Technical Report

Nuclear Power in India:

The Road Ahead

Anshu Bharadwaj,

L V Krishnan,

S. Rajgopal.

Center for Study of Science, Technology and Policy (CSTEP),
CAIR Building, Raj Bhavan Circle,
High Grounds, Bangalore 560001.
www.cstep.in

This study was supported by SSN Educational and Charitable Trust, Chennai and is part of CSTEP's on-going research in India's energy and electric power sector.

Center for Study of Science, Technology and Policy (CSTEP) is a private, nonprofit (Section 25) research corporation. CSTEP's mandate and vision is to undertake world-class research and analysis in chosen areas of science, technology and engineering and their intersection with policy and decision-making. CSTEP's studies do not necessarily reflect the opinions of its sponsors.

Center for Study of Science, Technology and Policy (CSTEP),
CAIR Building, Raj Bhavan Circle,
High Grounds, Bangalore 560001.
Telephone: + 91 80 22373311
Fax: + 91 80 22372619
www.cstep.in

Preface

Dr V S Arunachalam, Chairman, CSTEP

Nuclear energy is once again on the headlines. Not for the concerns that weighed down this technology in the past—and these have not vanished—but for the options it appears to provide for generating electricity without emissions of the greenhouse gas CO_2. The global workhorse for electricity generation today is coal, producing bulk of the electricity, and, in the process emitting over 12 billion Tons of CO_2 annually into atmosphere. Technologies for capturing, containing and sequestering the gas are to yet to become commercial. There are increasing concerns that global warming, due to heat-trapping gases like CO_2 is already beyond control and will only be getting worse, flooding land, turning rich pastures into deserts and making life on earth intolerable. Renewable energy options are still not large enough or commercially viable to substitute coal. What, then, prevents nuclear power emerging to control the unsatiated thirst for more coal?

There are three major concerns: *(i) nuclear weapons proliferation; (ii) perceived high cost of nuclear power, and (iii) safe disposal of nuclear wastes.*

The fuel for nuclear reactors, Uranium 235 and Plutonium are the very materials for making atomic bombs. A few kilograms would suffice to change the benign fuel for power generation into a fearsome weapon for mass destruction. Considering tons of these materials are needed to fuel reactors, how can we be assured that a few kilograms don't get stolen? Fortunately, in spite of over 400 reactors operating in different parts of the globe, this has not happened. For one thing, the physical security systems that are in place, and the internationally accepted procedures that have been erected to account for fissile materials are robust and effective and have secured nuclear fuels from diversion for over decades. There were real fears, when the Soviet Union unfolded, that tons of highly enriched uranium locked in Russian plants and repositories could be smuggled out for the global black market. Fortunately, this has not happened and Russian systems of command and control proved to be robust against smugglers. Even after two decades, no clandestine uranium has surfaced in the underground arms bazaar. There is also a technical safeguard inherent to nuclear fuels. The fissile materials content in fuel rods is always less than the high concentrations needed for making the bomb. These, of course, can be enriched, but would take sophisticated laboratory facilities and knowledgeable technicians and may not easily be available to terrorist groups. The case of nations pursuing weapons development clandestinely is a different case altogether and may not be prevented by shutting off nuclear power stations.

How costly is nuclear power? There are difficulties in obtaining reliable data. The recently conducted MIT study places it around $2 million for a megawatt. Recent quotations form Light Water Reactor manufacturers put the cost up to \$3 million per megawatt. We believe that these estimates are incomplete. Plutonium, extracted from reprocessed fuel, has as a fuel good commercial value and this should be accounted as also the costs of reprocessing. Such an integrated costing has not as yet been done, mainly because the western countries are only interested in the once-through technology, where reprocessing or plutonium extraction is not counted. Preliminary calculations that take into account reprocessing of Pressurized Heavy Water Reactor (PHWR) fuels—as distinct from Light Water Reactor (LWR) fuels that are relatively more difficult to reprocess—suggest that nuclear power when integrated with spent fuel reprocessing and plutonium accounting can be cost competitive to the various renewable energy options that are now being evaluated.[1]

Nuclear waste disposal was seen as a major problem a few decades ago with fears of radioactivity spreading all over the countryside. This has not borne out. The encapsulation technologies where ceramic impervious containers are able to seal radioactive wastes securely and without leaks are proving to be robust and reliable. Even the amount of high activity wastes when properly graded is smaller than originally calculated especially when fuel reprocessing and fast reactors are also integrated into the system. A rough calculation indicates that India, even after following the reactor building campaigns we suggest in this report, will generate just the amount of wastes that France has accumulated and successfully contained in the past five decades.

If India sees nuclear power as an option for generating carbon free electric power in the coming decades, how should it go about building this capability?

This report is prepared in an environment that India will not only have its indigenous technologies and reactors but also imported reactors and materials to choose from. Imports may be inevitable if India is to overcome the constraints placed by its own limited uranium ore reserves. Even for fully realizing its breeder programs, the country would require adequate uranium fuel. This report evaluates various options from total indigenous efforts to a mix of imports and indigenous systems. Breeders are included and become prominent in this analysis and also a sole thorium system. There is also a section comparing our analysis with that projected by the Department of Atomic Energy. Theirs appear to be more ambitious and the underlying assumptions that suggest such an aggressive growth are not available to us. Our analysis suggests that the Planning Commission's target for nuclear power in the coming years can be met, more or less. There is also a short summary on different class of reactors.

---

[1] Wind power is of course cost competitive. But, then, it has its constraints such as location specificity and intermittency of generation.

Even with the aggressive building of reactors—and at one stage suggested in this report, India would be constructing over 15 reactors of 10,000 Megawatts of total capacity in a single year—nuclear power's contribution to country's energy mix could grow to about 20% in the coming decades! But this very pursuit of building adequate fuel reprocessing facilities and breeder reactors will provide India with an energy security in the latter decades of the century. Only solar energy, in spite of our present knowledge constraints in harnessing it, can promise that much, and perhaps more.

Has India got the industrial infrastructure or reserves of workforce available for implementing the ambitious options suggested in this report? It hasn't presently, but is capable of quickly ramping, especially when it comes to manufacturing. The industrial growth in the automobile sector in the past decades and the building of quality are signs of encouragement. The training of human resource is another matter. The mushroom growth of engineering colleges with indifferent teaching and training are sources of concern. But these can be rectified by following the very procedures the Atomic Energy Establishment adopted in its formative years, by running training schools and deputing its scientists and engineers for foreign studies and training. But all these, we believe, are secondary and can be addressed, to the country embarking on a nuclear power mission, similar to what France adopted in the 1970's when it was hit by the oil crunch.

Some politicians have questioned the relevance of nuclear power as it contributes a mere percent or 3% the nation's energy mix. For a perennially energy deficient country like India, every percent matters. Just one percent, decides between illuminating 20 lakh households or plunging them into darkness. We submit that nuclear power has the potential for playing a major role in India's quest for more power.

Contents

Preface -- *2*

Figures -- *7*

Tables --- *9*

Executive Summary --- *10*

Acknowledgements --- *15*

Abbreviations --- *16*

Introduction -- *17*

Domestic Nuclear Program --- *19*

Uranium Requirement and Supply -- **22**

Fuel Fabrication -- **26**

Heavy Water -- **27**

Spent Fuel Accumulation and Reprocessing --- **28**

Fuel Fabrication for FBRs -- **29**

Sodium Requirement -- **29**

FBR and Total Capacity Addition -- **29**

Path of International Cooperation --- *36*

Capacity Addition through LWRs -- **38**

Economics of Light Water Reactors --- 44

Investments -- 46

Organization and Management --- 49

Civil Liability --- 49

Manpower Requirements --- 50

Nuclear Waste Management -- 51

Capacity addition through both LWRs and PHWRs ------------------------------------ *53*

Investments --- **57**

Recent DAE Projections --- *60*

Projections of a largely domestic programme -- **60**

Reprocessing of Spent Fuel -- 62

Metal fuelled FBRs with High Breeding Capability -- 62

Projections with imports enabled -- **63**

***Appendices* ---67**

Brief Description of Reactor Types -- 67

Pressurized Heavy Water Reactor (PHWR) ---67

Fast Breeder Reactors (FBR) ---68

Light Water Reactors ---69

Advanced Heavy Water Reactors (AHWR) --70

***References* --72**

Figures

Figure 1: PHWR Capacity Addition Projections based on NPCIL plans.. 20

Figure 2: Growth in nuclear installed capacity till 2020 as per DAE projections. 22

Figure 3: Uranium (UO_2) requirement of present and future PHWRs. 23

Figure 4: Cumulative fuel (UO_2) utilized in the PHWRs for various capacity factors.. 24

Figure 5: Present and future requirements of heavy water by PHWRs.. 28

Figure 6: Addition of new reprocessing plants.. 31

Figure 7: Total spent fuel reprocessed and stock of spent fuel. 32

Figure 8: FBR and AHWR addition schedule. 33

Figure 9: Cumulative plutonium utilized in the FBR and AHWR till 2030. 33

Figure 10: Impact of metal fuelled FBRs on capacity addition till 2030. 34

Figure 11: Maximum Capacity possible in the domestic program till 2030 35

Figure 12: Several theoretically possible pathways in India's nuclear landscape with international cooperation. 37

Figure 13: Present and future PHWR reactors under safeguards. 38

Figure 14: Uranium requirement of the PHWRs.. 39

Figure 15: Cumulative uranium utilization in PHWRs.. 39

Figure 16: Possible schedule of LWR capacity addition. 40

Figure 17: Imports of Light Enriched uranium (LEU) for the Light Water Reactors till 2030. 41

Figure 18: Cumulative plutonium recovered from spent fuel of LWRs and PHWRs under safeguards. 42

Figure 19: Likely nuclear capacity by 2030. 43

Figure 20: Total capital investments required for the nuclear power program till 2030.. 47

Figure 21: Annual Cost incurred in import of Light Enriched uranium (LEU), Natural uranium and reprocessing of LWR spent fuel abroad. 48

Figure 22: PHWR installed capacity if continued beyond 10,000 MW........ 53

Figure 23: Imports of natural uranium for the PHWRs under safeguards.. 55

Figure 24: Cumulative plutonium recovered from spent fuel of LWRs and PHWRs under safeguards. 55

Figure 25: Likely nuclear installed capacity by 2030. 56

Figure 26: Annual investments required with expansion of PHWR program 57

Figure 27: Breakup of total investments up to 2030 with an expansion of PHWR program 58

Figure 28: Nuclear power projections by DAE with international cooperation 64

Figure 29: Nuclear power projections by DAE with international cooperation (delayed LWR addition) 65

Figure 30: Schematic diagram of a Pressurized Heavy Water Reactor (PHWR)........ 67

Figure 31: Fuel requirements of 700 MW PHWR 68

Figure 32: Fuel requirements of 500 MW FBR 69

Figure 33: Fuel requirements of 300 MW AHWR........ 70

Tables

Table 1: Nuclear power projections by Planning Commission 17

Table 2: Present Nuclear Installed Capacity 18

Table 3: Plants under construction 19

Table 4: New reactors planned till 2020 19

Table 5: Location, reserves and production of uranium in India 26

Table 6: Maximum nuclear capacity achievable by 2030 in domestic program 35

Table 7: Operating characteristics of the Light Water Reactors 41

Table 8: Likely nuclear power capacity by 2020 and 2030 with international cooperation 43

Table 9: Economics of Imported Light Water Reactors 45

Table 10: Cost of electricity generation from some of the operating power plants 46

Table 11: Assumptions of Capital investments required for nuclear program 47

Table 12: Likely nuclear capacity by 2020 and 2030 with an expansion of PHWR program......... 57

Table 13: Nuclear power projections by Department of Atomic Energy 60

Table 14: Comparison of Metal fuelled FBR Capacity Addition 63

Table 15: DAE projections as read from the graph and comparison with this study................... 66

Table 16: Comparison of features of various reactor types 71

Executive Summary

India's growing economy requires an adequate supply of energy. As per several estimates, India's installed electric power generation would have to increase to 650,000 – 950,000 MW by 2030 to sustain economic growth of 8% - 9%. India can thus ill afford to disregard any energy source and nuclear energy is an important source of long-term energy security.

India's present nuclear capacity is 4,120 MW and contributes 3% of the electricity. In comparison, future nuclear growth projections by Planning Commission and Department of Atomic Energy (DAE) suggest the need for a dramatic growth in the coming decades. This study attempts to examine possible scenarios to achieve these growth projections. We consider a two decade time period (up to 2030) as we believe that the focus can be sharper and projections can be more realistic over a shorter time range. We consider two scenarios. In the first, we focus on India's domestic nuclear power program, in the absence of international cooperation. India is not a signatory to the Non Proliferation Treaty (NPT) and has been unable to import nuclear fuel, reactor technology and equipment. In the second scenario, we consider the likely capacity addition with international cooperation. International Atomic Energy Agency (IAEA) and Nuclear Suppliers Group (NSG) have approved India-specific safeguards agreements and permitted nuclear trade and commerce. Once this is ratified by the US Congress, India would be able to freely access nuclear technology, equipment and fuel.

Indigenous uranium resources, as presently estimated, are adequate to support a generation capacity of 10,000 MW in Pressurized Heavy Water Reactors (PHWRs) for about 40 years. Besides electricity, these reactors generate plutonium, which is a good nuclear fuel that can be used to operate Fast Breeder Reactors (FBRs). These FBRs can be designed to generate more plutonium than they consume paving the way to build new FBRs. This would allow expansion of electricity production capacity in the country with the limited uranium available. This is the basis of the second phase of the Indian nuclear power programme. At a later stage, the FBRs could be used to convert thorium, of which we have a plentiful source, into a form of uranium for use as fuel in novel types of reactors. This constitutes the third phase of the nuclear power programme.

Present nuclear capacity is dominated by PHWRs. With the experience gained over the past few decades, the Nuclear Power Corporation of India Limited (NPCIL) is now building PHWRs fairly quickly, in about five years. It has also graduated to larger designs of 700 MW as against 220 MW earlier. Present PHWR capacity is 3,800 MW. Three more reactors of 220 MW are likely to be commissioned shortly. Further, there are plans to complete eight more PHWRs of 700 MW each by 2017. With the completion of these, PHWRs would reach the peak capacity of 10,060 MW. While the reactors are being designed for an operating life of 60 years, domestic uranium resources would last only up to about 2050 with a long term average capacity factor of 75%.

NPCIL is also building two Light Water Reactors (LWRs) at Kudankulam, each of 1000 MW. NPCIL has also planned for six more LWRs, taking total LWR capacity to 8000 MW. There are also two LWRs of vintage design now operating at Tarapur with a combined capacity of 320 MW. The enriched uranium fuel requirement for the LWRs is met by import.

A Prototype Fast Breeder Reactor (PFBR) of 500 MW is currently being built by Bharathiya Nabhikiya Vidyut Nigam (BHAVINI) according to the design developed by the Indira Gandhi Centre for Atomic Research (IGCAR). The Department of Atomic Energy has plans to build four more similar reactors by 2020 taking the total FBR capacity to 2,500 MW.

Bhabha Atomic Research Centre (BARC) has been developing the design of a thorium based reactor to generate electricity known as the Advanced Heavy Water Reactor (AHWR) and hopes to commence its construction very shortly.

DAE's projection of 21,180 MW by 2020 is based on all the above plans being fulfilled. The addition of six more LWRs at Kudankulam depends on international cooperation. If these fail to materialize, capacity addition by 2020 would be limited to 15,180 MW.

Uranium production capacity in the country has not kept pace with the construction of PHWRs. Present production is estimated to be about 360 Tons per year, which is not sufficient to operate the existing reactors at high capacity factors. When the PHWR capacity reaches the peak of 10,060 MW by 2017, uranium production would have to rise to 1,400 – 1600 Tons per year to operate these reactors at 75% - 85% capacity factors. There are plans to increase uranium output to about 600 Tons per year by 2013 mainly from the mines in Jharkhand. Therefore, the balance would have to come from new mines in Andhra Pradesh and Meghalaya within the next eight years or so.

Besides uranium, zirconium alloy is another key material needed for PHWRs for fabrication of the uranium fuel rods and pressure tubes through which coolant flows. About 600 Tons of the alloy is required to meet the annual needs of all the PHWRs, as against the current production level of 150 Tons per year and so early capacity augmentation is necessary.

The country appears to be somewhat comfortable with respect to heavy water availability. With an assumed operation of the plants at 70% capacity, leading to an output of 430 Tons per year and a stock believed to be about 1,800 Tons built up over the years (arising from earlier slow pace of addition of the reactors), no new plants seem necessary until 2030 when some of the older ones would reach the end of their life.

Four FBRs of metal oxide type (2,000 MW) require 12 Tons of plutonium to be recovered from the spent fuel discharged by the PHWRs. About 5000 Tons of spent fuel is estimated to have been removed from all the PHWRs so far. We assume that enough of it has been reprocessed to provide the needed plutonium for the FBTR, the PFBR and experiments with MOX fuel in the Tarapur LWRs and other PHWRs. If we assume that plutonium fuel for future FBRs would come from spent fuel discharged by PHWRs after 2007, the currently available reprocessing capacity seems to be insufficient and only partial realization of the plans is likely.

New reprocessing capacity of 2,100 Tons per year is required to be set up between 2016 and 2019. With this, about 7,500 Tons of spent fuel could be reprocessed to recover 26 Tons of plutonium by 2020. Sufficient allowance is provided for the storage of the spent fuel till the radioactivity levels decrease and for the time needed to recover the plutonium and fabricate the fresh fuel for a new reactor. This could be utilized to start four FBRs after accounting for the plutonium requirements of the 300 MW AHWR. By 2030, 24,000 Tons of spent fuel could be reprocessed to recover about 82 Tons of plutonium. In addition to FBRs, India could choose to build some more AHWRs as thorium program is of long-term importance. In this option, by 2030, FBR capacity would increase to 9500 MW and AHWRs to 1,500 MW.

The FBR needs only an initial supply of plutonium and none thereafter, but the AHWR requires yearly supplements of plutonium. The initial requirement is about 1.75 Tons of plutonium followed by 500 kg per year for the first ten years and 230 kg per year thereafter. If, after the completion of 300 MW AHWR, no further AHWRs are built then the FBR capacity would increase to 11,500 MW by 2030. Therefore, plutonium is better utilized in FBRs and an early deployment of AHWRs appears undesirable until a large number of FBRs have been built.

The PFBR type of reactors is designed to operate with a mixture of uranium oxide and plutonium oxide as fuel because of the extensive experience available the world over with this kind of fuel. They breed plutonium at a very slow rate. FBRs with a metallic alloy of uranium, plutonium and zirconium are known to offer significant breeding. DAE is working on designs that can produce enough excess plutonium to start a new reactor in about nine years and intends to introduce them by 2020. With these FBR capacity could increase to 15,500 MW by 2030. The real impact of this step would be felt in the years after 2030.

In the absence of international cooperation (beyond the Kudankulam reactors), the domestic nuclear program could reach a maximum of 27,760 MW by 2030. This assumes uranium mining of 1600 Tons, total PHWR spent fuel reprocessing capacity of 2300 Tons and early introduction of metal fuelled FBRs and associated fuel cycle facilities.

International cooperation presents India with the opportunity to build many more LWRs. The higher rating of these reactors compared to the currently proposed PHWRs means a welcome larger rise in the share of nuclear energy for the same number of reactors built. Even with an aggressive capacity addition from LWR imports on a turnkey basis, India would still have to do a lot of groundwork in several fields such as site selection, large investments, availability of industrial infrastructure and trained manpower. Assuming a five year construction period, the LWRs could start getting commissioned from 2014 onwards. If India adds two reactors almost every year then up to 15 reactors would be under construction simultaneously for several years. India's total LWR capacity could then go up to about 32,000 MW by 2030. It could be higher if reactors with a larger rating than 1,000 MW are chosen. These reactors import Light Enriched Uranium (LEU). At peak capacity, annual imports of LEU would be about 600 Tons. By 2030, about 8,000 Tons of LEU would be imported.

India has offered 2060 MW of PHWRs to be put under international safeguards. It is reasonable to assume that all future PHWRs would be placed under safeguards. Thus, when the PHWRs reach the peak capacity of 10,060 MW, 7660 MW would be under safeguards and the balance (2,400 MW) outside safeguards. To maximize electricity generation, PHWRs under safeguards could be operated at high capacity factors of 85% with 1,200 Tons year of uranium imported. The reactors outside safeguards could likewise be operated at high CF with 380 Tons year of indigenously produced uranium. By 2030, PHWRs under safeguards would utilize about 21,000 Tons uranium. Reactors outside safeguards would utilize about 9,000 Tons.

About 65 Tons of plutonium can be recovered from the PHWRs under safeguards. This would enable a total FBR capacity of 11,500 MW (assuming that all FBRs built after 2020 are metal fuelled type). Spent fuel from the LWRs is assumed to contain about 11 kg of plutonium per Ton. With higher fuel burn up levels associated with LWRs, we allow longer cooling time of three years and a further two years for reprocessing and fuel fabrication. A little less than 30 Tons of plutonium would become available by 2030 from the LWRs which would enable establishing 4000 MW of FBRs. All together, total nuclear capacity could reach 57,760 MW by 2030 and 182,120 MW by 2050.

In addition to importing LWRs, India could also decide to build more PHWRs going beyond 10,000 MW. There is considerable merit in this option. India could import uranium from international markets and is thus freed from the present constraints of domestic mining and reserves. Second, there is considerable experience of having built several PHWRs indigenously. Natural uranium is cheaper to import than LEU and spent fuel from PHWRs is easier to reprocess. Also, for each ton of uranium used, PHWRs produce more plutonium than LWRs. The PHWR capacity could be increased to 25,360 MW. By choosing this option, the total nuclear capacity could reach 78,160 MW by 2030. This involves the construction of 70 to 100 new reactors, spent fuel reprocessing capacity of 4200 tons, new heavy water plants, FBR fuel fabrication plants and waste management facilities. In this case, the total nuclear capacity by 2050 would also be higher, 285,520 MW.

An examination of the recently built or ordered LWRs shows the capital cost to vary from $ 2 – 3 million per MW, which translates to Rs 9 – 13 Crores per MW. The cost of the electricity generation works out to about Rs 3.18 to 4.32 per unit.

India’s nuclear power program would require overall investments of about Rs 35,000 – 40,000 Crores per annum for about twenty years, equivalent to a total of about $ 160 billion. Over a lakh of trained personnel would be needed for construction and operation of the reactors and associated facilities. Early introduction of courses in nuclear science and engineering in our universities would help meet the requirements to some extent while training courses are also run by the operators of the facilities. Expertise in the field in the Universities would enable airing of independent views on safety aspects.

At the government level, several steps need to be taken expeditiously to realize the full potential of nuclear power. Private sector should be allowed to participate in the building of LWRs and this requires an amendment of the Atomic Energy Act. There should also be appropriate legislations for insurance and civil liability. Management of radioactive wastes from privately operated reactors is another area that deserves attention.

