
Costing plutonium: economics of reprocessing in India

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Abstract: The relative merits of reprocessing and direct disposal of spent nuclear fuel have been widely debated in Europe and the USA. An important aspect of the debate has been the economics of reprocessing. So far there have been no studies of the subject in the Indian context. This study assesses the economics of reprocessing in India and the cost of producing plutonium for the fast breeder reactor programme. Our results suggest that the cost of reprocessing each kilogram of spent fuel would cost approximately Rs. 26,000 (approx. \$600) with assumptions favourable to reprocessing, and close to Rs. 30,000 (approx. \$675) under other assumptions. These costs are lower than the corresponding figures for reprocessing plants in Europe, the USA, and Japan. As in their case, however, it is unlikely to be an economically viable method of waste disposal.

Keywords: reprocessing; plutonium; nuclear; India; breeder; reactors; energy economics; radioactive waste; spent fuel.

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1 Introduction

India's nuclear energy programme appears to be poised for a major expansion. This expansion includes plans for several fast breeder reactors,¹ which produce more fissile material than they consume. The Indian Department of Atomic Energy (DAE) has been long committed to such a programme and continues to pursue it even though many other countries have suspended their programmes due to economic and safety related reasons. The fuel used in breeder reactors is usually in the form of Mixed Oxide (MOX) Fuel, a mixture of uranium and plutonium oxides.² The plutonium for this is obtained through the reprocessing of spent fuel from the Pressurised Heavy Water Reactors (PHWRs) that form the bulk of the current fleet of reactors.

The relative merits of reprocessing and direct disposal of spent nuclear fuel have been widely debated in Europe and the USA. An important aspect of the debate has been the economics of reprocessing. So far there have been no studies of the subject in the Indian context. This paper assesses the economics of reprocessing and the cost of producing plutonium for the fast breeder reactor programme.

2 Technical background

Nuclear reactors are mostly fuelled by uranium. The uranium found in nature has two primary isotopes,³ U-235 and U-238. Only U-235 is capable of undergoing fission and producing energy in nuclear reactors. However, some of the U-238 in the original fuel absorbs neutrons and is converted into plutonium, an element not found in nature except in trace amounts. Plutonium is also capable of undergoing fission and can therefore be used to fuel reactors.⁴ This opens up the possibility of extracting a much greater amount of energy from the original uranium and a larger nuclear generation capacity based on the finite amount of uranium ore available.

To extract the plutonium, the spent (irradiated) fuel has to be chemically processed. The technology generally used to extract the plutonium (and uranium) from the spent fuel is called the Plutonium-Uranium Redox Extraction (PUREX) process (Benedict et al., 1981).⁵ The PUREX process also produces a nitric acid solution known as High Level Waste (HLW) that contains the intensely radioactive fission products of the original spent fuel. The rest of the radioactivity in the spent fuel is separated into Low Level and Intermediate Level Wastes (LLW and ILW).⁶ These different kinds of wastes are treated differently. Because the HLW, which contains the bulk of the radioactivity present in the original spent fuel, occupies only a fraction of the volume of spent nuclear fuel, some have argued reprocessing also offers a superior way to manage the radioactive spent fuel, when compared to the direct disposal of spent fuel in geological repositories.⁷ Reprocessing, thus, simultaneously takes care of two issues for economies and utilities operating nuclear reactors:

- it produces fuel for nuclear reactors
- it offers a way of dealing with the radioactive spent fuel coming out of the reactors.

3 Debate over reprocessing

There has been a debate over reprocessing in the Western context for decades. The economics of reprocessing is an important element in the discussion, in addition to others such as lack of adequate storage space, safety, and environmental issues.

The general consensus seems to be that it is economically unviable to pursue reprocessing for the following reasons. As a purely waste management option, reprocessing is expensive in comparison to direct disposal of spent fuel because of the high capital costs involved.⁸ What could make it more attractive is if a credit can be attached to the recovered plutonium. However, the fabrication costs of the MOX fuel are very high in comparison to the corresponding costs for uranium fuel. Therefore even if the plutonium were assumed to be available at zero cost, at current uranium prices, the cost of generating electricity using MOX fuel would be non-competitive (Berkhout, 1997; NEA, 1994; National Research Council, 1996; Bunn et al., 2003, 2005; Deutch et al., 2003). For example, Deutch et al. (2003) estimate a open fuel cycle cost of 0.515 ¢/kWh (US cents per kilo-Watt-hour) for a uranium ore price of \$30/kg whereas the corresponding figure for plutonium based fuel is 2.24 ¢/kWh.⁹

In other words, these studies show that at current uranium prices, the value of the plutonium is simply not high enough to offset the cost differences between reprocessing and direct disposal. For reprocessing to become economically competitive with direct disposal as a way of dealing with spent fuel, the price of uranium should increase many fold. For instance, Bunn et al. (2003) show that even at a hypothetical reprocessing cost of \$1,000 per kilogram of spent fuel, far lower than actual costs (let alone prices) at the large European reprocessing plants, Thorp and Cogema, reprocessing will continue to be more uneconomical than direct disposal of spent fuel, until the price of uranium increases from \$40/kg (price in 2003) to \$370/kg, which is unlikely for many decades to come.

Among these different studies, there are differences in overall costs because of the different cost figures assumed for various stages of the nuclear fuel chain, methodologies followed and the different ways economic credit or penalty is applied to the plutonium produced. The overall message, however, seems to be that currently, reprocessing neither serves as an efficient waste disposal option, nor is it economical to recycle the reprocessed fuel as an alternative to uranium.

