The Darlington Retube Waste Container System – A Full Life Cycle Design Solution

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Abstract

The Darlington Nuclear Generating Station (DNGS) supplies approximately 20 percent of Ontario's electricity needs. The Darlington Refurbishment Project will extend the operating lives of the Darlington reactors by 25-30 years. A key activity of the Refurbishment Project is "retubing" - the replacement of the reactor fuel channel components. The removed components will be radioactive and must be safely managed. The Darlington Retube Waste Container system has been developed for this purpose. It provides a full waste management life cycle solution. The System has been designed to address the challenges of containing and shielding the retube waste during on-site handling, interim on-site storage, off-site transportation, and transfer and emplacement in the final repository.

1. Introduction

The Ontario Power Generation (OPG) Darlington Nuclear Generating Station (DNGS) has been operational for almost 25 years. DNGS consists of four CANDU reactors supplying approximately 20 percent of Ontario's electricity needs [1]. The Darlington Refurbishment Project will extend the operating life of the station for another 25-30 years. A key activity of the Refurbishment Project is "retubing": the replacement of the major reactor fuel channel components, including pressure tubes, calandria tubes and end fittings. The removed components will be radioactive and the predicted quantity of intermediate level waste[1] (ILW) exceeds the capacity of OPG's existing radioactive waste management system. Therefore a new system had to be developed specifically for the Darlington retube ILW. OPG's approach to this problem is a full life cycle design solution utilizing shielded containers referred to as Retube Waste Containers (RWCs).

This paper provides a brief overview of the design solutions used for ILW management in previous reactor retubes in Ontario, and discusses the constraints and conditions shaping those solutions in contrast with the full life cycle design solution developed for Darlington. The Darlington RWC system is then presented with an explanation of the key design requirements and a description of the major features of the resultant design.

[1] There are 480 fuel channels per reactor – each consisting of 1 pressure tube, 1 calandria tube and 2 end fittings.

The initial conceptual design of the container system was developed by OPG's Nuclear Waste Design Engineering Department in conjunction with Nuvia Limited (Nuvia). The subsequent preliminary and detailed designs were developed by Rolls-Royce Civil Nuclear Canada Ltd. (Rolls-Royce), working together with Nuvia.

2. Previous Retube Waste Management Solutions

There have been two previous reactor retubing campaigns (also referred to as large scale fuel channel replacement) at Ontario nuclear generating stations.

The first campaign at the OPG (previously Ontario Hydro) Pickering NGS was prompted by the failure on August 1, 1983 of the Unit 2 G16 channel pressure tube. The failure (due to pressure tube material and spacer problems) prompted Ontario Hydro to retube Pickering Units 1 and 2 to solve the problems and to allow continued operation of the reactors. Later Units 3 and 4 were retubed to address the spacer problems in those reactors' fuel channels. [2]

The ILW management system that was utilized for the four Pickering retubes between 1984 and 1993 focused on a safe high capacity storage solution that could be developed and put in service in a very short timeframe (there was approximately one year lead-time for the Unit 2 retube). The resulting waste containers, referred to as Dry Storage Modules (DSMs), are very large (approximately 180 tonnes loaded) hollow horizontal cylinders made from reinforced heavy concrete with a painted carbon steel outer shell. Pressure tubes (full length) and end fittings (inboard portions only[2]) were shuttled from the reactor to the loading facility, where the waste components were individually loaded into each DSM. After loading, the DSM portal was sealed and the DSMs were then moved from the station to a secure on-site outdoor storage location.[3]

The retubing of Pickering reactors Units 1-4 produced 34 DSMs as can be seen in Figure 1A.

The second, more recent, retubing campaign was conducted for Bruce Power's Units 1 and 2 during the refurbishment (which included replacement of steam generators and other major systems in addition to the retubing) of the Bruce A NGS in 2010-2012. Bruce Power, and its contractor, Atomic Energy of Canada Limited (AECL), chose a retube waste management solution that was significantly different from the one used at Pickering. The solution utilized RWCs that were much smaller and lighter than DSMs. The limits on the container size and weight (less than 35 tonnes) were selected to allow the containers to be brought through each reactor's equipment airlock for loading inside the reactor vault.

