Nuclear Fuel Cycle Assessment of India: A Technical Study for Nuclear Cooperation

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ABSTRACT:

The recent civil nuclear cooperation proposed by the Bush Administration and Government of India has heightened the necessity of assessing India's nuclear fuel cycle including nuclear materials and facilities. This agreement proposes to change decades-old-policy which aimed at preventing the spread of nuclear weapons by denying cooperation with non-NPT signatory states. After the nuclear tests carried out by India in 1998, many were convinced that India would never formally and unilaterally cap its nuclear arsenal. This state of affairs drove the desire to approach the nuclear issue through civilian nuclear cooperation. 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 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) was simulated using declared capacity factors and modern simulation tools. The three stage nuclear power program entities and all the components of civilian and military significance were assembled into a flow-sheet analysis to allow for a macroscopic vision of the Indian fuel cycle. These assessments included historical analysis and future projection with various possibilities of resources used.

Keywords: fuel cycle assessment; India; uranium reserves

1. INTRODUCTION

A great deal of speculation has occurred with regards to the Indian fuel cycle (both military and civilian) since the initial agreement for nuclear cooperation between the U.S. and India was made on July 18, 2005. Much of this is moved by a misunderstanding of the technical details of the Indian fuel cycle and Indian nuclear facilities; however, some speculation is also a product of uncertainties in the status and disposition of various Indian facilities. This work is focused on the technical assessments for the Indian fuel cycle based on open source information on the Indian nuclear facilities and the usage of those facilities. Assumptions and uncertainties included in any of the models used here are explicitly declared.

2. INDIAN NUCLEAR FACILITIES

India has a large suite of nuclear fuel cycle facilities and reactors. The details of these facilities are described in other sources [1]. The first nuclear power project of India started with General Electric constructing and commissioning two units of Boiling Water Reactor (BWR) power plants at Tarapur in 1969. Soon India realized the difficulty in acquiring enriched uranium for these reactor types and believed that BWR's would ensure lifetime dependence on the U.S. for fuel needs. Even before India's first power plant at Tarapur was built, Homi Bhabha and his team were suggesting a three stage program and looking into the potential of CANDU reactors [4]. With this program India could make use of indigenous natural uranium for which production technology existed. This endeavour though carried the burden of acquiring heavy water for moderation and as a coolant. It led India to installing 15 operational pressurized heavy water reactors (PHWR), 3 under construction and 4 planned CANDU

power projects as of May 2007. All this however produces less than 2.5% of the electrical consumption [6]. Until the year 2005 India did not have a nuclear power producing unit greater than 220 MWe [5].

India also constructed a number of research and production reactor systems. Table 1 lists the currently operating and decommissioned non-power reactor systems in India [1]. The nuclear fuel cycle of India also includes a small enrichment facility at Mysore with a nominal capacity of 2000 SWU. Additionally, a number of facilities researching uranium enrichment methods also exist.

A large scale CANDU fuel fabrication facility is operational at the Nuclear Fuel Complex (NFC) at Hyderabad. This unit can manufacture 19 pincell fuel bundles for 6 power plants operating at 90% capacity factor. Expansion of the plant occurred recently to meet the needs of 14 PHWR's at 90% capacity factor. If India continues at the same rate of adding two power plants a year, then soon further expansion of the facility will be needed.

NAME	LOCATION	TYPE	START DATE	FUNCTION
CIRUS	Trombay	40 MW_{th} HWR	10 July 1960	Weapon Grade Pu
DHRUVA	Trombay	100 MW_{th} HWR	10 Aug 1985	Weapon Grade Pu
Apsara	Trombay	1 MW_{th} LWR	1956	Knowledge of Nuclear Reactors
PURNIMA – 1	Trombay	Critical Assembly	1989	Decommissioned
PURNIMA – 2	Trombay	LWR	1984	Decommissioned
PURNIMA – 3	Trombay	LWR	1994	Uses U^{233}
Zerlina	Trombay	PHWR	1961	Decommissioned
Compact High Temperature Reactor	Trombay	0.1 MW_{th} Small Reactor	2010	Will use U-Th and U^{233} to Produce Hydrogen
Kamini	Kalpakkam	30 KW_{th} Test Reactor	1996	Uses U^{233}
Andhra University	Visakhapatnam	0.1 MW_{th} Low Power Reactor	Unknown	Planned Research
FBTR	Kalpakkam	40 MW_{th} Fast Breeder Test Reactor	1998	Prototype Fast Breeder Research and Development

