Decommissioning the North Korean Nuclear Facilities: Approaches and Costs [1]

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ABSTRACT

If the agreed objective of complete denuclearization of Korean peninsula is to be achieved, it can be expected that dismantling and ultimately decommissioning North Korean plutonium production facilities have to be proceeded. This paper will focus on decommissioning the 5 megawatt-electric (MWe) plutonium production reactor and the reprocessing plant. It explores and recommends the best decommissioning approaches to those nuclear facilities. It also provides a discussion of the decommissioning costs for these nuclear facilities.

Decommissioning the 5 MWe Reactor

D&D Approaches

There are three main strategies for decommissioning of a nuclear facility: "Immediate dismantling/DECON," "Deferred dismantling" or "Safe enclosure/SAFSTOR," and "Entombment."[2]

DECON. "Immediate dismantling" normally starts within a few years of the shutdown of the facility, giving time for transition to prepare for implementation of the decommissioning strategy.

SAFSTOR. After removal of spent fuel and some peripheral items of equipment, the facility is kept in a state of safe enclosure for a period of 30 to 100 years before dismantling. This strategy requires control of the facility throughout the "safe enclosure" period to ensure the necessary level of safety.

ENTOMB. "Entombment" involves encapsulating the facility on site and keeping it isolated until the radionuclides have decayed to levels that allow the site to be released from nuclear regulatory control. Given that the option of facility entombment would result in an end-state that is essentially equivalent to a near surface disposal facility which could be not accepted under the current regulations, entombment is not a recommended decommissioning option in current situation. However, it could be used as a form of extended safe storage which would

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[1] More details could be found in Matthew Bunn and Hui Zhang, *Decommissioning North Korea's Nuclear Facilities: Issues, Options, and Costs*, Forthcoming.
[2] See, e.g., IAEA, *Selection of decommissioning strategies: Issues and factors*, Report by an expert group, IAEA-TECDOC-1478, IAEA, November 2005.

remove the entombment facility from the site to a waste disposal site. While a few small demonstration reactors have been entombed, no operators have proposed this option for any of the power reactors undergoing decommissioning. Essentially, decommissioning strategy selection is a selection between immediate and deferred dismantling.

Experts around the world have already accumulated experience in the decommissioning of Magnox-type reactors similar to the North Korean 5 MWe reactor. There are 26 Magnox reactors in the United Kingdom, though only four of them are still operating and will soon be shut down. The only two U.K.-exported Magnox reactors, the Tokai-1 in Japan and the Latina in Italy, have been shut down. Also all nine UNGG power reactors (Uranium Natural Graphite Gas, a French design similar to U.K. Magnox, except that the fuel cladding was a magnesium-zirconium instead of a magnesium-aluminum alloy) in France and the sole exported UNGG in Spain (Venio) have been shut down. The term Gas Cooled Reactor (GCR) is used generally to refer to all of these first generation, carbon dioxide-cooled, graphite-moderated reactors, most of which are in the process of being decommissioned. The techniques and equipment for decommissioning full scale commercial GCR power plants have been tested and are available.

Based on current GCR decommissioning plans, it may find some commons regarding to the key phases of the decommissioning. 1) it usually takes about 5-10 years for D&D planning. 2) it usually takes about 3-10 years for preparation of safestore. For DECON option, this period may be have an overlap with the safestore phase (as Japan’s Tokai-1 case). 3)In term of timing, the major difference between DECON and SAFSTOR is at this phase in that the later has a much longer duration. 4) During the last phase taking about 3-10 years, the reactor and remaining building will be dismantled and demolished. The Site will be cleanup and released for alternative reuse. Consequently, it could take least 15 years to complete a DECON project and several decades for a SAFSTOR strategy. Currently most GCR reactors are selecting the SAFSTOR decommissioning option.