The assumptions used in this study lead to estimates of realizable nuclear power capacities less than those found in the documents and presentations of the DAE.

Acknowledgements

CSTEP is grateful to several outstanding experts who provided key insights, inputs and feedback during detailed interactions. We thank Prof V S Arunachalam, Chairman CSTEP, Dr N Balasubramanian and Dr Rahul Tongia for their valuable suggestions and critical feedback during various stages of the report. We also thank several present and former colleagues for in- depth discussions. For this study, we did not seek or obtain any classified information from the government. We gratefully acknowledge the financial support provided by SSN Educational and Charitable Trust, Chennai. This study is part of CSTEP's on-going research on India's energy and electric power options.

Abbreviations

AEC	Atomic Energy Commission
AERB	Atomic Energy Regulatory Board
AFFF	Advanced Fuel Fabrication Facility
AHWR	Advanced Heavy Water Reactor
BWR	Boiling Water Reactor
CF	Capacity Factor
DAE	Department of Atomic Energy
FBR	Fast Breeder Reactor
FBTR	Fast Breeder Test Reactor
FCF	Fuel Cycle Facility
FRP	Fuel Reprocessing Plants
IAEA	International Atomic Energy Agency
LEU	Light Enriched uranium
LWR	Light Water Reactor
MOX	Mixed Oxide Fuel
NFC	Nuclear Fuel Complex
NPCIL	Nuclear Power Corporation of India Ltd
NPT	Non Proliferation Treaty
NSG	Nuclear Suppliers Group
PFBR	Prototype Fast Breeder Reactor
PHWR	Pressurized Heavy Water Reactor
SDT	Systems Doubling Time
WIP	Waste Immobilization Plants

Introduction

India's growing economy requires an adequate supply of energy. India's future energy requirements and fuel supply options have been assessed by various studies [1-4]. Most studies estimate that the elasticity of GDP with electricity is close to one[2]. Hence, electric power would have to grow at 8%-9% to sustain an equivalent economic growth. Thus, by 2031-32, India's installed electric power generation would have to increase to 650,000 – 950,000 MW for various assumptions of elasticity and economic growth projections [1, 2]. This is 5 – 7 times the present generation capacity of 140,000 MW.

Among the fuel supply options, wind, hydro, biomass and gas even if exploited fully, could contribute 20%-25% of India's future energy requirements[3]. Therefore, coal, nuclear and perhaps solar would have to provide the bulk of India's energy in the coming decades[4]. India's total coal reserves are estimated to be around 250 billion Tons, out of which 95 Billion Tons is proven reserves. Planning Commission estimates that if coal consumption increases at 5% per annum, then economically extractable coal could run out in 45 years. Therefore, nuclear power is crucial for India's long-term energy security. Planning Commission considers the likely growth prospects of India's nuclear power as in Table 1 [1]. A more recent projection from Department of Atomic Energy (DAE) confirms the 2020 target at 21,180 MW [5].

Table 1: Nuclear power projections by Planning Commission [1]

	Optimistic	Pessimistic
2010	11,000 MW	9,000 MW
2020	29,000 MW	21,000 MW
2030	63,000 MW	48,000 MW
2040	131,000 MW	104,000 MW
2050	275,000 MW	208,000 MW

---

[2] Elasticity of GDP with electric power (η) is the % increase in electricity generation required for every % GDP growth.

$$\eta = \frac{\Delta Electricity/Electricity}{\Delta GDP/GDP}$$

[3] India's hydro-electricity potential is 150,000 MW (35% capacity factor). Wind potential is 50,000 MW and is too intermittent (~ 20% capacity factor). Biomass potential is estimated at 18,000 MW from agro-residues and another 5,000 MW from cogeneration in rice and sugar mills.

[4] Most parts of India receive good solar radiation. Using 2 million hectares of land could generate about 500,000 MW. However, intermittency, cost and energy storage issues would have to be addressed.

India's present nuclear capacity is 4,120 MW and contributes 3% of the electricity generated [6](Table 2). In this context, the above projections are staggering numbers and suggest the need for a dramatic growth in nuclear power in the coming decades.

Table 2: Present Nuclear Installed Capacity[6]

Project	Location	Reactor Type	Date of Commissioning	Capacity (MW)
TAPS 1	Tarapur	BWR	28-Oct-69	160
TAPS 2	Tarapur	BWR	28-Oct-69	160
RAPS 1	Rawatbhatta	PHWR	16-Dec-73	100
RAPS 2	Rawatbhatta	PHWR	1-Apr-81	200
MAPS 1	Kalpakkam	PHWR	27-Jan-84	220
MAPS 2	Kalpakkam	PHWR	21-Mar-86	220
NAPS 1	Narora	PHWR	1-Jan-91	220
NAPS 2	Narora	PHWR	1-Jul-92	220
KAPS 1	Kakrapar	PHWR	6-May-93	220
KAPS 2	Kakrapar	PHWR	1-Sep-95	220
Kaiga 2	Kaiga	PHWR	16-Mar-00	220
RAPS 3	Rawatbhatta	PHWR	1-Jun-00	220
Kaiga 1	Kaiga	PHWR	16-Nov-00	220
RAPS 4	Rawatbhatta	PHWR	23-Dec-00	220
TAPS 4	Tarapur	PHWR	12-Sep-05	540
TAPS 3	Tarapur	PHWR	18-Aug-06	540
Kaiga 3	Kaiga	PHWR	6-May-07	220
			Total	4120

To achieve the above projections, India would have to significantly augment its capabilities in a large number of interconnected activities, such as: uranium mining, fuel fabrication, spent fuel reprocessing, site selection, investment decisions and waste management etc. Each of these is a separate subject in its own right and requires an independent and comprehensive study.

In this study, we attempt to examine possible scenarios for India to achieve the above targets. We consider a two decade time period (up to 2030) as we believe that the focus can be sharper and projections can be more realistic over a shorter time range. We also realize that longer term nuclear projections would depend on the technology developments and achievements in the near term in high breeding fast reactor systems and associated reprocessing activities.

In the first scenario, we focus on India's domestic nuclear power program. India is not a signatory to the Non Proliferation Treaty (NPT) and has been unable to import nuclear fuel, reactor technology and equipment. Therefore, India has placed reliance on the domestic program consisting of Pressurized Heavy Water Reactors (PHWR), Fast Breeder Reactors (FBR) and Thorium reactors.

Recently the International Atomic Energy Agency (IAEA) and Nuclear Suppliers Group (NSG) have approved India-specific safeguards agreements and permitted nuclear trade and commerce. Once this is ratified by the US Congress, India would be able to freely access nuclear technology, equipment and fuel. The second scenario presents the possibility of nuclear capacity addition with international cooperation.

Domestic Nuclear Program

India is pursuing the three phase nuclear program. The first phase consists of building Pressurized Heavy Water Reactors (PHWR). In the second phase, the spent fuel from the PHWR will be reprocessed to produce plutonium to be used in the Fast Breeder Reactors (FBR). Finally, the 3rd phase will have reactors using thorium as fuel[5]. India's domestic program now has several reactors under different stages of construction (Table 3) and in addition, several new projects are planned for the coming decade (Table 4).

Table 3: Plants under construction[6]

Project	Location	Reactor Type	First Pour of Concrete	Capacity (MW)
Kaiga 4	Kaiga	PHWR	Mar-08	220
RAPP5	Rawatbhatta	PHWR	Dec-07	220
RAPP6	Rawatbhatta	PHWR	Oct-08	220
KKNPP1	Kudankulam	LWR	Dec-08	1000
KKNPP2	Kudankulam	LWR	Jun-09	1000
PFBR	Kalpakkam	FBR	Dec-04	500
			Total	3160

Table 4: New reactors planned till 2020 [6]

Reactor Type	Capacity	Number	Total Capacity
PHWR	700 MW	8	5,600
FBR	500 MW	4	2,000
LWR	1000 MW	6	6,000[6]
AHWR	300 MW	1	300
		Total	13,900

---

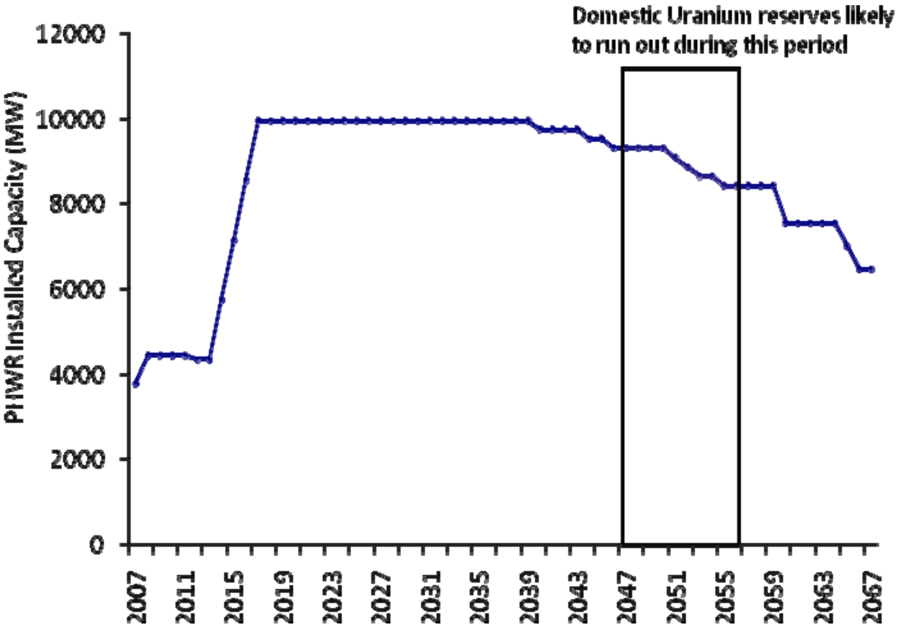
[5] Thorium is a fertile material and needs to be mixed with a fissile material such as plutonium.

[6] In the absence of international agreement, these additional LWRs would not materialize.

India has made good progress in the PHWR program in the last few decades. Nuclear Power Corporation of India Ltd (NPCIL) has standardized the design of PHWRs of 220 MW capacity. India has also successfully scaled up the power to 540 MW reactors operating at Tarapur. Three more PHWRs of 220 MW each are likely to be commissioned during 2008-09. In addition, DAE is planning to build a series of 700 MW reactors before 2020. India has also demonstrated impressive capability in undertaking successfully major repairs and refurbishments of the PHWR systems.

As per the present plan, PHWR installed capacity would reach a peak of 10,060 MW by 2017 (Figure 1). This peak capacity may appear relatively small, but is extremely crucial as it provides a base for a switch to plutonium fuel for FBRs and later for thorium utilization. Subsequently, as the PHWR reactors reach the end of their life (assumed to be 60 years in this study[7]), the PHWR capacity gradually declines. India's domestic uranium reserves are estimated to be 61,000 Tons and this can support a PHWR capacity of 10,000 MW for 40 years[8]. Therefore, India may have to look for additional uranium to run the reactors up to the design life.

Figure 1: PHWR Capacity Addition Projections based on NPCIL plans. PHWR capacity reaches a peak of 10,060 MW by 2017 and then gradually declines as reactors get decommissioned (Reactor life 60 years). If the PHWRs operate at 80% - 90% capacity factors, the domestic uranium reserves are likely to run out in 2047 – 2057.



---

[7] DAE plans to design new PHWRs to have a 60 year life.

[8] Thermal burn up of 6500 MW days per Ton initial heavy metal, 75% capacity factor and electrical efficiency 30%. Thermal burn up is the heat energy released per Ton of initial heavy metal.

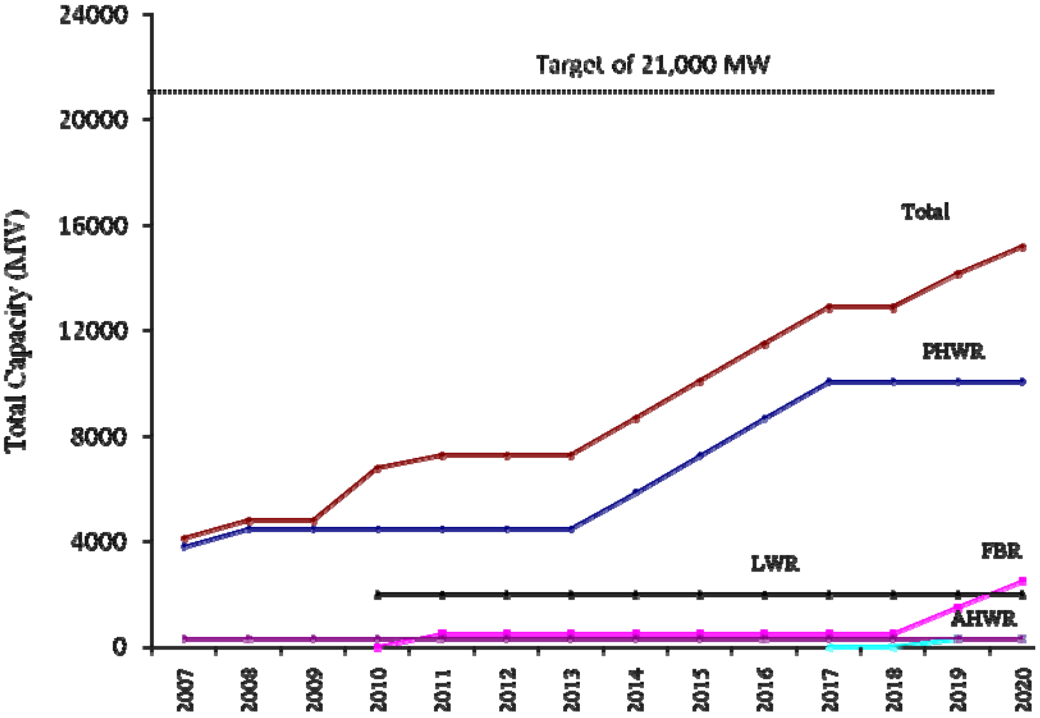
India is building two Light Water Reactors (LWR) of 1,000 MW each at Kudankulam with Russian collaboration. These along with the two operating BWRs at Tarapur depend on imported Light Enriched uranium (LEU). There is also a plan to build six additional LWR of 1000 MW each, but this is subject to an international agreement.

India is also constructing a 500 MW prototype fast breeder reactor (PFBR) at Kalpakkam. This is fuelled by a mixture of uranium and plutonium recovered from the spent fuel discharged by the PHWRs. This reactor initially requires about 3 Tons of plutonium [7]. Once the PFBR begins operation with its own fuel recycle facility, it is expected to generate sufficient plutonium to be self-sustaining. Following the completion of the PFBR, there are plans to build four more FBRs by 2020.

As part of India's long-term objective of the thorium program, there is a proposal to build a 300 MW Advanced Heavy Water Reactor (AHWR) in a few years time. This will operate on a mixture of thorium and plutonium. The reactor needs an initial load (fuel) of about 1.75 Tons of plutonium. In addition to recycling its spent fuel, it also requires an annual reload of 500 kg plutonium for the first ten years and 230 kg thereafter [8].

If all the reactors under construction (Table 3) and planned (Table 4) are completed on schedule, the total installed capacity would reach 21,180 MW by 2020. If the six LWRs indicated in Table 4 do not materialize, then the capacity would be limited to 15,180 MW (Figure 2). Further, as discussed later in the report, the present PHWR spent fuel reprocessing capacity in the country is inadequate to recover sufficient plutonium required for the four FBRs as in Table 4. Without these, the capacity would be further reduced to 13,180 MW. This falls short of the projection of 21,000 MW by the Planning Commission (Table 1) and by NPCIL[5]. The scenario of domestic program beyond 2020 depends entirely on the development of FBRs and this will be examined in the subsequent sections.

Figure 2: Growth in nuclear installed capacity till 2020 as per DAE projections. Cumulative capacity is expected to be 15,180 MW (PHWRs 10,060 MW, FBR 2500 MW, LWR 2000 MW, AHWR 300 MW and BWR 320 MW).



Uranium Requirement and Supply

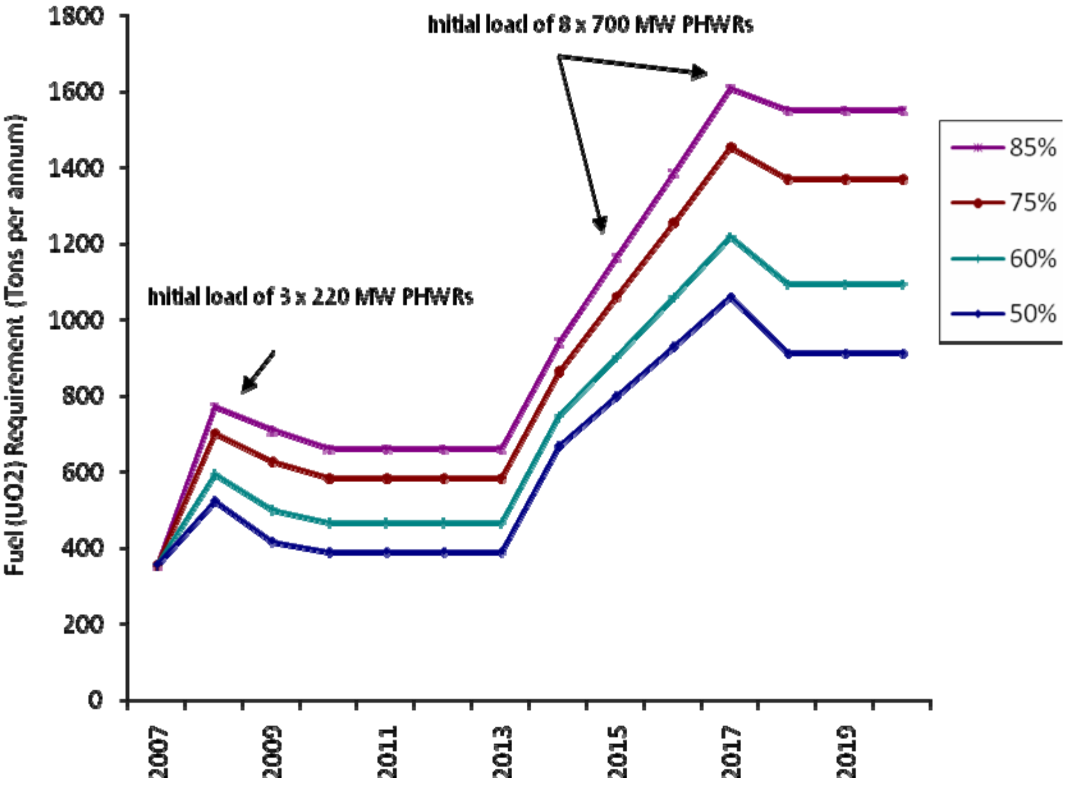
It is crucial to operate the PHWRs at high capacity factors for reasons of economics, fulfilling the energy needs and generation of plutonium for the breeder reactors. This requires an adequate and continuous supply of uranium. Natural uranium production in the country has to rise to cater to the 15 PHWRs already in operation (3800 MW), three more (220 MW) expected to be commissioned during 2008-09 and eight (700 MW) reactors to be commissioned in the coming decade. Uranium production in 2006-07 is estimated at about 360 Tons of UO_2[9], which can support the existing reactors at an average capacity factor of about 50%, generating about 16.6 billion kWh of electric power. To operate these reactors at higher capacity factors, the production would have to correspondingly increase. For instance, capacity factors of 75% and 85% require annual production of 533 Tons and 605 Tons of UO_2 respectively. Clearly, the present production is not adequate to run even the operating reactors at the higher power levels.

---

[9] This is an estimate based on the actual nuclear power generation of 16.6 million kWh during 2006 – 07 and an average Thermal Burn Up of 6500 MW Days per Ton.

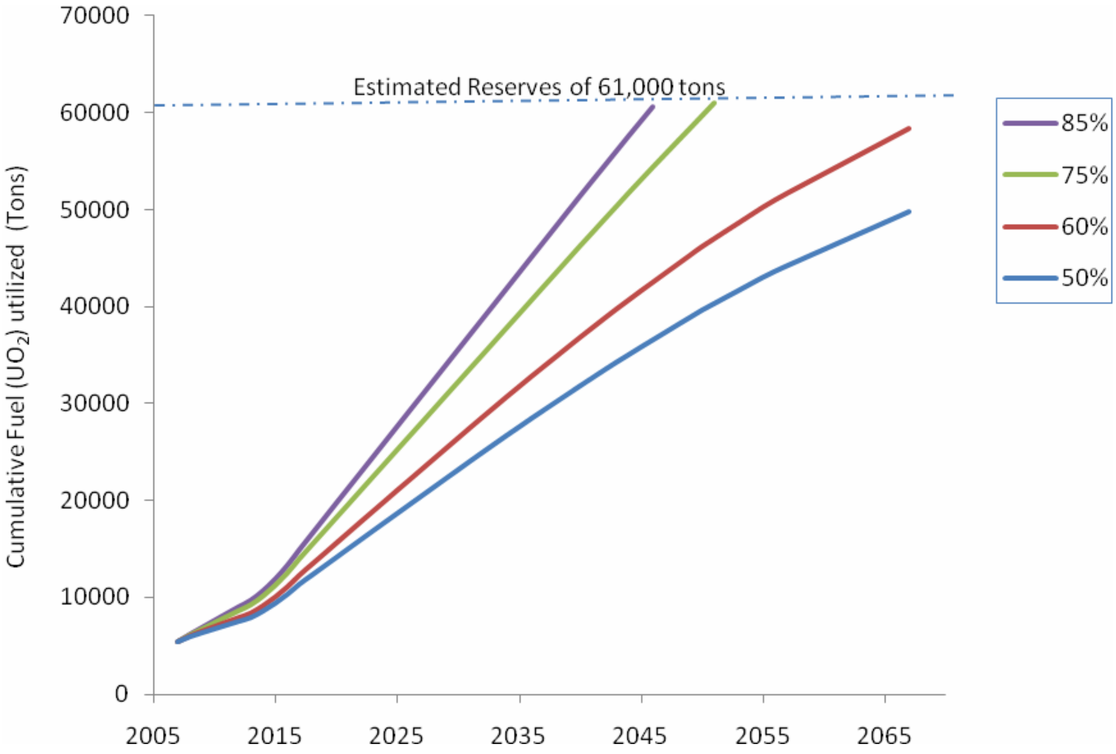
Three new PHWRs (220 MW) are expected to be commissioned in 2008 – 09. These would require an initial fuel load of about 135 Tons of UO_2 in addition to the reload requirements of the existing reactors. Consequently, unless uranium production goes up, the existing reactors will be forced to operate at around 35% capacity factor when the new reactors are commissioned. The first two units of 700 MW reactors are expected to become operational by 2014. These require an initial fuel load of about 280 Tons of UO2. When the PHWR installed capacity increases to 10,060 MW, the annual production would have to grow to about 1,400 Tons and 1,600 Tons of UO2 for operation at 75% and 85% respectively (Figure 3). Thus the present production would have to increase 4 – 5 times over the next ten years.

