5

LONG TERM SUSTAINABILITY OF NUCLEAR POWER IN INDIA - PROSPECTS AND CHALLENGES

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ABSTRACT: Nuclear power is emerging as a viable carbon – free option for India to meet the ever-increasing demand of base – load electricity at an affordable price, in a safe, secured and sustainable manner. Since the 1970s, India had been pursuing a self-reliant indigenous nuclear power program linking the fuel cycles of Pressurized Heavy Water Reactor (PHWR), Fast Breeder Reactor (FBRs) and thorium-based self-sustaining breeder in stage 1, 2 and 3 respectively, for efficient utilization of modest low grade (0.03-0.06 % U_3O_8) uranium reserves but vast thorium resources. Natural uranium fueled PHWR is the backbone of the program. India has achieved industrial maturity in PHWR and the related uranium fuel cycle technology. Presently, 21 reactors are in operation, including 16 units of PHWR 220 MWe, 2 units of PHWR 540 MWe, 2 units of Boiling Water Reactor (BWR) 160 MWe and a (Water Water Energy Reactor) VVER 1000 MWe. Six reactors including a VVER 1000, 4 units of PHWR700 and a Prototype Fast Breeder Reactor of 500 MWe (PFBR 500) is in an advanced stage of commissioning, as the first step to commercialization of Fast Breeder Reactor (FBR) technology and related 'closed' fuel cycle. Two additional FBRs of 600 MWe each and an integrated fast reactor fuel cycle complex are planned at the PFBR 500 sites. Since the year 2009, India has been given access to international uranium market and reactor technology. This has helped the country to enhance the expansion of nuclear power program in collaboration with overseas vendors. Negotiations are underway to set up several Generation III + light water reactor (LWR) parks with the assistance of leading reactor vendors like Rosatom, Russia (for VVER1000), Areva, France (for EPR 1650), Westinghouse, USA (for AP 1000) and General Electric, USA (for ESBWR 1350). These reactor vendors have given assurance of life time supply of low enriched uranium oxide fuel for these reactors. Several reactor sites are being developed for at least 12 additional indigenous PHWR 700 reactors. The target is to have ~ 45,000 MWe nuclear power by 2030. Since the last six years, India has also been importing natural uranium oreconcentrate (UOC) and finished natural UO_2 pellets tofuel the ten PHWR 220 units at Rawathbhata, Kakrapara and Narora. India has also been importing enriched UO_2 fuel for the two BWRs at Tarapur and the two VVERs at Kudankulunm. The present paper summarizes the on-going and the expanding nuclear power program in India highlighting the challenges of availability of uranium and plutonium for manufacturing nuclear fuels.

KEYWORDS

PHWR, BWR, VVER, FBR, LWR

1. INTRODUCTION

India is the third largest generator of electricity in the world and has presently an installed Electric power exceeding 300 GWe. Ironically, nearly 300 million people in India, out of the total population of 1.25 billion, do not have any access to electricity. The annual per capita consumption of electricity in India is in the range of 1000 kWh which is less than half of the global average. Hence, the installed electric power has to be augmented to ~ 1200 GWe by 2050 in order to bridge the gap between electricity demand and supply. Fossil fuel, in particular coal, contributes to some 70% of the electricity today and is likely to dominate the electric power market in India at least till 2030. However, India has pledged in the UN climate change meeting at Paris in December 2015 to reduce CO_2 emission relative to its GDP by 33-35% from 2005 level by 2030 and also declared that 40% of the country's electricity will come from non-fossil fuel-based resources, including solar, wind and nuclear, by 2030. Nuclear power is, therefore, emerging as an inevitable option for India to meet the ever increasing demand of high base-load electricity at an affordable price in a safe, secured and sustainable manner, leaving minimum carbon footprint.

The Department of Atomic Energy (DAE), Government of India is responsible for nuclear power and related activities in India. The Nuclear Power Corporation of India Limited (NPCIL), a public-sector undertaking (PSU) of DAE, is responsible for design, construction, operation and maintenance of all water cooled, thermal neutron reactors in India. NPCIL has generated some 37,835 million units of electricity, the highest ever nuclear electricity in India. But the contribution of nuclear electricity has so far been a meager 3% of the country's electricity production. Presently, NPCIL's reactor fleet consists of 21 reactors of which two are Boiling Light Water cooled and moderated Reactors (BWRs) of 160 MWe each, sixteen are Pressurized Heavy Water cooled and moderated Reactors (PHWRs) of 220 MWe each and two units of PHWR 540 MWe and a VVER 1000 MWe, the Russian acronym of Pressurized light water cooled and moderated Reactor (PWR). The VVER 1000 unit at Kudankulum Nuclear Power Plant (KKNP1) started commercial operation on December 31, 2014. Six reactors with total capacity of 4300 MWe are under construction. These include 4 units of PHWR 700 MWe, the second VVER 1000 unit at Kudankulum (KKNP2) and a Prototype Fast Breeder Reactor of 500 MWe (PFBR 500). The design, construction, operation and maintenance of Fast Breeder Reactors (FBRs) in India, including PFBR, is the responsibility of Bharatiya Navikiya Vidyut Nigam (BHAVINI), another PSU of DAE.