Table 1. Research Reactors

3.0 THE THREE STAGE NUCLEAR POWER PROGRAM

The importance of nuclear energy, as a sustainable energy source was recognized at the very inception of the atomic energy program in India more than five decades ago. A three stage nuclear power program (Fig. 1) based on a closed nuclear fuel cycle, was envisioned [3]. The three stage nuclear power program envisioned by Bhabha is:

STAGE 1: *Establishment of natural uranium fuelled, heavy water moderated and cooled PHWR for meeting electricity needs. Spent fuel from these operational reactors is to be reprocessed to separate plutonium for use in second stage reactor systems.*

STAGE 2: *Fast Breeder Reactors (FBR) would utilize plutonium based fuel obtained from the first stage. These FBR's breed ^{233}U from thorium and convert ^{238}U to plutonium.*

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

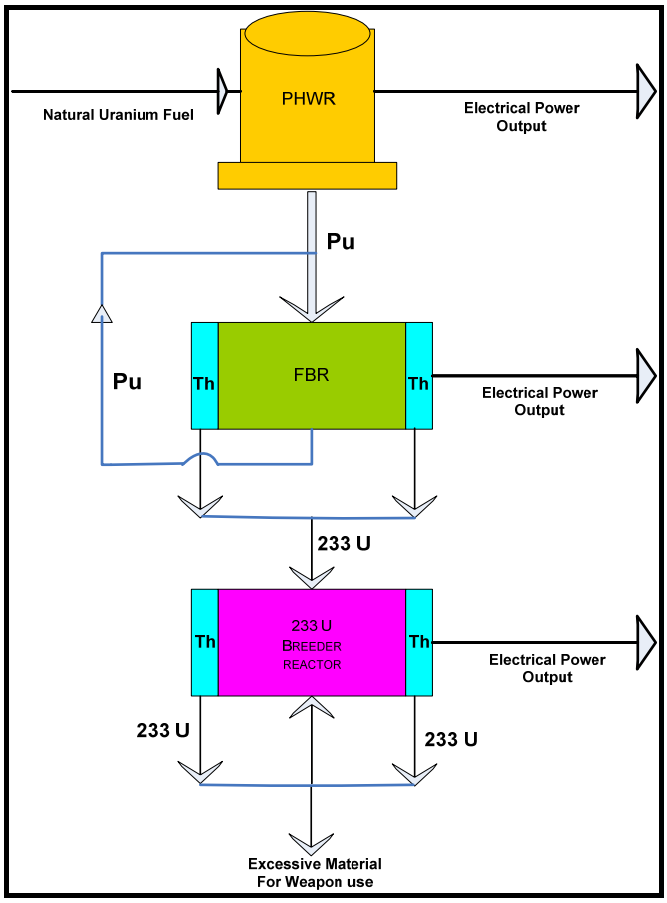

Fig. 1. India's three stage power production strategy

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.

Over a period of time India obtained self sufficiency in PHWR technology, but until recently all of the power plants were rated at 220 MWe and ran at a low capacity factor. To advance research on development of the second stage power reactor systems, a Fast Breeder Test Reactor (FBTR) was built, based on the French Rapsodie design. It was 40 MW_{th} with a mix of plutonium and uranium carbide as fuel. The design and operating experience obtained from it enabled the commencement of construction of a 500 MWe Prototype Fast Breeder Reactor (PFBR). Technological demonstration of a ^{233}U based reactor was done with the commissioning and operation of the 30 kW KAMINI reactor. However commercial scale systems have not yet been demonstrated.

4.0 FUEL CYCLE ANALYSIS TO PRESENT DAY

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). 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 concludes 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.

