A TECHNO-ECONOMIC ASSESSMENT OF PRIMARY HEAT TRANSPORT SYSTEM DECONTAMINATION IN SUPPORT OF DECOMMISSIONING PICKERING NUCLEAR GENERATING STATIONS

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ABSTRACT

The operating reactor units at Pickering are expected to be permanently shut down by approximately 2020 (this nominal date is for planning purposes only) and then decommissioned. OPG has adopted the ‘Deferred Dismantling’ strategy for decommissioning its nuclear plants. In contrast with prompt dismantling, radioactive decay leads to reduced dose expenditure during deferred dismantling. As part of the decommissioning strategy, chemical decontamination of the primary heat transport (PHT) system may be undertaken prior to Safe Storage.

Decommissioning costs depend significantly on the chosen deferral period. The overall objective of the present work was to contribute to the optimization of the existing decommissioning plan by assessing the benefits of decontamination. Accordingly, an overall cost-benefit analysis for PHT system decontamination was performed. Details are presented in this paper.

1.0 INTRODUCTION AND BACKGROUND

Currently, operating Pickering reactor Units are expected to be permanently shut down by approximately 2020 and then decommissioned. Pickering Units 2 and 3 have been shutdown since 1997 and are in Safe Storage.

Ontario Power Generation (OPG) has adopted the ‘Deferred Dismantling’ strategy for decommissioning its nuclear plants. Based on the current decommissioning plans, dismantling is nominally deferred for a period of 30 years. In contrast with prompt dismantling, radioactive decay leads to reduced dose expenditure during deferred dismantling. This benefit, however, is offset by the cost of maintaining the reactor unit in the preceding Safe Storage period.

Decommissioning costs must be optimized by selecting the appropriate deferral period. The overall objective of this work was to contribute to the optimization of the existing decommissioning plan by assessing the benefits of decontamination. The specific objectives of the study were to:

1) Determine the best timing and options available for decontamination,

2) Recommend the most suitable Primary Heat Transport (PHT) system decontamination process[1] and

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[1] Currently, Alkaline Permanganate/Citrox is the reference decontamination process in the Preliminary Decommissioning Plan [1].

3) Assess the need for decontamination, considering deferred dismantling periods of 10, 20 and 30 years.

Chemical decontamination may not be required at Units 2 & 3 because the prevailing radiation fields at these units are relatively low. Because the units have already been deactivated and prepared for Safe Storage, the cost of undertaking PHT system decontamination at these units could be prohibitive.

2.0 PHT SYSTEM DECONTAMINATION - GENERAL CONSIDERATIONS

Principle materials of construction employed in the Pickering PHT system include carbon steel, Monel-400, stainless steels 403/410 and zirconium alloys.

During reactor operation, carbon steel corrosion leads to the formation of a deposited magnetite layer overlying a thinner indigenous oxide layer formed at the base metal interface. On carbon steel surfaces (feeders and headers), the indigenous oxide layer is also principally magnetite. However, on stainless steel end fitting surfaces, the indigenous magnetite oxide layer is enriched in chromium, which also diffuses into the overlying deposited magnetite oxide. Similarly, copper and nickel from the indigenous Monel-400 steam generator (SG) oxide layer diffuse into and are incorporated into the overlying tube magnetite deposits.

As the oxide layer grows, radioactive activation and fission products are incorporated into its structure, resulting in the development of external radiation fields. Most of the fields are due to Co-60, Zr/Nb-95 and Sb-124. In order to decontaminate the radioactive components and hence reduce the radiation fields, the radioactivity present in the oxide structure must be freed up by dissolution of the oxides, followed by removal or regeneration of the solvent (alternately, mechanical means can also be employed for cleaning). Typically, dilute chemical decontamination reagents are employed because they can be regenerated using ion exchange resins, thereby avoiding the generation of large volumes of active liquid waste.

Dissolution of the oxides is also accompanied by base metal corrosion; both processes contribute to the dissolved metal loading of the solvent. Provided sufficient IX capacity is available, a single campaign, in principle, should be sufficient to clean out the entire PHT system. Repeat applications were necessitated during several Pickering PHT decontaminations in the early 1980s because of the inability at that time to correctly estimate the overall inventory of oxide in the PHT system. The flow path during these decontaminations included the SGs, which, because of their large surface areas, limited the magnitude of the achieved decontamination factor (DF), particularly, at the reactor face, where the radiation fields needed to be reduced the most.