4 The Indian case

All the studies referred to in the earlier section are based on data from US, UK or French reprocessing plants. There has been no corresponding study of the advantages or disadvantages of reprocessing in the Indian context. The economics of the closed nuclear fuel cycle in India has been an uncharted area because the cost of reprocessing is unknown. In this paper, we attempt to arrive at this cost, and thereby the cost of plutonium, which will enable an analysis of the economics of generating electricity through plutonium-fuelled reactors.

The results of the Western studies are not directly applicable in the Indian context for the following reasons. First, most of the nuclear reactors in India are PHWRs, and except for Canada, no other OECD country operates PHWRs. Because the nature of the spent fuel produced in LWRs is quite different from that of the PHWRs, the costs of dealing with its spent fuel would also be different.

Second, the DAE claims that the

“Indian reprocessing and storage costs in terms of installation and operation are substantially lower in comparison to the figures reported for western countries.” (Balu and Ramanujam, 1999)¹⁰

Similarly a former head of the DAE argues

“the cost of [the Trombay] plant was less than half the estimated cost of a similar capacity plant under construction at that time in another country. Our subsequent experience in the construction of a power reprocessing plant has confirmed our ability to set up and operate small capacity reprocessing plants at costs lower than indicative reprocessing costs elsewhere in the world.” (Sethna, 1979)

Therefore, despite the general conclusion in Western studies that reprocessing is uneconomical and although no rigorous study has been conducted to support its assertions, the DAE has maintained that “*economic considerations dictated the need for spent fuel reprocessing in India*” (Prasad, 1996, p.13) (our emphasis).

A more prevalent non-economic argument in favour of reprocessing in India has been that its reserves of uranium are “limited and low grade”, i.e., the ore is of poor quality (Chidambaram and Ganguly, 1996). Therefore, goes the argument, for nuclear power in India to expand, reprocessing and recovering plutonium is necessary. This is in line with the view expressed by the DAE that spent fuel is not to be considered waste and that “it is a resource to extract plutonium from” (Chidambaram, 1996).

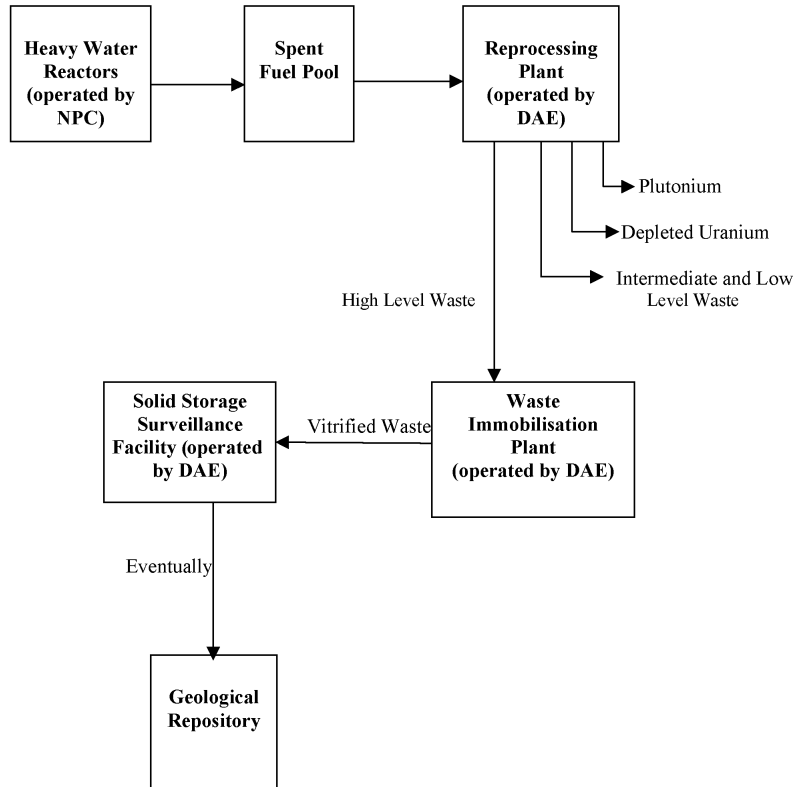
The Indian strategy for reprocessing envisions not just plutonium-based breeders as in other countries but also using thorium, of which it has large reserves. Thorium can not by itself be a fuel in nuclear reactors, but can be converted to an isotope of uranium (U-233) that can fuel a reactor. This offers the justification for the three-phase strategy originally proposed by Homi Bhabha, the first head of the Indian nuclear programme (Bhabha and Prasad, 1958). The first stage involves the use of uranium fuel in heavy water moderated reactors, the second stage involves fast breeder reactors that use plutonium from reprocessed spent fuel from PHWRs and uranium and thorium to produce plutonium and uranium-233 and the third stage involves breeder reactors using uranium-233 and thorium. This three-stage programme is seen as ensuring energy security (Chidambaram, 2000), but this is debateable (Suchitra and Ramana, 2006).¹¹ Fast breeder reactors based on plutonium fuel “thus form a vital link between reactors based on uranium fuel and the ... reactors based on thorium fuel”. Therefore, the DAE has labelled the reprocessing of fuel a key element of India’s long-term nuclear strategy (DAE, 1992a, p.2.24; Srinivasan, 1996).¹² Once again, no economic studies have been conducted to validate the assumption that the production of electricity through breeder reactors is comparable in cost to doing so through other means.

