Estimating nuclear waste production in India

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We estimate the amount of nuclear waste generated by different steps in the fuel cycle followed in the Indian nuclear programme, based on standard methodologies and public sources of information. The basic input in the case of power reactors is the amount of electricity they have produced. For research reactors, the inputs are their rated capacities and an average capacity factor. While our waste estimates are based on assumptions and the limited amount of public data available, it would be easy to modify the estimates, should new information become available.

NUCLEAR waste has been a contentious aspect of nuclear power programmes around the world[1]. The Nuclear Energy Agency, Organization for Economic Cooperation and Development (OECD), observes: 'One of the key issues that has dominated the nuclear debate in recent years has been the safe management of radioactive wastes . . . radioactive wastes have caused more public concern than any other type of waste'[2]. In India too, apprehensions have been expressed about this segment of the nuclear programme[3]. Any examination of this subject, however, must begin with the actual amount of nuclear waste produced. Since this figure does not seem to be available publicly, in this paper we estimate the amount of nuclear waste produced by the Indian nuclear programme. The basic data that we use to perform this estimate are the amounts of electricity produced by the various power reactors, and the nominal power rating and an assumed capacity factor for the research reactors, *CIRUS* and *Dhruva*. Using standard figures and methodologies, we estimate waste production from different steps in the nuclear fuel cycle.

The nuclear fuel cycle in India begins with the mining and milling of uranium and the processing of the mined uranium into U_3O_8. This is followed by fuel fabrication and use in research and power reactors. The resulting spent fuel is then reprocessed to recover uranium and plutonium[4]. At each stage of this cycle, different kinds of nuclear waste are produced.

The management of nuclear waste depends upon its radioactive and other physical and chemical properties. In order to evolve guidelines for such management, it is customary to classify nuclear waste into different categories. India classifies its wastes into Low-Level Waste (LLW), Intermediate-Level Waste (ILW) and High-Level Waste (HLW). The category, potentially active waste (PAW) is also used[5] (Table 1).

In some cases, these individual categories are further divided according to radioactivity levels for operational purposes. For example, low-level solid waste is placed in four categories (Category I–IV) based on the surface beta and gamma dose and alpha activity[6] (Table 2).

To calculate the amount of waste produced, we start with an estimate of the amount of fuel irradiated. The primary sources of irradiated fuel are the ten power reactors (two Boiling Water Reactors (BWR) at Tarapur and eight Pressurized Heavy Water Reactors (PHWR); we do not include the four PHWRs that have recently been commissioned) and the two research reactors, CIRUS and Dhruva. We estimate the amount of fuel irradiated based on figures published by the Nuclear Power Corporation of India, for the amount of electricity generated in the case of power reactors. Since CIRUS and Dhruva do not produce any electricity, we assume a capacity factor of 60% to make our estimates. There are other smaller research reactors, in particular the Fast Breeder Test Reactor (FBTR), but we will neglect their contribution. This is because these are relatively low in power and so do not produce too much waste and because there is no adequate basis (such as electricity generated) to calculate the amount of waste generated. In the case of the FBTR, electricity production would not be a good indicator of the amount of waste generated, since as a test reactor it was used to experiment with different kinds of fuel and so on. For power reactors, we use the formula:

Table 1. Categorization of wastes in India

Category	Activity level A (Ci/m^3)	Remark
PAW	$< 10^{-6}$	Potentially active
LLW 1	$10^{-6} < A < 10^{-3}$	
LLW 2	$10^{-3} < A < 10^{-1}$	May require shielding
ILW	$10^{-1} < A < 10^{4}$	Shielding necessary
HLW	$> 10^{4}$	Shielding and cooling necessary

Source: Rodriguez[5].

Table 2. Radioactive low level solid waste categories

Waste category	Surface dose rate (mGy/h)
I	< 2
II	2–20
III A	20–500
III B	> 500

Source: Guha[6].