Figure 3: Uranium (UO_2) requirement of present and future PHWRs. A new 220 MW reactor requires an initial load of about 45 Tons[2]. The 700 MW reactors require an initial load of 140 Tons [2]. Thus, there is a jump in uranium requirement in the year of commissioning of new reactors. At peak capacity (10,060 MW), PHWRs would require 1400 – 1600 Tons uranium per annum for 75% - 85% CF.



If uranium production goes up to meet the requirements of 10,000 MW at 85% capacity factor, then India's estimated reserves of 61,000 Tons (UO_2) would get consumed by 2047 (Figure 4). At lower levels of uranium production supporting 60%-75% capacity factors, the reserves could last up to 2055 – 67. It must be re-emphasized that operation of the PHWRs at high capacity factors is crucial not just for generating more electricity but also for production of plutonium for the breeder program.

Figure 4: Cumulative fuel (UO_2) utilized in the PHWRs for various capacity factors. If the reactors operate at 85% capacity factor, the uranium reserves are likely to run out by 2047. At lower capacity factors (60%-75%), the reserves could last up to 2055 – 67.



Uranium ore found in the country contains uranium (U_3O_8) to the extent of less than 0.1% [10] [9]. At Jaduguda, the ore grade ranges from 0.03% to 0.06% [10]. There are also other places in the world where uranium ore of this grade is being mined[11]. The world average ore grade is about 0.15%. At about 0.05%, which is closer to the average grade of the Indian ore, about 2100 Tons of ore have to be mined and processed to obtain a Ton of UO_2. Therefore, to support the PHWR requirement of 1400 Tons of UO_2, the mining capacity should grow to 9,500 Tons of *ore per day* (assuming 300 days of operation per year).

---

[10] Uranium occurs in the ore as U_3O_8 and this is referred to as “Yellow Cake”.

[11] Olympic Dam polymetallic mine in Australia processes ore of 0.06% grade and produces about 4,000 Tons of uranium per annum. Rossing mine in Namibia processes ore of poorer grade (0.03%) to produce over 3,000 Tons of uranium annually.

Awati and Grover report the availability of uranium in the category of Reasonably Assured Resources (RAR) to comprise 64,400 Tons of U_3O_8 equivalent to 61,500 Tons of UO_2 or 54,600 Tons of metal [11][12]. The AERB cites a higher figure in its National Safety Report compiled more recently and states, "uranium reserves in the country are estimated to be about 95,000 Tons (metal) excluding reserves in speculative category. After accounting for various losses in mining, milling and fabrication, the net uranium available for power generation is believed to be about 61,000 Tons (metal)" [12][13]. This is a rather high estimate for losses during ore processing. If the losses are minimized and speculative resources (17,000 Tons metal) are upgraded, the power potential in PHWRs would be higher[11] .

The details of the location, reserves and production of uranium are provided in Table 5. The Jharkhand region has the country's largest deposits, exceeding 20,000 Tons with an ore grade of 0.03% - 0.067%. A mining capacity of 5000 Tons of ore per day is expected to be available in a few years. The average ore grade being about 0.04%[14], it works out to annual production close to 600 Tons of UO_2. This has to be further augmented by 800 Tons of UO_2 per year from the proposed mines in other areas like Andhra Pradesh and Meghalaya to reach the desired level of 1400 Tons of UO_2 by 2017.

The mines at Lambapur-Peddagattu area in Nalgonda district of Andhra Pradesh are believed to have a modest resource of about 6,800 Tons. According to reports, an open cast mine and three underground mines are planned to be set up here, which would produce about 150 Ton UO_2 per year [13].

The Tummalapalle area in Cudappah district of Andhra Pradesh reportedly contains about 15,000 Tons of uranium (0.042% grade) comparable to the reserves in Jarkhand. An underground mine and associated plant to process about 3,000 Tons of ore per day could yield about 360 Tons of UO_2 per annum [14]. Uranium supply from this mine is likely to begin in 2010.

To meet the needs of the PHWR program, about 300 Ton of UO_2 per year would be required from the proposed mines in Meghalaya In addition to the production from the mines in Jharkhand and Andhra Pradesh as above. The uranium reserves here are fairly substantial at about 9,500 Tons and the ore is of relatively better quality (0.1% grade). The ore is located fairly close to ground making possible the

---

[12] 1 kg of U_3O_8 is equivalent to 0.962 kg of UO_2 and 0.848 kg of uranium metal.

[13] The AERB estimate of 95,000 Tons metal appears to include the three categories: Reasonably Assured Resources, Estimated Additional Resources I, and Estimated Additional Resources II.

[14] Parliament Question 1707

relatively easier process of open cast mining (or in situ leaching). There are reports that a milling capacity of 2000 Tons per day is proposed and the production is likely to commence later than 2010 [15]. It would produce about 600 Tons of UO_2 per year taking the total UO_2 production to 1700 Tons and support the operation of all the PHWRs at about 85% capacity factor. However, the area experiences heavy rainfall during the monsoon season and is also close to the Bangladesh border. These aspects need careful attention for uninterrupted production. Clearly, the production from Meghalaya becomes important if it is desired to operate the PHWRs at high capacity factors. Otherwise, the capacity factor would be limited to about 60%.

Table 5: Location, reserves and production of uranium in India [9]

Mine Location	Estimated Ore Reserves (Tons)	Ore Grade (Tons U_3O_8 per Ton of Ore)	Current Milling Capacity (Tons ore per day)	Possible UO_2 Production [15] (Tons per Year)
Jharkhand: Jaduguda (including Bhatin, Narwapahar, Turamdih, Bagjata, Banduhurang and Mohuldih)	Over 20,000	0.03% - 0.067%	5000 [16, 17]	600
Andhra Pradesh: Lambapur – Peddagattu	6800	0.093%	1250 [15]	150
Andhra Pradesh: Tummalapalle	15,000	0.042%	3000	360
Meghalaya: Domiasat	9500	0.104%	2000 [15]	600
			Total (if realized)	1710

Fuel Fabrication

The Nuclear Fuel Complex (NFC) plant at Hyderabad has the capacity to fabricate 600 Tons of PHWR fuel annually [18]. This can meet the annual needs of all present (3800 MW) and the three 220 MW reactors even at higher capacity factors of 85%. However, this would not be able to cope with the fuel requirements when the 700 MW reactors come on line in the next decade. The Department is proposing to build two more fuel fabrication plants to cater to the future needs, one for PHWRs and the other for FBRs [18]. The new plant for PHWR fuel is planned to be set up at Palayakayal in Tamilnadu with a

---

[15] Estimate based on 300 days of operation per year and an average ore grade of 0.04%.

capacity of 600 Tons per year and will have to be operational by 2014. It might have to be somewhat larger as otherwise it would prove to be inadequate even if operated at near 100% capacity factor, when the PHWR installed capacity reaches 10,000 MW and if the capacity factors are in the range of 85% and above.

Zirconium – Niobium alloy is another key material needed for fuel fabrication. Present manufacturing capacity for this alloy is about 150 Tons per annum[18]. Substantial increase in production is a prerequisite for successful implementation of the PHWR program. When the PHWR program reaches the peak capacity of 10,000 MW, the requirement of zirconium alloy for fuel fabrication would be about 600 Tons per annum. In addition, new 700 MW reactors would also require zirconium for manufacture of coolant channels. A new plant of 250 Tons per annum is under construction at Palayakayal [19]. The capacity of the new plant would have to be appropriately resized to ensure availability of 600 Tons of zirconium in combination with the existing plant at Hyderabad.

Heavy Water

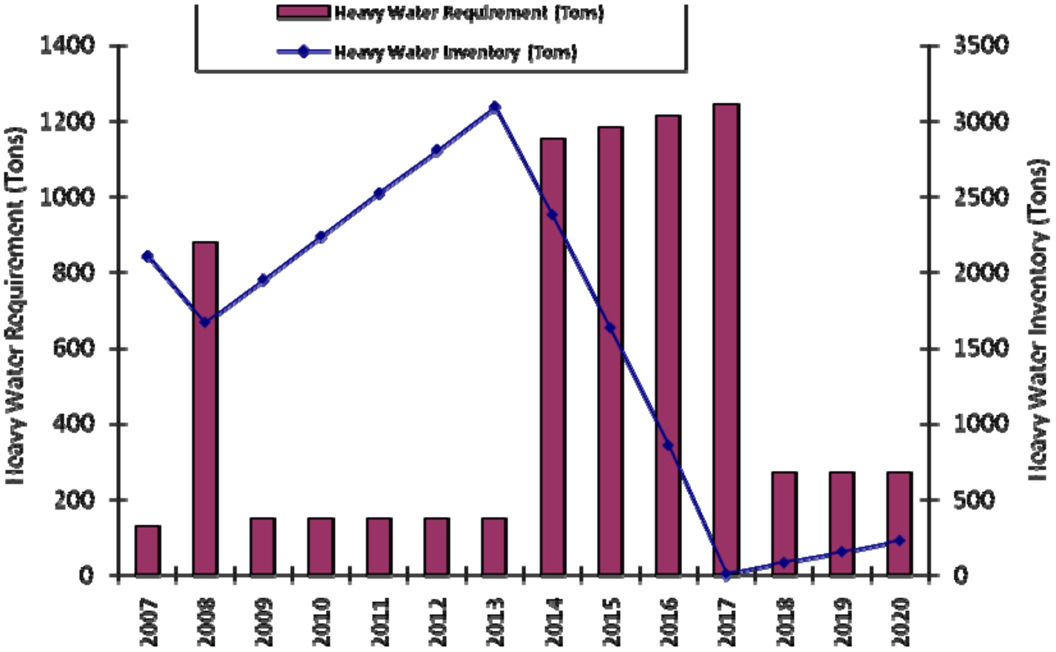
Heavy water plants of the DAE have been operating well for several years now, and have overcome the problems encountered in the very early stages of the program. The total design capacity of existing heavy water plants is about 600 Tons[16] [20] The existing 15 PHWRs (3800 MW) are believed to require a 3% make up of the initial inventory, which works out to 150 Tons per annum. In addition, the new reactors require an initial core heavy water inventory. The three reactors of 220 MW expected to be commissioned in 2008-09 would require about 750 Tons of initial inventory. Similarly, the eight reactors of 700 MW, which get commissioned during 2014 – 17, require a cumulative of 4000 Tons (1000 Tons per annum) leading to a sharp increase during that period (Figure 5).When the PHWRs reach the peak capacity of 10,000 MW, the annual heavy water make up would reach a steady state value of about 250 Tons.

The existing heavy water plants are assumed to operate at 70% capacity factor leading to an annual heavy water production of about 430 Tons. If we take the accumulated heavy water reserves to be about 1800 Tons, it should be able to take care of the heavy water requirements of PHWRs when the peak capacity is reached and in the years beyond. However, some of the old plants (Tuticorin and Baroda) could reach the end of their life (40 years) by 2030 and might be decommissioned. In that case, one new plant may have to be built at some time in the future to meet the heavy water requirement.

---

[16] Heavy Water plants are located at Nangal, Baroda, Tuticorin, Kota, Thal, Hazira and Manuguru.

Figure 5: Present and future requirements of heavy water by PHWRs. The new PHWRs require an initial core inventory (250 Tons for 220 MW and 500 Tons for 700 MW). The annual heavy water make up requirement is taken to be 3%. We assume a present heavy water stock of about 1800 Tons. This along with existing heavy water production capacity could adequately meet the requirements of the PHWR program.



Spent Fuel Accumulation and Reprocessing

Spent fuel generation and reprocessing is a vital step in India's breeder and thorium program. We can make reasonable estimates about the spent fuel generation from all the reactors operating till now. Total electric power generation from nuclear power plants up to January 2008 is 213,370 million kWh[17]. This implies that about 5000 Tons of uranium has been consumed so far by all the reactors operating in the country[18]. This however, represents the minimum value. If actual average burn-up levels were found to be lower, it would lead to proportionately larger quantity of spent fuel. But this will also imply a lower quantity of plutonium in the spent fuel.

There are presently two reprocessing plants, each with a reported design capacity of 0.5 Tons spent fuel per day and an annual throughput of 100 Tons [21]. In this study, we assume that these plants operate at

---

[17] Data compiled from NPCIL website (Plants under operation), http://www.npcil.nic.in/

[18] $\text{Uranium Consumed (Tons)} = \frac{\text{Total power generation (Million kWh)}}{\text{Thermal Burn Up (MW Days per Ton)} \times \text{Electrical Efficiency} \times 24000}$

Thermal Burn Up is taken to be 6500 MW Days per Ton and Electric efficiency of power plants to be 30%.

a conservative 65% capacity factor while any future plants would operate at 75%. The plutonium content in a Ton of spent fuel is taken to be 3.5 kg.

In the absence of published data about the amount of spent fuel that is likely to have been reprocessed so far, we assume that enough of it has been reprocessed to generate plutonium for FBTR power upgrade and the PFBR. Further, significant amount of plutonium has also been used up in fabrication of MOX fuel for irradiation in the BWR reactors in Tarapur and in PHWRs [22]. We therefore, assume that plutonium for any future FBRs would have to be obtained by reprocessing spent fuel generated after January 2008. Any leftover stock of spent fuel may be taken to serve as a reserve, but that could provide enough plutonium perhaps for just about one 500 MW FBR.

As mentioned earlier, India is planning to build four new FBRs by 2020. Sufficient plutonium (12 Tons) would have to be recovered and made available in time for these reactors. Present reprocessing capacity is inadequate and can at best support one 500 MW FBR over the next ten years. New Fuel Reprocessing Plants (FRPs) would have to be built and we examine this in detail in a subsequent section.

Fuel Fabrication for FBRs

The first few cores for the PFBR are likely to be manufactured by the Advanced Fuel Fabrication Facility (AFFF) at Tarapur [23]. Subsequently, the Fast Reactor Fuel Cycle Facility adjacent to the PFBR will become operational to provide reload fuel. As new FBRs come to be built in quick succession, fresh fuel fabrication capacity would have to be augmented to about 10 Tons per annum for fabrication of the initial cores.

Sodium Requirement

About 1,500 Tons of sodium is required for each 500 MW FBR. This has to be available well in time for the commissioning of the reactor. Facilities for manufacture and purification of sodium to the required levels have to be established to cater to the serial installation of FBRs. To meet the requirements of the 4 FBRs planned to be built by 2020, annual sodium production capability of 600 Tons would be needed. This would have to be augmented further for the FBRs which would come up beyond 2020.

FBR and Total Capacity Addition

Planning Commission's projection of 20,000 MW installed capacity is based on two assumptions: six LWRs of 1000 MW each and four FBRs of the PFBR type to be built by 2020. As mentioned earlier, in the absence of international cooperation, the prospects for six new LWRs are uncertain[19]. Therefore, India

---

[19] However, subsequent to the IAEA and NSG approvals, the prospects of these new LWRs coming up are brighter.

must focus on additional FBRs beyond the four already planned FBRs. This depends on enhanced efforts in uranium mining and even more on spent fuel reprocessing.

There are indications that two new reprocessing plants, each of 300 Tons per year capacity are likely to be taken up shortly [24]. It suggests that designs are available and that the plans may be awaiting clearances. These plants when completed will take the total installed capacity to about 800 Tons of spent fuel per annum, or an operational capacity of 580 Tons at a capacity factor of 75% for new plants.

It is generally observed that there is a long time interval between the commencement of design activities and the final commissioning of a Fuel Reprocessing Plant (FRP). Japan initiated basic design for the large Rokkasho Reprocessing plant to be built in private sector, with generous borrowing from the French, British and German technologies in 1985. They selected the technology in 1987, finalized the design in 1988 and approved the proposal for building the new plant in 1992. The commissioning tests began ten years later with help from a French company. Inactive tests with uranium were carried out in 2004-06 and active testing began only in 2007. The Indian situation could be different as considerable experience has been accumulated in the design, construction and operation of two plants so far with no outside help. Selection of suitable sites for the new plants is a key step, which if not done early could result in delays.

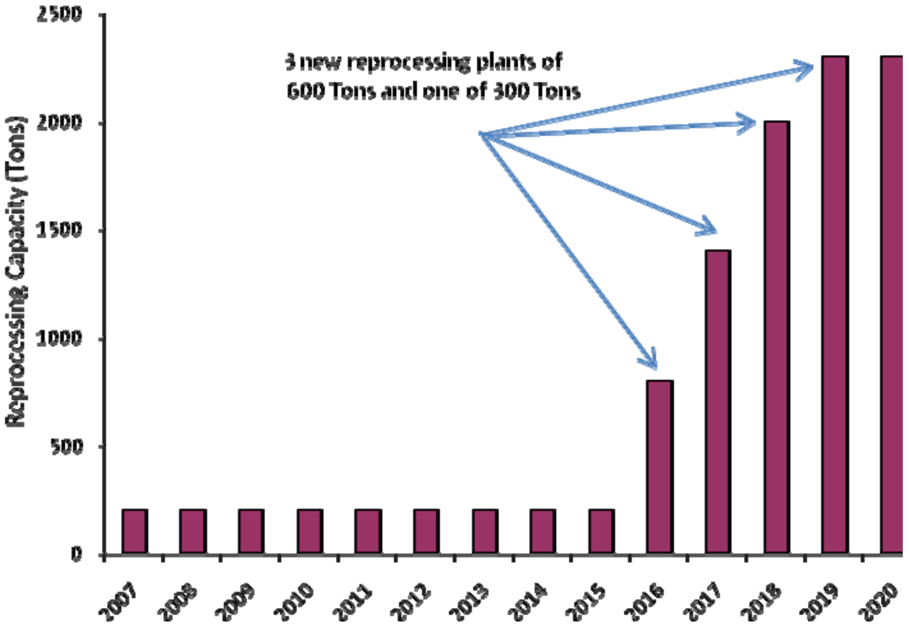
The performance of FRPs varies from country to country and so do the causes for the variation. France claims high capacity factors, followed by UK. In Russia, the plant RT-1 has operated for several years at less than half the design capacity. Therefore, assumptions in this study could be considered relatively optimistic. Unless the performance is in this range or better, the power addition from the fast reactor program could turn out to be less than predicted.

If we assume action is initiated without delay and first of the new reprocessing plants of 300 Tons becoming operational in 2014 and the second in 2018, these plants could cumulatively reprocess about 3500 Tons of spent fuel by 2020 and produce about 12 Tons of plutonium. This would be just enough to cater to the needs of two FBRs of 500 MW and AHWR by 2020. The total installed capacity would then reach only 14,180 MW by 2020.

By 2030, the total spent fuel reprocessed would be about 10,000 Tons yielding 35 Tons of plutonium. This could take the FBR installed capacity to 4,500 MW and the total nuclear capacity to only 16,760 MW by 2030. The eight FBRs together would have utilized 24 Tons of plutonium, while the 300 MW AHWR would consume almost 7 Tons till 2030. About 15,000 Tons spent fuel would still be available by 2030, which if reprocessed could facilitate building more FBRs. Without further capacity addition in reprocessing of spent fuel, the installed nuclear power capacity would be limited to the above level.

Clearly, further expansion of reprocessing capacity is required. We assume that one plant of 600 Tons is established every year for three consecutive years 2016 – 2018 and one more of 300 Tons in 2019. Thus, the total installed reprocessing capacity would be 2300 Tons of spent fuel per annum by 2020 (Figure 6). This would make India's reprocessing capacity the largest in the world[20]. Eventually (by 2019), the corresponding operational capacity at 75% capacity factor of 1700 Tons per year would match the spent fuel generation from PHWRs.

Figure 6: Addition of new reprocessing plants. A new plant of 600 Tons is assumed to be commissioned every year for three years (2016 – 2018) and one more of 300 Tons commissioned in 2019. By 2020, the total installed capacity for reprocessing would go up to 2300 Tons and operating capacity to 1700 Tons.

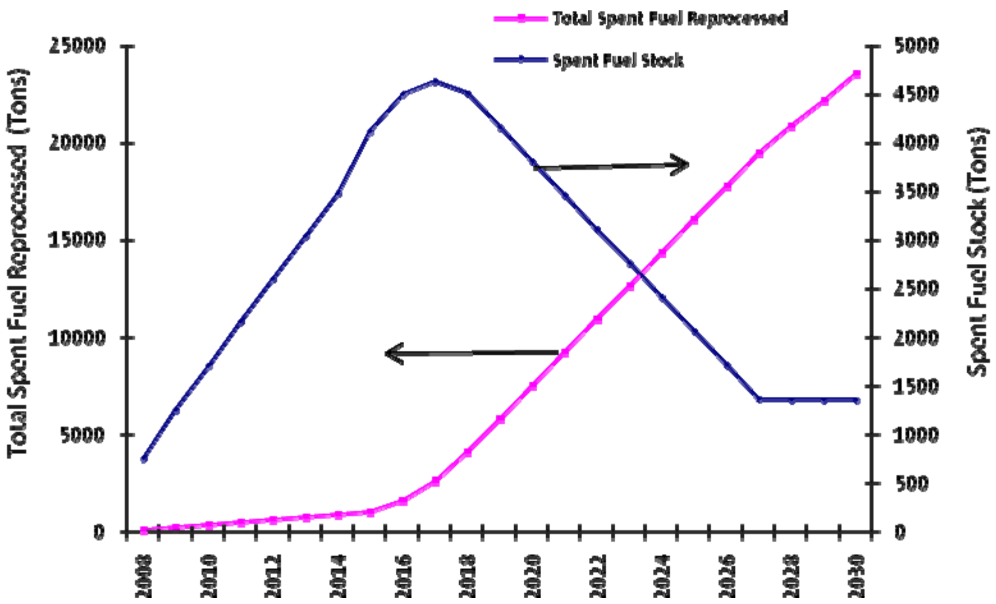


The expanded reprocessing capacity would enable recovery of plutonium from all the accumulated spent fuel by 2026 accelerating the addition of more FBRs. By 2030, a cumulative of 24,000 Tons of spent fuel could be reprocessed to yield about 82 Tons of plutonium (Table 7).

---

[20] France has a reprocessing capacity of 1600 Tons per year.

Figure 7: Total spent fuel reprocessed and stock of spent fuel with a reprocessing capacity as in Figure 6. The spent fuel accumulates while the new reprocessing plants are coming up. However, after 2020, the spent fuel inventory decreases and in steady state it matches with the spent fuel generation.