Since the last few year, India has been negotiating with leading Light Water Reactor (LWR) vendors like Rosatom - Russia, AREVA - France, Westinghouse - USA and General Electric - USA for joint construction of Generation III+ LWR parks along the coast lines of India. The sites for the LWR parks have been allocated. The reactor vendors have guaranteed life time supply of zirconium alloy clad, low enriched uranium (< 5 % U235) oxide fuel assemblies and have agreed to give the rights of reprocessing spent nuclear fuels to India. Simultaneously, NPCIL has planned at least 12 additional units of indigenous PHWR 700 at different inland sites. Hereafter, no more PHWR 220 units will be constructed and the focus will be on large (700 MWe and higher) PHWR and LWR parks. The World Nuclear Association (WNA), London has been updating the status of nuclear power program in India (Nuclear Power in India, 2017).

The present paper summarizes the on-going and upcoming nuclear power program in India, highlighting the challenges associated with the rapidly expanding nuclear power program, availability of uranium and plutonium for manufacturing nuclear fuels and the related issues.

Table 1 summarizes the location, capacity and safeguards status of the 21 operating power reactors and the 6 reactors that are under construction.

The revised short term targets of nuclear power in the country are ~ 14,600 MWe by 2021 and ~ 27,500 MWe by 2032. The long-term target is to have at least 25% of the electricity from nuclear power station by 2050.

Figure 1. shows the location of the sites in India where the 21 nuclear power reactors are in operation and 6 are under construction (Uranium 2014: Resource, Demand and Production, 2015). Figure 2. shows the sites in India where indigenous PHWR 700 units andFBRs and imported Generation III + LWRs have been planned in coming years.

Power Station & Number of Reactors	Location & State	Type & Capacity (MWe)	Fuel	Uranium Source	Safeguard Status
Tarapur Atomic Power Station (TAPS 1 & 2)	Tarapur, Maharashtra	BWR 160	Enriched UO2; U^{235}: 1.6%, 2.1% & 2.66 %	Imported UO2 pellets Russia	Under IAEA Safeguards
TAPS 3 & 4	Tarapur, Maharashtra	PHWR 540	Nat UO2	Indigenous	Not under Safeguards
Rajasthan Atomic Power Station (RAPS 1,2,3,4,5 & 6) **RAPS 7 & 8**	Rawathbhata, Rajasthan **Under Construction**	PHWR 220 **PHWR 700**	Nat UO2	Imported	Under IAEA Safeguards
Madras Atomic Power Station (MAPS 1 & 2)	Kalpakkam, Tamil Nadu	PHWR 220	Nat UO2	Indian Mines & Mills	Not under Safeguards
Narora Atomic Power Station (NAPS 1 & 2)	Narora, Uttar Pradesh	PHWR 220	Nat UO2	Imported	Under IAEA Safeguards
Kakrapar Atomic Power Station (KAPS 1 & 2) **KAPS 7 & 8**	Kakrapar, Gujarat **Under Construction**	PHWR 220 **PHWR 700**	Nat UO2	Imported	Under IAEA Safeguards
Kaiga Atomic Power Station (KGS 1, 2, 3 & 4)	Kaiga, Karnataka	PHWR 220	Nat UO2	Indian Mines & Mills	Under IAEA Safeguards
Kudankulum Nuclear Power Plant (KKNPP1)**KKNPP 2**	Kudankulum, Tamil Nadu **Under Construction**	VVER 1000 **VVER 1000**	Enriched UO2	Imported Fuel Assemblies	Under IAEA Safeguards
Prototype Fast Breeder Reactor	Kalpakkam, Tamil Nadu	**PFBR 500**	(U, Pu) O2	Indian Fuel	Not under Safeguards

TABLE 1. Location, capacity, fuel and safeguards status of nuclear power reactors in India.

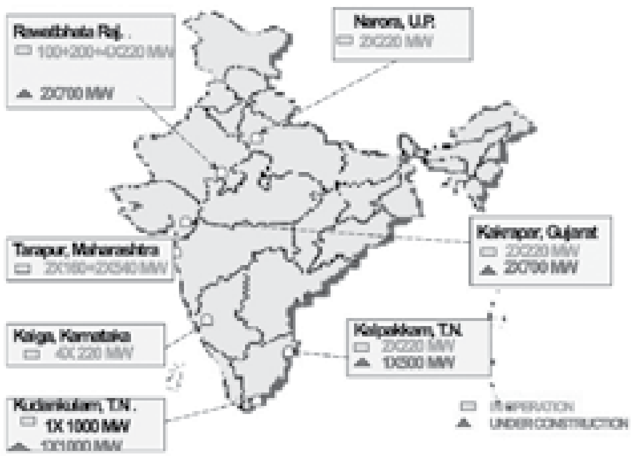


FIGURE 1. The locations of the 21 nuclear power reactors that are under operation and that are under construction in India

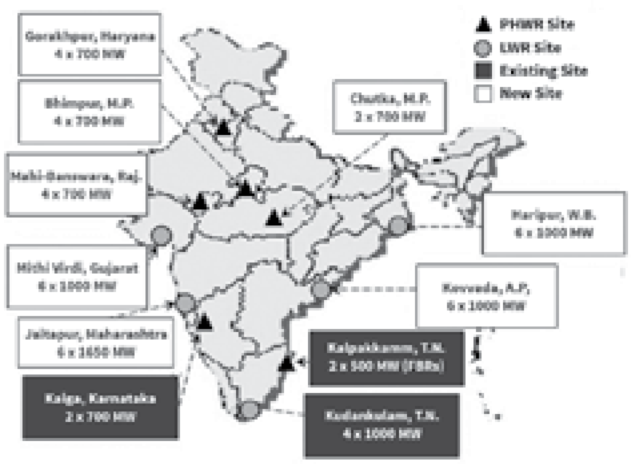


FIGURE 2. Location of the sites in India where indigenous PHWR 700 & FBRs and the imported generation III + LWRs have been planned.

