A Technical Study of the Nuclear Fuel Cycle and Three Stage Power Program of India for US-India Nuclear Cooperation

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ABSTRACT:

Given the recent steps toward civil nuclear cooperation between the US and the Government of India a necessity for assessing India's nuclear fuel cycle including nuclear materials, facilities and three stage nuclear power program has arisen. With this possible agreement a policy shift is eminent, thus opening the possibility of nuclear fuel acquisition by India from US and other members of the Nuclear Suppliers Group. This state of affairs drove the desire to model the three stage reactors, PHWR's, fast reactors and U-233 cores for power production that India plans to pursue for years to come. India's three stage nuclear power program entities and all the components of civilian and military significance were assembled into a flowsheet analysis to allow for a macroscopic vision of the Indian fuel cycle. Analysis of an alternate fuel for the Indian fuel cycle was made which couples uranium and thorium resources. This fuel would significantly simplify the complex three stage program and the verification methods for IAEA. The cornerstone of any civilian nuclear technological support necessitates the separation of military and civilian facilities. A complete nuclear fuel cycle assessment of India was performed to aid in assessing how entwined the military and civilian facilities in India are as well as to effectively move forward with the separation plan. To estimate the existing uranium reserves in India, a complete historical assessment of ore production, conversion, and processing was performed using open source information and compared to independent reports. Nuclear energy and plutonium production (reactor- and weapons-grade) were simulated using declared capacity factors and modern simulation tools. These assessments included historical analysis and future projection with various possibilities of resources used and technologies ventured.

Keywords: fuel cycle assessment; India; uranium reserves

1. INTRODUCTION

The recent civil nuclear cooperation proposed by the Bush Administration and the Government of India has highlighted the necessity for an accurate assessment of India's nuclear fuel cycle. The cornerstone of any civilian nuclear technological support necessitates the separation of military and civilian facilities.[3] The entwined nature of the Indian facilities was assessed by a full-scale microscopic view of the complete Indian nuclear fuel cycle. Assessment of uranium produced and consumed, plutonium generated and energy produced with available technology, and advanced projects attempted lead to a detailed view of the Indian situation. This study shows the possibilities of international collaboration and analyzes the future projections under different scenarios.

2. THREE STAGE POWER PROGRAM OF INDIA

The basis of the three stage program was the indigenously available technology for production of natural uranium fuel assemblies, the vast reserves of thorium, and the mastering of heavy water production and spent fuel reprocessing technology. When this program was devised, India did not have any existing power reactors and there were no commercial fast breeder reactor systems anywhere in the world. A three stage nuclear power program (Fig. 1) based on a closed nuclear fuel cycle was envisioned by Bhabha and his team.[1] The three stage program consists of:

STAGE 1: *Establishment of natural uranium fuelled, heavy water moderated and cooled Pressurized Heavy Water Reactors (PHWR) for producing about 420 GWe-yrs of electricity.*

Spent fuel from these operational reactors is to be reprocessed to separate plutonium for use in second stage fast breeder reactor systems.

STAGE 2: *Fast Breeder Reactors (FBR) would utilize plutonium-based fuel obtained from the first stage to generate an additional 54,000 GWe-yrs of electricity. These FBR's breed ^{233}U from thorium and convert ^{238}U to plutonium, thus producing more fuel than they utilize.*

STAGE 3: *Advanced nuclear power systems utilizing ^{233}U and Thorium as fuel to provide 358,000 GWe-yrs of electricity and breed more fissile content. These reactors would not only produce fuel for themselves but also enough for weapons use.*