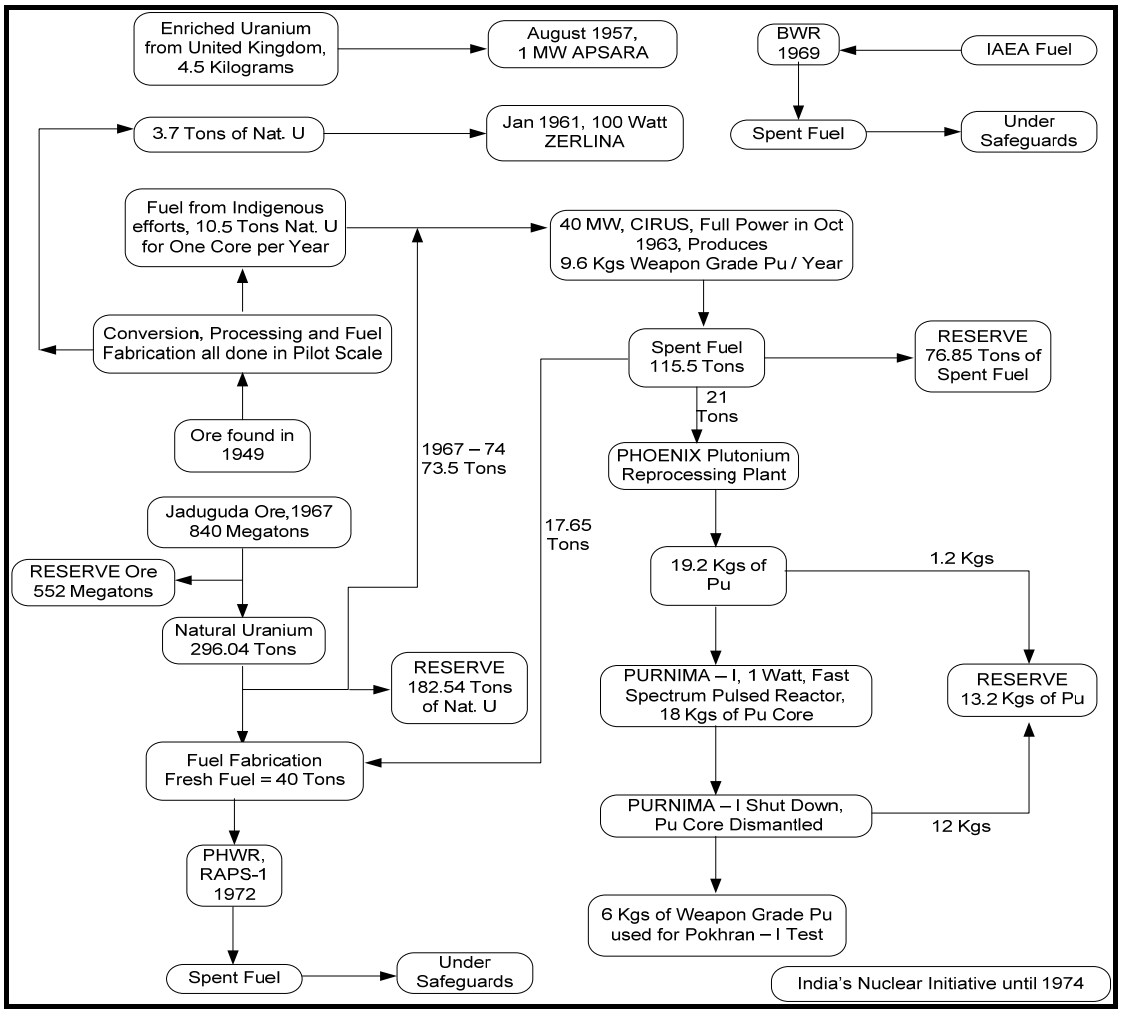

Fig. 2. Nuclear fuel cycle flowsheet until 1974

Figure 3 depicts the consolidated assessment of India's fuel cycle until the Pokhran-II tests in 1998. 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 (at 100% capacity factor) of 27.6 kgs of weapon-grade plutonium annually. An estimation of plutonium production by mid-1998 was produced from the fuel characteristics and an analysis of CIRUS and DHRUVA reactors using the ORIGEN2 and HELIOS-1.4 codes. After accounting for the weapons grade plutonium use for the Pokhran-II tests and the driver fuel for FBTR, India would have had enough plutonium for at least 44 implosion devices assuming IAEA significant quantity of 6 kgs of plutonium required for each weapon.