Such studies cannot be conducted rigorously because, as mentioned earlier, there are no estimates of the cost of reprocessing in India. Much of the data needed to undertake an independent analysis of this cost is difficult to come by in the public domain, given that the DAE’s operations with respect to reprocessing are shrouded in secrecy. Nevertheless, we have tried to use whatever data are available publicly to estimate the cost of reprocessing.

To calculate the cost of the plutonium produced, one has to remember that reprocessing in the Indian context provides both a service, i.e., dealing with the spent fuel, and a product, plutonium. Reprocessing also produces depleted uranium, but as we

discuss in the appendix, we assign this a zero economic value. Thus, the cost of plutonium will depend on whether the organisation that operates the reprocessing plant, which in the Indian case is the DAE, charges the utility that operates the nuclear reactor, which in the Indian case is the Nuclear Power Corporation (NPC), a fee for dealing with the spent fuel (See Figure 1 for a description of the fuel chain).

Figure 1 Nuclear fuel chain in India



There are in principle three possible scenarios. The first is that the DAE charges NPC a positive fee for dealing with the spent fuel. This is roughly analogous to what is practised in the West.¹³ The second is that the DAE buys the spent fuel from the NPC, i.e., the plutonium contained in the spent fuel is considered to have more than enough value to pay for the cost of reprocessing. This would be equivalent to a negative fee. The third option involves neither of these – the DAE simply takes over the spent fuel (and the responsibility of dealing with it) from the NPC for a zero fee. The third option is what is practised in India (Thakur and Chaurasia, 2005).

Once the DAE takes over the responsibility of dealing with the spent fuel, it bears all subsequent costs. We emphasise that the rational option would be for it to charge the NPC a fee because it offers a service to the latter. If such a fee were to be charged, it would then imply an increase in the cost of producing electricity in the NPC's PHWRs. But in the currently followed practice, such a fee is not charged. The cost of plutonium therefore would equal what it costs to produce it from the spent fuel, i.e., the cost of reprocessing. This cost then should be the basis for the rate at which the DAE either

'sells' or 'leases' the plutonium to the organisation operating the fast breeder reactor. In order to account for the first possibility, we also calculate the cost of plutonium with a credit given for the cost of direct disposal.

5 The Kalpakkam reprocessing plant

In India, currently there are three major reprocessing plants, one at Trombay, the second at Tarapur, and the third at Kalpakkam. Reprocessing of spent fuel started with the commissioning of the Trombay plant with a capacity of 30 tons of spent fuel per annum in 1964.¹⁴ The plant was shut down after the first Indian nuclear test in 1974 for renovation and capacity increase. When it restarted operations in 1985, its capacity was increased to 50 tHM/y (Anonymous, 1996). The second plant, PREFRE, at Tarapur, began operations in 1982 with a capacity of 100 tHM/y and reprocessed spent fuel from safeguarded power reactors. Since then it has also reprocessed spent fuel from other (unsafeguarded) power reactors. In the 1990s, it was reportedly running 'substantially' below its nominal capacity (Hibbs, 1992b, 1995). The third reprocessing facility, the Kalpakkam Atomic Reprocessing Plant (KARP) facility, with a capacity of 100 tHM/y, was commissioned in 1998 (DAE, 2000b, p.25). This plant was set up primarily to reprocess spent fuel from the Madras Atomic Power Station (MAPS) (Hibbs, 1997).¹⁵

The DAE envisions augmenting its reprocessing capacity in a phased manner, from the current annual capacity of 250 tHM to 550 tHM by the year 2010. There are also plans to further increase this to 850 tHM by 2014 to cater to the needs of additional breeder reactors (Dey, 2003). It is therefore important that the economics of reprocessing is examined now, before the large scale expansion envisaged actually happens.

We note, however, that such plans for expanding reprocessing capacity have been announced in the past too. In 1987, for example, Iyengar, who was to go on to head the DAE, wrote, that

"a plant with 400 t capacity is planned to become operational by mid 1990s to receive spent fuel from Narora and Kakrapar reactors. It is envisaged that another 400 t capacity plant would have to be suitably located for reactors beyond Kakrapar to bring the total reprocessing capacity to 1000 t by 2000." (Iyengar, 1993)

Neither of these plants was built.

The reprocessing plant that we use as the reference in our examination of the economics of reprocessing in India is KARP, because it is the most recently constructed reprocessing plant and is to serve as a standard design for future plants (Dey, 2003). After being commissioned in 1998, it is reportedly operating satisfactorily since 1999 (DAE, 2000a, 2001, 2002). The operation of the plant was originally planned for 1993 but delayed owing to quality control problems in piping and other equipment (Hibbs, 2003a). It is said to have two reprocessing lines each with a design capacity of 100 tHM/y.

6 Methodology

We use the standard Discounted Cash Flow (DCF) approach to arrive at the cost of reprocessing (Brealey and Myers, 2000). In this approach, all costs are discounted to

some arbitrary but fixed reference date; the total cost reckoned at this reference point is the sum of the Present Values (PV) or Future Values (FV) of costs discounted to this date. All the costs will be expressed in constant rupee terms (2004 prices). We use a real discount rate of 5%. We assume a dollar exchange rate of \$1 = Rs. 44. We assume that the total lifetime of the plant is 15 years.¹⁶ The cost of reprocessing is thus equal to the total cost spread over the lifetime of the plant assumed to function at a particular capacity factor.