2. NUCLEAR POWER REACTOR TECHNOLOGY AND THEIR APPLICATIONS IN INDIA

The present generation of nuclear power reactors, all over the world, derives energy from the fission of U235, the only fissile material in nature. Natural Uranium (NU) contains 99.3% U238, a fertile isotope and only 0.7% U235. NU is not only the basic raw material for U235 – based fuel but also produces the fissile isotope Pu239 in a reactor by neutron capture of the fertile U238 isotope followed by β-decay. Nearly 30% of the fission heat energy in a reactor is produced by in-situ fission of Pu239. Presently, 99% of the 439 operating nuclear power reactors in the world, with total installed power of ~ 480 GWe, are thermal neutron reactors. LWRs, consisting of PWR, VVER and BWRs account for nearly 85% of the reactors. The PHWRs, also known as CANDU in Canada and other countries, contribute to some 12% of the reactors. The PHWRs and LWRs use natural uranium and low enriched uranium (LEU:< 20 % U235) containing up to 5% U235 respectively as fuel in the form of high density cylindrical UO2 pellets that are stacked and encapsulated in zirconium alloy cladding tubes. The fuel rods thus produced are assembled in circular (in PHWRs), square (in PWRs & BWRs) or hexagonal (in VVERs) configurations to form fuel assemblies.

The spent LWRs and PHWRs fuels contain the fissile isotope Pu239 and other isotopes of plutonium, namely, Pu240, Pu241, Pu242 & Pu238, minor actinides (Np, Am & Cm) and fission products. The plutonium could be recycled in LWRs and PHWRs in combination with U238 but in spite of multiple recycling of the actinides, in thermal neutron reactors, the effective utilization of natural uranium resource is < 1%. Most of the uranium is locked as U238 in tailings of U235 enrichment plants and in spent fuels. The plutonium is best utilized in fast breeder reactors (FBRs), in combination with U238, to breed more Pu239 than what is consumed as fuel. FBRs are more expensive than water cooled reactors but are required for long term sustainability of nuclear power. With FBRs and 'closed' fuel cycle involving multiple recycling of actinides at least 60% of natural uranium resources could be utilized. Now, there are only 2 commercial FBRs that are in operation. Both are in Russia. LWRs, in general, and PWRs (including VVERs) will continue to dominate the world nuclear power market till the FBRs are commercially introduced.

The identified conventional uranium resources worldwide, recoverable at a price < 260 US$/kg U, is in the range of 7.6 million tons and the annual demand of uranium from mine to fuel the operating reactors is in the range of 65,000-70,000 tons (Annual Report 2015-2016, 2016). The identified uranium resource is adequate for at least 150 years for any foreseeable growth scenario of nuclear power even if the uranium is used in 'open' fuel cycle on once-through basis. If all conventional and unconventional uranium resources are used in 'closed' fuel cycle using FBRs, then the resource will last tens of thousands of years.

The major challenge of nuclear power is radiological safety and back end of the fuel cycle. Natural uranium and thorium, the basic raw materials for nuclear fuel are mildly radioactivity and do not pose any serious hazard from external radiation. The fission products,plutonium and its isotopes and minor actinides (MA:N, Am & Cm) are highly radioactive and health hazardous and are required to be fully contained and handled in leak tight and shielded glove boxes or hot cells using remote and automated machineries and equipment. The fissile isotopes, U235, Pu239 and U233 and even some of the MA isotopes have very low critical mass (10-100 kg) and are dual use (civil and weapon) materials. Hence proper safeguards and proliferation-resistance practices are required to be in place to avoid clandestine diversion of fertile and fissile materials for non-peaceful purpose. These materials are also associated with criticality hazard for which real time accounting is necessary to avoid any criticality accident. Safety, Security and Safeguards are of paramount importance in nuclear reactor and fuel cycle technology.

Nuclear electricity generation in India started in 1969 with the commissioning of two BWRs of 200 MWe each, in collaboration with General Electric (GE) USA. These reactors use imported low enriched uranium (U235 enrichments: 1.6%, 2.1% & 2.66%) in the form of zircaloy 2 clad UO2 fuel rods that are clustered into 6 x 6 square fuel assemblies. The 2 BWRs are under IAEA safeguards and are still in operation at a de-rated capacity of 160 MWe each.