The flow path selected and the choice of the decontamination process depend on the objectives of the decontamination. If SG fields are reasonably low and the main objective is to reduce radiation fields at the reactor face, then it would be desirable to valve out the SGs from the flow circuit and select a process which is effective for chromium-rich oxides existing on the stainless steel end fitting surfaces. Dissolution of chromium-rich oxides generally requires a multi-step process involving successive oxidizing and reducing steps in order to first solubilize the chromium present, thereby rendering the oxide more amenable to dissolution in a reducing reagent. The number of such alternating oxidizing and reducing steps depends on the desired cleanup target and is determined using reactor artifacts in a qualification program. On the other hand, if the primary objective is to reduce radiation fields generally, then there is no need for employing an oxidizing/reducing multi-step process, because the largely iron-rich magnetite deposits on other component surfaces can be effectively dissolved using a reducing reagent alone.

Chemical decontamination of the PHT system is a relatively complex undertaking involving a large number of trained personnel with expertise in station systems, chemistry, radiation protection and waste management. Because of this, the best time to perform a chemical decontamination in support of decommissioning is prior to, or soon after, permanent shutdown of the reactor unit, when trained personnel are still available. Other factors which also favor this course of action include a) escalation in costs for mounting a decontamination campaign when station systems have been partially or completely deactivated, b) deterioration in the condition of the system with time (e.g. drying-out of valve packings and gaskets) and c) possible unavailability of the station's active liquid waste system.

3.0 INVENTORY OF OXIDES IN PHT SYSTEM AT PICKERING

Data on metal loadings in solution, arising from both base metal corrosion and oxide dissolution, must be developed from characterization of reactor artifacts and decontamination tests to determine the anticipated DFs and IX resin requirements during a decontamination campaign. SGs, feeders and end fittings represent the components with the largest oxide loadings. While oxide loadings on SG surfaces are relatively well known, such data for feeders and end fittings are very limited. Most of the oxide loading in each SG is associated with the tube surface[2]. Therefore, the total oxide inventory in each SG was estimated based only on the oxide loading data for the tubes, as measured using the Oxiprobe technique.

Oxiprobe campaigns have been conducted at Pickering Units 1, 4, 6 and 8 [2]-[6]. Each campaign involved measurements, both in the hot as well as cold legs, in up to 8 tubes. Data were integrated as a function of tube length to obtain the total oxide inventory in the SG. The latter, based on the SG's service duration, was converted into an equivalent oxide growth rate. This, along with the projected total duration in service until final shutdown, was then used to estimate the total oxide inventory in all SGs for each reactor unit. The estimates ranged from 2200 kg for Unit 2 to a maximum of 5040 kg for Unit 6 as shown in Table 1.

Oxide loading data for feeders were developed based on results from a number of characterization studies [7][8] . The latter pertained to feeder pipe sections from Pickering Units 1-4 as well as from Bruce Units 1 & 2. Based on an assessment of the data, the growth rate of oxide on Pickering inlet feeders was considered to be 40 $g/m^2/y$ and the oxide loading on Pickering outlet feeders, independent of service duration, was considered to be 25 g/m^2. Note that the feeder pipe sections available for characterization were typically located within a few feet of the Grayloc hub. In this region, outlet feeders are subject to flow accelerated corrosion which prevents growth of the deposited oxide layer and hence leads to a relatively constant value for the oxide loading. The representative values for the oxide loadings on the inlet and outlet feeders were considered to be applicable over their entire lengths.

Available oxide loading data for end fittings are very limited and are based on the characterization of liner tube surfaces associated with the outboard section of Pickering Unit 2 end fittings [9]-[13]. Based on these data, the growth rate of oxide on the outer surfaces of Pickering inlet liners was considered to be about 10 $g/m^2/y$. The oxide loading on other

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[2] Each Pickering reactor unit has 12 SGs with approximately 2600 tubes per SG.

Pickering liner surfaces (inner inlet liner surfaces and both inner and outer outlet liner surfaces), regardless of service duration, was considered to be 25 g/m^2. The measured chromium content of the oxide was lower than 20%, the threshold above which an oxidative pre-treatment would be mandatory for effective decontamination. Note that the inner (inlet and outlet) liner surfaces are not likely to be accessible to reagents during decontamination.