With such a rapid addition of reprocessing capacity, ten more FBRs could be commissioned taking the cumulative FBR capacity to 9500 MW by 2030. Four more AHWR (each of 300 MW) could also be built in addition to the proposed 300 MW AHWR taking the AHWR capacity to 1500 MW by 2030. It is recognized that thorium program is important for India's long-term energy security. Therefore, even though plutonium could be better utilized in FBRs, it would be helpful to build a few more AHWRs to gain more knowledge and experience of the technology. The plutonium recovered in the reprocessing plants would be almost immediately utilized for fabrication of FBR fuel. Therefore, there would be no stock piling of plutonium; the inventory being limited to about 5 – 6 Tons at the end of every year (Figure 8).

FBRs require 54 Tons of plutonium for an installed capacity of 9500 MW[21] as against 21 Tons for 1500 MW of AHWR (Figure 9). If it is decided not to build four more AHWR (1200 MW), then the FBR capacity could grow up to 11,500 MW (as against 9,500 MW). This is because the four additional AHWRs would consume nearly 15 Tons of plutonium, which could be utilized to start four more FBRs. Therefore, an early deployment of commercial AHWRs appears undesirable until a large number of FBR reactors have been built. If metal fueled fast reactors become available in this period, then plutonium utilization would be more effective in building more FBRs rather than the AHWRs.

---

[21] This excludes the 3 Tons of plutonium already utilized in the 500 MW PFBR.

Figure 8: FBR and AHWR addition schedule. New FBR and AHWR are scheduled to match the plutonium production from the reprocessing plants. By 2030, FBR capacity would rise to 9500 MW and AHWR capacity to 1500 MW. Plutonium stock in any year doesn't exceed 5 – 6 Tons after utilization in reactors.

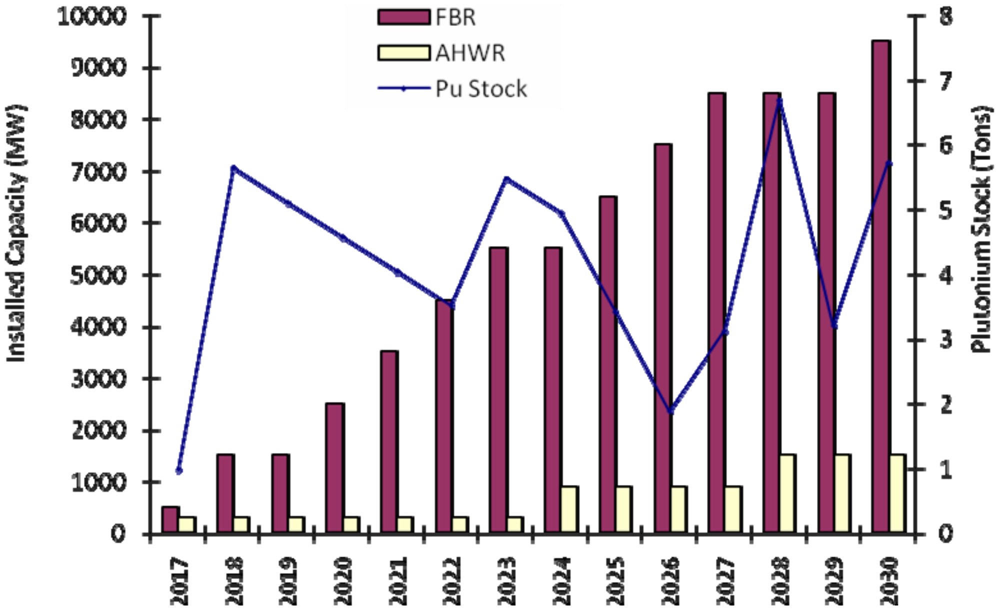
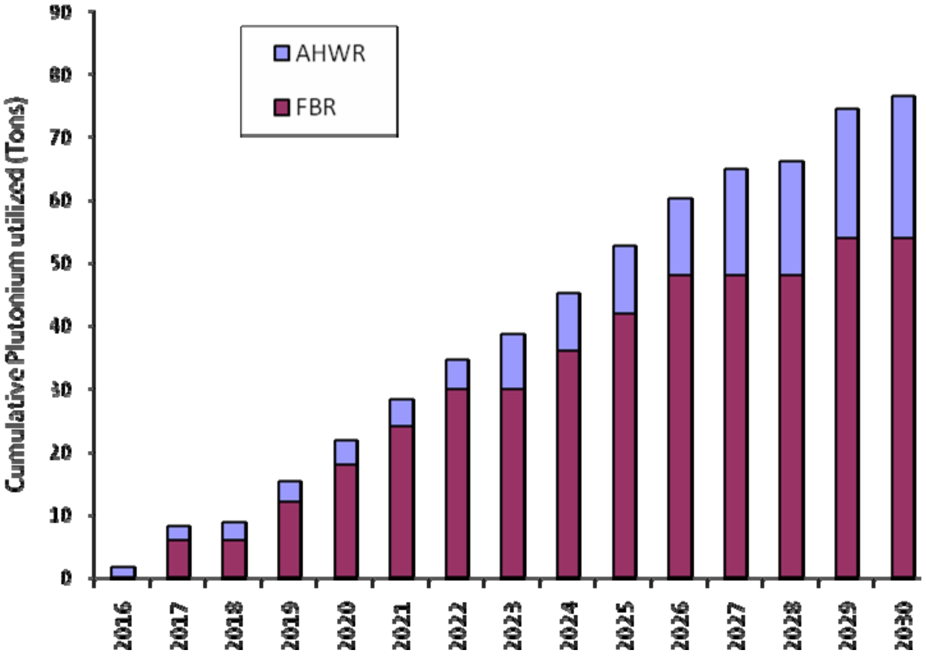
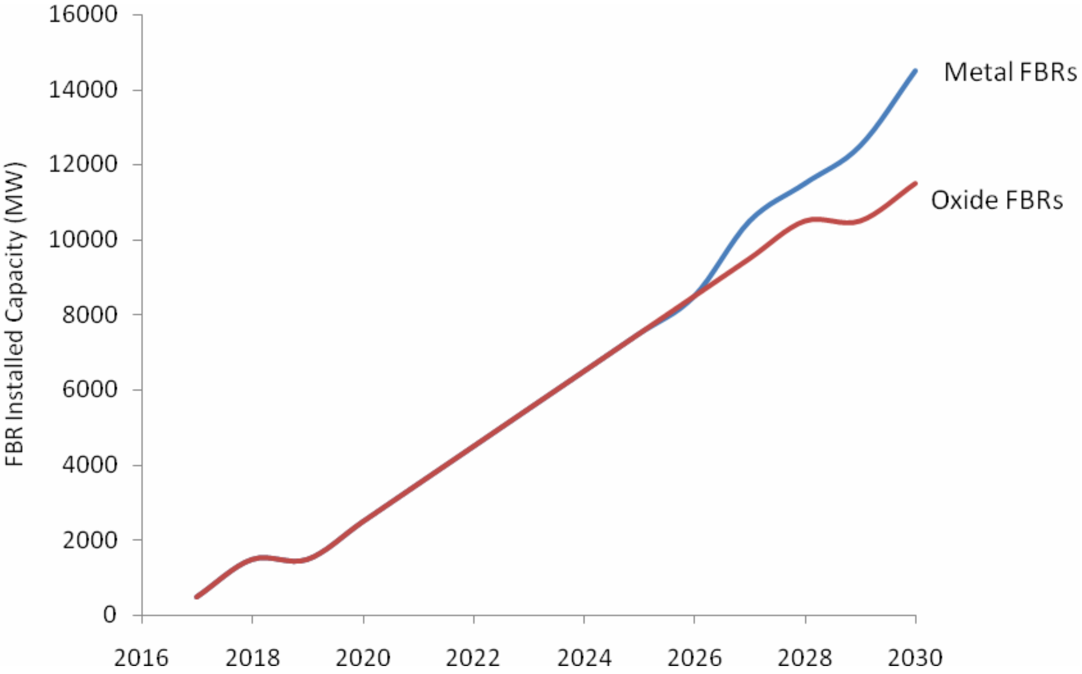


Figure 9: Cumulative plutonium utilized in the FBR and AHWR till 2030. FBRs capacity of 9500 Tons utilizes 54 Tons of plutonium, while 1500 MW of AHWR requires 22 Tons plutonium. If India decides not to build four additional AHWRs, then four more FBRs (2000 MW) could be added.



We now assume that the design of metal fueled fast breeders with a Systems Doubling Time (SDT) of 8.9 years[22] and associated fuel cycle facilities is ready and their introduction can begin from 2020 [2]. However, if there is a starting base of several metal fuelled FBRs, then the pooling of plutonium generated every year by these enables starting new reactors before the SDT. We provide an allowance of two years for cooling and fresh fuel fabrication for a new reactor after reprocessing of spent fuel. In this manner, the total FBR capacity could rise to 15,500 MW by 2030 as against 11,500 MW in the absence of metal fueled reactors (Figure 10). The impact of metal fueled reactors would be realized in the subsequent decades.

Figure 10: Impact of metal fuelled FBRs on capacity addition till 2030.



In this case, the total nuclear installed capacity would be 27,760 MW by 2030 (Figure 11, Table 6). In our assessment, this is about the limit of the domestic nuclear power program till 2030. This is well short of Planning Commission’s pessimistic projection of 48,000 MW. It should be reiterated that even achieving 27,760 MW critically depends on following assumptions and the actual capacity addition would be lower if these are not realized:

---

[22] The Systems Doubling Time (SDT) is defined as the time period (years) during which one reactor would produce excess plutonium sufficient for starting another reactor.

- Uranium mining capability of 1600 Tons per annum from the present 350 Tons
- Spent fuel reprocessing capacity of 2300 Tons per annum from the present 200 Tons
- Introduction of metal fueled FBRs and associated fuel cycle facilities after 2020.

Figure 11: Maximum Capacity possible in the domestic program till 2030. Total nuclear capacity could reach a maximum of 27,760 MW. This assumes spent fuel reprocessing capacity of 2300 Tons per annum and introduction of metal FBRs and associated fuel cycle facilities after 2020.

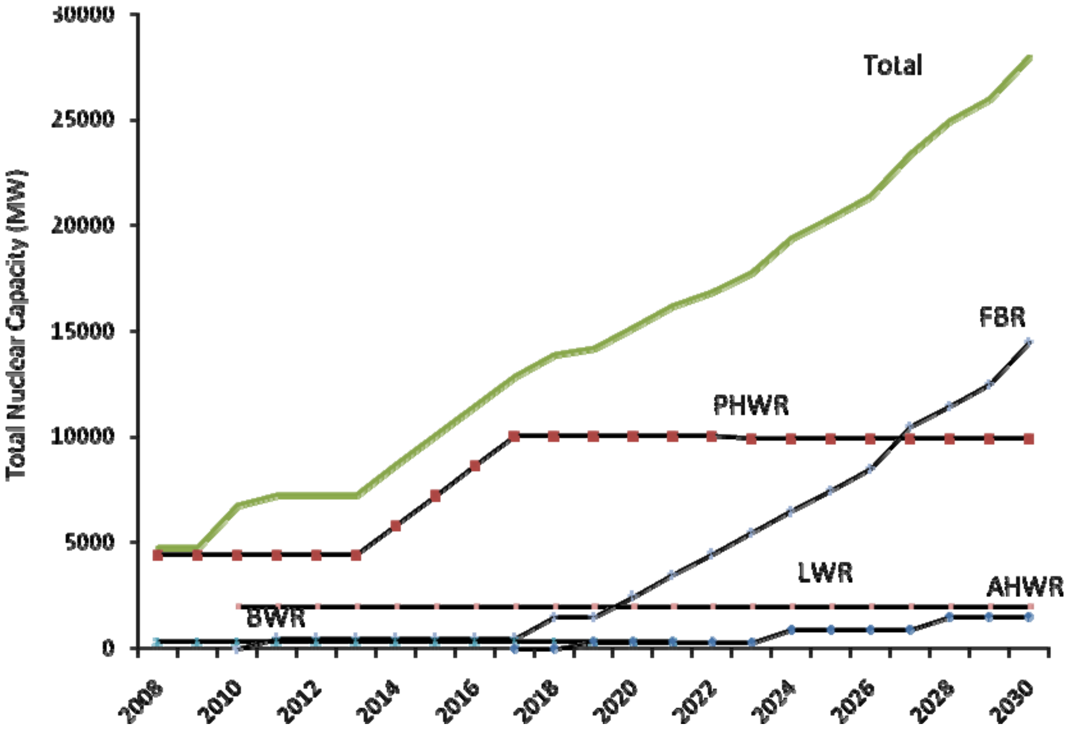


Table 6: Maximum nuclear capacity achievable by 2030 in domestic program[23]

PHWR	9,960
FBR (Oxide)	2,500
FBR (Metal)	13,000
LWR	2,000
AHWR	300
Total	27,760

---

[23] 320 MW BWR at Tarapur is assumed to be phased out by 2021. PHWR (RAPS 1) of 100 MW is phased out by 2012.

Path of International Cooperation

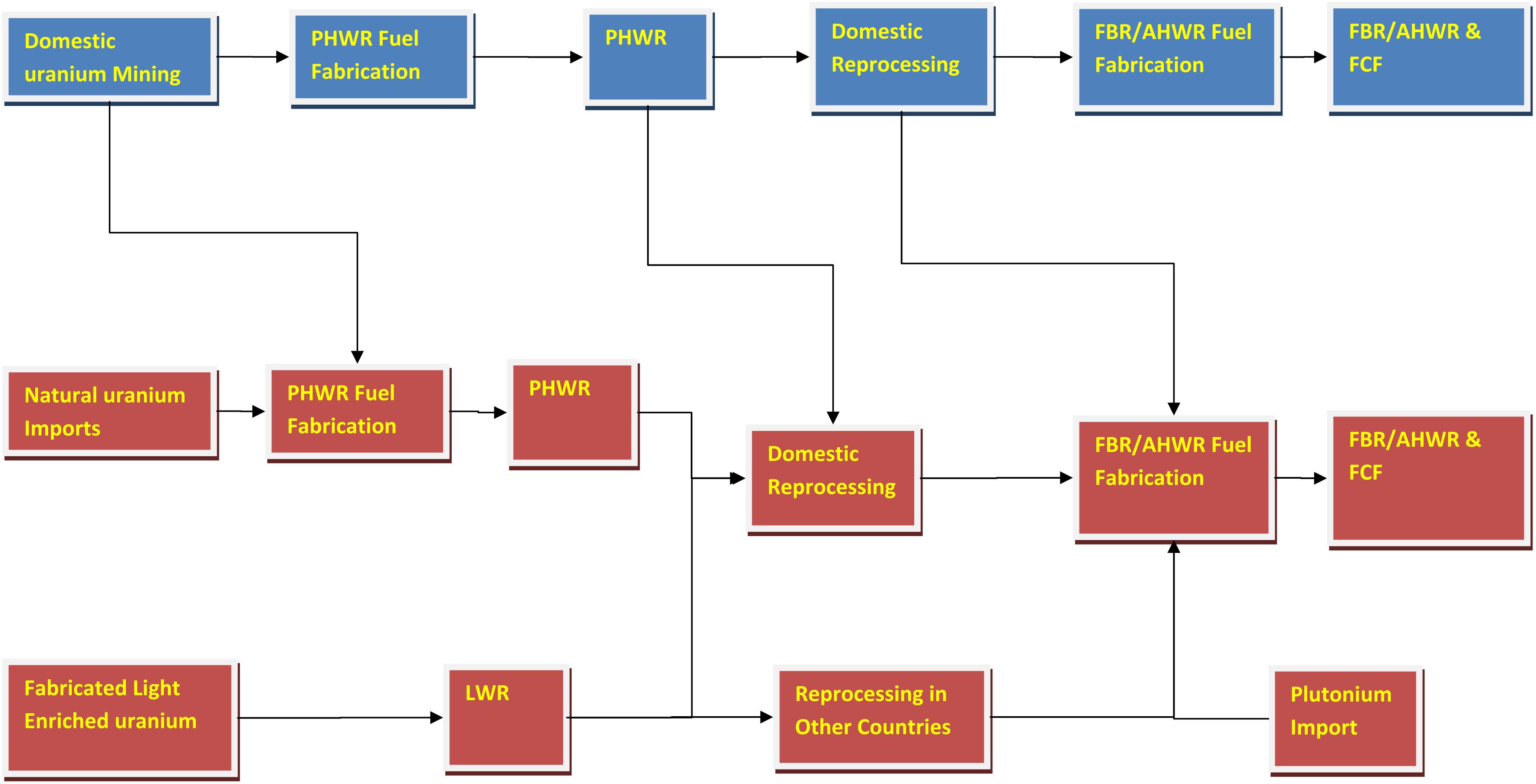
If India receives international cooperation in its nuclear program it could transform the nuclear power landscape by removing the current constraints on the domestic nuclear power program at several levels.

Figure 12 shows several theoretically possible scenarios if India is allowed import of nuclear technology, equipment and fuel. As per the separation plan, India has identified and offered for safeguards 14 thermal power reactors out of 22, between 2006 and 2014. This includes the four presently safeguarded operating reactors (TAPS 1&2, RAPS 1&2) and KK 1&2, which are under construction. In addition, 8 more PHWRs of 220 MW have been placed under safeguards. As for future thermal power reactors, "India has decided to place under safeguards all future civilian thermal power reactors and civilian breeder reactors, and the Government of India retains the sole right to determine such reactors as civilian".

The reactors under safeguards would have the option of using importing uranium fuel or using domestically mined uranium. The possibility of assured fuel supply should enable these reactors to operate at higher capacity factors. The spent fuel from PHWR or LWRs under safeguard could only be reprocessed in a facility under safeguards. Another option is to send the spent fuel abroad for reprocessing. The recovered plutonium could then be utilized in a Fast Breeder Reactor under safeguards.

Cooperation with other countries and import of uranium for safeguarded reactors opens up several options, each with its own merits and limitations (Figure 12). India could, in addition to KK 1&2, build more LWRs under safeguards with foreign collaboration. These reactors use light enriched uranium (LEU), which would have to be imported. In either case, the spent fuel could be reprocessed domestically, in which case several new reprocessing plants would have to be established. Alternatively, the spent fuel could be sent abroad for reprocessing. Another possibility is to seek plutonium or LEU from other countries to fuel reactors in India. In addition, freed from the current limitations of uranium availability, domestic program could be expanded to build more PHWRs to go beyond the present limit of 10,000 MW. We examine two options for the likely future shape of India's nuclear power program.

Figure 12: Several theoretically possible pathways in India's nuclear landscape with international cooperation. Red color indicates an activity under international safeguards. Blue color is for activities outside safeguards.



Capacity Addition through LWRs

In this option, we consider a halt to the present series of PHWRs after the installed capacity reaches a peak of 10,060 MW. if we assume that in addition to the present commitment of 2060 MW , all the eight 700 MW reactors are put under safeguards, then a total capacity of 7660 MW would be under safeguards and 2400 MW outside safeguards (Figure 13). The PHWRs under safeguards would utilize imported uranium and operate at higher capacity factors, enabling increased production of plutonium for FBRs. They would require about 1200 Tons uranium annually to operate at 85% capacity factor (Figure 14). The cumulative imports of uranium for these reactors would be about 21,000 Tons by 2030 (Figure 15). We also assume continuation of the breeder program utilizing the spent fuel from the PHWRs. In this case, a reprocessing capacity of about 1800 Tons per annum (3 plants of 600 Tons per annum each commissioned during 2015 – 17) could be sufficient to reprocess the spent fuel coming out PHWR capacity of 7660 MW. About 65 Tons of plutonium could be recovered by 2030. In theory, even the spent fuel of PHWRs outside safeguards could be reprocessed and the plutonium utilized in an FBR under safeguards. However, we have not considered that option.

Figure 13: Present and future PHWR reactors under safeguards. India has already committed to place 2060 MW of PHWRs under international safeguards. All the proposed new 700 MW PHWRs are assumed to be placed under safeguards. The total PHWR capacity under safeguards goes up to 7660 MW and outside safeguards 2400 MW.

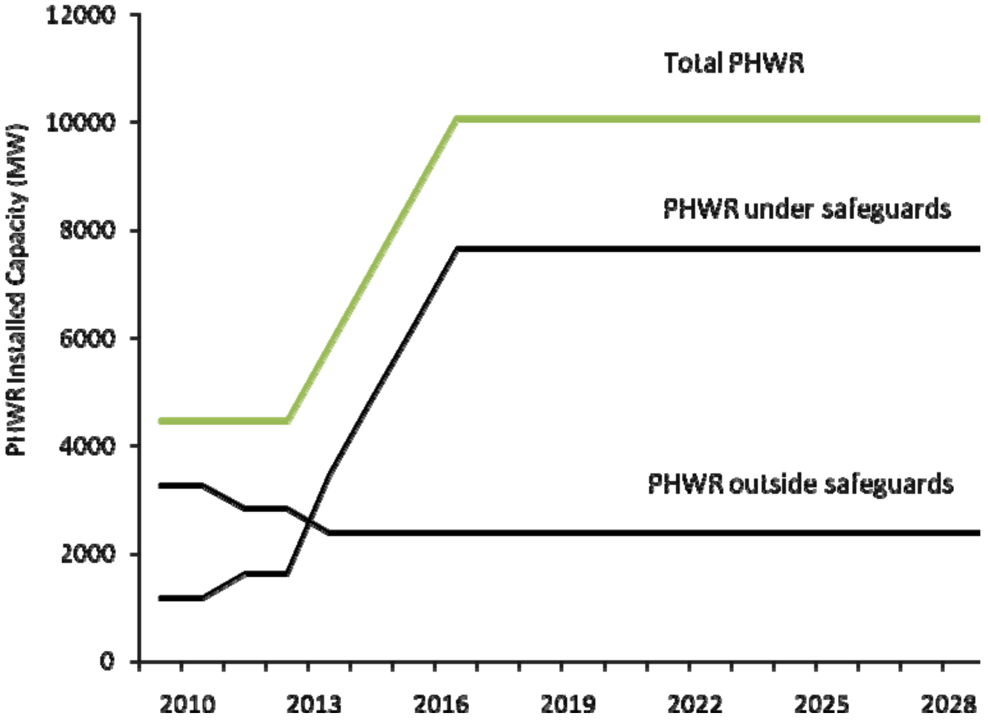


Figure 14: Uranium requirement of the PHWRs. When the PHWRs under safeguards reach peak capacity of 7,660 MW, they would utilize about 1200 Tons of imported uranium per annum at 85% CF. Unsafeguarded reactors (2400 MW) require about 380 Tons uranium from domestic production.

