the capacity of the PHWR 500 MWe units to 680 MWe by allowing partial boiling in the core. Eight such PHWR 680 MWe are in the planning stage.

Figure 3 describes the PHWR fuel cycle activities in India. The organizations involved are:

(i) Atomic Minerals Directorate for Exploration and Research (AMD) with Headquarters at Hyderabad – responsible for locating uranium, zirconium and thorium deposits.

(ii) Uranium Corporation of India Limited (UCIL) with Headquarters at Jaduguda, Jharkhand State – responsible for mining and concentration of uranium ore in the form of yellow cake [magnesium di-uranate (MDU)].

(iii) Indian Rare Earths Limited (IREL) with Headquarters at Mumbai (Bombay) – responsible for mining of heavy minerals, including zircon and monazite and for preparation of reactor grade thorium oxide powder from Monazite.

(iv) Nuclear Fuel Complex (NFC) with Headquarters at Hyderabad – responsible for manufacturing uranium oxide powder, pellets & fuel bundles, thorium oxide pellets & assemblies, reactor grade zirconium sponge, zirconium alloy ingots and zirconium alloy tubes & components for fuel bundles and core structurals.

(v) Nuclear Power Corporation of India Limited (NPCIL) with Headquarters at Mumbai – responsible for design, construction, operation and maintenance of nuclear power reactors in India.

(vi) Bhabha Atomic Research Centre (BARC) with Headquarters at Mumbai – responsible for reprocessing and waste management of PHWR spent fuel, fabrication of mixed uranium plutonium oxide fuel, in-service inspection of reactors and post-irradiation examination (PIE) of failed fuel.

NFC, an industrial unit of DAE, was set up at Hyderabad in the early 1970s, for manufacturing zirconium alloy clad natural uranium oxide fuel for PHWRs, using 'uranium concentrate' and 'zircon' as starting materials from UCIL and IREL respectively. During the last 30 years, NFC has manufactured more than 280,000 fuel bundles of the 19-element type for the 12 operating PHWRs. In addition, some 4,600 depleted uranium oxide bundles and nearly 300 thorium oxide bundles have been manufactured and utilized for neutron flux flattening of the initial cores during start-up. Depleted uranium was used in the first six PHWR 220 units at Rajasthan (RAPS 1&2), Madras (MAPS 1&2) and Narora (NAPS 1&2). Whereas some 350 to 550 depleted uranium oxide bundles were loaded in each core of these six PHWR 220 units, from the Unit 1 of Kakrapar Atomic Power Station (KAPS) onwards, some 35 ThO_2 bundles were adequate for each reactor to carry out effectively the neutron flux flattening in the initial core without violating specified channel power and bundle power limits and at the same time operating the reactor at rated full power. So far, 232 thorium oxide bundles were successfully irradiated in the initial cores of KAPS 1&2, Kaiga 1&2, RAPS 3&4 and RAPS 2, after retubing. The maximum power and burn-ups of these thoria bundles were 408 kW and 13,000 MWd/t respectively. Recently, a decision has been taken to use depleted uranium oxide bundles again in all future PHWR units for judicious utilization of the large quantities of depleted uranium that has stock-piled in the spent fuel reprocessing plants. Accordingly, in the first quarter of 2003, depleted uranium oxide bundles have been manufactured for MAPS 2, after retubing for neutron flux flattening. The manufacturing activity of 37-element natural uranium oxide fuel bundles and depleted uranium oxide assemblies has been initiated for the forthcoming PHWR 540 units at Tarapur, namely TAPP 3&4. Tarapur 4 is likely to attain criticality in December 2004, for which the fuel should be in site by July 2004. The criticality date of Tarapur 3 is December 2005. NFC has already supplied the zirconium alloy calandria tubes, coolant tubes, garter springs, reactivity and shut-off mechanisms for TAPP 4. The manufacturing activities of zirconium alloy core structurals for TAPP 3 are underway.

The present paper summarises the developments in PHWR fuel and fuel cycle in India during the last 2 years. The exploration and mining of uranium, the core loading concepts for large scale utilisation of depleted uranium oxide bundles in PHWR 220 & PHWR 540 units, the

manufacturing experience of natural uranium & depleted uranium oxide and MOX fuel pellets and fuel bundles and in-core performance of PHWR fuel have been highlighted.

2.0 EXPLORATION AND MINING OF URANIUM

India has modest uranium reserves of very low grade (0.04-0.06%), mostly in deep underground deposits. So far, 3 underground mines, namely Jaduguda, Bhatin and Narwapahar were in operation in the Singhbhum District of Jharkhand State. Since the beginning of 2003 the fourth underground mine has been opened in Turamdih in the vicinity of Narwapahar. The price of indigenous natural uranium concentrate is several times higher than the ones available in the international market because of the high cost involved in deep underground mining and treating very low grade ores. In recent years, the exploration and mining activities have been intensified in order to match the uranium demand of the rapidly expanding nuclear power programme. Figure 4 shows the important Proterozoic and Phanerozoic Basins of India, which are the target areas for uranium exploration. The summary of uranium exploration and mining activities are as follows:

- Singhbhum Deposits (Jharkhand State): These are relatively low grade 'vein' type deposits in schistose host rock with uranium content in the range of 0.04 – 0.06% U_3O_8. Some 42,000 tons of uranium has been proven in this area. Presently, 4 deep underground mines, namely Jaduguda, Bhatin, Narwapahar and Turamdih are in operation and feeding the uranium Mill at Jaduguda. Soon commercial exploitation would be started in Bagjata underground mine and the Bandhuhurang open cast mine in eastern Singhbhum District. Construction activity of a second uranium mill in the vicinity of the Turamdih mines would also be initiated soon.

- Cuddapah Basin (Andhra Pradesh State): The experts are of the opinion that this area is likely to emerge as a major uranium province, based on the indicative 'unconformity'. So far, some 5,000 tons of uranium of average grade 0.09% has been proven in Lambapur and Peddagattu in Nalgonda District. Advanced geophysical survey based on magnetic and electromagnetic equipment has been planned. For data reliability, procurement action of hydrostatic drilling rig with deviation control system, for nearly zero deviation up to greater depths, is underway. This would pave the way to intercept deep and concealed high-grade uranium ore bodies in this area. A Uranium Mill has been planned adjacent to the mines.

- Mahadek Basin & Shillong Basin (Meghalaya State): In the State of Meghalaya, there are two distinct type of ore bodies. In the 'sandstone' type deposits in the Mahadek Basin, some 15,000 tons of uranium with average grade 0.1% U_3O_8 have been proven in Domiasiat and Wahkyn. These are mostly shallow type deposits with the ore body some 30 to 50 meters below the surface. An additional, 15,000 tons uranium is expected in the Mahadek Basin. The uranium deposits at Shillong Basin are indicative of 'unconformity' type based on geological set up and the age of the 'unconformity'. Intensive geophysical survey is also planned in this area for intercepting deep and concealed high-grade uranium deposits, if any.

- Bhima Basin (Karnataka State): Though 'unconformity' type deposit is not ruled out in this area, presently 'vein' type uranium deposits have been observed in depths of 200 – 250 meters in both granite base and dolomitic limestone overburden. So far, some 2,000 tons have been proven of average grade 0.2% in Gogi. An alkaline leaching technique has been developed for extracting uranium both from granite and limestone ore bodies.

