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COST EVALUATION OF PROPOSED DECOMMISSIONING PLAN OF CANDU REACTOR

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Abstract

Nuclear decommissioning is the final technical and administrative process in the life cycle of nuclear power operation. Experience over the last decade has demonstrated that in general, the process of decommissioning and its cost evaluation has reached industrial maturity, although specific techniques continue to evolve. Owners and licensees of nuclear power plants are generally responsible for developing cost estimates of decommissioning, and a good understanding of these costs is fundamental for the development of estimates based on realistic decommissioning plans. The use of these techniques in the cost evaluation of the decommissioning of nuclear facilities continues to increase this experience. This research has been carried out keeping in mind to evaluate an economical and feasible cost for the proposed decommissioning plan of CANDU (Canada Deuterium Uranium) reactor. Work is done in the major areas of cost estimations for DECON (immediate dismantling), SAFESTOR (deferred dismantling) and ENTOMB (on site end-state). These alternatives were analysed and SAFSTOR method was recommended for 40+ years old, Canadian designed, first generation CANDU reactor decommissioning. This paper provides a cost estimation for a decommissioning as recommended in the analysis performed. A cost of 200 Million $ is evaluated for SAFSTOR decommissioning alternative of proposed CANDU reactor.

Keywords: CANDU, Cost estimation, Decommissioning, SAFESTOR method.

1. Introduction

The term "decommissioning" of nuclear facilities, as used within the nuclear industry, commonly occur when a power company decides to close a nuclear power plant permanently or to remove it safely from service [1-3]. Nuclear facilities decommissioning means the safe removal of a site from the operation and lessening residual radioactivity to a level that permits the release of the property for unrestricted use [4, 5]. The purpose of decommissioning a nuclear reactor site is to ensure safe decommissioning practice in a timely and efficient manner so that the site can be used for any other purposes. The licensees can choose one out of three types of decommissioning as by International Atomic Energy Agency (IAEA) standard, which are DECON (immediate dismantling), SAFESTOR (deferred dismantling) and ENTOMB (on site end-state) [6-9].

The decommissioning strategy is influenced by a few critical factors, such as national policies and regulatory framework, financial resources, cost of implementing a strategy, spent fuel and waste management system, Health, Safety and Environmental (HSE) impact, knowledge management and human resources, social impacts and stakeholder involvement and suitable technologies and techniques [10, 11]. Thus, considering the type of nuclear power reactor will massively contribute to the efficient decommissioning strategy [12].

According to Robertson [13], CANDU is a pressurized heavy-water power reactor designed first in the late 1950's by a consortium of Canadian government and private industry. The Nuclear Power Demonstration (NPD) Reactor is partially modelled on the National Research Universal (NRU) Reactor and is intended to be the first Canadian nuclear power reactor and a prototype for the CANDU design [14]. The Douglas Point plant was the first full-scale CANDU nuclear generating station and was basically a scale-up of the NPD reactor with similar design and components. Valuable experience was gained on this plant, which was subsequently applied later to CANDU nuclear power plants [15]. Early models of CANDU power plants (1970's) have a nominal design life of 30 years and once the design life is reached, the nuclear power plants are either decommissioned or refurbished to extend their design life [16, 17]. Table 1 shows 48 CANDU reactors operating all around the world and contributing 25 GW of electricity [18].

Table 1. Nuclear power units by reactor type (worldwide) [18].

Reactor type	Unit operational	GWe	Fuel
Pressurized lightwater reactor (PWR)	265	244	Enriched UO_2
Boiling light water reactor (BWR)	94	86	Enriched UO_2
Pressurized heavy water reactor (CANDU)	48	25	Natural UO_2
Gas-cooled reactor	18	10	Natural U (metal), enriched UO_2
Graphite moderated light water reactor	16	11	Enriched UO_2
Liquid metal cooled fast breeder reactors	2	1	PuO_2 and UO_2
Total	443	377	

Based on a study by Tapping et al. [17], there are three internationally recognized "stages" of decommissioning for CANDU in specific, which are mothballing, encasement, and dismantling.

Decommissioning activities for a CANDU power plant are essential and time-consuming. The impacts are usually caused by on-site energetic demands of component removal and peripheral tasks, such as handling, storage and final repository of low level and intermediate-level nuclear waste [14, 17, 19]. Decommissioning related activities, in turn, will generate a lot of data throughout the decommissioning project and require immediate and efficient cost evaluation for better project management. Cost evaluation is highly recommended in decommissioning of CANDU power plant as it can enhance the transparency around such costs and putting in place better methods to collect and share information, which would contribute greatly to the future assessments [2, 19-21].