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$$\text{Fuel irradiated} = \frac{\text{Electrical power generated}}{(\text{Thermal efficiency}) \times (\text{Burn up})}. \quad (1)$$

The thermal efficiency is the electricity generated per unit thermal power output. The burn up is the heat liberated per unit mass of fuel irradiated and varies according to the reactor type, the fuel used (level of uranium enrichment) and fuelling practices. For the Tarapur BWRs, which use low enriched uranium, the average burn up is 20,000 MWD/tU (Mega Watt Days per tonne of Uranium)[7], and the thermal efficiency is assumed to be the standard value of 0.33 (ref. 8). In the case of PHWRs, which use natural uranium, the average burn up is 7000 MWD/tU (ref. 9). The thermal efficiency for PHWRs is somewhat lower than that for light water reactors. In order to be conservative in our estimates of waste production, we take this to be 0.30, a bit higher than the design efficiency of 0.29 (ref. 10). When a reactor is first commissioned, some of the fuel is discharged at much lower burn ups. This will increase the amount of fuel used per unit of electricity produced by a few tonnes, but we will ignore this small (when compared to the total fuel used) additional amount, so as to be conservative in our estimates of the quantity of waste produced.

Using these values for burn up and thermal efficiency, we can calculate the uranium actually irradiated by each reactor. For example, the RAPS-I reactor in Rajasthan has produced 11047 MU (Mega Units; 1 Unit = 1 kilowatt-Hour) = 460291.7 MWeD (Mega Watt electric Days) of power[11]. (It may be noted that these are gross generation figures. The net electricity generated and delivered to the grid would be less than this by about 10–15%, due to in-plant consumption.) Thus, it would have irradiated 460291.7/(0.3*7000) = 219.2 metric tonnes of uranium. The results of similar calculations for all the power reactors are given in Table 3.

The range of figures usually quoted for the capacity factors of CIRUS and Dhruva is 50–80%, approximately the same as the lifetime capacity factors for the power reactors. The thermal power rating for CIRUS is 40 MWth (Mega Watt thermal); the corresponding number for Dhruva is 100 MWth (ref. 12). We assume that fuel from these reactors is discharged at a burn up of 1000 MWD/tU.

The date of criticality for CIRUS is 10 July 1960, but it started operating at full power only in October 1963 (ref. 13). At the end of September 1997, the reactor was shut down for refurbishment[14]. In October 2000, it was reported that CIRUS was still undergoing refurbishment[15]. Since it is an older reactor, we assume that it has been operating with a 50% average capacity factor.

Dhruva became critical in August 1985, but initially had various operating problems, including fuel vibration and oil leakage from the coolant pump[16]. In December 1986, it began operating at 25 MWth, increasing gradually to reach 100 MWth in January 1988 (ref. 17). Since then, we assume that it has been operating with an average capacity factor of 60%. Once again, in order to be conservative in our estimates, we ignore the fuel irradiated during the period when the two reactors had just been commissioned and were not operating at full power. (Linearly interpolating between 25 MWth and 100 MWth, we estimate that the amount of uranium irradiated by Dhruva during the start-up period is 11 tonnes, a 4% correction that is of the same order of magnitude as many other uncertainties involved in our estimates.) The results of this calculation are given in Table 4.

In all (i.e. till 31 December 2000) approximately 1963 tonnes of uranium has been irradiated in the PHWRs, 397 tonnes in the BWRs, and 533 tonnes in the research reactors. The spent fuel from the Tarapur BWRs has not been reprocessed[18]. So the irradiated fuel from these two reactors would remain in the form of spent fuel, and should be added to the waste inventory. All the other spent fuel is reprocessed.

Having obtained the amount of fuel irradiated, we can work backwards and calculate the amount of fuel fabricated, uranium mined and milled and the corresponding amount of waste generated. We can also work forward in the fuel cycle to estimate the amount of waste generated during reprocessing.