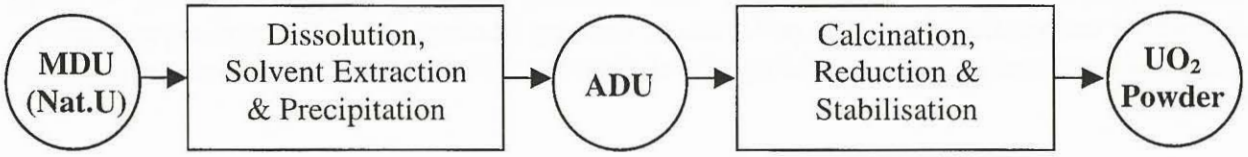
- Rohil-Ghateshwar, Sikar District (Rajasthan State): These are 'vein' type, deep underground deposits in depth of 200-250 meters, similar to the ones in the Singhbhum District, with average uranium in the range of 0.07% U_3O_8. Some 2,000 tons have been proven in this area so far.

3.0 CORE LOADING CONCEPTS FOR UTILISATION OF DEPLETED URANIUM

In recent years, a programme has been initiated at NPCIL for utilization of depleted uranium in the initial and equilibrium cores of PHWR 220 and PHWR 540 units. Accordingly, several core loading concepts have been proposed. Figures 5 and 6 show the loading pattern of depleted uranium oxide bundles in the initial cores of PHWR 220 and PHWR 540 units respectively. Some 1516 depleted UO_2 bundles were loaded in the initial core of MAPS 2, in the second quarter of 2003 after retubing. In the same way, some 2208 depleted uranium oxide bundles are proposed to be manufactured for the forthcoming PHWR 540 unit at Tarapur (TAPP 4 to start with). In equilibrium cores of operating PHWR 220 units, some 78 depleted uranium oxide bundles could be utilized in the inner channels as shown in figure 7.

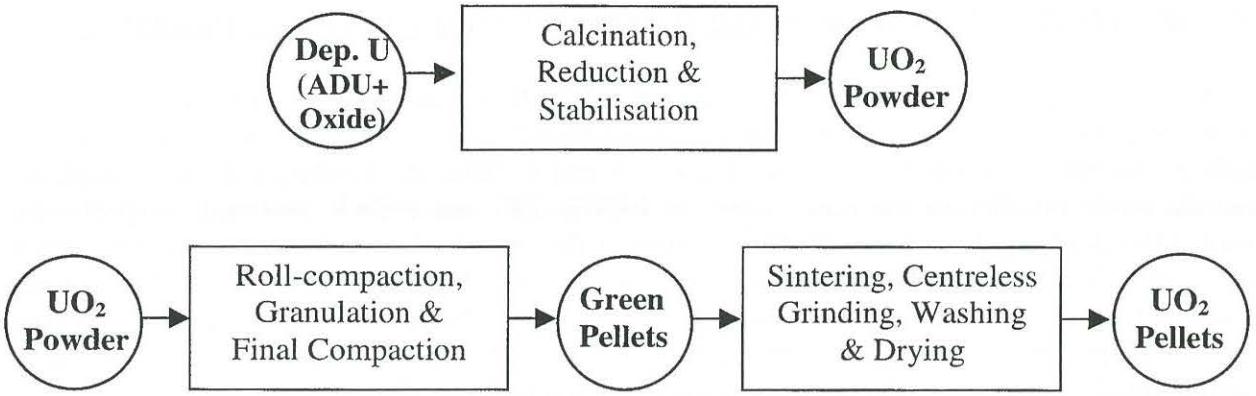
4.0 FABRICATION OF NATURAL & DEPLETED URANIUM OXIDE FUEL

The process flowsheet and quality control plan, followed at NFC, for manufacturing natural uranium oxide fuel pellets and fuel bundles for the PHWR 220 units in India have been described in the proceedings of earlier CANDU fuel conferences (1,2). The magnesium di-uranate (MDU) supplied by UCIL and uranium oxide scrap are processed through a series of chemical operations to obtain pure ammonium di-uranate (ADU), which is then subjected to air-calcination followed by hydrogen reduction and stablisation to obtain sinterable grade UO_2 powder. Nearly, 100% of the UO_2 powder lot qualified the sinterability test. Modifications in process equipment, steps and parameters led to significant reduction in the consumption of major chemicals like nitric acid, caustic lye, tributyl phosphate, etc. and reduced the uranyl nitrate raffinate cake (UNRC) formation per ton of the UO_2 powder. A pilot plant has been set up for recovery of uranium from uranyl nitrate raffinate and UNRC.

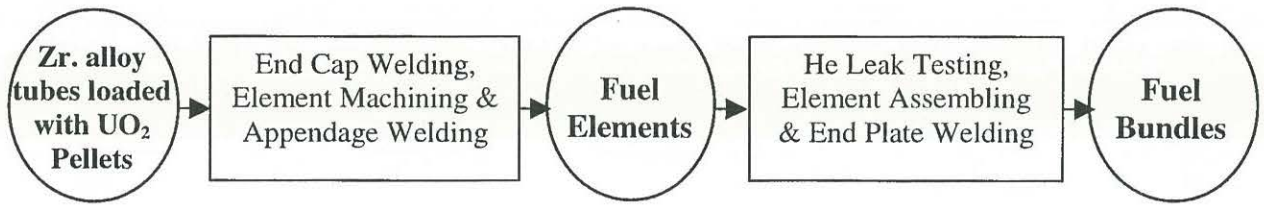


In the spent PHWR fuel reprocessing plant of BARC, plutonium and depleted uranium (Dep. U) are separated from the fission products by the PUREX process. Thereafter, from the pure plutonium nitrate solution, PuO_2 powder is produced by air-calcination of plutonium

oxalate. Likewise, the pure depleted uranium nitrate solution is converted to ammonium di-uranate (ADU), which is then calcined at around 500^0C and sent to NFC. The as-received depleted uranium from BARC, met all the chemical specifications and was in the form of yellowish powder consisting of a mixture of ammonium di-uranate (ADU) and the higher oxides of uranium as shown in the X-ray diffraction pattern (Figure 8a). Since the powder was chemically pure, additional process steps like nitric acid dissolution and solvent extraction were not required. Instead, the powder was directly subjected to air-calcination at around 650^0C in rotary calciner, followed by hydrogen reduction and stabilization. X-ray diffraction pattern of depleted uranium oxide powder thus produced, as shown in figure 8b, show single phase UO_2, which more or less matched with the natural uranium oxide powder (figure 8c).



The powder lots of natural and depleted uranium oxide were processed in the same way to obtain free-flowing press-feed uranium oxide granules. Roll-compaction followed by granulation was adapted for this purpose. Next, zinc stearate lubricant was admixed with the granules. A new organic lubricant has been developed in place of zinc stearate, thereby avoiding deposition of metallic zinc in the interior parts of the sintering furnaces. The granules were subjected to cold-pelletisation in hydraulic press using multi-cavity die punch set. Twelve pellets were compacted at a time. For powder compaction, use of tungsten carbide dies and cryogenic-treated die steel punches improved the tool life by a factor of 40. The green pellets were loaded in molybdenum charge carriers and subjected to high temperature sintering in cracked ammonia in pusher type molybdenum resistance furnace. The microstructure of as-sintered natural uranium oxide and depleted uranium oxide were more or less identical as shown in figure 9. It consisted of single phase equiaxed grains of uranium oxide and uniformly distributed porosity. The high density sintered pellets thus obtained were centreless ground to the specified diameter, washed, dried and loaded in zirconium alloy cladding tubes. Resistance welding is being followed for encapsulation of UO_2 pellet stack, welding bearing and spacer pad appendages on the fuel elements and projection welding of fuel elements with the end plates on both sides of the fuel bundles.



