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Confidence in Transportation Package Performance

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Confidence in Transportation Package Performance (Executive Summary)

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EXECUTIVE SUMMARY

1.1 Introduction

The Nuclear Waste Management Organization (NWMO) is responsible for the long-term management of Canada's used nuclear fuel (UNF). Canada's plan is known as Adaptive Phased Management (APM). It consists of containing and isolating UNF in a deep geological repository (DGR) using a multiple barrier system in a robust host geology. A DGR is a system of tunnels and placement rooms constructed underground, several hundred metres below the surface within a stable rock formation. Canada's UNF is currently safely stored on an interim basis in licensed facilities at reactor sites in Ontario, Québec, and New Brunswick, as well as at AECL's (Atomic Energy of Canada Limited) nuclear research laboratories in Ontario and Manitoba.

NWMO is in the process of identifying a willing host community or region for the repository site with plans to select one community by 2024. The site selection process started in 2010, with 22 municipalities and Indigenous communities showing interest. NWMO has narrowed down the options through technical evaluations and engagement activities to ensure safety and community partnerships. Managing all of Canada's UNF in a single repository location will require the transport of UNF from these interim storage facilities to the centralized DGR location.

NWMO's responsibility includes designing and developing a transportation system for the safe and secure delivery of UNF from current interim storage locations to the deep geological repository. Current plans are to begin operations at the repository facility no sooner than the 2040s. The transport of UNF from the existing interim storage sites to the repository will commence once the facility is licensed and operational. NWMO is considering two transportation system options: an all-road option or an intermodal road/rail option to each potential host site. The transportation program is anticipated to take place over a period of approximately 45-50 years.

Community and Indigenous engagement activities conducted as part of the DGR siting process have determined that transportation safety is a topic of broad interest for Canadians and Indigenous peoples. Feedback from engagement activities has shown that there are opportunities to enhance NWMO's dialogue with the public about radioactive materials currently transported in Canada and internationally.

This Executive Summary summarizes the *Confidence in Transportation Package Performance* report [1] (hereafter referred to as the "report") which aims to provide insights into transportation regulations for radioactive materials, emphasizing the safety of people and the environment. The report discusses package design, regulatory requirements, and testing processes, with case studies and examples from countries with established transportation programs and those planning DGRs. The report also addresses frequently asked questions from NWMO's engagement activities.

1.2 Overview of Radioactive Materials Transportation Package Types and Requirements

Approximately one million packages containing radioactive materials are safely transported in Canada every year [10]. This includes sources used by industry, waste generated during power generation activities, and life-saving medical radioisotopes. The responsibility for ensuring the safe transport of radioactive material at the federal level is jointly shared between the Canadian Nuclear Safety Commission (CNSC) and Transport Canada. The International Atomic Energy Agency (IAEA) has published regulations for transporting radioactive materials – the *Regulations for the Safe Transport of Radioactive Material* (referred to as SSR-6 in this Executive Summary). Canada's *Packaging and Transport of Nuclear Substances Regulations, 2015* (referred to as PTNSR in this Executive Summary) are based on SSR-6. The PTNSR is primarily concerned with the health, safety and security of the public, and protection of the environment related to the transport of radioactive materials.

Transport Canada has adopted the *Transportation of Dangerous Goods Regulations* (referred to as TDGR in this Executive Summary). The TDGR is concerned with the transport of all classes of dangerous goods. The TDGR defines nine classes of dangerous goods based on hazards associated with the goods to be transported. UNF only falls under Class 7 – Radioactive Materials. The main hazard for Class 7 dangerous goods is the emission of ionizing radiation, which, in high doses, can affect the body's cells and disrupt other metabolic processes. However, packages for shipping radioactive materials are designed to protect the public and the environment from this radiation. Figure 1 shows the label for Class 7 – Radioactive Materials.

Figure 1: Class 7 TDG label

1.2.1 Radioactive Materials Transportation Safety Regulations

Figure 2: Used Fuel Transportation Package (UFTP)

Transportation safety regulations for radioactive materials follow a graded approach, imposing stricter requirements as the hazards of the materials increase. There are limits on the radioactive contents inside a package that determine the package type required. UNF in the NWMO's transportation program will be shipped using Type B packages. An example Type B package, the Used Fuel Transportation Package (UFTP), is shown in Figure 2. Additional information on other package types is provided in Section 2.3.2 of the report.

The graded approach for transportation packages is illustrated in Figure 3. Figure 3 also lists the requirements for each package type. Note that the requirements are cumulative as the hazard increases – this means that Type B packages are subject to general requirements as well as the requirements for routine, normal, and accident conditions of transport. Packages containing fissile material, uranium hexafluoride, or that are to be shipped by air (Type C packages) are subject to additional requirements. In general, package safety standards are less strict for materials with lower activity concentrations, become stricter for larger quantities that are readily dispersible, and add additional safety requirements for fissile material. The World Nuclear Transport Institute offers a comparison between Type A and Type B packages as an example of the graded approach [12]. A more detailed description of the graded approach is illustrated in Table D-4 in Appendix D of the report.

Increased Hazard

Not Regulated	No requirements
Excepted Quantities	General Requirements + Routine Conditions of Transport
Type A Package	+ Normal Conditions of Transport
Type B Package	+ Accident Conditions of Transport

Figure 3: Graded approach for transportation packages and applicable requirements

1.2.2 Controls for Transport

Controls for transport are implemented to ensure transportation of UNF packages comply with the regulations. This includes ensuring that radioactive materials were properly classified and the appropriate package type for transport was selected. These controls are described in more detail in Section 2.4 of the report.

Limits are enforced for radioactive contamination on accessible surfaces of transport packages. Packages are leak-tested to ensure the constructed package meets the performance specifications of the design. Radiation dose limits are in place on the amount of radiation the public and nuclear energy workers may receive.

Shipment communications, such as shipping papers, the labelling and marking of packages, placarding, and paneling of vehicles, are key methods for communicating the presence and potential hazard of radioactive materials to workers, emergency responders, and the public. Before a shipment, these systems communicate the potential hazards of the material to be shipped and ensure the correct procedures are applied when selecting and preparing the package.

In the event of an accident, the placards facilitate the identification of the dangerous good being carried. This allows emergency responders to take actions to protect public health and safety. Figure 4 shows the UFTP with a dangerous goods category label and information plate.

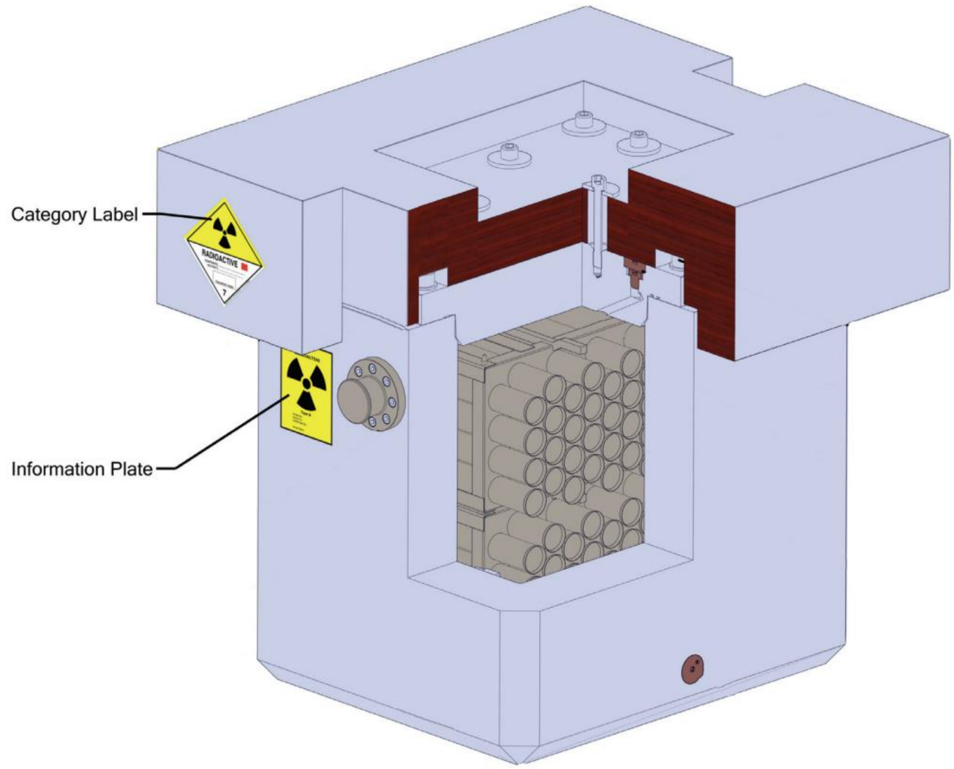


Figure 4: Dangerous good category label and information plate on the UFTP

1.3 The Design of Type B Packages to Withstand Severe Accident Conditions

The IAEA has established a classification system for packages used to transport radioactive materials that is based on a graded approach. The Type B classification signifies that the package is intended for materials with higher levels of radioactivity, such as used nuclear fuel.

The approval of Type B packages is based on a rigorous testing and certification process to ensure their compliance with internationally accepted safety standards. Package certification in Canada is conducted by the CNSC. The test conditions described in the safety standards are used to demonstrate that a package can provide adequate radiation shielding and containment of radioactive materials under normal conditions of transport and the conditions expected in a severe accident.

The Type B package types being considered for use by the NWMO transportation program are the UFTP, the Dry Storage Container Transportation Package (DSC-TP), and the Basket Transportation Package (BTP). Information on these three packages is provided in Section 3.4 of the report. The BTP is excluded from the assessments contained in the report as its design is currently under development. The applicable regulatory tests for Type B packages are described in this subsection and illustrated in Figure 5.

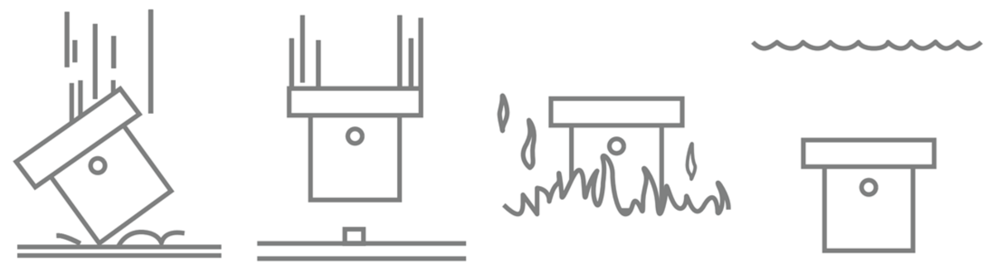


Figure 5: Regulatory tests applicable to Type B packages

To prove a package's performance under severe accidents conditions, the regulations require that a package design be evaluated for four major tests. The tests are designed to bound the conditions that are normally associated with severe accidents. The four tests are:

Free-Drop Test: The Free-Drop Test is conducted by dropping a package from a height of 9 meters onto a flat, unyielding surface in an orientation which will inflict maximum damage. This test measures the package's integrity in an accident by assessing the damage caused by an impact with an unyielding surface.

Puncture Test: The Puncture Test is conducted by dropping a package from a height of 1 m onto a rigid, perpendicularly mounted 15 cm diameter steel bar, at least 20 cm long, attached to an unyielding surface. This test must use the same package as used in the Free-Drop Test and must be in the orientation that has the package suffering the maximum damage. The Puncture Test simulates what would happen in a collision with an object, such as exposed rebar, guardrail, or a jutting piece of rail track.

Thermal Test: After the Free-Drop and Puncture tests, the same package undergoes a fully engulfing fire. The fire must maintain an average temperature of 800°C for a minimum of 30 minutes, starting from an ambient temperature of 38°C. The fire's heat flux must be equivalent to that of a hydrocarbon fuel-air fire with specific parameters. The fire test conditions mimic real-life fire scenarios.

Immersion Tests: There are two immersion tests applicable to the Type B packages being considered as part of NWMO's transportation program. Both tests may be conducted with a different package than the Free-Drop, Puncture, and Thermal tests.

a. *Water Immersion Test*: The package is subjected to an external water pressure of 150 kPa (equivalent to 15 m depth) for 8 hours, in the orientation that results in the most damage to the package. The test is used to assess the damage that a package could experience in transport accidents that occur by water bodies near most bridges, roadways, and harbours, where 15 m is a reasonable estimate of water depth. The test ensures that the integrity of the package body and use of properly designed seals prevents the significant release of radioactive material in shallow waters.

b. *Enhanced Water Immersion Test*: The package is subjected to an external water pressure of 2 MPa (equivalent to 200 m depth) for 1 hour without rupture of the containment system. This test was implemented to facilitate the recovery of large quantity radioactive material packages from the continental shelf should an accident occur during maritime shipping.

The regulations allow several methods to demonstrate that a package meets regulatory requirements. These include full-scale testing, scale models, mock-ups of specific parts of a package, calculations (analytical and computational methods) and reasoned arguments or a combination of these methods. The intent is to allow an applicant to use accepted engineering practices to evaluate a package design. Regardless of the method used, documentation should be sufficiently accurate and complete to allow an approving authority (e.g., Canadian Nuclear Safety Commission) to determine that all safety requirements have been met and all modes of failure considered. In practice, a package design for used fuel typically uses a combination of computer modeling, scale model testing and full-scale mock ups of package components.

The use of a particular method or combination of methods is left to the discretion of the approving authority who must make the ultimate decision that a used package design meets the safety regulations.

Additional information on package testing is provided in Section 3.3 and Appendix E of the report.

1.4 Demonstration Tests

This section explores some of the demonstration tests conducted over the last five decades to validate the effectiveness of IAEA package safety standards, and the performance of packages under accident conditions. Some of the most relevant demonstration tests to Canadian UNF transportation are summarized in Table 1.

Table 1: Most relevant demonstration tests to Canadian used nuclear fuel transportation

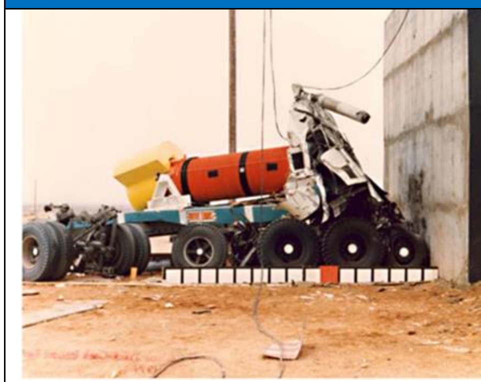
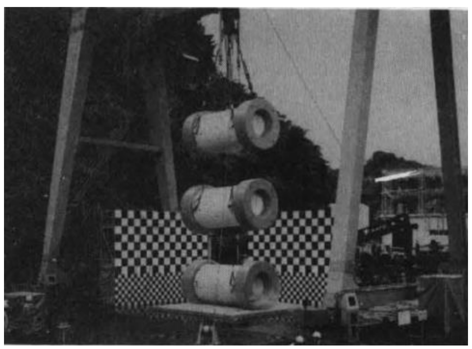
Image	Performing Organization	Description of the Test	Results Summary
United States (Section 4.2 in the report)			
	Sandia National Laboratories	A tractor-trailer carrying a 20.5 tonne lead shielded used fuel package was impacted against a rigid barrier at a velocity of 97 km/hr. The 626 tonne concrete barrier was backed by more than 1 580 tonnes of earth. This target was designed to be an unyielding surface. [32], [29]	While the tractor-trailer rig was completely demolished during the impact, the package itself suffered only superficial surface damage. The package was subsequently equipped with a new front impact limiter, was remounted on an identical shipping trailer attached to another tractor, and impacted at 135 km/hr. This time, some fuel pin buckling occurred; however, no cladding failure was detected.
	Sandia National Laboratories	A 109 tonne locomotive was crashed at a speed of 130 km/hr into a 23 tonne used fuel package mounted on a trailer attached to a conventional tractor at a simulated grade crossing. [32], [30]	The locomotive impacted the tractor-trailer rig broadside. The inside cavity of the package was not deformed although some of the fuel rods had bowed slightly, the assembly was otherwise undamaged. Leak testing after impact indicated a small leak in the head seal. However, had the package contained cooling water, as older package designs were designed to have, this leakage would have caused no risk to the public.

Image	Performing Organization	Description of the Test	Results Summary
	Sandia National Laboratories	A 136 tonne rail package shipping system was crashed into a massive concrete barrier at 129 km/hr. The shipping package itself weighed 68 tonnes. [32], [31]	The impact resulted in extensive damage to the railcar structure, but the damage to the concrete barrier was minimal and barrier deflection was negligible. The package body was not deformed except for minor deformations to the external cooling fins.
United Kingdom (Section 4.3 in the report)			
	Central Electricity Generating Board	This test simulated a severe rail accident involving a full-sized Magnox used fuel package and consisted of a 140 tonne Class 46 locomotive traveling at 160 km/hr colliding with a stationary 47 tonne Magnox package attached to a 13 tonne rail car. [33]	The package survived the test with minimal damage and during post-test examination, was found to have held its internal pressure to within 0.002 MPa of the 0.69 MPa to which it had been pressurised originally.
Germany (Section 4.4 in the report)			
	BAM	A fire test was performed with a 45 m^3 Liquefied Propane Gas (LPG) tank wagon, partially filled with 10 m^3 of pressurised liquid propane. A CASTOR THTR/AVR used fuel package was positioned above a fuel oil pool beside the propane tank to suffer maximum damage from the subsequent explosion. [34], [35]	Although the unprotected closure lid of the CASTOR package was exposed to fire and severely hit by tank wagon fragments, post-test investigations demonstrated that no loss of leak tightness occurred following the propane tank's explosion.

Image	Performing Organization	Description of the Test	Results Summary
	BAM	A 1:2 scale model of the TN 8/9 used fuel package certified to the IAEA transport regulations was dropped 200 m from a helicopter onto a 20x30 m concrete target consisting of a 60 cm layer of pit gravel and 40 cm layer of concrete reinforced by steel mats. [34], [35], [37]	While the outside of the package suffered superficial damage, there was no loss of integrity of containment components, and no leaks were detected following the test.
Japan (Section 4.5 in the report)			
	CRIEPI	Two 9-metre drop tests and a 1-metre puncture test were performed on a full-scale ductile cast iron (DCI) package. The first 9-metre drop included an artificial flaw of 20-mm in depth in the package. For each 9-metre test, the package was cooled down to less than -40°C (233K). During the 1-metre test, the DCI package was dropped horizontally onto a mild steel pin. [38], [39]	Sufficient fracture toughness data of full-scale DCI package bodies was obtained for quality assurance and to evaluate brittle failure. With the 1-meter test no penetration occurred, confirming the integrity against brittle failure with strain measurements. During the 9-metre tests, no crack propagation was observed from the artificial flaws.
	CRIEPI	Drop tests on DCI packages with no impact limiters were conducted in three different drop orientations, i.e., vertical, horizontal, and oblique with drop heights of 1.5 m, 7.5 m, and 17 m. [40]	The structural integrity of the packages without impact limiters was maintained against drop accidents at the tested heights.
	CRIEPI	In addition to the 15 m and 200 m immersion tests, packages designed for high-level waste (HLW) were immersed in 3 000 m of water for an hour. [40]	The maximum strain in the package body was within an elastic range and no rupture was observed during the test. No leakage was detected at any sealing boundary during the immersion test and no reduction in the sealing characteristics was observed.

1.5 Real-World Accident Reconstructions

An important tool in addressing the safety of used fuel shipments is the use of accident reconstructions to predict the performance of used fuel packages and transport systems under severe real-world accident conditions. Table 2 summarizes real-world accident reconstructions selected for discussion in the report. In all scenarios, had these accidents involved used fuel transportation packages, the packages would have survived the accidents and met regulatory requirements for containment and dose rate limits, demonstrating the robustness of the regulatory framework.

Table 2: Real-world accident reconstructions selected for discussion in the report

Description of the Accident	Accident Reconstruction	Results Summary
Baltimore Tunnel Fire (Section 5.2.1 in the report)		
On July 18, 2001, a freight train carrying non-nuclear dangerous goods derailed and caught fire in Baltimore, Maryland. The most severe part of the fire in the Howard Street tunnel lasted approximately 3 hours, while less severe fires continued for over 3 hours. Firefighters confirmed that the last tank car was no longer burning about 12 hours after the fire started. [44], [43], [45], [46]	The reconstruction was done to determine the thermal conditions and to analyze the potential effects of those conditions on three different Type B package designs certified to transport UNF. A detailed fire analysis was performed to determine the temperatures reached by the tunnel air, wall, floor and ceiling during the accident. The temperatures were used to model the performance of the three used fuel packages.	The study concluded that larger transportation packages would sustain only minor damage in a fire similar to the Baltimore tunnel incident. This is due to their thermal inertia and compliance with regulations. Although the likelihood of a release is low, any potential releases would be minimal due to factors, such as tight clearances, low-pressure differentials, and the settling of CRUD particles[1]. The analysis shows that none of the package designs would exceed regulatory dose rate limits or result in significant releases or direct radiation in the fire scenario.
Caldecott Tunnel Fire (Section 5.2.2 in the report)		
In the Caldecott Tunnel accident on April 7, 1982, a tanker truck carrying gasoline overturned and caught fire. The fire lasted approximately 2.7 hours, with the intensely hot gasoline-fueled portion estimated to have lasted about 40 minutes. Firefighters entered the tunnel about 46 minutes after the fire started to search for survivors and approach the location of the tanker truck. [48], [47], [49]	The reconstruction was done to assess the fire's thermal conditions and potential effects on Type B truck packages used for transporting nuclear fuel. It used temperature predictions from National Institute of Standards and Technology's (NIST) to model its response to the fire.	The evaluation indicated that a severe tunnel fire, like the Caldecott Tunnel fire, would not result in the release of UNF particles or fission products from a shipping package. The design analyzed for the scenario did not reach temperatures that could cause fuel cladding rupture, ensuring that radioactive material would remain contained within the package and the fuel rods.

Description of the Accident	Accident Reconstruction	Results Summary
MacArthur Maze Fire (Section 5.2.3 in the report)		
On April 29, 2007, a tanker truck carrying gasoline caught fire on the MacArthur Maze interchange in Oakland, California. The intense heat weakened the steel girders of the roadway above, causing two spans of the elevated roadway to collapse onto the freeway below. A surveillance video from a nearby wastewater treatment plant captured the fire's progression. The first span sagged and collapsed at around 17 minutes, while the second span descended slowly and partially collapsed after about 37 minutes. The fire continued to burn intensely for about 102 minutes until the fuel was fully consumed. [50], [51]	The reconstruction was done to assess the fire's impact on the applicable truck package for transporting UNF. The accident, which involved a severe and prolonged fire causing the collapse of roadway segments, was chosen due to its unique structural consequences as the fire caused the overhead roadway segments to collapse. The study used fire modeling and physical examination of samples to define a bounding scenario of a fully engulfing pool fire at 1 100°C before the collapse and a less severe fire at 900°C afterward. Thermal and structural analyses showed that the package could withstand the fire and the loads imposed by the collapsing roadway segments.	The analysis shows that the package, in the event of the MacArthur Maze fire scenario, would not exceed regulatory dose rate limits for accident conditions, despite the expected loss of neutron shielding. The gamma shielding in the stainless-steel package body remains effective even at higher temperatures. While there is potential for radioactive material to escape due to seal loss and fuel rod rupture, the lid closure bolts prevent significant release. The estimated maximum release for this scenario is below the prescribed limit, ensuring that public health and safety would not be at risk.
Newhall Pass Tunnel Fire (Section 5.2.4 in the report)		
The Newhall Pass Tunnel accident involved a chain reaction traffic collision and fire in California. It affected 33 commercial tractor-trailer rigs and one passenger vehicle on the southbound US Interstate 5 truck route. The fire started near the tunnel exit and quickly spread, engulfing the entire tunnel. The fire destroyed all 24 trapped tractor-trailer rigs, which were carrying foodstuffs and not hazardous materials. The severe tunnel fire lasted for an estimated duration of 2 to 5 hours. [53], [52]	The reconstruction was done to assess the impact of the fire on a used fuel truck package. The accident was chosen for its prolonged fire duration and varied fire exposure scenarios due to multiple vehicles involved. A bounding fire scenario was defined based on fire modeling and physical examination of on-site material samples. Five specific fire modeling cases were used to encompass the range of possible fire conditions.	The potential radiation dose rates and package integrity of the packages were assessed in this fire scenario. The analysis showed that the package would not exceed regulatory dose rate limits despite the loss of neutron shielding, as it is already accounted for in the approval process. The gamma shielding of the package was expected to remain intact and functional. However, the study noted that the package could experience seal degradation in this severe accident scenario, potentially leading to a small release, approximately one quarter of the quantity permitted by regulations, and would not pose a risk to public health and safety.

Notes:

1. CRUD is a colloquial term used to denote corrosion products (e.g., rust particles) that adhere to the outside of used fuel rods that become radioactive when exposed to radiation.

1.6 Real-World Canadian Transport Accidents

An analysis of historical Canadian highway and rail accidents (from 1979 to 2022) was performed to identify relevant severe accidents and determine the impact those types of accidents could have on the highway and rail transport of used nuclear fuel. A list of severe accidents was compiled based on the presence of significant physical impacts (i.e., collisions and explosions), long-duration fires, release of dangerous goods, fatalities and injuries, and major property damage. None of the accidents listed involved the shipment of used fuel, or the transport or release of radioactive material.