As mentioned earlier, the capacity of KARP is 100 tHM/y. Because there is no information available on the actual capacity at which the plant has been operating, we estimate the costs assuming a capacity factor of 80%. We will vary this to 70% to check the sensitivity of the costs to capacity factor.

Studies based on reprocessing plants in the West also assume capacity factors in the range of 70–80%. In the OECD/NEA study, for example, the reprocessing plant is assumed to operate at a capacity factor of 75% (NEA, 1994). Actual performance figures may be even lower; for example, the British THORP reprocessing plant has been running at 50% of capacity for the last several years (Brown, 2003). Similarly the Tokai reprocessing plant in Japan operated at less than 45% capacity between 1977 and 2005 (Walker, 2006).

Our assumption of a capacity factor of 80% is optimistic (and favourable to the economics of reprocessing). Past performance of reprocessing plants in India has been mediocre at best. PREFRE, at Tarapur, operated at an average throughput of less than 25 tHM/y for over a decade, while its nominal design capacity was 100 tHM/y (Hibbs, 1995). A lot of refurbishment was required to keep the plant running (DAE, 1992a, 1995a, 1996a, 1998, 2005).¹⁷ This is not very surprising because reprocessing, by its very nature, uses harsh chemicals and deals with extremely radioactive materials. KARP itself was shut down at least once for an extended period in 2003 because of an accident (Anand, 2003). Such shut downs would imply a lower throughput.

KARP is designed to process spent fuel from PHWRs with an “average irradiation or burnup of about 7000 MWd/T and an out-of-pile cooling of not less than one year” (DAE, 1996b). Burnup is the amount of energy produced per unit mass of fuel irradiated. Table 1 gives the amounts of the different isotopes of plutonium in PHWR spent fuel with a burn up of 7000 MWd/tU.¹⁸ Therefore for each ton of spent fuel reprocessed in KARP, approximately 3.75 kg of plutonium is recovered (We assume that 100% of the plutonium is recovered).

Table 1 Plutonium and Americium Isotope Content in PHWR spent fuel (g/tHM)

<i>Radionuclide</i>	<i>3-year cooling</i>	<i>5-year cooling</i>
Pu238	3.29E+00	3.24E+00
Pu239	2.72E+03	2.72E+03
Pu240	8.42E+02	8.42E+02
Pu241	1.60E+02	1.45E+02
Pu242	4.10E+01	4.10E+01
Am241	2.67E+01	4.18E+01

The total cost of reprocessing consists of three components. These are the capital cost of constructing the facility, the annual Operations and Maintenance (O&M) costs, which will be incurred for as long as the facility is running and the waste management expenses from the running of the facility in an environmentally acceptable manner. Apart from these, there is also the cost of decommissioning the facility and disposing the radioactive and other materials after the plant has finished its operating life.

The data sources that we use for the estimation of these costs are the Performance Budgets and Annual Reports of the DAE, the Expenditure Budgets of the Government of India and reports of the Comptroller and Auditor General (CAG) and the Ministry of Statistics and Programme Implementation. Unfortunately, none of these sources is comprehensive in reporting the expenditure on the reprocessing plant and associated facilities. There are also various inconsistencies between different reports (and sometimes different pages on the same report) that we have tried our best to resolve. Owing to these reasons, therefore, we had to make various assumptions to supplement these sources. These are discussed in the respective sub-sections.

6.1 Capital costs

The largest component of the cost of reprocessing is the capital cost of the plant, which includes the cost of constructing the plant, and all other costs incurred on the plant till its commissioning. KARP was sanctioned in 1983 (DAE, 1987, p.19) at a cost of Rs. 0.96 billions (DAE, 1997, p.20).¹⁹ This seems to have been subsequently revised to Rs. 1.43 billions (DAE, 1997, p.20; DAE, 1999, p.81). However, the estimated cost of KARP has been variously mentioned as Rs. 1.74 billions (DAE, 1987, p.41), Rs. 2.65 billions (DAE, 1991), Rs. 2.95 billions (DAE, 1992b, p.37), Rs. 3.51 billions (DAE, 1993, p.29) and Rs. 3.78 billions (DAE, 1995b, p.35).

To estimate the capital cost, we use the figures on annual expenditure on KARP from 1983–1984 to 1999–2000 given in the DAE's Performance Budgets. The sum of these is Rs. 5.58 billions (Mixed year Rs), which translates to an overnight construction cost of Rs. 12.85 billions (2004 Rs.).²⁰ At Rs. 44 per US Dollar, this is \$292.2 millions or \$2.9 millions/tHM.

This could be compared to the capital cost of the 800 tons per annum THORP plant in England of \$5.9 billions (Bunn et al., 2003). Its unit capital cost is therefore \$7.4 millions/tHM. The French UP2 and UP3 reprocessing facilities with a combined capacity of 2000 tHM/y at La Hague cost over \$16 billion (2003 dollars), implying a unit capital cost of over \$8 millions/tHM (Schneider, 2006).²¹ Thus, the capital cost for the Indian reprocessing plant is about 40% of the cost of the cheapest of the European plants under operation.²²

6.2 Operations and Maintenance (O&M) cost

This includes the expenses incurred during the day-to-day functioning of the reprocessing plant after its commissioning. It includes the costs of running the plant, materials for maintenance, payment of salaries to employees, monitoring activities, as well as some of the costs involved in dealing with radioactive and other wastes. There appears to be no publicly available data on these costs; the DAE Performance Budgets as well as the government Expenditure Budgets have not published any expenditure figures on KARP after 1998.²³ We therefore use the available annual O&M expenditure on the Tarapur

PREFRE plant, which is similar in size and capacity. We take the average of the O&M costs of the plant from 1984–1985 up to 1997–1998 as the annual O&M expenditure on KARP.²⁴ This works out to be Rs. 94 millions/year (\$2.14 millions/year).