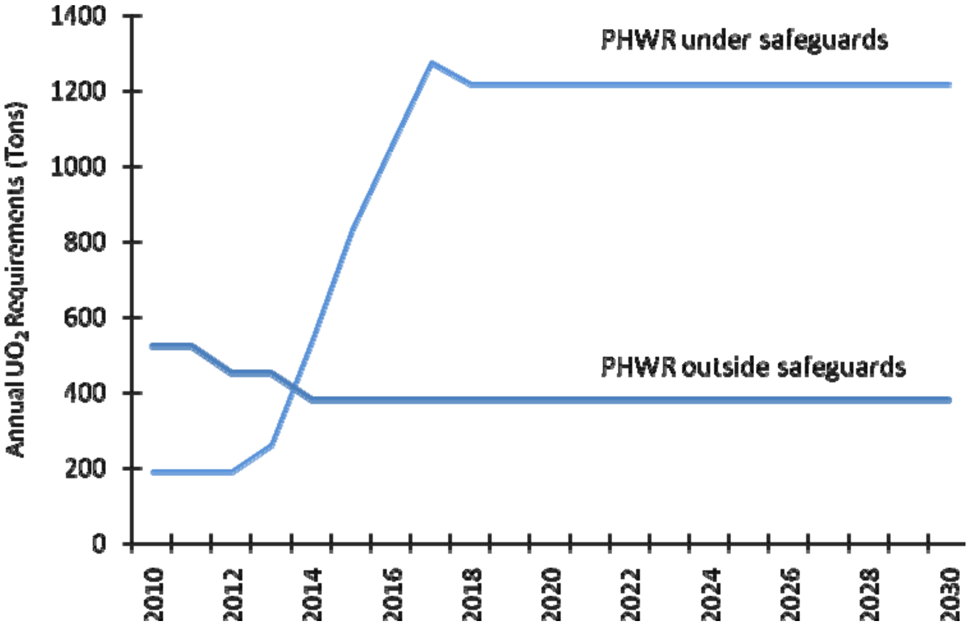
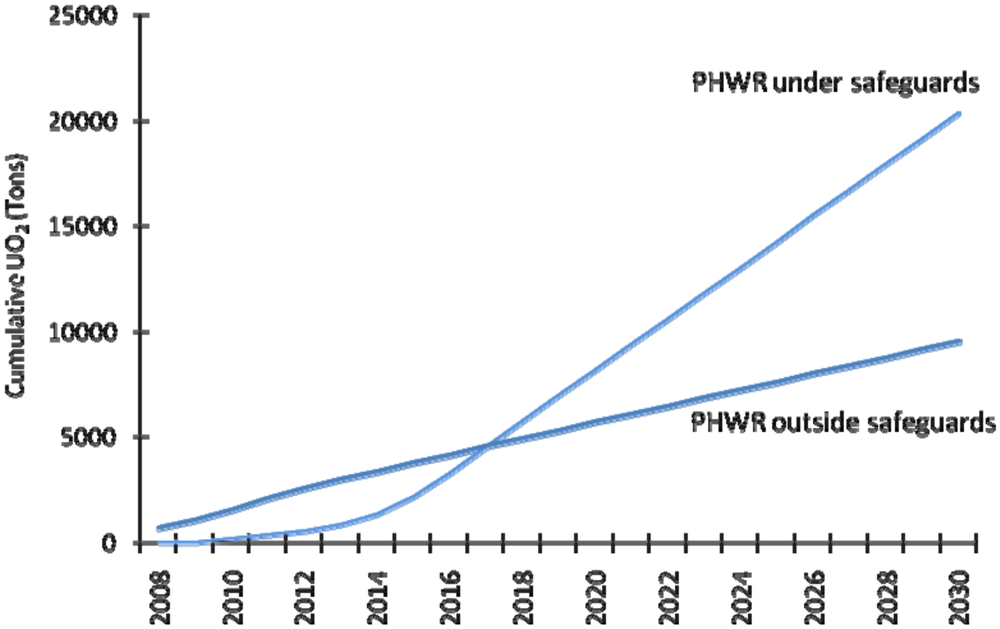


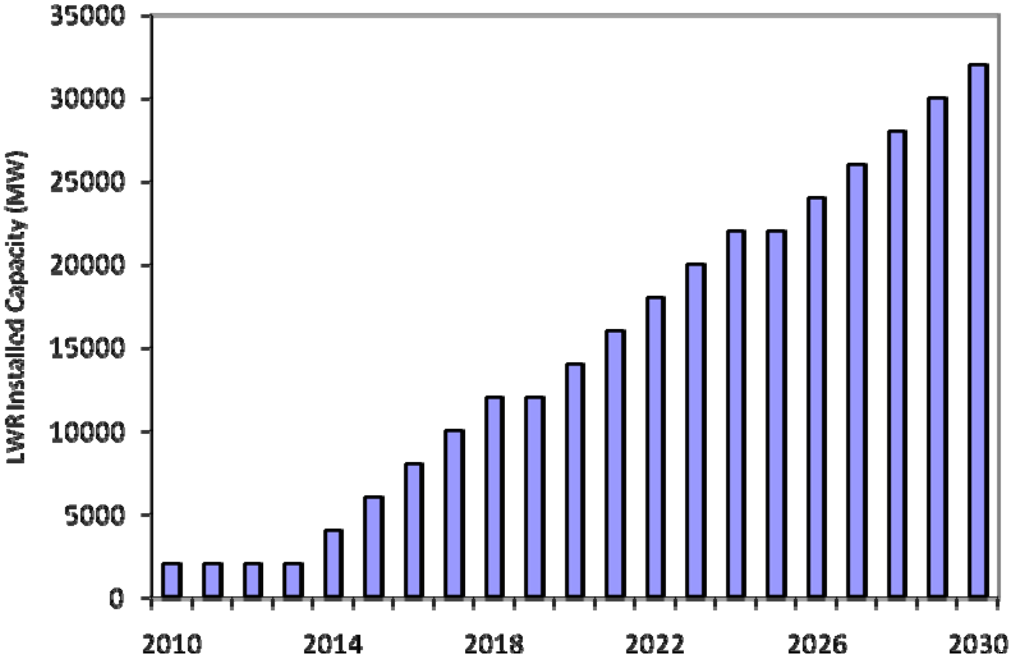
Figure 15: Cumulative uranium utilization in PHWRs. Reactors under safeguards utilize about 21,000 Tons of uranium from imports. Unsafeguarded reactors utilize about 9000 Tons of domestic uranium.



International cooperation presents India with the opportunity to build many more Light Water Reactors (LWR). The higher rating of these reactors compared to the currently proposed PHWRs means a welcome larger rise in the share of nuclear energy for the same number of reactors built. There is keenness on the part of some supplier countries, notably Russia and France to sell LWRs to India. Now that IAEA has approved India specific safeguards and NSG has granted waiver, Russia could possibly build four more LWRs at Kudankulam if the price is competitive.

Even with an aggressive capacity addition from LWR imports on a turnkey basis, India would still have to do a lot of groundwork in several fields such as site selection, large investments, availability of industrial infrastructure and trained manpower. We assume a five year construction period for LWRs and thus the reactors could start getting commissioned from 2014 onwards. If India adds two reactors almost every year then up to 15 reactors would be under construction simultaneously for several years. France at one point of time had 30 reactors under construction and commissioned 9 reactors in 1980. India’s total LWR capacity could then go up to about 32,000 MW by 2030 (Figure 16). We consider this to be a reasonable assessment. It is also possible to import LWRs of higher rating of 1400 – 1650 MW. With a proper mix of reactors of different ratings, the total achievable LWR installed capacity could be higher.

Figure 16: Possible schedule of LWR capacity addition. We assume 5 year construction time. Two reactors are commissioned almost every year. The total LWR capacity reaches 32,000 MW by 2030.

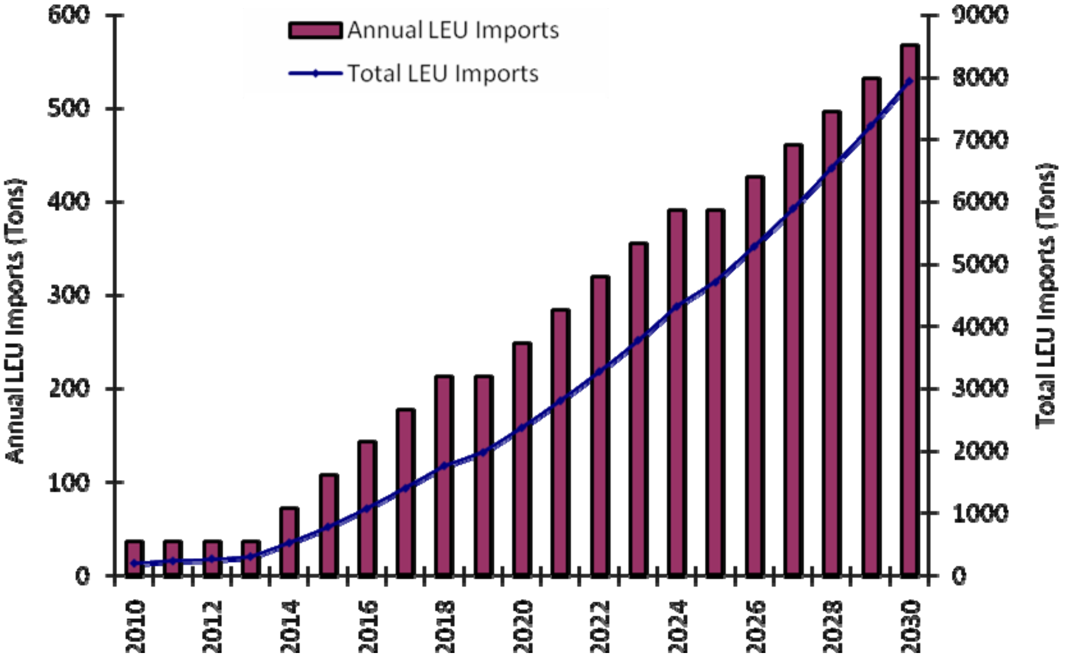


We assume the LWRs to operate at a burn up of 50,000 MW-days per Ton and at 85% CF (Table 7). India would have to import Light Enriched uranium (LEU) to operate these reactors. A new LWR of 1000 MW rating requires an initial loading of 75 Tons of LEU and an annual reload of 18 Tons LEU to operate at 85% CF. When the LWR installed capacity reaches 32,000 MW, the annual operating LEU requirement would be around 600 Tons. India would have imported 8000 Tons of LEU by 2030, including the initial loading of these reactors (Figure 17).

Table 7: Operating characteristics of the Light Water Reactors

LWR Capacity	1000 MW
Burn Up	50,000 MW Days per Ton
Capacity Factor	85%
Initial Loading of LEU (3% – 4% U^{235})	75 Tons
Annual LEU utilization at 85% CF	18 Tons
Plutonium content in spent fuel	11 kg per Ton spent fuel

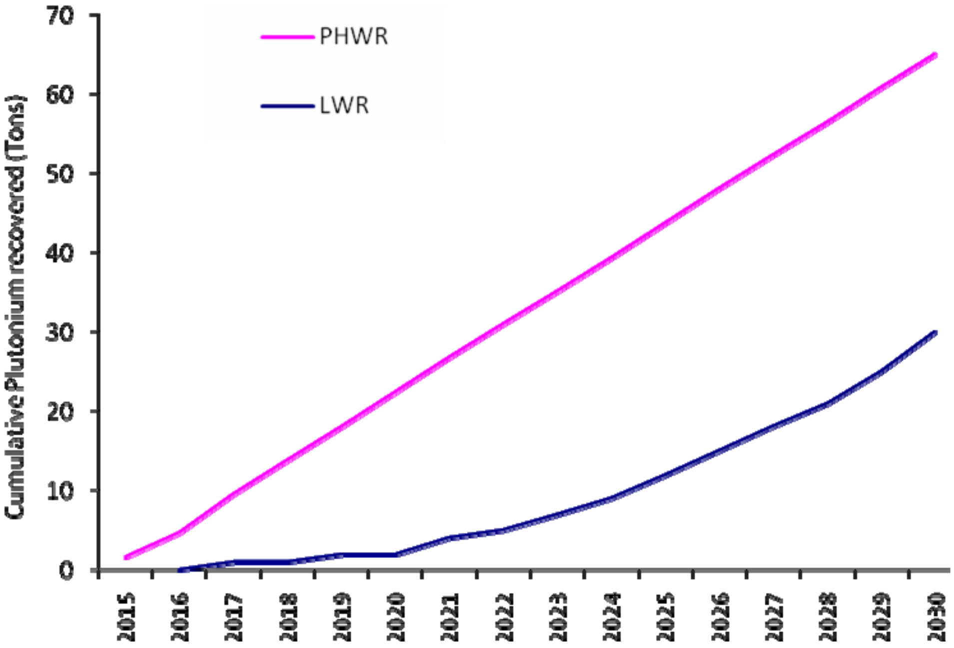
Figure 17: Imports of Light Enriched uranium (LEU) for the Light Water Reactors till 2030. At peak capacity (32,000 MW), LWR reactors require about 600 Tons of LEU annually. Cumulative imports of LEU would be about 8000 Tons.



The LWR spent fuel could be reprocessed to produce plutonium for use in FBRs. However, spent fuel from modern LWR designs has higher radioactivity. This is because, compared to the PHWRs, about ten times more number of fissions occur in the fuel of the LWRs. Hence, LWR spent fuel requires longer cooling times of at least three years to allow the radioactivity levels to drop before plutonium could be recovered for use in FBRs. In this study, we assume that about 11 kg plutonium is recovered from every Ton of LWR spent fuel. It is assumed to be available as fabricated fuel about five years after being discharged from the reactor. The first of the LWRs in Kudankulam is expected to become operational in late 2010. Hence, plutonium from LWR spent fuel would be available at the earliest by around 2019. As of now, there are no facilities for reprocessing LWR spent fuel in India and therefore it may have to be sent abroad.

A recent proposal in the UK suggests that an ‘advance allocation’ of plutonium from the existing stock could be offered against contracts for reprocessing of foreign spent fuel in the country. If the proposal is accepted that could help gain earlier access to plutonium from the LWR spent fuel [25].By 2030, a little less than 30 Tons plutonium could be recovered from the LWR spent fuel (Figure 18), which would be sufficient for starting up 4 FBRs of 1000 MW each. This augments the 65 Tons of plutonium derivable from PHWR spent fuel under safeguards. We assume that the FBRs built after 2020 are metal fuelled type.

Figure 18: Cumulative plutonium recovered from spent fuel of LWRs and PHWRs under safeguards. By 2030, about 65 Tons of plutonium can be recovered from PHWR spent fuel and a little less than 30 Tons from LWR spent fuel.



This scheme could lead to a totaled installed capacity of 27,080 MW by 2020 and 57,760 MW by 2030 (Figure 19 and Table 8). International cooperation thus enables a larger capacity addition than the pessimistic projection of 48,000 MW indicated by Planning Commission for 2030[24]. However, it is emphasized that achieving such a projection depends on PHWR Spent fuel reprocessing capacity of 1800 Tons and LWR spent fuel is reprocessed abroad or domestic facilities are established on time.

Figure 19: Likely nuclear capacity by 2030. The total capacity could be 57,760 MW

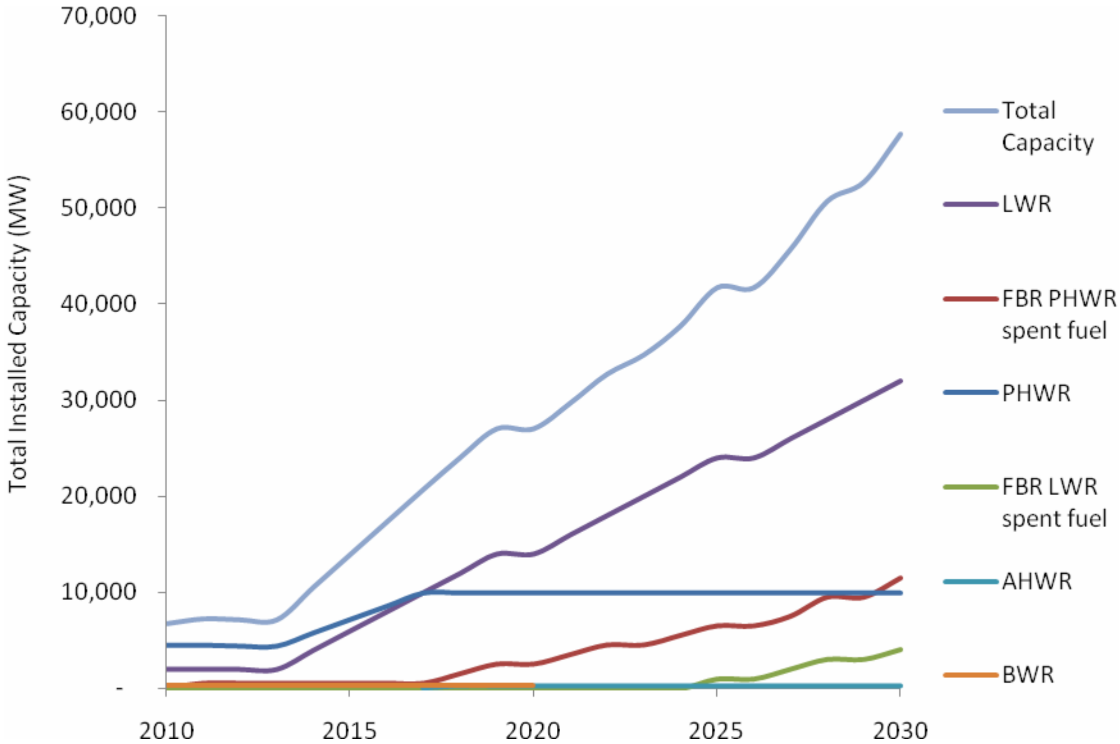


Table 8: Likely nuclear power capacity by 2020 and 2030 with international cooperation

	2020	2030
PHWR	9,960	9,960
FBR from PHWR Spent Fuel	2,500	11,500
LWR	14,000	32,000
FBR from LWR Spent Fuel	0	4,000
PWR	320	
AHWR	300	300
Total	27,080	57,760

---

[24] However, Planning Commission's estimate of 48,000 MW does not consider large-scale LWR imports.

Economics of Light Water Reactors

The nuclear industry is making serious efforts to introduce design modifications and novel construction methods to make nuclear power more economic and safe. While there is significant success in this direction, this has been offset to some extent by recent increase in the cost of materials, equipment and services.

An MIT study in 2003 reported an overnight construction cost of Light Water Reactors of $ 2000 per kW [26]. In May 2008, a report of Cambridge Energy Research Associates (CERA) of US concluded that a power plant that cost $ 1 billion in 2000 would on average cost $2.31 billion in 2008 [27]i.e., a rise of 131%! Recent estimates by NEI, a body reflecting nuclear industry's views, places the overnight cost of new nuclear power plants in the US at $2,400/kW to $4,540/kW. The costs of recently built LWRs as reported in the literature show considerable variation. Overnight construction costs of plants built in Japan and Korea in the period 1994 to 2005 range from $1880 to $2818 per kW [28]. In 2006-07, China built two reactors each of 1060 MW with Russian assistance. These reportedly cost $3.2 billion or about $1600 per kW [29].

In Dec 2006, China signed a contract with Westinghouse for building four reactors of 1,100 MW each at a total cost of $ 8 billion (about $ 1800/kW) [30]. This is believed to include some technology transfer as well. In November 2007, China entered into an agreement with the French firm Areva to build two 1600 MW reactors at a cost of about $ 10 billion (about $ 3120/kW) [31]. The contract includes supply of materials and services to operate the reactors. The press release does not mention the duration of these supplies but it is reported to cover fuel supply for 12 years. China has sold Electricite de France (EDF) a 30% share in the Taishan Nuclear Power Company that will own and operate the reactors. This is presumably to reduce to cost burden and to secure cooperation in handling operational problems as required.

In January 2008, Russian news agency Prime Tass reported that the governments of Russia and Bulgaria have signed a Euro 4 billion ($5.9 billion) deal on the construction of the Belene nuclear power plant consisting of two 1000 MW reactors [32]. In South Korea, the first pair of third-generation APR-1400 reactors is to be built at a cost of $5 billion ($1850/kW) with the first pour of concrete expected in October 2008[33].

With the observed range in capital costs that works out to Rs 9 – 13 Crores per MW, the cost of electricity from LWRs is likely to be Rs 3.18 to 4.32 per kWh (Table 9). In the absence of data to compare the cost of electricity from a new LWR and other types of power plants constructed at about the same time, we examine how the cost from new LWRs compares with that of existing plants of different types (Table 10). The cost of electricity from coal plants is found to lie in a range of Rs 1.44 – 4.82 per kWh, with most values between Rs 2 -3 per kWh[25]. Gas and naphtha based power is found to cost between Rs 2.88 to 7.54 per kWh[26]. As is to be expected, cost of generation of many hydro power plants is well below the range mentioned above, though some of the recent projects in difficult terrain are more expensive (Rs 3.51 per kWh)[27]. The nuclear power costs are found to be quite comparable as they lie somewhere in the middle of the wide range of values cited in Table 10. There could be a further reduction if a large number of LWRs are constructed.

Table 9: Economics of Imported Light Water Reactors [3, 34]

Capital Cost		
Plant Size	1000 MW	Typical LWR capacity
Capital Cost	Rs 9 – 13 Crores per MW	$ 2000 – 3000 per kW
Weighted Average Cost of Capital	10%	Assuming 70:30 debt equity ratio
Decommissioning Charge	Rs 0.45 Crores per MW	
Plant Load Factor	85%	
Interest during construction	20%	5 year construction period
Capital Costs normalized per kWh	Rs 2.28 – 3.42 per kWh	
Operating Costs		
Fuel Cost	Rs 0.16 per kWh	Fabricated LEU cost of $ 1.5 Million per Ton
Other Operating Costs	Rs 0.67 per kWh	
Waste Disposal Cost	Rs 0.07 per kWh	
Total Cost	Rs 3.18 – 4.32 per kWh	

---

[25] Coal based electricity could become more expensive by 50% - 100% from CO2 emission control considerations.

[26] Gas prices exhibit considerable volatility.

[27] Future large hydro power projects will mainly be in Himalayan regions and would encounter high environmental and construction costs.