Four representative historical accidents were chosen to examine how a shipment of used fuel might have fared during each accident. The results are summarized in Table 3 and described in greater detail in appendices G – M in the report.

Table 3: Real-world Canadian transport accidents selected for discussion in the report

Accident	Description	Predicted Outcome
Mississauga Train Derailment and Explosion – November 15, 1979	A freight train carrying hazardous materials derailed and caught fire in the middle of the town. The train was carrying a variety of chemicals, including propane, styrene, and chlorine, among others. The fire resulted in several explosions and an evacuation.	None of the forces (impact, puncture and explosion), or the fire that occurred in the Mississauga train derailment would be sufficient to either breach the package wall or severely damage the welded closure area of a DSC-TP.
Hinton Rail Collision – February 8, 1986	A westbound freight train and an eastbound passenger train collided head-on on a single-track section of the Canadian National Railway (CN) mainline. The collision resulted in the deaths of 23 people, including three crew members on the freight train, and 20 passengers on the passenger train. A fire was caused by fuel leaking from locomotives.	Neither the impact or puncture force that occurred in the Hinton train collision and derailment would be sufficient to either breach the package wall or severely damage the welded closure area of a DSC-TP. The Hinton collision resulted in a localized diesel fire that would not have seriously impacted a Type B package. There were no explosions. It is predicted that no release of radioactive material or increase in external radiation would have occurred under the conditions actually experienced in the Hinton collision.
Lac Mégantic Derailment and Explosion – July 6, 2013	A freight train carrying crude oil derailed causing fires and explosions resulting in the deaths of 47 people and the destruction of much of the town's downtown area.	None of the forces (impact, puncture and explosion), or the fire that occurred in the Lac Mégantic Derailment and Explosion train derailment would be sufficient to either breach the package wall or severely damage the welded closure area of a DSC-TP.

Accident	Description	Predicted Outcome
James Snow Parkway Accident – March 24, 1986	A gasoline tanker truck carrying 51 000 liters of gasoline collided with a flatbed truck under a highway overpass. The tanker exploded. The resulting fire caused concrete to burn away, exposing the inner steel reinforcing cables.	Neither the impact or puncture force that occurred in the James Snow collision would be sufficient to either breach the package wall or severely damage the package sealing area of a UFTP. A small release could be possible for a UFTP if the package seal operating temperature and fuel rupture temperature are exceeded.

Section 6 of the report also reviews transport practices and design features which could be employed to lessen the chances of a severe accident occurring or to mitigate possible impacts. These include the use of dedicated trains, enhanced safety standards for rail cars, providing escorts for truck shipments and employing advanced train instrumentation for early detection of conditions that lead to train derailments.

1.7 International Experience Transporting Used Nuclear Fuel and High-Level Waste

For more than sixty years, radioactive materials have been transported globally, adhering to a stringent regulatory regime established by the IAEA. The implementation of these regulations has resulted in an impressive safety record in that there has never been a transport incident that resulted in significant radiological harm to people or the environment. The World Nuclear Association currently estimates that about 15 million packages of radioactive material are transported around the world each year. Additional estimates show that since 1961, when the IAEA's safe transport regulations were first issued, it is likely that over one billion nuclear material consignments have been safely completed [60].

In 2016, the U.S. Department of Energy (DOE) published *A Historical Review of the Safe Transport of Spent Nuclear Fuel* which is considered the most extensive effort to describe the worldwide record on the transport of UNF. In summary, the report estimated that at least 25 400 shipments of UNF were made worldwide, but that number could potentially be more than 44 400. A significant finding from the report is that all of these shipments were undertaken without any injury or loss of life caused by the radioactive nature of the material transported.

1.7.1 Countries with Strong Used Fuel Transportation Programs

Non-defense UNF transportation programs are designed to support a nation's nuclear energy program and its chosen methods for treating, storing, and disposing of UNF. Some countries, like Japan, France and the United Kingdom, opt for recycling their UNF through a closed-end system where the transportation program must safely handle UNF being transported for reprocessing, the reprocessed fuel, and the radioactive by-products of reprocessing (High Level Waste, or HLW).

The NWMO transportation program, on the other hand, supports an open-end system for the CANDU fuel used in Canada's nuclear energy program and research at the Canadian Nuclear Laboratories (CNL). The fuel passes through the reactor once, is subsequently cooled in pools, stored temporarily, and eventually transported to a permanent geological disposal site. As the UNF ages for several decades after leaving the reactor, it becomes cooler and less radioactive. Key country's employing the open-end system for used fuel include Finland (Posiva Oy), Switzerland (NAGRA), Sweden (SKB), and the United States (U.S. Department of Energy).

1.7.2 Key Country Transportation Plans

Table 4 summarizes the status of each key country's transportation program and plans. The information is based on publicly available sources about transportation modes, conveyances, contents being transported, number of shipments anticipated, distances, extent/scope of transportation systems and challenges.

Table 4: Summary of key country transportation plans and UNF management programs [62]

Country and Implementing Organization	Status of Repository Site Selection Process	Reprocessing	Central Interim Storage Facility	Transportation System in Place to Move UNF/HLW to DGR	Anticipated Start of Repository Operations
Canada Nuclear Waste Management Organization (NWMO)	The site selection process is expected to be completed by 2024.	No	No	Road and rail are being considered.	Anticipate construction beginning in 2033, operations planned to begin in the 2040s.
Finland Posiva Oy	The Finnish Government approved construction of the Onkalo DGR in 2015.	No	No	Road and sea are the most likely choices.	DGR facility is expected to be operational in 2023. Disposal activities expected to begin in 2025.
France National Agency for Radioactive Waste Management (Andra)	A site near the village of Bure was selected in 2006.	Yes - reprocessed used fuel from France, Japan, Germany, Belgium, Switzerland, Italy, Spain and the Netherlands.	No	Preference is for rail to DGR.	Plan to begin the pilot phase in 2025–2027 timeframe.
Japan Nuclear Waste Management Organization of Japan (NUMO)	NUMO plans to complete the site selection process before 2030.	Yes - Reprocessing takes place at the Tokai Reprocessing Plant. Rokkasho Reprocessing Plant expected to be completed in 2023.	Yes - at the Recyclable-Fuel Storage Center.	No decision has been made.	Plan to start repository operations before 2040.

Country and Implementing Organization	Status of Repository Site Selection Process	Reprocessing	Central Interim Storage Facility	Transportation System in Place to Move UNF/HLW to DGR	Anticipated Start of Repository Operations
Sweden Swedish Nuclear Fuel & Waste Management (SKB)	A site in the municipality of Östhammar was selected in 2009.	No	Yes – at Clab near Oskarshamn Nuclear Power Plant.	Plan to transport UNF to Östhammar using a specially designed ship, the Sigrid.	SKB expects to start repository operations sometime in the 2030s.
Switzerland National Cooperative for the Disposal of Radioactive Waste (NAGRA)	NAGRA plans to submit a license application by 2024 and be operational in 2060.	Yes - commercial UNF was reprocessed in France and the UK HLW has been returned to Switzerland.	Yes - the central storage facility (ZZL) near Beznau Nuclear Power Plant.	Road and rail transport options are being considered.	Repository operations are expected to start in 2060.
United Kingdom Nuclear Waste Services (NWS)	NWS expects it will take 5 to 20 years to complete the site selection process.	Reprocessing at Sellafield took place from 1964 to 2022.	Yes - at Sellafield. The facility will be used for UNF and HLW until the 2070s.	Road, rail and sea transport options are being considered.	No decision has been made.
United States U.S Department of Energy (DOE)	The Yucca Mountain site was approved for development by Congress in 2002. Congress has not funded construction.	U.S. does not currently reprocess commercial UNF.	Two Consolidated Interim Storage Facility licenses have been approved by NRC. Neither are accepting UNF at this time.	Considering road and rail. No rail transportation is available to the Yucca Mountain site or from many reactor sites.	No decision has been made.

2. REFERENCES

The references are numbered in alignment with the report (reference [1] below).

[1] Calian Ltd., "Confidence in Transportation Package Performance," NWMO-0009-03, Ver. 1.0, 2023.

[10] Canadian Nuclear Association (CNA), "Backgrounder: Transportation of Nuclear Substances in Canada," 2015.

[12] World Nuclear Transport Institute, "Package Types used for Transporting Radioactive Materials, - Fact Sheet," London, 2021.

[29] Sandia National Laboratories, "Analysis, Scale Modeling, and Full-Scale Tests of a Truck Spent-Nuclear-Fuel Shipping System in High Velocity Impacts against a Rigid Barrier," SAND77-0270, April 1978.

[30] Sandia National Laboratories, "Study and Full-Scale Test of a High-Velocity Grade-Crossing Simulated Accident of a Locomotive and a Nuclear-Spent-Fuel Shipping Cask," SAND79-2291, February 1983.

[31] Sandia National Laboratories, "Analysis, Scale Modeling, And Full-Scale Test of a Railcar And Spent-Nuclear-Fuel Shipping Cask in a High-Velocity Impact against a Rigid Barrier," SAND78-0458, June 1981.

[32] K. Sorenson, R. Salzbrenner and G. Wellman, "Results of the Sandia National Laboratories MOSAIK Cask Drop Test Program," Sandia National Laboratories, Albuquerque, NM, 1992.

[33] J. Miles, M. Shears, E. Tufton, R. Blythe, J. Hart, Central Electricity Generating Board and Ove Arup and Partners, "The Central Electricity Generating Board Flask Test Project," PATRAM 1986, Proceedings of the 8th International Symposium on Packaging and Transportation of Radioactive Materials, Davos, Switzerland.

[34] B. Droste, "A Survey on 35 Years of Packaging, Transport, and Storage of Radioactive Material," Bundesanstalt für Materialforschung und -prüfung (BAM), Berlin, Germany, 2013.

[35] B. Droste, "Testing of type B packages in Germany to environments beyond regulatory test standards," Bundesanstalt für Materialforschung und -prüfung (BAM), Berlin, Germany, 2014.

[37] B. Droste, H. Vo¨lzke, G. Wieser and L. Qiao, "Safety Margins of Spent Fuel Transport and Storage Casks Considering Aircraft Crash Impacts," Bundesanstalt fu¨r Materialforschung und -pru¨fung (BAM), Berlin, Germany, 2002.

[38] C. Ito, A. Kosaki, T. Arai and T. Saegusa, "Brittle Fracture Tests at Low Temperature for Transport Cask Materials," Central Research Institute of Electric Power Industry (CRIEPI), 1992.

[39] T. Kusakawa, T. Kishi, H. Ohtsubu, S. Shiomi, H. Takaku, C. Ito and T. Saegusa, "Full-Scale Tests and Evaluation for Quality Assurance of Ductile Cast Iron Casks," Central Research Institute of Electric Power Industry (CRIEPI), PATRAM 1989, Proceedings of the 9th

International Symposium on Packaging and Transportation of Radioactive Materials, Washington, DC, U.S.A., CONF-890631-Vol. 1, 712-719, 1989.

[40] C. Itoh, T. Saegusa, H. Yamakawa and K. Shirai, "Testing of Type B Packages In Japan to Conditions Different From the Regulartory Packages Test Standard," Central Research Institute of Electric Power Industry (CRIEPI), 2007.

[43] United States Nuclear Regulatory Commission (USNRC), "Spent Fuel Transportation Response to the Baltimore Tunnel Fire Scenario," NUREG/CR-6886, Rev. 2, 2006.

[44] United States Nuclear Regulatory Commission (USNRC), "Numerical Simulation of the Howard Street Tunnel Fire, Baltimore, Maryland, July 2001," NUREG/CR-6793, 2003.

[45] United States Nuclear Regulatory Commission (USNRC), "Analysis of Rail Car Components Exposed to a Tunnel Fire Environment," NUREG/CR-6799, 2003.

[46] United States Nuclear Regulatory Commission (USNRC), "Performance of Metal and O-Ring Seals in Beyond Basis Temperature Excursions," NUREG/CR-7115, 2012.

[47] United States Nuclear Regulatory Commission (USNRC), "Shipping Container Response to Severe Highway and Railway Accident Conditions," NUREG/CR-4829, Vols 1 and 2, 1987.

[48] United States Nuclear Regulatory Commission (USNRC), "Spent Fuel Transportation Package Response to the Caldecott Tunnel Fire Scenario," NUREG/CR-6894, Rev. 1, 2007.

[49] United States Nuclear Regulatory Commission (USNRC), "Reexamination of Spent Fuel Shipment Risk Estimates," NUREG/CR-6672, 2000.

[50] United States Nuclear Regulatory Commission (USNRC), "Spent Fuel Transportation Package Response to the MacArthur Maze Fire Scenario," NUREG/CR-7206, 2016.

[51] United States Nuclear Regulatory Commission (USNRC), "Analysis of Structural Materials Exposed to a Severe Fire Environment," NUREG/CR-6987, 2009.

[52] United States Nuclear Regulatory Commission (USNRC), "Spent Fuel Transportation Package Response to the Newhall Pass Tunnel Fire Scenario," NUREG/CR-7207, 2016.

[53] United States Nuclear Regulatory Commission (USNRC), "Structural Materials Analyses of the Newhall Pass Tunnel Fire, 2007," NUREG/CR-7101, 2011.

[60] K. J. C. a. R. B. Pope, "A Historic Review of the Safe Transport of Spent Nuclear Fuel," US Department of Energy, August 2016.

[62] Nuclear Waste Technical Review Board, "Survey of National Programs for Managing High-Level Radioactive Waste and Spent Nuclear Fuel: 2022 Update," (Table has been amended to reflect changes since publication.), July 2022.

Confidence in Transportation Package Performance

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GLOSSARY

Acronyms and Initialisms

AAR	American Association of Railroads
AGR	Advanced Gas-cooled Reactor
ANSI	American National Standards Institute
BAM	Federal Institute for Materials Research and Testing (Bundesanstalt für Materialforschung und -prüfung)
BLEVE	Boiling Liquid Expanding Vapour Explosion
BTP	Basket Transportation Package
BWR	Boiling Water Reactor
CANDU	Canada Deuterium Uranium
CEGB	Central Electricity Generating Board
CFD	Computational Fluid Dynamics
CN	Canadian National Railway
CNA	Canadian Nuclear Association
CNSC	Canadian Nuclear Safety Commission
CPR	Canadian Pacific Railway
CRIEPI	Central Research Institute of Electric Power Industry
DCI	Ductile Cast Iron
DDF	Deep Disposal Facility
DG	Dangerous Goods
DGR	Deep Geological Repository
DOE	Department of Energy (U.S.)
DOT	Department of Transportation (U.S.)
DRS	Direct Rail Services
DSC	Dry Storage Container
DSC-TP	Dry Storage Container Transportation Package
DU	Depleted Uranium
EBS	Engineered-Barrier System
EM	Environmental Management (U.S. DOE Office)
FEA	Finite Element Analysis
GDF	Geological Disposal Facility
HLW	High-Level Waste
IAEA	International Atomic Energy Agency
ICRP	International Commission on Radiological Protection
ILW	Intermediate-Level Waste
IMO	International Maritime Organization
INS	International Nuclear Services
IP	Industrial Package
ISO	International Organization for Standardization
JAEA	Japan Atomic Energy Agency

JNFL	Japan Nuclear Fuel Limited
LL-LLW	Long-Lived Intermediate Level Waste
LLW	Low-Level Waste
LPG	Liquified Propane Gas
LSA	Low Specific Activity
MOX	Mixed Oxide
MPC	Multi-Purpose Canister
NAS	National Academy of Sciences (U.S.)
NDA	National Decommissioning Authority (UK)
NFT	Nuclear Fuel Transport Co, Ltd.
NIST	National Institute of Standards and Technology
NNSA	National Nuclear Security Administration (U.S. DOE)
NPP	Nuclear Power Plant
NRA	Nuclear Regulation Authority (Japan)
NRC	Nuclear Regulatory Commission
NTS	Nuclear Transport Solutions (UK)
NTSB	National Transportation Safety Board (U.S.)
NUHOMS	NUTECH HOrizontal MOdular Storage
NUMO	Nuclear Waste Management Organization of Japan
NWMO	Nuclear Waste Management Organization
NWS	Nuclear Waste Services (UK)
OCRWM	Office of Civilian Radioactive Waste Management (U.S. DOE Office)
PATRAM	The International Symposium on the Packaging and Transportation of Radioactive Materials
PNNL	Pacific Northwest National Laboratories
PTNSR	Packaging and Transport of Nuclear Substances Regulations
PWR	Pressurised Water Reactor
REMM	Radiation Emergency Medical Management
RWM	Radioactive Waste Management Limited
SCO	Surface Contaminated Object
SFRO	Spent Fuel Reprocessing Organisation (Japan)
STUK	Radiation and Nuclear Safety Authority (Finland)
TC	Transport Canada
TDG	Transport of Dangerous Goods
TDGR	Transportation of Dangerous Goods Regulations
UFTP	Used Fuel Transportation Package
UNF	Used Nuclear Fuel
VCD	Vapor Cloud Detonation

Definitions

Accident Reconstruction: Analysis of an accident after it has occurred to determine more information and gather data. (See Section 5)

Contamination: Radioactive material that is deposited in water or air, or on the surfaces of structures, areas, objects, or people. (Based on [1])

Deep Geological Repository (DGR): A network of underground tunnels and rooms that safely stores, contains and isolates used nuclear fuel over the long term. (Based on [2])

Demonstration Test: Planned test that represents a viable transportation accident and where the test parameters (e.g., temperature, drop height, velocity) are controlled to allow measurement of the output results. (See Section 5)

Dose: When radiation (see definition below) penetrates or passes through an object or a living organism (such as a person), some of the energy of the radiation may be absorbed. This absorbed energy is called radiation *dose*. Dose is the physical effect, or consequence, of the radiation.

High-Level Radioactive Waste: Used nuclear fuel whose owners have declared it as radioactive waste and/or which generates significant heat through radioactive decay. Radiation shielding and long-term isolation is required. (Based on [3])

Interim Storage Facility: Location for safe management of used nuclear fuel over the short or intermediate term.

International Atomic Energy Agency (IAEA): An international organization that promotes the safe, secure and peaceful use of nuclear technologies. (Based on [4])

Package: Packaging with its radioactive contents, as presented for transport. [5]

Packaging: One or more receptacles and its components necessary to perform safety functions when transporting radioactive contents. (Based on [6])

Radiation: Energy emitted by a radioactive material. Materials that emit radiation are called radiation *sources*. Radiation sources can be in many forms (solid, dust, gas, liquid). Radiation can occur from natural sources (called *background radiation*) such the earth's crust and minerals found in soil or bedrock as well as artificial sources such as smoke detectors or televisions. Exposure to radiation from these natural and artificial sources occurs on a daily basis. *Ionizing* radiation is radiation that has enough energy to free electrons from atoms or molecules, which can result in a higher risk to human health. (Based on [7])

Radionuclide: A material (with an unstable atomic nucleus) that produces radiation. (Based on [8])

Special Form Radioactive Material: Either an indispersible solid (meaning that it cannot break up, scatter in different directions, or dissipate) or a sealed capsule.

Transportation Package: The complete product of the packing operation - meaning the *packaging* (what stores the contents during transport) and the contents prepared for transport. (Based on [6])

Used Nuclear Fuel (or Spent Nuclear Fuel): Used fuel assemblies removed from a reactor after irradiation and treated as waste. Also called irradiated nuclear fuel or spent fuel in many references used throughout this report. Note: In Canada, *irradiated nuclear fuel* or *used nuclear fuel* is a more accurate term for *spent fuel* (a term used internationally and in some Canadian reports with the same meaning in this definition, to align with international agreements and conventions), because discharged fuel is considered a waste material even when it is not fully spent. (Based on [8])

1. INTRODUCTION

1.1 Background

The Nuclear Waste Management Organization (NWMO) is responsible for the long-term management of Canada's used nuclear fuel. Canada's plan is known as Adaptive Phased Management (APM). It consists of containing and isolating used nuclear fuel in a deep geological repository (DGR) using a multiple barrier system in a robust host geology.

A DGR is a system of underground tunnels and storage rooms for used nuclear fuel containers. It is constructed underground several hundred metres below the surface of a stable rock formation (at depths between 250 m and 1000 m for mined repositories). Isolation of the used fuel is provided by a combination of engineered and natural barriers (rock, salt, clay) and no obligation to actively maintain the facility is passed on to future generations. Figure 1-1 and Figure 1-2 depict the Engineered-Barrier System (EBS) designed by the NWMO specifically to manage used CANDU fuel in a DGR and the conceptual design of the site layout as proposed by the NWMO.

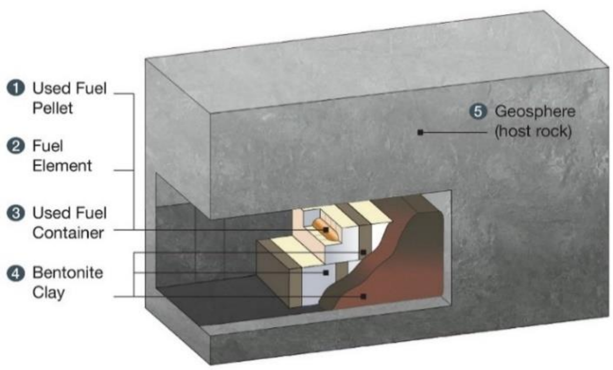


Figure 1-1: Engineered-Barrier System (EBS)

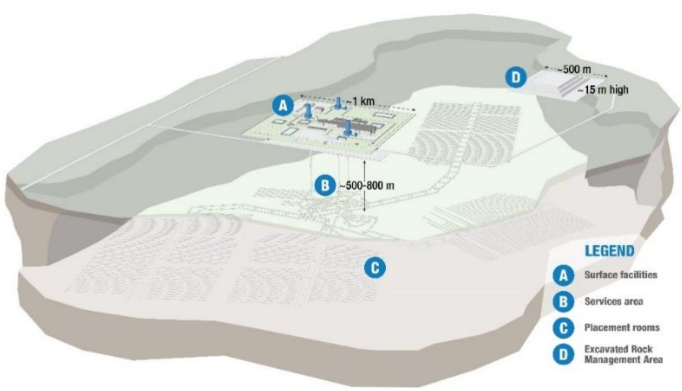


Figure 1-2: Conceptual Design of Deep Geological Repository Site

NWMO is in the process of identifying a willing host community or region for the repository site with plans to select one community by 2024. The site selection process has been underway since 2010. The process started with 22 municipalities and Indigenous communities expressing interest in learning more and exploring their potential to host the project. NWMO has gradually narrowed the focus to two remaining areas through technical site evaluations and social engagement activities to assess overall safety and the potential of the communities to build partnerships.

NWMO is currently engaging with communities and interested parties, including First Nations and Métis communities in the area. The Wabigoon Lake Ojibway Nation-Ignace area in Northwestern Ontario and the Saugeen Ojibway Nation-South Bruce area in Southern Ontario are considered potential host areas for the project. Figure 1-3 includes a map that shows the locations of the interim storage facilities as well as the two potential host communities.

Canada's used nuclear fuel is currently safely stored on an interim basis in licensed facilities at reactor sites in Ontario, Québec, and New Brunswick, as well as at AECL's (Atomic Energy of Canada Limited) nuclear research laboratories in Ontario and Manitoba. Managing all of Canada's used nuclear fuel in a single repository location will require the transport of used nuclear fuel from these interim storage facilities to the centralized DGR location. Figure 1-3 provides a visual overview of the interim storage site locations, alongside potential repository host communities.

Figure 1-3: Interim storage facilities and potential DGR siting areas across Canada

NWMO's responsibility includes designing and developing a transportation system for the safe and secure delivery of used nuclear fuel from current interim storage locations to the deep geological repository. Current plans are to begin operations at the repository facility no sooner than the 2040s. Once the facility is licensed and operational, the transport of used nuclear fuel from the existing interim storage sites to the repository will commence.

NWMO is considering two transportation system options which include: (1) an all-road option; and (2) a road/rail option to each potential host site. The transportation program is expected to take place over a period of approximately 45-50 years.

Community and Indigenous engagement activities conducted as part of the DGR siting process have determined that transportation safety is a topic of broad interest for Canadians and Indigenous peoples. Engagement activities have demonstrated that while general information about the regulatory framework for transportation and the transportation package's ability to withstand severe accident conditions is available, people have many additional questions about the severity of the required tests and how the package would perform in real-world accident conditions. Feedback from engagement activities has also shown that there are opportunities to enhance NWMO’s dialogue with the public about radioactive materials currently transported in Canada and internationally.

1.2 Scope and Objective

The safe and secure transportation of radioactive materials is an important part of the nuclear energy industry. It is crucial to make sure that materials like used nuclear fuel are transported safely and securely so that people and the environment are protected. The United Nations (UN) Model Regulations [9] serve as a basis for harmonizing international and domestic dangerous goods transport regulations and are reviewed and updated every two years. Regulations for the safe transport of radioactive materials are developed by the International Atomic Energy Agency (IAEA), a UN organization, and are also reviewed and updated regularly. The IAEA regulations are submitted to the Transport of Dangerous Goods (TDG) Sub-Committee of the UN for incorporation into the Model Regulations. In turn, the Model Regulations and the IAEA transport safety regulations are voluntarily adopted by regional or national regulatory authorities, including the Canadian Nuclear Safety Commission and Transport Canada [5]. These regulations are designed to make sure that transportation packages can ensure the safety of people and the environment during credible, severe accidents.