Table 2 shows the cost estimation for CANDU reactor decommissioning by deferred dismantling strategy; SAFSTOR method. The cost estimation provided CANDU reactors for deferred dismantling decommissioning option is based upon financial guarantee assumptions [22]. The decommissioning cost for CANDU estimates at a range between 270 and 435 USD/kWe with 360 USD/kWe as average.

Table 2. Decommissioning cost estimation for CANDU reactor by deferred dismantling strategy [21].

Country	Name of the plant	Capacity MWe	Total cost M USD	Total cost USD/kWe
Canada	Bruce A	825 x 4	906	275
	Bruce B	840 x 4	904	269
	Darlington	935 x 4	1289	345
	Gentilly 2	680	294	432
	Pickering A	542 x 4	830	383
	Pickering B	540 x 4	858	397
	Point Lepreau	680	295	433

In this research paper, the study is being undertaken to analyse the various decommissioning strategies for the proposed CANDU reactor. Out of these, decommissioning with SAFESTOR (deferred dismantling) method was suggested. Finally, a cost estimation is provided based on recommended decommissioning process.

2. Methodology

2.1. Decommissioning flow

Each commercial nuclear reactor is designed with their own decommissioning plan and the activities are controlled by the local regulatory body with guidance from the international authority. This act is necessary to ensure that the decommissioning activities are conducted according to the legal requirements and specifications to the national regulations [22]. The decommissioning of the nuclear reactor or specifically CANDU, are likely comprehensive of all aspects, such as public safety and health, waste disposal and environmental protection issues [22]. A decommissioning plan of a nuclear facility should take into deliberation all the facilities present on site and being affected by nuclear regulations [23, 24]. For the pre-decommissioning strategies, the operator shall submit a detailed decommissioning plan, that includes role and timing of the detailed plan, the content of the detailed plan, factors affecting the level of detail and plan flexibility, and uncertainty [25].

Another pre-decommissioning step includes the submission of a license application to carry out decommissioning activities. This evaluation will determine the effect on human health and the environment regarding the decommissioning activities. Once, the environmental assessment is issued and approved, the operator's license for decommissioning will be considered [9].

Decommissioning of a nuclear facility involves decontamination, dismantling, cutting, packaging and transportation of the plant equipment and materials and handling, treatment, conditioning, storage/disposal of radioactive and inactive wastes generated. Thus, after the approval of decommissioning licenses, the basic alternative strategies for CANDU reactor may include prompt removal, deferred removal, which allow for the decay of relatively short-lived nuclides, in-situ confinement to secure and abandon the affected portions of the facility in place and combinations of the above [26].

The evaluation method should ensure the relative advantages and disadvantages of the strategies. There are examples of factors to evaluate the alternative decommissioning strategies such as:

- Forms and characteristics of radioactive and conventional contaminants.
- Integrity of containment and other structures over time.
- Availability of decontamination and disassembly technologies.
- Potential for recycle or reuses of equipment and materials.
- Availability of knowledgeable staff.
- Potential environmental impacts and worker and public doses.
- Potential revenues, cost and available.
- Funding availability of waste management and disposal capacity.
- Regulatory requirement and public input.

Three practices adopted for the waste disposal of the CANDU reactor decommissioning activities are as follow:

- Any discharge of radioactive liquid or gaseous waste to the environment, such that the collective doses shall be as low as reasonably achievable (ALARA), economic and social factors are being considered but not exceed the regulatory authority prescribed discharged limits.
- Solid waste resulting from the reactors operation and research laboratories are to be placed in the near-surface disposal facilities specifically constructed for the purposes. Low-Level Waste (LLW) and Intermediate Level Waste (ILW), which containing trace quantities of alpha contamination from the operation of fuel reprocessing units are permitted to be placed in a near-surface disposal facility.
- High-Level Waste (HLW) and alpha contaminated liquid waste from fuel reprocessing facilities, which are initially stored in tanks shall be vitrified and the solidified products shall be stored in near-surface engineering storage facilities. This provides appropriate cooling and surveillance for long period minimum 20 years and shall be transferred to deep geological repositories at the end.

Based on a study by Laraia [26], the operating organization should select an appropriate method of solid waste disposal.