Table 10: Cost of electricity generation from some of the operating power plants

Name of Power Plant	Installed Capacity	Cost of Generation (Rs per kWh)
Coal		
Anpara, Uttar Pradesh	1000	1.49
NTPC, Ramagundam, Andhra Pradesh	2600	1.44
NTPC, Dadri, Uttar Pradesh	840	2.25
NTPC, Tanda, Uttar Pradesh	440	2.48
Panipat Thermal Power Station (2 x 250)	500	2.47
Indraprastha Power Station, Delhi	247	3.62
Faridabad Thermal Power Station	165	4.82
Panki, Uttar Pradesh	220	3.30
Obra, Uttar Pradesh	550	3.30
Ennore, Tamil Nadu Electricity Board	450	3.80
Hydro		
Bhakra Complex, Punjab	1480	0.13
Chamera, NHPC, Himachal Pradesh	300	1.49
Ranganadi, North Eastern Electric Power Corporation, Arunchal Pradesh	405	1.21
Tehri 1, Tehri Hydro Development Corporation, Uttarakhand	1000	3.51
Gas & Naphtha		
Dadri Gas, NTPC, Uttar Pradesh	830	2.88
Kawas, NTPC, Gujarat	656	5.54
Rajiv Gandhi Kayankulam, NTPC, Kerala	360	7.60
Nuclear (NPCIL)		
Rajasthan	640	1.77
Madras	440	1.39
Narora	440	1.78
Kaiga	440	2.08

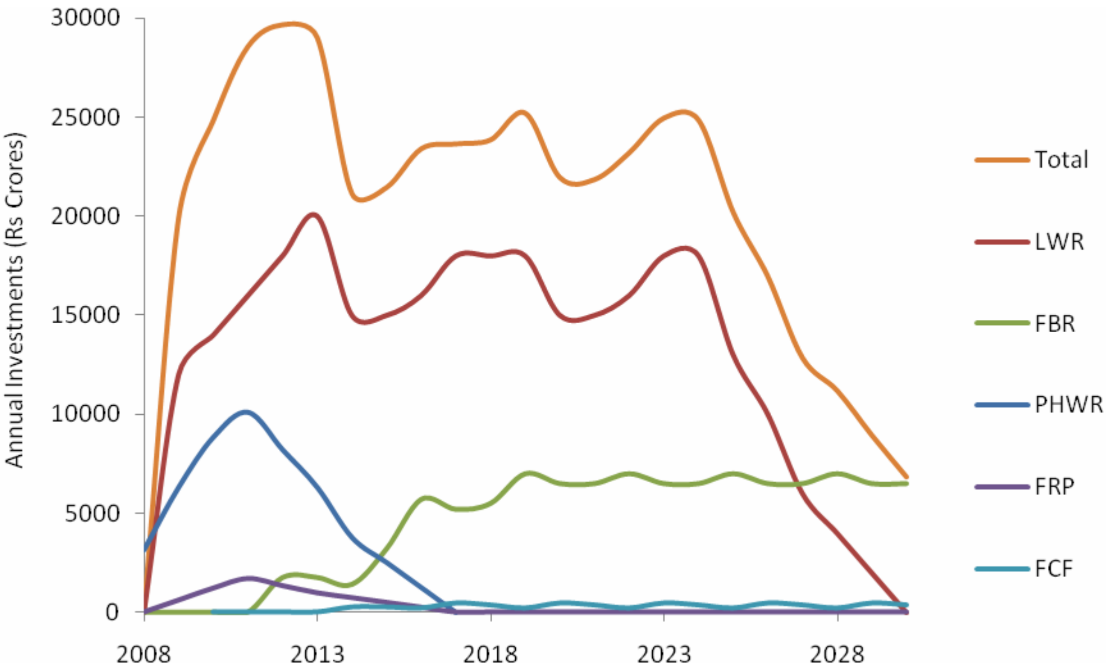
Investments

We now consider the likely investments in the nuclear power program. Table 11lists the assumptions used in this analysis. These may be considered simplistic assumptions; however, they provide a reasonable estimate of the investments required. We consider the investments required to build LWRs, fuel reprocessing plants, PHWRs, fuel fabrication plants, waste immobilization plants and FBRs. To realize the indicated large contribution from nuclear power, an annual investment of at least Rs 20,000 – 25,000 Crores would be required for more than two decades (Figure 20), about 0.5% of India's present GDP. Thus, there is a total investment of about Rs 400,000 – 500,000 Crores in these two decades. During this period the PHWRs and LWRs are completed and thereafter, FBRs continue to be built. Therefore, the annual investments decline in the years following 2030.

Table 11: Assumptions of Capital investments required for nuclear program

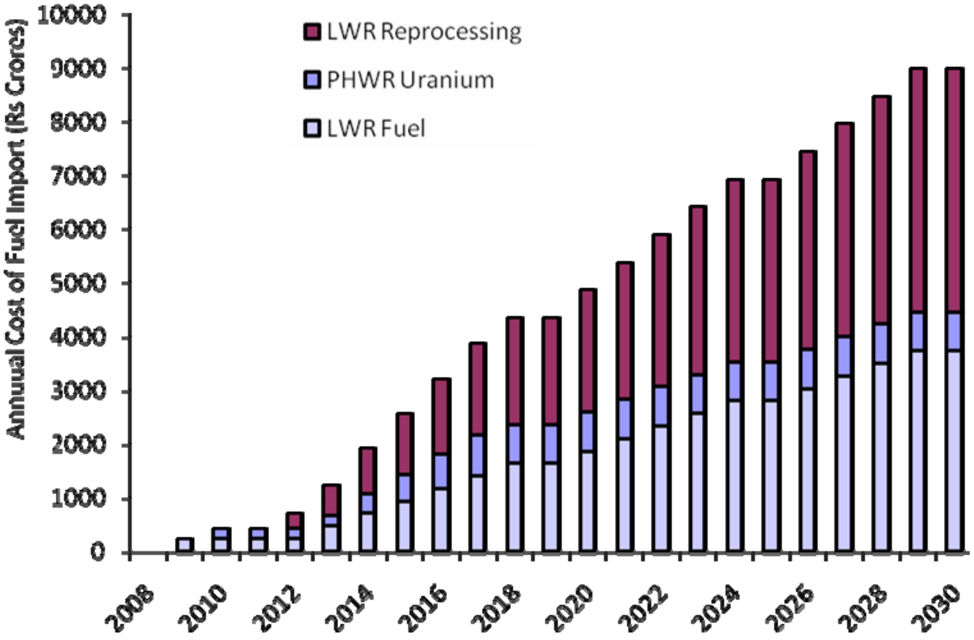
	Overnight Construction Cost	Construction Time	Year wise Cost Breakdown
Light Water Reactors (LWR)	Rs 10 Crores per MW	5 Years	25%, 25%, 20%, 20%, 10%
Fuel Reprocessing Plants (FRP)	Rs 5 Crores per Ton	5 Years	25%, 25%, 20%, 20%, 10%
PHWR	Rs 9 Crores per MW	5 Years	25%, 25%, 20%, 20%, 10%
FBR	Rs 10 Crores per MW	6 Years	25%, 25%, 20%, 10%, 10%, 10%
Fuel Cycle Facility (per 2000 MW FBR)	Rs 1000 Crores	5 Years	25%, 25%, 20%, 20%, 10%

Figure 20: Total capital investments required for the nuclear power program till 2030. India would have to invest about Rs 20,000 – 25,000 Crores per annum.



In addition to the capital investments required to build the reactors and other facilities, India would have to import Light Enriched uranium (LEU) and natural uranium for a reasonable time period to guard against sudden interruptions in supply. In the absence of any plans to set up a large enrichment plant within the country, the stockpile for LWRs would have to be either fabricated fuel or as lightly enriched uranium (LEU). The 60 year lifetime stockpile, as proposed in some quarters, for each 1000 MW LWR amounts to about 1080 Tons of LEU as fabricated fuel. At today's cost, this comes to about $ 1.6 billion for a single plant. If eventual indigenous fuel fabrication is considered, LEU would be imported as uranium hexafluoride gas to be used for fuel fabrication as and when needed. The corrosive nature of the gas warrants attention to long term storage problems. Till such time indigenous fabrication capacity is established, one has to consider potential problems of quality assurance during storage of fabricated fuel. In relative terms, the quantity of fuel to be stockpiled per LWR reactor is about a fifth of that for a PHWR. But, the process of converting the yellow cake into uranium hexafluoride and enriching it to the required level increases the cost of a kilogram of LEU by about 100% over natural uranium. A recent report estimates that natural uranium (as UF_6) costs $300 per kg and LEU (as UF_6) costs $670 per kg [35][28]. The cost of reprocessing LWR spent fuel abroad, if that option is chosen, would also have to be taken into account. Natural uranium prices have exhibited considerable volatility in recent times and we assume a price of $ 150,000 per Ton. The price of imported fabricated LEU fuel for LWRs is reported as $ 1.6 million per Ton. Recently, France has quoted a figure amounting to about $ 2 million per Ton for reprocessing spent fuel from Italy including the cost of transportation and fixing of high level waste in glass. Figure 21 gives the details of combined cost of importing fabricated fuel for LWRs, natural uranium for PHWRs and reprocessing of LWR spent fuel abroad. This reaches a maximum of about Rs 8000 Crores per annum by 2030. LWR fuel accounts for bulk of this cost and natural uranium imports account only about 10%.

Figure 21: Annual Cost incurred in import of Light Enriched uranium (LEU), Natural uranium and reprocessing of LWR spent fuel abroad.



---

[28] This depends on the U235 content of the depleted uranium left behind after the enrichment process is complete.

Organization and Management

As India’s nuclear power program grows with a large number of reactors being built, it is important to examine whether all of them could or should be under one operating organization. In France, all 59 reactors come under Electricite de France, which is somewhat similar to a Public Sector Undertaking (PSU) in India. The 37 reactors in Japan were built and are operated by nine different utilities in the private sector. Several utilities in the US own and operate the 104 reactors. There are 17 reactors now in operation in China with 6 more under construction. Seven companies have undertaken the construction and operation of these reactors. These companies too appear to be somewhat similar to the Indian PSUs.

For rapid expansion of the nuclear power program, it is desirable that the government encourages participation of the private sector after establishing an effective regulatory mechanism to ensure safety and security. There are several activities relating to the front end and back end of the fuel cycle that would have to be undertaken by the government. With its established expertise, DAE could continue with the PHWR, FBR and AHWR programs and the private industry could participate in the LWR program. The government would have to amend the Atomic Energy Act to allow the entry of private industry in nuclear power. The legislative procedure would take its own time and therefore, in the meantime, PSUs such as National Thermal Power Corporation (NTPC), Bharat Heavy Electrical Limited (BHEL) and Nuclear Power Corporation of India Ltd (NPCIL) could be allowed to build LWR with foreign collaborators. Several other issues would need to be addressed: civil liability arrangements, cost and purchase agreement of the power generated, value of plutonium produced and charges for services like ultimate waste management and decommissioning.

The entry of private players would also have an impact on safety regulation. Going by the experience of other countries, AERB would have to ensure that that safety is not compromised either because of a large number of reactors under construction or due to cost considerations. At the same time, AERB may benefit by charging the private sector players for the services. The Nuclear Regulatory Commission in the US is obligated by law to recover 90% of its expenses from licensees [36] However, it would also require timely clearances without undue delays. If safety is well regulated, the presence of more than one player might also lead to a healthy competition in all aspects including safety.

Civil Liability

Despite the elaborate safety and protective measures, operators of nuclear plants are required to consider the likelihood of accidents that could cause some form of damage to the public and property. Some form of insurance therefore becomes necessary. By common convention, it is the operator who is liable exclusively, both legally and economically, in most countries even in force majeure conditions. The designer of the systems or the supplier of equipment or materials is not liable except in some case of accident during transportation. With the possible entry of private operators in the nuclear power, it is essential to establish measures for clear liability arrangements. Most countries are party to one or both of two international conventions on civil nuclear liability, one known as the Paris Convention and the other the Vienna Convention. There are also some countries, Japan for instance, that are not party to any convention but have national laws that generally conforms to the provisions of the conventions. Both the conventions require the operator to establish financial security in the form of insurance or other resources and the State makes a contribution over and above that.

These conventions prescribed an overall liability level of 360 million Euros. In 1997, Member States of IAEA adopted a Convention on Supplementary Compensation that defined contribution by the respective States of an equal value. India is not a party to this Convention. More recently the Paris convention has set new limits of €700 million for the operators, €500 million from public funds by the State and a collective contribution of member States of €300 million. This has not yet entered into force.

Manpower Requirements

The nuclear program would require the training of a large number of personnel for reactor construction and operation. The construction of a twin reactor power station requires about 1000 personnel of various education levels and its operation needs about 800 personnel. Therefore, the nuclear program would require close to 100,000 personnel in the coming two decades. These would have to be trained in India or abroad. Some of them could be trained abroad. However, in the long run, India would have to significantly augment the training facilities in the country to cater to construction and operation of the large number of PHWRs, FBRs, AHWRs as well as the LWRs and FRPs. To accelerate induction, engineering institutions will have to run special courses in these subjects. The country went through a similar experience a few decades ago when many new steel plants were built at the same time. The universities came forward by training a large number of engineers. We have to repeat this experience; fortunately we have far more public and private educational institutions to depend on.

There is some concern in the US about the likely shortage of trained manpower with nuclear skills at various levels to support revival of nuclear power. This may evoke some surprise since there are at least 14 Universities that offer courses in Nuclear Engineering and many of these also have a research reactor in the campus to help train the students. Clearly the challenge is in finding personnel with relevant training could turn out to be a more formidable one in India where presently the various units of the DAE are the only places with required training facilities.

An NEA/OECD publication of 2003 on ‘Nuclear Education and Training’ speaks of worrying erosion of the knowledge base. Some of the recommendations made in the report are equally valid for India where we need a significant expansion of the existing resource and expertise to cater to the ambitious program that is being charted for harnessing nuclear energy. Urgent efforts have to be made to set up facilities for education in nuclear science and engineering in the universities. Educational network or bridges have to be developed between Universities, Industry and Research Centers in the DAE. Generous investments could be made by Industry for University R&D Projects and by the Government for experimental facilities like research reactors for research as well as education. The Governmental support becomes particularly important in all R&D activities relating to development work in the fields of reprocessing, reactor engineering, metal fuelled fast reactors and if eventually an indigenous design of the LWRs is envisaged.

Nuclear Waste Management

Presently, the responsibility for operations relating to management of radioactive wastes from all nuclear installations is with BARC. This is in addition to undertaking development of appropriate methods and techniques for the safe management of the wastes. This has worked well because of the relatively small size of the program.

As the nuclear power program expands and a large number of reactors are built at different locations in the country, quite possibly in both the public as well as the private sector, measures must be in place for coordination of steps for safe management of the radioactive wastes generated by the various facilities. The general practice as in many countries is to entrust the responsibility for waste management to a single governmental agency.

On average, the volume of low and intermediate level radioactive waste generated in one year by different reactor types normalized to a power level of 1,000 MW is as given below [37]:

BWR	500 m3
PWR	250 m3
PHWR	200 m3

According to the World Nuclear Association, a typical large (1000 MW) LWR will generate 200 - 350 m3 low and intermediate level waste per year. (Morris Rosen: 200 m3 low level, 70m3 intermediate level). The approach currently adopted is to store the operational wastes of the reactors at the respective sites. They are expected to remain there even after the reactors reach the end of their life.

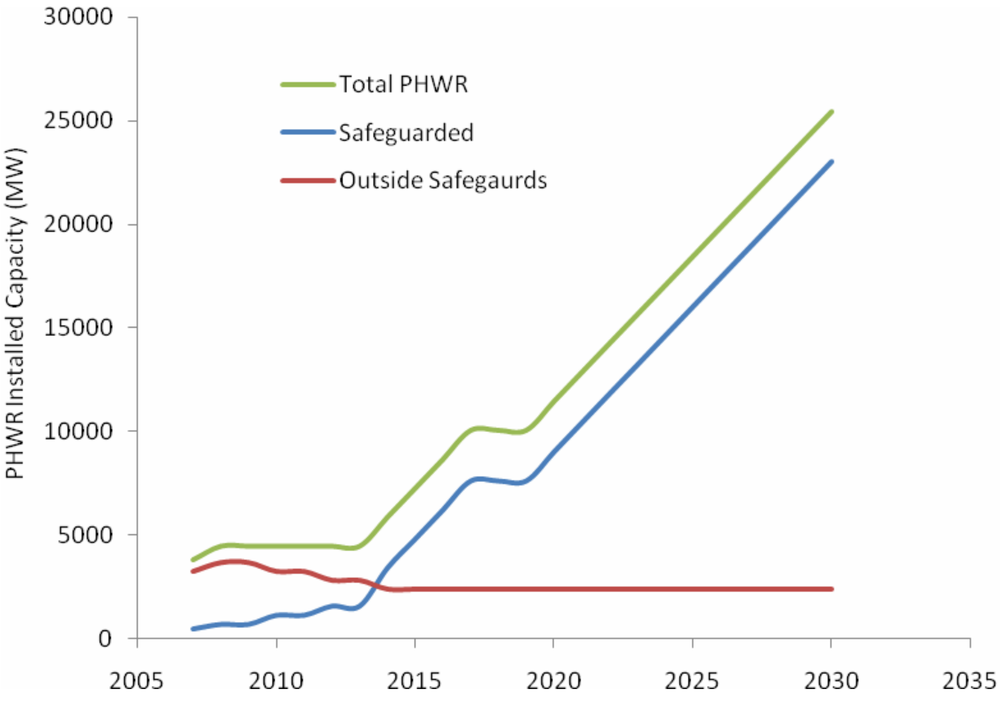
For commercial nuclear power plants built by private parties at sites owned by them, some arrangements would need to be worked out for safeguarding the wastes after the plants cease operation. If it is decided to move the wastes to a central location as is being practiced in some countries, suitable sites would need to be chosen and an organization identified to take charge of the management of the wastes. The general practice is to assign ownership of the operational waste to the producer namely the power plant operator. It is not transferable to the organization that might eventually take charge of the waste for a fee. Some decisions then need to be made on determination of the cost payable by the owners of the wastes on whose behalf the waste would be managed by the central agency.

Spent fuel discharged from the power reactors is sent to fuel reprocessing plants. High level wastes remaining after recovery of plutonium from the spent fuel are fixed in glass blocks in a Waste Immobilization Plant (WIP). The blocks are suitably encased in stainless steel containers and stored at the Plant Site awaiting eventual removal to a deep geological repository after a few decades. The low and intermediate level wastes could be stored at the reprocessing plant site and eventually removed to a central location if so decided. It is envisaged that the reprocessing plants as well as the WIPs would always be in the government.

Capacity addition through both LWRs and PHWRs

In this section, we consider an alternate approach. In addition to the import of LWR, India can choose to continue to build more PHWRs beyond 10,000 MW. This option has several merits. India has gained considerable experience and expertise in design, construction and operation of PHWRs. As per DAE's plan, 8 PHWRs of 700 MW are expected to be commissioned before 2020 and this appears to be within the reach of NPCIL. Building more PHWRs has an additional advantage. For each Ton of natural uranium used in them, PHWRs yield nearly twice the amount of plutonium compared to LWRs[29]. India is banking on plutonium availability for the fast breeder and thorium programs for long-term energy security and additional PHWRs assist in this goal. India could continue and build more PHWRs in the decade 2020 – 30. It could be possible to increase the total PHWR capacity to 25,360 MW by 2030. PHWRs under safeguards would be about 23,060 MW and the remaining reactors outside safeguards. All the new reactors under safeguards would operate with imported natural uranium.

Figure 22: If the PHWR program is continued beyond 2020, the total PHWR installed capacity in 2030 could rise to 25,360 MW. Out of this 23,060 MW would be under safeguards.



---

[29] Corresponding to a Burn Up of 50,000 MW days per Ton in LWRs.

At the same time as more PHWRs are built, it is also necessary to set up a fairly large reprocessing program with new plants built to recover the plutonium from the spent fuel discharged by the PHWRs. The total reprocessing capacity would have to go up to about 4200 Tons per year[30]. Eight new plants of 600 Tons per annum each would have to be commissioned between 2015 and 2022. All of these new plants can be under international safeguards since they would reprocess the spent fuel from PHWRs under safeguards. An International Nuclear Fuel Recycle Facility, along the lines proposed by the IAEA, could be set up in India to service the Indian PHWRs as well as reactors from other interested countries.

Expansion of PHWRs also requires augmenting the heavy water production capability. Two new plants, each of 600 Tons capacity would have to be built by 2017 and 2020 to take care of the requirements of PHWRs to be commissioned in the decade 2020 – 30.

Apart from recovery of plutonium from the spent fuel discharged by the PHWRs, the reprocessing program would also include construction of fuel cycle facilities associated with the FBRs and AHWRs. The design and operation of these would need to be such as to permit high availability factors to make recycled plutonium available in time for uninterrupted reactor operation on a self-sustaining mode.

The removal of barriers for cooperation with other countries could assist in accelerating the reprocessing program and in finalizing the design of plants for reprocessing metal fuel discharged from fast breeders, earlier than if it had to be a total indigenous effort. As for the reactors, switching from oxide fuel to metal fuel would require no significant modifications. If metal fuelled FBRs with higher breeding ratio are set up beginning 2020, their impact would be marginal in the decade 2020 – 30.

Being a larger program, this would require significant contribution from the public/private sector and a more robust regulation of safety and security of the facilities. When all the proposed PHWRs are built, India would import about 3500 Tons of uranium per annum to operate the reactors at 85% capacity factor. The cumulative uranium imports till 2030 are expected to be 36,000 Tons (

Figure **23**).The spent fuel from PHWRs could be recovered to generate about 100 Tons plutonium by 2030 (

Figure 24). This is in addition to 30 Tons of plutonium from LWR spent fuel.

---

[30] This capacity is more than double what exists in France presently.

Figure 23: Imports of natural uranium for the PHWRs under safeguards. At the peak capacity of 23,060 MW, they would require about 3500 Tons annually to operate at 85% capacity factor. The cumulative uranium imports till 2030 would amount to about 36,000 Tons.

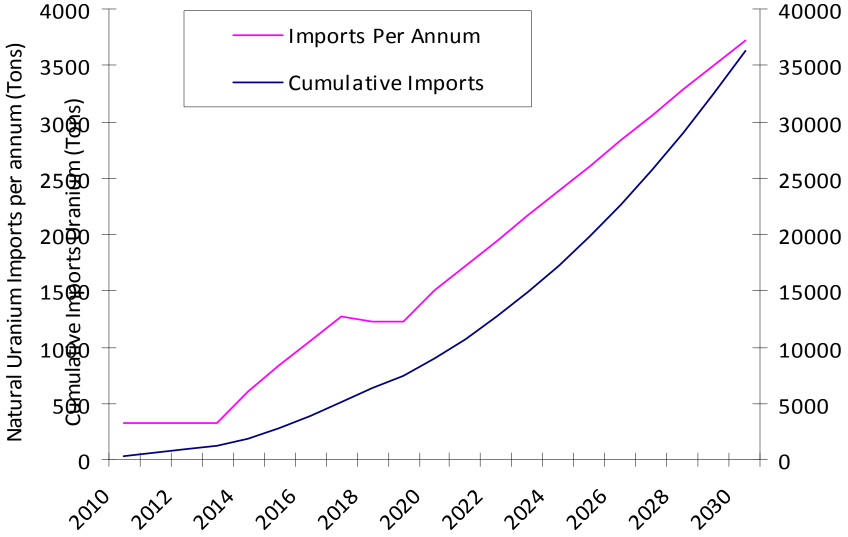
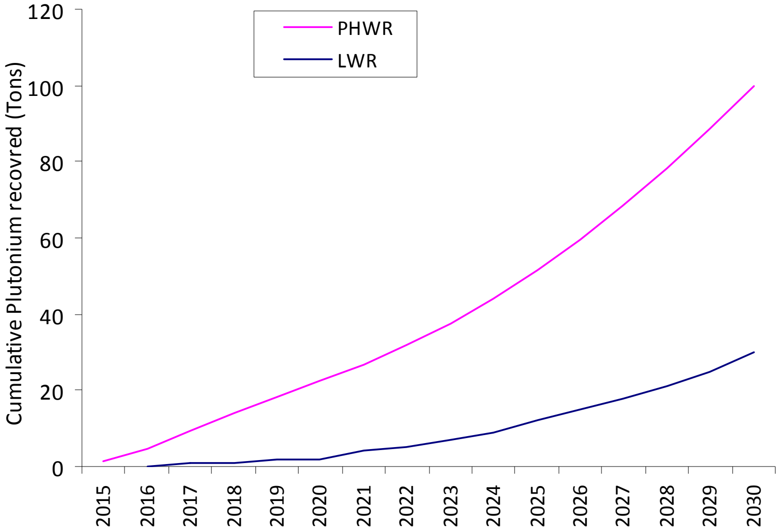


Figure 24: Cumulative plutonium recovered from spent fuel of LWRs and PHWRs under safeguards.