Immediately after the Pokhran-II tests, India was facing a dual challenge of international sanctions and diminishing uranium reserves at the flagship mine in Jaduguda. Prior to that date, the bottle neck for uranium fuel production was the milling capabilities but in the matter of a few months the focus point shifted to the uranium ore reserves. Mining activities at many other sites were attempted but

were not rigoursly pursued because of political and social reasons. In contrast, the building of nuclear power reactors increased and 6 more PHWR's were added (2 being of 540 MWe). Capacity factors of the order of 80% were achieved as of 2003 for certain power plants.

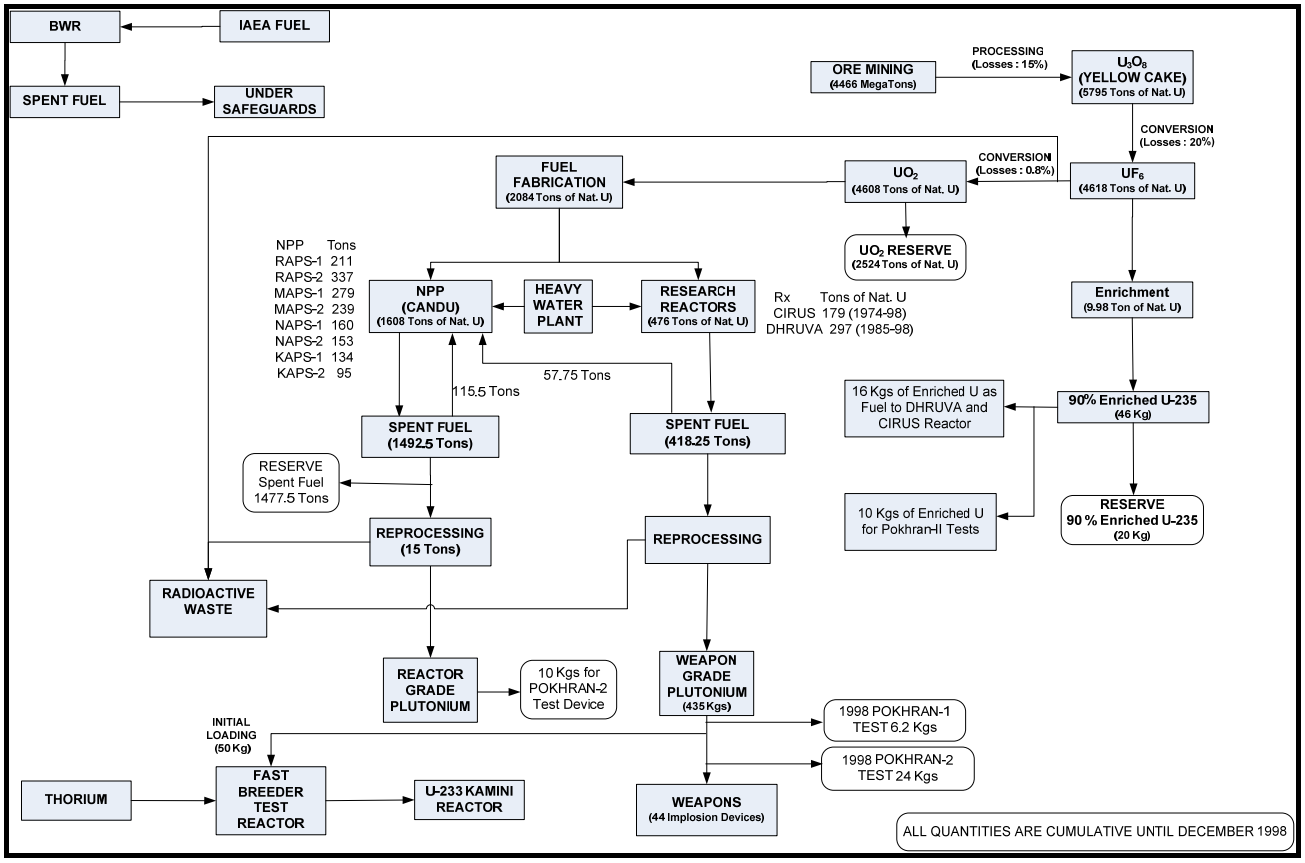

Fig. 3. Nuclear fuel cycle flowsheet until 1998

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. 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 DRUVA reactor. This amount of enriched uranium could fuel a nuclear submarine core if India continues in that program.

In 2006, the 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.

