3rd Canadian Conference on Nuclear Waste Management, Decommissioning and Environmental Restoration
Ottawa Marriott Hotel, Ottawa, ON, Canada, September 11-14, 2016

# RADIONUCLIDE INVENTORY ESTIMATES FOR DECOMMISSIONING WASTES FROM ONTARIO POWER GENERATION'S NUCLEAR STATIONS

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**Abstract**

Wastes generated from the decommissioning of Ontario Power Generation's (OPG) nuclear stations at Pickering, Bruce and Darlington are planned for disposal in a Deep Geological Repository (DGR). An estimate of the radionuclide inventory for the wastes is required for planning purposes and to support the safety case and licensing of the DGR. Kinectrics was contracted to develop a comprehensive estimate for the radionuclide inventory of the decommissioning wastes. This paper presents an overview of the methodology employed and the overall findings. The inventory was based on estimates for the reactor core, bioshield, steam generators/preheaters and carbon steel components. They are based on a combination of neutron-induced specific activities for in-core components obtained using the ORIGEN-S code and estimates for deposited activity on out-core components obtained from characterization for various reactor artefacts.

## 1. Introduction

The 4-unit Nuclear Generating Stations (NGS) located at Pickering-A & B, Bruce-A & B and Darlington in Ontario will eventually be decommissioned by the owner Ontario Power Generation (OPG) in accordance with a 'Deferred Dismantling' strategy whereby each unit is placed in 'Safe Storage' for a period extending up to 30 years before being 'Dismantled'.

- Units 2 and 3 at Pickering-A, permanently shut down in December 1997, are now in Safe Storage; the other Pickering-A units and all Pickering-B units, at the time of initiating this study, were planned to be shut down in 2020[1].
- Bruce-A was temporarily shut down in the late 1990s. Following refurbishment, which started in 2006, Units 1 & 2 returned to power in 2012 while Units 3 and 4 were directly restarted in 2004 and 2003, respectively.
- Bruce Units 3-8 and Darlington are planned to be refurbished in the near future. At the time of initiating this study, the anticipated final shutdown dates of the refurbished units ranged from 2042 to 2055[2].

A comprehensive radionuclide inventory estimate for Darlington's decommissioning waste was first reported in 2003 [1]. It was developed for neutron activated reactor core components including reactivity mechanisms. In 2014, Kinectrics was contracted to develop comprehensive radionuclide inventory estimates for decommissioning waste from all OPG stations. This paper presents a detailed

[1] This date has recently been revised to 2024.
[2] This date has recently been revised to 2063.

assessment of the radionuclide inventory developed. The first step was to develop a consistent list of components and associated weights for Systems, Structures and Components (SSCs) at each station. Radionuclide inventories for components subject to neutron activation were estimated from available data obtained using ORIGEN-S. For out-core components, such as feeders, projections were based on characterization data for component radioactive surface deposits.

## 2. Description of OPG reactor systems

Figure 1 is a simplified schematic of the two-loop CANDU Primary Heat Transport System (PHTS).

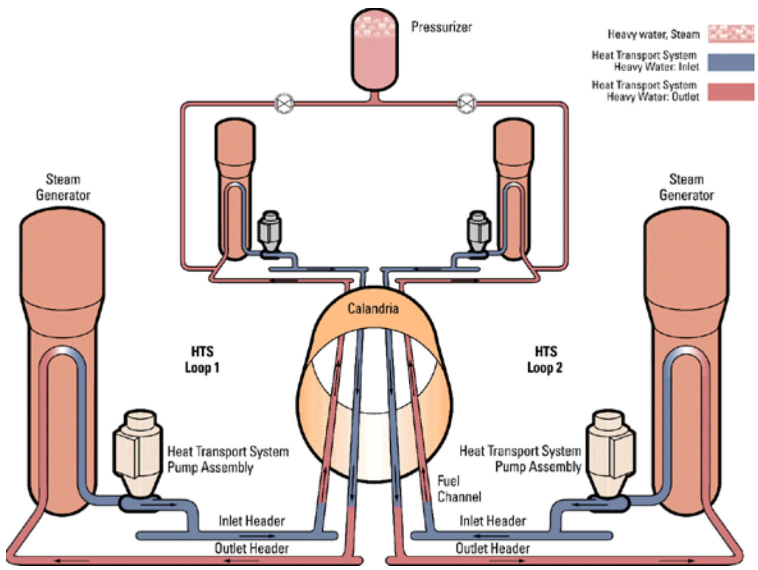


**Figure 1 Simplified Schematic of the Two Loop Primary Heat Transport System**

A description, based on the Darlington reactor design, is presented next and differences between this design and earlier Pickering and Bruce designs are highlighted. Key features of the Pickering, Bruce and Darlington reactor systems are compared in Table 1. The reactor assembly is comprised of:

1. Calandria, end-shields and the shield tank,

   The calandria is the outer reactor vessel which houses the heavy water moderator. The end-shield is a cylindrical vessel spanned horizontally by lattice tubes, and enclosed at its two ends by tube sheets. At Darlington and Bruce, the calandria, with end-shields attached, are installed in a shield tank which forms the bioshield; the tank contains natural water, and shielding slabs and balls. While the end-shield designs at Darlington, Bruce and Pickering-B contain steel shielding balls, the Pickering-A end-shield contains shielding slabs. At Pickering-A, the calandria is housed in an air-filled high density concrete vault, while at Pickering-B, it is submerged in a light water filled, carbon-steel lined, regular density, concrete vault.

2. Fuel channel assemblies

   Typically, several hundred fuel channels with end fittings are mounted across the calandria vessel. Each channel consists of two concentric tubes: the inner tube (pressure tube) houses a string of fuel bundles cooled by heavy water coolant. The outer tube (calandria tube) is surrounded by heavy water contained in the calandria vessel. Individual feeder pipes connect the end fittings to the distribution headers.

3. Reactivity control and safety shutdown units

The reactivity mechanism deck provides a mounting area for the vertical reactivity control (liquid zone, adjuster, shutoff, solid absorber and flux detector) units. At Darlington, the deck structure is supported on the top surface of the shield tank extension, thus providing a containment boundary. Guide tubes for the reactivity control units penetrate the calandria, pass between the tubes and lock into locators on the opposite wall of the calandria shell. The control units are supported by thimbles welded to nozzles on the calandria. The thimbles extend to the reactivity mechanism deck in the case of vertical control units and to the shield tank wall in the case of horizontal reactivity control and safety shutdown units (i.e., ion chambers, liquid injection and horizontal flux detectors).

A unique feature at Pickering-A is the provision of a large cylindrical dump tank which permits rapid draining of the calandria water, thereby augmenting reactor shutdown.

**Table 1 Selected Features of Pickering, Bruce and Darlington Reactor Units**

| Item | Pickering-A | Pickering-B | Bruce-A | Bruce-B | Darlington |
|---|---|---|---|---|---|
| Calandria shielding | Air-filled concrete vault | Light water filled steel-lined concrete vault | Light water filled steel shield tank | Light water filled steel shield tank | Light water filled steel shield tank |
| End-shielding | Steel plates and light water | Steel balls and light water | Steel balls and light water | Steel balls and light water | Steel balls and light water |
| Reactor Headers | 4 inlet 4 outlet | 4 inlet 4 outlet | 4 inlet 2 outlet | 4 inlet 2 outlet | 4 inlet 4 outlet |
| No. of SGs | 12 | 12 | 8 | 8 | 4 |
| Preheaters | Integral in SG | Integral in SG | 4 | 4 | Integral in SG |
| Surface Area per SG ($m^2$) | 1858 | 1843 (based on 2573 tubes) | 2368 (excluding preheaters) | 2400 excluding preheaters | 4830 |
| No. of PHT Pumps | 12 + 4 spare | 12 + 4 spare | 4 | 4 | 4 |
| Main Moderator System Volume ($m^3$) | 260 | 242 | 296 | 296 | 302 |
| Adjuster Rods (Absorbers) | 6 SS (immobilized) | Unit 5: 21 SS Unit 6-8: 21 Co | NA | 24 (cobalt) | 24 (SS) |
| Control Absorbers (Cadmium) | NA | 4 | 4 | 4 | 4 |
| Vertical Flux Assemblies | 6 | 20 (14 for Unit 6) | 12 | 27 | 23 |
| Horizontal flux Assemblies | NA | 7 | 2 | 8 | 14 |
| Shutoff Rods | 23 (21 for Unit 3) | 28 | 30 | 32 | 32 |
| Poison Injection | NA | 6 | 7 | 8 | 8 |
| Liquid Zone Control | 6 | 14 | NA | 6 | |
| Ion Chambers | 6 | 6 | NA | 6 | |

NA, Not Applicable; SS, Stainless Steel; SG, Steam Generator

## 3. Weight breakdown of various reactor components

Detailed breakdowns of the weights of various components associated with the Pickering, Bruce and Darlington calandria vessels were developed in order to estimate total radionuclide inventories from specific activity data. The breakdowns were based on miscellaneous source documents, recognizing similarities, where they exist, between the designs of various stations. Because of inconsistencies in the descriptions and weights of the components and data gaps, the overall weight estimates presented here are subject to significant uncertainty. For consistency and ease of comparison, a common detailed listing of various reactor components was used to populate the data.