Table 1: Estimated Inventory of Oxide in Pickering Steam Generators at Final Shutdown

Unit	Estimated Growth Rate (kg/SG/y)	Total Years in Service Until Final Shutdown	Estimated Loading at Shutdown (kg/SG)	Total Oxide Inventory - 12 SGs (kg)
1	9.2	35.7	329	3,950
2[a]	8.7	21.0	183	2,200
3[a]	8.7	22.6	197	2,360
4	7.7	37.8	293	3,515
5[b]	9.9	34.7	343	4,120
6	12.4	33.9	420	5,040
7[b]	9.9	35.0	347	4,160
8	7.4	33.9	252	3,020

[a] Based on average oxide growth rate for Units 1 and 4; [b] Based on average oxide growth rate for Units 6 and 8

4.0 RADIATION FIELDS AROUND THE PRIMARY HEAT TRANSPORT SYSTEM AND THEIR RADIONUCLIDE COMPOSITIONS

Routine radiation field surveys at the reactor face, feeder cabinet and SGs at Pickering typically yield data on the magnitude of radiation fields, their radionuclide composition and radionuclide surface activities. This section presents a broad overview of the survey data. These data were used to derive dose estimates for dismantling as discussed later.

Among the radionuclides generally observed during reactor surveys, only Nb-94 is long-lived, followed next by Cs-137, Co-60 and Sb-125 (half-lives of Nb-94, Cs-137, Co-60 and Sb-125 are 20300 y, 30 y, 5.2 y and 2.8 y, respectively). The other observed radionuclides (Zr/Nb-95, Sb-124, La/Ba-140, Fe-59 etc.) have a half-life of about 2 y or less. Based on observed levels for various radionuclides, Co-60 is still the dominant radionuclide present 10 y after final shutdown; beyond 10 y, however, the relative contribution of Nb-94 increases, with Co-60 and Nb-94 having comparable activities 30 y after shutdown.

Radiation fields @ 30 cm from the reactor face are relatively constant with time at various Pickering units [14]-[16]. They are bounded at the low end by the fields at Units 4 & 7 (about 90 mrem/h) and at the upper end by the fields at Unit 8 (about 190 mrem/h). Unit 8 survey data from 2012 [14] indicated similar (about 1.0E+05 Bq/cm^2) surface activities of the key radionuclides Co-60, Zr/Nb-95 and Sb-124 although their field contributions were somewhat different: Co-60 (about 40%), Sb-124 (about 25%) and Zr/Nb-95 (about 23%). Reactor vault fields decrease steadily with distance from the reactor face. At 5 m from the face, which is representative of working distances during reactor dismantling, fields are expected to be about 50% of the values prevailing @ 30 cm from the reactor face.

Figure 1 shows the variation in radiation fields at the horizontal feeder cabinet (HFC) as recorded in Unit 8 in 2012 [14]. The solid line depicts model predictions. Because of the higher specific activity of deposits in the inlet feeders, the fields peaked at about 500 mrem/h at the center of the inlet feeder assembly, while fields at the center of the outlet feeder assembly were significantly lower, about 300 mrem/h. Note that these fields are much higher than the corresponding reactor face fields at Unit 8. This is because the walls of the feeder pipes provide significantly less self-shielding than the thicker walled reactor face end fitting components.

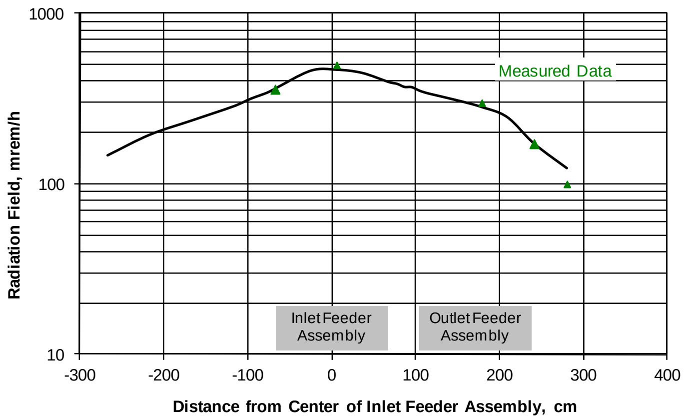

Figure 1: Variation of Radiation Fields within the HFC (P1281 Outage)

Measured contact SG dose rate data for several Pickering reactor units, after correction for nearest neighbors (SGs are arranged in two banks of 6 each), yielded cold leg dose rates of about 17 mrem/h, approximately a factor of 3-4 higher than the corresponding hot leg dose rates [14]-[16]. This is consistent with the higher activity of the cold leg oxide deposits. Similar to the reactor face fields, the overall SG fields have been relatively constant over time (over 1000 EFPD). Note that fields were measured for water filled (both primary and secondary sides) SGs. For fully drained SGs, the state during dismantling, radiations fields are expected to be a factor of 2 higher.