Radiological condition assessment must be conducted prior to and during decommissioning activities. Radiation assessment is performed at various stages in the decommissioning process that includes:

- Pre-operational, to establish background conditions prior to construction.
- Operational, to add to the radiological contamination knowledge-base.
- Post-operational, to complete and refine the knowledge-base for detailed planning.
- During decommissioning, to support worker radiation protection programs, environmental monitoring programs and releases of material and equipment from decommissioning site.
- Post-decommissioning, to support site de-licensing and required follow-up.

Post decommissioning action requires follow-on remedial action for soils and water bodies to complete the clean-up. Actual post-decommissioning activities may include continuing site control activities, pending property or facility release of transfer to another authorized party or administrative actions. The licensee should establish long-term monitoring to provide for the physical safety and security of the facility and to assure compliance with restrict end condition established for the CANDU facility. This long-term monitoring is considered a low-cost program that may continue for many years. The sites also may be transferred to remedial action for clean-up of adjacent soil or groundwater in accordance with the environmental regulatory requirement and future land use [27, 28].

2.2. Decommissioning methods

In general, there are 3 decommissioning strategies, which are DECON, SAFSTOR, and ENTOMB. DECON or immediate dismantling is immediate decommissioning of Nuclear Power Plant (NPP) in which, equipment, structures and systems are removed. SAFSTOR or deferred dismantling or delayed decommissioning is where NPP site is safely stored until the condition to decommissioning any equipment, structure and system are achieved. In ENTOMB method, the NPP site is encased with a long-lived structure such as concrete and continued surveillance is carried out [29, 30]. In many cases, SAFSTOR or DECON strategies is often chosen, but in some cases, both SAFSTOR and DECON are implied. According to Laraia [30], rarely ENTOMB strategies are selected. There are various factors involved when choosing the most appropriate decommissioning strategies for CANDU reactor. These factors include radioactivity level, high-level waste disposal, low-level waste management, transportation methodology, the technology available, safety factors, site redevelopment and the most influential is decommissioning cost. In recent years, cost dealing with waste and decommissioning proved to be greater than expected in the nuclear power plant industry. The cost of decommissioning grew at rates not experienced by other industries such as oil, coal and gas industries [31].

Even though decommissioning cost for DECON is much lower than SAFSTOR, but SAFSTOR is preferred because it gives ample time to NPP license holder to obtain enough funds for decommissioning to take place. The cost to dismantle site structures, equipment and component with a workforce already mobilized are less costly and more efficient than if the process is delayed [29].

NPP site can be released for unrestricted use if the radioactivity level is such that, the average critical group would not receive a Total Effective Dose Equivalent (TEDE) in excess of 25 millirems per year (mRem/yr) [29, 32]. Besides that, the higher the radioactivity level, the shorter the time given for a worker to conduct decommissioning works. This is to reduce the exposure rate to the workers based on shielding, time and distance principle. For this reason, a number of workers to conduct decommissioning work will be increased, thus, leading to a higher cost in term of a worker's salary. As shown in Fig. 1, the main reduction activity content takes place over the first few decades.

This is an evidence that the radiological properties of Co-60 are so dominant, that its decay governs the reduction in gamma dose rates over the first 50 to 70 year [31].

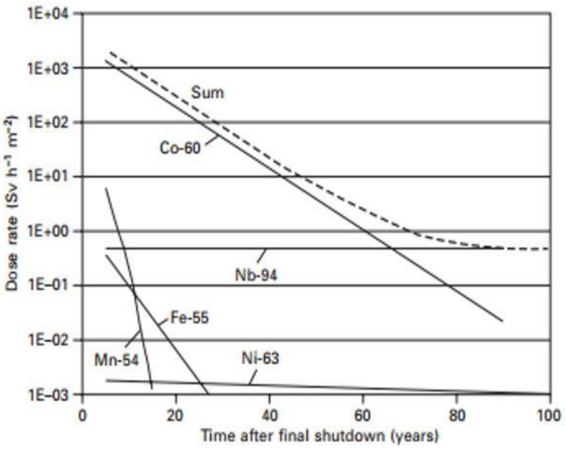

Fig. 1. Development of dose rate over time because of radioactive decay.

High-level waste such as spent nuclear fuel arises after the decommissioning process needs to be disposed of. High-level waste needs to be stored at repository until any long-lived radionuclide had decayed to a safer level. Some countries have the technology to reprocess the spent fuel. Thus, SAFSTOR decommissioning strategy gives countries enough time to plan the high-level waste management [29].