The weight of the Pickering-A dump tank was estimated from its dimensional information, while the weight of the Pickering-A bioshield was estimated corresponding only to its neutron activated zone. This was considered to be a cylindrical shell of approximate width 51 cm surrounding the calandria; the rest of the concrete was considered to be radiologically clean and hence not pertinent.

For brevity, a summary of the weight breakdown is presented in Table 2. Note the following:

- End-shields at Pickering-A contain shielding slabs while those at Pickering-B contain shielding balls. This difference accounts for the higher weight of the Pickering-A end-shields. Similarly, calandria at Pickering-A contain shielding slabs while those at Pickering-B do not, thus resulting in a significantly higher weight.
- Pickering-B has a light water bioshield bounded on the inside by the calandria shell and on the outside by concrete; no weight was assigned to it as the concrete will not be activated.
- The shielding slabs, concrete bioshield and to a lesser extent the dump tank account for the significantly greater weight for Pickering-A relative to Pickering-B.
- Similar to Pickering-B, Bruce and Darlington reactor units also utilize a light water bioshield; in these cases, the listed weights, however, represent the weights of the shield tank structure and the shielding slabs/balls contained within the tanks.
- Despite the larger number of fuel channels and, therefore, larger calandria and end shields at Bruce and Darlington, total weight estimates for the two stations differ from those for Pickering-B largely because of the contribution from the bioshield.

**Table 2 Summary of the Weight Breakdown of Various Reactor Components**

| Reactor Component | Component Weight (kg) | | | |
|---|---|---|---|---|
| | Pickering-A | Pickering-B | Bruce | Darlington |
| End Shields | 439,200 | 320,800 | 386,000 | 411,800 |
| Calandria | 143,100 | 36,700 | 39,100 | 38,200 |
| Fuel channels | 280,600 | 273,300 | 317,300 | 333,700 |
| Reactivity mechanism deck | 214,100 | 214,100 | 214,100 | 212,600 |
| Miscellaneous | 174,000 | 174,000 | 235,200 | 235,200 |
| Dump Tank | 35,000 | | | |
| Biological Shield | 235,000* | | 836,700** | 755,200** |
| **Total** | 1,521,000 | 1,018,900 | 2,028,200 | 1,986,700 |

*Concrete; ** Shield Tank

## 4. Scope and overall methodology

The key components for estimating the radionuclide inventory can be categorized as follows:

1. Reactor Core Components: These refer to fuel channels and associated components including end fittings, the end-shield, the calandria and reactivity control and safety shutdown mechanisms (RCSSMs). Typically, most of the radioactivity associated with these components arises from neutron activation. Estimates of neutron induced activity for several of these components have previously been developed using the ORIGEN-S code. In addition, measured data, particularly for pressure tubes and end fittings, are also available.

2. Balance of plant: This refers to the out-core surfaces of all PHTS and moderator system components. They are not subject to neutron activation but become contaminated as a result of radionuclide deposition from the coolant. Most of the surface area in the PHTS is associated with steam generators and feeder pipes, while moderator heat exchangers represent the largest surface area component in the moderator system. The inventory associated with steam generators and feeders was directly estimated from the available characterization data, with the results then extrapolated to other carbon steel components such as pressurizers, bleed condensers and bleed coolers. The inventory of radionuclides in the moderator system, considered to be significantly lower, was not addressed.

In the case of Pickering-A, the activity associated with the concrete bioshield is also an important contributor to its overall decommissioning waste inventory.

### 4.1 Equivalent full power year (EFPY) values for estimating radionuclide inventories

Generally, the magnitude of the neutron induced activity is a function of the irradiation period or EFPY. Two categories of decommissioning wastes were distinguished based on EFPY values:

- Category A: Wastes generated from new components installed during re-tube campaigns; and
- Category B: Wastes generated from original plant components, e.g., calandria vessel.

The EFPY values for Category A and B wastes from Pickering, Bruce and Darlington stations were deduced considering the previous history (retube and layup) and planned final shutdown dates of the stations. Applicable EFPY values for various components are shown in Table 3. Based on these EFPY values, available ORIGEN code specific activity estimates were revised to obtain pertinent estimates for Categories A and B decommissioning wastes. The next sub-section presents the basis for the projection.