There were several configurations of Bruce RWCs depending on the waste components that the containers were intended to receive. The containers for end fittings were large rectangular boxes in which the full-length end fittings were stacked like cord-wood using remote tooling. The

[2] The outboard portions were managed separately as low-level waste.

containers for pressure tubes and calandria tubes[3] were rectangular boxes that were top loaded via a volume reduction tool that segmented and flattened the tubes before dropping the waste into each container. The containers for the pressure tubes and calandria tubes (and another ring-shaped fuel channel component called a calandria tube insert) were externally identical but had different thicknesses of shielding. All of the containers were made of concrete enclosed in stainless steel shells.

After each Bruce RWC was loaded, its lid was remotely installed and then fastened in place with long bolts that were manually installed. After each container was brought out of the reactor vault, the container's closure joint was covered with plates welded in position. The completed containers were then transferred across the Bruce site to the OPG Western Waste Management Facility (WWMF). The transfers were not subject to radioactive materials transportation regulations as the Bruce site is an access-controlled property. However the containers were designed to withstand a set of hypothetical on-site accident conditions. At the WWMF the containers were brought into the storage building using a heavy-lift forklift and stacked to reduce the footprint of the building. Figure 1B shows the stacks of Bruce RWCs (end fitting type) in the storage building. A total of 188 Bruce RWCs are in storage at the WWMF.

The Bruce RWCs were designed so they can be transferred from the WWMF to the proposed OPG Deep Geological Repository (DGR) for low and intermediate level waste (expected to be built adjacent to the WWMF), and each RWC will fit within the Repository's primary hoist cage (and not exceed its 35 tonne capacity) for movement to the underground emplacement rooms and final storage.

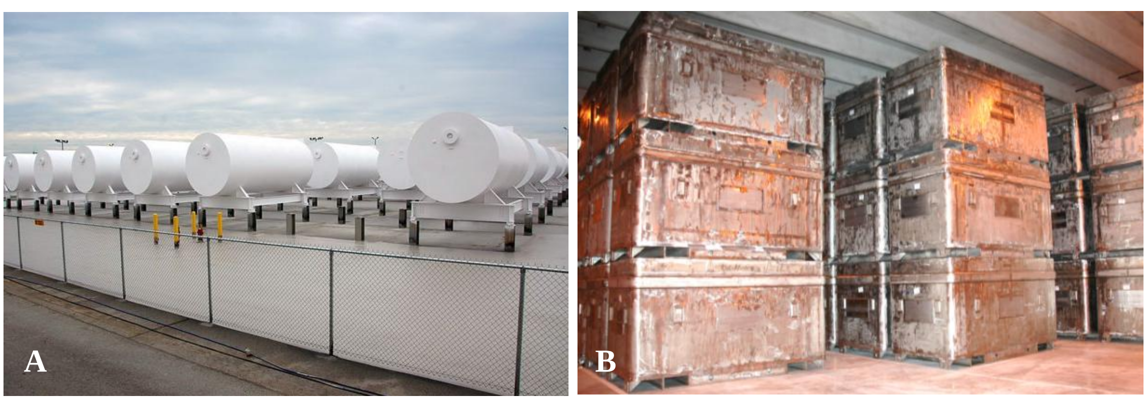

Figure 1: Existing Retube Waste Containers
(*A*: Pickering Dry Storage Module [4], *B*: End Fitting Style Bruce RWC [5])

The Pickering and Bruce Power approaches were considered, as well as the New Brunswick Power Point Lepreau canister storage system, and international ILW management systems and containers, when OPG began developing the Darlington retube waste management solution.

3 The Bruce retube campaign included removal and replacement of calandria tubes; these components were not removed and replaced in the Pickering retubes.

OPG chose to develop a full life cycle design solution that addressed all of the following major operating phases:

- On-site handling and transfers,
- On-site interim storage,
- Off-site transportation,
- Repository handling and final storage.

Table 1 shows the differences between the Pickering, Bruce Power and Darlington retube waste management system designs when considering these operating phases.

SYSTEM/ CONTAINER	ON-SITE HANDLING & TRANSFER	INTERIM STORAGE	OFF-SITE TRANSPORTATION	REPOSITORY HANDLING & STORAGE
PICKERING DSM	✓	✓	NOT ADDRESSED	NOT ADDRESSED
BRUCE RWC	✓	✓	NOT REQUIRED	✓
DARLINGTON RWC	✓	✓	✓	✓

Table 1: Retube Waste Management Systems Overview

It can be seen from the Table 1 that the life cycle for the Darlington RWC includes an operating phase, off-site transportation, which the previous solutions did not address. This difference was one of main reasons that a new RWC design was necessary for Darlington. The requirements and considerations for the new design are described in greater detail in the following sections.