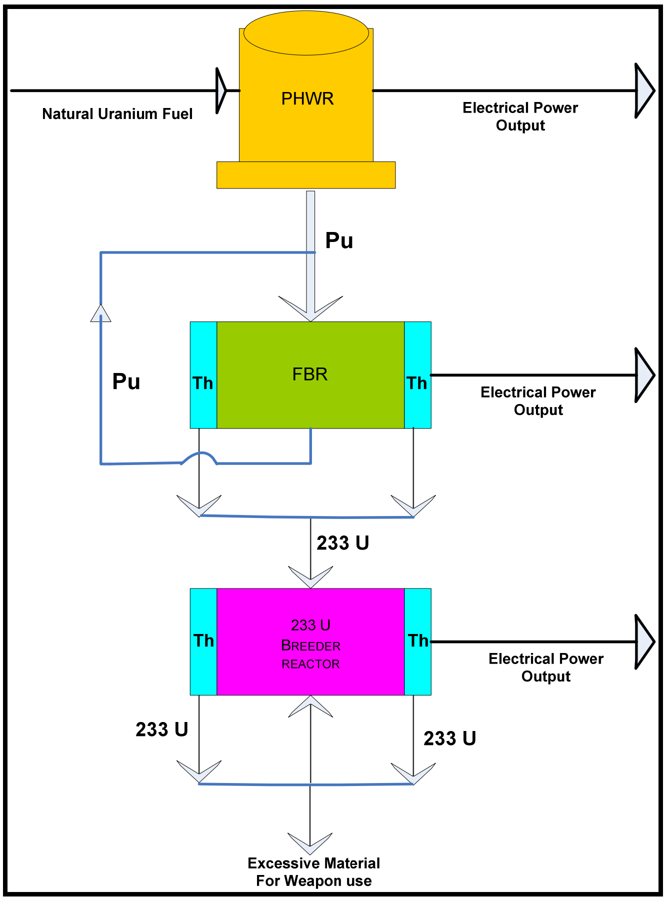

Fig. 1. India's three stage power production strategy

India obtained self-sufficiency in 220 MWe PHWR technologies, but until recently all of the power plants ran at a low capacity factor. After two decades of advanced research and development on the Fast Breeder Test Reactor (FBTR), the second stage power reactor system the Prototype Fast Breeder Reactor (PFBR), is being built.[4] The two units of the 500 MWe PFBR's should be operational by 2012.[7] The technology of a ^{233}U based reactor was demonstrated with the commissioning and operation of the 30 kW KAMINI reactor; however, commercial scale systems have yet to be attained.

3. ASSESSMENT OF NUCLEAR FUEL CYCLE

The fuel cycle assessment performed, accounts for the significant milestones in the Indian timeline of 1974 (first nuclear explosion), 1998 (Pokhran-II tests), and 2006 (the US-India Nuclear Cooperation Agreement) and the assessment (including material production, loss and storage from all sources and facilities) was performed from inception to present day. Figure 2 shows the nuclear fuel cycle flowsheet of India until 1974. This study concluded that by 1974 a 13.2 kg reserve of weapon-grade plutonium existed in India. Reiterating the fact that by the time India conducted the Pokhran-I test, it had the material to build only two more weapons. Figure 3 and 4 depicts the consolidated assessment of India's fuel cycle until the Pokhran-II tests in 1998 and year of proposed agreement 2006 respectively.