6.3 *Waste management costs*

As mentioned earlier, reprocessing generates three kinds of waste, which are treated differently. At KARP, the Low Level Wastes (LLW) are treated and released into the environment. The two streams containing the concentrated fission products (ILW and HLW) are stored in liquid form in waste storage tanks.

As the first stage of management, these wastes are sent to a Waste Immobilisation Plant (WIP) to be vitrified. Such a plant is also being built at Kalpakkam. Although it was assumed that vitrification technology had developed sufficiently to carry it out concurrently with the reprocessing (Prasad, 1996, p.18), this has not happened at KARP. Even in its 2004–2005 Annual Report, the DAE described WIP, Kalpakkam as an ‘ongoing project’ and as recording ‘good progress’ (DAE, 2005, p.4).

The initial cost estimate of WIP, Kalpakkam in 1983–1984 was Rs. 165 millions (GoI, 1985, p.44). However, this seems to have been revised to Rs. 500 millions (DAE, 1997, p.21). We have come across nothing more recent than that. Therefore even though the plant has so far not been constructed, we assume that the total cost is the revised estimate of Rs. 500 millions (mixed year Rs); in 2004 Rs, this works out to be Rs. 912 millions (\$20.7 millions).²⁵ Based on the O&M expenses of the WIP in Tarapur as reported in the DAE Performance Budgets, we assume that the annual O&M expenditure on WIP, Kalpakkam will be Rs. 62 millions/year (\$1.4 millions/year). We assume no decommissioning costs for WIP.

Several countries have chosen to store HLW (and ILW in some cases) at interim storage sites for long periods, typically projected at many decades, to provide flexibility in final disposal plans and to reduce the heat generation rate. This is followed by the DAE too and constitutes the second stage of waste management. The vitrified HLW from WIP, Kalpakkam is to be stored for some decades at the Solid State Surveillance Facility (S3F) at Tarapur.

S3F was commissioned on 26 July 1999 (Anonymous, 1999). The initial financial sanction of Rs. 100.1 millions for the S3F facility was issued in December 1979 and the project was to be completed in 1985. The financial sanction was revised to Rs. 165.8 millions in June 1985 and to Rs. 173.8 millions in July 1992. As of September 1995, Rs. 171.5 millions had been spent on the S3F (CAG, 1996). There is no publicly available information on the final cost; hence we assume that it was the same as the sanctioned amount of Rs. 173.8 millions (mixed year Rs); in 2004 Rupees, this works out to be Rs. 664 millions (\$15.1 millions). There are no public figures whatsoever on its O&M costs and we assume that this is negligible, an assumption favourable to the economics of reprocessing. Similarly we ignore its decommissioning cost. The storage cost for the HLW derived from each ton of spent fuel reprocessed turns out to be Rs. 0.5 million or \$12217.²⁶

After some decades of cooling at the S3F facility, the vitrified wastes are to be eventually stored in a geological repository (quite akin to that which would be used in the case of direct disposal). There are no estimates whatsoever of the cost of such a facility, in part because even the potential location of the repository has not been finalised. No other country has experience with reprocessing of spent fuel from PHWRs

(CANDU reactors). The DAE has not presented any public estimates of the cost of geological disposal of reprocessed and vitrified waste from PHWRs.

When compared to LWR fuel, geological disposal of PHWR fuel (either directly or after reprocessing) should be cheaper on account of lower burn up and consequently lower concentration of fission products. This reduces heat production and toxicity levels. Because PHWRs use natural uranium, there is less danger of the material reaching criticality (and starting a chain reaction) either.

In order to estimate the cost of geologically disposing of vitrified HLW, we use the cost of the geological repository in the direct disposal route. The detailed estimate is presented in Appendix 2. The overall direct disposal cost (including the transportation cost, the cost of interim storage and of the geological repository) in India works out to be Rs. 1.1 millions/tHM (\$25000), of which the cost connected with the geological repository alone constitutes Rs. 0.45 million/tHM (\$10200).

In order to use this to estimate the cost of geologically disposing of vitrified HLW, we note that the cost of the potential geological repository depends on the heat produced by the vitrified HLW and the volume of the packaging used (Bunn et al., 2003). Further, the cost of the geological repository includes both a fixed component and a component that varies with the volume of the waste disposed. Based on these considerations, Bunn et al. (2003) estimates that the cost of a geological repository for reprocessed waste would be only 45% of the same in the case of the direct disposal route. We adopt the same reduction factor and assume a cost of Rs. 0.2 million/tHM (\$4550) for the geological disposal of vitrified waste. We assume a similar reduction in the case of transportation of vitrified waste to arrive at a figure of Rs. 0.135 million/tHM (\$3070). Therefore, the total cost of dealing with the HLW after it leaves the S3F facility is estimated as Rs. 0.335 million/tHM (\$7600).