The constraints associated with the lack of waste management system and funds could limit the North Korean strategies for decommissioning to deferred dismantling, which would require several decades to complete the D&D project. However, in decommissioning the North Korean nuclear facilities, not only are long-term safety and environmental issues emphasized, but also security aspects. To speed up North Korean denuclearization, these nuclear facilities, including the 5 MWe reactor, should be dismantled as soon as possible. For example, the 1994 Agreed Framework called for a complete dismantlement of the 5 MWe reactor and related facilities within 10 years, by which time a project to supply North Korea with two LWRs would have been completed. Such a timeframe will not be realistic. Based on the above discussion, even if the DECON strategy were employed, completing the D&D project would take least 15 years.

Considering both the security concerns and the different decommissioning strategies, North Korea should find a way to permanently disable the reactor as quickly as possible that also fits in with a suitable decommissioning strategy. One such way could be to cocoon the reactor first, as the United States has been doing at its Hanford reactor site, which would effectively disable the reactor, and then dismantle it after a period of safestore. U.S. decommissioning of the Hanford reactors provides a good example of the SAFSTOR approach.[3]

In summary, applying the Hanford experience to the North Korean case, the North Korean 5 Mwe reactor could be cocooned within 5 years for a cost in the range of $20- 30 million. The safestore period could last for decades (e.g. 75-100 years). Eventually, it could take about 3-10 years for the final stage of dismantling and site clearance. This approach would permanently disable the reactor within 5 years, while providing time for the regulators to determine the final disposal method and to allow radiation levels in the reactor cores to decay to a lower level.

D&D Costs

As discussed above, if U.S. decommissioning of the Hanford reactors can be used as a guide, decommissioning costs of North Korean 5 MWe reactor could be estimated. DOE has projected the *total* costs of various alternatives for decommissioning the Hanford reactors. In its Environmental Impact Statement for decommissioning of the Hanford reactors, DOE evaluated several decommissioning alternatives, including no action (leaving the reactors as they were); immediate one-piece removal (which would involve lifting the entire graphite block of the reactor onto a transporter, moving it elsewhere on the site, and dumping it into a trench for burial); safe storage followed by one-piece removal (same one-piece dumping idea after 75 years of SAFSTOR); safe storage followed by dismantlement (in which the reactor would be disassembled block by block after the 75-year SAFSTOR period, and the blocks similarly buried in a trench), and in situ decommissioning (essentially the ENTOMB approach).[4]DOE chose a period of SAFSTOR followed by one-piece disposal as the preferred alternative for implementation (though reportedly plans may be changing). The total cost for implementing this option for nine reactors was estimated to be $442 million ($467 million in 2007 dollars), or just over $50 million per reactor.

Thus, if North Korean 5 MWe reactor is to apply Handford " cocooning" experience, the decommissioning cost could be around 50 MUSD. However, in practice it would be difficult to estimate the total decommissioning cost of the 5 MWe reactor with precision. For example, as can be seen in table 1, estimated decommissioning cost per reactor varies from $264 million (in the case of France's Chinon reactors) to over $1.6 billion (for Japan's Tokai-1 reactor). Morevoer, if the estimate of D&D costs is based on unit in dollars per MWe (i.e. a range of 0.8-14 million USD per MWe as shown in table 1, then the decommissioning cost of the North Korean 5 MWe reactor could be estimated at around 4 -70 MUSD. It is should be noted that while a variety of international studies estimate decommissioning costs in dollars per MWe, suggesting a linear relationship between a reactor's electrical capacity and the cost of decommissioning it, no such relationship leaps out from Table 1. Consequently, the decommissioning cost of the North Korean 5 MWe reactor could have a huge range, e.g., from a few tens million to over one billion. A serious estimate needs detailed engineering studies and further refined during the SAFSTOR.

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[3] U.S. Department of Energy, *Surplus Reactor Final Disposition Engineering Evaluation*, DOE/RL-2005-45, Rev. 0 (Washington, DC: DOE, August 2005.)