5.0 OPTIONS FOR DECONTAMINATION

The underlying objective of a successful decontamination is to maximize the dissolution of the radioactively contaminated metal oxide, while at the same time minimizing base metal corrosion. Although the latter is not critical in a *decontamination for decommissioning* campaign, it is, nevertheless, important from the perspective of reducing secondary waste generation.

5.1 CHEMICAL DECONTAMINATION

Table 2 presents a list of chemical processes, including the reference alkaline permanganate/Citrox process, which may be suitable for decontaminating the PHT system prior to decommissioning [17]. Except the DFD (Decontamination for Decommissioning) process, all the processes listed were developed for operating reactors with corrosion minimization as an important consideration. The DFD process is the only one that has been specifically developed to obtain high DFs as a result of the significant corrosion rates achievable using fluoroboric acid [18]. Unlike in a CANDU, the DFD process when applied to a defueled PWR or BWR does not come in contact with any zirconium (the PWR/BWR pressure vessel is constructed of stainless steel clad carbon steel). Use of the DFD process in a CANDU, however, would result in very high zirconium alloy corrosion rates [19], leading to the transport and potential deposition of large amounts of highly activated zirconium on out-core surfaces. In addition, high carbon steel corrosion rates would necessitate lower application temperatures to mitigate hydrogen production.

Table 2: Chemical Processes for PHT System Decontamination

Process	Applied to CANDU	Applied to PWR/BWR	Chemistry
CAN-DECON / AP	Y	Y	Reducing Cycle – EDTA, Citric and Oxalic Acids Oxidizing Cycle - Alkaline Permanganate
CAN-DEREM / AP	Y	Y	Reducing Cycle – EDTA, Citric Acid Oxidizing Cycle - Alkaline Permanganate
CAN-DEREM Plus / AP	Y	N	Reducing Cycle - Higher concentration EDTA and Citric Acids than in CAN-DEREM Oxidizing Cycle - Alkaline Permanganate
CITROX / AP*	N	Y	Reducing Cycle - Citric and Oxalic acid Oxidizing Cycle - Alkaline Permanaganate
CORD / HP	N	Y	Reducing Cycle - Oxalic Acid Oxidizing Cycle - Permanganic Acidic
LOMI / NP	N	Y	Reducing Cycle - Vanadium Picolinate Oxidizing Cycle - Nitric / Permanganic Acidic
EMMA	N	Y	Reducing Cycle - Ascorbic and Citric acid Oxidizing Cycle - Potassium Permanganate / Nitric and Sulfuric Acids
DFD	N	Y	Reducing Cycle - Fluoroboric Acid Oxidizing Cycle - Potassium Permanganate

* Reference decontamination process considered in Preliminary Decommissioning Plan [1].

Use of other solvents, including DFD, would necessitate an elaborate process development program with achievable DFs similar to the previously utilized solvents and for this reason is not recommended. Therefore, subsequent discussion is limited to the use of the proven reagents. Only the Can-Decon and Can-Derem /Can-Derem Plus reagents along with the alkaline permanganate (AP) oxidizing reagent have been demonstrated and field hardened for application in CANDU reactors. To date, 11 decontamination CAN-DECON campaigns have been conducted between 1975 and 1991, of which 8 have been at Pickering Units 1-4. For most applications, the reactor was not defueled. The number of SGs in the flow path at Pickering varied from a minimum of 4 to a maximum of 12. The campaign at Pickering Unit 3 in 1989 included an alkaline permanganate step. Results for the two applications at Pickering Unit 3 suggest that the oxidizing step had very little benefit and significantly increased the amount of secondary waste generated. Judging from the DFs obtained, the most successful campaigns were at Pickering Unit 2 in 1984 and at Pickering Unit 3 in 1985 &1989; DFs at the reactor face exceeded 5.

5.3 MECHANICAL DECONTAMINATION

One option for enhancing the effectiveness of chemical decontamination of the PHT is to exclude the SGs from the flow path and instead clean the SG tube internals mechanically. Framatome ANP's Sivablast and Candu Energy's CANDU Clean processes have been specifically developed for this purpose and rely on the use of abrasive blast media. Generally, steel beads are introduced under pressure into a tube at its cold-leg end and collected at the other end of the tube in the hot-leg. The reusable media and the removed oxide are gathered using a suction header that covers the entire hot leg tube sheet surface. An air ejector conveys the collected material, through a vacuum hose, to the reclaimer where the oxide is screened from the blast media[3] with the latter being subsequently returned for renewed service [20]. The separated oxide is collected in shielded containers. Note that for effective application of the technique, the SG oxide must be dried prior to shot blasting applications.