3. The Design Requirements

The Darlington RWC system shall provide, in each operating phase, a means to contain and attenuate the radiation from the retube waste consisting of volume-reduced pressures tubes (PT), volume-reduced calandria tubes (CT), calandria tube inserts (CTI) and in-board sections of end fittings (EF) including shield plugs (SPs).

3.1 Design Requirements for Darlington On-site Operating Phases

The RWC design shall provide a means to receive the waste after it has been processed. Each container shall then be closed, and the closure method shall ensure that the waste remains contained under all normal and abnormal operations, and conditions. The normal on-site operations consist of transfer of the containers from the waste processing/container loading facility across the DNGS site to the Retube Waste Storage Building (RWSB), and handling of the RWCs within the RWSB. Abnormal operations and conditions include a variety of hypothetical handling accident scenarios, Darlington site accident scenarios, and the effects of earthquakes and extreme weather during the interim storage phase. The hypothetical accidents are described further in Section 4.5.

3.2 Transportation Phase Design Requirements

The RWC system shall provide a means to transport the waste off-site after the interim on-site storage phase, without removing the waste from the containers. The means of transport must comply with the requirements for a Type B radioactive materials transportation package as specified in the Packaging and Transport of Nuclear Substances (PTNS) Regulations [6]. The requirements address structural, containment, shielding and thermal performance under normal and hypothetical accident condition of transport. A key requirement is that the containment integrity of the package closure must be demonstrable prior to each shipment. The transportation package and its conveyance must also comply with the dimensional and weight limitations set out in the Ontario regulations for public highway transport [7].

3.3 Repository Storage Design Requirements

The intended destination of the Darlington RWC system is the OPG DGR. The RWC must comply with the OPG DGR's Waste Acceptance Criteria (WAC) that specifies dimensional and weight limits, and excludes certain materials from the containers and waste contents (e.g. liquid or flammable materials). The RWC system shall be designed to allow for removal of the RWC from the transportation package at the OPG DGR surface facility, and then transferred underground via the main hoist cage. The RWCs must be compatible with the OPG DGR transfer carts and handling equipment (heavy forklifts). The RWCs shall be moved to the allocated emplacement room for final storage.

The RWCs shall be designed to withstand the OPG DGR hypothetical handling accident scenarios and earthquakes.

Also, the RWC system shall be designed so that the RWCs can be retrieved from final storage as a contingency.

4. Design Considerations

The development of the RWC system design, through conceptual, preliminary and detailed design stages, was an iterative process that evaluated the following factors:

- number of containers/container capacity
- size/weight limits
- materials of construction
- dose rates/shielding requirements
- performance in all operating conditions
- handling methods

The interactions between these factors and considerations are discussed in Sections 4.1 – 4.6.

4.1 Number of Containers/Container Capacity

There are constraints on the space available for the RWSB at DNGS, and within the OPG DGR. It is therefore necessary to minimize the number of RWCs. The means to reduce the number of RWCs is to maximize their capacity. The Refurbishment Project had early on decided to volume-reduce the pressure tubes and calandria tubes as was done with the Bruce A Units 1 and 2 retube waste. Also, the end fittings will be severed and only the in-board ILW portions will go into RWCs (similar to what was done with the Pickering DSMs). These two decisions reduced the absolute quantity and volume of waste to be contained in RWCs.

The RWC design iterations evaluated two ways of maximizing individual RWC capacity versus the other design considerations: increasing the overall RWC size and/or reducing the proportion of each RWC occupied by shielding relative to the payload.

Maximizing container size to achieve high capacity is the logic that produced the Pickering DSMs. However the full life cycle approach taken with the Darlington RWC system design imposed a variety of size and weight constraints (discussed further in Section 4.2) that meant that the Darlington RWCs had to be nearer in size to the Bruce RWCs rather than the Pickering DSMs.

The efforts to reduce the proportion of each RWC given to shielding considered use of different materials of construction (see Section 4.3) and different shielding designs (see Section 4.4).

4.2 Size/Weight Limits

It was determined early in the Darlington RWC system design effort that it would not be practical to process the retube waste and load the RWCs inside the Darlington reactor vaults due to space constraints and conflicts with other operations. Therefore the size of the Darlington RWCs was not limited by the DNGS reactor airlock dimensions. However the Darlington RWC system's transportation and OPG DGR operating phases did impose constraints on the RWC size and weight.