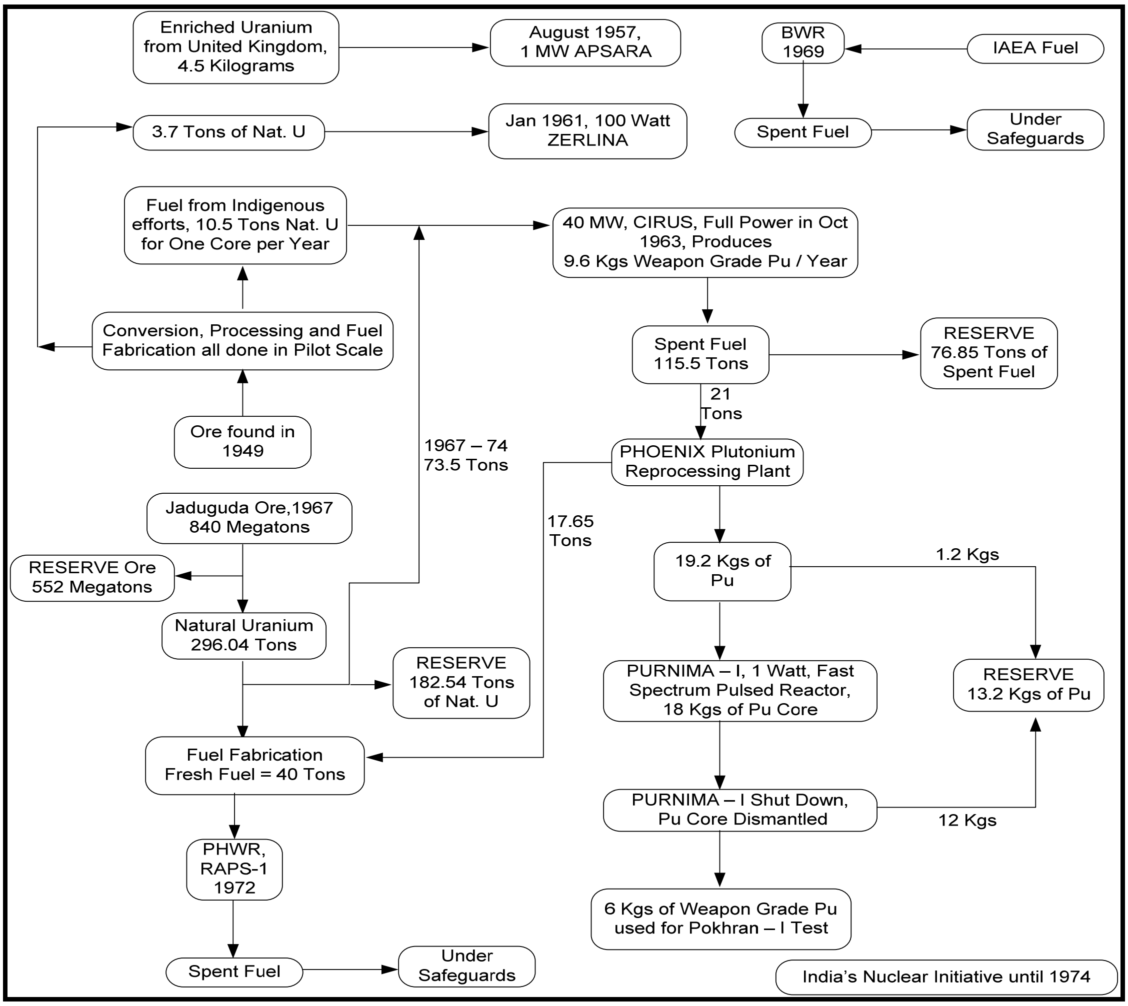

Fig. 2. Nuclear fuel cycle flowsheet until 1974

By the time of the Pokhran-II tests, India had 8 PHWR's of 220 MWe ratings and the DHRUVA reactor was producing a maximum of 27.6 kgs of weapon-grade plutonium annually. The plutonium production by mid-1998 was estimated from the fuel characteristics and an analysis of CIRUS and DHRUVA reactors using the ORIGEN2 and HELIOS-1.4 codes.[5] After accounting for the weapons-grade plutonium use for the Pokhran-II tests and the driver fuel for the FBTR, India would have had enough plutonium for at least 44 implosion devices assuming 6 kgs of plutonium for each weapon. Analysis of uranium enrichment capabilities was performed with an assumption of P1 centrifuge machines of 3 SWU/yr capacities having a total plant load of 2000 SWU per year.[6] India could have accumulated 94 kilograms of 90% enriched uranium by the end of 2006 after accounting for its possible use in the Pokhran-II test and as experimental fuel in the DHRUVA reactor. This amount of enriched uranium could fuel a nuclear submarine core if India continues in that program. In 2006, the Nuclear Fuel Complex (NFC) had more than doubled its capacity. Furthermore, in 1992, two 100 tHM/yr reprocessing facilities were added. This infrastructural development shrinks the gap between the first and second stages by meeting the fuel needs of the PFBR.

4. URANIUM USE AND PLUTONIUM PRODUCTION ANALYSIS

The primary source of weapon grade plutonium production is from two reactors: CIRUS and DHRUVA. The thermal power rating for CIRUS and DHRUVA is 40 and 100 MW_{th} respectively. Since these reactors do not have a declared operational history, a capacity factor of 50% and 80% is assumed for CIRUS and DHRUVA respectively to compute plutonium estimates.