The purpose of this report is to provide insight into the key aspects of the transportation regulations. The report describes how used nuclear fuel packages are designed, tested and certified using these stringent regulatory requirements to ensure the health and safety of people and the environment. The report also demonstrates the soundness of the regulatory design and testing regimen for transportation packages (with an emphasis on Type B packages - those which transport used nuclear fuel).

Over many decades, organizations and research institutions from around the world have contributed to a robust body of knowledge encompassing regulations, rigorous testing of packages, and evaluations of applicable accident scenarios associated with the transport of radioactive material. This report aims to present portions of relevant historical reports and sources in a manner that more clearly showcases the safety of radioactive material transport and packages. In certain sections (i.e., demonstration tests (Section 3), accident reconstructions (Section 5)) this report presents findings as originally written to avoid misrepresenting the research and conclusions presented by their original authors. The report also showcases countries with well-established transportation programs and provides information on how countries with proposed deep geological repositories (DGRs) plan to transport their used nuclear fuel and high-level waste. Finally, this report provides answers to questions frequently asked during the NWMO's community and Indigenous engagement activities.

1.3 Structure

This report is organized according to the following structure:

Section 1: Introduction

Provides an introduction to the report as well as background and context.

Section 2: Overview of Radioactive Materials Transportation Package Types and Requirements

Provides an overview of the graded approach applied to transportation packages as well as the requirements for the various types of transportation packages.

Section 3: The Design of Type B Packages to Withstand Severe Accident Conditions

Describes the regulatory tests used to demonstrate that Type B packages can withstand severe accident conditions.

Section 4: Demonstration Tests

Outlines demonstration tests that were completed to demonstrate the survivability of transportation packages under conditions of severe accidents.

Section 5: Real-World Accident Reconstructions

Describes severe transportation accident reconstructions that have been analyzed to assess the performance of transportation packages.

Section 6: Real-World Canadian Transport Accidents

Describes severe Canadian transport accidents and provides a qualitative assessment of these accidents against regulatory tests.

Section 7: International Experience Transporting High-Level Waste

Provides an overview of the transport of used nuclear fuel and high-level waste (HLW) in countries with established transportation programs and their strategies for the management of used nuclear fuel transportation.

Section 8: Frequently Asked Questions

Provides answers to questions frequently asked during the NWMO's community and Indigenous engagement activities.

2. OVERVIEW OF RADIOACTIVE MATERIALS TRANSPORTATION PACKAGE TYPES AND REQUIREMENTS

2.1 Introduction

Approximately one million packages containing radioactive materials are safely transported in Canada every year [10]. This includes industrial sources, waste generated during power generation activities, and life-saving medical radioisotopes. The responsibility for ensuring the safe transport of radioactive material at the federal level is jointly shared by the Canadian Nuclear Safety Commission (CNSC) and Transport Canada. As described in Section 2.3, the International Atomic Energy Agency (IAEA) has put in place regulations for transporting radioactive materials – the *Regulations for the Safe Transport of Radioactive Material* [6] (referred to as SSR-6 in this report).

Based on SSR-6, the CNSC has developed the *Packaging and Transport of Nuclear Substances Regulations, 2015* (referred to as PTNSR in this report). The PTNSR is primarily concerned with the health, safety and security of the public, and protection of the environment related to the special characteristics of radioactive material.

Transport Canada has developed the *Transportation of Dangerous Goods Regulations* [11] (referred to as TDGR in this report). The TDGR regulates the transport of all classes of dangerous goods – see Section 2.2 for an overview of the various types of dangerous goods. The framework for transport regulations in Canada as applicable to radioactive materials is presented in Figure 2-1. Note that the *Provincial/Territorial Dangerous Goods Transportation Acts* are not discussed in this report since federal regulations have primacy for radioactive materials.

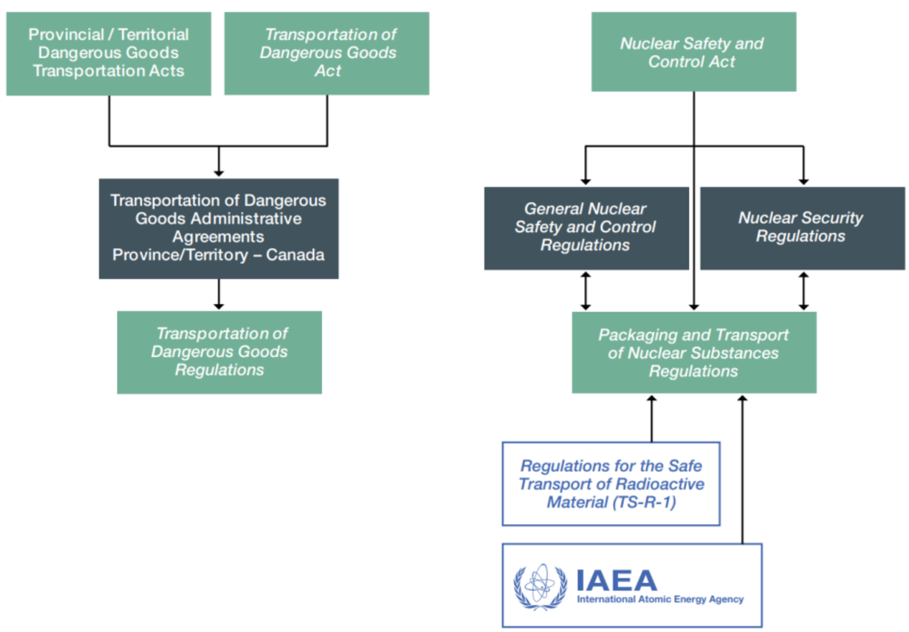


Figure 2-1: Canadian regulatory framework for transportation of radioactive materials

2.2 Classes of Dangerous Goods

The TDGR defines nine classes of dangerous goods, as shown in Figure 2-2. These classes of dangerous goods are based on hazard types associated with the goods to be transported. Note that the safety marks in Figure 2-2 are examples of safety marks for each class but do not represent all possible options.

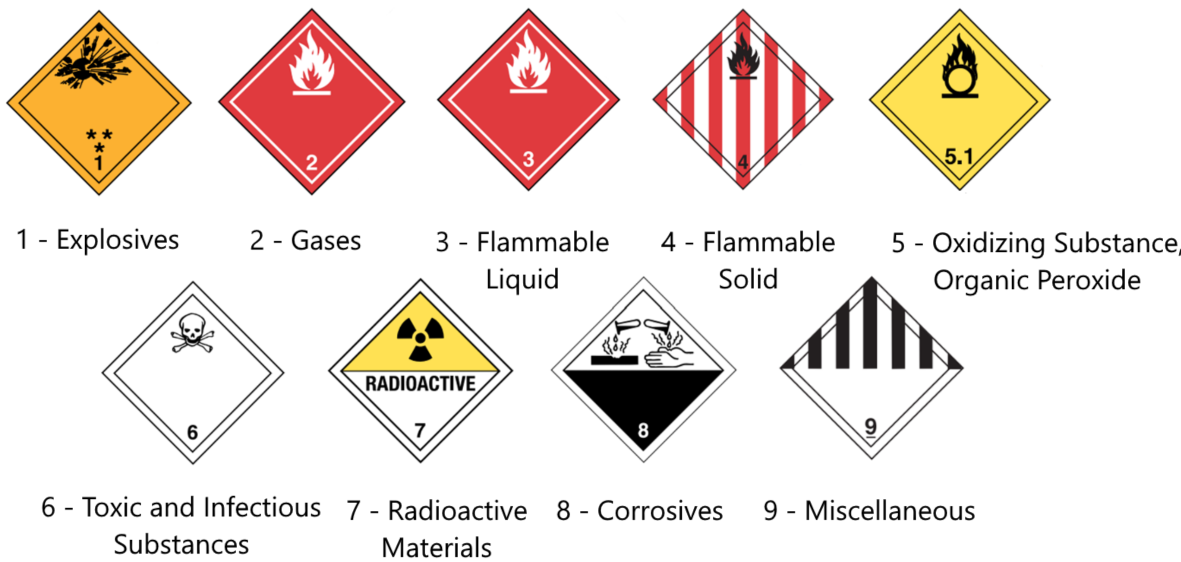


Figure 2-2: Nine classes of dangerous goods in Canada's TDGR

Used nuclear fuel typically only falls under Class 7 – Radioactive Materials. However, Class 7 also includes a broader range of radioactive material than used nuclear fuel. Class 7 dangerous goods include any nuclear substance with an activity above the exemption quantity defined in the PTNSR. This includes goods such as radioactive ores (from mining), medical isotopes, some medical equipment and parts, and industrial testing sources.

The main hazard for Class 7 dangerous goods is the emission of ionizing radiation, which, in high doses, can affect the body's cells and disrupt other metabolic processes. Packages for shipping radioactive materials are designed to protect humans from this radiation. Appendix A provides some of the most common types of ionizing radiation emitted by Class 7 radioactive materials.

As noted in Section 2.1, approximately one million packages containing radioactive materials are safely transported in Canada every year. The transportation of radioactive materials is essential to medical, industrial and research applications such as medical diagnosis and therapy, food irradiation, crop research, industrial gauges, and non-destructive testing.

This report will refer interchangeably to *Class 7 dangerous goods* and *radioactive materials*.

2.3 Radioactive Materials Transportation Safety Regulations

As demonstrated in Figure 2-1 in Section 2.1, radioactive materials are subject to the requirements of the CNSC's PTNSR in addition to Transport Canada's Transportation of Dangerous Goods Regulations and Act. The requirements in the PTNSR are structured based on a graded approach – this means that more stringent or strict requirements are applied as the hazards of the materials contained in the package increases. The hazards of different radioactive materials depend on such parameters as quantity, concentration, and dispersibility.

The CNSC issues certificates for the packaging and transport of nuclear substances, as stipulated in the PTNSR. Note that when the CNSC certifies (approves) a shipping package design, it is actually approving the package design for a set of specific contents. This means that use of a package is only valid for the contents that have been specifically analyzed and approved in the certificate. Any significant changes in package design or in contents requires additional approval from the issuing authority.

The inclusion and evaluation of specific package contents as a condition of the approval is important in the design of used nuclear fuel packages. The design and required performance of the package is based on the physical and chemical properties of the contents (e.g., nature, form and activity). For packages certified to transport used nuclear fuel, important parameters to consider are fuel type, quantity, initial enrichment, burnup and cooling time.

2.3.1 Graded Approach

The transportation safety regulations for radioactive materials apply a graded approach. Package types are assigned based on parameters such as quantity (activity), concentration (specific activity), dispersibility (i.e., form) and the fissile nature of the radioactive material. Special requirements are added for shipping contents with high activities by air due to the increased dispersibility of a package's contents in severe air accidents. In general, package safety standards are less strict for materials with lower activity concentrations, become stricter for larger quantities of material that are readily dispersible, and add additional safety requirements for fissile material.

Used nuclear fuel that is planned to be transported as part of the NWMO's transportation program does not qualify as special form (non-dispersible) radioactive material and therefore, is referred to as normal form material. As such, detailed information on special form material is not included in this report.[1,2]

[1] Special form is radioactive material that is encapsulated or an indispersible solid. Special form material cannot be inhaled in significant quantities if released during a severe accident. Qualification as special form material requires that the encapsulation itself must meet severe accident conditions. A sealed radioactive source used in radiography operations is a common example of a special form radioactive material.

[2] Normal form is radioactive material that is dispersible. While used fuel is "encapsulated" in sheathing, the sheathing is not qualified as special form.

The limit for the quantity of normal form radioactive material in terms of radioactivity is defined in the regulations as the A_2 value. The A_2 value reflects the maximum activity that can be transported in a Type A package. The A_2 limit is the basis used to select the type of package required and defines the design and testing requirements for that package.

An example of a graded approach in comparing Type A and Type B packages is as follows [12]:

- **Type A package**: Type A packages are used for the transport of relatively small, but significant, quantities of radioactive material. Since it is assumed that this type of package theoretically could be damaged in a severe accident and that a portion of their contents may be released, the amount of radionuclides they can contain is limited by the IAEA Regulations (i.e., the A_2 value). In the event of a release, these limits ensure that the risks from external radiation or contamination are at a level which protects public health and safety.

- **Type B package**: These packages must withstand the same normal transport conditions as Type A packages, but because their contents exceed the Type A limits or the A_2 value, it is necessary to specify additional resistance to release of radiation or radioactive material due to accidental damage. The concept is that this type of package must be capable of withstanding expected accident conditions without a release of radioactive material or an increase in radiation level which would endanger the general public and those involved in rescue or clean-up operations.

Additional context on the A_2 values is provided in Appendix B.

As the hazards associated with a transportation package increase, the graded approach is applied to the requirements applicable to that package. All radioactive materials are subject to general requirements.

The following severity levels are applied according to the package type:

(a) Routine conditions of transport (incident free)
(b) Normal conditions of transport (minor mishaps)
(c) Accident conditions of transport

Appendix D includes detailed information on the regulatory requirements based on the conditions of transport listed above, as well as a more detailed view of the graded approach.

For normal form radioactive material, the A_2 value defines the content limits for a Type A package. Type A packages can only contain an amount of contents **less than or equal to the A_2 value**. If the contents are **above** the A_2 value, a Type B package is required. This graded approach to quantity limits in transportation packages is illustrated in Figure 2-3. Figure 2-3 also lists the requirements for each package type.

Note that the requirements are cumulative as the hazard increases – this means that Type B packages are subject to general requirements as well as the requirements for routine, normal and accident conditions of transport. Packages containing fissile material, uranium hexafluoride or that are to be shipped by air (Type C packages) are subject to additional requirements.

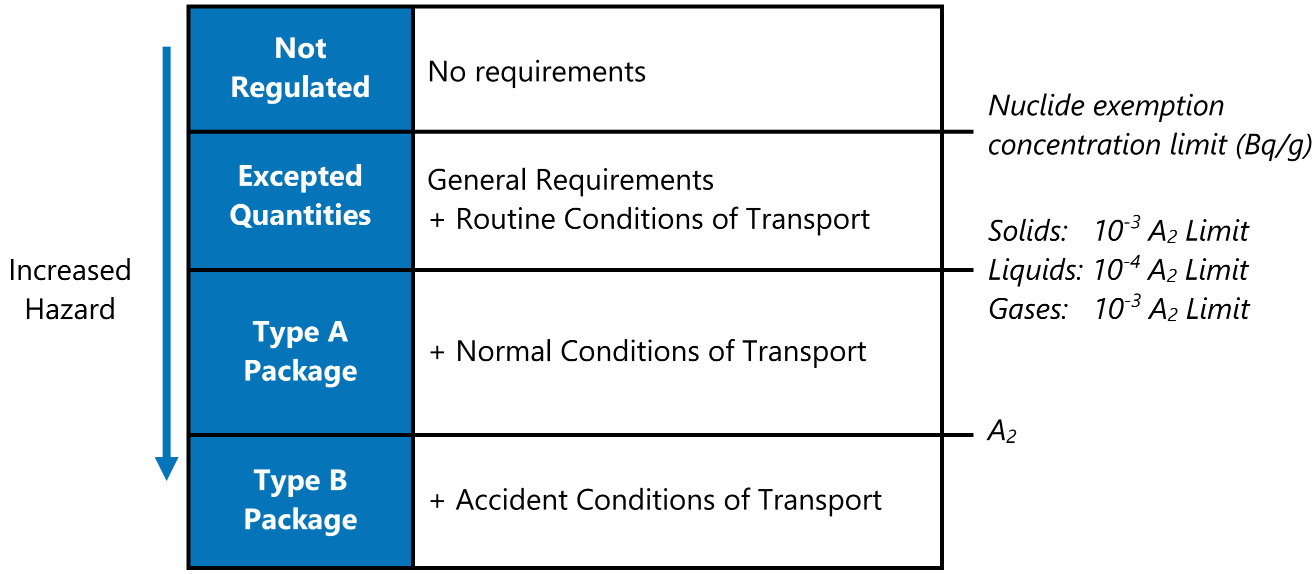


Figure 2-3: Graded approach based on quantity/activity (A_2) in transportation packages with normal form contents

2.3.2 Transportation Package Types

As discussed in previous sections, the requirements applicable to a transportation package depend on the transportation package type. The transportation package types described in the regulations are presented in Table 2-1.

Table 2-1: Transportation package types described in the regulations

Package Type	Description	Example Image [13] [14] [15] [16] [17]
Excepted Package	Excepted packages are utilized in the shipment of limited quantities of radioactive material that would pose a very low radiological hazards to members of the public. Examples of materials transported in excepted packages include consumer goods such as smoke detectors as well as empty used nuclear fuel packages.	
Industrial Package (For LSA and SCO – see Appendix C)	Industrial packages are used to transport certain low specific activity (LSA) materials and surface contaminated objects (SCOs). Most low-level radioactive waste is shipped in these packages. Examples of materials transported in industrial packages include uranium ores (from mining), contaminated dirt or contaminated laboratory clothing.	
Type A Package ($\leq A_2$)	Type A packages are intended to provide a safe means of transporting small quantities of radioactive material with higher concentrations of radioactivity than those shipped in industrial packaging. Examples of materials transported in Type A packages include radiopharmaceuticals (for medical use) and radioactive sources used in industrial applications. Unirradiated CANDU fuel is included in this category.	

Package Type	Description	Example Image [13] [14] [15] [16] [17]
Type B Package ($\geq A_2$)	Type B packages are designed to transport material with the highest levels of radioactivity. Examples of materials transported in Type B packages include high-level radioactive waste (such as used nuclear fuel) as well as materials with high concentrations of cesium and cobalt[2]. Used CANDU fuel is included in this category.	
Type C Package (Very Large Quantities Transported by Air)	Type C packages are designed to transport material with the highest levels of radioactivity by aircraft. Examples of materials transported in Type C packages include plutonium and mixed oxide fuel.	

Notes:

1. Additional requirements are required for packages containing fissile material or uranium hexafluoride [5], [6].
2. Cesium and cobalt are frequently shipped for use in the medical industry. Cobalt-60 and Cesium-137 are commonly used for cancer treatment as well as medical device sterilization.

2.4 Controls for Transport

Controls for transport are implemented to ensure transportation of used nuclear fuel packages are in compliance with the regulations. This includes ensuring that radioactive materials were properly classified and the appropriate package type for transport was selected. Controls for transport deemed most relevant to the NWMO's transportation program for Type B packages are described in this section. Additional information on controls for transport is provided in Section V of SSR-6 [6] and the PTNSR [5].

2.4.1 Contamination and Package Leak Testing

Limits are applied to the amount of radioactive contamination on all normally accessible working surfaces of packages. The surface contamination limit is based on limiting the amount of radioactive material that can be removed from the package surface from routine activities to an amount that will not significantly affect public health and safety. Any package that has become contaminated above the regulatory limits during the transport of radioactive material is to be decontaminated as soon as possible by a qualified person and is not to be reused unless the contamination no longer exceeds the limits.

Prior to shipment, a Type B package must be leak tested to assure that it is properly sealed and meets the criteria for acceptable release.[3] A helium leak test is a common method used to test whether a package meets the release requirement, because it is impractical to test the release of radioactive material directly. The small release rates required by the regulations result in extremely small clearances between the package body, the O-ring seals, and the lid, which would likely be plugged by any small particles. Using a helium leak test enables a package containment to be tested to leak tightness, defined as 1×10^{-7} cm^3/s [18]. This is approximately one teaspoon of gas every three years. Most used fuel packages are designed to be leak tight.

2.4.2 Dose Limits

Limits are in place on the amount of radiation the public and nuclear energy workers may receive. Canadian regulations draw upon the recommendations of the IAEA regulations and guides which follow the recommendations of the International Commission on Radiological Protection (ICRP). Both organizations comprise some of the world's leading scientists and other professionals in the field of radiation protection. As such, radiation dose limits are applied to the transportation of radioactive material. When assessing a package's integrity at an accident scene, radiation dose limits can also be used to determine if damage has occurred to the package (e.g., damage may have occurred if the radiation around the package is measured to be higher than the limits).

[3] The acceptable release is defined in the regulations as a very small quantity, one-millionth of an A_2 per hour.

2.4.3 Shipment Communications

Shipment communications, such as shipping papers, the labelling and marking of packages and placarding and paneling of vehicles, are key methods for communicating the presence and potential hazard of radioactive materials to workers, emergency responders, and the public.

Before a shipment, these systems communicate the potential hazards of the material to be shipped and ensure correct procedures are adhered to when selecting and preparing the package.

During an accident, the placards facilitate the identification of the dangerous good being carried. This allows emergency responders to take actions to protect public health and safety. These actions are described in Transport Canada's *Emergency Response Guidebook: A Guidebook for First Responders* [19]. Pages 258 to 269 provide potential hazards, public safety information, and emergency response guidance for radioactive materials.

Figure 2-4 shows the Used Fuel Transportation Package (UFTP) (a Type B package – see Section 3 for more details) with a dangerous goods category label and information plate. Note that in a typical transportation arrangement by road, the UFTP would be covered by a weather barrier and as such, the visible shipment communications would be on the weather barrier.

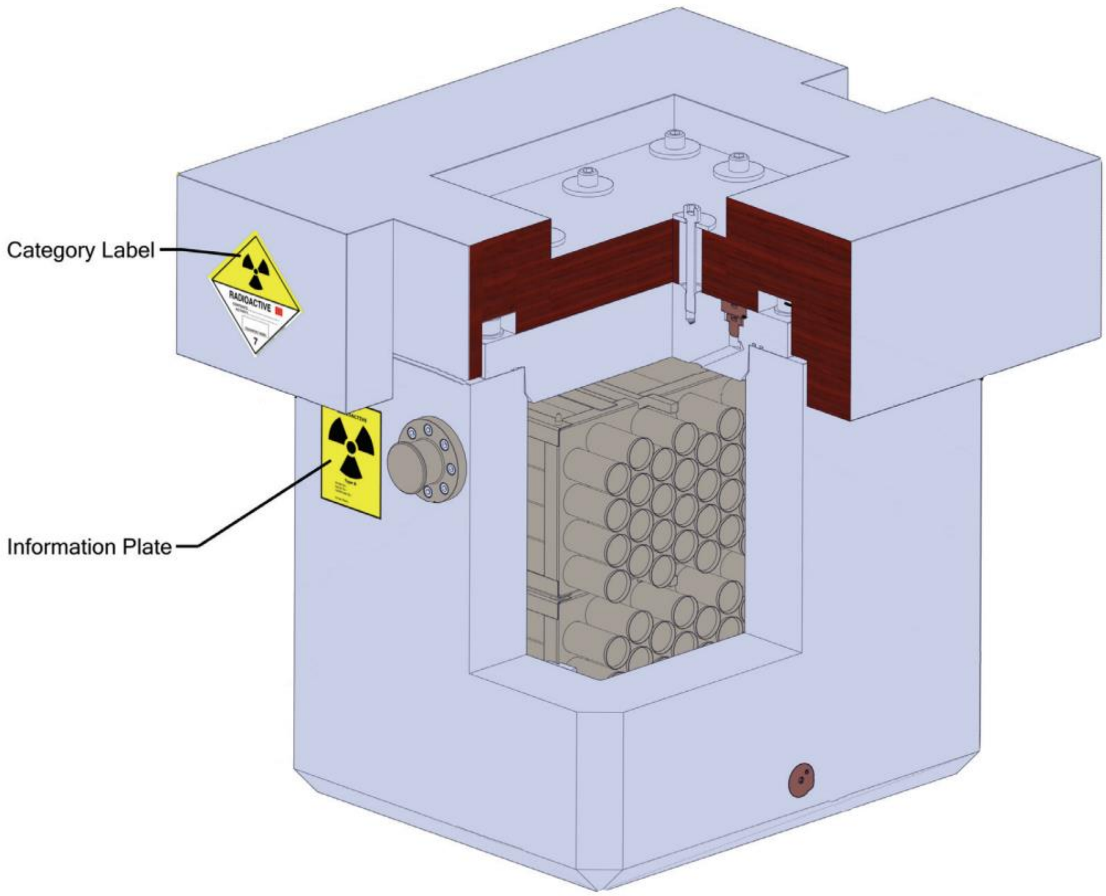


Figure 2-4: Dangerous good category label and information plate on the UFTP

3. DESIGN OF TYPE B PACKAGES TO WITHSTAND SEVERE ACCIDENT CONDITIONS

3.1 Introduction

The International Atomic Energy Agency's (IAEA) SSR-6 regulations and Canadian regulations (PTNSR) require that Type B package designs limit any loss of the radioactive contents and retain adequate shielding under normal and accident conditions of transport. Based on international research and technical input, the IAEA and national regulatory authorities established a set of accident test conditions which a Type B transportation package design must pass to be certified for use. These tests are defined in the IAEA's 'Regulations for the Safe Transport of Radioactive Material' requirements (SSR-6). As applicable to the Type B packages to be transported during the NWMO's transportation program these tests are as follows and illustrated in Figure 3-1.