The annual production of natural uranium oxide fuel bundles has increased progressively during the last 5 years, as shown in figure 10. In the year 2002-03, the annual fuel bundle production crossed the 30,000 mark for the first time since the inception of NFC in early 1970s.

Quality control and quality assurance (QC/QA) activities have been geared up to meet the enhanced production target. The synergy among production & QC/QA groups and the customer (NPCIL) has paved the way for uninterrupted and timely delivery of PHWR fuel bundles of high quality to the different operating reactor sites. This contributed to a great extent to improving the PLF of operating PHWRs during the last 5 years and reach international levels of ≥85%.

5. UTILISATION OF MOX BUNDLES FOR IRRADIATION IN KAPS

As a first step to recycling of plutonium in PHWR, recently, NPCIL has proposed a core loading pattern of MOX fuel bundle in PHWR 220, as shown in figure 11. Accordingly, some 50 numbers of zirconium alloy clad 19-element MOX 7 fuel bundles have been manufactured for irradiation-testing in one of the units of KAPS. The MOX 7 bundles consist of 7 inner fuel elements containing mixed uranium plutonium oxide pellets with 0.4% plutonium and 12 outer fuel elements of natural uranium oxide.

The MOX fuel pellets were manufactured by BARC in collaboration with NFC. The ex-ADU derived UO_2 powder and ex-oxalate PuO_2 powder were subjected to co-milling in an attritor, followed by granulation, admixing lubricant, pelletisation and high temperature sintering in hydrogen atmosphere. Next, the sintered pellets were ground to the desired diameter, washed, dried, inspected, loaded in zirconium alloy cladding tubes and encapsulated by TIG welding of the zirconium alloy end-plugs.

6.0 PHWR FUEL PERFORMANCE

So far, more than 250,000 fuel bundles have been irradiated in the 12 operating PHWR 220 units to discharge burn-up in the range of 6,500 – 7,250 MWd/TeU. The in-core performance of PHWR fuel has progressively improved over the years and presently the iodine activities in coolant circuit in most of the reactors are being maintained at levels less than 5 μCi/l. For the first time, the failure rate has been below 0.1% (actual number: 0.096%). Most of the fuel failures have been mainly due to fuel handling events particularly the ones, which failed at relatively low burn-up. Accordingly the frequency of checking the alignment of tubes in fresh fuel transfer system has been increased. In fabrication side, 100% ultrasonic testing of end plug welds and helium leak testing of finished fuel bundles have brought down significantly the fuel failure rate due to manufacturing defects. The improved fuel management practices now followed at all reactors have also contributed to minimization of fuel failure.

7.0 CONCLUDING REMARKS

PHWR and its fuel cycle technology has reached a stage of maturity in India. During the last 3 decades, all operations in front- and back-end of the fuel cycle have been streamlined and are now being carried out on an industrial scale. 12 units of PHWR 220 are in operation and 6 PHWRs are under construction, of which 2 are of the PHWR 540 type. The Department of

Atomic Energy has planned 8 more PHWR 680 MWe units in coming years. One of the major challenges being faced is the high cost of natural uranium from indigenous sources because of low-grade (0.04 – 0.06%) uranium ores and the high cost of deep underground mining. In recent years, uranium exploration activities have been significantly augmented in order to intercept concealed, deep underground, high-grade uranium deposits based on indicative 'unconformity'. A few more mines are likely to be opened in coming years. However, till these mines become operational, several alternatives, including large scale utilization of depleted uranium in initial and equilibrium cores, recycling plutonium as MOX and utilization of thorium are being pursued for conserving natural uranium.

Nuclear energy is an inevitable option for India for meeting the ever-increasing demand of electricity. Such non-carbon based primary source of energy should be encouraged through international collaboration for generation of clean or 'green' electricity, particularly in large developing countries like India. Thus, emission of greenhouse gas and in turn global warming would be minimized. For this, the existing international treaties and guidelines of Nuclear Suppliers Group for trading of uranium should be made more flexible in order to facilitate peaceful use of nuclear energy (like generation of electricity) while ensuring non-proliferation of such material for military activities. Countries with expanding nuclear electricity programme, but having modest uranium resources like India, should have easy access to natural uranium from international market for their nuclear electricity programme. Thus, new uranium market would open-up and countries having large uranium resources with no or small nuclear power programme would be encouraged to expand their uranium mining and milling activities.

ACKNOWLEDGEMENTS

The author is grateful to all his colleagues from different units of DAE associated with PHWR fuel cycle programme. The present paper is a summary of the natural and depleted uranium oxide fuel fabrication activities of NFC during the last 2 years and in-core performance of PHWR fuel. The other papers in this proceedings from NFC and NPCIL gives details of the PHWR fuel cycle activities in India. The author would like to thank Mr. R.M.Sinha, Director, AMD, Mr. A.K.Bagchi, Additional Director, AMD, Mr. S.A.Bhardwaj, Executive Director, NPCIL, Mr. H.S.Kamath, Director, Nuclear Fuels Group, BARC and Mr. R.N.Jayaraj and Mr. Komal Kapoor his colleagues from NFC for preparation of this paper. The author is grateful to the International Atomic Energy Agency (IAEA) Vienna for sponsoring his participation in the 8th International CANDU Fuel Conference and presenting the paper.

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TABLE 1 : WATER-COOLED NUCLEAR POWER REACTORS IN OPERATION, UNDER CONSTRUCTION AND AT PLANNING STAGE IN INDIA

(Total: 18,420 MWe by the year 2020)

Plant (Site)	Reactor Type	Capacity
IN OPERATION : 2,720 MWe [2 BWRs + 12 PHWRs (220 MWe type)]		
TAPS 1&2 (Tarapur)	BWR-220	2x160 MWe (rerated)
RAPS-1 (Rawatbhatta)	PHWR-220	1x100 Mwe (rerated)
RAPS-2 (Rawatbhatta)	PHWR-220	1x200 MWe (rerated)
MAPS-1&2 (Kalpakkam)	PHWR-220	2x170 MWe (rerated)
NAPS-1&2 (Narora)	PHWR-220	2x220 MWe
KAPS-1&2 (Kakrapar)	PHWR-220	2x220 MWe
Kaiga-2&1 (Kaiga)	PHWR-220	2x220 MWe
RAPS-3&4 (Rawatbhatta)	PHWR-220	2x220 MWe
UNDER CONSTRUCTION: 3,960 MWe [4xPHWR 220 + 2xPHWR 540 +2xVVER 1000]		
TAPP-3&4 (Tarapur)	PHWR-500	2x500 MWe
Kaiga 3&4	PHWR-220	2x220 MWe
RAPP 5&6	PHWR-220	2x220 MWe
KK-1&2 (Kudankulam)	LWR-1000 (VVER type)	2x1000 MWe
PLANNING STAGE: 11,740 MWe [8xPHWR 680 + 1 AHWR 300 + LWR 1000]		
AHWR	AHWR 300	1x300 MWe
PHWR	PHWR 500	8x680 MWe
LWR (including VVER)	LWR 1000	6x1000 MWe