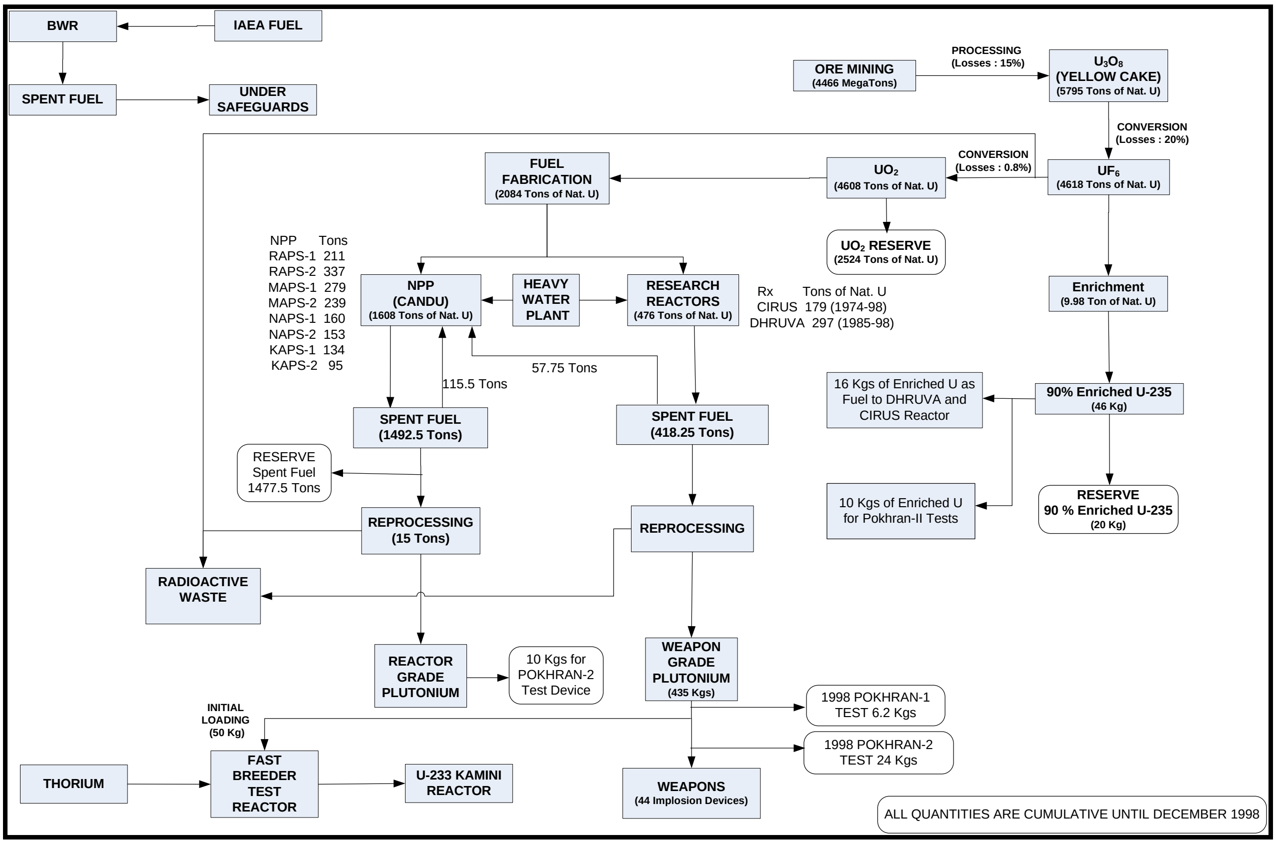

Fig. 3. Nuclear fuel cycle flowsheet until 1998

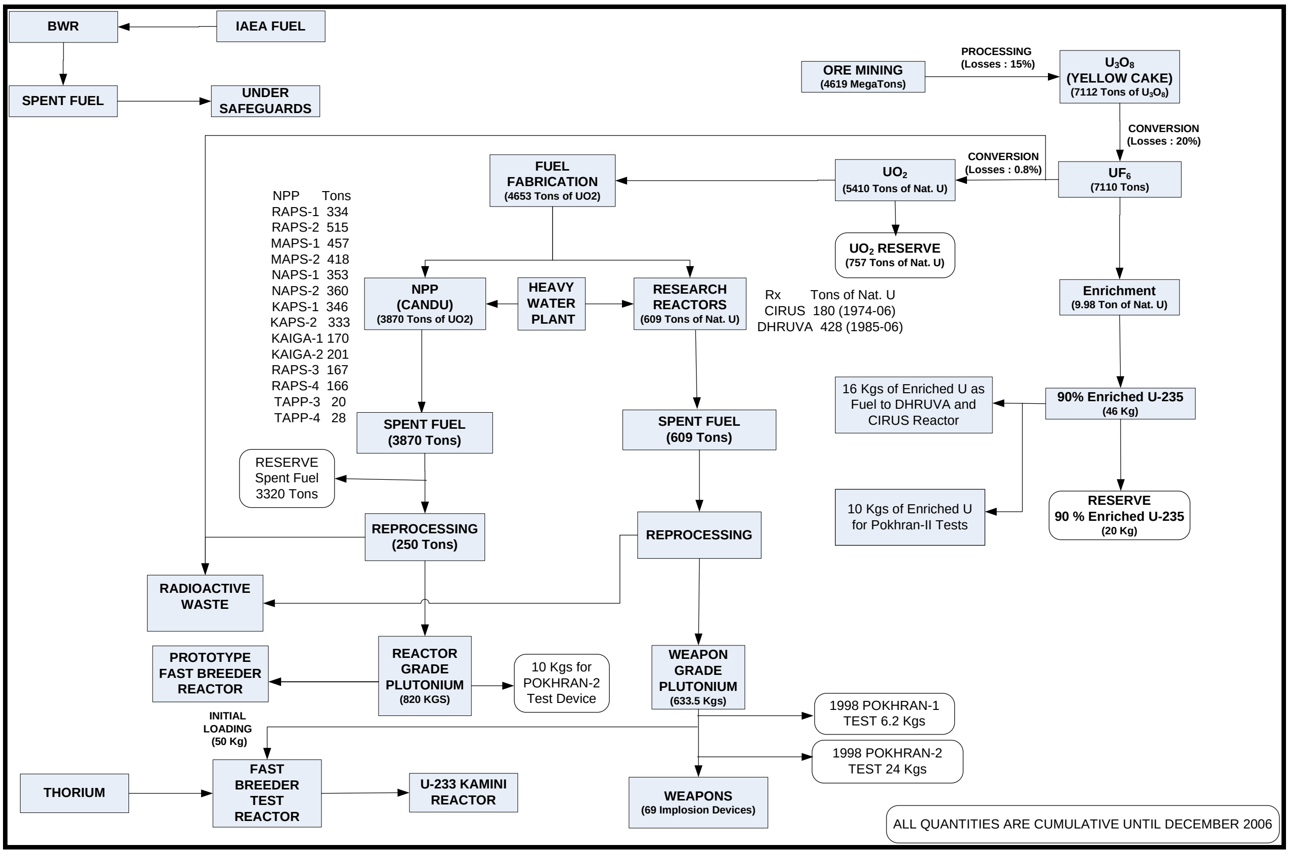

Fig. 4. Nuclear fuel cycle flowsheet until 2006

This predicts that the CIRUS reactor produces 9.6 kgs of weapon-grade plutonium per year using 10.5 tons of natural uranium fuel. DHRUVA, with a much shorter cycle of 67 days uses 6.35 tons of natural uranium as fuel and produces 5.53 kgs of weapon-grade plutonium per cycle. Considering a pragmatic situation of five core changes per year, DHRUVA can produce 28 kgs of plutonium per year. Calculations of these core fuels show that the total plutonium production of India by 1997 was 393 kgs after accounting for losses in reprocessing. Extrapolating the computations with similar assumptions and inputs, the plutonium reserves would have been 633.5 kgs by the year 2006. Table 1 shows a summary of the historical plutonium production by India.