Besides that, transportation needed to transport high-level waste, low-level waste and any other waste produced during the decommissioning process. The contaminated material is packaged in industrial packages for low-level waste [29]. High-level waste is transported by the truck or train, using dry cask [23, 32]. Transportation cost depends on the method of transportation used, distance from NPP site to waste repository and package used. Cost of transporting dry cask is much expensive than industrial packages over the same distances.

Novel technologies alleviate the decommissioning process. Such as in-situ chemical decontamination. In the 1970s, Canadian companies successfully developed the proprietary Candecon and Canderem decontamination methods to remove or reduce contamination in CANDU reactors. These involved a multi-step process of injecting chemicals into the system and circulating them for several days while monitoring the Decontamination Factor (DF) achieved. Besides that, many technologies are available to cut down the big components, such as plasma arc torch, gasoline torch and laser cutting [33]. With these technologies, huge components can be cut down easily.

It is generally recognized today that decommissioning should be viewed as an integral part of a facility's lifecycle. Beyond decommissioning, site reuse was not considered. Current recommendations and practices already include site redevelopment as an extension of decommissioning [31], and it should be considered at the planning stage of decommissioning.

2.3. Decommissioning activity alternatives

The following basic decommissioning alternatives have been discussed:

Entombment preparation phase

- Decontamination of the systems and equipment not required in decommissioning.
- Required reinforcement of the reactor and other localized structures.
- Localization of the high-radioactive unit elements and the reactor in place.
- Total localization of the unit construction.
- Erection of additional protective barriers around localized highly radioactive structures.
- Handling of operational radioactive waste.
- Servicing of the systems and equipment remaining in operation.

Entombment phase (100 years or more)

- Entombment of the localized highly radioactive unit elements and the reactor.
- Decontamination of the unit's rooms and equipment out of the entombment zones to ensure safety.
- Dismantling of the systems and equipment out of the entombment zones.
- Handling of the radioactive waste formed in the dismantling of the systems and equipment out of the entombment zones.
- Radiation monitoring and bundling of wastes reusable with or without restrictions.
- Bringing the remaining unit structures and site up to the radiation and sanitary requirements.
- Servicing of the systems and equipment remaining in operation.
- External monitoring of the entombment zones and the environment.

List of decommissioning activities with the immediate dismantling of the reactor structures.

Preparation for dismantling of reactor structures

- Decontamination of the systems and equipment not required in decommissioning.
- Inspection of the unit's equipment and systems required in decommissioning.
- Decontamination of the unit's rooms and equipment to ensure radiological safety.

- Dismantling of the systems and equipment in a control room.
- Handling of operational radioactive waste.
- Servicing of the systems and equipment remaining in operation.
- Preparation of the personnel for works at the next stage.

Dismantling and demolition of the meter and other unit structures

- Dismantling of the reactor and other structures.
- Handling of radioactive waste formed in the dismantling of the structures.
- Radiation monitoring. Sorting and storage of wastes reusable with or without restrictions.
- Decontamination or cleaning of reactor concrete cavity.
- Servicing of the systems and equipment remaining in operation.
- Dismantling and removal of other unit structures not used.
- Decontamination and dismantling of technological equipment used for dismantling.
- Bringing the remaining unit structures and site up to the radiation and sanitary requirements.
- Final survey of the unit and its site.

These are various combinations of decommissioning options, which may be considered. The following activities shall be performed for any decommissioning options:

- Typical reactor shutdown and cool down
- Nuclear fuel holdup in the reactor core
- Removal of nuclear fuel
- Drainage of multiple forced circulation circuit
- Progress of required organizational, technical and design documentation
- Handling of operational radioactive wastes
- Operation and maintenance of unit systems and equipment remained
- Preparations for the next decommissioning phase.

2.4. SAFSTOR stage for CANDU reactors

The pit-shutdown stage is a stage in which, the decommissioning started before the final shutdown of the reactor. A detailed program for comprehensive engineering and radiation survey shall be conducted. The flow of the main activities carried out during SAFSTOR alternative is shown in Fig. 2 [9].

The SAFESTOR decommissioning alternative includes the following stages:

- Preparation for decommissioning.
- Preparation for long-term safe storage.
- Long-term safe storage.
- Dismantling and demolition of the reactor and other unit structures.

The preparation for the decommissioning must be completed counterpart to the final shutdown of the CANDU reactor.