However, from the inception of the nuclear power program in India in the 1960, great emphasis has been given to self-reliance and indigenization. Accordingly, based on India's limited and low grade uranium resources (0.03-0.06% U3O8) but vast thorium deposits, a three stage nuclear power program, linking natural uranium (0.7% U235) -fueled PHWR in stage 1, plutonium (mainly Pu239) -based FBR in stage 2, using U238 and Th232 blankets and self-sustaining Th232 – U233 breeder in stage 3, was chalked out. India initiated construction of two PHWR 220 MWe units at Rajasthan Atomic Power Station (RAPS 1 & 2), at Rawathbhata, in collaboration with Atomic Energy of Canada Limited (AECL) in the late

1960s. Both RAPS 1 and 2 are under IAEA safeguards. RAPS 1 was commissioned in 1972 jointly by AECL and NPCIL. RAPS 2 was delayed and commissioned in 1982, mainly through the indigenous efforts of NPCIL because after India conducted the Peaceful Nuclear Explosion (PNE) in May 1974. Canada, USA and several other developed countries, discontinued nuclear collaboration with India, which is also not a signatory to the international Nuclear Non-Proliferation Treaty (NPT). In May 1998, India tested several nuclear devices and announced its nuclear weapon capability. Thereafter, the country was excluded from trade in nuclear plant, equipment or materials.

PHWR is the backbone of the indigenous nuclear power program in India that is underway for more than four decades. The country has achieved industrial maturity in PHWR and related technologies namely, UO2 fuel, zirconium sponge and zirconium alloy components and heavy water. After RAPS 1 and 2, NPCIL has constructed 14 PHWR 220 and 2 PHWR 540 MWe units with progressive improvement in design and safety features. However, the trade ban and inadequate indigenous source of natural uranium resulted in significant slowing down of the civil nuclear power program.

Fortunately, based on India's impeccable records in nuclear non-proliferation in import and exports of Special Nuclear Material (SNM) and excellent cooperation with IAEA in issues related to safeguards and safety, in the last quarter of 2008, the US Congress, IAEA and the Nuclear Supplier's Group (NSG) paved the way for India to have access to international uranium and reactor technology. From the year 2009 onwards, India started negotiations with reputable reactor vendors like Rosatom, Areva, Westinghouse and General Electric for setting up several Gen III + LWR parks jointly, with the understanding that except for a few critical components, most of the plants will be manufactured in India, thereby reducing the capital cost of the plant significantly. These vendors have now been allotted coastal sites. Pre-project activities and financial negotiations are underway. The LWRs will come with life time guarantee of supply of finished fuel assemblies. The vendors have also agreed to give the rights of reprocessing of spent fuel to India.

India will be entering the second stage of its nuclear power program with the commissioning of PFBR 500 in 2016. Austenitic stainless steel clad (type D9), mixed uranium plutonium oxide (MOX) fuel, containing 20-25% PuO2, is the reference fuel for PFBR and most of the demonstration, prototype and commercial sodium cooled FBRs constructed and operated in the world. Two additional FBR 600 MWe units have been ear marked alongside PFBR 500. The site development activities for the two FBR 600 units are underway at Kalpakkam. These reactors will also use MOX fuel. The FBR Park at Kalpakkam will also have an integrated and co-located spent FBR fuel reprocessing plant and an industrial facility for fabrication of MOXfuel.

3. NUCLEAR FUEL CYCLE ACTIVITIES IN INDIA

Nuclear power reactor and related nuclear fuel cycle technology go hand in hand. Long term sustainability of nuclear power will be possible only if nuclear electricity is economic and affordable and nuclear power reactors and fuel cycle facilities are safe, secured and proliferation-resistant and the highly radioactive and health-hazardous waste from the back end is properly managed, immobilized and kept ready for permanent disposal in deep underground geologically stable repository.

The 3-stage nuclear power program in India is being slightly modified as shown in Fig. 3. The first stage will now consist of indigenous PHWR 220, 540 and 700 MWe units fuelled with indigenous and imported natural uranium and Gen III + LWRs built in collaboration with reputable overseas reactor vendors with guaranteed life time supply of zirconium alloy clad enriched uranium oxidefuel. The U235 content in spent LWR fuel is in the range of 0.8 to 1.2% which is higher than that in natural uranium (0.7% U235). Hence, the Reprocessed Uranium (RU) from spent LWR fuel could be recycled in PHWRs. In the second stage, the plutonium from PHWRs and LWRs will be recycled in sodium cooled FBRs, in the form of stainless steel (type D9 or HT9) or oxide dispersion strengthened (ODS) steel clad mixed uranium plutonium ceramic or metallic fuel containing 15-25% plutonium. The uranium in FBR fuel could be Depleted Uranium (DU: < 0.7% U235) from the tailings of U235 enrichment plant or Reprocessed Depleted Uranium (RDU) from spent PHWR fuel. DU and RDU will also be used as blanket material in FBRs. The FBRs will produce more plutonium from U238 in fuel core and blanket than plutonium consumed in fuel. Thus, multiple recycling of Pu with DU and RDU in FBRs will enable at least 60% utilization of natural uranium resources which is otherwise <1% if plutonium is recycled in thermal reactor. At a much later date (way beyond 2050), thorium could be used a blanket to breed U233 for the third stage.