In this scenario, total nuclear capacity is likely to be 78,160 MW by 2030 (Figure 25, Table 12). This exceeds the optimistic projection of 63,000 MW by Planning Commission (Table 1). It must be noted that this is based on the following assumptions:

- LWR import of 32,000 MW
- Expansion of PHWRs to 25,360 MW
- PHWR spent fuel reprocessing capacity of 4200 Tons
- Development of metal FBRs and associated fuel cycle facilities and introduction after 2020

Figure 25: Likely nuclear installed capacity by 2030. Total capacity is expected to be 78,160 MW

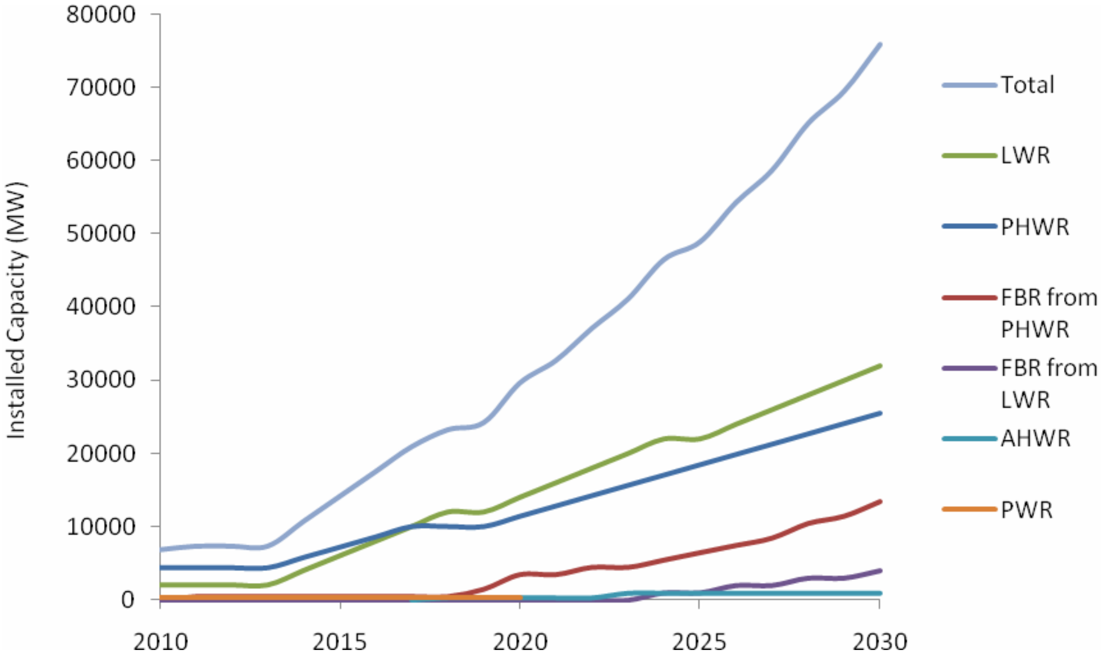


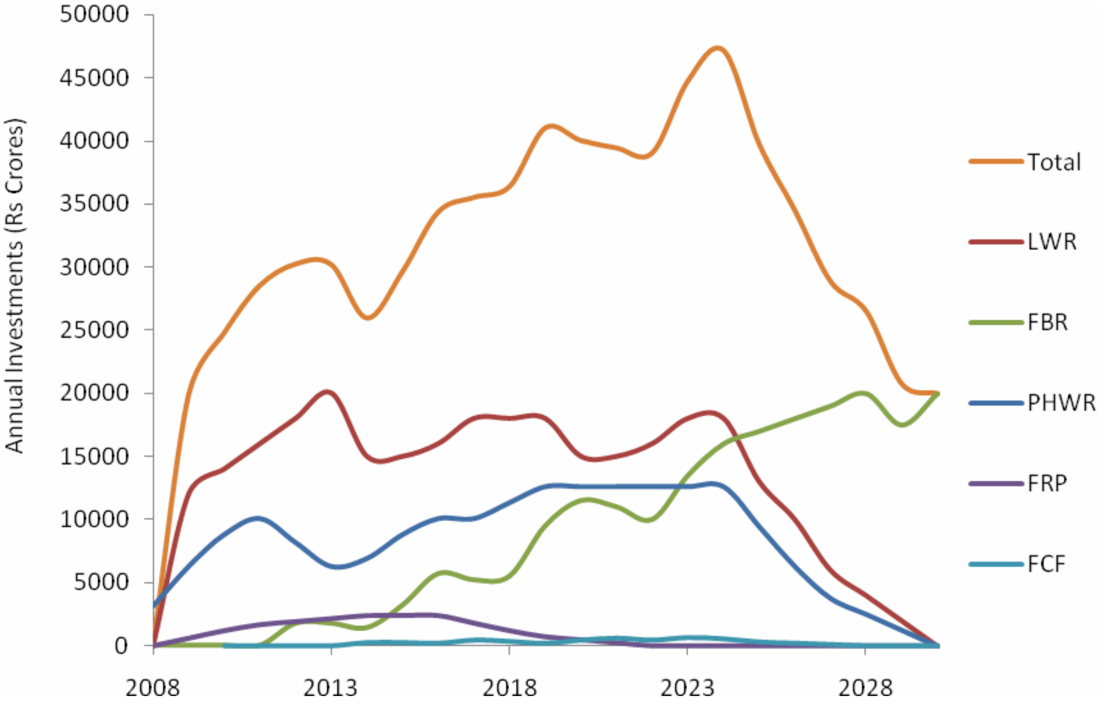
Table 12: Likely nuclear capacity by 2020 and 2030 with an expansion of PHWR program

	2020	2030
PHWR	11,360	25,360
FBR from PHWR Spent Fuel	2,500	16,500
LWR	14,000	32,000
FBR from LWR Spent Fuel	0	4,000
PWR	320	
AHWR	300	300
Total	28,480	78,160

Investments

Using the assumptions mentioned in Table 11, the total annual investments in this option works to about Rs 35,000 – 40,000 Crores per annum for the next two decades, or a cumulative of about Rs 750,000 Crores (**Figure 26**). Once the LWRs and PHWRs get completed, the annual investments decline to about Rs 20,000 Crores corresponding to the simultaneous construction of a large number of FBRs.

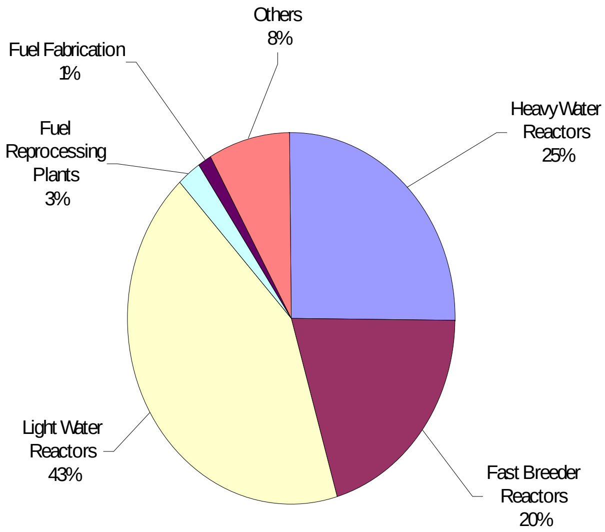
Figure 26: Annual investments required with expansion of PHWR program



Imported LWRs constitute almost half of this (Figure 27). Even imported reactors need active participation from indigenous industry: ancillary equipment, civil works, forgings, electronics, computers and other engineering equipments would all have to be built indigenously. Thus, Indian industry should be looking at a market of at least Rs 300,000 Crores over the next two decades. The manufacturing base of existing engineering companies would have to increase several times to meet this and they should plan for it now. It is important to note that fuel reprocessing plants constitute a mere 3% of the total investments; however, it is essential that these plants are built on priority. Otherwise, the breeders cannot take off.

Figure 27: Breakup of total investments up to 2030 with an expansion of PHWR program

Total Investments till 2030: RS 750,000 Crores ($ 160 Billion)



Recent DAE Projections

Projections of a largely domestic programme

Well before the Indo-US civilian nuclear cooperation was mooted, DAE published a study titled "A Strategy for Growth of Electrical Energy in India"[2]. A table from the above study is reproduced here (Table 13)[31]. This study expected that PHWR capacity would reach the peak level of 10,000 MW before 2022 and taper off rapidly to 4060 MW by 2052. Further, 6000 MW additional capacity was planned through LWRs at Kudankulam, over and above the 2000 MW already under construction with Russian assistance. The study considered 2500 MW of oxide fuelled FBRs using plutonium from PHWR spent fuel. In addition, it also considered 9000 MW of metal fuelled FBRs by 2022 - a major part of it (6000 MW) from PHWR spent fuel and the rest (3000 MW) from LWRs spent fuel.

Table 13: Nuclear power projections by Department of Atomic Energy [2, 38]

Year	PHWR, AHWR & FBR, based on plutonium from PHWR			LWR & FBR, based on plutonium from LWR			Total
	Thermal	Fast		Thermal	Fast		
	Oxide	Oxide	Metal	Oxide	Oxide	Metal	
2002	2,400	-	-	320	-	-	2,720
2022	9,960	2,500	6,000	8,000	-	3,000	29,460
2032	9,400	2,500	33,000	8,000	-	10,000	62,900
2042	7,860	2,500	87,000	8,000	-	26,000	131,360
2052	4,060	2,500	199,000	8,000	-	61,000	274,560

The Table provides some indication of how the projections in the Planning Commission Report were worked out (Table **1**). The total nuclear capacity in 2032 is the optimistic projection of 63,000 MW. If the contribution from LWRs (6,000 MW) and metal fueled FBRs derived from LWR spent fuel (10,000 MW) are excluded, we get a figure nearly the same as the pessimistic projection of 48,000 MW.

Tongia and Arunachalam had earlier examined the technology, viability and options of India's breeder programme in 1998 [39]. They concluded that a high performance PHWR programme with high plant load factors and a large reprocessing capability are vital for launching an FBR programme. Further, the breeder

---

[31] This Table can also be found on the DAE website as part of Document 10 titled 'A Strategy for Growth of Electricity in India' (http://www.dae.gov.in/publ/doc10/index.htm)

design must be so chosen – preferably the metal fuelled system - as to permit a significant excess production of fissile material. In the absence of these developments, they saw no alternative but to import LWRs on a fairly large scale. In their response, Rodriguez and Lee exuded confidence that high load factors are achievable as also early introduction of metal fuelled FBRs [40].

Impressive changes can be seen in the Indian nuclear programme since then. That includes very high performance levels of the PHWRs. This is limited now only by availability of fuel supplies, which are currently running very low. Short construction times as low as five years and deployment of multiple construction teams numbering five at a time are the other notable achievements.

It is noted from Table 13 that PHWR installed capacity drops down from 9960 MW in 2022 to 4060 MW by 2052 according to DAE projections. We have assumed a slower decrease taking the reactor life to be 60 years leading to a residual capacity of 8880 MW by 2052. If the PHWRs operate at 85% capacity factor, then the presently estimated uranium reserves of 61,000 Tons could run out by that time. The rate at which the PHWR capacity tapers off has a significant effect on the continued generation of plutonium for the FBR program.

A Prototype Fast Breeder Reactor of entirely indigenous design, based on oxide fuel, is now being built with all major components fabricated within the country. There is now a high degree of confidence that more reactors of the kind could be built following its commissioning. But, importantly, the changes yet to be brought about include expansion of reprocessing capacity and early introduction of metal fuelled fast reactors of high breeding capability, both of which are very essential if the FBRs are to make any significant contribution. There is ongoing work to establish a process for recovery of plutonium from the metallic spent fuel of the FBRs, but it would take several years before it can be implemented on a commercial scale[32]. As a result, it would seem that a substantial increase in nuclear share could only come from building several LWRs with external help similar to the suggestion made by Tongia and Arunachalam.

Presently, the requisite capability to build PHWRs exists and that for FBRs may be expected to be available once the PFBR is successfully commissioned. Spent fuel availability from the PHWRs is not in doubt. What remains to be established is the reprocessing capacity.

---

[32] The design of FBRs that run on metallic fuel is easier done. However, without the availability of proven methods for reprocessing the spent fuel from them to recycle the plutonium, capacity addition through FBRs cannot occur.

Reprocessing of Spent Fuel

About 51 Tons of plutonium would have to be reprocessed from PHWR spent fuel to establish total FBR capacity of 8,500 MW indicated in Table 13 (3 Tons for each FBR of 500 MW, assumed to be somewhat independent of the fuel type). About 15,000 Tons of PHWR spent fuel would need to be reprocessed before 2022 and this requires a reprocessing capacity of at least 800 Tons per year operating at 100% capacity factor for 18 years[33] (reckoned from the date of publication of the article). There are indications of plans for two new plants of 300 Tons each [24]. If these plants are operational by 2015, it would enable the recovery of 13 Tons plutonium, sufficient for only four new FBRs (2000 MW) by 2020. There is no information on steps to implement the above plans and to consider addition of required reprocessing capacity.

Similarly, 18 Tons of plutonium would have to be recovered from 180 Tons of LWR spent fuel to establish 3000 MW of FBRs indicated in Table 13. If we assume the 8 LWRs are commissioned in successive years beginning 2010, the cumulative spent fuel by 2020 would contain only 11 Tons of plutonium[34].

The success of the projections thus crucially depends on the availability of reprocessing capacity. In the absence of early plans for new reprocessing capacity, there is uncertainty about the FBR projections up to 2022.

Metal fuelled FBRs with High Breeding Capability

The current DAE plans call for introduction of metal fuelled systems from the beginning of the decade of 2020s. This requires the construction of a prototype well before that date. Perhaps, at least one of the four breeders now planned to be built before 2020 should be of this design, complete with the associated fuel recycle facility. Unless the design is ready now, this would appear unlikely, since safety review and construction time demand sufficient time for completion. There are plans to utilize both FBTR and PFBR as test beds for metal fuel to finalize the core design. A pilot plant for reprocessing the metal fuel would be a useful first step before the launch of a commercial program.

Rapid expansion of installed capacity of power generation through breeders depends on the breeding gain as well as the initial starting base capacity. DAE's projections assume an SDT of 8.9 years [2] and a starting base of 6 metal FBRs in 2022 (Table 13). As mentioned earlier, we consider a rapid expansion in the installed reprocessing capacity to 2300 Tons per annum (Figure 6), which enables recovering about 38

---

[33] Present reprocessing capacity is 200 Tons

[34] With a burn up of 50,000 MW days per Ton, at a capacity factor of 85%, spent fuel accumulation would amount to 1000 Tons by 2020. Plutonium yield is taken as 11 kg per Ton of spent fuel.

Tons plutonium by 2022. This is sufficient to start four FBRs of metal oxide type (2000 MW) and four more of metal fuel type (2000 MW) by 2022. With a starting base of 2000 MW of metal fuelled FBRs, the capacity addition in the future decades would be slower than shown in Table 13 as given below (Table 14).

Table 14: Comparison of Metal fuelled FBR Capacity Addition

	DAE Projections	This Study
2022	6,000	2,000
2032	33,000	15,000
2042	87,000	45,000
2052	199,000	113,000

The estimate in this study is based on the following assumptions:

- PHWRs reach peak capacity of 10,060 MW by 2017 and operate at 85% capacity factor
- PHWR spent fuel is allowed to cool for one year before reprocessing
- Spent fuel reprocessing capacity of 2300 Tons per annum (about 1700 at 75% Capacity Factor)
- 3.5 kg plutonium per Ton spent fuel
- FBR fresh fuel fabrication capacity of 40 Tons per annum of mixed oxide
- Two years allowance for cooling and reprocessing of FBR spent fuel
- Sites and investments are made available well in time for building new FBRs

Projections with imports enabled

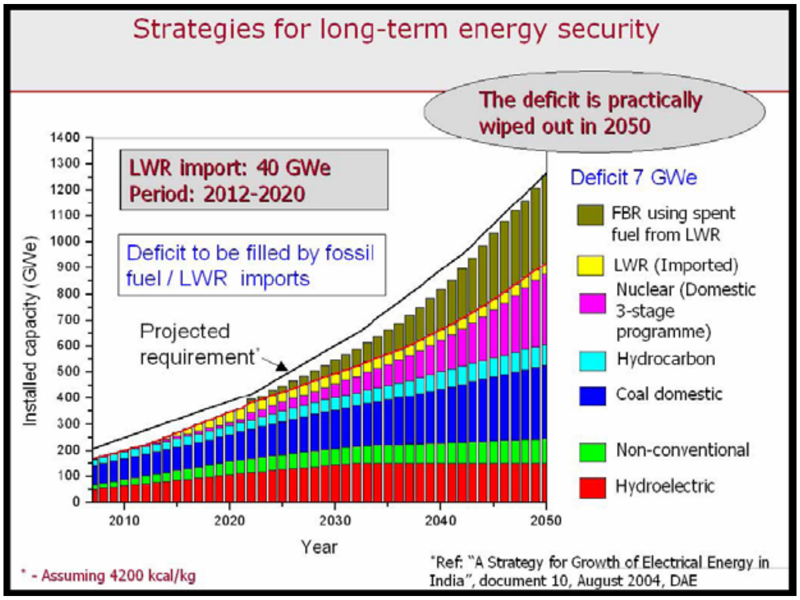
At a recent meeting organized by the Indian Academy of Sciences, the Chairman, AEC spoke of a projected aggressive import of LWRs to add 40,000 MW by 2020 in 8 years based on enablement of India's nuclear trade with other countries [41]. Plutonium contained in the spent fuel discharged by these LWRs is then expected to help build a very large fleet of FBRs with a capacity nearly ten times that of the LWRs themselves, by 2050. It follows that there should be a simultaneous plan for reprocessing LWR spent fuel.

If a mixture of LWR units of capacity 1000 MW and 1500 MW is chosen, there would be 16 units of each kind. For some time now, there have been suggestions that large clusters of six to eight reactors should be built at a site. With eight units at a site, just four sites could accommodate the required number of reactors. It would free other potential sites for locating fuel reprocessing plants.

The aggressive schedule as proposed would require a wide range of decisions regarding safety review, private sector participation, financial investments, power purchase agreements and manpower availability and training. These decisions and arrangements would have to be completed within the next 4 years so that the construction of the first of the LWR series could commence at least by 2012[35]. This would require an average annual investment of about Rs 35,000 Crores for the years 2012-20 on LWRs.

The expectation that the import of LWRs in such a short time could hasten the launch of a much larger FBR capacity presupposes the existence of a matching reprocessing program. At the peak capacity of 40,000 MW, LWRs would generate about 720 Tons of high burn up spent fuel per annum yielding 8 Ton of plutonium. However, the reprocessing operations have to provide for sufficient cooling time for recovery of plutonium. Alternatively, the spent fuel could be reprocessed abroad.

Figure 28: Nuclear power projections by DAE with international cooperation [41]


Strategies for long-term energy security

The deficit is practically wiped out in 2050

LWR import: 40 GWe
Period: 2012-2020

Deficit to be filled by fossil fuel / LWR imports

Deficit 7 GWe

* - Assuming 4200 kcal/kg

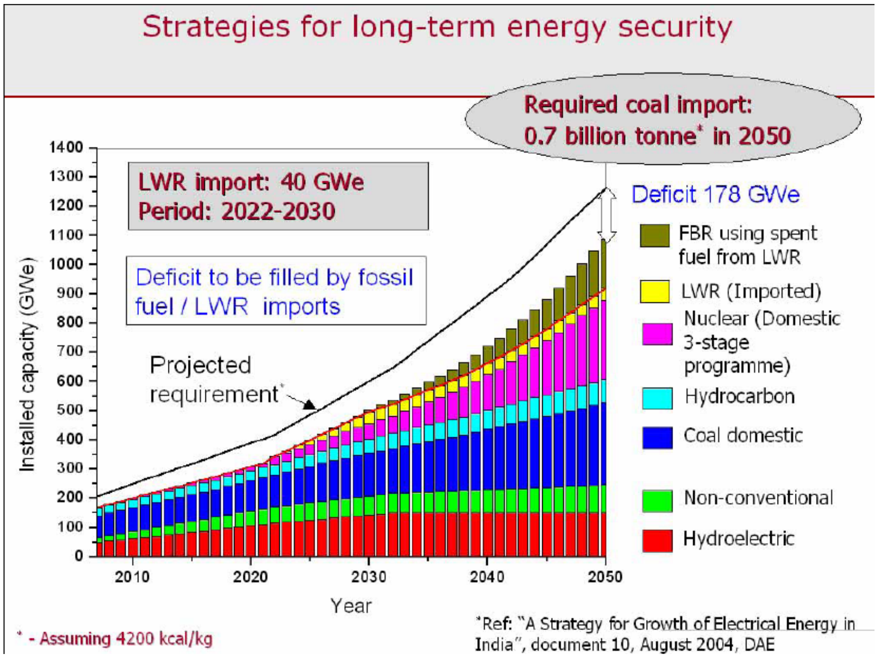
*Ref: "A Strategy for Growth of Electrical Energy in India", document 10, August 2004, DAE

Another observation made in the course of the lecture is that the FBR build up would be reduced to nearly half the value if the LWR installation of the same capacity is deferred by ten years (Fig 28). The same would result if the LWRs were to be built as projected but the recovery of plutonium is delayed by 10 years due to the absence of adequate plans for reprocessing either domestically or abroad.

---

[35] It is to be noted that construction of additional units in Kudankulam could commence earlier than 2012.