1. **Free-Drop Test:** Dropping 9 m onto a flat, unyielding, horizontal surface, in the orientation that results in the package suffering the maximum damage. A description and rationale for this test is provided in Section 3.2.1.
2. **Puncture Test:** Dropping 1 m onto a rigidly, perpendicularly mounted 15 cm diameter steel bar at least 20 cm long. This test must use the same package as used in the *Free-Drop Test* and must be in the orientation that results in the package suffering the maximum damage. A description and rationale for this test is provided in Section 3.2.1.
3. **Thermal Test:** Fully engulfed in fire for 30 minutes at an average temperature of 800°C. This test must again use the same package as the *Free-Drop Test* and *Puncture Test*. A description and rationale for this test is provided in Section 3.2.2.
4. **Immersion Tests:** There are two immersion tests applicable to the Type B packages being considered as part of NWMO's transportation program. Both tests may be conducted with a different package than the *Free-Drop*, *Puncture*, and *Thermal* tests.
    a. *Water Immersion Test*: Subjected to an external water pressure of 150 kPa (equivalent to 15 m depth) for 8 hours, in the orientation that results in the most damage to the package. A description and rationale for this test is provided in Section 3.2.3.
    b. *Enhanced Water Immersion Test*: Subjected to an external water pressure of 2 MPa (equivalent to 200 m depth) for 1 hour without rupture of the containment system. A description and rationale for this test is provided in Section 3.2.4.

To gauge the cumulative effects on the package design, the first two tests are conducted in the sequence and in the orientation that results in the package suffering the maximum damage, followed by the thermal test on the same specimen. The regulations allow for computer-simulated as well as physical testing (using scale-model and full-scale model testing) to demonstrate the package's suitability for regulatory certification.

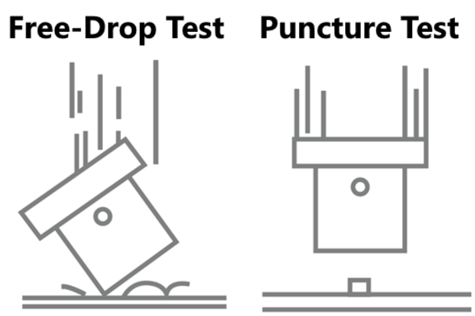


Figure 3-1: Regulatory tests in SSR-6 applicable to the NWMO's Type B packages [20]

3.2 Regulatory Tests for Type B Packages under Accident Conditions

As introduced in Section 3.1, the IAEA regulations describe a set of tests that Type B packages must undergo to demonstrate their ability to withstand accident conditions. The following subsections provide details on each of the tests applicable to Type B packages in the NWMO's transportation program. It also discusses the basis for their development and their bounding aspects when compared to real-world accident conditions.

The following information is summarized in subsequent sections:

- An overview of the regulatory test requirements for Type B packages under accident conditions is provided in Section 3.2.
- A description of the impact tests and rationale for the tests are provided in Section 3.2.1.
- A description of the thermal test and rationale for the test is provided in Section 3.2.2.
- A description and rationale of the water immersion and the enhanced water immersion tests are described in Section 3.2.3 and 3.2.4.
- A description of testing methods is provided in Section 3.3.
- The various packages being considered as part of NWMO's transportation program are described in Section 3.4.

Paragraphs 726-729 of SSR-6 describe the tests for demonstrating a package's ability to withstand accident conditions of transport as per the test acceptance criteria established in the IAEA regulations. Paragraph 730 of SSR-6 describes the *Enhanced Water Immersion Test* for Type B packages containing more than 10^5 A_2 (i.e., packages with a large amount of radioactive material – these include the packages being considered in the NWMO transportation program).

3.2.1 Impact Tests

The impact tests (an inclusive term for the *Free-Drop* and *Puncture* tests) consist of a series of two tests: *Free-Drop Test* and *Puncture Test*. The order of the two impact tests must ensure that the package will suffer the maximum damage during the thermal test that follows (see Section 3.2.2). Typically, this means that the *Puncture Test* follows the *Free-Drop Test*, depending on the package design. There is a third test called the *Crush Test,* described in Paragraph 727(c) of SSR-6 which is not applicable to the transport packages being considered in the NWMO transportation program (in part due to their total weight).

Both impact tests must drop the package in the orientation that would result in the package suffering **maximum damage**. Typically, this means that the package is dropped on a corner in the *Free-Drop Test,* and near the seals, ports, or lid in the *Puncture Test*. Designers often perform several drops to ensure the most damaging sequence of orientations is identified.

The basis for both impact tests is described in Section 3.2.1.1, Section 3.2.1.2 and 3.2.1.3 explain why the *Free-Drop Test* and *Puncture Test*, respectively, bound the forces occurring during severe accidents.

3.2.1.1 Basis For the Impact Tests

The *Free-Drop Test* simulates an impact that is spread over a larger area, while the *Puncture Test* simulates what would happen in a collision with an object, such as exposed rebar, guardrail, or a jutting piece of rail track.

3.2.1.2 Why the Free-Drop Test Bounds the Forces Occurring During Severe Accidents

The *Free-Drop Test* measures the damage and the deformation of the package from an impact with an **unyielding surface**. An unyielding surface is rigid (e.g., metal plate and/or reinforced concrete pad) and is used for testing because it is stiffer than soil, soft rock, and some concrete structures which would be experienced in real-world accidents. Since the unyielding surface does not move or deform when hit by the package, all the energy (or damage) from the impact is imparted onto the package body. Most of this energy causes deformation to the package body. The concept of the unyielding surface is illustrated in Figure 3-2.

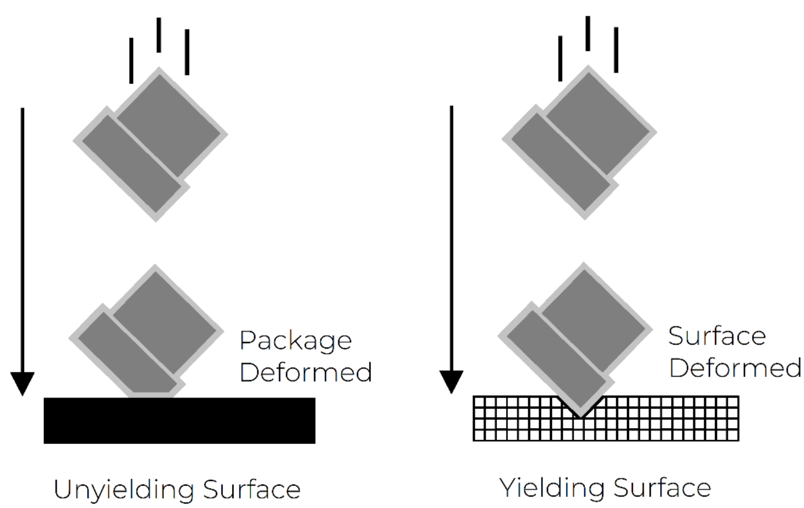


Figure 3-2: Deformation in an impact with an unyielding or yielding surface

In real-world scenarios, significant energy from the impact is transferred to the kinetic energies of the impacting vehicles, the package, the tie downs, and impact limiters [21]. The remaining energy is the amount available to be absorbed by the vehicle causing the collision (e.g., truck tractor, locomotive or ship), package trailer, or the package itself. Demonstration tests, such as Operation Smash Hit (see Section 4.3), have shown that the peak forces imparted to a package during a severe accident are in the order of 40% of those measured during a 9 m drop test onto an unyielding surface. [22]

The peak force on the package in the *Free-Drop Test* is larger than in real-world accident scenarios precisely because it is dropped on an unyielding surface. This means that, unlike in real-world accidents, the *Free-Drop Test* ensure that all impact energy is absorbed by the package rather than the object which the package strikes.

In addition, because the impact point is designated as the most damaging orientation for the package, the *Free-Drop Test* is bounding of the forces found even in very severe accidents. Furthermore, many package designs, including those being considered by in the NWMO transportation program, have impact limiters, which are non-rigid components designed to deform in an accident, thereby absorbing impact energy which would have otherwise been transferred to the package.

The *Free-Drop Test* bounds severe accidents because Type B transportation packages are designed to be much stiffer than objects they may collide with. The stiffness of the package is derived largely from the fact that a package is designed to absorb the total energy of a 9 m drop on to an unyielding surface with very little deformation to integral package components.

3.2.1.3 Why the Puncture Test Bounds the Forces Occurring During Severe Accidents

The *Puncture Test* assesses the vulnerability of packages to a through-wall puncture or lid deformation. Much like the *Free-Drop Test*, the *Puncture Test* is applied to the package in the orientation that results in the package suffering maximum damage. Additionally, the bar used during the test is rigidly, perpendicularly mounted to an unyielding surface.

As stated in Section 3.1, the regulatory tests are based on analyses of real-world accidents. Figure 3-3 and Figure 3-4 illustrate why puncture-type accidents are not a credible issue for Type B packages.

In Figure 3-3, data from the Association of American Railroads (AAR) shows the fraction of railroad tank cars that were punctured in an accident based on their shell thickness [23]. Railroad tank cars with a shell thickness greater than 1 in (2.5 cm – blue dashed line in Figure 3-3) were seldom seen to experience punctures. The two right-most red dots indicate that tank cars at these thicknesses (>1 in) had a fraction punctured of 0.00. The images of railroad tank cars on the right of Figure 3-3 are examples of tank cars susceptible to puncture. Accidents involving these tank cars are discussed in Section 5.

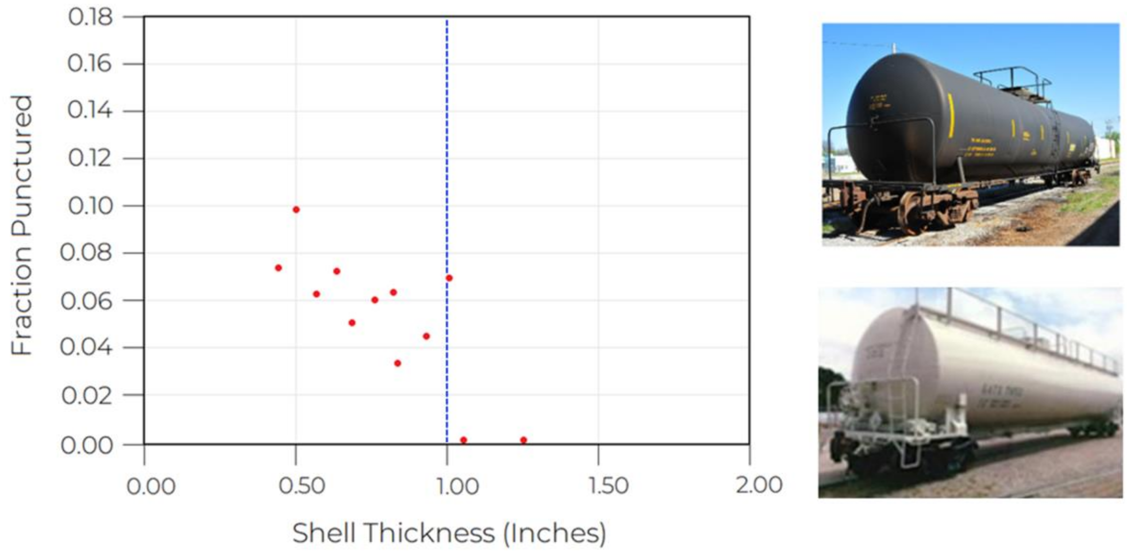


Figure 3-3: Fraction of railroad tank cars involved in puncture-type accidents based on shell thickness [23]

This data can be compared to the packages to being considered in the NWMO’s transportation program. For example, the UFTP and Dry Storage Container Transportation Package (DSC-TP) have been designed and certified for use and are described in Section 3.4. The UFTP and DSC-TP have walls over 10 in (25 cm) thick. As such, failure due to puncture during an accident is highly improbable for these Type B packages.

Figure 3-4 shows these packages and their wall thicknesses superimposed on the same data featured in Figure 3-3. The x-axis has been scaled significantly to accommodate the thicknesses of these packages. The red dashed line again denotes a thickness of 1 in. The dark grey represents steel and the light grey represents concrete.

Unlike the Type B packages being considered as part of NWMO’s transportation program, thin-walled and sandwich-walled packaging designs are susceptible to puncture loads, which can result in a loss of containment integrity, damage to the confinement system, or loss of thermal insulation. Even thick-walled designs may have weak points, such as closures of drain holes and valves. Puncture loads can occur during accidents when impact surfaces are uneven. To ensure safety, the 1 m drop test on a rigid bar was developed, with the drop height and punch geometry parameters being determined by engineering calculations.

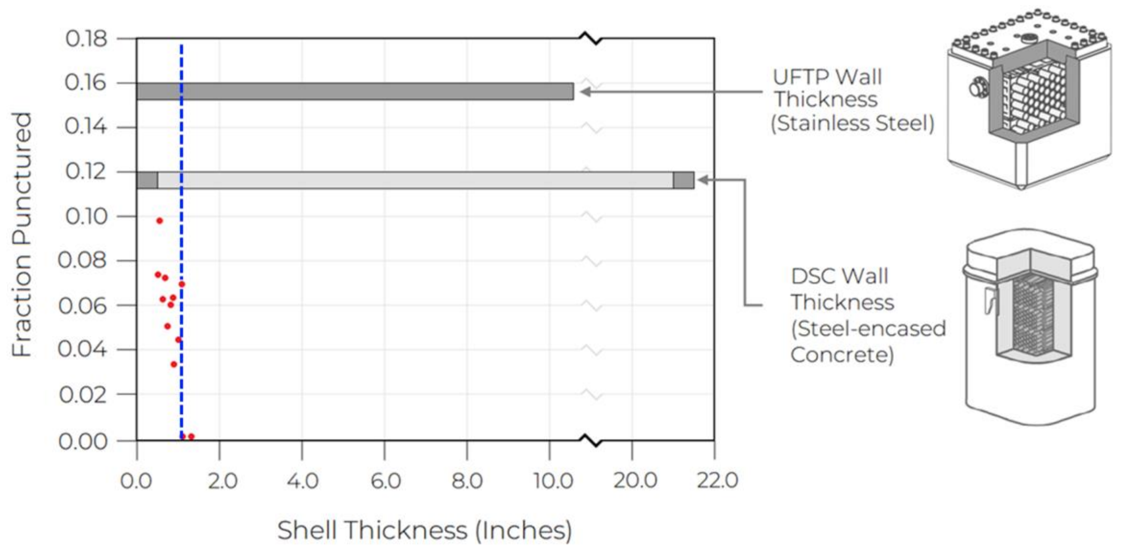


Figure 3-4: Fraction of railroad tank cars in puncture-type accidents with the thicknesses of the UFTP and DSC-TP overlayed

3.2.2 Thermal Test

Following the *Free-Drop* and *Puncture* tests, the same package used in these tests is subjected to a fully engulfing fire. The average fire temperature must reach 800°C for at least 30 minutes, with a starting ambient temperature of 38°C. The fire must provide a heat flux (rate of heat energy transferred through the surface) at least equivalent to that of a hydrocarbon fuel–air fire with specific fire parameters (see Paragraph 728 of SSR-6).

Following the fire, the package is exposed to an ambient temperature of 38°C and subject to solar insolation conditions (i.e., solar radiation on the package is simulated). The test considers the maximum rate of internal heat generation in the package and is only complete once the temperatures in the package are decreasing in all parts and/or are approaching initial steady state conditions. During and following the test, the package is not artificially cooled and if any combustion of package materials (i.e., wood impact limiter core) occur, it is permitted to proceed naturally. Note that CANDU fuel is not classified as explosive or flammable as it is solid high-density ceramic material encased in a durable zircaloy metal.

3.2.2.1 Basis For the Thermal Test

The *Thermal Test* assesses a package's performance to the effects of heat which could result from a typical fully engulfing hydrocarbon fuel-air fire. The test is based on a hydrocarbon fire as it is the most common type of fire in severe transportation accidents (i.e., petroleum or liquid natural gas).

The thermal test defines a number of physical parameters to use in evaluating the heat flux from a fire, such as fuel source, average flame temperature, duration, and location of package relative to the fire, package absorptivity, and flame emissivity. The intent of the test is not to maximize each individual parameter, but rather to result in a heat flux that bounds that found in most severe transportation accidents.

3.2.2.2 Why the Thermal Test Bounds Fire Parameters Occurring During Severe Accidents

Type B packages are designed to withstand a fully engulfing fire for 30 minutes while maintaining critical functions, including limiting the release of radioactive material and protecting the public from external doses of radiation exceeding regulatory limits. The 800°C fire environment used in a certification test applies a heat flux similar to those found in real fires. The average turbulent flame temperature for hydrocarbon fuels in a moderate sized pool fire is approximately 800°C and is independent of the type of hydrocarbon fuel (Paragraph 728.3 of the IAEA's *Advisory Material for the IAEA Regulations for the Safe Transport of Radioactive Material (2018 Edition)* (SSG-26) [24]. In the real-world, flammable liquids typically do not burn for more than 30 minutes in a single location because the fire exhausts its fuel supply (Paragraph 728.2 of SSG-26) [24].

In real accidents, the impact of a fire is determined by the orientation and location of the package in relation to the fire. In the *Thermal Test*, the fire is **fully engulfing** (Figure 3-5A) – this means that 100% of the package surface is exposed to the heat flux. In a real-world accident, one or more sides of the package would likely be protected by the transport vehicle involved in the accident, or the fire could act primarily on one side of the package (Figure 3-5B). If the package detached from the conveyance, the ground would act as a heat shield when compared to the fully engulfing fire required in the regulations (Figure 3-5A). The impact of the fire also rapidly decreases as the distance between the fire and package increases. These concepts are portrayed in Figure 3-5.

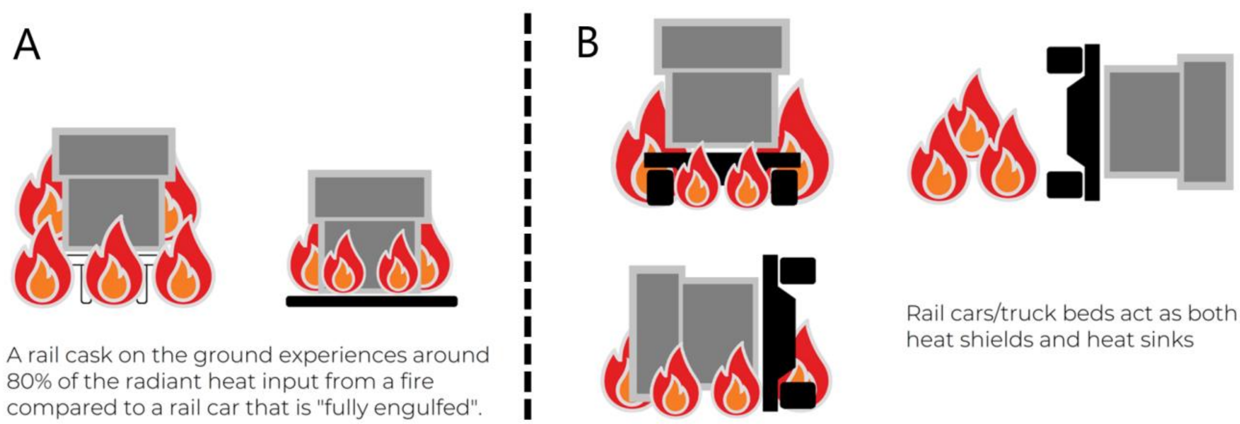


Figure 3-5: Comparison of the fire parameters in a real-world accident scenario versus a fully engulfing fire

Overall, the *Thermal Test* conditions simulate and bound the forces occurring in real-life scenarios as it creates a scenario which is fully engulfing and consistent. This subjects the package to thermal conditions which are equal to or greater than the thermal conditions occurring during a real-life accident.

3.2.3 Water Immersion Test

The *Water Immersion Test* requires that a package be immersed under 15 metres (50 feet) of water for at least eight hours in the attitude that will lead to the maximum damage. The test may be satisfied by immersion of the package, a pressure test on critical components combined with calculations, or by calculations for the whole package. For demonstration purposes, an external gauge pressure of at least 150 kPa can be used for the pressure test and calculations.

3.2.3.1 Basis For the Water Immersion Test

The *Water Immersion Test* is used to assess the damage that a package could experience in transport accidents that occur by water bodies near most bridges, roadways, and harbours which are less than 15 m deep. The main purpose of the test is to limit the potential consequences of a significant release of radioactive material near the coast or in a shallow body of water.

The test can be performed on a separate package from that used in *Free-Drop*, *Puncture* and *Thermal* tests, as the probability that this type of accident would involve significant impacts or fires is low [24]. The test duration (8 hours) was chosen to be long enough to allow the package to reach a steady state that is independent from processes that vary based on the speed at which they occur (rate-dependent processes) that might occur during immersion (e.g., the flooding of a package's exterior components such as the impact limiter).

3.2.3.2 Why the Water Immersion Test Bounds Pressures Occurring During Severe Accidents

The *Water Immersion Test* exerts a pressure of 150 kPa (15 metres of depth) on the package. The 15 m depth bounds the pressures occurring during severe accidents as the potential consequences of a significant release would be greatest near the coast or in a shallow body of water and 15 m is a reasonable estimate of water depth near most bridges, roadways or harbors.

This test ensures that the thick walls and lid of Type B packages are not susceptible to collapse or buckling at this pressure. In addition, design of the elastomer seals for packages would be required to withstand an external gauge pressure of 150 kPa. This test ensures that integrity of the package body (i.e., walls and lid) and use of properly designed seals prevents the significant release of radioactive material in shallow waters.

3.2.4 Enhanced Water Immersion Test

The *Enhanced Water Immersion Test* requires that packages with large radioactive contents (i.e., an activity of 10^5 A_2 or greater) be immersed under a head of water of at least 200 m for a period not less than one hour. Most Type B packages containing used fuel fall under this category. For demonstration purposes, an external gauge pressure of at least 2 MPa can be used for the pressure test and calculations. The acceptance criterion for passing the test is that the package must not experience rupture of its containment system. This is different from the acceptance criteria of other accident condition tests (see previous sections).

3.2.4.1 Basis For the Enhanced Water Immersion Test

The *Enhanced Water Immersion Test* was implemented to facilitate the recovery of large quantity radioactive material packages from the continental shelf. The impact of the expected radioactive release into the environment would be acceptable at this depth, as shown by risk assessments [24]. Despite this, the test was imposed because recovery would be facilitated after the accident if the containment system was not ruptured, and thus only the retention of solids was considered necessary (Paragraph 660.3 of SSG-26) [24]. This test is conducted with a timeframe of 1 h as this is the time taken for the package to reach steady state under the pressures induced by the 200 m depth.

3.2.4.2 Why the Enhanced Water Immersion Test Bounds Pressures Occurring During Severe Accidents

The 200 m depth corresponds roughly to the depth of the continental shelf surrounding terrestrial continents, and where long-term radiological exposure to persons through the ocean food chain could occur. Although the *Enhanced Water Immersion Test* is primarily intended to facilitate recovery of large quantity packages, it requires that the package containment system remain unruptured in accidents involving a package sinking at particularly deep locations. This would allow the salvage of the package without endangering the health and safety of salvage workers. Assessments have been performed in the past that demonstrate that a package sinking to this depth would result in doses far less than regulatory limits [25]. Additional information is provided in *Consequences of Postulated Losses of LWR Spent Fuel and Plutonium Shipping Packages at Sea* [26].

3.3 Testing Methods

Testing to demonstrate Type B package design compliance with regulatory requirements can be performed using a combination of full-scale physical testing, scaled physical testing, computer modelling, and/or calculation. The following list (from IAEA SSR-6, Paragraph 701) presents the most common testing methods for Type B transportation packages.

- **Impact Tests (*Free-Drop Test* and *Puncture Test*):** The impact tests are often done by a combination of computer modelling and full-scale and/or scale-model testing. Full-scale physical tests and/or scale model physical tests (with consideration to scaling relationships – see Appendix E.1.2) are used to extract information about variables that are challenging to model computationally (e.g., O-rings, impact limiters).
- **Thermal Test:** Typically performed using full-scale physical tests or computer modelling (or a combination of both - see Appendix E.3). These tests are most often conducted using

computer modelling as full-scale models are costly and specialized facilities are required to conduct fire testing.

- **Immersion Tests:** Typically performed using computer modelling as it is the most cost effective and the data/variables can be obtained and controlled easily.

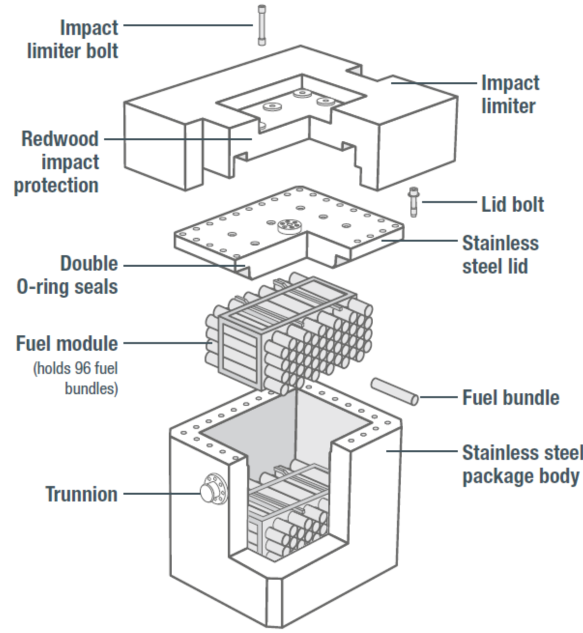
Note that this list does not mean that other methods cannot be used for these tests. Appendix E provides additional information on these various testing methods as well as the combined use of computer modelling and physical testing.