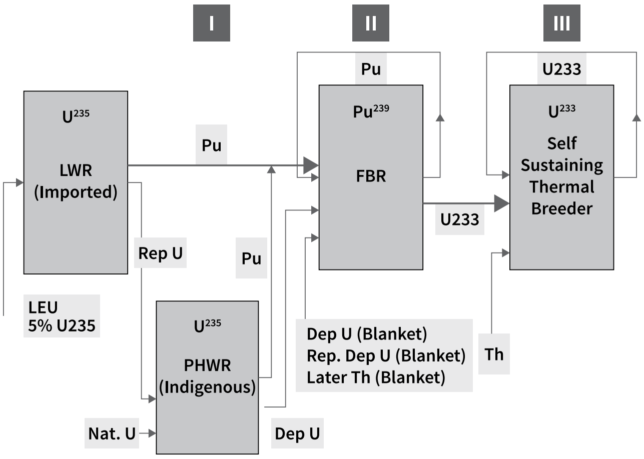


FIGURE 3. Closed nuclear fuel cycle in India, linking imported LWRs & indigenous PHWRs in stage I with FBRs in stage II and Th232-U233 thermal breeders in stage III

4. FRONT END OF URANIUM FUEL CYCLE

According to the latest update of Atomic Minerals Directorate of exploration and research (AMD) , Hyderabad, India has modest reserves of some 2,14,000 tons of identified conventional uranium resources which are of very low grade (0.03-0.06% U3O8) (Ganguly & Jayaraj, 2004). The vein type deposits in Singhbhum district of Jharkhand state are being mined and milled by Uranium Corporation of India Limited (UCIL) for more than four decades and have so far been the main source of indigenous uranium supply. Other vein type deposits at Gogi, Karnataka and Rohil, Rajasthan will be exploited in coming years. In recent years, uranium mine and mill have started operation at Cuddapah, Andhra Pradesh where huge strataboundurанium reserves (>100,000 tons U3O8) have been located. The sandstone type deposit at Meghalaya state has so far been the highest-grade Uranium ore (0.1-0.2% U3O8 average) but is yet to be exploited. The unconformity type deposits in northern Cuddapah district are being developed.

At the Singhbhum district, the uranium mines at Jaduguda, Bhatin, Narwapahar and Bagjata feed the uranium mill at Jaduguda. The Turamdih, Banduhurang (the only open cut uranium mine in India) and Mohuldih mines at Singbhum feed the Turamdih mill. At the Jaduguda and Turamdih mill the crushed and milled uranium ore is leached with sulfuric acid followed by purification using Ion Exchange (IX) resins and precipitation of UOC as magnesium diuranate (MDU) and uranium peroxide. The uranium ore from Tummalapallemine in south Cuddupah is subjected to alkali leaching because of high carbonate content in ore. High pressure, high temperature leaching technique has been developed, followed by ion exchange purification and precipitation of UOC as sodium diuranate (SDU).

5. MANUFACTURING OF ZIRCALOY CLAD UO2 FUEL ASSEMBLY (BUNDLES) AT NFC, HYDERABAD

Since the early 1970s, the Nuclear Fuel Complex (NFC) at Hyderabad has been manufacturing zircaloy (an alloy of Zr and ~ 1.5% Sn with traces of Fe, Cr and Ni; zircaloy 4 is nickel-free) clad natural UO2 fuel bundles for the PHWR units. The starting materials till 2009 have been: i) UOC from the UCIL uranium mills at Jaduguda and Turamdih and ii) Zircon (zirconium silicate) sand mined by Indian Rare Earths Limited (IREL) from the beach sands in Kerala, Tamil Nadu and Orissa states. Since 2009, NFC has been importing natural UO2 pellets from JSC-TVEL (Russia) and UOC from Kazatomprom (Kazakhstan). Areva, France has also supplied one consignment of natural UOC. In 2015, Cameco Corporation, Canada supplied the first consignment of natural UOC. Negotiations are underway to import natural UOC from Uzbekistan, Namibia and Australia. So far, in 10 PHWR 220-unit fuel bundles manufactured from imported UOC or UO2 pellets have been used, namely, the 6 units at RAPS and the two units each at Narora Atomic Power Station (NAPS) and Kakrapar Atomic Power Station (KAPS). These reactors have been placed under IAEA safeguards. Indigenous natural uranium is used to fuel the two PHWR 540 at Tarapur (TAPS 3 & 4), the 4 units of PHWR 220 at Kaiga Atomic Power Station (KGS 1-4) and the two PHWR 220 at Madras Atomic Power Station (MAPS). In coming years, some or all upcoming PHWR 700 units are also likely to use imported UOC or UO2 pellets and will be also placed under IAEA safeguards. In recent years, NFC has been receiving UOC in the form of SDU from Tummalapalle.

The UOC from indigenous and overseas sources are refined and processed in different plants. The plants using imported uranium are under IAEA safeguards. The UOC is dissolved in nitric acid and purified by solvent extraction using tri butyl phosphate in kerosene as solvent in a series of mixer-settlers. The purified uranium nitrate solution is then converted to ammonium diuranate (ADU) and precipitated. The ADU is next converted to fine and sinterable UO2 powder by sequential air-calcination, hydrogen reduction and stabilization. The UO2 powder is then granulated and cold-compacted into cylindrical pellets which are then sintered at high temperature (~ 1700 C) in continuous pusher type sintering furnace in hydrogen atmosphere to form high density UO2 pellets. The pellets are centerless ground to the desired diameter, stacked into fuel columns and loaded in zircaloy 4 cladding tubes with bearing and spacer pad appendages on outer surface and graphite coating on inner surface. The end caps of the fuel elements are resistance-welded. Next the fuel pins are assembled in circular configuration as 19-fuel element bundles for PHWR 220 and 37-element bundles for PHWR 540/700. Figure 4. shows the major steps in fabrication and quality control of PHWR fuel at NFC. typical fuel bundles/ assemblies for PHWR 220 and PHWR 540/700 (Raj, Chellapandi, & Rao, 2014). The quality and quantity of PHWR fuel at NFC has significantly improved over the years and in 2014-2015, NFC became the largest PHWR fuel producing plant in the world with an annual production of ~ 1250 tons. Figure 3. shows the fuel elements for PHWR 220 and PHWR 540/700 units in India.