6.4 Decommissioning

After the reprocessing plant has gone through its operating life, it will have to be decommissioned. Decommissioning plants which treat plutonium present a “significantly greater challenge” than facilities that only deal with uranium (Gordelier, 1997). This makes the process very expensive. The cost of decommissioning the French UP1 reprocessing plant is estimated at 5.6 billion Euros (\$6.7 billions) (UIC, 2006). Decommissioning the Japanese Rokkashomura plant after 40 years of operation is estimated at a staggering 2.6 trillion yen (\$22 billions) (Hibbs, 2003b).

We follow the OECD’s Nuclear Energy Agency and assume that the decommissioning of the reprocessing and associated servicing plants cost “30% of the original capital cost (in constant money terms)”, and that the expenditure is assumed to start 20 years after the end of the operating life of the plant and be spread out over seven years (NEA, 1994, p.114). The total amount in 2004 Rupees is Rs. 4.12 billions (\$94 millions); when discounted to 2004 this turns out to be Rs. 830 millions (\$19 millions).

7 Results

The data that have gone into our calculation of the cost of reprocessing are summarised in Table 2. Based on these figures, we estimate the cost of reprocessing to be

Rs. 25,983 per kg of spent fuel (\$591) without any credit for direct disposal. This translates to Rs. 6745 (\$153) per gram of plutonium. If a credit of Rs. 1100 per kg of spent fuel is applied, these become Rs. 24,882 (\$565) and Rs. 6633 (\$151) respectively.

Table 2 Costs of reprocessing and direct disposal

	<i>Reprocessing</i>	<i>Direct disposal credit</i>
Overnight construction cost of reprocessing plant	\$292.2 millions	–
Annual O&M expenses of reprocessing plant	\$2.14 millions	–
Overnight construction cost of WIP	\$20.7 millions	–
Annual O&M expenses of WIP	\$1.4 millions	–
Capital cost of S3F	\$15.1 millions	–
Transportation	\$3070 ²⁷	\$6818/tHM
Away from reactor storage	–	\$8400/tHM
Geological repository costs	\$4500/tHM	\$10000/tHM
Decommissioning of KARP	\$94 millions	–
Efficiency of reprocessing plant	80%	–
Amount of Plutonium (kg) per ton of spent fuel	3.75	–

All figures are in 2004 US dollars.

At face value, these costs are lower than the corresponding costs at reprocessing plants in Europe and the USA, which are estimated to be in the range of \$1350–2000 per kg of spent fuel (Bunn et al., 2003). We emphasise, however, that these are not directly comparable because of the different kinds of spent fuel being processed and the different financing structures. Nevertheless, this is consistent with the DAE's claims that reprocessing costs in India are cheaper.

The largest component of the total cost of reprocessing is the capital cost of the reprocessing plant. The unit capital cost may be lower in larger capacity reprocessing plants because of economies of scale. However, there are other considerations that are at play. As a former DAE official argued,

“While in industrialised countries large capacity centralised reprocessing plants may be favoured for achieving economies of scale experience has shown that apart from other considerations the optimum capacity of a processing plant is essentially a function of the parameters specific to the country in which it is located. In India, the problems of transporting heavy spent fuel shipping casks over long distances via heavily loaded rail links (involving in some cases, trans-shipment because of different rail gauges) or by roads of variable quality, are formidable. This has led to the concept of multiple smaller-capacity reprocessing plants, located as close as possible to the reactor sites.” (Srinivasan, 1985)

Nevertheless, we do assume a lower capital cost to allow for future developments. The general rule of thumb is that capital costs scale with a power of 0.6 (National Research Council, 1996, p.421). In other words, if a new plant were to have a capacity of twice that of KARP (i.e., 200 tHM/y), then the overnight construction cost of the plant per unit capacity will be \$2.2 millions/tHM/y. Similarly all the associated facilities (WIP, S3F) will have lower unit capital costs. In this scenario, the cost of reprocessing comes down to about Rs. 20,374 per kg of SF (\$463).

The significance of the capital cost to the cost of reprocessing is also demonstrated through the sensitivity to the choice of discount rate. At a real discount rate of 3%, the levelised cost of reprocessing goes down to Rs. 21,385 (\$486) whereas at a real discount rate of 6% the cost goes up to about Rs. 29,010 (\$659) per kg of SF.

The cost of reprocessing depends sensitively on the efficiency with which the plant operates. As mentioned earlier, we have assumed an optimistic 80% in our calculations. If the efficiency were to decrease to 70%, then the reprocessing cost goes up to Rs. 29,569 per kg of SF (\$672).

In the way we have calculated them (at a 5% discount rate), waste disposal costs are a relatively minor part of the cost of reprocessing. There has been a big debate on how to deal with costs that are to be borne by future generations for thousands of years and some have argued that a zero discount rate ought to be applied for these situations (Howarth and Norgaard, 1993). Nevertheless, we use a non-zero discount rate in our calculations in order to be favourable to the economics of reprocessing.