3.4 Design of UFTP, DSC-TP and BTP

Information on the UFTP and the DSC-TP is provided in this section from NWMO's Preliminary Transportation Plan [27]. Note that the Basket Transportation Package (BTP) design is excluded from assessments contained in this report as it is currently under development.

Used Fuel Transportation Package (UFTP)

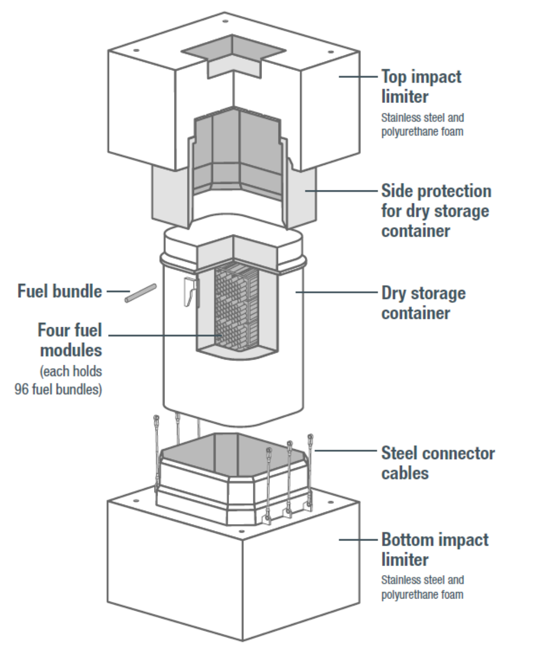
The UFTP consists of three main components: the body, lid and impact limiter. The body and lid are made of solid stainless steel with walls nearly 30 centimetres thick. The lid is attached to the body by 32 bolts. The impact limiter consists of a redwood core encased in a stainless steel skin. The stainless steel body and lid provide containment, shielding and impact resistance. The impact limiter is designed to protect the body and lid closure in the event of an accident. The reusable package can carry 192 used fuel bundles and weighs approximately 35 tonnes when loaded.



Dry Storage Container Transportation Package (DSC-TP)

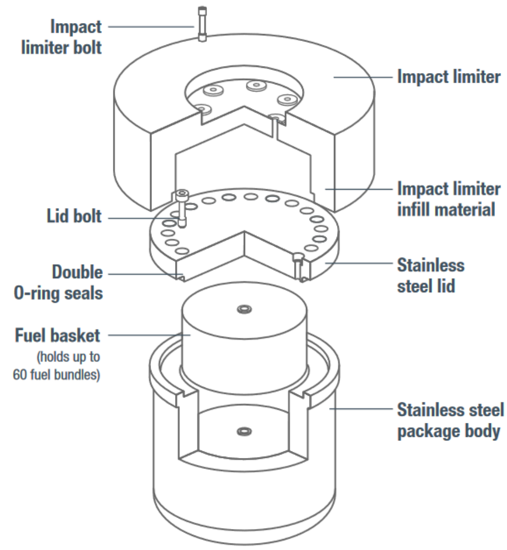
Used nuclear fuel is currently stored on an interim basis in dry storage containers (DSCs) at Ontario Power Generation Waste Management Facilities. The DSC-TP consists of a DSC fitted with impact limiters on each end.

The DSC consists of a body and lid made of high-density concrete encased in a carbon steel skin. The DSC body and lid are welded closed after being filled with used fuel. The reusable impact limiters consist of stainless steel shells filled with rigid polyurethane foam. The impact limiters are fastened together using steel cables. The DSC provides containment and shielding, and the impact limiters are designed to protect the DSC in the event of an accident. The DSC can carry 384 used fuel bundles and weighs approximately 100 tonnes when loaded.



Basket Transportation Package (BTP)

The BTP is under development and designed to move used fuel that is currently stored in dry storage baskets. The BTP consists of the following main components: body, lid, and one or two impact limiter(s). The image on the right shows the BTP concept with one impact limiter. Impact limiters are designed to protect the BTP in the event of an accident. This reusable package can carry up to 120 used fuel bundles (two baskets) and is anticipated to weigh 28 tonnes when loaded.



As the BTP design is currently under development, it has been excluded from the assessments contained in this report.

4. DEMONSTRATION TESTS

4.1 Introduction

The goal of the International Atomic Energy Agency (IAEA) transportation safety regulations is to assure that Type B packages are designed, tested, and certified in such a way that people and the environment will be protected from the effects of ionizing radiation under any credible accident that might be encountered during transport [6]. This assurance is based on a combination of rigorous package safety requirements, the safety margins built into package designs, and the use of physical testing and analytical studies (e.g., computer modeling) to validate the performance of packages under severe accident conditions. As a result, Type B package use has seen decade's long records of shipping used fuel without a significant package failure both in Canada and abroad.

This section explores some of the demonstration tests conducted over the last five decades to validate the effectiveness of IAEA package safety standards, and the performance of packages under extreme accident conditions. The selected demonstration tests cover a wide range of topics, including severe transport impacts and fires, including the effects of explosions and airplane crashes on transport packages, the behavior of specific materials used in package fabrication, and the effectiveness of O-ring seals at low temperatures. These tests use dummy fuel to assess how fuel would interact with the package in these scenarios.

In large part, demonstration tests have been performed by countries which have significant experience in used fuel shipments. These countries include the United Kingdom, Germany, France, Japan and the United States. Some of the most relevant demonstration tests to Canadian used nuclear fuel transportation are summarized in the following subsections and listed in Table 4-1. References are cited in each section for a more detailed description and discussion of each test.

Table 4-1: Tests covered in this Section 4

Performing Organization	Package Tested	Type of Demonstration Test	Section
United States			
SANDIA National Laboratory	20.5-tonne Package	Truck – Rigid Barrier Collision (100 and 135 km/hr)	4.2
SANDIA National Laboratory	22.7-tonne Package	Rail – Truck Collision (130 km/hr)	4.2
SANDIA National Laboratory	68-tonne Package	Rail – Rigid Barrier Collision (130 km/hr)	4.2
United Kingdom			
Central Electricity Generating Board	MAGNOX	Stationary Package - Rail Collision (160 km/hr)	4.3
Germany			
BAM	CASTOR	Liquified Propane Gas Explosion	4.4.1
BAM	TN 8/9	200-metre Drop Test	4.4.2
BAM	CASTOR	19.5-metre Drop Test	4.4.3
BAM	Elastomeric Seals	Behaviour at Low Temperature (-40°C)	4.4.4
BAM	TN 1300	Aircraft Crash (300 m/s)	4.4.5
Japan			
CRIEPI	Ductile Package Iron	9-metre Drop Test (-40°C)	4.5.1
CRIEPI	NFT-32B	5- and 17-metre Drop Tests without impact limiters	4.5.2
CRIEPI	HLW Package	3000-metre Immersion Test	4.5.3

4.2 Sandia National Laboratories – Crash Testing of Used Nuclear Fuel Shipping Systems

In the late 1970's, Sandia National Laboratories undertook a test program on behalf of the U.S. Department of Energy (DOE) to subject full-scale shipping packages and transport systems to severe accident conditions [28] . The program objectives were:

1. To assess and demonstrate the validity of current analytical and scale modelling techniques for predicting damage in severe accident conditions by comparing predicted results with the measured results from full-scale tests.
2. To gain quantitative knowledge of the response of full-scale shipping systems to extreme accident environments.

The results of the full-scale tests were not intended to validate regulatory standards. Three accident scenarios were chosen to represent severe road and railway accidents:

1. The crash of a tractor-trailer rig carrying a 20.5-tonne used fuel package traveling at velocities of 100 and 135 km/hr.
2. The high-speed impact of a 130 km/hr locomotive into a 22.7-tonne, truck mounted, used nuclear fuel package at a simulated grade crossing.
3. The crash of a railcar carrying a 68-tonne used nuclear fuel package into a massive concrete barrier at 130 km/hr, followed by exposure to a fire.

Each of the accident scenarios was evaluated in three separate phases:

Phase 1 – Structural Analysis
The basic dynamic response of the package system was determined analytically by a mathematical lumped parameter model using the one-dimensional SHOCK code. The HONDO code, a two-dimensional finite-element code, was used to calculate damage to the package shipping system using the impact velocity calculated by the SHOCK code.

Phase 2 – Scale Model Testing
A 1/8 scale model was used to predict the damage to the package and transport vehicle. The result of the 1/8 scale model test was compared to the results from the structural analysis.

Phase 3 – Full-Scale Testing
The results from the full-scale tests were compared to the results from both the structural analysis (i.e., SHOCK and HONDO) and the 1/8 scale model tests.

Description of the Tests

Truck – Rigid Barrier Collision [29]

Figure 4-1: Results of truck package impact into rigid barrier

A tractor-trailer (Figure 4-1) carrying a 20.5 tonne lead shielded used fuel package carrying an un-irradiated NS Savannah merchant ship reactor fuel assembly was impacted against a rigid barrier at a velocity of 97 km/hr [29]. The 626 tonne barrier was backed by more than 1 580 tonnes of earth and designed to be an unyielding surface with respect to the impact of the tractor-trailer rig (see Section 3.2.1.2 for a description of unyielding surfaces). While the tractor-trailer rig was completely demolished during the impact, the package itself suffered only superficial surface damage. The package was subsequently equipped with a new front impact limiter, remounted on an identical shipping trailer attached to a new tractor, and the test was repeated at a speed of 135 km/hr. In this test some fuel pin buckling occurred, which was similar to that experienced by a comparable fuel assembly in the regulatory drop tests. Despite this, no cladding failure was detected.

Rail – Truck Collision [30] [28]

Figure 4-2: Results of rail-truck collision

A 109 tonne locomotive (Figure 4-2) was impacted against a 22.7 tonne used fuel package mounted on a trailer attached to a conventional tractor at a simulated grade crossing [30]. The impact speed was 130 km/hr. The 109 tonne diesel--electric six axle locomotive was pushed up to speed by a sled containing six rockets fired in three stages. The locomotive impacted the tractor-trailer rig broadside. After crushing part of the trailer, the locomotive frame struck the package approximately 22 cm below the centerline of the package. Leak testing of the package after impact indicated a small leak in the head seal, when the package was pressurized. However, it was determined that, had the package contained cooling water, as older package designs were originally designed to do, this leakage would have caused essentially no risk to the public. Current package designs do not use cooling water as more efficient design methods have been adopted.

Rail – Rigid Barrier Collision [31]

Figure 4-3: Results of rail package impact into rigid barrier

A decommissioned 136 tonne rail package shipping system (shown in Figure 4-3), was crashed into an unyielding concrete barrier at 129 km/hr [31]. The shipping package itself weighed 68 tonnes. The package was fabricated from stainless steel with lead shielding. During the test the package was loaded with nine mock assemblies and one real unirradiated assembly. The impact resulted in extensive damage to the railcar structure. Damage to the rigid concrete barrier (which acted as an unyielding surface) was confirmed to be minimal. The package body was un-deformed except for minor deformations to the external cooling fins. No leakage was detected following the test.

Conclusions

The primary purpose of these tests was to demonstrate the validity of using analytical code tools (i.e., SHOCK and HONDO) and 1/8 scale modelling to predict the damage of a severe transportation accident as represented by the measured results from a full-scale test. The analytical and scale modelling techniques were used to predict the behavior of the full-scale system. The full-scale system responded as expected based on the predictions of the rigid body dynamics of the package during impact, and the resulting damage to the package was consistent with that predicted in pre-test analysis and scale modelling.

Preliminary calculations predicted how the package would impact the target. The second step in the analysis (the dynamic finite element model) predicted the deformation that would be sustained by the package. These two analytical techniques predicted the response of the vehicle and package in an extreme accident scenario.

The study concluded that both the analytical (i.e., SHOCK and HONDO codes) and scale modelling techniques could be used to accurately predict accident impacts and the vehicular and package damage in each of three accident scenarios used to represent extremely severe accident conditions. According to the study, *"The tests showed that, without exception the cask designs that were tested were not stressed in excess of the environments resulting from exposure of the designs to the regulatory standards* [28]*."* The study also demonstrated that the used fuel packages involved in the full-scale tests were capable of surviving the severe accidents modelled with little or no damage, and without loss of containment. See [29] [30] [31] [32] for additional information about these tests.

4.3 Central Electricity Generating Board - Operation Smash Hit (Railway)

Description of the Test

Figure 4-4: Resulting impact during Operation Smash Hit

In 1984, the Central Electricity Generating Board (CEGB) simulated a severe rail accident. The test involved a full-sized Magnox used fuel package on a railcar [33] being struck by an oncoming locomotive. To maximize the severity of the impact, the railcar carrying the Magnox package was turned on its side and orientated on a railway track so that the coupler of the oncoming train would directly strike the edge of the package lid at its most vulnerable location (Figure 4-4). The locomotive pulling three railcars and travelling at 160 km/h was then impacted into the Magnox package.

The results from the test were then compared to results obtained from a 9-metre drop test performed on an identical Magnox package. The comparison was performed to assess the forces on the package from the regulatory 9-metre drop against those experienced in the collision. To facilitate the comparison, the drop and crash tests were conducted so that the Magnox packages would be impacted at the same location.

Methodology

The CEGB set up a wide-ranging program of theoretical and experimental work to develop a detailed understanding of the way in which packages behave in severe transport accidents. At the time, there had been significant advances in computer analysis and in methods of physical testing and measurement. Given this, it was decided to use the latest available technology to study package accident behaviour from a more fundamental viewpoint than had been possible previously. Specific objectives of the project included an investigation into the validity of the use of scale models to represent full-size package behaviour, and a study of the relevance of the IAEA regulatory tests in relation to unlikely but credible transport accidents.

The project took place over a period of approximately four years and was based on a steady progression from the study of fundamental principles to the execution of a full-scale, 160 km/hr train crash. The main purpose of the work was to investigate the ways in which forces acting on a package resulted in permanent damage (i.e., package modelling studies) and to study the ways in which accidents generate forces on a package (i.e., real accident studies). The package test project focused on the Magnox package, since this package was at the time the most widely used in the United Kingdom. In all, over a hundred tests on package components, model packages and other test pieces were conducted culminating in the drop testing of a full-sized Magnox package and a full-scale rail crash demonstration carried out in public view in July 1984.

Results

The package survived the test with minimal damage, and during post-test examination, was found to have held its internal pressure to within 0.002 MPa of the 0.69 MPa to which it had been pressurised originally. Measurements of transient and permanent deformations in the region of the lid/body interface confirmed that the impact experienced by the package was much less severe than that imposed upon it during the 9-metre regulatory drop onto a rigid target. The peak impact force produced by regulatory 9-meter drop test was 75 MN, while the rail crash test was found to have produced 29 MN - approximately 40% of the peak force produced by the regulatory test.

Conclusions

The following conclusions were drawn from the package test project:

i. The use of scale models can be justified for estimating the impact performance of Magnox packages.
ii. Mathematical (computer) models are an essential tool for developing a proper understanding of package impact behaviour. Properly validated models can be used in a predictive manner with a high degree of confidence.
iii. The IAEA regulatory 9-metre drop test appears to cover credible severe accidents which can be expected to occur during transport. This is because there are added mitigation measures to minimize impact loads imposed on packages in real accident environments (e.g., impact limiters, tie down systems).

See [33] for additional information about this test.

4.4 Federal Institute for Materials Research and Testing (BAM)

The Federal Institute for Materials Research and Testing (Bundesanstalt für Materialforschung und -prüfung or BAM) conducted a series of tests over the years to assess the safety of Type B package designs [34]. These tests included:

1. An explosion of a liquified gas tank wagon beside a CASTOR THTR/AVR spent fuel package [35].
2. A drop test of a 1:2 scale model of a Type B package (TN 8/9 model) from a height of 200 meters [35].

3. A drop test of a Type B package (CASTOR 1C) from a height of 19.5 m onto a 1 000 tonne unyielding target [35].
4. A gas leakage test of various sealing materials through thermal cycles between +20°C and -70°C [36].
5. Aircraft crash simulation tests to determine the effects of impact loads, building debris dropping onto standing packages, and the thermal effects of kerosene fires [37].

4.4.1 Liquified Propane Gas Explosion Beside CASTOR THTR/AVR Spent Fuel Package

Figure 4-5: Before fire and explosion test with CASTOR THTR/AVR package placed beside LPG tank wagon

On 27 April 1999, a fire test was performed by BAM with a 45 m^3 Liquified Propane Gas (LPG) tank wagon, partially filled with 10 m^3 of pressurised liquid propane. A CASTOR THTR/AVR package (22 450 kg package with 370 mm thick walls; double lid closure with inner 250 mm thick steel lid and outer 70 mm thick steel lid) was positioned above a fuel oil pool, and beside a propane tank to suffer maximum damage from the subsequent explosion (shown in Figure 4-5).

Figure 4-6: After explosion

The propane tank ruptured 17 min after the fuel oil fire ignition. This resulted in a boiling liquid expanding vapour explosion (BLEVE) with an expanding fire ball (100 m in diameter), heat radiation, and an explosive blast wave. Propane tank fragments were blown into the package lid. Figure 4-6 shows the completely destroyed test assembly. The shockwave and shrapnel acting directly on the CASTOR package moved it approximately 7 m away from its original position along with overturning the package as shown in Figure 4-7.

Figure 4-7: Package thrown out of pre-test

Although the closure lid was exposed to fire and severely hit by tank wagon fragments, post-test investigations demonstrated that no loss of leak tightness occurred.

4.4.2 Drop Test (200 m) with Half Scale TN 8/9 Package

Figure 4-8: 1:2 scale model TN 8/9 package and helicopter before test

Another test within the BAM research project consisted of a 1:2 scale model of a Type B package which had been tested and certified to the IAEA transport regulations being lifted and dropped from a helicopter at a height of 200 meters (Figure 4-8). The package (a TN 8/9 model) consisted of a cylindrical cavity made of 12.5 mm thick steel sheets, and 100mm lead gamma shielding between outer and inner steel sheets. At both ends of the package, there were circumferential impact limiters filled with balsa wood. The total weight of the package was 4 125 kg, including a steel tube of 75 kg representing the package contents.

Figure 4-9: Package after drop from 200 m, penetrating concrete layer

A 20x30 m concrete drop target was selected. The target structure consisted of 60 cm layer of pit gravel; 40 cm concrete reinforced by steel mats. The model struck the target in an inclined, nearly horizontal position, penetrated the upper concrete layer, and caused a crater approximately 75 cm deep, 3 m long, and 1 m wide (Figure 4-9). The package was in freefall for 6.35 seconds, corresponding to an impact velocity of 225 km/hr. Figure 4-10 shows the TN 8/9 model after being lifted out of the penetrated concrete target. As a result of this impact, the following observations were made:

Figure 4-10: Package after lifting off the concrete ground

(i) both shock absorbers sheared off as well as all clamping bolts. The lid shock absorber was nearly completely flattened.

(ii) pressing of the cavity's closure and compressing of the respective screws, the lock could only be removed by machine.

(iii) complete flattening of the cooling fins in the impact area, destruction, and loss of the concrete-resin mixture.

(iv) no loss of integrity of containment components.

(v) no leaks could be detected through bubble testing, i.e., no leakage >10^{-3} mbar*L*/s occurred. [35]

As a result of this test, BAM concluded that "*for this type B package large margins of safety beyond the 9 m regulatory drop test existed*". The package maintained its integrity, and it was resistant to leaks while being subject to an extreme impact. Since this package had been certified to the IAEA regulations, it showed that packages which meet these regulatory requirements can withstand extreme real-world impacts.

4.4.3 Drop Test (19.5 m) of Package onto Heavy Truck Road Target

Around 1982, the question concerning the drop of used fuel packages from a reactor building crane (where lifting heights can reach up to 25 m) became of interest. In response, BAM performed a drop test from a height of 19.5 m (the maximum height between test object and target that could be obtained at the BAM drop test site) onto a 1 000 tonne target layer simulating a typical heavy truck road. The package used for testing was a CASTOR 1C used fuel transport and storage package which weighed 83 tonnes, had a length of 5.455 m, and a 1.73x1.73 m cross-section. It was dropped without the use of impact limiters. During the test, the package penetrated approximately 0.55 m into the target. Measured deceleration values (60 and 70 g) indicated that the impact force from this 19.5 m drop was less than half of the peak impact force measured in a regulatory 9-metre drop of a similar package design.

4.4.4 Behaviour of Elastomeric Seals at Low Temperature (-40ºC)

Regulations require packages to perform at low temperatures down to -40°C. Elastomers are the common sealing material in packages. The major concern is the elastomer's glass transition temperature, below which, the material elasticity is reduced and its ability to provide sealing force may be compromised. A study was performed to investigate the low temperature behavior of sealing systems, particularly the critical temperature at which seal materials no longer provide sealing. [36]. The study measured the gas leakage rate of various sealing materials through thermal cycles between +20°C and -70°C. The temperature at which the gas leakage rate suddenly increased was deemed the critical temperature at which the material no longer provided sealing. For all seals studied, the critical temperature was well below the glass transition temperature of the elastomer. These tests concluded that the sealing function is still preserved at low temperatures while sufficient sealing force maintains contact between the elastomer seal and the flange surfaces.

4.4.5 Aircraft Crash Simulating Tests and Calculations

Between 1978 and 1982, six full-scale tests were performed in Germany to assess the impact of steel pipe projectiles at 300 m/s (1 080 km/hr) on different packages specimens to assess the response of the package to an aircraft crash [37]. After the terrorist attacks of September 11, 2001, the assessment of aircraft crash impacts was re-examined to include the effects of large civil aircraft crashes. BAM investigated the resulting mechanical impacts from aircraft engine crash loads (represented by calculated force–time relationships after penetration of an aircraft through building structures), building debris dropping onto standing packages, and finally the thermal effects of kerosene fires. The calculations focused on the package walls, lids and lid bolts stresses, gasket temperatures, and flange (axial and radial) displacements at gasket locations to verify the components integrity and to evaluate the influences on potential leakage rates. BAM concluded that from the information gathered through the tests, *"the displayed stresses and displacements are within limits where the safety of the cask function is preserved* [35]."

4.5 Central Research Institute of Electric Power Industry (CRIEPI) Tests

The nuclear policy of Japan involves reprocessing used fuel and recycling nuclear materials. However, the storage and transport of used fuel has become increasingly important in the country's nuclear fuel cycle, leading to concerns about safety. To ensure the safety of used fuel storage and transport, various tests using full-scale packages were conducted, in addition to regulatory tests. This section provides a summary of the tests conducted by the Central Research Institute of Electric Power Industry (CRIEPI) in Japan on Type B packages. These tests aimed to assess the integrity of the packages under conditions that differed from the standard regulatory tests, such as extreme impact and enhanced immersion. The purpose was to demonstrate the packages' ability to withstand conditions that deviate from the regulatory standards and simulate real accidents that may occur during transport or storage.

4.5.1 Quality Assurance of Ductile Cast Iron Packages

CRIEPI organized *The Quality Assurance Committee on Cast Iron Casks* (the QA Committee) to carry out research on the employment of Ductile Cast Iron (DCI) packages in Japan. This was due to there being insufficient material data on fracture toughness and because brittle failure acceptance criteria were not yet established for DCI in package applications. The specimens used for these tests were sampled from full-scale DCI package bodies (with wall thickness varied from 350 to 500 mm) in order to evaluate real material data [38], [39]. The QA Committee undertook various drop tests and computer evaluations to confirm the proposed brittle failure design criteria and the integrity of the DCI package against mechanical impact.

The QA Committee developed a neutral design specification for the DCI package to ensure that the test results could be applied generally to DCI packages of different designs. The results from these tests, while being a different material than the NWMO's transportation packages, are still applicable to all nuclear fuel and high-level waste packages as a point of comparison. DCI is a "low ductility" material that is prone to fracture in very cold temperatures. These tests demonstrated that transportation packages fabricated from a low ductility material, such as DCI, can withstand severe impacts even at temperatures as low as -40°C. On the other hand, most packages are fabricated from stainless steel, which has a much higher ductility and is less susceptible to embrittlement and fracture. By comparison, a package made of stainless steel would perform at least as well against brittle fracture failure modes as a package fabricated from DCI if subjected to a similar test at -40°C.

Before the drop tests were conducted, pre-drop tests were modelled using the DYNA-30 code on the DCI package for the 9-metre drop and 1-metre puncture test conditions in different drop directions (horizontal, vertical, and corner) to find the orientation of maximum tensile stress, which was determined as horizontal. Drop tests were planned for DCI packages with a sharp flaw, and an artificial flaw with a 0.1-mm tip radius. Fracture toughness tests were performed on specimens with a fatigue crack and artificial flaws to ensure equivalency in their fracture toughness values.

Two 9-metre drop tests and one 1-metre puncture test were performed on a full-scale DCI package. The first 9-metre drop test aimed to demonstrate the integrity of the DCI package with an artificial flaw (a crack in the package with a 20-mm depth). The second 9-metre drop test aimed to verify the proposed brittle failure design. The DCI package body was cooled down to less than -40°C (233K) before each test using vaporized liquid nitrogen, and impact limiters were attached to both ends of the package. After each 9-metre drop test, the artificial flaw was examined using an optical fiberscope, and no crack propagation was observed from the artificial flaw. The DCI package was also dropped horizontally from 1-metre onto a mild steel pin, and no penetration occurred, confirming the integrity against brittle failure with strain measurements. Sufficient fracture toughness data of full-scale DCI package bodies was obtained for quality assurance and to evaluate brittle failure.