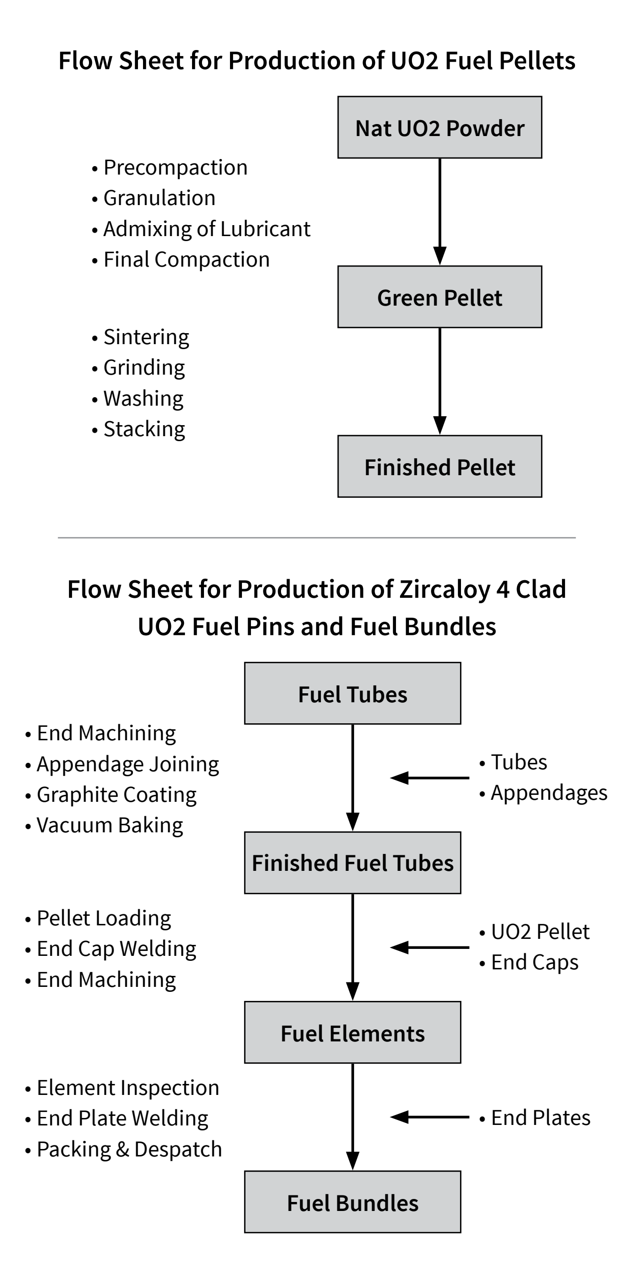
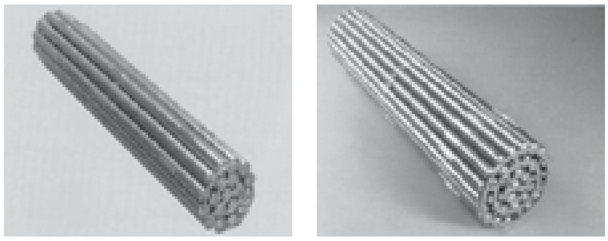


FIGURE 4. Major Process Steps Followed Innfc, Hyderabad For Manufacturing 19 - Pin Phwr 220mwe & 37 - Pin Phwr 540/700 Mwe Fuel Bundles

NFC has also been manufacturing Zircaloy 2 clad enriched UO2 fuel assemblies for the two BWR 160 units. Initially, enriched uranium containing 1.6%, 2-1% and 2.66% U235 was imported from USA, France and China in the form of UF6, but since 2002, JSC-TVEL, Russia has been supplying enriched UO2 pellets for TAPS 1 & 2. Figure 3. shows the 6x6 BWR 160 fuel assembly that is being routinely manufactured at NFC (Hemantha Rao, 2005).