[4] See description and assessment in DOE, *Surplus Reactor Final Disposition Engineering Evaluation.*

Table 1 : The Published Cost of GCR Decommissioning (in 2007 USD)

country	Plant (Number of reactors)	Capacity (MWe gross)	Total cost	Total cost in B USD (2007)	M USD /MWe	B USD/ reactor (2007)
France	Chinon (3)	760 MWe	€600M (2006)	0.793	1.0	0.264
Spain	Vendellos (1)	500	360 MUSD (2001) [a]	0.418	0.83 [b]	0.418
Italy	Latina (1)	210	750 M Euro (2002) [a]	0.847	5.6	0.847
Japan	Tokai 1 (1)	166	1.3 b USD (1998) [a]	1.60	9.6	1.60
UK	Calder Hall (4)	200	1.03 bp(2006) [c]	1.99	9.9	0.498
	Berkeley (2)	276	1.11 bp(2006)	2.15	7.8	1.07
	Bradwell (2)	242	1.07 bp(2006)	2.07	8.6	1.03
	Chapelcross (4)	196	1.37 bp(2006)	2.65	13.5	0.662
	Dungeness (2)	420	1.16 bp(2006)	2.24	5.3	1.33
	Hinkley (2)	434	1.22 bp(2006)	2.36	5.4	1.12
	Hunterston (2)	300	1.08 bp(2006)	2.09	7.0	1.18
	Oldbury (2)	434	1.31 bp(2006)	2.53	5.8	1.04
	Sizewell (2)	420	0.99 bp(2006)	1.92	4.6	1.27
	Trawsfynydd (2)	390	1.16 bp(2006)	2.24	5.7	0.958
	Wylfa (2)	980	1.69 bp(2006)	3.27	3.3	1.12

Note: a)For Spain's Vandellos reactor, published cost estimates do not include waste management costs, and hence were lower than other decommissioning cost estimates. See NEA, *Decommissioning Nuclaer Power Plants—Policies, Strategies and Costs*, OECD 2003. b)cost estimates for Chinon, Latina and Tokai1- reactor decommissioning are based on Pierre Saverot presentation : Experiences in Decommissioning PUREX Reprocessing plants and Graphite Rectors, Workshop on Decommissioning North Korea's Nuclear Facilities, Harvard University, Cambridge, Mass., 27-28 June 2007. c) cost estimates for all UK magnox reactors are from website of UK's Nuclear Decommissioning Authority, http://nda.gov.uk.

Finally, the decommissioning cost could be reduced significantly by some factors. For example, if North Korea does not pursue complete decommissioning to a green field as the United Kingdom and Japan are doing. Moreover, since the labor cost could account for up to 50% of the total D&D cost, the decommissioning costs could be reduced significantly if North Korean are employed. On the other hand, some factors (e.g., poor safety conditions at the reactor build and auxiliary buildings) could increase the cost, however.

Decommissioning the Reprocessing Plant

D&D Approaches

The reprocessing plant at Yongbyon will also be a major decommissioning project. In principle, as discussed above, there are three main strategies for decommissioning a reprocessing facility: DECON, SAFSTOR and "Entombment". In practice, unlike the decommissioning strategy for the reactor, the SAFESTOR option would have no benefits in decommissioning a reprocessing plant.[5] In most cases, entombment is also not considered a reasonable option for the decommissioning of reprocessing facilities, since they are contaminated by alpha radionuclides with a long half-life. Thus, the most feasible strategy for decommissioning North Korean reprocessing plant would be a variation of the DECON option.