6.0 STRATEGIES FOR DECONTAMINATION OF PHT SYSTEM

PHT decontamination would likely be implemented prior to final station shutdown, or soon thereafter, before vital station systems are deactivated. This will ensure that the vast resources required to implement PHT system decontamination are readily available. Decontamination may be carried out with or without a defueled reactor. Advantages of decontaminating a defueled reactor core include:

- Decontamination can be carried out using light water. Therefore, deuteration and de-deuteration of the large quantities of ion exchange resins needed for the decontamination are avoided and drips from leaky closure plugs and valve packings do not give rise to significant tritium exposures.

- Reduced inventory of in-core deposits - these deposits, otherwise, may contribute to out-of-core activity transport during a decontamination,

The principal disadvantage of decontaminating a defueled reactor core arises from the displacement of the fuel bundles (4680 for a Pickering reactor) which causes an increase in PHT system volume and hence an increase in the purification half life of the system.

Three strategies for the decontamination of Pickering reactors were considered:

Strategy 1	Chemical decontamination of the PHT system including all SGs
Strategy 2	Chemical decontamination of the PHT system excluding all SGs
Strategy 3	Chemical decontamination of the PHT system excluding all SGs + Mechanical decontamination of SGs

Strategy 1 or 3 can be implemented if radiation fields need to be reduced both at the reactor face as well as at the SGs. In Strategy 1, a rig consisting of a filter and cation/mixed bed resin columns is temporarily installed to permit the decontamination solvent from the bleed cooler to bypass the normal purification system (this does not have adequate filtration and ion exchange

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[3] Oxide dust and debris are separated from the reusable beads by an adjustable air wash unit [Semmler et al 1998]. A pneumatically vibrated tray-type screen is installed below the air wash unit.

capacity) and flow instead through the decontamination rig; a minimum of one pump and, therefore, one SG from each quadrant are included in the flow circuit to provide pump heat.

Engineering modifications are required to implement Strategy 2 or Strategy 3 in order to reduce the purification half-life of the decontamination system these are relatively straightforward to make in the context of decommissioning. A rig consisting of a filter, cation/mixed bed resin columns and pumps is temporarily installed in each quadrant. Decontamination is carried out one quadrant at a time.

Mechanical decontamination of SGs using abrasive steel shot is a mature technology that has been applied several times in CANDU SGs and can remove over 80% of the oxide on SG tubes [21]. In contrast with chemical decontamination, mechanical cleaning of SG tubes generates much lower volumes of secondary waste.

The purification half life[4] in Strategy 1 will exceed 30 min while that in Strategy 2 and 3 would be lower because of the reduced system volume.

7.0 DECONTAMINATION OF PHT SYSTEM - SECONDARY WASTE GENERATION

An assessment of secondary waste generation during the PHT decontamination of Pickering reactor units was performed. For this purpose, corrosion and oxide loading data were assembled. Corrosion values were based on data observed during Pickering decontaminations. Oxide loadings were estimated as per the discussion in Section 3. Table 3 summarizes the estimates for metal contribution from oxide dissolution and corrosion. Note that both contributions are of comparable magnitudes for carbon steel as well as stainless steel components.

Table 3: Contribution of Metals from Oxide Dissolution and Metal Corrosion

Metal Contribution	Carbon Steel Feeders, Headers and SG Bowl	Monel 400 Steam Generator Tubes	Stainless Steel End Fittings, Liners and Shield Plugs
Oxide Dissolution (kg)	1723	3649	261
Metal Corrosion (kg)	1150	196	182

Estimates for secondary waste volumes generated during decontamination are presented in Table 4. Excluding SGs from the flow path led to significantly reduced resin requirements for both Strategy 2 and Strategy 3 compared to that for Strategy 1. In Strategy 3, additional waste consisting of the abraded SG tube oxide and the spent abrasive grit media is also generated; the volume of this additional waste[5] was estimated to be 6 m^3.

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[4] Purification half life refers to the time required to achieve a 50% reduction in concentration.

[5] The amount of abrasive media used during a clean, based on mechanical cleaning data for various CANDU SGs, was estimated on average to be about 54 g per tube. Based on this, cleaning of the 12 SGs at each Pickering unit (each SG contains 2600 tubes) would generate about 1700 kg of media waste. Based on 80% cleaning efficiency, the maximum quantity of dry oxide waste generated would be 0.8*5040 or about 4000 kg. Thus, the total secondary waste generated during the mechanical clean would be 5700 kg. Based on a bulk density of about 1000 kg/m^3, its volume would be about 6 m^3.