TIME PERIOD	WG Pu PRODUCED (KG)	NAT. U IRRADIATED (TONS)	
1964 – 1974	48	53	
1964 – 1997	393	CIRUS / DHRUVA	173 / 270
1964 – 2006	**633.5**	**CIRUS / DHRUVA**	**205 / 486**
2006 – 2011	141	DHRUVA	108

Table 1. Plutonium production and natural uranium use in two production reactors

POWER PLANT	% of C.F.	CRITICALITY YEAR	TONS OF UO_2 USED
RAPS-1 / RAPS-2	23.31 / 52.65	1972 / 1980	255 / 436
MAPS-1 / MAPS-2	52.82 / 52.92	1983 / 1985	378 / 339
NAPS-1 / NAPS-2	60.62 / 67.82	1989 / 1991	274 / 281
KAPS-1 / KAPS-2	70.91 / 84.14	1992 / 1995	267 / 254
KAIGA-1 / KAIGA2	80.7 / 80.91	2000 / 1999	91 / 122
RAPS-3 / RAPS-4	77.98 / 79.2	2000 / 2000	88 / 90

Table 2. Fuel consumed by PHWR’s until 2003

POWER PLANT	C. F./YEAR	YEAR OF CRITICALITY	TONS OF UO_2 USED
All 12 Plants	81% / 2004	Operating	366
TAPP-4 + 12 Plants	76% / 2005	TAPP-4 on 09/2005	352
TAPP-3, 4 + 12 plants	52.4% / 2006	TAPP-3 on 01/2006	257

Table 3. Fuel consumed by PHWR’s from 2004 to 2006

India’s nuclear power plant analysis involves assessment of fuel consumed along with spent fuel characterization for plutonium and other minor actinides recovery by reprocessing. The total estimated quantity of UO_2 produced is 5410 tons and the amount consumed being 4330 tons (adding up the last column of Table 2, 3 and considering 40 tons being used for initial core loading for each of the 12 plants) by NPP’s and 690 tons by production reactors. All the NPP’s in India are presently operating at 60% or lower capacity factor. The same is assumed for all the under-construction power plants that may come online at the projected dates. Recently, the NFC handling capacity was increased from 250 to 600 tons of UF_6 per year to account for the demand for producing 450 tons of UO_2 annually considering 14 power plants operating at 92% capacity factor. By December of 2007, India would consume 388 tons of UO_2 (operating all the 16 PHWR’s at 60% capacity factor). If the operating capacity factors are maintained, then with the additions of newly built CANDU power plants, 397 tons of UO_2 will be consumed by the end of 2008. This makes the total fuel to be used in its lifetime equal to 4835 tons. The amount of UO_2 produced after subtracting the UO_2 consumed by the plutonium production reactors is 4833 tons. Thus, if additional uranium production does not occur then the consumption of uranium will exceed production and reserves by the end of December 2008.

5. ALTERNATE POWER PROGRAM WITH INTERNATIONAL COOPERATION

The present three stage program can produce all the three weapon usable materials (^{233}U, ^{235}U and Pu) under the closely entangled civilian and weapons program. This makes full-scope safeguards implementation difficult if not impossible. If the US-India nuclear cooperation agreement is finalized, a nuclear power program that addresses the verification and monitoring requirements of an international collaboration needs to be formulated. To serve the purpose of effective use of resources under the realm of proliferation concerns, an alternate nuclear program to that of the three stage program has been proposed. This proposed program is based on the use of existing PHWR technology which has been demonstrated under safeguard regimes. In this program, a thermal breeder reactor (TBR) would be used that uses PHWR spent fuel as its blanket material and a mixed thorium/enriched uranium fuel as its driver material. An illustration of the material flow is shown in Fig 5.