The Eurochemic reprocessing plant[6] could be used as a model for decommissioning the DPRK's Radiochemical Laboratory. The Eurochemic reprocessing facility in Belgium was constructed between 1960 and 1966. It reprocessed 180 tons of natural and low-enriched and 30 tons of high-enriched uranium fuels from 1966 to 1974. After shutdown in 1974, the plant was decontaminated from 1975 to 1979 to keep it in a safe standby condition. The decision to decommission to a stage3 status was taken in 1986. A pilot project was carried out on two storage buildings in 1987 in order to test techniques and costs as well as to train personnel. Both buildings were emptied and decontaminated to background levels and demolished, the remaining concrete debris was disposed of as industrial waste and green field conditions restored. The main decommissioning project has been progressing since 1989 and is expected to take about 23 years (1989-2012) to complete. The total decommissioning cost is estimated at about € 200 million (in 2004).[7]

The main process building is about 80 m long, 27 m wide and 30 m high. It consists of 40 main cells containing the chemical processing equipment. A total of 106 individual cells have to be dismantled. By the end of 2004, 43 cells had been dismantled to background levels; 20 cells were emptied; and equipment removal is in progress for 37 cells. The D& D activities have generated up to 4000 tonnes of waste. Thirty nine operators are involved in the decommissioning activities, 8 operators take care of the decontamination activities. All activities are assisted, supervised and managed by 12 supervising and management personnel.[8]

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[5] IAEA, *Decommissioning of Nuclear Fuel Cycle Facilities*, Safety Guide, No. WS-G-2.4, IAEA 2001.
[6] Jean-Marc Wolff, *Eurochemic 1956–1990: Thirty-five years of international cooperation in the field of nuclear engineering: The chemical processing of irradiated fuels and the management of radioactive wastes*, NEA/OECD, Paris, 1996.
[7] Pierre Saverot, *Experiences in Decommissioning PUREX Reprocessing Plants and Graphite Rectors*, op.cit.
[8] See ,e.g. , *The Decommissioning of the Eurochemic Reprocessing Plant*, at

Based on past experience of decommissioning small reprocessing plants,[9] a possible minimum timeframe for decommissioning the North Korean reprocessing plant could be broken down into the following phases 1) 1-2 years for D&D planning studies; 2) one year for flushing out the pipes and tanks; 3) 1-2 years for decontamination; 4) around 3 years for dismantling the main cells. Based on the decommissioning experience for Eurochemic reprocessing, dismantling one main process cell could take around half a year. Thus dismantling the six main cells at the Yongbyon reprocessing plant would take about three years. 5) several years (around 5-7 years) to process and dispose of various wastes; 6) a few years to restore the site for other uses. Consequently, a complete D&D for the North Korean reprocessing plant would take about 10 to 15 years.

However, it should be noted that it should not take such a long time to reach a point of a permanent disablement of the reprocessing plant. For instance, it could take only 5-6 years (i.e. after finishing the first four steps as listed above) to arrive a point where all main process cells are dismantled. In practice, from the perspective of disablement, it may not need to wait for dismantling all the cells. For example, after dismantling the main cell for fuel dissolution and main cell for the first codecontamination, the reprocessing facility would be effectively permanently disabled. In addition, planning studies and rinsing and decontamination processes could be conducted simultaneously. Thus, an effective disablement could be arrived at within three years. To further reduce the timeframe for disablement, another option could be to entomb the main cells after rinsing and decontamination. Thus, it could take only around two years to achieve disablement. However, it would exclude potential reuse of those cells.

D&D Costs

The cost of decommissioning a reprocessing facility is determined by a number of factors including the size and complexity of reprocessing facility, the number of main process cells, operating history, cleaning and classification levels, labor costs, the amount of waste.

Based on the decommissioning experience of Eurochemic reprocessing (see table 2), the two largest cost items, making up for the majority of total costs for a reprocessing facility are dismantling and waste management. For example, based on the cost estimates as shown in table 2,[10] the combined decontamination and dismantling costs for the whole D&D project account for about 75%, and the cost for waste management is around 22%.

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http://www.belgoprocess.be/03_act/docs/BP02_Eurochemic.pdf.

[9] See, e.g., Bunn and Zhang, *Decommissioning North Korea's Nuclear Facilities: Issues, Options, and Costs*, Forthcoming.