Table 4: Estimates for Secondary Waste Volumes Generated during PHT Decontamination

Waste	Waste Volume* (m^3)		
	Strategy 1 (SGs in Flow Path)	Strategy 2 (SGs Excluded from Flow Path)	Strategy 3 (SGs Mechanically Decontaminated)
Cation Bed Resin	106	37	37
Mixed Bed Resin	21	7	7
Filter	5	5	5
Other	0	0	6**
Total	**132**	**49**	**55**

*Cation resin requirements were estimated assuming a capacity of 1.9 equivalents / L. The amount of mixed bed resin required to remove added decontamination reagents was conservatively assumed to be 20% of the cation resin volume. Filter wastes were assumed to be 5 m^3.

** Abraded magnetite and abrasive media.

8.0 DOSE REDUCTION DURING DECOMMISSIONING RESULTING FROM PHT SYSTEM DECONTAMINATION

In order to quantify the dose benefit from decontamination of the PHT system, estimates of work performed (person-hours) in PHT radiation fields during decommissioning were first required.

Most of the labor during decommissioning is expended during the Dismantling phase. While dose associated with moderator system activities will largely be unaffected by PHT decontamination, dose associated with most, but not all, activities pertaining to the PHT system will be positively impacted. Thus, for example, dose during dismantling of the reactor channels (i.e., removal of end fittings, pressure tubes and calandria tubes) arises dominantly from the bulk activated components which will not be affected by PHT system decontamination. On the other hand, dose associated with the removal of feeder pipes and headers will be positively impacted.

Person-hours estimates for the dismantling of PHT system components deemed to be positively impacted by decontamination were obtained based on the analysis of Work Breakdown Structures developed by TLG Services, Inc. (TLG) for estimating decommissioning costs for Pickering reactors [22][23]. Because only a fraction of the person-hours associated with each activity or sub-task is spent in a radiation field, TLG also provided an estimate of this fraction and its breakdown into 3 distance categories namely, a) Contact (@ 0.3m), b) Immediate area (1-2 m) and c) General area in order to permit calculation of dose estimates. These estimates were then combined with estimates for the radiation fields at the various work locations to determine the overall dose.

Doses were estimated for 3 deferred dismantlement periods, namely, 10, 20 and 30 y. Radionuclides, contributing to the radiation fields, 10 y or more after final shutdown, are limited to the relatively longer-lived Co-60, Nb-94, Cs-137 and Sb-125. Based on measured gamma survey data,

- The percentage contribution of Co-60 to the reactor face, feeder cabinet and steam generator radiation fields at final shutdown was considered to be about 40%, 75 % and 60 %, respectively; in general, levels of Nb-94,Cs-137 and Sb-125 were typically below 1 % [14]-[16].

- The average reactor face and feeder cabinet fields @ 0.3 m from the surface were estimated to be 100 - 200 mrem/h and 200 - 500 mrem/h, respectively. Drained steam generator cold and hot leg fields, @ 0.3 m from the surface, were 24-44 mrem/h and 4-12 mrem/h, respectively [14]-[16].

Variation of fields with distance for the above components was assessed based on plots such as that shown in Figure 1. Radiation fields for other PHT system components such as pumps/motors, bleed condenser, bleed cooler and assorted piping, although variable, were assigned the following conservative values (based on OPG's database for Darlington): 50 mrem/h @ 0.3 m, 25 mrem/h at 1-2 m and 10 mrem/h general area with their composition assumed to be identical to that for the reactor face fields.

Based on previous experience, PHT system decontamination was considered to be generally capable of reducing radiation fields by a factor of 5 or 80% for all components and radionuclides. Thus, the dose benefit as a result of decontamination equals 80% of the estimated pre-decontamination dose. Considering that decontamination is conducted just prior to or soon after permanent shutdown, Table 5 summarizes the Dose Benefit as a function of the deferred dismantling duration. Because Co-60 is the dominant contributor to the fields, the dose benefit essentially decreases with elapsed time based on the half-life of Co-60. Although the details are not presented here, most of the benefit is realized during the dismantling of feeders/headers compared to which, the dose benefit realized during the dismantling of the SGs is relatively small (about 5 %).

Note that the dose benefit was generally estimated considering only the relatively long-lived radionuclides Co-60, Nb-94, Cs-137 and Sb-125. This yielded an estimate of 1155 rem for the first case presented in Table 5. For this case, inclusion of the shorter-lived radionuclides such as Zr/Nb-95, Sb-124, La/Ba-140 and Fe-59 yielded a significantly higher dose benefit estimate of 1600 rem. Because the shorter-lived radionuclides will decay away rapidly, the lower value of 1155 rem is considered to be a more realistic estimate of the initial dose benefit.