### 4.2 Theoretical basis for activity projections

Based on the reaction scheme $X_{projectile} + X_{target} \rightarrow X_1 \rightarrow X_2 \rightarrow X_3$ for the formation of a product $X_1$ by irradiation and its subsequent disappearance by decay, the activity as a function of time is governed by the relationships [2].

$$A_{Eq} = A_{t_1}\,\{1 - \exp\,(-\lambda\, t_1)\}^{-1} \qquad \text{(1a)}$$

$$A_{t_2} = A_{Eq}\,\{1 - \exp\,(-\lambda\, t_2)\} \qquad \text{(1b)}$$

where the notations have the following meanings:

$A_{Eq}$ Activity at equilibrium following an extended irradiation time,
$A_{t_1}$ , $A_{t_2}$ Activity corresponding to a reference irradiation period of $t_1$ and $t_2$, respectively, and
$\lambda$ Decay constant of the radionuclide.

Equation (1) assumes that the number of target atoms remains substantially constant during the irradiation period. It yields a conservative estimate because loss of nuclide $X_1$ by further neutron capture is ignored. Assessment indicated that activities obtained using ORIGEN code for one EFPY value can be reasonably projected using Equation (1) to another EFPY value without the need for re-computing them using ORIGEN.

**Table 3 EFPY Values Selected for Activity Projections**

| Station /Unit | Re-tube Status | Applicable EFPY Values | | | | |
|---|---|---|---|---|---|---|
| | | Fuel Channel Components | Calandria | Bioshield | Steam Generator | Carbon Steel |
| Pickering Units 1 & 4 | See Note A | CT: 30<br>Other: 20 | 30 | 30 | 30 | 30 |
| Pickering Units 2 & 3 | See Note A | CT: 20<br>Other: 5/10 | 20 | 20 | 20 | 20 |
| Pickering Units 5-8 | No re-tube planned | 30 | 30 | NA | 30 | 30 |
| Darlington Units 1-4 | See Note B | 25 | 45 | NA | 45 | Feeders: 25<br>Headers: 45 |
| Bruce Units 1 & 2 | See Note B | 25 | 40 | NA | 25 | Feeders: 25<br>Headers: 40 |
| Bruce Units 3 & 4 | See Note B | 25 | 55 | NA | 25 | Feeders: 25<br>Headers: 55 |
| Bruce Units 5-8 Scenario 1 | No re-tube planned | 30 | 30 | NA | 30 | 30 |
| Bruce Units 5-8 Scenario 2 | See Note B | 20 | 45 | NA | 20/45 | Feeders: 20<br>Headers: 45 |

NA, Not applicable; Note A: CT and feeders were not replaced; Note B: All fuel channel components and feeders were replaced.

## 5. Approach for estimation of radionuclide inventory

This section presents a summary of the approaches taken to develop the radionuclide inventories for various components. While core components are the dominant contributors to the overall decommissioning waste inventory, the importance of accurately estimating the inventory of the out-core components, albeit minor contributors to the overall inventory, was recognized because of the need to develop sound disposal strategies for each type of waste. Because ORIGEN based estimates are available for key in-core components and can be readily projected to EFPY values of interest, this section focusses to a greater extent on the estimation of inventories for the out-core components.

### 5.1 Fuel channel components

#### 5.1.1 Estimates based on ORIGEN-S

Radionuclide inventories for pressure tube, calandria tube, calandria tube insert, annulus spacer, shield plug and end fitting wastes have been previously developed using ORIGEN-S in support of ongoing and planned refurbishment projects. The available data estimates for Pickering-B, Bruce and Darlington stations correspond to 23- 25 EFPY. The data for Pickering-B were used to supplement the limited data available for Pickering-A.

A critical assessment of the data from the above sources was first carried out. They were normalized by decay correcting them to the discharge date, where applicable. Also, data for end fittings and shield plugs, typically estimated for only for their hot tips, were converted into the equivalent specific activity for the overall component. Subsequently, data for the various stations were assessed for their mutual consistency. With some exceptions, they were generally in reasonable agreement. This assessment indicated that the estimates are relatively insensitive to small differences in reactor design parameters although differences in trace element compositions may have a significant impact.

Besides the fuel channel components, the calandria, end-shields, and Reactivity Control and Safety Shutdown Mechanisms (RCSSMs) make significant contributions to the activation based radionuclide inventory. The inventories for these additional components were compiled from the previous estimates for Darlington generally available for EFPY 40. The reference Darlington inventory was then used to obtain estimates for the OPG stations at other EFPY values of interest (as per Equation 1). Inventory estimates for Bruce and Pickering were obtained generally by adjusting the Darlington estimates by relative weights of each component (or relative numbers in the case of RCSSMs).