The low enriched uranium used in the Tarapur BWRs is imported. However, it is made into fuel elements within the country. Therefore, it too would contribute to the

Table 3. Fuel irradiation by power reactors (till 31 December 2000)

Reactor	Reactor type	Commercial operation from	Power generated till 31 December 2000 (MU)	Fuel irradiated (Tonnes of uranium metal)
RAPS 1	PHWR	16 December 1973	11047	219.2
RAPS 2	PHWR	1 April 1981	18588	368.8
MAPS 1	PHWR	27 January 1984	16414	325.7
MAPS 2	PHWR	21 March 1986	14891	295.5
NAPS 1	PHWR	1 January 1991	10465	207.6
NAPS 2	PHWR	1 July 1992	10471	207.8
KAPS 1	PHWR	6 May 1993	9027	179.1
KAPS 2	PHWR	1 September 1995	8034	159.4
TAPS 1	BWR	28 October 1969	28663.6	199.1
TAPS 2	BWR	28 October 1969	28502.8	197.9

waste generated in the process of fuel fabrication, though not to the waste generated during uranium mining and milling. Indigenous fuel is used in all the other reactors (with the exception of half of the first fuel loading for CIRUS and RAPS-I)[19].

We assume that there is 0.5% loss in uranium during conversion and manufacture of fuel elements[20]. This would increase the total amount of uranium required by the PHWRs to 1973 tonnes, by the BWRs to 399 tonnes, and by the research reactors to 536 tonnes.

Assuming the same figure as for Canadian PHWRs, the amount of waste generated during the process of fuel fabrication is approximately 0.7 m^3 of low level waste (with alpha activity), for every tonne of uranium used to manufacture fuel[21]. Hence the total amount of low-level waste from fuel fabrication is 2036 m^3.

During milling, we assume a 97% uranium recovery rate that is typical of uranium mills that use the acid leaching process (also used at the Jaduguda mill)[22]. Therefore the total amount of uranium that must be mined to fuel the PHWRs and research reactors is 2509 tonnes. Since the Tarapur reactors do not use indigenous fuel, no uranium need be mined in India to fuel them and there will be no contribution to the waste generated during mining and milling from them. On an average, Indian uranium ores contain about 0.067% of U_3O_8 (ref. 23). With continued mining, the ore grade has reportedly dropped to about 0.03%, but in order to be conservative we use the former figure. Therefore, the total amount of uranium ore mined would be about 3.7 million tonnes. Including process reagents and refinery wastes, which contribute a little over 11% to the waste generated[24], the total amount of waste produced during mining and milling is 4.1 million tonnes. Using the lower figure for uranium ore grade of 0.03%, would increase this estimate to 9.3 million tonnes.

In reactor operation and maintenance, a number of solid and liquid wastes are produced. Some are classified as low-level and others as intermediate-level wastes. Low-level liquid wastes are released into rivers, reservoirs or the sea[25]. Intermediate-level liquid wastes are concentrated and fixed in cement.

The volume of low-level solid waste generated in a typical power reactor facility (with two reactors) is reported to be 200 m^3 per year; the corresponding figure for research reactors is 60 m^3 per year[26]. This may be somewhat smaller than the actual amount. For example, in 1976–77, RAPS I generated approximately 120 m^3 of solid waste[27]. In 1982–83, the two RAPS reactors together generated 260.8 m^3 of solid waste[28]. However, in order to be conservative, we use the figure of 100 m^3 per power reactor per year.

We have not come across any estimates of intermediate-level reactor waste production in India. In Canadian PHWRs, it was reported that in 1997 a total of 6871 m^3 of waste was produced by the Bruce, Pickering and Darlington nuclear-generating facilities (with a combined generating capacity of 15020 MWe)[29]. Of this, 88 m^3 was intermediate-level waste and the remaining 6783 m^3 was low-level waste. This translates to an annual low-level waste volume per unit generating capacity of 0.45 m^3/MWe, which is the same as those reported for Indian 220 MWe PHWRs[26]. Assuming, therefore, that Indian PHWRs create the same average volume of intermediate-level waste per unit generating capacity per year as Canadian PHWRs, the amount of intermediate-level waste produced every year by each 220 MWe PHWR, is 1.3 m^3. Assuming the same ratio for ILW to LLW for CIRUS and Dhruva, the two research reactors each produce 0.8 m^3 per year of ILW. (Note that while we only include the period of full power operations when it comes to producing irradiated fuel, ILW and LLW will be produced even when operating at low power and during refurbishment.)