4.5.2 Drop Test of DCI Package with No Impact Limiter

Impact limiters are common features used in many Type B package designs to absorb impact forces during accidents. They are typically removed during handling at storage facilities to access the package contents. As such, the effects of a package dropped without its impact limiter in place were studied [40]. For testing purposes, DCI packages were chosen due to their economic feasibility, and a reinforced concrete slab was used as a target for the drop tests based on the conceptual design of a storage building.

The most plausible drop orientations for a package drop accident in a storage building were expected be vertical and oblique, coinciding with the failure of a lifting cable. Another credible accident orientation was expected to be a drop in the horizontal orientation at the time of unloading from a truck. As such, drop tests were conducted in the three drop orientations: vertical, horizontal and oblique. Test drop heights were set as 1.5 m, 7.5 m, and 17 m to correspond with different potential lifting conditions. The conclusions drawn from the tests included:

i. The structural integrity of packages was maintained under drop test conditions even without impact limiters present.
ii. The packages maintained leak-tightness through the testing regiment.
iii. The assessment of integrity after the 17 m drop test suggested that packages have a sufficient margin of safety when considering package lifting operations.
iv. No damage was observed for the package contents during testing.

4.5.3 Enhanced Water Immersion Test Beyond Regulatory Requirements

A water immersion test under a head of water at 3 000 m for one hour was performed in addition to the 15 m and 200 m immersion tests required by the IAEA regulations to test the package in extreme conditions [40]. The specimens chosen for testing were packages designed for handling high-level waste (HLW) similar to the TN 28 VT package designs. The package body consisted of forged carbon steel and neutron shielding material. The contents of the package (basket and HLW canister) and the package's impact limiters were removed during the 3000 m water immersion test.

The internal pressure of the package cavity was continuously monitored during the immersion test. Any intrusion of water into the package cavity would have been detected as part of the test.

The maximum strain at the package body resulting from the 3 000 m immersion was found to be within the package's elastic range, meaning that no rupture was observed. The package's lid plate was found to have bowed slightly as a result of the pressure. However, it was found that the package retained its leak tightness following the 3 000 m immersion test. The results of the testing include:

i. No leakage was detected at any sealing boundary during the immersion test and no reduction in the sealing characteristics was observed.
ii. At 3 000 m water pressure, most of the package body was within the elastic limit and the allowable stress intensity of the material was not exceeded.
iii. Deformation by water pressure at depth was found to be 1 mm or less for the package body and 2 mm or less for the lid.
iv. No reduction in performance was observed for the radiation shielding.
v. The package was found to retain its integrity during the regulatory (200 m) enhanced immersion test. A significant safety margin was found to exist with regards to exposure to a water pressure of 3 000 m depth.

4.6 Summary

The stringent IAEA transportation regulations and package safety standards were tested and validated through various demonstration tests carried out by multiple agencies internationally. These tests demonstrated the robustness of packages that abide by the IAEA regulations and standards, ensuring that workers, the public, and the environment will remain safe from the effects of ionizing radiation being transported by such packages. In addition, a number of these tests have showcased that the forces generated during regulatory tests are often bounding of credible accident scenarios as discussed in Section 3.

5. REAL-WORLD ACCIDENT RECONSTRUCTIONS

5.1 Introduction

An important tool in addressing the safety of used fuel shipments is the use of accident reconstructions. Accident reconstructions are used to predict the performance of used fuel packages and transport systems under severe, real-world accident conditions. The evaluations have been used historically to:

1. Assess the performance of specific used fuel package designs in real life accident scenarios.
2. Compare impact and thermal forces generated in historical accidents with the impact and thermal forces generated during regulatory drop and fire tests used to certify used nuclear fuel (UNF) package designs.
3. Evaluate a package's performance against the acceptance criteria in the regulations for containment (release of radioactive contents) and shielding (external dose rates).

The key elements in any accident reconstruction are the identification and quantification of the impact and thermal forces present. The impact and thermal forces for most accident reconstructions are determined based on parameters reported by first responders, investigators, and any physical measurements taken at the accident scene. However, the limitations of relying solely on official accident reports and media accounts are that important parameters (such as temperatures, fire durations, and pressures) are often not reported, or reported inaccurately.

This has resulted in two general approaches to estimating the impact and thermal forces in a particular accident scenario:

- The first approach is the use of physical modelling where actual package models are constructed and subjected to a simulated accident. This approach has been illustrated in Section 4 (e.g., Operation Smash Hit and the BAM propane explosion). This approach allows the accident to be observed and photographed in real time. The use of physical models also allows the direct measurement of accident parameters that can be used to directly calculate factors such as temperature, pressure, velocity, and decelerations.
- The second approach involves the use of analytical techniques (e.g., simulations, calculations) in the reconstruction of an accident using investigative and media reports. In this case, the impact and thermal forces are initially determined based on parameters reported by first responders and investigators. These are subsequently verified by physical measurements taken at the accident scene or on vehicles and transportation infrastructure involved in the accident. The accident is then simulated using computer models.

The U.S. Nuclear Regulatory Commission (USNRC) used this second approach to analyze a series of accidents involving severe long duration fires. In analyzing these accidents, the USNRC used videos captured by security cameras, post-accident metallurgical examinations of rail tank cars, tanker trucks, concrete rebar, and bridge components. They also made use of physical data and computer models developed from the U.S. National Institute of Standards and Technology's (NIST) extensive testing of tunnel fires, which was conducted in an out-of-commission highway tunnel.

5.2 Examples of Analyses based on Real-World Accident Reconstructions

In 2006, the U.S. National Academy of Sciences (NAS) published a safety study of a large-scale shipping campaign for used fuel [41]. While the study concluded that existing regulatory standards provided a high degree of safety, it recommended that additional studies be undertaken to look at very long duration fire scenarios that bound expected real-world accident scenarios for a representative set of package designs that are likely to be used in future large-quantity shipping programs.

In response, the USNRC conducted a series of accident studies that looked at real-world rail and highway accidents involving long-duration fires [42]. The major goals of the studies were to identify a list of historical accidents that resulted in severe long-duration fires, and then to analyze the response of typical used fuel package designs to the impact forces and fires found in those accidents.

The studies reconstructed four accident scenarios and looked at the performance of used fuel packages for both rail and truck transport. In each of the four accident scenarios, the package designs were found to meet or exceed the regulatory requirements for containment and dose limits for severe accidents. All the scenarios examined demonstrate that Type B transportation packages certified under International Atomic Energy Agency (IAEA) standards are able to protect first responders, the public and the environment from radiological harm even under extreme real world fire scenarios.

The studies are summarized in the following subsections. Note that these studies were conducted using package designs approved in the U.S. to transport used fuel from Pressurized and Boiling Water Reactors. While all certified Type B package designs have to comply with international regulatory requirements (IAEA's SSR-6), the packages studied by the U.S. feature different specific designs than those used in Canada to transport CANDU fuel. Differences include the types of used fuel being transported, the configuration of the package (i.e., round versus square cross section), and the use of different materials for gamma and neutron shielding.

A brief description of the packages used in the USNRC studies can be found in Appendix F. Information on the UFTP, DSC-TP and BTP is provided in Section 3.4.

5.2.1 Baltimore Tunnel Fire

5.2.1.1 Description of the Accident

On July 18, 2001, a freight train caught fire while passing through the Howard Street railroad tunnel in downtown Baltimore, Maryland. The freight train consisted of 60 cars pulled by 3 locomotives. It was carrying paper products and pulp board in boxcars, as well as hydrochloric acid, liquid tripropylene, and other hazardous liquids in tank cars.

Eleven of the 60 rail cars derailed as the train was passing through the tunnel. A tank car containing approximately 108 263 liters (28 600 gallons) of liquid tripropylene was punctured by the car's brake mechanism during the derailment.

The exact duration of the fire is not known with certainty. Based on interviews of emergency responders conducted by the U.S. National Transportation Safety Board (NTSB), it was determined that the most severe portion of the fire in the Howard Street tunnel lasted approximately 3 hours. Less severe fires burned in the tunnel for periods of time greater than 3 hours. Approximately 12 hours after the fire started, firefighters were able to visually confirm that the tripropylene tank car was no longer burning.

5.2.1.2 Purpose

The accident was reconstructed by the USNRC to determine the thermal conditions that existed in the Howard Street tunnel fire and to analyze the potential effects of those conditions on three different Type B package designs certified to transport used nuclear fuel.

Figure 5-1: Image of the Baltimore Tunnel Fire

5.2.1.3 Methodology and Assumptions

A team of experts from NIST, the Centre for Nuclear Waste Regulatory Analyses, and the Pacific Northwest National Laboratory was assembled to analyze the Baltimore Tunnel Fire. They performed a detailed fire analysis to determine the temperatures reached by the tunnel air, wall, floor, and ceiling during the accident. They also conducted a metallurgical examination of numerous samples taken from the tripropylene tank car to verify that the damage observed for the rail car was consistent with the temperatures predicted in the fire analysis.

The temperatures obtained were then used to model the performance of the used fuel packages. A description of the packages can be found in Appendix F.

The three package designs chosen represent the different ways that used fuel could be shipped. Used fuel can be shipped in rail packages either as bare fuel that is usually loaded directly from an irradiated fuel pool, or as canistered fuel, in canisters that have been used for dry fuel storage. The TN-68 (Appendix F) is a large capacity rail package that is used to ship bare (i.e., uncanistered) used fuel. The HI-STAR 100 (Appendix F) is a large capacity rail package that is used primarily to ship canistered used fuel (that has been stored in canisters). The NAC-LWT (Appendix F) is a legal weight truck package used primarily to ship bare used fuel assemblies.[4] Truck packages are too small to handle canistered fuel. The NAC-LWT can also be shipped by rail.

5.2.1.4 Results and Conclusions

The study concluded that larger transportation packages resembling the TN-68 and HI-STAR 100 would withstand a fire with thermal conditions similar to those that existed in the Baltimore tunnel fire event with only minor damage to peripheral components. This is due to their sizable thermal inertia[5] and compliance with regulatory requirements.

While a release is not expected to occur for these conditions, any release that could occur would be very small due to a number of factors. These include;

1. The tight clearances maintained between the lid and package body by the closure bolts,
2. The low-pressure differential between the package interior and exterior,
3. The tendency of such small clearances to plug, and,
4. The tendency of CRUD particles[6] to settle or plate out.

The analysis indicates that the regulatory dose rate limits for accident conditions would not be exceeded by releases or direct radiation from any of these packages in this fire scenario. While highly unlikely, the NAC-LWT could experience some slight loss of lead shielding as a consequence of this fire scenario. However, this loss would not result in dose rates that exceeded regulatory limits. There would be no release from the HI-STAR 100 because the inner welded canister remains leak tight under the observed conditions. The potential releases calculated for the TN-68 rail package and the NAC-LWT truck package indicated that any release of CRUD from either package would be very small – less than an A_2 quantity.

In summary, the potential releases of radioactive material from all three packages are well below the internationally accepted safety standard of an A_2 quantity per week, and would not pose a risk to first responders or public health and safety. [7]

Additional information is provided in [43], [44], [45] and [46].

[4] A legal weight truck package is a package that meets the legal weight restrictions for U.S. highway shipments.

[5] An object with a large thermal inertia will absorb a large amount of heat with a small change in temperature.

[6] CRUD is a colloquial term used to denote corrosion products (e.g., rust particles) that adhere to the outside of used fuel rods that become radioactive when exposed to radiation.

[7] The A_2 quantity per week is based on limiting potential exposures to first responders and the public following a severe transportation accident to no more than the occupational dose of 100 mrem. This limit represents approximately 25 percent of the normal background dose of 400 mrem/yr.

5.2.2 Caldecott Tunnel Fire

5.2.2.1 Description of the Accident

On April 7, 1982, a tanker truck and trailer carrying 33 310 liters (8 800 gallons) of gasoline was involved in an accident in the Caldecott Tunnel on State Route 24 near Oakland, California. The tank trailer overturned and subsequently caught fire.

The overall duration of the fire is estimated at approximately 2.7 hours. However, based on NTSB evaluations of the fire debris and interviews with emergency responders, the intensely hot gasoline-fueled portion of the fire is estimated to have lasted about 40 minutes. At about 46 minutes after the start of the fire, firefighters in protective gear entered the tunnel to search for survivors and were able to approach the location of the tanker truck.

5.2.2.2 Purpose

The accident was reconstructed by the USNRC to determine the thermal conditions that existed in the Caldecott tunnel fire and to analyze the potential effects of those conditions on Type B truck packages certified to transport used nuclear fuel.

5.2.2.3 Methodology and Assumptions

The USNRC first analyzed the Caldecott tunnel fire in a 1987 study (*Shipping Container Response to Severe Highway and Railway Accident Conditions,* NUREG/CR-4829 [47]) and concluded that no radioactive release or increase in radiation level would be expected from a typical (generic) used nuclear fuel truck package in this fire scenario.

Figure 5-2: Image of the Caldecott Tunnel Fire

In this reconstruction, the USNRC evaluated the potential impact of the Caldecott Tunnel fire on a specific used nuclear fuel transportation package design – the NAC-LWT truck package.

A team of experts from NIST, the Centre for Nuclear Waste Regulatory Analyses, and the Pacific Northwest National Laboratory was assembled to develop a model of the Caldecott Tunnel fire and perform an analysis to determine the range of temperatures present in the tunnel during the fire event.
The temperatures obtained were then used to model the performance of the used fuel packages.

5.2.2.4 Results and Conclusions

The results of this evaluation strongly indicate that neither used nuclear fuel particles nor fission products would be released from a used fuel shipping package involved in a severe tunnel fire such as the Caldecott Tunnel fire. The NAC-LWT design analyzed for the Caldecott Tunnel fire scenario does not reach internal temperatures that could result in rupture of the fuel cladding.[8] Therefore, radioactive material (i.e., UNF particles or fission products) would be retained within the fuel rods. The potential release calculated for the NAC-LWT package in this scenario indicates that any release of CRUD from the package would be very small - less than an A_2 quantity.

The potential release from the NAC-LWT package based on five-year cooled fuel is estimated to be approximately 0.01 Curies (Ci) of Cobalt60 (Co-60).[9,10] Since the A_2 value for Co-60 is 11 Ci, the potential release is about 0.001 of an A_2 quantity. Therefore, the potential release of radioactive material from the NAC-LWT package for the Caldecott fire scenario is well within regulatory limits and would not pose a risk to first responders or public health and safety.

Additional information is provided in [48], [47], and [49].

[8] Fuel cladding consists of a thin-walled metal tube that forms the outer jacket of a nuclear fuel rod. If the fuel rod is heated beyond its rupture temperature, the cladding may experience a longitudinal split, allowing used fuel particulates to escape from the rods.

[9] The A_2 quantities for radioactive materials are defined in units of radioactivity such as the Curie.

[10] Cobalt-60 is the main radioactive component of CRUD (corrosion products) on the outside of fuel rods. (see also footnote 6 on page 17)

5.2.3 MacArthur Maze Fire

5.2.3.1 Description of the Accident

On April 29, 2007, a tanker truck and trailer carrying 32 554 liters (8 600 gallons) of gasoline overturned and caught fire on the Interstate 880 (I-880) connector of the MacArthur Maze interchange located in Oakland, California. The intense heat from the fire weakened the steel girders of the Interstate 580 (I-580) roadway above the fire, collapsing two adjacent spans (approximately 48 m (156 feet)) of the elevated roadway onto the section of freeway below.

A surveillance camera from the monitoring system of the East Bay Municipal Utility District Wastewater Treatment Plant adjacent to the roadway captured a video of the fire. This video shows the first I-580 roadway span beginning to sag around 10 minutes into the fire and collapsing completely after approximately 17 minutes. The video also shows a second span of the I-580 roadway descending slowly to the lower (I-880) roadway, beginning at about 17 minutes and reaching its final (partially collapsed) configuration after about 37 minutes (post-accident).

The collapse of the second span greatly reduced the size of the fire, but it continued to burn until about a duration of 102 minutes. As a fire management decision, the first responders on the scene allowed the fire to burn until the hydrocarbon fuel was fully consumed. At that point, the fire began to noticeably decrease in brightness, diminishing to a small glowing spot by approximately 108 minutes after the start of the fire.

Figure 5-3: Surveillance footage of the MacArthur Maze Fire

5.2.3.2 Purpose

The accident was reconstructed by the USNRC to determine the thermal and impact conditions that existed in the MacArthur Maze fire and to analyze the potential effects of those conditions on the GA-9 truck package certified to transport used nuclear fuel.

The MacArthur Maze accident was selected because of the severity and duration of the fire, along with the unusual structural consequences in which the heat from the fire caused the overhead roadway segments to collapse.

5.2.3.3 Methodology and Assumptions

A bounding fire scenario was defined for this accident based on fire modelling with the NIST's Fire Dynamics Simulator code, and the physical examination of material samples obtained onsite from the tank truck and steel girders from the collapsed overpass. Based on the modelling and sampling, the bounding scenario was represented as a fully engulfing pool fire at 1 100°C (2 012°F) prior to the overhead roadway collapse, and as a smaller and less severe fully engulfing pool fire at 900°C (1 652°F) afterward.

Thermal modelling of the GA-4 package was conducted to determine the response of the package to the fire scenario, including the long post-fire cooldown period. Additional detailed structural and thermal-structural models were developed for the roadway and package, which showed that the falling overhead segments could impose only relatively insignificant loads on the package's stainless-steel body and depleted uranium (DU) gamma shield,[11] compared to the structural loading the package is designed to withstand during accident conditions of transport.

5.2.3.4 Results and Conclusions

The analysis indicates that the regulatory dose rate limits specified for accident conditions would not be exceeded for this package in this fire scenario, even though the package would be expected to lose its neutron shielding. This is because the complete loss of neutron shielding is already assumed to occur as part of the package design approval process.

The gamma shielding for the GA-4 consists of a layer of DU within the stainless-steel package body. The shielding function of this material is not affected by the higher temperatures seen in the MacArthur Maze fire scenario. There is no credible scenario in this fire accident that could result in neutron and gamma dose rates for the GA-4 package exceeding the regulatory limits for accident conditions.

Loss of the package seals due to exceeding seal material thermal limits means that there is the potential for radioactive material to escape from the package. However, it is not physically possible for very much of it to actually escape because the lid closure bolts maintain positive clamping force throughout the transient.

Type B regulations specify a maximum allowable release rate of an A_2 per week for accident conditions. The maximum possible release as estimated for this accident scenario was one-fourth of the A_2 quantity permitted by the regulations. This predicted release estimate is below the prescribed limit and indicates that the potential release from this package in the MacArthur Maze fire scenario would not pose a risk to public health and safety.

Additional information is provided in [50] and [51].

[11] Because of its density, depleted uranium is often used for radiation shielding in medical radiation therapy and industrial radiography equipment, and packages for transporting radioactive materials. Most depleted uranium is produced as a by-product of the production of enriched uranium for use as fuel in nuclear reactors. DU is only about 60% as radioactive as natural uranium.

5.2.4 Newhall Pass Tunnel Fire

5.2.4.1 Description of the Accident

The Newhall Pass Tunnel accident consisted of a chain reaction traffic collision and fire involving 33 commercial tractor-trailer rigs and one passenger vehicle. It occurred on a section of the southbound US Interstate 5 truck route where it passes under the main north-south lanes of US Interstate 5 in California.

A fire started near the tunnel exit and spread rapidly into the tunnel, eventually filling the entire tunnel and destroying the twenty-four tractor-trailer rigs trapped inside. The cargoes of the trucks consisted mainly of foodstuffs, and none were carrying flammable dangerous goods. The severe tunnel-fire is estimated to have lasted more than 2 hours, and possibly as long as 5 hours.

5.2.4.2 Purpose

The purpose of the reconstruction was to determine what effects the Newhall Pass fire would have on a used fuel package transported by truck. The Newhall Pass Tunnel accident was selected because of the long duration of the fire and the wide range of potential fire exposure scenarios, due to the large number of vehicles involved in the accident and fire.

5.2.4.3 Methodology and Assumptions

Since this was a highway accident, the only type of UNF package that could potentially be involved would be a legal weight truck package. The General Atomics GA-4 package was selected for this investigation, mainly because it can carry a relatively large payload for a legal weight truck package, and therefore the potential consequences of package failure could be more severe than for packages with smaller payload capacities. The GA-4 package is designed to transport up to four intact pressurized water reactor used fuel assemblies, with a maximum total package decay heat load of 2.5 kW. Note that this is the same package that was evaluated in the MacArthur Maze highway interchange fire and roadway collapse.

Figure 5-4: Image of the Newhall Pass Tunnel Fire

Based on fire modelling and physical examination of material samples obtained onsite, a bounding fire scenario was defined for this accident. Due to uncertainties in the overall fire timeline and incomplete information on the actual cargo of some of the trucks, five specific fire modelling cases were defined to bound the possible range of fire conditions. Detailed thermal models of the GA-4 package were used to determine the response of the package to the five bounding cases defining the fire scenario.

The peak fire temperatures obtained in the modelling for vehicles at the hottest fire location and longest fire location were used to define the fully engulfing fire conditions for the GA-4 package.

5.2.4.4 Results and Conclusions

The study evaluated the potential for increased neutron and gamma radiation dose rates from the GA-4 as a result of exposure to the Newhall Pass tunnel fire scenario.

The analysis indicates that the regulatory dose rate limits specified for accident conditions would not be exceeded by this package in this fire scenario, even though the package would be expected to lose its neutron shielding. This is because the complete loss of neutron shielding is already assumed to occur as part of the approval process. The package's DU gamma shielding is expected to remain intact and functional even if subjected to the severe conditions of the Newhall Pass Tunnel fire scenario.

The study also concluded that the GA-4 package could experience degradation of some seals in this severe accident scenario. The maximum temperatures predicted in the regions of the lid and the vent and drain ports exceed the rated service temperature of the seals, making it possible for a small release to occur.

The potential release from the Newhall Pass fire scenario was compared to and found to be bounded by that from the more severe MacArthur Maze fire scenario, where the predicted release was approximately one-fourth of the A_2 quantity permitted by the regulations. Since the regulatory limit is specified in Type B regulations as an A_2 quantity per week for accident conditions, the estimated release is below the prescribed limit for safety.

This very conservative estimate indicates that the potential release from this package, were it to be involved in a fire accident as severe as the Newhall Pass Tunnel fire scenario, would not pose a risk to public health and safety.

Additional information is provided in [52] and [53].

6. REAL-WORLD CANADIAN TRANSPORT ACCIDENTS

This section presents a summary of the history and characteristics of severe transportation accidents that have occurred in Canada from 1979 through 2022. The summary was compiled from official accident reports and public media accounts. Four severe accidents were selected for further examination to determine the possible consequences of a used nuclear fuel (UNF) package being involved in each accident. The representative accidents were selected based on their different accident characteristics. The selections include rail accidents involving explosions, impact and severe fires, and a road accident involving a severe fire in a highway overpass.

This section also provides a brief description of the two main features used to ensure the safe shipment of UNF by highway and rail: shipping package design and transport controls.

6.1 History and Characteristics of Canadian Transport Accidents

6.1.1 Survey of Severe Canadian Road and Rail Accidents

An analysis of historical highway and rail accidents (from 1979 to 2022) was performed to identify relevant severe accidents and determine the potential impact those types of accidents could have on the highway and rail transport of UNF. The primary sources used were accident investigation reports compiled by the Transportation Safety Board of Canada, the Commission of Inquiry for the Hinton Train Collision, the evaluation of the Mississauga Evacuation by the Ministry of the Solicitor General, and historical media accounts and publications. A representative list of severe accidents is given in Appendix G. The accidents were chosen based on the presence of significant physical impacts (i.e., collisions and explosions), long-duration fires, release of dangerous goods, fatalities and injuries, and major property damage. It is important to note that none of the accidents listed involved the shipment of UNF, or the transport or release of radioactive material.

6.1.2 Characteristics of Severe Rail Accidents

Most of the severe rail accidents identified in Appendix G involved the derailment of long trains (i.e., in excess of 100 cars) and the subsequent release of non-radioactive dangerous goods (primarily flammable liquids) from tank cars. The releases from the tank cars occurred from damage to top and bottom fittings, thermal tears, and punctures (see Appendix H). A thermal tear occurs when the pressure inside a tank car increases to the point that the tank car hydraulically ruptures (i.e., splits open). This occurs because the liquid inside the tank car expands when heated. If the expansion occurs rapidly enough, the tank car can explode in what is known as a boiling liquid expanding vapor explosion (BLEVE). The release of flammable liquids most often results in long duration fires and less often in explosions. The various scenarios (accident pathways) that occur in an accident involving a tank car breach are shown in Appendix H.

Accidents involving collisions between trains occur either when the trains collide head-on, or when the front of one train collides with the rear of another train. In these cases, most of the direct impact is absorbed by the locomotives or end cars. As noted in Appendix G, there were no examples of severe accidents where two trains collided in a side-by-side impact. For NWMO shipments of UNF, these types of accidents are considered to be extremely rare because many of the rail routes that would be used to transport UNF are single track. Additionally, no tracks that intersect at 90-degree angles were identified, and therefore are not considered in this summary.