Preparation for SAFSTOR.
Decontamination of systems and equipment are not required in decommissioning
Requirement of the inspection of the equipment units
Isolation of the highly radioactive elements and the reactor in specific place
Requirement of radiation and sanitary to allow for servicing the systems and equipment located in unit rooms
Handling of operational radioactive waste
Service on the unit systems and equipment remaining in operation
Preparation for next long-term SAFSTOR decommissioning phase, includes training of personnel

Long-term SAFSTOR
Preparation of places for storage of radioactive waste and other wastes
Dismantling of component out of the localized zones
Conditioning, transportation, and storage of radioactive wastes
Servicing of the unit systems and equipment remaining in operation
Preparation for the next decommissioning phase

Dismantling and demolition of the reactor and other unit structures
Inspection of the equipment and systems
Dismantling of localized reactor core and other highly radioactive structures
Handling of radioactive waste formed during dismantling
Radiation monitoring, sorting and storage of reusable wastes with or without restrictions
Decontamination or cleaning of reactor concrete cavity (If necessary)
Servicing of the remaining operation unit systems and equipment
Dismantling and removal of unit structures not used
Conditioning, processing and storage of radioactive wastes
Decontamination and dismantling of the equipment
Convey the remaining unit structures up to the radiation and sanitary requirements
Final survey on the units and sites

Fig. 2. SAFESTOR decommissioning alternative.

3. Results and Discussion

3.1. Cost Analysis for SAFSTOR

As stated by Hedin [33], in order to understand cost estimates and to analyse them in a relevant and robust way, it is important to know certain information related to the estimations, such as how, why and by whom those estimates were established. Decommissioning cost estimates may serve a variety of purposes, which vary, depending on the stage in the facility's lifecycle [34].

Generally, decommissioning cost estimates are used for three main functions. The first one is to inform the government and guide their policy for assuring that decommissioning funds will be available when needed. Secondly, to determine funding requirements and financial liabilities and lastly is to serve as a basis for industrial strategy and decommissioning activity planning.

Based on research by Bems et al. [35], decommissioning projects for various types of nuclear facilities have also demonstrated that decommissioning costs can be managed through scheduled planning. However, comparisons of individual cost estimates for specific facilities may show relatively large variations.

Different cost estimation methodologies might need to be used depending on specific objectives and as a project advances. These include an order of magnitude estimates, budgetary estimates, and definitive estimates [36]. Cost estimation includes costs for the component, piping, equipment removal, decontamination, packaging, transportation and burial [37].

In this paper, the decommissioning cost evaluation was made depending on the parameters and conditions discussed and stated before. The cost estimations are based on the following four major components, which have been considered for cost calculations.

- Cost of different stages and activities of decommissioning.
- Safe storage cost of spent fuel.
- Safe storage cost for heavy water inventory.
- Cost for permanent disposal of radioactive materials (processing, packaging, transport).

3.2. Cost of different stages and activities of decommissioning

According to Bayliss and Langley [10], various information of person-hours for different stages and decommissioning activities are taken into consideration (Table 3). Total cost for different stages and activities has been estimated to be 100 Million $ [38, 39].

Table 3. Cost estimation of different components and activities.

Components of cost estimations	Person-hour	Average pay per person ($)	Total cost ($)
A. Planning activities for unit decommissioning	636,000	6/hr	4M
1. Comprehensive survey of unit and experimental design necessary to develop a unit-decommissioning project.			
2. Development and approval of the unit decommissioning project.			
3. Official registration of decommissioning license.			
4. Development of specification and distribution of orders for manufacturing of			

required dismantling equipment.			
B. Preparation for long-term safe storage	2,130,200	5/hr	11M
1. During the preparation stage of unit decommissioning.			
2. Rebuild standard heating and ventilation, power supply, sewage, fire and radiation safety, and other necessary systems.			
3. Upgrade or installation of dosimeter and radiological inspection systems.			
4. Dismantling of technological channels and channels of control and protection systems.			
5. Dismantling of equipment, pipes and structures below bottom load-bearing structures.			
6. Dismantling of equipment, pipes and structures above top load-bearing structures.			
7. Installation of plugs in circuits of the bottom load-structure.			
8. Installation of protective floor above the reactor.			
9. Seal ventilation, cable and pipe runs from the reactor cavity			
10. Total isolation of the reactor construction space.			
C. Dismantling of reactor structures.	531,000	3/hr	1.6M
a. Training of unit personnel.			
b. Installation of required equipment, power supply, dust suppression and gas purification systems.			
c. Installation of equipment to dismantle reactor structures.			
d. Open protective engineering barriers and remove structures obstructing access to the reactor.			
e. Dismantling of reactor structures elements.			
D. Planning activities for unit decommissioning.			
1. Regularly inspect, repair and operate the required	255,000*	8/hr	2M

equipment and systems of unit:			
a. During the preparation stage of unit decommissioning.			
b. During the stage of safe storage.			
c. During the stage of reactor structure dismantling			
2. Operate the radioactive waste processing and storage complex.	255,000*	8/hr	2M
a. During the preparation stage of unit decommissioning.			
b. During the stage of safe storage.			
c. During the stage of reactor structure dismantling.			
3. Operate the spent nuclear fuel storage facility:	255,000*	8/hr	2M**
a. During the preparation stage of unit decommissioning.			
b. During the stage of safe storage.			
c. During the stage of reactor structure dismantling.			
Total cost for different stages			100 Million $