A series of design studies evaluated the maximum size and weight that the RWC transportation package could have for highway shipment without special permits, and what proportion of the transportation package had to be provided by protective components rather than the RWC itself. It was determined the transportation package weight had to be limited to approximately 40 tonnes and the RWC could only contribute about 24 – 26 tonnes of that value. Therefore the Darlington RWCs could not be as heavy as the Bruce RWCs (approximately 30 tonnes each).

The size and weight constraints in the repository operating phase are imposed by the OPG DGR's main hoist cage. The weight limit is nominally 35 tonnes and the dimensional constraints are 2650 mm x 5200 mm x 4600 mm. Therefore the most severe constraint was the RWC weight limit for transportation.

4.3 Materials of Construction

The RWC design effort considered a variety of materials of construction to address the capacity, transportable weight limit, and shielding challenges. The materials review included ductile cast iron, lead, concrete and steel in different proportions and configurations. Consideration was given to the ability of the materials to contribute to the RWC's structural and shielding functions, the practicality for mass production, and the OPG DGR's favouring of concrete over metals.[4]

The selected materials for the Darlington RWCs were steel and high-density concrete, similar to the construction of the Pickering DSMs and Bruce RWCs.

4.4 Dose Rates/Shielding Requirements

During all operations of the Darlington RWC system the external dose rates on each container shall be limited to 2 mSv/hr on contact, and 0.1 mSv/hr at a distance of 1 metre. These limits are based on the International Atomic Energy Agency (IAEA) Regulations for the Safe Transport of Radioactive Material [8], as incorporated by reference in the PTNS Regulations. Although these limits originate from the transportation regulations, they are a de facto industry standard for radioactive waste containers. The Bruce RWCs were designed to meet these limits and the OPG DGR Waste Acceptance Criteria (WAC) also includes these limits.

It was determined in the Darlington RWC conceptual engineering studies that it would not be possible to design a container that had similar capacity as the Bruce RWCs, the same dose rate limits, and yet weigh 20% less (so as to be immediately transportable). It should be noted that the Darlington retube ILW will have significantly higher radioactivity levels than the Bruce Units 1 and 2 ILW because the two Bruce reactors had been shut-down for more than ten years prior to retubing.

The conceptual solution to this design challenge was a "container inside a container" approach. Each RWC will be held within a shielding overpack during on-site handling, transfer and interim storage phases of operation. The combined shielding of the overpack and RWC will be sufficient to meet the dose rate requirements at the time the RWC is loaded with waste. After the interim storage phase is completed and the activity of the waste has decayed, the RWC's integral shielding will be sufficient, and the RWC can be extracted from the overpack and shipped to the OPG DGR. The empty overpacks could be used for other purposes or recycled.

It was determined through the conceptual engineering studies the on-site storage period would have to be approximately 25 years to make the RWC/overpack concept viable.

[4] The DGR's safety analyses include evaluations of the long –term effects of gas generation due to corrosion of metals in the containers and waste emplaced in the Repository.

It should be noted the RWC can have four different payloads, each with different radioactive properties and source configurations. Therefore the RWC system design effort required many shielding analyses.

4.5 Performance

As was previously mentioned, there are abnormal and accident conditions for each operating phase for the Darlington RWC system. These conditions are summarized in Table 2.

The design of the RWC system has to be robust to withstand, without reduction of the containment and shielding performance, this range of physical challenges. Although the RWC is not a pressure vessel, the RWC's structural design is robust as it conforms to the requirements of the American Society of Mechanical Engineers (ASME) Boiler and Pressure Vessel Code, Sections III and VIII.

ON-SITE HANDLING, TRANSFER & INTERIM STORAGE	OFF-SITE TRANSPORTATION	REPOSITORY HANDLING & FINAL STORAGE
Design Basis Earthquake	Minor Impact/Drop (0.3 m Drop Test)	Design Basis Earthquake
Drop During Stacking	Penetrating Bar (1 m Bar Drop Test)	Drop During Stacking
Railway Explosion	Impact - Flat Surface (9 m Drop Test)	--
Hydrogen Gas Explosion	Impact - Pin (1 m Drop Test)	--
Design Basis Tornado	Fire - 30 minutes at 800^{o}C (Thermal Test)	--
Tornado-Generated Missiles	Water Immersion - Depth of 15 m	--

Table 2: Darlington RWC System – Abnormal Operating and Accident Conditions

4.6 Handling Methods

Another design consideration associated with designing the RWC system for the full life cycle was addressing the multiple methods of handling the RWC, shielding overpack, and components in the different operating phases.