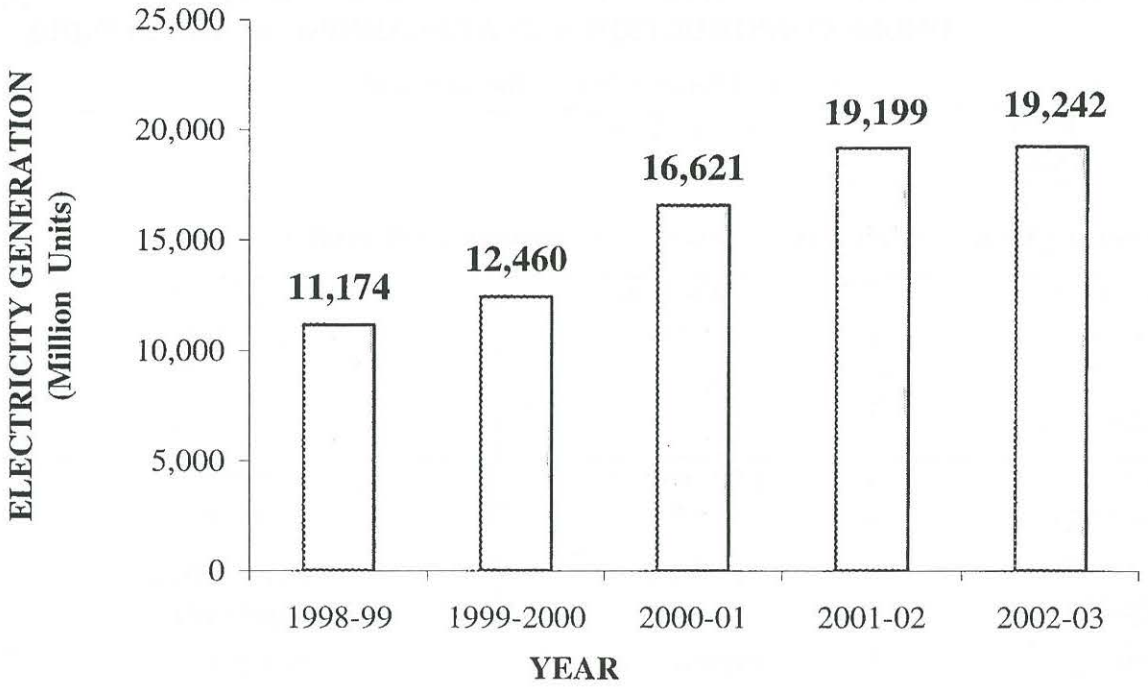


FIGURE 1: ELECTRICITY GENERATED BY NUCLEAR POWER CORPORATION OF INDIA LTD. (NPCIL) DURING THE LAST FIVE YEARS.

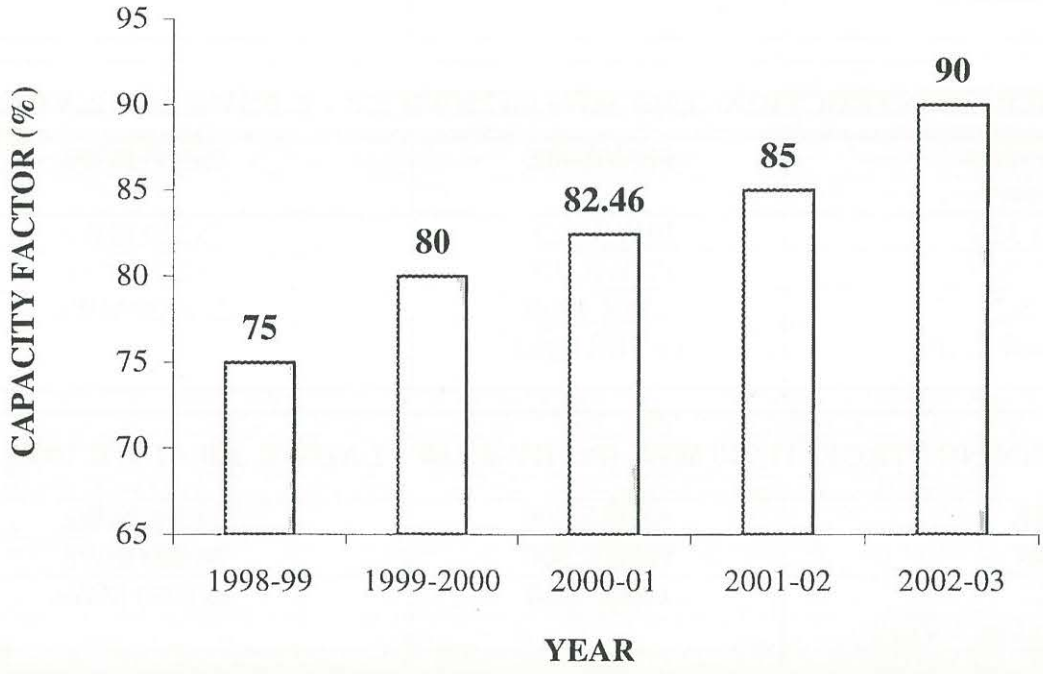


FIGURE 2: CAPACITY FACTOR ACHIEVED BY NUCLEAR POWER PLANTS OPERATED BY NPCIL DURING THE LAST FIVE YEARS.