*Person hr/yr

**Million $/yr

Assumptions:

- For stage A: Management level personnel will be required whose individual salary is taken as $1000/month.
- For stage B: Design and implementing personnel will be required. Their average salary is taken as $800/month.
- For stage C: Staff and labour personnel will be required. Their average salary is taken as $500/month.
- For stage D: Supervisory personnel will be required. Their average salary is taken as $1200/month.

3.3. Safe storage cost of spent fuel

Decommissioning, based on Khurana et al. [39], whether it is a direct or deferred method, it raises the question of how to store low-to high-level radioactive wastes. The waste must be removed and stored immediately, whichever path is chosen. Different assumptions and data are taken from resources reports [8, 40] describing the detailed study of DRY STORAGE of the spent fuel bundles. A steel basket accommodates 60 bundles are suggested. A total of 6 fuel baskets will be accommodated in one concrete CANISTER. A total cost of 0.69 Million $ is estimated for the safe storage of spent fuel. Its break up is tabulated in Table 4.

3.4. Safe storage cost for heavy water inventory

Safe storage of heavy water will be carried out in the drums (2.5 ft. diameter each). Therefore, a total of 750 drums will be required with a base area of 13,125 sq. ft. A total cost of 0.35 Million $ is estimated for the safe storage of heavy water. Its break up is tabulated in Table 5.

Table 4. Cost calculations for the safe storage of spent fuel.

Serial No.	Details	Quantity
1.	Total number of fuel bundles at the end of year 2017.	28777
2.	Number of steel fuel baskets required (60 fuel bundles will be accommodated per steel basket).	480
3.	Number of concrete CANISTERS required (6 steel boxes will be accommodated in one concrete CANISTER).	80
4.	Outer diameter of each CANISTER.	2.6 m
5.	Base area of each CANISTER.	5.3 sq m
6.	Base area needed for each CANISTER.	425 sq m
7.	Total space needed for 80 CANISTERS drums.	1487.5* sq m
8.	Construction raft foundation.	0.21 Million $
	Cost of one CANISTER (including material and construction).	6000 $
	Total cost for 80 CANISTERS	0.48 Million $
	Net total cost	**0.69 Million $**

Table 5. Cost calculations for the safe storage of D_2O.

Serial No.	Details	Quantity
1.	Capacity of each storage drum	0.2 tons/drum
2.	Total inventory of D_2O	150 tons
3.	Total drums needed	750
	Base area needed for 750 drums	
1.	Diameter of each drum	
2.	Radius of each drum	2.5 ft
3.	Base area of each drum.	4 ft
4.	Base area of each drum.	4.9 sq ft
5.	Total space needed for 750 drum	17.5* sq ft
6.	Construction cost for raft base structure	13,125 sq ft
	Total construction cost	0.175 Million $
	Total construction cost (for top and bottom bases)	**0.35 Million $**

*To accommodate necessary maintenance, base area is taken as 350% of the original value.

3.5. Cost for permanent disposal of radioactive materials (processing, packaging, transport)

For radioactive material (boiler room equipment and RCC structure), the cost is calculated for the safe transportation to the burial site (Table 6). The weight of the radioactive equipment has been estimated from data resources. A total cost of 58 Million $ is estimated for the safe processing, packaging and transport of boiler rooms equipment.

A total of 42.6 Million $ are required for safe transportation of concrete (Table 7). With this cost estimations and calculations, a total of 200 Million $ is evaluated for the SAFSTOR decommissioning alternative, which depends on the parameters and conditions that have been described.

Table 6. Cost of boiler room equipment (processing, packaging, transport).