The lids of the RWC and shielding overpack require lifting features that can be remotely engaged/disengaged for use inside the shielded loading cell. The RWC lifting features must be non-protruding to prevent interference between the RWC and the shielding overpack. The overpack also required remotely engaged/disengaged lifting features to allow for stacking.

It was necessary for the transportation phase to consider lifting features that would allow for recovery of the package in the event of a vehicle breakdown or accident.

In the OPG DGR handling and final storage phase the default method of handling waste containers in the underground facility is by forklift, and the RWCs are to be stacked.[9]

5. The Design Solution

The design of the Darlington RWC system addresses all of the previously described requirements and considerations. The major components of the Darlington RWC system and the different configurations to suit each operating phase are shown in Table 3 and Figure 2.

COMPONENT	INTERIM STORAGE	OFF-SITE TRANSPORTATION	LONG-TERM STORAGE
DARLINGTON RETUBE WASTE CONTAINER	✓	✓	✓
WASTE LINER	✓	✓	✓
DARLINGTON STORAGE OVERPACK	✓	--	--
TRANSPORTATION LID	--	✓	--
IMPACT LIMITERS	--	✓	--

Table 3: Darlington RWC System – Major Component Overview

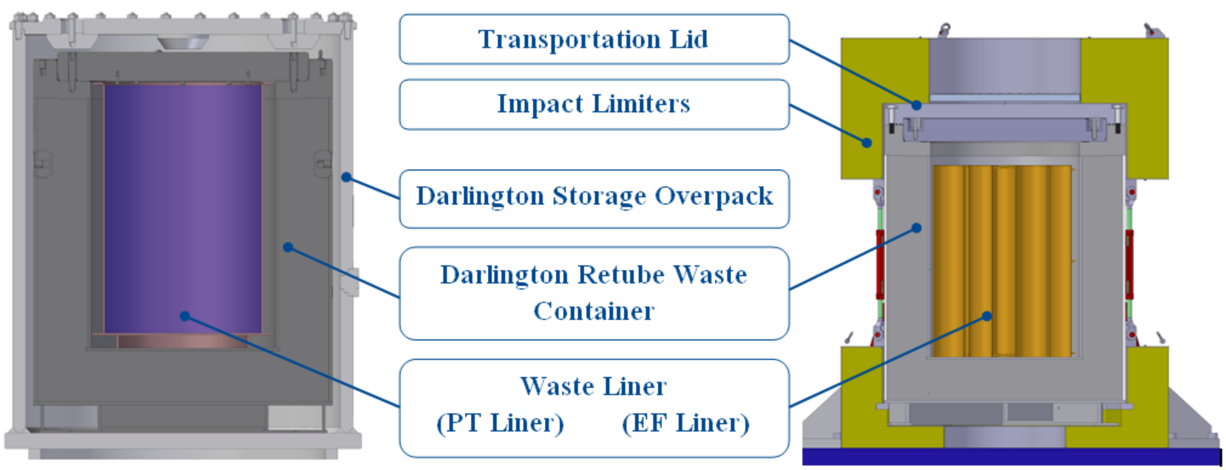

Figure 2: Darlington RWC System – Major Components

5.1 Darlington Retube Waste Container

The basic unit of the system is the RWC. The same RWC design is used for all of the different retube waste payloads.

The RWC is a cylindrical container whose body is made from reinforced high-density concrete enclosed within carbon steel shells. The RWC's Primary Lid is made of monolithic steel. It is fastened to the body, after the container has been loaded with waste, using an array of studs and nuts. The RWC closure has been designed for remote installation and fastening. The closure incorporates an elastomeric seal for contamination control.

The RWC has two sets of lifting features. The first set, mounted in the Primary Lid, is a set of threaded studs designed to be grappled using Zip-lift™ connectors [10]. The Zip-lift™ connector is a proprietary lifting tool, consisting of a segmented nut captured within an actuating housing, and it can be remotely or locally engaged/disengaged. The second set of lifting features are fork-lift pockets, built into the bottom structure of the RWC, designed to interface with the heavy forklift proposed for use at the OPG DGR [9].

The RWC has an outside diameter of 1.9 m and an overall external height of 2.5 m. The maximum weight of the fully loaded RWC, including waste liner and payload is 26 tonnes.

5.2 Waste Liner

The waste liner is carbon steel structure installed inside a RWC to configure the interior cavity to receive and centralize the waste. There are three types of waste liners to suit end fittings, pressure or calandria tubes, and calandria tube inserts. The latter two types of liners also provide supplemental shielding. The waste liner remains within the RWC for the full life cycle.