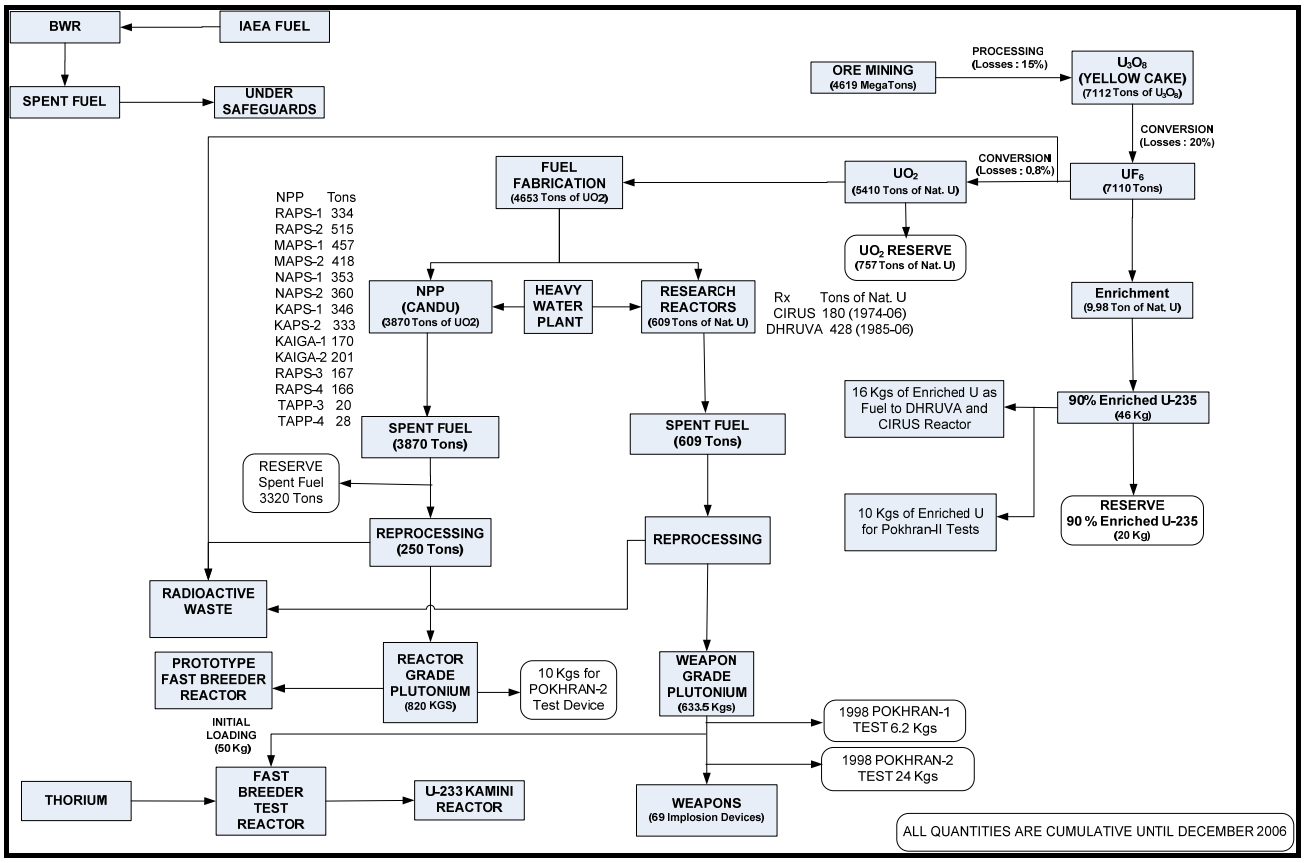

Fig. 4. Nuclear fuel cycle flowsheet until 2006

5.0 MATERIAL PRODUCTION

Exploration of uranium ores in India started as early as 1967. Beginning with Jaduguda (located in the eastern part of India), six to seven different locations were discovered over a period of time. The Jaduguda Mine had the capacity to produce up to 200 Megatons of yellowcake annually. Its actual production had been 115 Megatons per year averaged over a period of 40 years (1967-2006). For 32 years (1967-1998), the ore excavation was at the rate of 141 Megatons of yellowcake per year which dropped to an average of 10 Megatons of yellowcake per year for 1999-2006.

Mines at different locations are receiving increased attention after the exhausting of Jaduguda mines in 1999. The Narwapahar Uranium Mine became fully operational in 1999 at a cost of approximately $48.2 million. Considered one of the most modern mines in India, it has the capacity to process 7.3 Megatons/Year. The Bhatin Mine currently produces approximately 5.5 Megatons/Year.

The Mysore enrichment plant needs a feed of 2.15 tons of UF_6 per year to produce 10 kilograms of 90% ^{235}U and the Trombay plant consumes 0.43 tons of UF_6 every year to produce 2 kilograms of 90% ^{235}U. Table 2 describes the quantity of materials produced per year over the stated time periods and ending with 2006. The process losses and conversions were appropriately computed for calculating the quantities of U_3O_8, UF_6 and UO_2.

Time Line	Total Ore	U_3O_8	U_3O_8	UF_6	UO_2
	MEGATONS/ YEAR	TONS / YEAR			
			15% LOSSES	20% LOSSES	0.8% LOSSES
1967-86	141	254	216	217	165
1986-95	147	264	224	225	171
1995-98	154	277	236	236	180
1998-06	23	41	35	35	27

Table 2. Estimated values of U_3O_8, UF_6 and UO_2 annual production