### 5.1.2 Measured radiochemical characteristics

Available measured radiochemical data for fuel channel components were summarized to validate predicted ORIGEN code specific activity estimates and to establish a reference set for those activation, as well as, fission based radionuclides whose activities could not be reliably predicted.

- A State-of-the-Art report documenting the physical, chemical and radiochemical characteristics of pressure tubes has been prepared recently [3]. A comparison between measured and ORIGEN code based predicted activities showed reasonable agreement for some radionuclides but poorer agreement for others, notably H-3, actinides and fission products. In the case of H-3, the discrepancy is due to its permeation from coolant into the bulk pressure tube material, while in the case of actinides and fission products, the discrepancy is due to other sources, notably deposition from coolant. Thus, pressure tube radionuclide inventories for selected radionuclides were estimated based on measured specific activities, while for all other activation based radionuclides, predicted values were considered to be appropriate.
- In-situ gamma spectrometry of Bruce Units 1 & 2 refurbishment waste containers, performed in 2009, revealed the presence of only Co-60 and Nb-94 in pressure tube waste and only Co-60 in calandria tube and end fitting waste containers. Measured radionuclide activities agreed within a factor of 2 with activities calculated using the ORIGEN code.
- Reported Co-60 specific activity data for irradiated Bruce and Darlington Inconel X-750 spacers was in reasonable agreement (factor of 3) with estimated value for Darlington spacers.

## 5.2 Characterization data for outboard end fitting sections

Four investigations on the characterization of outboard end fitting sections (inlet and outlet) have so far been reported (no inboard sections have been characterized yet). The sections characterized originated from Pickering Unit 2 (EFPY 9.3), Bruce Units 1, 2 and 4 (EFPY 8.4-10.8) and Darlington Unit 2

(EFPY 18.5). The Pickering and Bruce end fitting investigations involved only liner sections; on the other hand, both the bodies and liners of the Darlington end fitting sections were characterized. For the Pickering and Bruce sections, oxide loading (g/m$^2$), specific activity (Bq/g) and surface activity (Bq/m$^2$) data were reported for the inner and outer surfaces of each liner as a function of axial location. For the Darlington sections, only surface activity data for liner and end fitting body surfaces were reported. For each type of surface, data from all sources were combined to obtain average oxide loading, oxide growth rate (g/m$^2$/EFPY), and specific and surface activity values.

The measured surface activity values were projected to the desired EFPY as follows. The surface activity, S (Bq/m$^2$) is related to the specific activity of the initially depositing oxide $S_0$ (Bq/g) and the oxide loading rate, R (g/m$^2$/y) by the relationship

$$S = \int_0^t S_0 \, exp(-\lambda t) R \, dt = \frac{R\, S_0}{\lambda} \{1 - \exp(-\lambda t)\} \qquad (2)$$

Because the total oxide loading (g/m$^2$) is given by the product *R.t*, it follows that the specific activity of the oxide (Bq/g) at time *t*, $S_t$ is given by

$$S_t = \frac{S}{R\,t} = \frac{S_0}{\lambda\,t} \{1 - \exp(-\lambda t)\} \qquad (3)$$

Substituting the average measured value of $S_t$ (Bq/g) and corresponding EFPY derived from Pickering and Bruce data yielded a value for $S_0$, which was then used to estimate *S* from Equation (2) for other reactors and/or EFPY. The total radionuclide activity for each type of surface was then obtained from the product of S and surface area.

## 5.3 Radionuclide inventory estimates for the bioshield

In order to estimate the radionuclide inventory of the Pickering A concrete bioshield, existing characterization data [5] for Pickering Unit 1 (15.7 EFPY) and Unit 4 (19.6 EFPY) bioshield concrete cores were reviewed. H-3, Co-60 and Fe-55 were the dominant radionuclides present in the bulk concrete. Co-60 and Cl-36 were associated primarily with the aggregate phase, while C-14 and Ca-41 with the cement phase. Other radionuclides present included Mn-54, Eu-152, Eu-154 and Ni-63. Generally, the radionuclide concentrations decreased with distance from the vault face of the concrete cores. With some exceptions, the concentration profiles of various radionuclides could be expressed by an exponential fit, consistent with their mode of production via neutron activation.