Table 5: Estimated Dose Benefit from PHT Decontamination - Deferred Dismantlement

Deferral (y)	Dose without Decontamination* (Rem)	Dose with Decontamination* (Rem)	Dose Benefit (Rem)
0	1444	289	1155 (1600**)
10	394	79	315
20	114	23	90
30	38	8	30

* Considering only Co-60, Nb-94, Cs-137 and Sb-125
** Considering all radionuclides.

9.0 PROJECTED COSTS FOR PLANNED DECONTAMINATIONS

The overall cost for PHT decontamination was developed considering costs for design, equipment, consumables, secondary waste and labor. Cost data from previous CAN-DECON decontaminations and from other sources were compiled [24]-[26]. In general, because of limited availability of data, the quality of the estimates is not considered to be high. Cost for the abrasive mechanical cleaning of SG tubes was estimated based on Bruce Power's data of $300 per tube [27]. Waste management costs were estimated based on the estimates for secondary waste volumes generated during decontamination and OPG's ILW disposal cost of $ 18,542 per m^3 [28].

Decontamination cost estimates are given in Table 6. Costs for engineering modifications required to implement Strategy 2 and Strategy 3 were not included. As shown, the differential between the costs for Strategy 1 and Strategy 2 is only $1.6 M even though all 12 SGs are additionally decontaminated in Strategy 1. This is explained below:

- Limitations on installed IX capacity necessitate Strategy 1 to be conducted in at least 4 phases; the required capacity will, therefore, be a quarter of the IX resin needs, i.e., about 32 m^3. In contrast, because Strategy 2 must be conducted one quadrant at a time, and hence in 4 phases also, the required installed IX capacity will similarly be about 11 m^3.

- The process implementation costs for both strategies (the highest cost item in Table 6) were considered to be the same because both must be conducted in 4 phases. Equipment design and fabrication costs for all strategies were considered to be the same also: in Strategy 2, the cost of more equipment (pumps and heaters) on the decontamination rig is offset by the substantially lower requirements for installed IX capacity.

Table 6: Breakdown of Decontamination Costs for Pickering

Cost Element	**Overall Cost* ($ M)**		
	Strategy 1	**Strategy 2**	**Strategy 3**
Equipment design and fabrication	2.3	2.3	2.3
Process development	4.2	4.2	4.2
Resin supplies	1.2	0.49	0.43
Decontamination chemicals	0.12	0.05	0.04
Process implementation	6.0[a]	6.0[a]	6.0[a], 9.4[b]
Waste management	2.5	1.0	0.91
Total	**15.1**	**13.5**	**23.0**

*, 2012 dollars; a, chemical decontamination; b, mechanical cleaning

Based on cost and process considerations, Strategy 2 is recommended, provided that the costs for engineering modifications are relatively modest. Although SGs are excluded from the flow path in Strategy 2, the net impact on dose during dismantling is small as they contribute less than 5% to the overall dose. A more robust assessment is needed to substantiate the cost estimates developed here.

10.0 OVERALL COST-BENEFIT ASSESSMENT

This section presents a differential cost - benefit analysis for PHT decontamination based on the following considerations:

- Strategy 1 with a decontamination cost of $ 15.1 M, was chosen as the reference case,

- A value of $ 50,000 per person-rem averted [29] was used to monetize the expended dose and the dose benefit from decontamination (see Table 5).

- Based on data developed by TLG [22][23], the cost for Safe Storage per unit per year was considered to be $ 2.5 M. TLG's cost estimate for dismantling (about $ 180 M per unit), does not take into account the dose benefit from decontamination and is nominally the same for all deferred dismantling scenarios. It was, therefore, disregarded in the present differential analysis.

Table 7 presents a decontamination cost benefit analysis for various deferral scenarios. A similar analysis, considering no decontamination, is presented in Table 8. In both tables, Item 3 represents the cost of dose expended during dismantling (see Table 5) while Item 4 represents the monetary value (shown with a negative sign) of the dose benefit from decontamination (see Table 5). The analysis indicates the following:

- Following decontamination, prompt decommissioning results in a net savings of $ 28.2 M. Deferral of dismantling progressively adds cost as the increased cost for Safe Storage offsets the decreasing dose benefit. The net cost is zero at some intermediate time between 0 y and 10 y.

- In the absence of decontamination, the optimum deferral period appears to be around 10 y. Before this, the cost of the expended dose is high while beyond this period, the cost for Safe Storage becomes dominant.

- Deferral of dismantling beyond 10 y progressively eliminates the benefit from decontamination, i.e., the net cost with decontamination exceeds that without it.