Figure 29: Nuclear power projections by DAE with international cooperation (delayed LWR addition) [41]



DAE projections as read from the graph (Figure 28) for 2030 and 2050 and comparison with the results of this study are in Table 15. For this study, we have used the following assumptions as mentioned in earlier sections:

- LWR capacity addition of 32,000 MW during 2014 – 2030.
- In one scenario, PHWRs peak at 10,060 MW (7,660 MW under international safeguards). In the second, more PHWRs are built 25,360 MW (23,060 MW under safeguards).
- The spent fuel from only PHWRs under safeguards is considered for adding FBRs after reprocessing. In theory, spent fuel from reactors outside safeguards (2400 MW) could also be used to build more FBRs under safeguards; however we have not considered that option.
- 3.5 kg plutonium per Ton PHWR spent fuel
- PHWR spent fuel reprocessing capacity of 2300 Tons and 4200 Tons per annum corresponding to PHWR capacities of 10,060 MW and 25,360 MW respectively
- Allowance of one year for cooling of PHWR spent fuel before reprocessing
- LWR spent fuel is either reprocessed abroad or domestic reprocessing capacity is established
- 11 kg plutonium per Ton LWR spent fuel
- Total allowance of five years for cooling, transport, reprocessing and fuel fabrication for preparing FBR fuel from LWR spent fuel
- FBR fuel fabrication capacity of 48 Tons and 80 Tons per annum of mixed oxide corresponding to PHWR capacities of 10,060 MW and 25,360 MW respectively
- Metal fuelled FBRs and associated fuel cycle facilities are available after 2020
- Allowance of two years for cooling and reprocessing of FBR spent fuel to recover plutonium

Table 15: DAE projections as read from the graph (Figure 28) and comparison with this study

	2030			2050		
	DAE Projections	This Study		DAE Projections	This Study	
		PHWRs peak at 10,060 MW	Expansion of PHWRs to 25,360 MW		PHWRs peak at 10,060 MW	Expansion of PHWRs to 25,360 MW
Domestic 3 Phase Program (PHWR & FBR from PHWR spent Fuel)	50,000	21,460	41,860	275,000	87,820	191,220
LWR	40,000	32,000	32,000	40,000	32,000	32,000
FBR from LWR spent fuel	44,000	4,000	4,000	350,000	62,000	62,000
AHWR	300	300	300	300	300	300
Total	134,300	57,760	78,160	665,300	182,120	285,520

If PHWRs peak at 10,060 MW then the total capacity could go to 57,760 MW by 2030 and 182,120 MW by 2050. If more PHWRs are built, then total capacity could be 78,160 MW in 2030 and 285,520 MW by 2050. If these projections are realized, then nuclear power could contribute about 10% of the total power by 2030 and at least 25% by 2050. If international cooperation is realized, it assists in quick capacity addition from import of LWRs in the initial years; 32,000 MW of installed capacity or more could be achieved by 2030. Further, the spent fuel from LWRs could add 62,000 MW FBRs by 2050. However, the domestic program consisting of PHWRs and FBRs is still vital for large capacity addition. International agreement allows import of uranium, which facilitates operating the PHWRs at high capacity factors and makes plutonium available early which is crucial for the breeder program. Thus, there is considerable merit in building more PHWRs beyond 10,000 MW.

Appendices

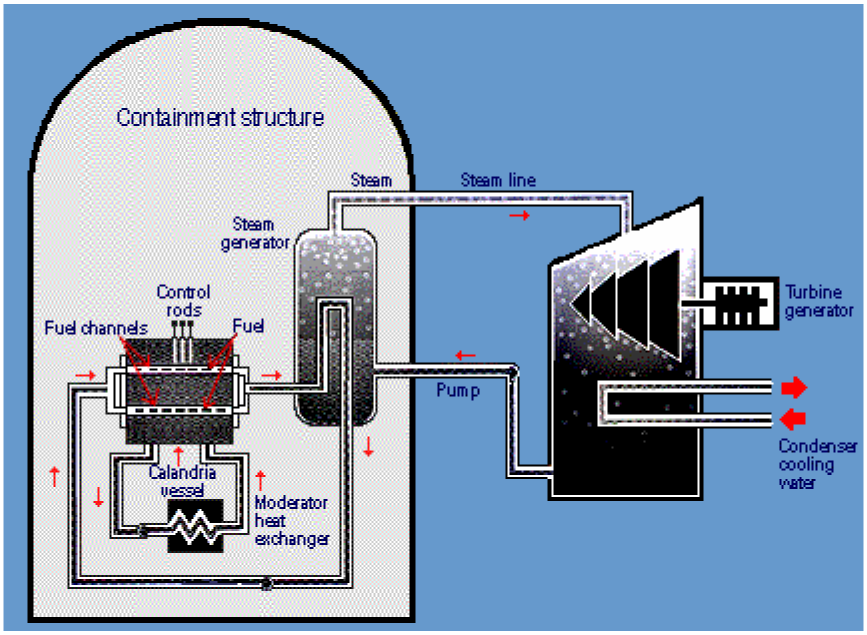
Brief Description of Reactor Types

Pressurized Heavy Water Reactor (PHWR)

The Pressurized Heavy Water Reactor (PHWR) uses heavy water as moderator and natural uranium as fuel. It was first conceived by Canadian scientists, which earned it the name CANDU (Canadian Deuterium uranium reactor). India built two units in Rajasthan with Canadian help and subsequently wholly adopted the design with significant modifications.

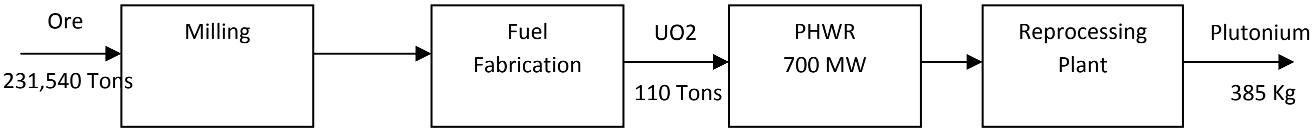
The reactor consists of a cylindrical vessel, known as 'calandria', placed with its axis horizontal, with both ends closed. Several hundred horizontal tubes pass through the calandria (Figure 30). The space between the tubes is filled with heavy water at low pressure that serves to slow down the neutrons produced in fission. Through each calandria tube passes a coolant channel, which is a tube that houses the fuel and allows coolant heavy water to flow around the fuel and carry the heat generated by fission when the reactor is running.

Figure 30: Schematic diagram of a Pressurized Heavy Water Reactor (PHWR) (from World Nuclear Association web page on "Nuclear Power Reactors")



The fuel is in the form tiny pellets of uranium oxide which are packed in a thin tube about half a meter long, made of zirconium alloy and sealed hermetically. The packed tubes are known as fuel rods. Nineteen such rods are held together to form a fuel bundle. Twelve such bundles are placed in each coolant channel. The space between the coolant channel and the calandria tube is filled with an inert gas to prevent loss of heat to the moderator. Hot heavy water from the coolant channels is taken to the boiler where it heats up ordinary water to produce steam. The steam drives a turbine generator and produces electricity. Most of the reactors now built are designed to generate 220 MW. Two larger units have also been built with a 540 MW rating. There are plans to build eight 700 MW units in the next decade. A 700 MW PHWR requires a fuel requirement of 110 tons UO2 per annum. Thus, about 231,540 Tons of ore would have to be mined and milled to produce this (assuming an ore grade of 0.05%). The spent fuel can be reprocessed to yield about 385 Kg plutonium (**Figure 31**).

Figure 31: Fuel requirements of 700 MW PHWR operating at 85% CF



An attractive feature of the PHWR is that unloading of used fuel and loading of new fuel can be carried out without having to shutdown the reactor. These operations are performed by two fuelling machines placed at each end of the calandria which lock on to a coolant channel from either side. One of them pushes new fuel into the channel while the other receives the used fuel at the other end. Ten fuel bundles are replaced each day (15 in the larger version of the reactor of 500 MW), if the reactor operates at full power.

Fast Breeder Reactors (FBR)

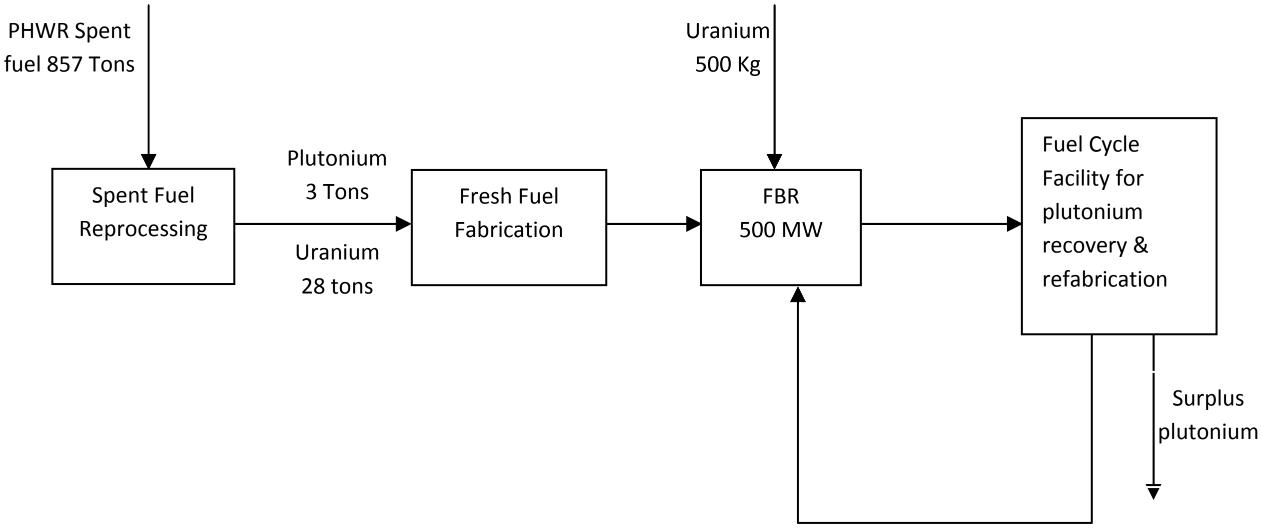
In reactors of the PHWR type and the LWR type, the fast moving neutrons released in fission are slowed down by collision with atoms of a moderator material. This is because slow moving neutrons have a better chance of causing fission to sustain the chain reaction. But, the slow neutrons are also likely to be lost because of capture by atoms of other material than the fuel.

Reactors can also function with no moderator, with the chain reaction sustained by the fast moving neutrons. Such reactors are known as fast neutron reactors or simply fast reactors. But, they require fuel with a high concentration of fissile material, like uranium 235, plutonium 239 or uranium 233. The core size is quite small in this type of reactors and so a coolant that is a very good conductor of heat, like liquid sodium or liquid lead is used in them.

An advantage of these reactors is that neutron loss through capture by atoms of coolant or structural materials is much less. Therefore some excess neutrons are available for converting uranium 238 atoms into plutonium 239 or to produce uranium 233 atoms from thorium 232 atoms. If this conversion is such that there is more fissile material produced in the reactor than is consumed, the system becomes a breeder reactor. Some fast reactor designs are such that there is enough fissile material produced to provide for refueling the reactor, not much more. The PFBR with oxide fuel is one such design. There are other possible designs, for example one with fuel in the form of a metal alloy of plutonium, uranium and zirconium, that can generate more fissile material to start up another reactor in course of time.

While a fast breeder reactor can be commissioned with the core fully loaded, some extra fuel is also needed to keep the reactor running until the spent fuel is reprocessed and the fissile material is recovered and recycled to feed the reactor. The total quantity of fissile material made up of both the components is the system inventory. The time period over which the accumulation of excess fissile material produced by the breeder equals the system inventory is the system doubling time. A 500 MW FBR has an initial requirement of 3 Tons of plutonium (**Figure 32**).

Figure 32: Fuel requirements of 500 MW FBR



Light Water Reactors

In the beginning of the nuclear age, large plants were built to produce highly enriched uranium for weapons purposes. With a huge surplus capacity for enrichment available in these plants, they were then used to produce lightly enriched uranium as fuel for compact reactors to provide propulsion power in submarines. Success in the design of such reactors led to design of larger versions to generate electricity to feed industries and cities. With light water serving as moderator and also as coolant, they came to be known as Light Water Reactors.

Two versions of LWRs can be found. In one, the coolant water is allowed to boil and turn to steam within the reactor core and this steam at high pressure is directly made to drive the turbine generator. This is the Boiling Water Reactor (BWR) version. The first two reactors built at Tarapur in India are of this type.

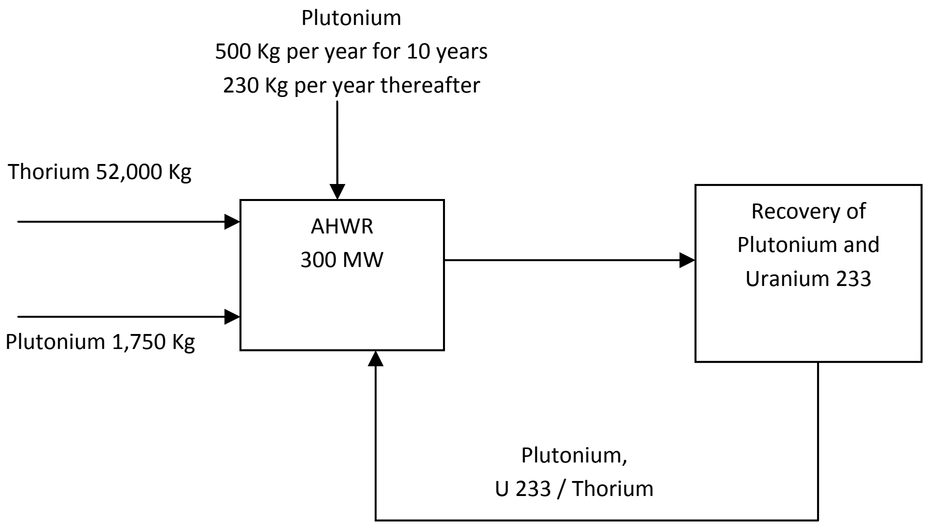
In another version of LWRs, coolant water flows through the reactor core at higher pressures so that boiling is prevented. It is then taken to a boiler where it is made to transfer its heat to another loop of water producing steam for driving the turbine generator. This is referred to as the Pressurized Water Reactor or PWR. The two Russian reactors being built at Kudankulam are PWRs. The reactors that France appears willing and ready to build in India also are PWRs. Japanese-American companies are interested in selling India BWRs.

Advanced Heavy Water Reactors (AHWR)

Indian interest in the utilization of thorium has led to a more serious research, design and development of a power generating reactor that is initially started up with plutonium and thorium, but subsequently produces uranium 233 which replaces the plutonium gradually. A 300 MW AHWR initially requires 1.75 Tons of plutonium. Subsequently, it requires 500 kg per year for 10 years and 230 kg thereafter (**Figure 33**).

Known as the "Advanced Heavy Water Reactor" or AHWR, it incorporates many features to enhance safety as well as economics. For instance, it uses heavy water as moderator but ordinary water as coolant instead of the more expensive heavy water. The coolant is not pumped into the core, but flows through it by natural convection. Also, the water passing through the core is allowed to boil and the steam used to drive the turbine. With no pumps and a separate steam generator, the system is more economical to build and less susceptible to equipment failure. There are also other safety features that help mitigate and even prevent adverse effects of accidents.

Figure 33: Fuel requirements of 300 MW AHWR



Nevertheless, there are some complex issues that relate to fuel design and fuel reprocessing. The fuel assembly is a mixed cluster of pins some containing thorium and plutonium and others containing thorium and uranium233. Reprocessing of spent fuel should include steps to separate all three components. The fuel refabrication operations would be required to be carried out remotely because of rather high radioactivity levels arising from the presence of some uranium232 atoms.

Initially, the reactor would be fuelled with a mixture of thorium and plutonium only to generate uranium 233, which would then be recovered and recycled replacing some of the plutonium. As a result, the system is not a breeder but is well suited to burning plutonium, which is of current interest in many countries with large stocks of plutonium.

A comparison of the operating characteristic of various reactors is in Table 16

Table 16: Comparison of features of various reactor types

	PHWR	LWR	FBR	AHWR
Thermal Power (MW)	800/2060	3300	1250	750
Electrical Power (MW)	220/700	1000	500	300
Efficiency (%)	30	33	40	29
Fuel Type	UO2 (Natural)	UO2 (4%LEU)	UO2 (Depleted) with PuO2 (21 and 28%)	ThO2 with 2.7- 4 %PuO2 initially and later ThO2 with 3 – 5 % ^{233}UO2
Fuel in Core (Tons)	56/140	70	12 of uranium oxide and 2 of plutonium oxide	1.75 tons Pu initially plus 56 tons thorium
Annual Fuel Reload (Tons)	33/110 at 65%CF	18	5	500 kg Pu for 10 years and 230 kg Pu after that
Moderator Material	Heavy Water	Light Water	None	Heavy Water with amorphous carbon
Heavy Water - Total Inventory (Tons)	250	---	----	About 250
Coolant Material	Heavy Water	Light Water	Sodium	Light Water
Steam Temperature (C)	290	500	493 at 17 MPa	285
Fuel Burn Up	6,500	50,000	100,000	20,000

References

1. Planning Commission *Integrated Energy Policy Report*; Government of India: New Delhi, 2006.

2. Department of Atomic Energy *A Strategy for Growth of Electrical Energy in India*; Government of India, http://www.dae.gov.in/publ/doc10/index.htm: August 2004.

3. Bharadwaj, A., Tongia, R., Arunachalam, V.S., Whither Nuclear Power? *Economic and Political Weekly* **March 25, 2006**, 1203 - 1212.

4. Bharadwaj, A., Carbon Counting. *Economic and Political Weekly* **December 15, 2007**, 13 - 15.

5. Jain, S. K., Chairman and Managing Director, Nuclear Power Corporation of India Ltd, *ICAPP, Nice, France*, 2007.

6. Nuclear Power Corporation of India Ltd *Annual Report*; Government of India: Mumbai, 2006-07.

7. Govindrajan, S. In *Economics of FBR Fuel Cycle*, Ind Nucl Soc Ann Conf INSAC 2003.

8. Bhattacharjee, B., Invited Talk: "An Overview of R&D in Fuel Cycle Activities of AHWR", *INSAC*, 2003.

9. Sinha, R. M., Exploration for Atomic Minerals in India- An Overview. *IANCAS Bulletin* **June 2005**.

10. Kundu, A. C., Jaduguda Uranium Mine, Singhbhum, Jharkhand : Some facts on Radioactivity, Radiation and Environmental Impact. *Nuclear India* **2006,** *39*, (7-8).

11. Awati, A. B., Grover, R.B. In *Demand and availability of Uranium Resources in India*, p 7 et seq in IAEA Tecdoc 1463 on Recent Developments in Uranium Exploration, Production and Environmental Issues' Proceedings of a Technical Meeting 2004.

12. AERB, National Report to The convention on Nuclear Safety, September 2007.

13. Anonymous, UCIL hopeful of nod for Nalgonda project, http://www.thehindubusinessline.com/2005/07/22/stories/2005072202630900.htm. *The Hindu Business Line* July 22, 2005.

14. Somasekhar, M., 'Uranium Corp set to start production soon', http://www.thehindubusinessline.com/2007/11/29/stories/2007112951190300.htm *The Hindu Businessline* November 29, 2007.

15. Ramachandran, R., Better shore up domestic Uranium resources. *The Hindu* July 11, 2008.

16. Gupta, R., Towards sustainable supply of fuel for nuclear power. *NuPower* **2004,** *18*, (2-3).

17. http://www.world-nuclear.org/info/inf53.html, World Nuclear Association on Nuclear Power in India.

18. Sanyal, T., Zirconium Technology for Cladding and Calandria Tubes, *IANCAS Bulletin*, July 2005.

19. Somasekhar, M., NFC's Zirconium Project Gets Green Signal, http://www.thehindubusinessline.com/2004/10/25/stories/2004102502120500.htm *Business Line* Oct 25,2004.

20. Heavy Water Board Department of Atomic Energy, Government of India.

21. Dey, P. K., Spent Fuel Reprocessing: An Overview. In *INSAC* 2003.

22. Sahoo, K. C., Bharadwaj, S.A., Fuel Performance in Water Cooled Reactors' In *IT12/2, INSAC*, 2003.

23. Kamath, H. S., Kumar, A., Development of Plutonium Fuel for Thermal and Fast Reactors. *IANCAS Bulletin* **July 2005**.

24. Kumar, S. V., Former Vice Chairman, AERB, 'Reprocessing in India: Development, Demonstration and Deployment', Talk given on the occasion of BARC Founder's Day, Oct 30, 2007, http://www.barc.ernet.in/webpages/special_talks/spltalks.htm

25. BERR *Proposal on how to manage overseas spent fuel awaiting processing at Sellafield, www.berr.gov.uk/files/file42361.pdf;* Department for Business Enterprise and Regulatory Reform, UK: 2007.

26. MIT *Future of Nuclear Power: An Interdisciplinary Study*; 2003.

27. Cambridge Energy Research Associates (CERA) *Construction costs of new power plants continue to escalate, energy.ihs.com/news/pressreleases/2008/ihs-cera-power-capital-cost-index.html*; May 27, 2008.

28. www.keystone.org

29. World Nuclear Association *Nuclear Power in China, http://www.world-nuclear.org/info/inf63.html*; September 2008.

30. www.nucwatch.com/platts/2006/platts061221.txt.

31. www.uic.com.au/news108.htm

32. www.nucwatch.com/platts/2008/platts080123.txt.

33. http://www.chns.org/s.php?id=15&id2=293.

34. Fetter, S., Economics of Nuclear Power. In *Summer workshop on the role of nuclear power, Washington and Lee University and Council on Foreign Relations*, September 2007.

35. Shropshire, D. E., Williams, K.A., Boore, W. B., Smith, J. D., Dixon, B. W., Dunzik-Gougar, M. , Adams, R. D., Gombert, D. *Advanced Fuel Cycle Cost Basis*; Idaho National Laboratory, Prepared for US Department of Energy, Contract DE-AC07-05ID14517: April 2007.

36. http://www.nucwatch.com/platts/2008/platts080208.txt, In.

37. International Atomic Energy Agency (IAEA) *Estimation of Global Inventories of Radioactive Waste and Other Radioactive Materials, Tecdoc 1591*; June 2008.

38. Kakodkar, A., Nuclear Energy in India - Retrospect and Prospects. *NuPower* **2004,** *18*, (2-3).

39. Tongia, R., Arunachalam, V.S., India's Nuclear breeders: Technology, viability and options. *Current Science* **1998,** *75*, (6).

40. Rodriguez, P., Lee,S.M., Who is Afraid of Breeders? *Current Science* **1998,** *75*, (10).

41. Kakodkar, A., Evolving Indian Nuclear Programme: Rationaleand Perspectives. In *Public lecture at Indian Academy of Science, Bangalore, http://www.dae.gov.in/*, July 4th, 2008.