The NFC has an annual handling capacity of 250 tons of yellow cake or 216 tons of UF_6 after losses (see Table 2). The calculated quantity of yellow cake (U_3O_8) was 6834 tons by 1998. Table 3 also illustrates the quantities of all the three compounds of uranium until 1998 and 2006. The scarcity of natural uranium reserves is stated as the catalyst for the India–US nuclear cooperation. Given the numerous prospective mining projects ongoing the uranium production scenario might be completely different in the future. India's ability to sustain nuclear power projects using domestic reserves may need to be reconsidered if the ore prospects are not realized.

	U_3O_8	UF_6	UO_2
ENDING PERIOD	15% LOSSES	20% LOSSES	0.8% LOSSES
Until 1998	6834 tons	6830 tons	5197 tons
Until 2006	7112 tons	7110 tons	5410 tons

Table 3. Cumulative U_3O_8, UF_6 and UO_2 production until 1998 and 2006

6.0 WEAPON GRADE PLUTONIUM PRODUCTION ASSESSMENT

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 two do not have a declared operational history, a capacity factor of 50% and 80% is assumed respectively to compute plutonium estimates. This predicts that CIRUS reactor produces 9.6 kgs of weapon-grade plutonium per year with 10.5 tons of natural uranium fuel. DHRUVA has much shorter cycle of 67 days with 6.35 tons of natural uranium as fuel for producing 5.53 kilograms of weapon-grade plutonium per cycle. Considering a pragmatic situation of five core changes per year, DHRUVA can produce 28 kilograms of plutonium per year. Calculations of these core fuels show that total plutonium production of India by 1997 was 393 kilograms after accounting for losses in reprocessing. Extrapolating the computations with similar assumptions and inputs, the plutonium reserves would have been 633.5 kilograms by the year 2006. Table 4 shows a summary of the historical plutonium production by India.