For the Tarapur BWRs, we estimate the waste produced from the annual figure of 0.77 m^3/MWe of generating capacity based on a survey of BWRs in the US (and assuming a 50% volume reduction factor)[30]. This translates to an annual waste production of 125 m^3 for each of the 160 MWe Tarapur BWRs. Assuming the same ratio of ILW to LLW as PHWRs, the ILW produced by each of the Tarapur BWRs per year is 1.6 m^3. The amount of low- and intermediate-level waste generated till December 2000 by nuclear reactors is given in Table 5.

The irradiated fuel from the PHWRs is earmarked for reprocessing at the Power Reactor Fuel Reprocessing

Table 4. Fuel irradiated by research reactors (till 31 December 2000)

Reactor	Year of operation	Capacity factor	Fuel irradiated (tonnes U)
CIRUS	1963–1997	0.50	248.2
Dhruva	1988–present	0.60	284.7

Table 5. Cumulative low level and intermediate level waste production

Name	Date of commencement	Intermediate level waste (m^3)	Low level waste (m^3)
RAPS 1	16 December 1973	35.1	2700
RAPS 2	1 April 1981	24.7	1900
MAPS 1	27 January 1984	20.8	1600
MAPS 2	21 March 1986	18.2	1400
NAPS 1	1 January 1991	13.0	1000
NAPS 2	1 July 1992	10.4	800
KAPS 1	6 May 1993	9.1	700
KAPS 2	1 September 1995	6.5	500
TAPS 1	28 October 1969	49.6	3875
TAPS 2	28 October 1969	49.6	3875
CIRUS	10 July 1960	32.0	2400
Dhruva	10 August 1985	12.0	900
Total		281.0	21650

(PREFRE) Facility in Tarapur. The reprocessing capacity of PREFRE is 100 MT/year[31]. However, there have been reports that it has been running substantially below capacity and that transporting fuel to PREFRE, has been difficult due to problems with the rail line that goes to Tarapur[32]. In that case, some of this irradiated fuel from PHWRs may not have been reprocessed. However, with the commissioning of the 125 MT/year Kalpakkam Reprocessing Plant (KARP), the capacity to reprocess all the stored spent fuel certainly exists[33]. Therefore, in order to estimate the amount of waste generated, we will assume that all the spent fuel generated in PHWRs has been (or will be) reprocessed. Similarly, it may be assumed that the 50 MT/year Trombay reprocessing facility has reprocessed all the spent fuel from the CIRUS and Dhruva reactors[31].

Reprocessing spent fuel produces different kinds of waste. The largest component (by volume) is low-level waste that comprises 84% (volume) of the waste stream; however, this only contains about 0.1% of the total activity from the spent fuel. Intermediate-level waste accounts for 14% (volume) and contains about 1% of the radioactivity. High-level waste constitutes the remaining 2%, but contains nearly 99% of the total radioactivity[5].

Modern reprocessing plants generate about 0.4 to 1 m^3 of HLW per tonne of spent fuel reprocessed[34]. But older plants generate more; for example, the Savannah River plant in the United States generated about 4.3 m^3/MT (Zhang, M., to be published). In the Indian case, the Department of Atomic Energy reported that till 1985, 440 m^3 of HLW had been produced[35]. We use this figure to first estimate the amount of HLW generated per tonne of spent fuel reprocessed.