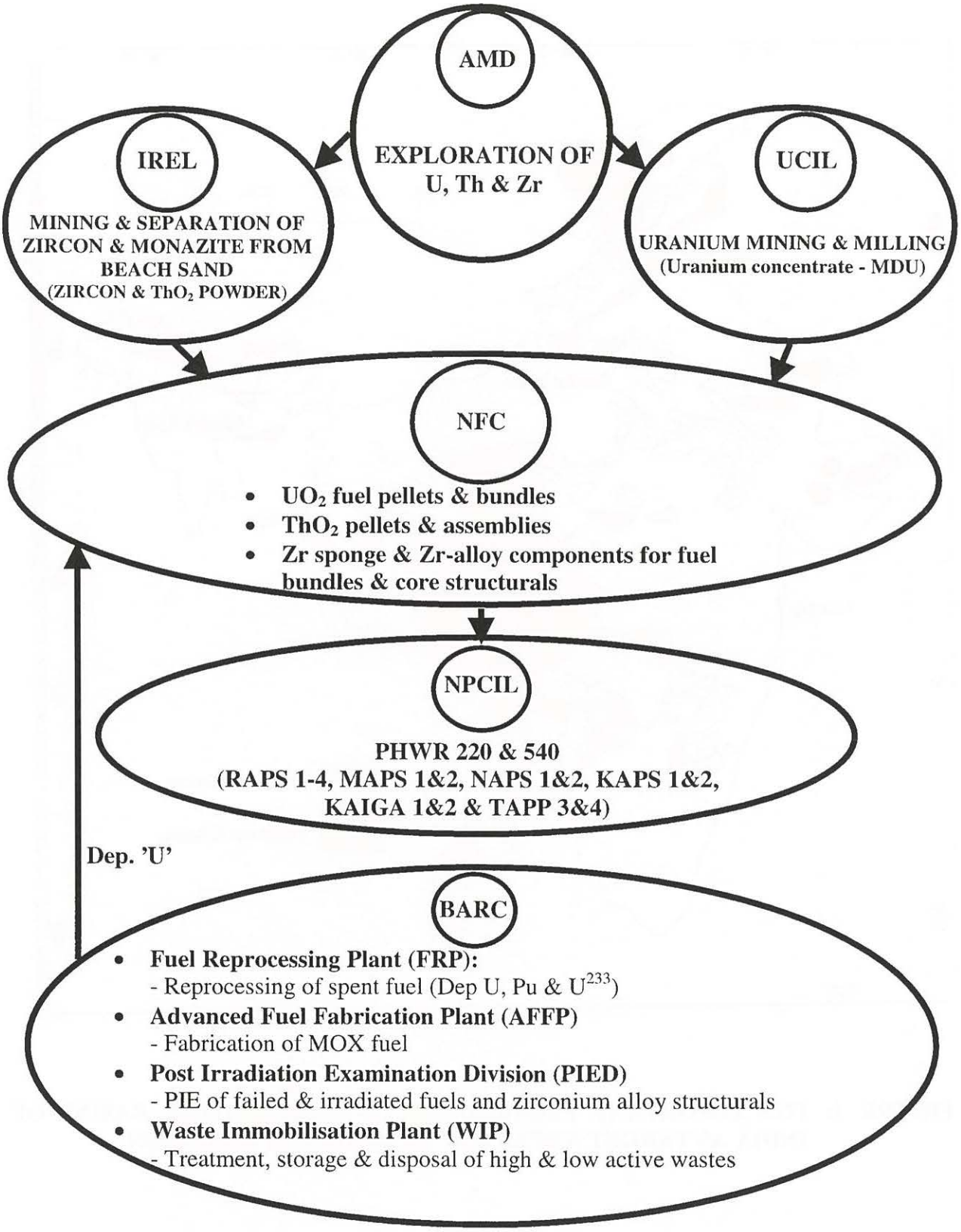


FIGURE 3: PHWR FUEL CYCLE ACTIVITIES IN INDIA

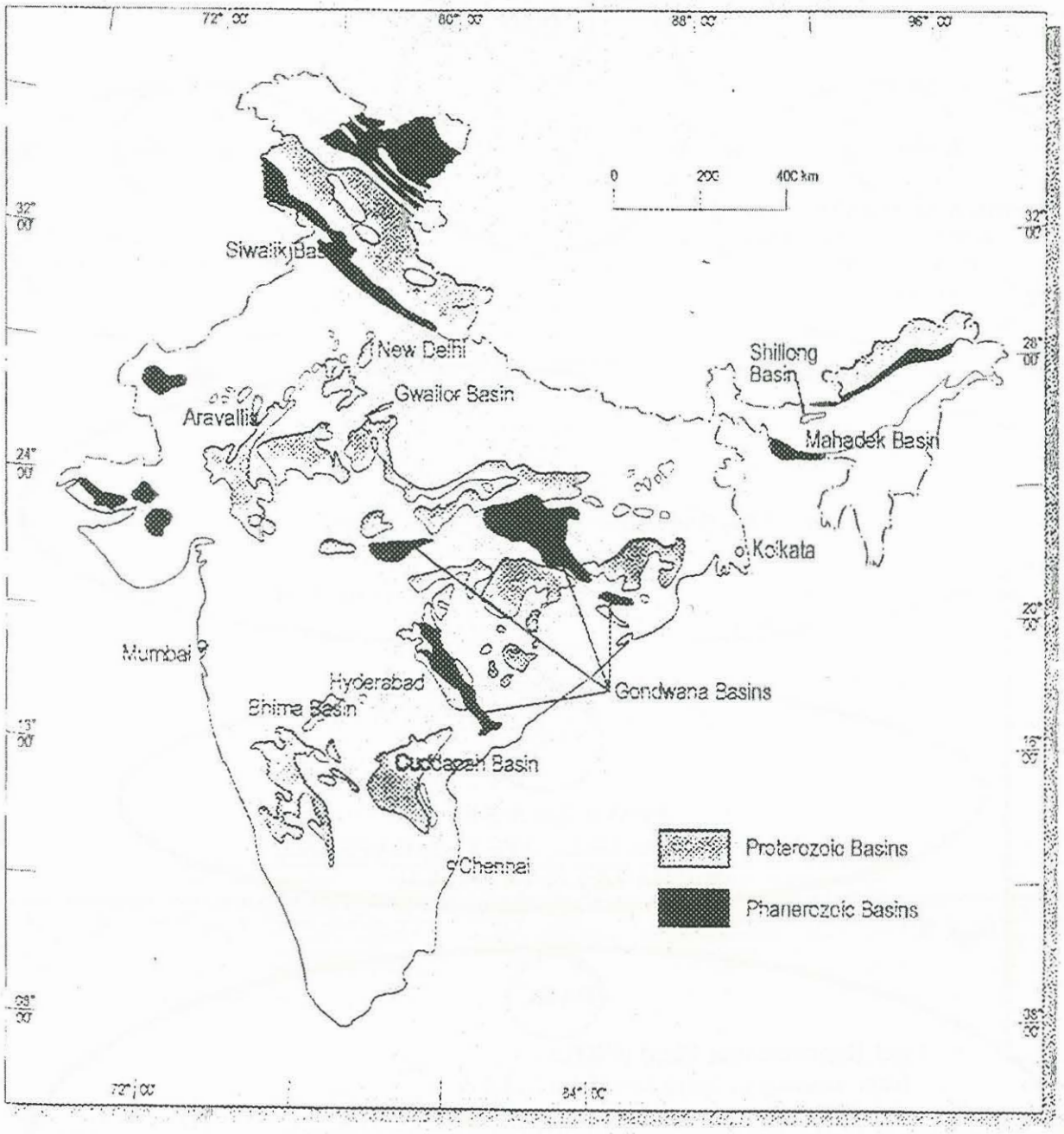
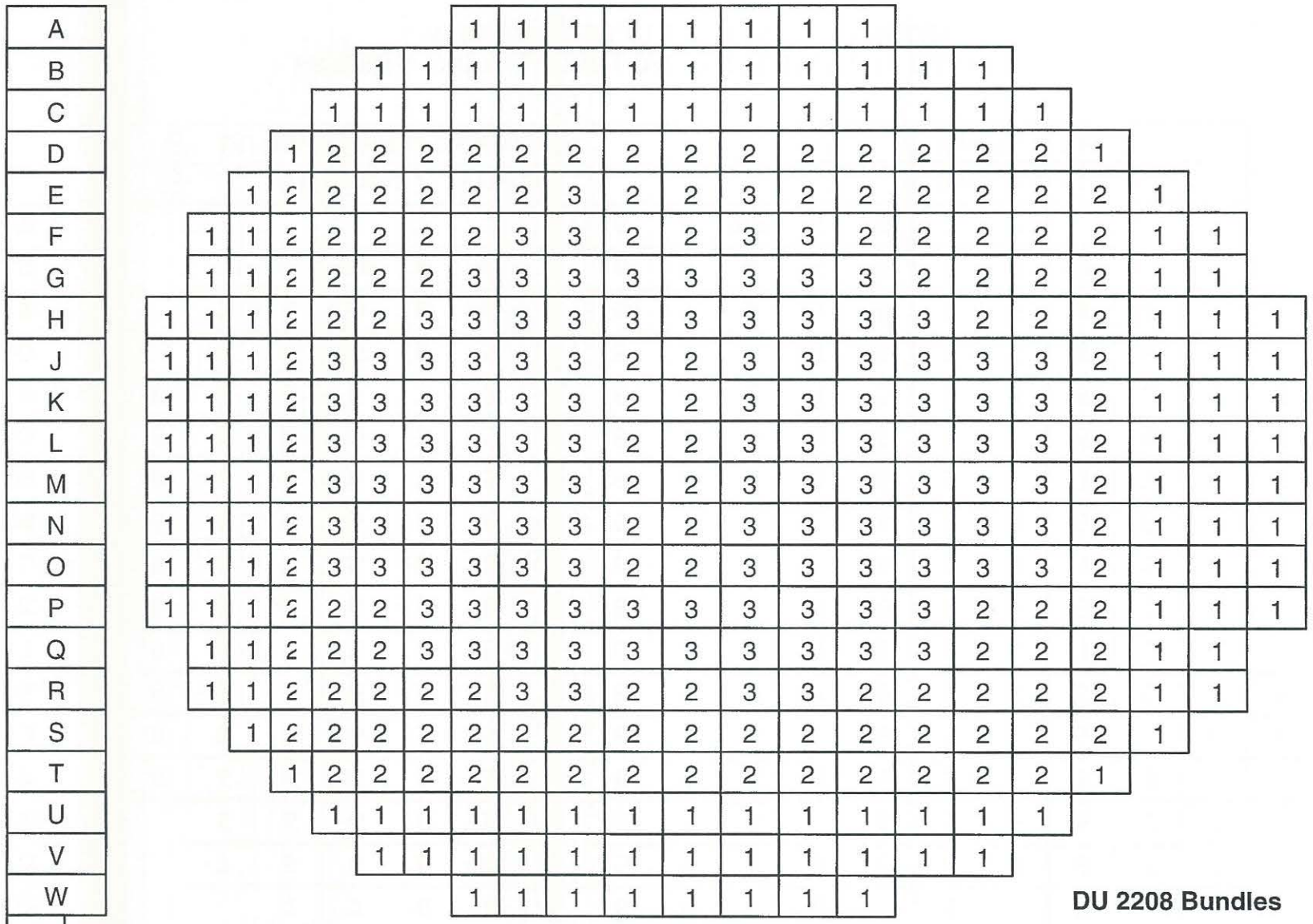