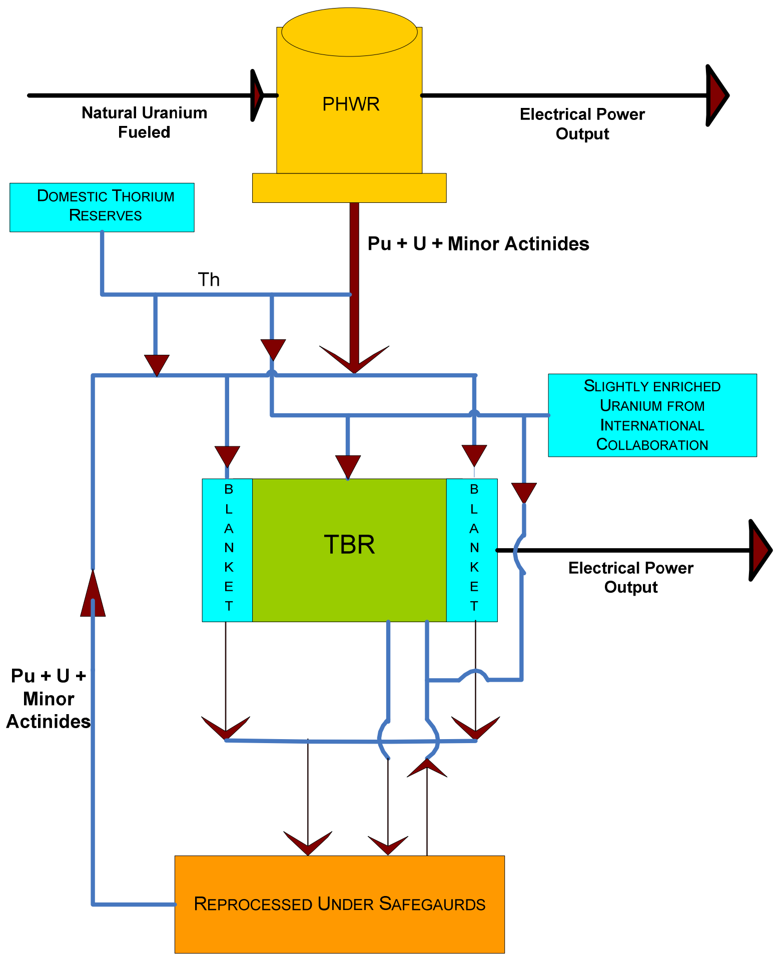

Fig. 5. Proposed thermal breeder based nuclear power program

Through this proposed power program a higher burn up for the initial fissile content is foreseen for the first few cycles of the reactor system and finally ending in an equilibrium state. The TBR could use a fissile content of 3% LEU along with 20% thorium for the driver fuel and spent fuel of PHWR's as well as thorium in a mix of 80:20 in the blanket. This achieves a burn-up of approximately 19.2 GWDays/tU. The end of life fuel configuration after the first cycle has fissile content of 1.71% for the whole core with a conversion ratio of 82%. This quantity of fissile content was made is mixed with more LEU to make 3.0% fissile content of the whole core for the next cycle. After eleven cycles spanning over 11 years the TBR core achieves equilibrium with 4% excess fissile content being produced at the end of each equilibrium cycle. After every cycle the percentage of ^{233}U and fissionable isotopes has increased along with the power production share of the blanket. The proportion of plutonium and uranium quantity in the end of equilibrium cycle fuel is close to 2.4% and 1.69% respectively. The actual doubling time for the reactors in a fuel cycle is dependent on the number of reactors and the rate of reprocessing of spent fuel. A series of eleven TBR cores built at a rate of one per year can make an equilibrium breeding fuel cycle.