Based on the attenuation of thermal neutrons, 99 % of the neutron activation products in the bioshield are expected to be contained within a region about 51 cm thick immediately surrounding the calandria. Accordingly, integration of the fitted radionuclide profile between the limits 0 and 51 cm yielded the average concentration (*Bq/g*) of each radionuclide in the core. This combined with the estimated weight of the 51 cm thick concrete annulus yielded the total inventory of key radionuclides in the irradiated Pickering Units 1 & 4 bioshields. A reference bioshield radionuclide inventory, based on the higher of the values for Pickering Units 1 and 4, was prepared; considering this to correspond to 15.7 EFPY, inventory projection to other EFPY values of interest were made using Equation (1).

## 5.4 Inventory of radionuclides in steam generators

During operation, radioactive magnetite deposits are formed on the internal tube surfaces with cold leg tube deposits being generally more copious than hot leg tube deposits. Data on oxide loadings and radiochemical characteristics of steam generator deposits have been extensively developed using the Oxiprobe technique and to a more limited extent based on characterization of removed tube sections and using in-situ gamma spectrometry of steam generator tubes. A summary of the Oxiprobe data for various stations (mainly Pickering and Darlington) [6], detailed assessments of the radionuclide inventories for Bruce A steam generators [7] and characterization data for Bruce Unit 6 preheater tube oxide [8] have been reported.

Generally, Co-60 is the dominant gamma emitting radionuclide present in steam generator deposits. The overall methodology for estimating the radionuclide inventory in steam generators was, therefore, based on the estimation of Co-60 activity at final shutdown, followed by estimation of the activities of other selected gamma emitters (Nb-94 and Eu-154) and DTM radionuclides using scaling factors. In order to estimate Co-60 levels at final shutdown, measured data were extrapolated considering that increase in tube activity with time from additional deposition is offset by a decrease as a result of radioactive decay. The total Co-60 activity at shutdown can, therefore, be expressed as:

$$A(t_2) = A_{initial}(t_1) \cdot \exp(-\lambda \cdot (t_2 - t_1)) + A_{deposited}(t_2) \qquad (4)$$

where, the first term represents the contribution of the activity at time $t_1$, decay-corrected to the final shutdown date (time $t_2$) and the second term represents the decay-corrected contribution from the additional activity which deposits between $t_1$ and $t_2$. The second term can be obtained from Equations (5) & (6) where *R* denotes the constant deposition rate (atoms/s) and *N* the atoms of Co-60 at time *t*.

$$dN = R \cdot dt - \lambda \cdot N \cdot dt \qquad (5)$$

$$A_{deposited}(t_2) = \lambda N(t_2) = R \cdot (1 - \exp(-\lambda \cdot (t_2 - t_1))) \qquad (6)$$

Average values of *R* were estimated from Co-60 data for various stations/units. Based on this value and the measured activities of Co-60, its activity at the desired EFPY value was estimated from Equations (4) - (6). In general, the activities of other radionuclides were obtained either by scaling with respect to the activity of Co-60 or Cs-137 or by considering some radionuclides (e.g. Sb-125, Cs-137) to obey specific time dependencies (e.g., linear increase in activity of deposited Cs-137).

Based on the methodology outlined above, detailed radionuclide inventory estimates were developed for all steam generators and preheaters. The radionuclide estimates are likely conservative because they ignore the amount of oxide removed during mechanical cleaning campaigns at selected stations/units.

### 5.5 Inventory of radionuclides associated with carbon steel PHTS surfaces

Feeder pipes and headers (including pump headers) represent the largest carbon steel surfaces in the PHTS. The other significant carbon steel components include the steam generator bowls, bleed condenser and the pressurizer. A detailed inventory of radionuclides associated with these components at final shutdown was developed. The main focus was on feeder pipes, which to date represent the only carbon steel surface with a modest level of characterization data. Typically, deposits on inlet feeder surfaces are substantially greater than those on outlet feeder surfaces. However, availability of inlet feeder pipe sections for characterization is rather limited and, therefore, the database available to support the estimation of radionuclide inventories is relatively sparse. Radiochemical characteristics of deposits on the hot and cold leg steam generator bowls were assumed to be, respectively, similar to those of the hot and cold leg steam generator tube deposits. Further, the characteristics of the pressurizer and the bleed condenser surface deposits were considered to be similar to those of the steam generator hot and cold legs, respectively.