FIGURE 4: THE IMPORTANT PROTEROZOIC & PHANEROZOIC BASINS OF INDIA AS TARGET AREAS FOR URANIUM EXPLORATION

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20
A								7	7	7	7	7	7							
B						7	7	6	6	6	6	6	6	7	7					
C				7	7	6	6	6	6	6	6	6	6	6	6	7	7			
D			7	6	6	6	6	6	5	5	5	5	6	6	6	6	6	7		
E			6	6	6	6	5	5	5	5	5	5	5	5	6	6	6	6		
F		6	6	6	6	5	5	5	8	8	8	8	5	5	5	6	6	6	6	
G		6	6	6	6	5	5	8	8	8	8	8	8	5	5	6	6	6	6	
H	6	6	6	5	5	5	5	8	8	8	8	8	8	5	5	5	5	6	6	6
J	6	6	6	5	5	8	8	8	8	8	8	8	8	8	8	5	5	6	6	6
K	6	6	6	5	5	8	8	8	8	8	8	8	8	8	8	5	5	6	6	6
L	6	6	6	5	5	8	8	8	8	8	8	8	8	8	8	5	5	6	6	6
M	6	6	6	5	5	8	8	8	8	8	8	8	8	8	8	5	5	6	6	6
N		6	6	5	5	5	5	8	8	8	8	8	8	5	5	5	5	6	6	
O		6	6	6	6	5	5	8	8	8	8	8	8	5	5	6	6	6	6	
P		6	6	6	6	5	5	5	8	8	8	8	5	5	5	6	6	6	6	
Q			6	6	6	6	5	5	5	5	5	5	5	5	6	6	6	6		
R			7	6	Q	6	6	5	5	5	5	5	5	6	6	6	6	7		
S					SP	6	6	6	6	6	6	6	6	6	6	SP				
T						7	7	6	6	6	SP	6	6	7	7					

5	DU Bundles in 11 and 12	7	DU Bundles in 1 to 12
6	DU Bundles in 1 to 2 and 11 to 12	8	DU Bundles in 5 to 12

FIGURE 5: INITIAL CORE LOADING MAPS-2 (PHWR 220)
WITH 1516 DEPLETED URANIUM BUNDLES



1	6 Depleted Uranium bundles in 140 channels at positions 1,2,3,11,12,13 (840 nos.)
2	4 Depleted Uranium bundles in 140 channels at positions 1,2,12,13 (528 nos.)
3	7 Depleted Uranium bundles in 140 channels at positions 1,2,4,6,10,12,13 (840 nos.)

FIGURE 6: INITIAL CORE OF 540 MWe PHWR (LARGE SCALE USE OF DEPLETED URANIUM)