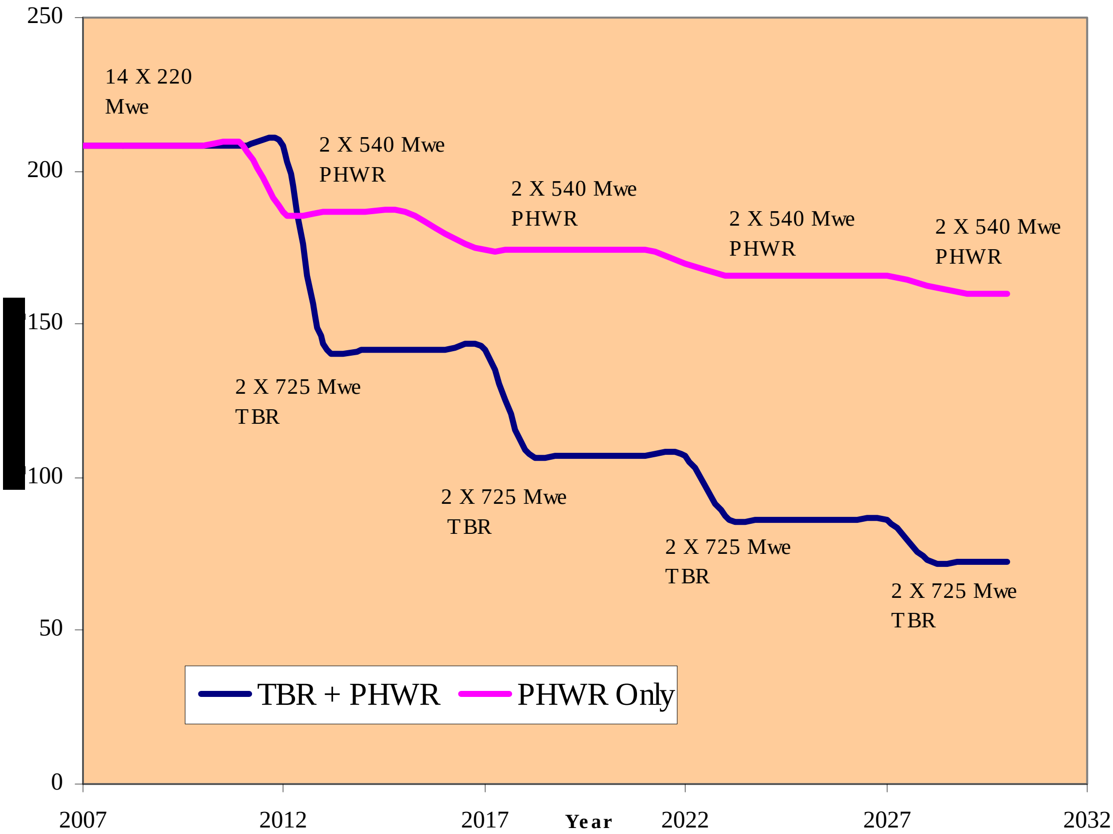

Fig. 6. Comparison of uranium use against electricity with/with out cooperation

The energy output of TBR was calculated with the assumption of a 30% overall plant cycle efficiency and 75% operational capacity factor for each power plant. The TBR core has thermal output of 3214 MW_{th}. This is approximately double the output of the present Indian PHWR's and the PFBR. Since the TBR is based on technology that is well developed in India, construction time scales would be similar to existing plants. Also, the TBR has an advantage over the PFBR since TBR uses only two loops. Starting with fourteen PHWR's all the future reactors would be under safeguards too. If the pertaining plan is replaced with TBR power program then beginning with early 2012 and extending till 2030 and beyond there is all through a gain in electricity production from unit fissile content. Under the India-US civilian nuclear cooperation India would have to supply fuel to 8 PHWR's, where as without the agreement the domestic uranium reserves are required for all the 22 reactors along with future PHWR's. Figure-7 shows the break even point of lowering the use of domestic uranium per unit of electricity production being 2021. This phenomenon shifts to as early as 2012 with the proposed TBR power program (as shown in Fig. 6).

6. CONCLUSIONS

The signing of the India–US nuclear agreement brings 14 of the 22 reactors under India specific safeguards. As such 4 reactors are already under IAEA safeguards. This cooperation also brings all future PHWR's, under the safeguards. The most controversial research reactor of the non-proliferation debate, CIRUS, would be shut down by 2010.

A large part of the plutonium supply from the 8 commercial reactors not under safeguards will be needed for India's fast breeder program which will initially be fuelled by plutonium. There is significant opposition to including the breeder program in the India–US civilian nuclear cooperation agreement. An alternative to fast breeders has been suggested. A power program with PHWR's followed by thermal breeders poses many benefits from the point of view of proliferation resistance, uranium use, and easily established thorium breeding cycles. Unlike the FBR, the thermal breeder makes dirtier plutonium, does not impart huge radiation risk from spent fuel because of lower quantities of ^{228}Th being produced, uses existing core geometry, and does not involve the sodium-water heat transfer phase.

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