16 x PHWR 220 MWe in Operation

- 19-Element Fuel Bundles for PHWR 220 MWe
- 328 Welds per Fuel Bundle (FB)
- Resistance Welding for All Welds
- Contains ~ 15.2 kg UO2 Fuel Pellets
- Each Fuel Assembly Generates 700,000 kWh
- PHWR 220 MWe Contains 12 x 306 = 3672 FBs
- No. of welds in PHWR 220 MWe Fuel Core

2 x PHWR 540 MWe in Operation

4 x PHWR 700 MWe Under Construction

- 37-Element Fuel Bundles for PHWR l540/700 MWe
- 622 Welds per Fuel Bundle (FB)
- Resistance Welding for All Welds
- Contains ~ 22.5 kg UO2 Fuel Pellets
- Each Fuel Assembly Generates 1,100,000 kWh
- PHWR 540/700 MWe Contains 12 x 392 = 4704 FBs
- No. of welds in PHWR 540/700 MWe Fuel Core: 4704 x 392 = 1,843968

ALL SUBSEQUENT PHWR UNITS IN INDIA WILL BE OF PHWR 700 MWE

FIGURE 5. PHWR 220 and PHWR 540/700 Fuel Assemblies Manufactured at NFC routinely

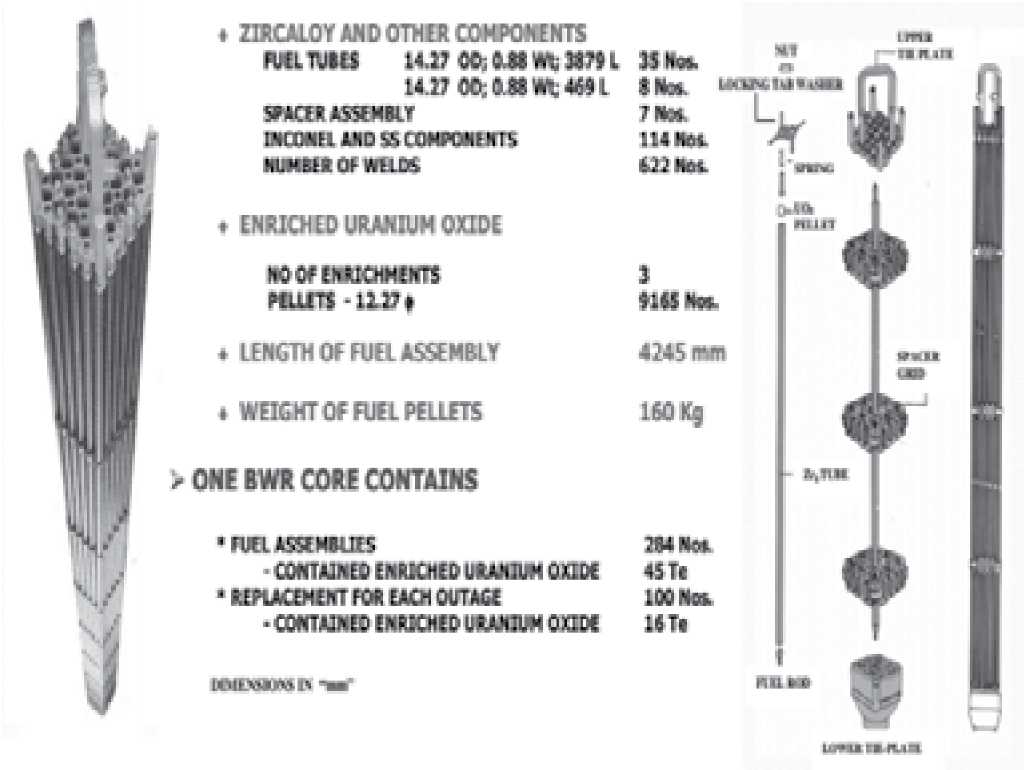


FIGURE 6. A Typical 6 X 6 BWR 160 Mwe Fuel Assembly Manufactured At NFC For Taps 1 & 2

6. BACK END OF NUCLEAR FUEL CYCLE AND MANUFACTURING OF FAST REACTOR FUEL

The growth and long term sustainability of nuclear power in India will depend on early introduction of many sodium cooled FBRs and multiple recycling of uranium and plutonium in these reactors. At a later date efforts should be made to separate the minor actinides (Np, Am & Cm) from spent fuel and use them as fissile and fertile materials in FBRs. Thus, the quantity and volume of radioactivity and decay heat in high level waste for permanent disposal in deep underground repository will be significantly reduced.

The first spent fuel reprocessing plant in India was set up in 1965 at the Bhabha Atomic Research Centre (BARC) at Mumbai, mainly to reprocess spent aluminum clad uranium metal fuel from research reactor. The classical PUREX (plutonium uranium refining by solvent extraction) was adapted. Based on the successful experience at BARC, Mumbai, three reprocessing plants (two at Tarapur and one at Kalpakkam) were set up to reprocess zircaloy clad UO2 spent fuel from water cooled reactors. Today, India has an annual reprocessing capacity of 330 tons uranium. The three plants are not under IAEA safeguards. The plutonium from these plants are being utilized for manufacturing MOX fuels containing 20-25% PuO2 at the MOX plant at Tarapur.

Figure 7. shows the PFBR 500 core and some details of the MOX fuel assembly (Kamath, Anatharamanand, & Purushotham, 2000). Manufacturing of the MOX fuel, with RDU oxide axial blanket at both ends of the fuel column, for the first core of PFBR 500 is underway at the MOX plant at Tarapur. The stainless-steel cladding tubes, hexcans and other SS hardware and SS clad RDU pellets for PFBR blanket assemblies have been fabricated at NFC, Hyderabad. The first few reload MOX fuel for PFBR 500 will be manufactured at the Tarapur MOX plant till the integrated MOX facility at the Kalpakkam FBR park is commissioned.