It is clear that simply the cost of reprocessing spent fuel is higher than directly disposing it. What could make reprocessing economically viable would be if the plutonium were to be used in nuclear reactors to produce electricity and that turns out to be cheaper than the corresponding costs of producing electricity using uranium fuel. It has been established that this is not the case with Western reactors and associated facilities till uranium prices are much higher than current values (Bunn et al., 2003). But as we have noted before, and have found in our calculation of reprocessing costs, economic figures in the Indian case are somewhat different. Whether reprocessing might be economically viable if the plutonium were to be used at the DAE's fast breeder reactors will be explored in a future paper.³⁰

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Notes

¹A breeder reactor is a nuclear reactor in which non-fissile material such as uranium-238 is converted to fissile material at a rate greater than the rate at which fissile material is used up by the reactor. In this way, fuel is 'bred'. A 'fast breeder reactor' is fuelled by plutonium in a reaction using 'fast' neutrons, i.e., energetic neutrons not slowed down by a moderator such as water or graphite used in more common 'thermal' reactors.

²There are plans to develop metallic and carbide fuel for breeder reactors as well but these are currently largely at a Research and Development stage.

³Isotopes are different varieties of the same element (i.e., same atomic number) with different atomic masses.

⁴A small fraction of the Pu-239 nuclei produced when U-238 absorbs neutrons also undergo fission.

⁵This extraction is achieved by manipulating the chemical reduction-oxidation states of the plutonium and uranium ions in solution. For details see Benedict *et al.* (1981)

⁶These terms refer to the concentration of radioactivity in these waste mixtures. According to the categories followed by the DAE, the activity level of LLW is less than 0.1 Curies/m³, of ILW is between 0.1 and 10,000 Ci/m³, and HLW is greater than 10,000 Ci/m³.

⁷If the spent fuel is reprocessed and the plutonium extracted is used to fuel nuclear reactors, then the fuel cycle is called a closed cycle. If the spent fuel is directly disposed, then it is termed an open cycle.

⁸Nevertheless reprocessing is often justified as a way of dealing with the vast quantities of spent fuel produced in countries with large nuclear power capacity. This is especially true in several Western European countries like Germany and countries like Japan where there is considerable public opposition to opening new spent fuel storage sites.

⁹The latter figure is for a reactor fully loaded with plutonium based MOX fuel. For safety reasons, Light Water Reactors are typically operated with only about 30% of the fuel being MOX. The cost of generating electricity at such a reactor would be $0.7 \times 0.515 + 0.3 \times 2.24 = 1.03$ €/kWh.

¹⁰If this be the case, then one would also expect lower costs for the direct disposal route. However, there are no public estimates of the costs of direct disposal in the Indian context.

¹¹For an argument about why nuclear power in general, and India's nuclear power programme specifically, does not ensure energy security, see Suchitra and Ramana (2006).

¹²The DAE also claims that as far as India is concerned, economics aside, reprocessing has represented something else, "a spirit of adventure" (Srinivasan, 1996).

¹³European reprocessing plants like COGEMA and THORP charge utilities owning nuclear reactors a fee in the range of \$1,800–2,300 per kilogram of spent fuel (kgHM) currently, to take care of the spent fuel. After reprocessing, the extracted plutonium and uranium, as well as the HLW, are shipped back to the country of origin. Because the primary function of reprocessing is seen as dealing with spent fuel, the plutonium is seen more as a byproduct of this whole process and a cost of production is not calculated rigorously.

¹⁴The Trombay reprocessing facility is used to reprocess the spent fuel produced by CIRUS and Dhruva, the two research reactors used to produce weapons grade plutonium. The processing capacity of reprocessing plants is expressed typically in terms of tons of spent fuel that it can handle at full capacity. Some also use the term tons of Heavy Metal (tHM) to express the same quantity (Hibbs, 2003a).

¹⁵For reprocessing the spent fuel from the FBTR, the Indira Gandhi Centre for Atomic Research (IGCAR) set up a Fast Reactor Fuel Reprocessing Plant (FRFRP) at Kalpakkam with a sanctioned cost of Rs. 35 crores. It was the first plant of its kind in the world to reprocess large quantities of mixed carbide fuel (DAE Performance Budget, 1996–1997, p.21).

- ¹⁶Before KARP was commissioned, it was stated that the two reprocessing lines would not be run in parallel; the first was supposed to run for seven to eight years and then decommissioned, at which time the second line would take over (Hibbs, 1997). According to the 2005 Annual Report of the DAE, KARP is undergoing major modifications, which may be an indication that the process of switching from one line to another is underway (DAE, 2005).
- ¹⁷Since the 1990s, several Annual Reports of the DAE mention PREFRE as undergoing revamping or being started up after revamping, indicating that it must have been shut down for extended periods of time (DAE, 1992a, p.2.24), (DAE, 1995a, p.2.2), (DAE, 1996a, p.18), (DAE, 1998, p.2.2) and (DAE, 2005, p.37).
- ¹⁸These are based on MCNP calculations by Alexander Glaser and have been corrected for radioactive decays. The americium results from radioactive decay of plutonium-241 and is a contaminant that has to be removed before fuel is fabricated from the plutonium.
- ¹⁹All of these figures are in Mixed Year Rupees. The assumptions about the projected annual expenditures and inflation rates are not publicly available. Therefore, it is not possible to convert these to 2004 Rupees.
- ²⁰This does not include any interest due to construction component for two reasons. First, KARP has been constructed by the DAE and financed by the government, which does not seem to have charged any interest. Second, we are interested in exploring the inherent economical viability of reprocessing and plutonium based reactors, and including an interest based component would make this dependent on the financing package.
- ²¹The 2000 tHM/y is the technical capacity. The licensed capacity is 1700 tHM/y. In recent years, because of a lack of foreign contracts, it may be operating at even lower capacity (Schneider, 2006).
- ²²As mentioned earlier, the kind of fuel reprocessed in Indian plants has lower radioactivity content and heat generation rate compared to the fuel reprocessed at European plants. So these may not be directly comparable.
- ²³This appears to be a general tendency in the DAE's performance budgets after 1998.
- ²⁴We have not included the costs of revamping PREFRE in our estimate of O&M costs.
- ²⁵Since relatively few figures for annual expenditure on WIP, Kalpakkam are available in the public domain, we also assume that the expenditure was evenly distributed across different years (except for those years where the DAE Performance Budgets listed the expenditure or some estimate thereof).
- ²⁶Note that this is not the cost per ton of vitrified High Level Waste, but that of the amount of high level waste generated from reprocessing one ton of spent fuel.
- ²⁷This is for vitrified waste generated by each ton of SF.
- ²⁸It has also been stated that this facility "has been constructed" (Kulkarni *et al.*, 2003). But this is not corroborated elsewhere.
- ²⁹Our results are not particularly sensitive to this assumption.
- ³⁰Our preliminary results suggest that this is unlikely to be the case.