Most of the data developed prior to 2006 involved feeder pipe sections which had been removed following one or more PHTS decontaminations at Pickering, thus limiting use of the data. Since 2006, however, a number of inlet and outlet feeder pipe sections from Bruce and Pickering have been additionally characterized. Based on an assessment of oxide loading data, the representative growth rate of oxide on inlet feeders was considered to be about 39 $g/m^2$/EFPY and the corresponding oxide loading on outlet feeders, regardless of service duration, was considered to be 23 $g/m^2$.

Gamma activity data for inlet and outlet feeders were decay corrected to the tube removal date. No correlation was observed between radioactivity levels and EFPY for any radionuclide. Reference values were, therefore, established based on the average value in the case of Co-60 but in other cases, a rounded value consistent with the order of magnitude of measured values was adopted. Scaling factors for feeder pipe wastes were used to estimate the activities of DTM radionuclides from the activity of Co-60 and/or Cs-137. Because no systematic trends with EFPY or location along the feeder pipe were observed, the reference values were assumed to apply universally. Radionuclide inventories for each station were determined using the surface concentration values and the applicable surface area for all carbon steel components.

## 6. Radionuclide inventory of overall decommissioning wastes

Consolidated radionuclide inventory estimates were developed for each station based on the estimates for individual components; with some exceptions, radionuclides with relatively short half-lives (« 1 y) were ignored. For neutron activated components which are exposed to the PHT coolant, a reference list of radionuclide activities was compiled based on the combined contributions of neutron induced and coolant deposited activities. In order to obtain consolidated estimates for each station, the projected activity estimates were based on the applicable EFPY value for each individual component as shown in Table 3. Selected results are presented in Figures 2 and 3.

The results presented in Figures 2 and 3 indicate the following:

- Coolant deposited activity represents only about 0.01 % of the total activity at shutdown.
- The total activity decreases by 2 orders of magnitude over a period of 30 years after shutdown, with a further 25-30 % reduction experienced between 30 and 60 years.
- Ni-63 is the dominant radionuclide after about 15 years of decay.

The activity of fuel channel components is initially dominated by contributions from pressure tube, calandria tube and shield plug activities; however, after 30 years of decay, garter spring activity becomes dominant. This assumes continued use of Inconel X-750 springs in refurbished reactors.

Overall, as shown in Table 4, the inventory estimates for various stations are comparable in magnitude. After 30 years of decay, Ni-63, the dominant contributor, represents approximately 90 % of the total inventory with Co-60 about 8 % and Nb-94 about 1 %.