TIME PERIOD	WG Pu PRODUCED (KG)	NAT. U IRRADIATED (TONS)	
1964 – 1974	48	53	
1975 – 1997	345	121	
1964 – 1997	393	CIRUS / DHRUVA	173 / 270
1964 – 2006	**633.5**	**CIRUS / DHRUVA**	**205 / 486**
2006 – 2011	141	DHRUVA	108

Table 4. Plutonium production and natural uranium use in two research reactors

7.0 ASSESSMENT OF POWER PRODUCTION AND URANIUM CONSUMPTION

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.

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 5. 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 6. Fuel consumed by PHWR's from 2004 to 2006

The total amount of UO_2 produced is 5410 tons (Table 3) and the amount consumed being 4330 tons (adding up the last column of Table 6, 7) by nuclear power plants and 690 tons by research reactors (CIRUS & DHRUVA). Considering the present state of ore exploration with no additional exploration activity being added, the reserves and the meagre amount of production can last for only few years. New and bigger power plants are also under construction and would add up to the demand for fuel. Table 7 depicts the demand for fuel for 2007 from present operating plants and newer additions.

POWER PLANT	RATED POWER	CRITICALITY YEAR	TONS OF UO_2
TAPP-4	540	Sep-05	55
TAPP-3	540	Jan-06	55
KAIGA-3	220	Mar-07	17
KAIGA-4	220	Sep-07	6
RAPP-5	220	Aug-07	6
RAPP-6	220	Sep-08	0
11 Operating			249

Table 7. Fuel to be consumed by PHWR's at 60% capacity factor for the Year 2007

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 line up at the projected dates. Recently the NFC handling capacity was increased from 250 tons of UF_6 to 600 tons of UF_6 per year to take care of the demand for producing 450 tons of UO_2 annually considering 14 power plants operating at 92% capacity factor. [600 tons of UF_6 per year would lead to 458 tons of UO_2 per year]

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 end of 2008. This makes the total fuel to be used in its lifetime equal to 4835 tons. Now the amount of UO_2 produced after subtracting the UO_2

consumed by plutonium production reactors is 4833 tons. This evens out the production and consumption. The fuel exchequer thus goes to zero by the end of December 2008.

8.0 SPENT FUEL ANALYSIS

As can be inferred from the flowsheet representation of the fuel cycle, most of the spent fuel of the CANDU reactors is available for reprocessing. For first six cores depleted bundles were loaded for flux flattening. Later thorium bundles were used for flux flattening in fresh cores. A 220 MWe power plant, operating at 100% capacity factor needs eight 19-pincell fuel bundle replacements every day.[2] After correcting for the spent fuel loading for the fresh cores, actual capacity factor of operations and expecting that none has ever been sent to reprocessing facilities, 5020 tons of depleted uranium is assumed to be in the spent fuel bays (4330 tons from NPP's and 690 tons from RR's).

Taking into account an average burnup of 6500 MWd/tU for CANDU fuel bundles, 4.1 kgs of plutonium (in the ratio of $^{240}Pu/^{239}Pu$ = 42%) can be extracted from one ton of spent fuel. Given the fully operational reprocessing capability of 50 tons of spent fuel per year, India can extract 205 kilograms of plutonium every year from the spent fuel. This is appropriately sufficient to support the second stage of nuclear energy comprising of FBR's. If the two semi-operational reprocessing plants of 100 tons each become fully operational then a 500 MWe FBR can be added every year to the power grid.

9.0 CONCLUSIONS

Presented was a flowsheet assessment of the Indian nuclear fuel cycle. This assessment shows that without additional uranium mines being discovered in India, domestic uranium production will not be able to support the power reactor program beyond 2008. The weapons program however does not seem to be deterred by the present status. The fuel needs of CIRUS and DHRUVA can be met with the domestic production of uranium. The plutonium production reactors can still continue to operate with the meagre annual production and the separations capacity is adequate to continue weapons production at the current rate.

International supplies of uranium would allow India to continue the civilian energy production program indefinitely. Again, however, this has little effect on the weapons program. It remains likely that the weapons program will continue at the present rate irrespective of the status of the U.S.-India Nuclear Cooperation Agreement.

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