The annular MOX fuel pellets for PFBR are manufactured by the classical 'powder- pellet' route starting with UO2 and PuO2 powders. The oxide powders are co milled in an attritor to ensure excellent UO2 and PuO2 micro-homogeneity, cold-pelletized in rotary compaction press and sintered at 1650 C in Ar-H2 atmosphere in batch type sintering furnace (Kumar, 2013),(Ganguly & Rajaram, 2013). The MOX pellets are subjected to dry centre less grinding to the specified diameter, inspected, stacked and loaded in SS(D9) cladding tubes and the end plugs are welded by Tungsten Inert Gas (TIG).

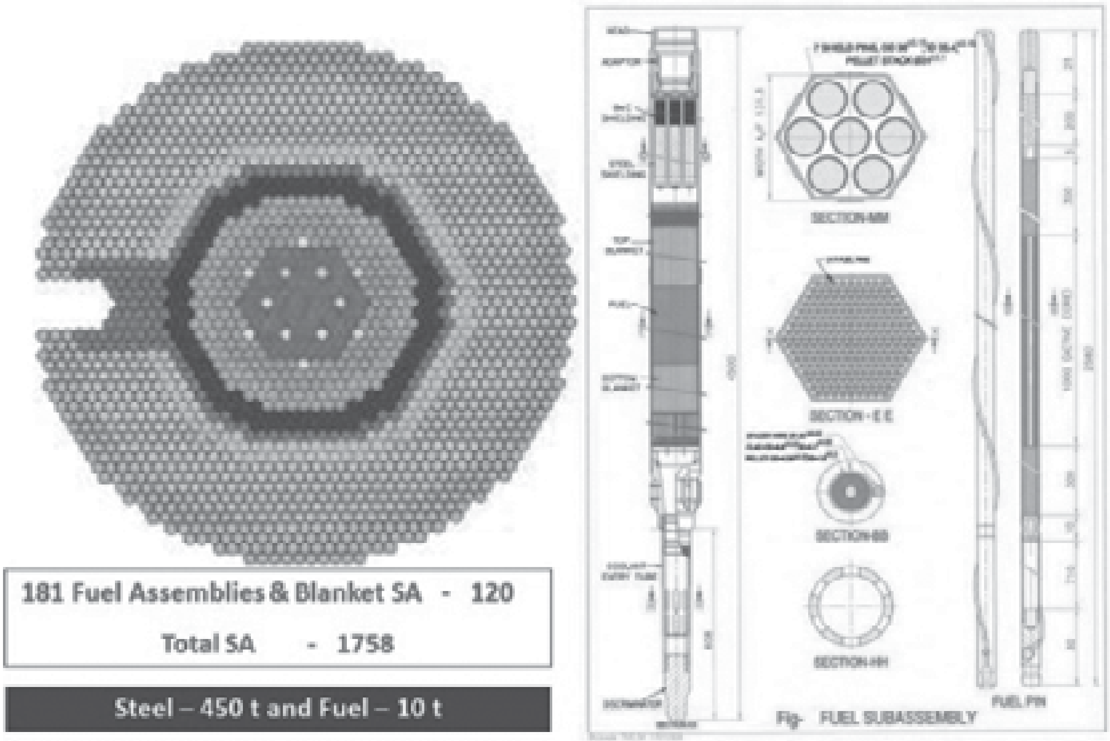


FIGURE 7. PFBR 500 Core With 181 MOX Fuel Assemblies In Centre Surrounded By 120 RDU Oxide Blanket Assemblies

7. EXPLORING POSSIBILITY OF IMPORTING PLUTONIUM

The key to the commercial success of FBRs in India would be availability of plutonium, on time, and development of FBR fuel that will perform satisfactorily to high burn up (>100,000 MWD/ton heavy metal – preferably up to 200,000 MWD/tom HM), breed plutonium efficiently and will be easy to reprocess, re-fabricate and recycle in FBRs.

Regarding availability of plutonium, India should explore the possibility of importing plutonium from countries like USA, Russia and UK which have several hundred tons of separated plutonium of either weapon grade (>93% Pu239) or civilian grade and launch several safeguarded and integrated FBR parks, each having 4 to 6 FBRs and co-located facilities for reprocessing and re-fabrication of FBR fuels (Megatons to Megawatts program concludes, 2013). The project should follow the successful “megaton to megawatt” joint mission of USA and Russia during 1993-2013. Under this mission, 500 tons of weapon grade high enriched uranium (HEU: >20% U235) containing >90% U235 dismantled from nuclear war heads in Russia was down blended to low enriched uranium (LEU < 20% U235) containing < 5% U235 that was used as fuel in LWRs in USA (Chang, 2007).

Metallic fuel is considered as advanced fuel for sodium cooled FBRs because of much higher breeding ratio and nearly seven times higher thermal conductivity compared to the reference mixed uranium plutonium oxide fuel. Metallic fuel of composition U-20 Pu-10 Zr, sodium bonded and clad with ferritic SS HT-9 or ODS, have demonstrated inherent and passive safety and excellent performance in EBR II in USA. Metallic fuel pins are easy to manufacture by induction melting followed by injection casting [12]. Spent metallic fuel is amenable to pyro-electrolytic refining which is simpler than the classical PUREX aqueous route. India should seriously consider adapting the Integrated Fast Reactor (IFR) model for large scale implementation of FBRs with metallic fuel, preferably in collaboration with USA.

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