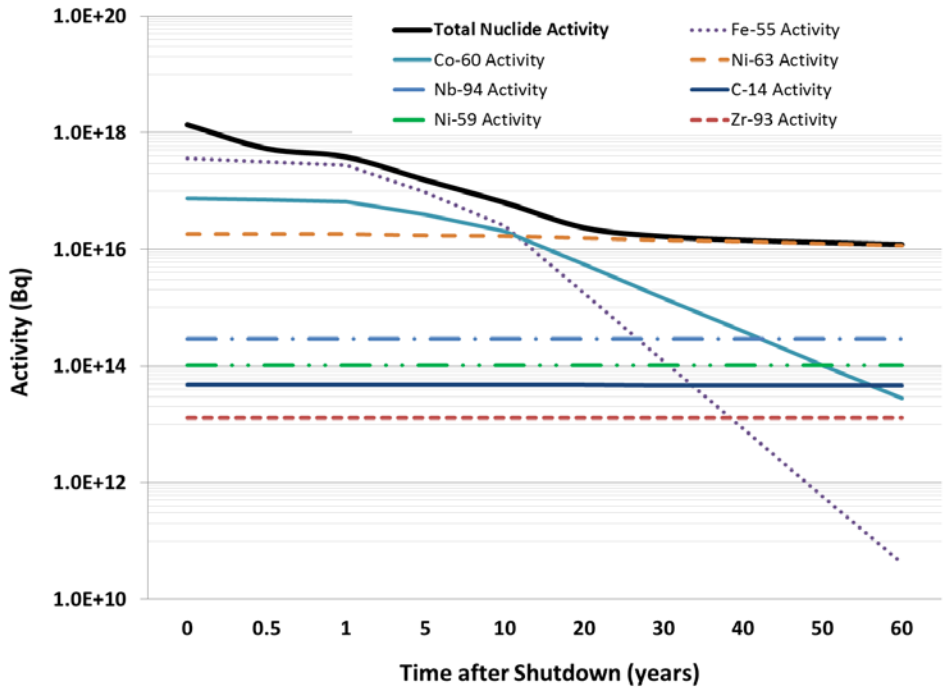


**Figure 2 Contribution of Key Radionuclides to the Total Decommissioning Waste Activity for Pickering-A Station**

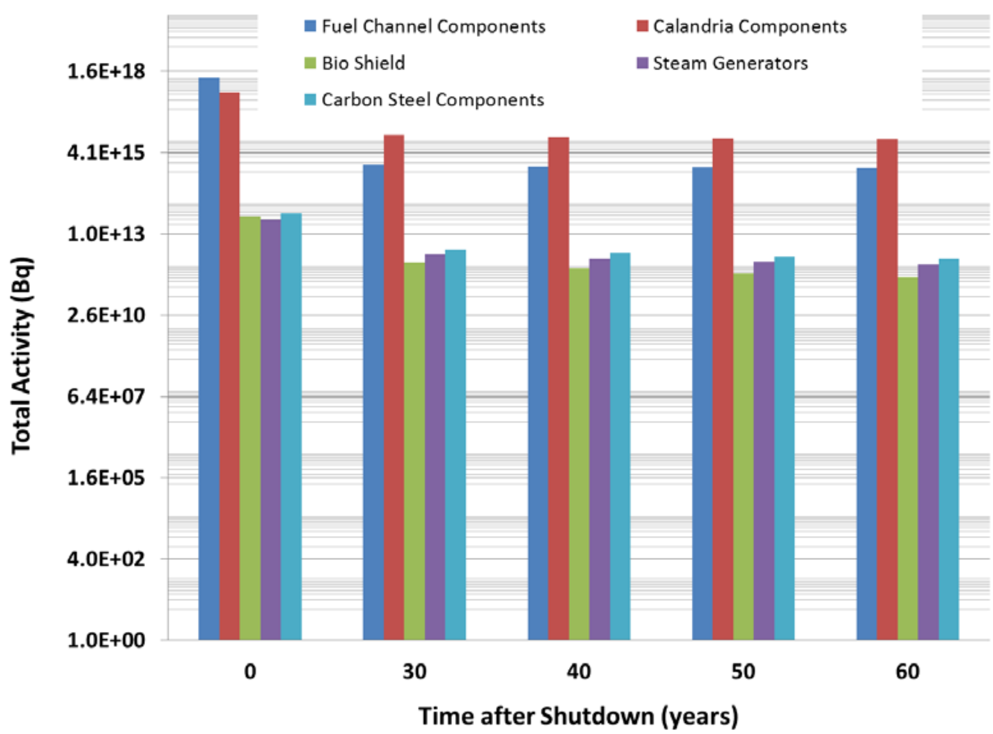


**Figure 3 Contributions of Various Components to the Total Decommissioning Waste Activity for Pickering-A Station**

**Table 4 Overall inventory estimates for various stations**

| Total Radionuclide Inventory | Pickering-A | Pickering-B | Bruce-A | Bruce-B | Darlington |
|---|---|---|---|---|---|
| At Shutdown | 1.4E+18 Bq | 1.4E+18 Bq | 1.5E+18 Bq | 1.5E+18 Bq | 1.8E+18 Bq |
| 30 years after shutdown | 1.7E+16 Bq<br>Ni-63 - 88 %<br>Co-60 - 9 %<br>Nb-94 - 2 % | 1.7E+16 Bq<br>Ni-63 - 88 %<br>Co-60 - 9 %<br>Nb-94 - 2 % | 2.8E+16 Bq<br>Ni-63 - 91 %<br>Co-60 - 6 %<br>Nb-94 - 1 % | 2.4E+16 Bq<br>Ni-63 - 90 %<br>Co-60 - 8 %<br>Nb-94 - 1 % | 2.8E+16 Bq<br>Ni-63 - 90 %<br>Co-60 - 7 %<br>Nb-94 - 1 % |

## 7. Conclusion

Overall, the decommissioning waste inventory developed in this study is considered to be a reasonable first estimate. The uncertainty in the overall estimate is associated with both the radiochemical characteristics of the wastes as well as with the inconsistent weight data of various components. Future revisions to the inventory should address these uncertainties and also quantify the inventories associated with facilities such as the Tritium Removal Facility at Darlington and components such as moderator heat exchangers which were not addressed because of lack of characterization data.

## 8. References

[1]. A. Husain, “Estimation of the Radionuclide Inventory of Activated Decommissioning Waste from Ontario Power Generation’s Darlington Nuclear Generating Station”, IAEA Third Coordinated Research Program Meeting on Disposal Aspects of Low and Intermediate Level Decommissioning Waste Held at Vienna, Feb 20-24, 2006.

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