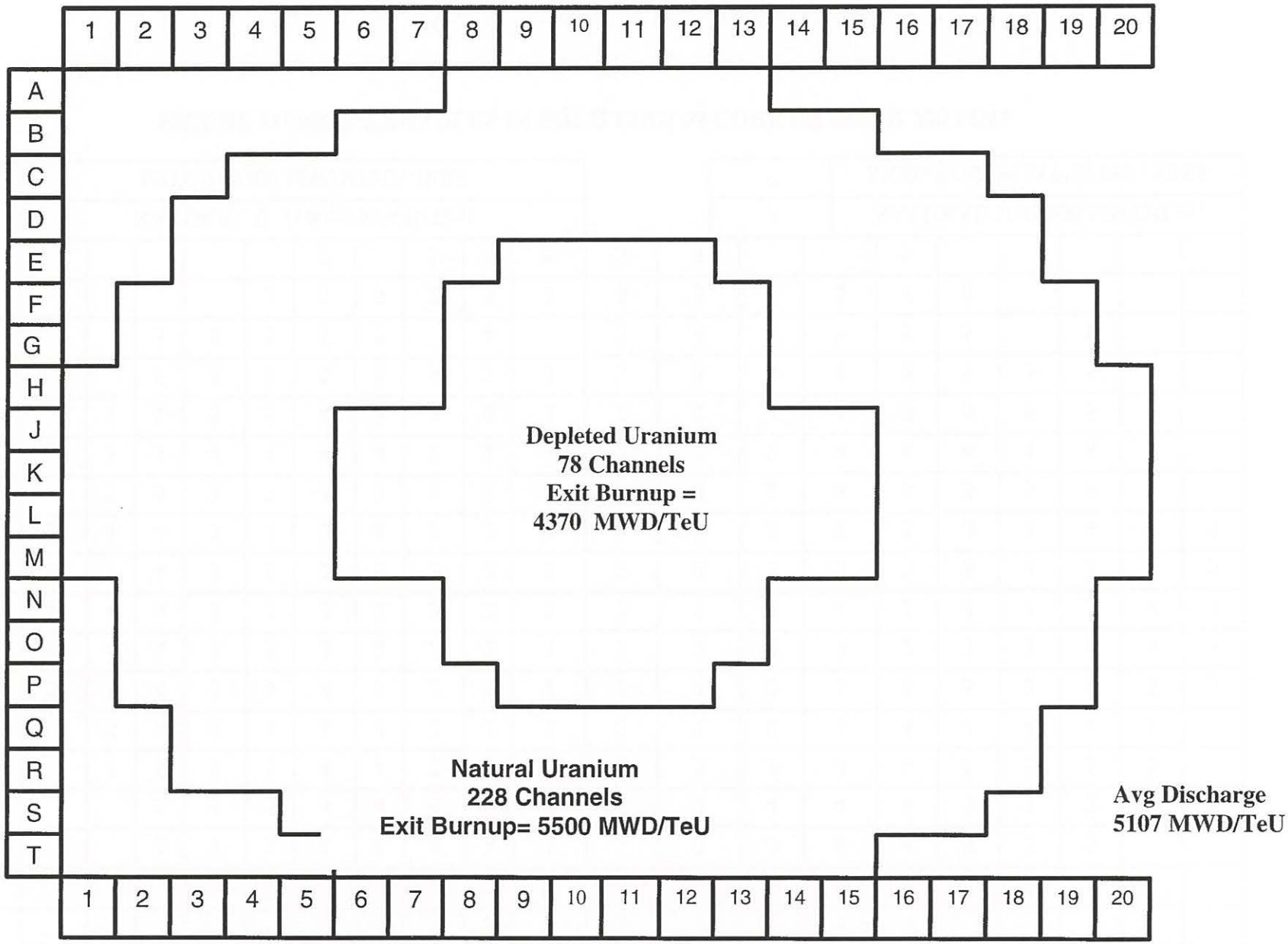


FIGURE 7: EQUILIBRIUM CORE BURNUP OPTIMISATION FOR 220 MWe PHWR DEPLETED and NATURAL URANIUM FUEL

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20
A								5	5	5	5	5	5							
B						5	5	5	5	5	5	5	5	5	5					
C				5	5	5	5	5	5	5	5	5	5	5	5	5	5			
D			5	5	5	4	4	4	3	3	3	3	4	4	4	5	5	5		
E			5	5	5	4	4	4	2	2	2	2	4	4	4	5	5	5		
F		5	5	5	5	4	4	2	2	2	2	2	2	4	4	5	5	5	5	
G		5	4	4	4	4	4	2	2	2	2	2	2	4	4	4	4	4	5	
H	5	5	4	3	3	3	3	2	2	2	2	2	2	3	3	3	3	4	5	5
J	5	4	4	3	3	2	2	2	2	2	2	2	2	2	2	3	3	4	4	5
K	5	4	4	3	3	2	2	2	2	2	2	2	2	2	2	3	3	3	4	5
L	5	4	4	3	3	2	2	2	2	2	2	2	2	2	2	3	3	3	4	5
M	5	4	4	3	3	2	2	2	2	2	2	2	2	2	2	3	3	4	4	5
N		5	4	3	3	3	3	2	2	2	2	2	2	3	3	3	3	4	5	
O		5	4	4	4	4	4	2	2	2	2	2	2	4	4	4	4	4	5	
P		5	5	5	5	4	4	3	2	2	2	2	3	4	4	5	5	5	5	
Q			5	5	5	5	5	4	3	3	3	3	4	5	5	5	5	5		
R			5	5	5	5	5		4		3	4	4	5	5	5		5		
S					5	5	5	5	5	5	5	5	5	5	5	5				
T						5		5	5	5	5	5			5					

2	NATURAL U (10000 MWD/Teu)	3	NATURAL U (5800 MWD/Teu)
4	MOX-7 (9700 MWD/TeU) 4BSS	5	MOX-7 (10350 MWD/TeU) 8BSS

FIGURE 11: MOX-7 BUNDLES IN EQUILIBRIUM CORE OF PHWR 220 MWe

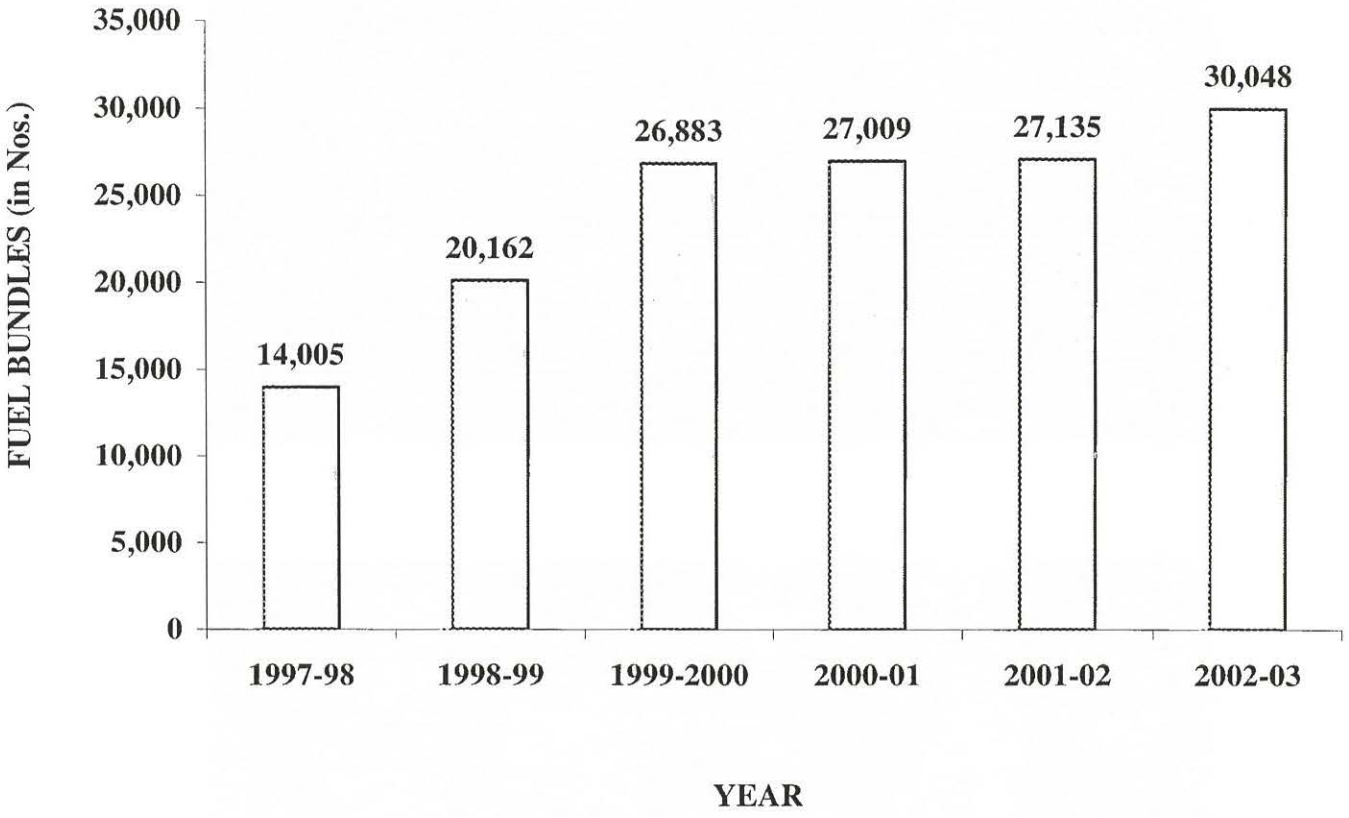


FIGURE 10: PRODUCTION OF ZIRCONIUM ALLOY CLAD 19-ELEMENT NATURAL URANIUM OXIDE FUEL BUNDLES AT NFC FOR PHWR 220 UNITS IN INDIA