The assembled RWC and waste liner (of the appropriate type) can accommodate the following separate payloads.

END FITTINGS	PRESSURE TUBES	CALANDRIA TUBES	CALANDRIA TUBE INSERTS
15	36	62	240

5.3 Shielding Overpack

The shielding overpack, referred to as the Darlington Storage Overpack (DSO), is a welded carbon steel cylindrical container. As previously explained the RWC will be installed within the DSO prior to loading the waste into the RWC. After the waste loading is completed, the RWC lid will be installed and fastened, followed by the DSO lid. The DSO's lid is of similar design to the RWC's lid: it is made of monolithic carbon steel and the fastening arrangement uses studs and nuts. The lid of the DSO is fitted with Zip-lift™ studs sized to allow for lifting of the assembled DSO plus the RWC, waste liner and payload.

The RWC will remain within the DSO during all Darlington on-site operations. The DSO is sufficiently robust that it can protect the RWC and remain intact under all on-site abnormal operating and accident conditions. It is sized for two-high stacking to minimize the footprint of the storage building.

The DSO has an outside diameter of 2.3 m and an overall external height of 2.9 m. The maximum weight of the fully loaded DSO (including the fully loaded RWC) is 44 tonnes.

5.4 Transportation Lid and Impact Limiters

After the on-site storage phase period (and radioactive decay of the RWC contents), the waste will be ready for transportation to, and final storage at the OPG DGR. Each RWC/DSO pair will be retrieved from storage, and the RWC will be removed from the DSO. Although the dose rates on the RWC will be acceptable for transportation, the radioactivity of the contents will still be sufficiently high that a Type B transportation package is required. The RWC will be turned into a Type B transportation package (referred to as the RWC Transportation Package) through the installation of the Transportation Lid and Impact Limiters.

The Transportation Lid is fabricated from stainless steel and fits over the RWC's Primary Lid and is secured in place with high-strength bolts. The Lid incorporates o-ring seals, which mate with a machined surface on the periphery of the RWC, to provide the containment closure. The Transportation Lid includes a test port for verification of the containment seal prior to shipment.

The Impact Limiters are intended to protect the RWC and Transportation Lid from the hypothetical impact and fire accident conditions during transportation. The Upper and Lower Impact Limiters are fitted to each end of the Darlington RWC and secured by an array of turnbuckles that connect the Impact Limiters together. Each Impact Limiter is fabricated from a stainless steel shell with rigid polyurethane foam infill.

The assembled RWC Transportation Package (see Figure 3) will be secured to the transport trailer using a set of horizontal stops and turnbuckles to ensure that the Package cannot be dislodged from the trailer under normal driving conditions. The complete RWC Transportation Package has an outside diameter of 2.6 m and an overall external height of 3.3 m. The weight of the Package including tie-downs is 37 tonnes.

After delivery of the RWC Transportation Package to the OPG DGR surface facility, the Impact Limiters and Transportation Lid will be removed and sent back to Darlington for future shipments. The RWC will then be transferred to the underground Repository for final storage.

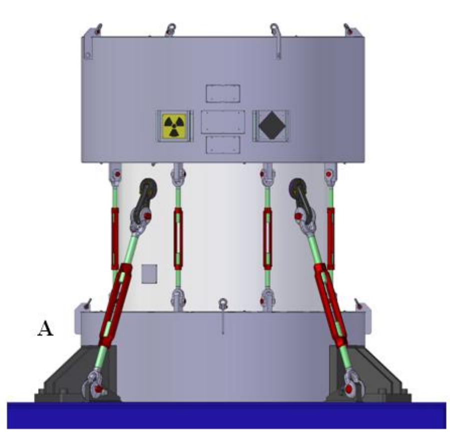

Figure 3: Darlington RWC Type B(U) Transportation Package

6. Conclusion

The Darlington Retube Waste Container system is a full life cycle design solution that addresses all of the operational phases from the time of waste loading to final long term storage. The development of this solution drew upon OPG's experience with earlier retube waste management systems and transportation packages.

Rolls-Royce and OPG are in the final stages of completing the detailed design of the Darlington RWC system, including the RWC, DSO, Waste Liners, Transportation Lid and the Impact Limiters. Upon completion of the design process, the Darlington RWC, DSO and Waste Liners will be released for fabrication. The Transportation Package design will be submitted to the Canadian Nuclear Safety Commission for review and certification as a Type B(U) package.

7. References

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