Serial No.	Details	Quantity
1.	Total volume	494.06 m^3
2.	Density of iron	7870 kg/m^3
3.	Total mass of equipment	3.8×10^3 tons
4.	Fuel casks required	950
5.	Cost of 950 casks	950 $
6.	Transportation cost of 3.8×10^3 tons of radioactive equipment	57 Million $
	Net Cost (Transportation + Casks)	**58 Million $**

Assumptions:
1. Cost of one shielding cask: 1000 $/day.
2. Transportation cost: 75 $/ton mile.
3. Total journey from site: 200 miles.

Table 7. Cost of RCC structure of reactor building (processing, packaging, transport).

Serial No.	Details	Quantity
Heavy concrete		831.01 m^3
1.	Total volume of concrete	
2.	Mass of concrete (a)	2.39×10^3 tons
Standard concrete		
1.	Total volume of concrete	10,540.49 m^3
2.	Mass of concrete (b)	26×10^3 tons
Total mass (a+b)		**28.4×10^3 tons**

4. Conclusion

The deferred decommissioning alternative was recommended. The immediate dismantling alternative was not chosen because of the current economic conditions that made the alternative impractical. The burial in place alternative has also not been recommended keeping in mind the site unavailability for any future use. A cost of 200 Million $ is evaluated for SAFSTOR decommissioning alternative of proposed CANDU reactor.

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References

1. Seier, M.; and Zimmermann, T. (2014). Environmental impacts of decommissioning nuclear power plants: Methodical challenges, case study, and implications. *The International. Journal of Life Cycle Assessment*, 19(12), 1919-1932.
2. Laraia, M. (2012). *Nuclear decommissioning. Planning, execution and international experience*. Camridge, United Kingdom: Woodhead Publishing Limited.
3. Nesse, S.; Lind, E.; and Jarandsen, B. (2002). New handbook for guidance in assessing impacts of decommissioning and disposal of redundant offshore

installations. *Proceedings of the International Conference Health, Safety and Environment in Oil and Gas Exploration and Production*. Kuala Lumpur, Malaysia, 4 pages.

4. Jahn, F.; Cook, M.; and Graham, M. (2008). Decommissioning introduction. *Hydrocarbon, Exploration and Production*, 55, 419-425.
5. D'Souza, J.; Jacob. J.; and Soderstrom, N.S. (2000). Nuclear decommissioning costs: The impact of recoverability risk on valuation. *Journal of Accounting and Economics*, 29, 207-230.
6. Seward, D.W.; and Bakari, M.J. (2005). The use of robotics and automation in nuclear decommissioning. *Proceedings of the 22nd International Symposium on Automation and Robotics in Construction (ISARC 2005).* Ferrara (Italy), 6 pages.
7. Laraia, M. (2018). *Nuclear decommissioning:* Its history, development, and current status. Springer International Publishing.
8. Babilas, E.; and Brendebach, B. (2015). Selection and evaluation of decontamination and dismantling techniques for decommissioning of large NPPs components. *Progress in Nuclear Energy*, 84, 108-115.
9. McIntyre, P.J. (2012). Nuclear decommissioning policy, infrastructure, strategies and project planning. *Nuclear Decommissioning: Planning, Execution and International Experience*, 33-48.
10. Bayliss, C.R.; and Langley, K.F. (2003). *Nuclear decommissioning, waste management, and environmental site remediation*. Oxford, United Kingdom: Butterworth-Heinemann.
11. Gurau, D.; and Deju, R. (2014). Radioactive decontamination technique used in decommissioning of nuclear facilities. *Romanian Journal of Physics*, 59(9-10), 912-919.
12. Laraia, M. (2012). *Nuclear decommissioning: Planning, execution and international experience*. Sawston, Cambridge: Woodhead Publishing Ltd.
13. Robertson, J.A. (1978). The CANDU reactor system: An appropriate technology. *Science*, 199(4329), 657-664.
14. Garland, W.J. (2016). *The essential CANDU.* A textbook on CANDU nuclear power plant technology. Canada: University Network of Excellence in Nuclear Engineering (UNENE).
15. Boczar, P.; Dastur, A.; Dormuth, K.; Lee, A.; Meneley, D.; Pendergast, D.; and Luxat, J. (1998). Global warming and sustainable energy supply with CANDU nuclear power systems. *Progress in Nuclear Energy*, 32(3-4), 297-304.
16. Wongwises, S. (1996). Two-phase countercurrent flow in a model of a pressurized water reactor hot leg. *Nuclear Engineering and Design*, 166(2), 121-133.
17. Tapping, R.L.; Nickerson, J.; Spekkens, P.; and Maruska, C. (2000). CANDU steam generator life management. *Nuclear Engineering and Design*, 197(1-2), 213-223.
18. Cacuci, D.G. (2010). *Handbook of nuclear engineering.* Nuclear engineering fundamentals. New York: Springer-Verlag
19. Hickethier, G.; Anbergen, H.; Hofacker, A.; and Gehbauer, F. (2011). Set-based planning in the decommissioning of a nuclear power plant. *Proceedings of the*

19th Annual Conference International Group for Lean Construction (IGLC 2011). Lima, Peru, 402-412.