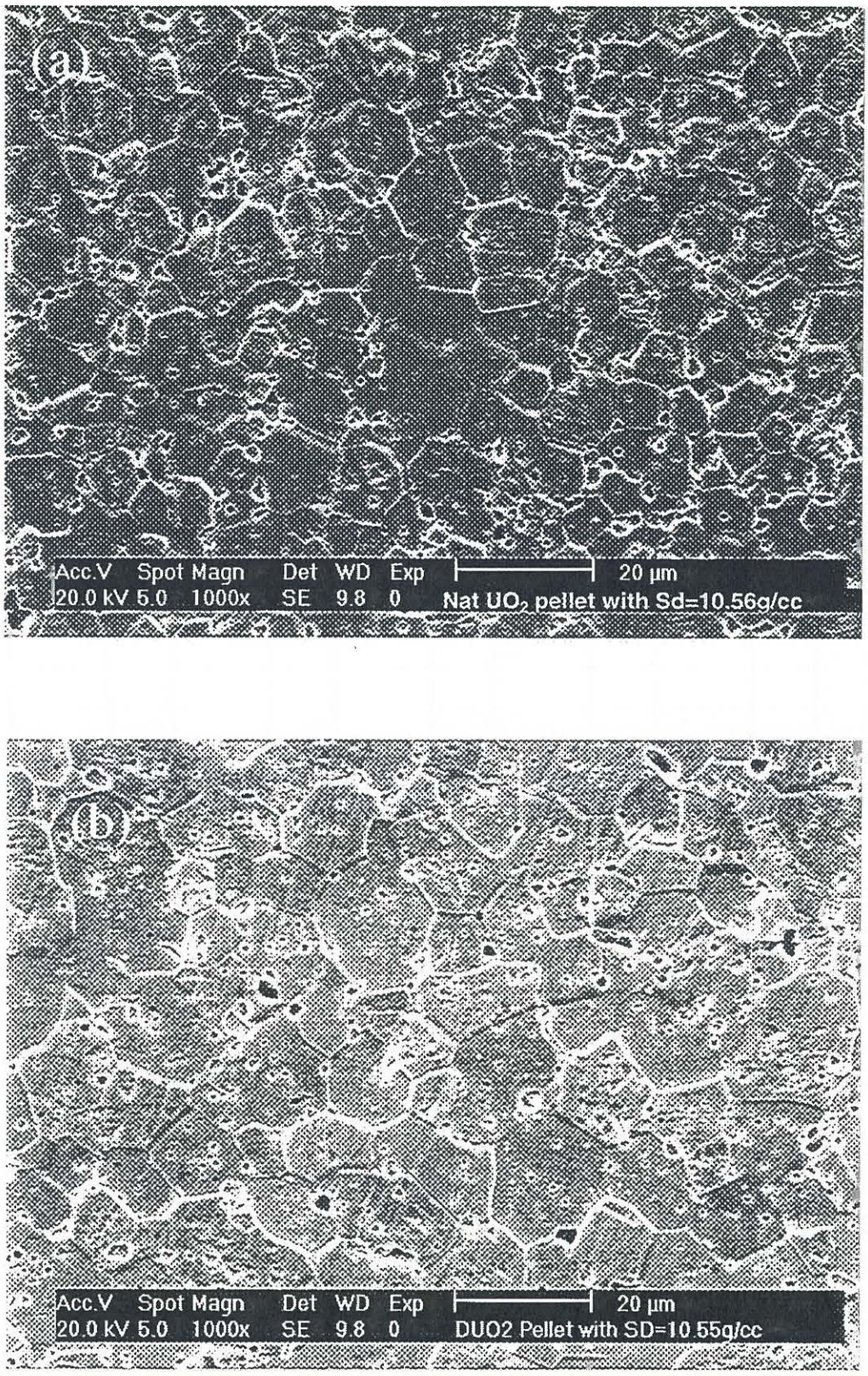


FIGURE 9: SEM MICROSTRUCTURE OF AS-SINTERED (a) NATURAL URANIUM OXIDE AND (b) DEPLETED URANIUM OXIDE SHOWING SINGLE PHASE, EQUIAXED GRAINS & RESIDUAL POROSITY IN BOTH CASES

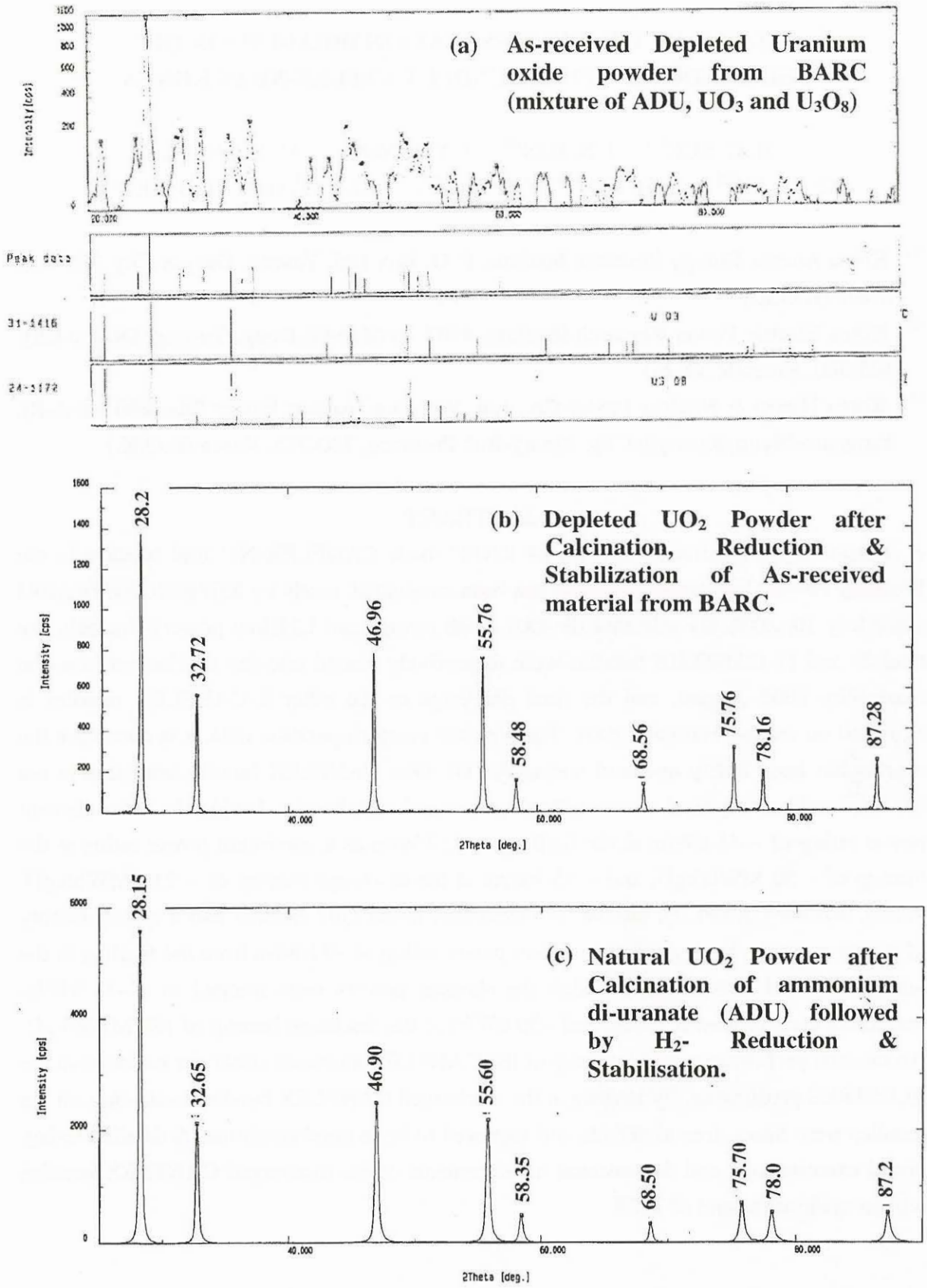


FIGURE 8: X-RAY DIFFRACTION PATTERN OF (a) AS-RECEIVED DEPLETED URANIUM OXIDE POWDER SHOWING MIXTURE OF ADU, UO_3 & U_3O_8 (b) AFTER CALCINATIONS, REDUCTION & STABILIZATION OF AS-RECEIVED POWDER SHOWING PEAKS OF PURE UO_2 (c) NATURAL UO_2.