6.1.3 Characteristics of Severe Road Accidents

In contrast to severe rail accidents, there were very few highway accidents that had accident investigation reports. This is because such accidents are generally limited in scope, and the causes for the accidents are well understood or readily discerned. However, based on studies done in the U.S. (see Section 5) and as it pertains to the shipment of UNF, the most severe highway accidents involve the shipment of flammable materials. This is because the greatest impact on a UNF shipment would likely result from the effects of a large fire, such as the James Snow Parkway collision (see Table 6-1 in Section 6.1.4 as well as Appendix L). The James Snow Parkway incident involved the collision of a gasoline tank truck with another large truck beneath a highway overpass. The tank truck ruptured and spilt its flammable contents (in this case gasoline). This resulted in a large fire in a “confined” space. Fires in confined spaces may experience much higher temperatures than open pool fires prescribed by Type B package regulations. In addition, the accident consisted of a scenario where a package might suffer a significant impact after the fire (e.g., a highway overpass collapsing onto the package as a result of being exposed to high temperatures). This scenario is similar to the MacArthur Maze fire described in Section 5.2.3. It is likely that this scenario bounds the severity of most highway accidents that could occur.

6.1.4 Selection and Evaluation of Representative Accidents

A set of four severe accidents were chosen from the list in Appendix G that represent the worst categories of severe transportation accidents that have occurred in Canada. These include:

- Rail accidents with explosion (Mississauga Train Derailment)
- Rail collisions with large impacts (Hinton Train Collision)
- Rail accidents with large fires (Lac Mégantic Train Derailment)
- Highway collisions in a confined space (James Snow Highway Collision)

For the rail cases identified above, the accidents were examined using data from rail accident investigation reports, historical media accounts and publications. Important parameters included the placement of railcars after the accident occurred, the nature of hazardous goods involved, the accident timeline and the description of damage and emergency response efforts. An assessment for each accident was then conducted to assess the potential response of a UNF package to the impact force and resulting thermal (fire) environment. For the purpose of these assessments, it was assumed that the DSC-TP would have been used for rail shipments and the UFTP for shipment by highway. As described in Section 3.4, the BTP design is excluded from assessments contained in this report as it is currently under development.

The results of the quantitative assessments are summarized in Table 6-1. The quantitative assessments are presented in Appendix J – Appendix M.

Table 6-1: Summary of quantitative assessments for selected accidents

Accident	Description	Predicted Outcome
Mississauga Train Derailment and Explosion (November 15, 1979) Appendix J	A freight train carrying hazardous materials derailed and caught fire in the middle of the town. The train was carrying a variety of chemicals, including propane, styrene, and chlorine, among others. There were several explosions.	None of the forces (impact, puncture and explosion), or the fire that occurred would be sufficient to either breach the DSC-TP wall or severely damage the DSC-TP's welded closure area.
Hinton Rail Collision (February 8, 1986) Appendix K	A westbound freight train and an eastbound passenger train collided head-on on a single-track section of the Canadian National Railway (CN) mainline. The collision resulted in the deaths of 23 people, including three crew members on the freight train, and 20 passengers on the passenger train. A fire was caused by fuel leaking from locomotives.	Neither the impact or puncture force that occurred would be sufficient to either breach the DSC-TP wall or severely damage the DSC-TP's welded closure area. The collision resulted in a very localized diesel fire that would not have seriously impacted a Type B used fuel package. There were no explosions. No release of radioactive material or increase in external radiation would have occurred under the conditions experienced in the collision.
James Snow Parkway Accident (March 24, 1986) Appendix L	A gasoline tanker truck carrying 51 000 liters of gasoline collided with a flatbed truck under a highway overpass. The tanker exploded and erupted into huge fireball. The resulting fire caused concrete to burn away, exposing the inner steel reinforcing cables of the overpass.	Neither the impact or puncture force that occurred would be sufficient to either breach the UFTP wall or severely damage the UFTP's sealing areas. A small release could be possible for the UFTP if the package seal operating temperature and fuel rupture temperature are exceeded.

Accident	Description	Predicted Outcome
Lac Mégantic Derailment and Explosion (July 6, 2013) Appendix M	A freight train carrying crude oil derailed, causing fires and explosions resulting in the deaths of 47 people and the destruction of much of the town's downtown area.	None of the forces (impact, puncture and explosion), or the fire that occurred would be sufficient to either breach the DSC-TP wall or severely damage the DSC-TP's welded closure area.

6.2 Assuring the Safety of Used Fuel during Severe Accidents

A shared goal of nuclear regulators and shippers is to reduce the overall risk of shipping UNF. This is accomplished by lessening the probability of severe accidents from happening, and by designing packages and transport systems that minimize the consequences of a severe accident should it occur.

6.2.1 Package Design

The primary method used to limit the potential consequences during a severe accident (i.e., release of radioactive material and increased radiation exposure) is the design of the shipping package. In Canada, packages used to ship UNF are certified by the Canadian Nuclear Safety Commission (CNSC) as Type B packages that are designed to withstand conditions that might result during severe transport accidents. These conditions include impacts due to large drops when loading or due to collisions during transport, severe fires, and immersion in water. As a result, Type B safety standards have specific tests that a package must meet to assess a package's ability to prevent package breaches during severe impacts, resist puncture, and preclude loss of containment or radiation shielding during large fires.

The application of Type B standards to package design has resulted in most UNF packages having common design features to address impact, puncture and fire. For example, most UNF packages have:

- Thick container walls to limit radiation exposure, and prevent puncture or breach
- Impact limiting devices, such as impact limiters or fins
- Recessed lids to lessen impact
- Welded or bolted lids
- Ports (package opening used to drain, dry or sample package contents) that are recessed with bolted lid covers
- High temperature seals and tight-fitting sealing areas

In addition, the UNF is shipped in a solid encapsulated form that is largely indispersible.

6.2.2 Transport Controls

The probability of a severe accident involving a UNF package can be reduced by requiring conditions on the way a package is transported. Potential considerations and controls for safe and secure rail and road shipments are described in the following subsections.

6.2.2.1 Transport Controls for Rail

<u>Dedicated Trains</u>

A dedicated train means that no other hazardous goods are shipped in the same train as UNF. This minimizes the threat that explosions and long duration fires could pose to a UNF package. The use of a dedicated train also eliminates the need for a train to pass through rail classification yards – where train cars are added, removed or switched around to accommodate the efficient make-up of larger trains. In addition, the use of a dedicated train often involves fewer stops and can reduce or avoid track switches. Train classification yards are a location where many train accidents occur (although the vast majority of these accidents are minor in nature).

Furthermore, the use of short, dedicated trains can offer several advantages in reducing the probability of severe rail accidents. Most severe train accidents result from derailments caused by wheel, axle and track defects, abrupt braking, and operator error. Statistically, the vast majority of train derailments occur in long trains (i.e., 100 or more cars), with the derailed cars positioned in the center of the train. Many derailments could probably be prevented by enhanced train control and monitoring for wheel and axle defects that are often precursors to a derailment.

The use of short, dedicated trains (e.g., typically ten cars or less[12]) allows a train to be configured with defect monitoring and enhanced brake control:

- Traditional trains are equipped with pneumatic brakes on railcars which act in sequence. The brakes depend on air pressure being transmitted from the front to the back of the train, with each subsequent car breaking after the preceding car.
- In contrast, electronically controlled brakes can more effectively transmit the brake signal to each railcar in the train consist. The electric pathway needed for the electronically controlled brakes also allows the use of real time monitoring for derailment precursors.

The precursors include monitoring for:

- Wheel bearing condition
- Wheel flats

[12] For example, a typical ten car dedicated train might consist of three UNF cars, four interspaced buffer cars, two locomotives, and an escort car.

- Truck hunting
- Location tracking
- Speed

Examples of specifications for electronic braking and remote monitoring are described in the Association of American Railroads (AAR) standard, *Performance Specification for Trains Used to Carry High-Level Radioactive Material* (AAR S-2043) [54]. The AAR S-2043 standard was developed by the rail industry to provide performance guidelines for trains carrying UNF and/or high-level waste (HLW). The AAR S-2043 standard also includes standards for railcars shipping HLW to enhance their crashworthiness. Compliance with the AAR S-2043 standard is not required by Canadian regulations, but it represents recommended practices for the North American rail industry.[13]

Buffer Cars

Buffer cars can be used in both dedicated and non-dedicated trains. For non-dedicated trains, buffer cars can be used to separate cars carrying UNF from locomotives or tank cars carrying other dangerous goods. In a severe accident, this would allow additional spacing between a UNF package and a tank car carrying other dangerous goods, such as flammable liquids.

Buffer cars can also be used in dedicated trains to achieve load distribution, enhancing train operations and handling.

Operating Practices

Other controls could include restrictions on transit speed, track condition, routing, and train makeup.

Transport Canada currently applies transport restrictions of these types to trains carrying one or more loaded tank cars of Class 2.3 (dangerous goods that are toxic by inhalation), and on twenty or more loaded tank cars containing dangerous goods [55]. The restrictions currently do not include rail shipments of UNF. The transport controls are implemented by Transport Canada by defining trains carrying the affected dangerous goods as key trains and requiring that such dangerous goods be transported on key routes.

The railroad industry, through the AAR, has developed recommended railroad operating practices for transporting dangerous goods that extends the concept of key trains and key routes to the rail shipment of UNF and HLW. These practices are described in AAR Circular No. OT-55, *Recommended Railroad Operating Practices for Transportation of Hazardous Materials* [56].

[13] Canada's two national freight railways are full members of the AAR: the Canadian National Railway Company and Canadian Pacific Kansas City.

Train Consist

The concepts described in the discussions on train design and transport controls are depicted in Figure 6-1. While the diagram depicts a train that incorporates most of the design features and operation controls discussed in this section, not all of them may be needed to support a particular shipment or shipping campaign. The transportation package is the prime method for assuring transportation safety and provides a high level of assurance that a UNF package could survive the historical accidents that have occurred in Canada.

6.2.2.2 Transport Controls for Road

The major operating controls for highway UNF shipments are the use of security escorts, approved routing, shipment scheduling, and communications and tracking.

Use of Security Escorts

In order to provide adequate protection during transport, as well as to comply with relevant regulations and guidance, escort personnel or escort vehicles are commonly utilized by consignors of UNF and HLW. Shipments of UNF or HLW would be accompanied by one or more escorts such as nuclear security guards. These escorts should maintain constant surveillance of the shipment.

Planned and Alternative Routing

Canadian regulations stipulate that consignors of certain nuclear materials, including certain types of UNF and HLW, must submit a transportation security plan containing descriptions of the planned route, along with alternate routes to be used in case of an emergency [57]. Use of pre-assessed routes ensures that the consignor has taken into account applicable regulations and ordinances regarding the transport of hazardous materials, the feasibility and logistics of the chosen routes, and any obvious hazards that could affect the transport along the routes. This reduces the likelihood that unexpected conditions or hazards will be encountered when transporting UNF or HLW, and allows for pre-planning and dissemination of route-specific knowledge to the drivers and security escorts, further decreasing the likelihood of an incident or collision taking place along the route.

Shipment Scheduling

In Canada, regulatory guides stipulate that consignors should take into account the scheduling of UNF and HLW shipments to minimize hazards along the route (such as periods of increased traffic), make use of varied transport schedules to avoid malicious acts such as theft or sabotage, and that specifics regarding scheduling are to be treated as prescribed information. This ensures that opportunities for malicious activities are minimized, and that provisions are taken to ensure the physical safety of the UNF or HLW being transported with regards to scheduling.

Communications and Tracking

It is typical for consignors of UNF and HLW to ensure that adequate and secure communications methods are utilized during transport operations. Communication arrangements are to be made between the licensee, the carrier, and the consignee, as well as with any law enforcement agency along the route. It also is expected that consignors notify responsible police agencies along the transportation route that a shipment will be carried out, and that the carrier has the capability for immediate communication to summon appropriate response or assistance. This ensures that rapid and effective actions can be taken in the event of incidents or unexpected conditions on the route.

It is also expected that the consignor establishes a plan of action in the event that communications are lost during shipping, such as back-up communication methods. Use of tracking devices, such as transponders that can be concealed on a vehicle or in the shipment, are particularly useful in situations where communications are interrupted.

6.3 Conclusion

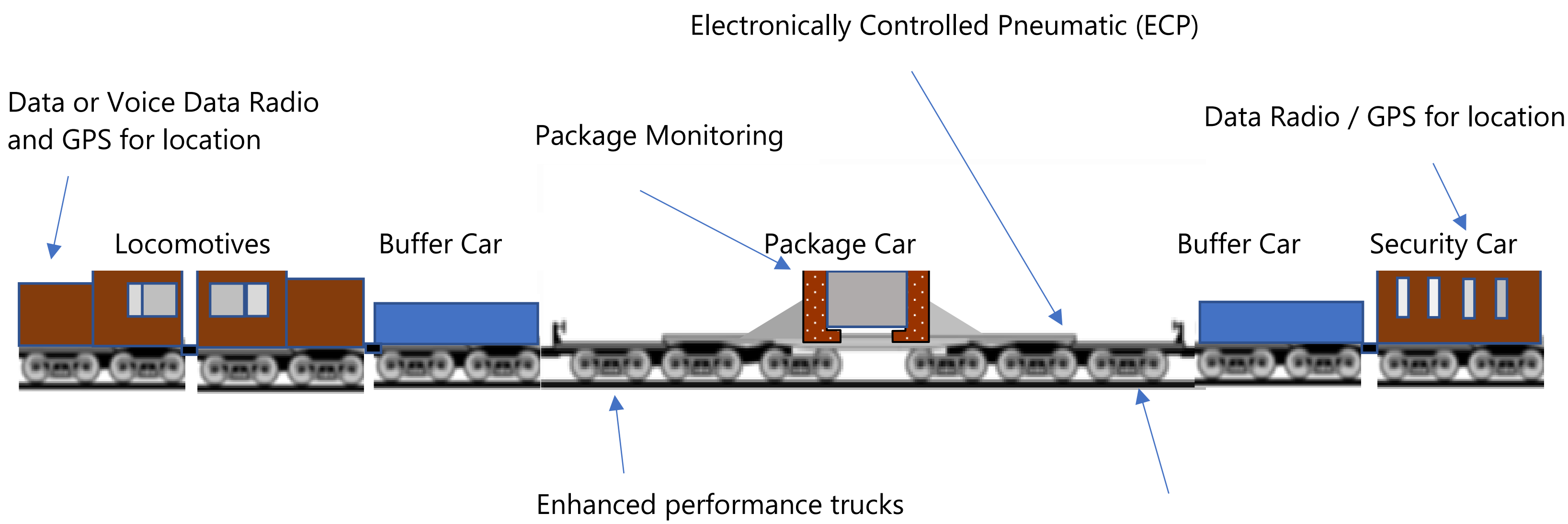
A survey of severe accidents in Canada was conducted. The survey revealed that most of the severe accidents were caused by the derailment of trains carrying flammable dangerous goods. There were also severe accidents involving head-on train collisions, and a highway collision of a gasoline tanker that occurred under a highway overpass that resulted in a severe fire.

The transportation accidents were sorted into four main categories, and the potential impact on a UNF package assessed for each one. The categories are shown below along with the accident used in the assessment:

- Rail accidents with explosion (Mississauga Train Derailment)
- Rail collisions with large impacts (Hinton Train Collision)
- Rail accidents with large fires (Lac Mégantic Train Derailment)
- Highway collisions in a confined space (James Snow Parkway)

The assessments show that UNF packages adequately protect the environment and public health and safety in each case, in that they would limit the release of radioactive material to levels consistent with regulatory requirements, and thus provide assurance that a UNF package could survive the historical accidents that have occurred in Canada.

While the transportation package is the prime method for assuring transportation safety, additional transport controls could be applied to reduce the occurrence or severity of severe accidents. For rail transport, these include the use of dedicated trains, standards for train design, monitoring for accident precursors, and operation restrictions such as speed limits, conditions on track condition and train car placement. For road transport, these include the use of security escorts, approved routing, and shipment scheduling.



Defect detection (all cars) including:

- Truck hunting
- Rocking
- Wheel flats
- Bearing condition
- Braking performance
- Vertical acceleration
- Longitudinal acceleration

Dedicated Train – advantages include:

- Short
- No other Dangerous Goods
- Fewer stops
- Fewer switches
- No classification yards
- Package Monitoring
- ECP Brakes
- On board defect monitoring

Operating Practices and Controls [56]

- Key Train
- Speed Limits
- Enhanced Track Maintenance

Design and Performance [54]

- Performance monitoring
- Crashworthiness
- Applies to all railcars

Figure 6-1: Train design and transport controls that could be applied to the shipment of UNF

7. INTERNATIONAL EXPERIENCE TRANSPORTING USED NUCLEAR FUEL AND HIGH-LEVEL WASTE

7.1 Introduction

This section utilizes publicly available information on the transport of used nuclear fuel (UNF) and high-level waste (HLW) worldwide to estimate total shipments made, the number of shipments made by key countries, and to describe transportation plans for those key countries. The Canadian Nuclear Safety Commission (CNSC) estimates there are over one million radioactive material shipments made each year in Canada [10]. Only a small number of these shipments contain UNF (estimated at 10 or less). For example, used fuel samples from nuclear power plants are shipped to Chalk River Laboratories annually for testing purposes.

The Nuclear Waste Management Organization (NWMO) is currently planning a transportation system to transport used nuclear fuel from interim storage facilities to a deep geological repository (DGR). As NWMO prepares its transportation system, it will take into account Canada's past experiences in shipping used nuclear fuel and incorporate best practices and lessons learned from 60 years of experience of other countries.

The terms *transport* and *shipment* are used in this section to refer to the movement of UNF between sites (such as from an interim storage facility to a geologic repository location). The terms do not refer to movements within the boundaries of a facility or complex of facilities. Most movements of UNF currently occur between the different stages of the used nuclear fuel cycle within a complex of facilities, such as between cooling pools to an on-site interim used fuel storage installation.

For purposes of this report, shipments by air are not considered since the NWMO is not planning to use this mode.

7.2 Historic Shipments of Used Fuel and Key Factors Influencing Used Fuel Transportation Program Composition

7.2.1 Worldwide Transportation Estimates

Radioactive materials have been transported worldwide for more than sixty years. Over that period, a stringent regulatory regime has been developed by the International Atomic Energy Agency (IAEA) and adopted internationally, including within Canada for shipments of radioactive materials. This regulatory regime has produced an impressive safety record in that there has never been a transport incident that has resulted in significant radiological harm to people or the environment.

While there have been efforts by the IAEA to establish databases to track shipments of radioactive materials worldwide, participation by the international community has been mixed, with many government authorities foregoing publishing official shipment numbers citing security concerns [58]. As such, much of the information and shipment estimates made worldwide are based on information sourced from professional organizations, conference presentations, and other government sources.

7.2.1.1 Historic Estimate of UNF and HLW Shipments

The World Nuclear Association estimates that about 15 million packages of radioactive material are transported around the world each year. Since 1961, when the IAEA's safe transport regulations were first issued, it is likely that over one billion nuclear material consignments have been safely completed [59].

In 2016, the U.S. Department of Energy (DOE) published *A Historical Review of the Safe Transport of Spent Nuclear Fuel* which is considered the most extensive effort to describe the worldwide record on the transport of used nuclear fuel [60]. In summary, the report estimated that at least 25 400 shipments of UNF were made worldwide, but that number could potentially be more than 44 400.

A significant finding from the report is that all these shipments were undertaken without any injury or loss of life caused by the radioactive nature of the material transported. In general, there have been few transportation accidents worldwide in the history of transporting UNF and none have had significant radiological consequences [60].

Revised Used Fuel Shipment Estimates

Since 2016, the purpose and volume of UNF shipments has changed dramatically to support changing national and international UNF storage and treatment policies. Several key countries have eliminated or modified their reprocessing facilities causing a growing use of on-site interim storage facilities. France and the UK have stopped accepting UNF from other countries for reprocessing while continuing to reprocess domestic UNF. This has caused other countries (notably Japan) to develop their own reprocessing capacity, thereby eliminating the maritime shipments which had previously taken place between Europe and Japan.

The U.S. terminated its reprocessing program in 1972 and decided in 1982 to develop a permanent geological disposal facility. Commercial UNF is being stored at reactor sites until a disposal facility is licensed and operational. With the exception of defense-related UNF and the international return of highly-enriched research reactor fuel, most UNF shipments in the U.S. occur between different reactor sites owned by the same utility. These shipments are undertaken to make use of available storage space, rather than build new storage facilities.

Germany shut down its last nuclear power reactor in April 2023. The UK stopped reprocessing UNF in 2022. The result is many European countries are increasing their dependence on interim storage at reactor facilities until a DGR is operational in their respective countries. Based on current developments, Finland and Sweden are expected to be the first countries to construct and operate a DGR. This shift towards using interim storage until a permanent DGR is operational has reduced the dependency on transporting UNF and HLW since 2017.

7.2.1.2 *Safe shipment of UNF and HLW*

UNF and HLW shipments are made in many countries and are conducted by power utilities, specialized private transporters, and governmental organizations. The actual transport of the UNF and HLW is often made under contract with a highly experienced transportation company with exemplary safety record. These companies often own the certified packages in which the UNF and HLW is transported.

While each shipment of UNF and HLW is different, adherence to a robust regulatory framework that places an emphasis on shipping package design safety is a common thread across every shipment taking place. This framework also requires shipments to be made in a prescribed manner to enhance safety and security.

In addition to the robustness of the packages and enhanced transportation safety regulations, UNF and vitrified HLW are solid materials which is an important factor. These materials are characterized by their stability, low solubility in water, and their ability to stay in a solid form even after an accident involving severe impact and high temperature fire (see Sections 2, 3, and 4). In Canada, used CANDU fuel is in the form of solid pellets which are contained within zirconium alloy metal tubes or “pencils”. These pencils are welded together into bundles the approximate shape and size of a fireplace log. Zirconium is used throughout the nuclear industry and has a melting point of 1 852°C (3 366°F) [61].

In the case of vitrified HLW from reprocessing, the vitrification process incorporates the radioactive products into molten glass, which is then cooled and stored in steel canisters. As a result, the fission products are immobilized, and the vitrified product is protected by the steel canister.

7.3 Countries with Strong Used Fuel Transportation Programs

UNF transportation programs support a nation’s nuclear energy program and that nation’s preferred processes for treating, storing and disposing of the used nuclear fuel. Some countries have chosen to recycle their UNF (i.e., Japan, France and United Kingdom) – also known as a closed end system. The transportation program must be capable of safely transporting hot used nuclear fuel (i.e., used fuel having both high thermal and radioactive values), reprocessed fuel, by-products of reprocessing (HLW), and eventually the disposal of both the used nuclear fuel and reprocessing by products.

The NWMO transportation program supports a once-through nuclear energy program (or open-end system) with a deep geological repository for disposal. This means the CANDU fuel passes through a reactor once, is cooled in water-filled storage pools, placed into interim dry storage and eventually transported to a permanent DGR.

7.4 Key Country Transportation Plans

This section describes key country transportation programs and their respective plans. The list of key countries was determined based on the description in Section 7.3, and includes:

- Finland (Posiva Oy)
- France (Andra)
- Japan (NUMO)
- Sweden (SKB)
- The United Kingdom (NDA)
- Switzerland (NAGRA)
- The United States (U.S. Department of Energy

A summary for Canada (NWMO) is included for reference purposes. Table 7-1 summarizes the status of each key country's transportation program and plans. The details presented are based on current publicly available information about transportation modes, conveyances, contents being transported, extent/scope of transportation systems and challenges. As stated above, each country's transportation program is dependent on that nation's program for managing, storing, and disposing of their used nuclear fuel. A summary of each nation's program is included for the reader's reference.

Table 7-1: Summary of key country transportation plans and UNF management programs [62]

Country and Implementing Organization	Status of Repository Site Selection Process	Reprocessing	Central Interim Storage Facility	Transportation System in Place to Move UNF/HLW to DGR	Anticipated Start of Repository Operations
Canada Nuclear Waste Management Organization (NWMO)	A consent-based process for selecting a site was initiated in 2010. Sites for consideration have since been narrowed to two regions: Ignace and South Bruce. NWMO is currently engaging with communities and interested parties, including First Nations and Métis communities in the area; the Wabigoon Lake Ojibway Nation-Ignace area in Northwestern Ontario and the Saugeen Ojibway Nation-South Bruce area in Southern Ontario. The site selection process is expected to be completed by 2024.	No	No - UNF and HLW is currently managed by the waste producers on site.	No decision has been made on mode, transport or delivery schedule. Road and rail are being considered, with the all-road option being used as the reference case.	Two regions have been identified for technical study and dialog. Federal impact assessment and licensing processes are expected to begin in 2024. NWMO's five-year strategic plan anticipates construction beginning in 2033, with operations beginning between 2040 and 2045 [63].
Finland Posiva Oy	In 2015, the Finnish government approved construction of the Onkalo DGR near Olkiluoto in the municipality of Eurajoki in western Finland.	No	No - UNF and HLW is currently stored at the reactor sites.	Transportation for the used nuclear fuel from Loviisa to the repository in Olkiluoto is not decided. Options are road, railway and sea. Road and sea are the most likely alternatives. Posiva is considering leasing a purpose-built vessel from	Posiva Oy applied for an operating licence in December 2021. The DGR facility is expected to be operational in 2023. Disposal activities are expected to begin in 2025.