Appendix 1: The value of depleted uranium

As mentioned earlier, reprocessing separates out both plutonium and the uranium that has not undergone fission when it is in the reactor. However, the isotopic composition of this remaining uranium is depleted in U-235 and so cannot be used for fuelling reactors as such. The fuel used in PHWRs is natural uranium with a U-235 content of 0.71% whereas the uranium in the spent fuel with a burnup of 7000 MWd/tU contains only about 0.23% of U-235. To use this in PHWRs, the uranium has to be enriched in the U-235 component. In many countries with a large fleet of Light Water Reactors and

enrichment facilities, therefore, credit is given for this recovered uranium because the cost of enrichment may be less than the costs of mining and milling. However, the Indian uranium enrichment facility in Rattehalli, Karnataka is relatively small and focussed on producing enriched fuel for the nuclear submarine that is being developed (Ramana, 2004a, 2004b). It does not appear to have the necessary capacity to enrich all the depleted uranium produced by even one reprocessing plant.

Depleted uranium is also used in reactors directly either as fuel (in the case of FBRs) or for neutron flux flattening. However, depleted uranium should be copiously available from the enrichment facility at Rattehalli, which is estimated to produce 4–12 tons every year. We estimate that the initial core for the Prototype Fast Breeder Reactor requires about 6 tons and the annual requirement is about 2.5 tons. When compared to depleted uranium from enrichment facilities, depleted uranium from reprocessing plants suffers from the disadvantage that it contains undesirable isotopes of uranium in small quantities.

Therefore, there is no reason to assume that the depleted uranium produced as a result of reprocessing has any economic value. We therefore assign no credit to it.

Appendix 2: The cost of direct disposal

Direct disposal involves long-term storage of the spent fuel followed by its encapsulation and permanent storage in a geological repository. Direct disposal services are currently not available in the world market and each individual country pursues its own approach.

The direct disposal route involves two stages after cooling of the spent fuel in pools at the reactor site. In the first stage, the spent fuel is stored in an interim storage plant for some years allowing for further cooling. In India, there are two such Away From Reactor (AFR) facilities. One was constructed between 1986 and 1990 at Tarapur (Srinivasan, 1995, p.59). The second one is being constructed in Rajasthan.²⁸ This plant will allow for “storage of spent fuel in concrete casks with minimum ten years cooling” (Kulkarni et al., 2003).

The AFR is said to take care of the spent fuel storage for an operating life of 15 or more years for RAPS 1 and 2 (Expenditure Budget, 2005–2006, p.20). At design capacity, these two reactors together would generate about 54 tHM a year. Therefore, the AFR should store 810 tHM. The revised expenditures for this facility during the years 2003–2004 was Rs. 4.13 crores and for 2004–2005 was Rs. 7.71 crores. Assuming that like the Tarapur facility, this takes 5 years to be constructed, we assume that its total cost would be about Rs. 30 crores.²⁹ Therefore, the unit cost of interim storage is Rs. 0.37 millions/tHM (\$8400/tHM).

The second stage in direct disposal involves transporting the cooled spent fuel from the interim storage plant to the geological repository. We assume that the cost of transporting cooled spent fuel is Rs. 300,000/tHM.

The third component is the actual geological disposal. Because no country has to date constructed a geological repository, estimating the cost of the third component is challenging. However, many countries have put out projections for the cost of such a repository. The only country which has done so for PHWR fuel is Canada. We therefore use their projections to estimate the cost of this stage of direct disposal.

The Canadian Joint Waste Owners estimate that just the cost of constructing a deep geological repository is \$12.9 billions for the disposal of 3.7 million fuel bundles, each weighing 20 kg (Joint Waste Owners, 2004). However, much of this expense is several years in future and so the present value of this is \$4.3 billions at a real discount rate of 3.25. To be consistent with our calculations, we do the same using a 5% real discount rate. At this discount rate, the unit cost of geological disposal is Rs. 1120 (2004 Rs.) per kilogram. Just as with the capital cost of the reprocessing plant, the corresponding Indian costs are likely to be less. We therefore scale by the same 40% factor that we calculated in the case of the capital cost, and assume that the unit cost of geological disposal in India would be Rs. 450,000/tHM (\$10,200/tHM).

The sum of these three components (AFR, transportation, and geological disposal) would be the cost of direct disposal of spent fuel and is therefore Rs. 1.1 millions/tHM (\$250,000).