20. Bizet, R.; and Leveque, F. (2015). Early decommissioning of nuclear power plants: Is there an economic rationale? *The Electricity Journal*, 28(2), 53-62.
21. Hong, S.; Bradshaw, C.J.A.; and Brook, B.W. (2013). Evaluating options for the future energy mix of Japan after the Fukushima nuclear crisis. *Energy Policy*, 56, 418-424.
22. Organization for Economic Co-operation and Development. (2003). Decommissioning nuclear power plants. Nuclear energy agency organisation for economic co-operation and development. *Policies, Strategies and Costs*.
23. Beckitt, S. (2012). Decommissioning of legacy nuclear waste sites: Dounreay, UK. *Nuclear Decommissioning. Planning, Execution and International Experience*, 701-744.
24. International Atomic Energy Agency (IAEA) (2013). Safety assessment for decommissioning. *Safety Reports Series No. 77*.
25. International Atomic Energy Agency (2012). Safety of nuclear power plants : Design. *Specific Safety Requirements*. No. SSR-2/1 (Rev. 1).
26. Laraia, M. (2012). Overview of nuclear decommissioning principles and approaches. *Nuclear Decommissioning*. Planning, execution and international experience, 13-32.
27. Jeong, K.-S.; Lee, K.-W.; and Lim, H.-K. (2010). Risk assessment on hazards for decommissioning safety of a nuclear facility. *Annals of Nuclear Energy*, 37(12), 1751-1762.
28. Yamaguchi, A.; Jang, S.; Hida, K.; Yamanaka, Y.; and Narumiya, Y. (2017). Risk assessment strategy for decommissioning of Fukushima Daiichi nuclear power station. *Nuclear Engineering Technology*, 49(2), 442-449.
29. Bradbury, D. (1992). Decommissioning of civil nuclear facilities: A world review. *Energy Policy*, 20(8), 755-760.
30. Laraia, M. (2012). Introduction to nuclear decommissioning: Definitions and history. *Nuclear Decommissioning: Planning, Execution and International Experience*, 1-10.
31. Alonso, A. (2012). *Infrastructure and methodologies for the justification of nuclear power programmes*. Sawston, Cambridge: Woodhead Publishing Limited.
32. Lough, W.T.; and White, K.P. (1990). A critical review of nuclear power plant decommissioning planning studies. *Energy Policy*, 18(5), 471-479.
33. Hedin, A. (2014). License application for a spent nuclear fuel repository in Sweden. *Proceedings of the Probabilistic Safety Assessment and Management Conference (PSAM 2014).* Honolulu, Hawaii.
34. Torp, O.; and Klakegg, O.J. (2016). Challenges in cost estimation under uncertainty - A case study of the decommissioning of Barseback Nuclear Power Plant. *Administrative Sciences*, 6(4), 21 pages.
35. Bems, J.; Knapek, J.; Kralik, T.; Hejhal, M.; Kubancak, J.; and Vasicek, J. (2015). Modelling of nuclear power plant decommissioning financing. *Radiation Protection Dosimetry*, 164(4), 519-522.

36. Bond, A.; Palerm, J.; and Haigh, P. (2004). Public participation in EIA of nuclear power plant decommissioning projects: A case study analysis. *Environmental Impact Assessment Review*, 24(6), 617-641.
37. LaGuardia, T.S.; and Murphy, K.C. (2012). Financing and economics of nuclear facility decommissioning. *Nuclear Decommissioning: Planning, Execution and International Experience*, 49-86.
38. Takashima, R.; Naito, Y.; Kimura, H.; and Madarame, H. (2007). Decommissioning and equipment replacement of nuclear power plants under uncertainty. *Journal of Nuclear Science and Technology*, 44(11), 1347-1355.
39. Khurana, I.K.; Pettway, R.H.; and Raman, K.K. (2001). The liability equivalence of unfunded nuclear decommissioning costs. *Journal of Accounting and Public Policy*, 20(2), 155-185.
40. MacKerron, G. (1989). The decommissioning of nuclear plant. Timing, cost and regulation. *Energy Policy*, 17(2), 103-108.