[10] Pierre Saverot, *Experiences in Decommissioning PUREX Reprocessing plants and Graphite Rectors*, op.cit.

Table 2: Eurochemic D&D Cost Estimates

Activity	**Cost (million Euros, 2004)**	**Cost (% of total)**
Decontamination and dismantling 1989-2012	151.7	74.62
Waste Management	44.4	21.84
Site restoration and cleanup	7.2	3.54
Total	203.3	100

Some estimates show that manpower costs generally represent a significant share of total costs. An estimate for decommissioning cost of the UK's B205 reprocessing facility yielded the same conclusion.[11]

Table 3 lists decommissioning cost estimates for several different reprocessing plants. The decommissioning cost for a small scale reprocessing facility could be as high as several hundred millions of dollars.

Regarding the costs of decommissioning for the North Korean reprocessing plant, it would be difficult to estimate these precisely. Roughly speaking, if the decommissioning costs for Eurochemic reprocessing are used as a guide, the decommissioning cost for the North Korean reprocessing plant could amount to several hundred million dollars. However, considering the breakdown of costs, the North Koreanplant is likely to be less costly to decommission than Eurochemic. Based on thedecommissioning experience for Eurochemic reprocessing, the decontamination and dismantling activities make up the largest portion (over 75%) of the total decommissioning cost. In practice, one major factor dictating the dismantling activities is the number of main cells to be dismantled. It usually takes around half a year to dismantle one main cell. If the number of main cells to be dismantled dictate the dismantling cost, then the cost for dismantling the 6 main cells at Yongbyon reprocessing building will be much lower than dismantling the 40 main cells at Eurochemic reprocessing.

Moreover, one consideration that may significantly reduce the decommissioning cost is that North Korea will not pursue complete decommissioning to a green field as the Eurochemic reprocessing plant is scheduled to. The setting of clearance levels has a significant effect on the quantity of materials that remain for disposal as radioactive waste and hence on the overall costs of waste management. Given the fact that the reprocessing site has already been used to store various nuclear wastes, it may be so contaminated that it is not worth cleaning. Moreover, no waste storage facilities exist elsewhere. Thus it may be both feasible and cost-effective to reuse the site for waste treatment and storage. For example, after dismantling the cells, they can be used for ILW storage and mid-term storage for conditioning HLW while awaiting final disposal. In practice, the Italian EUREX pilot reprocessing plant of ENEA is being decommissioned and some cells are to be reused for a vitrification plant.[12]

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[11] NEA, *Decommissioning of Nuclear Facilities: An Analysis of the Variability of Decommissioning Cost Estimates*, OECD 1991.
[12] M.Troiani and P.Risoluti, *Direct Dismantling of Reprocessing Plant Cells-the EUREXPlant Experience,* WM'03 Conference, February 23-27, 2003, Tucson, AZ.

Table 3: Decommissioning Cost Estimate for Various Reprocessing Plants[13]

Facility	Estimated costs	Converted cost in M USD (2007)
Eurochemic (Belgium)	203 Meuros (2004)	267
AT-1 pilot reprocessing (France)	400 M FF (1990)	101
AMP (France)	450 Meuro (2005)	594
EUREX (Italy)	€396 M (2004)	521

Conclusions and Suggestions

The best approaches for decommissioning the 5 MWe reactor would be SAFSTOR option. The D&D cost could have a huge range, e.g., from a few tens million to over one billion. However, if North Korean 5 MWe reactor is to apply Handford " cocooning" experience, the decommissioning cost could be at the very low end of the range. A serious estimate needs detailed engineering studies and further refined during the SAFSTOR.

The best approaches for decommissioning the reprocessing would be DECON option. A complete D&D for the North Korean reprocessing plant would take about 10 to 15 years. An effectively permanent disablement could be arrived at within a few years. The D&D cost could be up to a few million USD.

[13] See, e.g., Bunn and Zhang, *Decommissioning North Korea's Nuclear Facilities: Issues, Options, and Costs.*