Table 7: Cost Benefit Analysis for Various Deferred Dismantling Periods – Decontamination Performed

#	**Cost Element**	**Estimated Costs** ($ M) per Unit**			
		0 y (Prompt Decommissioning)	**10 y Deferred Dismantling**	**20 y Deferred Dismantling**	**30 y Deferred Dismantling**
1	Decontamination prior to or following final shutdown	15.1	15.1	15.1	15.1
2	Safe Storage	0	25	50	75
3	Dose Expended during dismantling	14.4	3.9	1.1	0.4
4	Dose Benefit during dismantling	-57.8	-15.8	-4.6	-1.5
5	Net Cost due to Decontamination and Deferred Dismantling*	-28.2	28.3	61.7	88.9

* Sum of #1 - 4   ** 2012 Dollars

Table 8: Cost Benefit Analysis for Various Deferred Dismantling Periods – No Decontamination Performed

#	Cost Element	Estimated Costs** ($ M) per Unit			
		0 y (Prompt Decommissioning)	10 y Deferred Dismantling	20 y Deferred Dismantling	30 y Deferred Dismantling
1	Decontamination prior to or following final shutdown	0	0	0	0
2	Safe Storage	0	25	50	75
3	Dose Expended during dismantling	72.2	19.7	5.7	1.9
4	Dose Benefit during dismantling	0	0	0	0
5	Net Cost due to Decontamination and Deferred Dismantling*	72.2	44.7	55.7	76.9

* Sum of #1 - 4 ** 2012 Dollars

12.0 CONCLUSIONS

- Chemical decontamination of the PHT system is a relatively complex undertaking involving a large number of trained station personnel with diverse expertise. Because of this, the best time to perform a chemical decontamination is prior to or soon after final shutdown when trained personnel are still available. As decommissioning progresses through to Safe Storage, many station systems will have been partially or completely deactivated which would significantly escalate costs for mounting a decontamination campaign.

- Amongst the available decontamination processes, only the reducing Can-Decon and Can-Derem /Can-Derem Plus reagents along with the oxidizing alkaline permanganate reagent have been demonstrated and are field hardened for application in CANDU reactors. These processes are recommended for future use to avoid an expensive development program based on alternate reagents.

- Three strategies for decontamination of Pickering reactors were considered:

  Strategy 1: Chemical decontamination of the PHT system including all SGs
  Strategy 2: Chemical decontamination of the PHT system excluding all SGs, and
  Strategy 3: Chemical decontamination of the PHT system excluding all SGs + Mechanical decontamination of SGs

  Strategy 1 or 3 can be implemented if radiation fields need to be reduced both at the reactor face as well as at the SGs. Engineering modifications are required to implement Strategy 2 or Strategy 3 in order to reduce the purification half-life of the decontamination system; however, these are relatively straightforward to make in the context of decommissioning. Mechanical decontamination of SGs using abrasive steel shot is a mature technology that has been successfully applied in CANDUs. It generates much lower volumes of secondary waste compared with chemical decontamination. However, based on its substantially higher cost ($ 23 M), implementation of Strategy 3 is not recommended. Costs for implementing

Strategy 1 was estimated to be about $15 M while that for implementing Strategy 2 is about $ 13.5 M plus the costs for engineering modifications,.

- Based on an assessment of the various dismantling activities to be undertaken, most of the dose benefit from decontamination will be realized during the dismantling of feeders and headers and to a much smaller extent (< 5 %) during SG dismantling. This suggests that SGs could be excluded from the flow path without significantly impacting the dose incurred. Strategy 2 is, therefore, recommended, provided that the costs for engineering modifications are relatively modest.

- An overall cost benefit analysis of PHT system decontamination indicated that prompt decommissioning, following PHT decontamination prior to or immediately after final shutdown, would result in the greatest benefit, a net savings of about $ 28 M per unit. Deferring the dismantling progressively adds cost as the increased costs for Safe Storage offsets the decreasing value of the dose benefit. The net costs for deferred dismantlement are summarized below

Deferral period	0 y	10 y	20 y	30 y
Net costs with decontamination ($M)	-28	28	62	89
Net costs without decontamination ($M)	72	45	56	77

  Thus, decontamination is beneficial if dismantlement is deferred no later than about 20 y after final shutdown. It yields a net cost benefit until some intermediate period between 0 and 10 y.

- Dose reduction estimates and the decontamination cost-benefit assessment did not consider the impact of alpha and beta emitting isotopes on both work processes and potential dose commitments. Past incidents strongly favor performing a decontamination.

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