The minimum time of cooling for power reactor spent fuel is 430 days[36]. Assuming that on average, PHWR spent fuel is cooled for 2 years, and the reprocessing process takes another year, the HLW inventory in 1985 would come from spent fuel produced prior to 1982. The only PHWRs operating prior to 1982 were RAPS-I and RAPS-II, which produced 1,59,079 MWeD of electricity from 1978 to 1982 (ref. 37). Thus, it would have produced 75.6 tonnes of spent fuel. Since Dhruva was commissioned only in 1986, only spent fuel from CIRUS could have been reprocessed prior to 1985. Using the methods outlined earlier and assuming a burn up of 1000 MWd/tU and a capacity factor of 0.5, we estimate that the spent fuel produced by CIRUS till 1982 is 138.7 tonnes. Clearly the PREFRE and the Trombay reprocessing plants had sufficient capacity to reprocess all this spent fuel. Using the figure of 440 m^3 and a total spent fuel arising of 214.3 tonnes, we obtain a specific volume of 2.05 m^3 per tonne of spent fuel reprocessed. If we assume that CIRUS fuel, because of its lower burn up and consequently lower heat production rate, is cooled for a shorter period of time, and we include the spent fuel produced in 1983 as well, we obtain a total spent fuel arising of 221.6 tonnes and a specific volume of 1.99 m^3 per tonne of spent fuel reprocessed. We will use a figure of 2 m^3 of HLW per tonne of spent fuel reprocessed.

Using a value of 2 m^3 of liquid HLW per ton of reprocessed spent fuel, we estimate the HLW inventory resulting from reprocessing all the fuel irradiated till 31 December 2000, to be 4992 m^3. The corresponding cumulative production of ILW and LLW is 34,944 and 2,09,664 m^3 respectively.

The actinide content of the HLW can be calculated by using standard computer programs like ORIGEN2. For the research reactor fuel, the total actinide content in spent fuel is approximately 0.9 kg/tU, 90% of which is plutonium (predominantly Pu-239). In the case of PHWR fuel, due to the higher burn up the total actinide content is approximately 4 kg/tU, 97% of which is plutonium[38].

The Indian nuclear programme covers every step of the nuclear fuel cycle. In this paper we have estimated the total nuclear waste generation from the various steps using public sources of information and standard methodologies. These are summarized in Table 6, where we have rounded-off all quantities to 2 significant digits.

Our assumptions have been conservative and may underestimate waste generation. We have ignored several contributions; for example, the waste generated during decommissioning of nuclear facilities or during maintenance operations like coolant channel replacement. This could be significant: coolant channel replacement in the RAPS-II reactor produced '200 tonnes of radioactive waste comprising 306 coolant tubes, 612 end-fittings, 612 garter springs, 612 shield plugs, etc. having radiation fields ranging from 50 to 800 R/hr'[39]. We have also ignored waste generation from the FBTR and smaller research reactors, and associated fuel cycle facilities and operations.

The available information in the public literature is limited and our estimates could consequently have inadequacies. Our estimate, therefore, has to be considered as a preliminary one. However, the methodology that we have followed has been described in sufficient detail so that it could be used to modify estimates, when new data is available. It could also be used as a rough check, should

Table 6. Total nuclear waste generation in India

Step in nuclear fuel cycle	Waste estimate (2 significant digits)
Uranium mining and milling	4.1 million tonnes
Fuel fabrication	2000 m^3
Reactor operations (low-level waste)	22000 m^3
Reactor operations (intermediate-level waste)	280 m^3
Spent fuel storage (not to be reprocessed)	400 tonnes
Reprocessing (high-level waste)	5000 m^3
Reprocessing (intermediate-level waste)	35000 m^3
Reprocessing (low-level waste)	210000 m^3

there be official declarations of the quantities of waste produced.

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A new feature of low latitude geomagnetic storms

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It has been shown that the geomagnetic storms during their main phase cause significant decrease in the geomagnetic *H* field at low latitudes, in addition to that expected due to the disturbance ring current. This additional westward equatorial ionosphere current at low latitude coincides in time with the period of high interplanetary magnetic *B* field, its southward direction and large auroral electrojet current. It is suggested that this auroral electric field associated with high latitude field-aligned currents and is transmitted to low latitudes by the earth and ionosphere transmission line processes.

MOOS[1] was the first to identify the characteristics of geomagnetic storms at a low latitude station, Colaba, India. He also found an additional solar daily variation (now called disturbance daily variation, *SD*) imposed on the normal daily variation (*Sq*) during disturbed days. Egedal[2] had discovered that the range of solar daily variation of the horizontal geomagnetic field *H*, shows a maximum within ± 3° latitudes around the magnetic equator. Chapman[3] explained the effect as due to an eastward-flowing hand of current in *E* region of the

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