Country and Implementing Organization	Status of Repository Site Selection Process	Reprocessing	Central Interim Storage Facility	Transportation System in Place to Move UNF/HLW to DGR	Anticipated Start of Repository Operations
				Sweden to reduce the number of trips. The transportation package has not been selected [64].	
France National Agency for Radioactive Waste Management (Agence Nationale Pour la Gestion des Déchets Radioactifs [Andra])	France is one of the few countries which currently reprocesses used nuclear fuel (UNF) for potential reuse in light water reactors [65]. The Cigeo DGR is intended for HLW and long-lived intermediate-level waste (LL-ILW) resulting from reprocessing operations, rather than for UNF. The Cigeo DGR site, which is near the village of Bure, was selected in 2006 [66].	Yes - since the start of operations in the mid-1960s, the La Hague plant has processed over 23 000 tonnes of used fuel from France, Japan, Germany, Belgium, Switzerland, Italy, Spain and the Netherlands. It is France’s policy to return foreign HLW back to the country of ownership.	No for UNF - UNF is currently stored at the reactor sites. Vitrified HLW is stored at the La Hague reprocessing plant.	The current policy is that most of the waste packages will be transported by rail to the Cigeo DGR.	Andra submitted its construction licence application for Cigeo in January 2023. Andra plans to begin the pilot phase in the 2025–2027 timeframe.
Japan Nuclear Waste Management Organization of Japan (NUMO)	Kamoenai Village in Hokkaido prefecture and Suttu town in Hokkaido prefecture have responded to solicitation for a literature survey, which is the first stage in the site selection process. NUMO plans to complete the site	Commercial UNF from Japan was historically reprocessed in France and the UK. The reprocessed fuel was returned to Japan for use in a mixed oxide (MOX) reactor. The vitrified HLW from reprocessing was sent	Yes - at the Recyclable-Fuel Storage Center at Mutsu in the Aomori Prefecture for UNF. Currently, HLW is stored temporarily in the Aomori prefecture in northwest Japan at	No decision has been made at this time on the configuration of a transportation system from interim storage to a DGR. Historically, HLW from France and the UK was transported by ship and by	NUMO currently plans to begin repository operations before 2040.

Country and Implementing Organization	Status of Repository Site Selection Process	Reprocessing	Central Interim Storage Facility	Transportation System in Place to Move UNF/HLW to DGR	Anticipated Start of Repository Operations
	selection process before 2030.	back to Japan for storage awaiting disposal [67]. Domestic reprocessing took place at Tokai Reprocessing Plant until 2007. 360 cubic meters of HLW is stored at the plant. Construction of the Rokkasho Reprocessing Plant is expected to be completed in 2024. Currently Japan Nuclear Fuel Limited (JNFL) operates both Low-Level Waste (LLW) and HLW storage facilities at Rokkasho near Higashidori nuclear power plant [68].	the Japan Nuclear Waste Storage Management Center.	road from Tokai port to interim storage sites. Currently, domestically produced used fuel is stored at the reactor or is transported by road to an interim storage site.	
Sweden Swedish Nuclear Fuel and Waste Management Company (Svensk	A site in the municipality of Östhammar was selected in 2009.	No - while some commercial UNF has been reprocessed in France and the UK, no vitrified waste was returned to Sweden.	Yes - a central near surface interim UNF storage facility (Clab) at Oskarshamn nuclear power plant (NPP) was commissioned in 1985.	Waste is planned to be transported to the Östhammar site by a specially designed ship, the M/S Sigrid [69].	The Swedish government approved SKB's proposed repository system in January 2022. The next step is for the Swedish Land & Environment Court to

Country and Implementing Organization	Status of Repository Site Selection Process	Reprocessing	Central Interim Storage Facility	Transportation System in Place to Move UNF/HLW to DGR	Anticipated Start of Repository Operations
Kärnbränslehantering AB [SKB])					establish conditions for the facilities and the Swedish Radiation Safety Authority to define permit conditions. SKB expects to start repository operations sometime in the 2030s.
Switzerland National Cooperative for the Disposal of Radioactive Waste (NAGRA)	In September 2022, NAGRA announced Laegern as the preferred location for a DGR. NAGRA plans to submit a licence application by 2024 and become operational in 2060.	Yes - commercial UNF was reprocessed in France and the UK until a moratorium on reprocessing went into effect in 2006. For UNF that was reprocessed, all the resulting vitrified HLW has been packaged and returned to Switzerland.	Yes - the central storage facility (ZZL) operated by ZWILAG in Würenlingen, near the Beznau Nuclear Power Plant.	No decision has been made at this time. Road and rail transport options are being considered.	NAGRA currently plans to begin repository operations in 2060 with emplacement circa 2075.
United Kingdom National Decommissioning Authority (NDA) Nuclear Waste Services (NWS)	The community of Halethorpe established a working group, the first step in the site selection process. The communities of Allerdale, Mid Copeland, and South Copeland formed community partnerships, the second step in the site selection process. It is expected to take 5 to 20	Reprocessing at Sellafield took place from 1964 to 2022. The government's position is that the decision to reprocess in the future should be left to the commercial judgment of the owners of the UNF.	Yes - at Sellafield, the facility which will be used to store UNF and HLW until the 2070s. UNF is stored in pools at reactor sites. UNF is transported from nuclear power stations to Sellafield reprocessing facility by rail. Each flask weighs	No decision has been made at this time. Road, rail and sea transport options are being considered.	No decision has been made at this time regarding repository operation timelines.

Country and Implementing Organization	Status of Repository Site Selection Process	Reprocessing	Central Interim Storage Facility	Transportation System in Place to Move UNF/HLW to DGR	Anticipated Start of Repository Operations
	years to complete the site selection process.		more than 50 tonnes (110 000 lb), and transports no more than 2.5 tonnes (5 500 lb) of UNF.		
United States U.S. Department of Energy (DOE)	The Yucca Mountain site was characterized and approved for development as a repository by Congress in 2002. In 2010 U.S. DOE filed a motion with the U.S. Nuclear Regulatory Commission (NRC) to withdraw its 2008 licence application. Licensing processing was suspended in 2011. At this time, the U.S. Congress has not funded the project or amended the Nuclear Waste Policy Act to change the site.	The U.S. reprocessed defense-related UNF as part of its weapons plutonium production program. Small amounts of commercial UNF were reprocessed at West Valley, New York. Two commercial reprocessing plants were constructed, but never operated. The U.S. does not currently reprocess commercial UNF.	Two Consolidated Interim Storage Facility licences have been approved by NRC. Neither site is operating at this time.	Transportation modes are dependent on repository location. There is no rail transportation system currently available to the Yucca Mountain site. The U.S. DOE had planned a new rail line within Nevada providing access from Caliente, NV to Yucca Mountain.	No decision has been made at this time regarding repository operation timelines.

7.4.1 Canada (NWMO)

The NWMO's transportation program is in the early phase of planning, data collection, and community relationship building. Major decisions related to the design, transportation modes, available infrastructure, support services, and operation of a UNF transportation system are dependent on the location, timing, and operating requirements of the DGR. As the NWMO advances towards the DGR site selection and regulatory licencing processes, the transportation system design will be refined in turn.

The NWMO has published two transportation planning documents describing the transportation planning process. The *Transportation Planning Framework* [70] sets out objectives, priorities, and considerations for transporting UNF. A second document, the *Preliminary Transportation Plan* [27] provides an overview of the technical approaches, regulatory requirements and planning assumptions on which NWMO will build its system to ensure safe and secure transportation along with protection of people and the environment.

The majority of Canada's used nuclear fuel is stored at reactor sites in specially designed interim storage facilities. The UNF will be moved from these interim storage facilities to a DGR. The transportation program is planned to begin operations in the 2040s, when the DGR is licensed for operation.

7.4.2 Finland (Posiva Oy)

Posiva Oy, Finland's operating authority, is currently in the final stages of licensing a DGR near the Olkiluoto nuclear power plant. The operating licence application for this facility (the Onkalo used nuclear fuel repository) is currently being reviewed by the Radiation and Nuclear Safety Authority (STUK), Finland's regulator.

No final decision has been made on the mode of transport for moving UNF to the Onkalo used nuclear fuel repository. The options being considered for transportation to the DGR are road, rail, and sea. Road and sea are considered likely given rail is inflexible and would require significant capital investment. Annual volumes to be transported will be determined once the repository is licensed. Posiva Oy is considering the option of leasing a purpose-built vessel from Sweden, which would make one or two trips per year as part of its transportation operations. No decision has been made on the transportation package.

7.4.3 France (Andra)

France operates 58 nuclear power reactors producing nearly 72% of France's electricity. France's nuclear fleet is responsible for producing a significant amount of used fuel and radioactive waste. The keystone of France's national used fuel policy is its used nuclear fuel recycling program.

To manage the nearly 1 150 tonnes of used fuel produced each year, France decided early on to close its national nuclear fuel cycle by reprocessing its used fuel. In doing so, the French nuclear industry recovers uranium and plutonium from the used fuel for reuse, thereby reducing the volume of HLW over the life of the program. Through recycling, up to 96% of the reusable material in used fuel can be recovered. About 4% of the HLW is vitrified, then placed in stainless steel canisters and stored at the La Hague site, pending disposal.

Orano is the French company (resulted from a restructuring of Areva) in charge of the nuclear fuel cycle and manages the waste from the country's nuclear power plants. After a few years of cooling in pools at nuclear power plants, used fuel is shipped to the Orano La Hague reprocessing plant in licensed packages by road, rail, or sea. Nuclear material transport and storage services are provided through Orano TN. Since 2017, Orano TN uses the NUTECH HOrizontal MOdular Storage (NUHOMS) System, a dual-purpose storage and transportation canister [71].

Used fuel from other countries is also sent to La Hague plant in Normandy for reprocessing. This plant has the capacity to reprocess up to 1 700 tonnes per year of used fuel in its UP2 and UP3 facilities. Since the launch of La Hague in 1976, it has treated nearly 40 000 tonnes of radioactive material as of February 2023 [72]. The treatment extracts 99.9% of the plutonium and uranium for recycling, leaving 3% of the used fuel material as HLW which is vitrified and stored there for later disposal.

Andra, a state-owned undertaking, has the mission of sustainable management of radioactive materials and the creation of Cigeo. On January 16th, 2023, Andra submitted the construction licence application for Cigeo, the French the DGR facility for the most highly radioactive waste. This is a crucial step marking both a culmination and a new start for the project [66]. Cigeo is to be built near the Village of Bure in the Paris Basin of France. The chosen mode of transport for the Cigeo project is rail, with a connection from the site to the national rail network. Vitrified waste (HLW) transportation packages are in the process of being designed and certified.

7.4.4 Japan (NUMO)

Implementation of Japan's UNF disposal program is the responsibility of the Nuclear Waste Management Organization of Japan (NUMO). Japan has been reprocessing its used fuel for over 50 years, which historically included shipping the UNF to British Nuclear Fuels Ltd (UK) and COGEMA (France) facilities for reprocessing. The reprocessed nuclear fuel and vitrified wastes were shipped back to Japan for reuse and interim storage.

Between 1969 and 1990, more than 160 shipments of UNF were made between Japan and Europe, traveling over 8 million kilometers. Recovered fissile materials were returned to Japan as MOX fuel. The first shipment to Japan of vitrified HLW from reprocessing took place in 1995 and the

12th and last shipment from France in 2007. Over the 12 years, a total 1 310 canisters containing almost 700 tonnes of vitrified HLW were returned to Japan [67].[14] [15]

The European shipments were off-loaded at the port and transported by specialized road vehicles to JNFL's Rokkasho facility. This facility services four functions: reprocessing of UNF, vitrification and storage of HLW, uranium enrichment, and low-level waste disposal (see Table 7-2). Used fuel has been accumulating at Rokkasho since 1999 in anticipation of its full-scale reprocessing operation starting (shipments to Europe finished in 1998).[16]

Japan's nuclear fuel cycle plan is dependent on reprocessing its UNF at the Rokkasho Nuclear Fuel Reprocessing Facility, which is planned to have an annual capacity of 800 tons of uranium and 8 tons of plutonium. At the end of 2012, Japan had a total of 14 460 tonnes of used fuel in storage, much of it at reactors using dry storage with convection cooling. In March 2017, JNFL had 2 968 tonnes of used fuel in storage at Rokkasho, which has a total capacity of 3 000 tonnes.

Table 7-2: Facilities at Rokkasho Aomori Japan [73]

	Reprocessing	Vitrified Waste Storage Capacity	Uranium Enrichment Plant	LLW Disposal Facility
Capacity	Main plant capacity: 800 ton U/y Used Nuclear Fuel Storage Pool: 3 000 ton U	Waste returned from overseas: 1 440 canisters Future capacity from reprocessing: 3 000+ ton	Current capacity: 1 050 tons Separative Work Unit (SWU)/y Total capacity: 1 500 SWU/y	Authorized capacity: 200 000 m^3 Total capacity: 600 000 m^3
Schedule	Constructed 1993 Operational ~ 2024[17]	Constructed 1992 Operational 1995	Constructed 1988 Operational 1992	Constructed 1990 Operational 1992

Tokai had been the main site for Japan Atomic Energy Agency's HLW treatment and disposal until Japan's Nuclear Regulation Authority (NRA) approved the decommissioning of the Tokai reprocessing plant in 2018. Decommissioning will require 70 years to complete. An immediate priority is to reduce the risk from radioactive waste held at the plant. Accordingly, the intention is to complete the vitrification of all the HLW by 2028. To accommodate the vitrification process, the storage capacity at Tokai was increased from 420 HLW packages to 630. Eventually, the HLW packages will be moved to a final disposal facility which is to be constructed by NUMO.

[14] The double hulled ships used to transport the UNF were built in the 1980s and continue to meet the highest safety rating of the International Maritime Organization (IMO), a United Nations regulatory agency. The ships' safety record is second to none, without a single incident resulting in the release of radioactivity.

[15] There is a discrepancy between the numbers reported by the World Nuclear Association and the Federation of Eclectic Power Companies of Japan table.

[16] Since 2011, following the Fukushima Daiichi tsunami accident, the Nuclear Regulation Authority (NRA) has been applying lessons learned to all of Japan's nuclear facilities. This has caused delays in the construction and licensing for operation of several key facilities, including the reprocessing facility at Rokkasho and the interim used fuel storage facility in Mutsu, Aomori prefecture.

[17] In January 2023, JNFL announced that it expects the reprocessing plant under construction at Rokkasho in Japan's Aomori Prefecture to begin commercial operation in 2024.

The Japan Atomic Energy Agency (JAEA) also operates used fuel storage facilities at Tokai, containing an estimated 110 tonnes of UNF in 2014. In May 2016, a new entity was created responsible for reprocessing, the Spent Fuel Reprocessing Organisation (SFRO), which will collect funds from the utilities and contract out reprocessing and MOX fuel fabrication to JNFL.

Nuclear Fuel Transport Co, Ltd. (NFT) is the only company that transports used nuclear fuel in Japan and boasts of a flawless safety record with no accidents since its formation. NFT graphically illustrates in Figure 7-1 and Figure 7-2 the transportation of UNF and HLW in Japan. NFT owns and maintains the road transports, ships, and packages used to transport used fuel and high-level vitrified waste in support of Tokai and Rokkasho facilities.

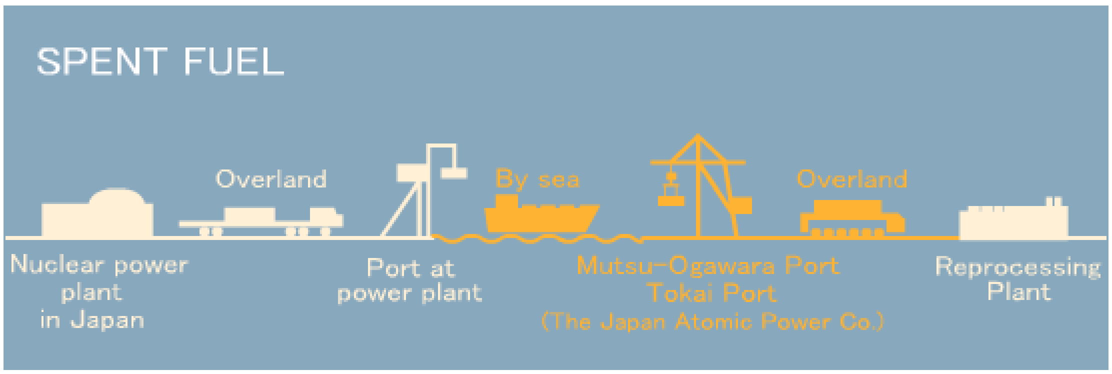


Figure 7-1: Transportation of UNF in Japan

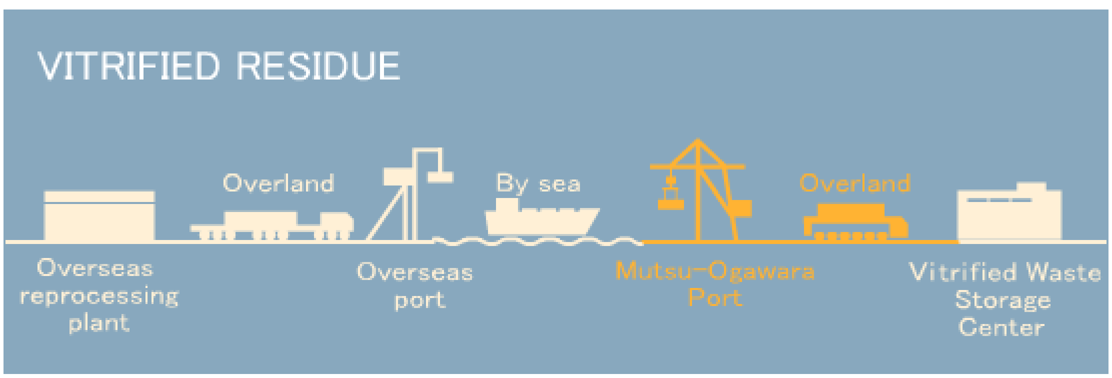


Figure 7-2: Transportation of HLW in Japan

7.4.5 Sweden (SKB)

Nuclear power companies in Sweden jointly established the Swedish Nuclear Fuel and Waste Management Company (Svensk Kärnbränslehantering AB (SKB)) in the 1970s. SKB's assignment is to manage and dispose of all radioactive waste from Swedish nuclear power plants in such a way as to secure maximum safety for human beings and the environment. Twelve nuclear power reactors have been built in Sweden and ten of them are still in operation.

The keystones to SKB's management system are:

Operating facilities

- A marine based transport system which has been in operation since 1983.
- The transportation system includes the Sigrid, 10 transport packages for used fuel, 2 packages for used core components and 5 terminal vehicles for transport at the ports.
- A central interim storage facility for used nuclear fuel (Clab) facility operating since 1985.
- A final repository for short-lived, low and intermediate level waste, SFR, in operation since 1988.
- An encapsulation plant for used nuclear fuel, in testing phase.

Planned or in-construction facilities

- A deep disposal facility (DDF) for encapsulated used fuel and other long-lived radioactive wastes.

All the nuclear power plants and the Clab facility have their own ports, therefore SKB's transportation system is marine-based. This allows for a higher load capacity per trip and low interference with road and rail traffic.

The Sigrid, a new INF-3 special purpose ship, transports used nuclear fuel and nuclear waste from Sweden's nuclear power plants to Clab at Oskarshamn and the waste facilities at Studsvik and Forsmark. It has been designed to the most restrictive IMO rules concerning floatability after damage, similar to those for ships carrying chemicals in bulk. The ice breaking capability of the ship increases the availability in winter conditions.

In Sweden, more than 80 large UNF transport packages are moved annually from nuclear power plants to Clab, located at Simpevarp, about 25 kilometers north of Oskarshamn. Initially, the used fuel is stored at the nuclear power plant, but after about a year it is moved to Clab where it is stored in underground pools. Today there are approximately 77 750 tonnes of used nuclear fuel in interim storage in the Clab facility outside Oskarshamn. Clab has been operating since 1985 [74].

When a repository is licensed, the UNF and HLW will be moved to the repository which is to be constructed in Forsmark in the Östhammar Municipality for final disposal. Transportation of the encapsulated UNF from Clab to the repository at Forsmark is to be by marine transport using the Sigrid. This transportation system is illustrated in Figure 7-3.

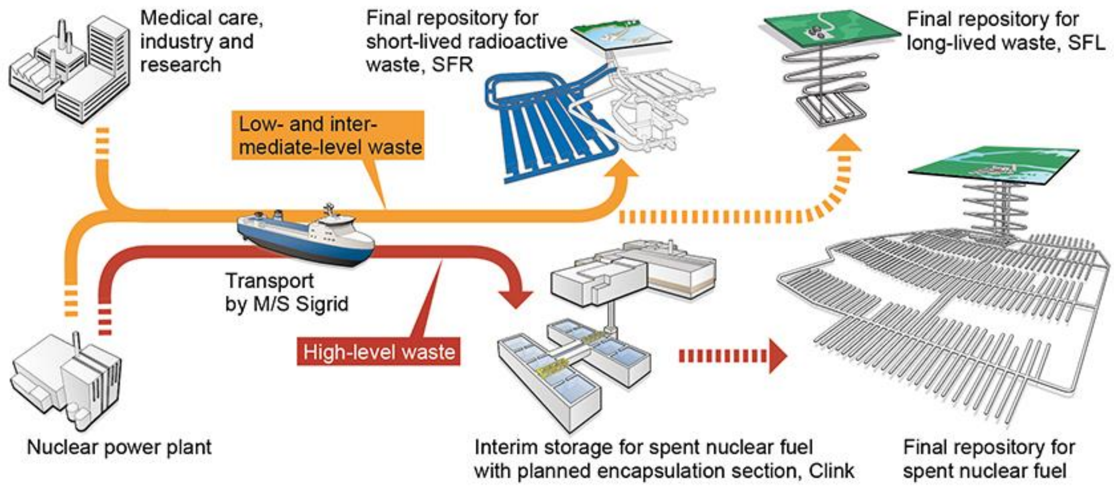


Figure 7-3: Radioactive waste management and transportation system in Sweden [74]

7.4.6 Switzerland (NAGRA)

The Swiss Federal Nuclear Energy Act stipulates that radioactive waste must be disposed of in Switzerland in a DGR. In 1972, a national co-operative for disposal of radioactive waste (NAGRA) was set up, involving power plant operators and the federal government. Currently, both wet and dry interim storage sites are used in Switzerland.

Used fuel and HLW are stored at the Zwilag interim storage facility located in Würenlingen in Canton Aargau. The facility provides storage capacity for transport and storage packages containing used fuel assemblies and other high-level waste. The ZWIBEZ interim storage facility, where used fuel assemblies and low-level waste are also held, is located on the site of the Beznau nuclear power plant. The Gösgen nuclear power plant houses a wet storage facility for used fuel assemblies [75].

The CASTOR package is used to move used fuel and HLW to interim storage. The CASTOR package is a storage and transport package for radioactive materials and is a trademarked package. The packages are about six metres high, are cylindrical shaped, weigh about 130 tonnes and are made of steel.

Once the containers arrive at the interim storage facility in Würenlingen, they are tested for leak tightness before being moved to the storage hall of the facility, which currently holds 34 containers (equivalent to 17% of the maximum storage capacity).

In 2022, NAGRA announced its siting proposal for the construction of a DGR. NAGRA's plan is to submit an application for a general construction licence in 2024. No decision has been made related to the transport of used fuel from the reactor sites to the repository. Road and rail options are being considered.

7.4.7 United Kingdom (National Decommissioning Authority)

The National Decommissioning Authority (NDA) is tasked with decommissioning the UK's 17 nuclear sites and the siting and operation of the nation's disposal facilities. They are the owners of one of the largest nuclear decommissioning and remediation programs in Europe and play an important role in supporting government's aspiration for the UK to be a global leader in the civil nuclear sector [76].

In 2021, NDA launched Nuclear Transport Solutions (NTS) which consolidated the UK's two nuclear transportation companies, Direct Rail Services (DRS) and International Nuclear Services (INS). NTS will inherit one of the world's most experienced nuclear shipping companies, having delivered over 180 shipments of UNF, MOX Fuel, and HLW over a 40-year history. DRS operates a fleet of more than 100 locomotives and since 1995 has transported nuclear material over 5 million miles by rail in the UK. INS operates three specialist nuclear transport ships. So far it has shipped over 2 000 nuclear packages some 5 million miles to countries including: Belgium, Finland, France, Germany, Greece, Italy, Japan, the Netherlands, Portugal, Sweden, Switzerland and the USA.

Radioactive Waste Management Limited (RWM) is an NDA subsidiary responsible for providing a range of waste management services including delivering a geological disposal facility in Britain. This includes finding a suitable site with a willing community to host this permanent and safe solution for managing radioactive waste.

NDA has several varieties of used nuclear fuel to manage until they can be placed in a geological disposal facility, circa 2075. As of April 2022, the UK had six operating nuclear power stations. The stations comprise ten Advanced Gas-cooled Reactors (AGRs) and a single Pressurised Water Reactor (PWR) - generating about 10% of the UK's electricity supply. Eleven Magnox nuclear power stations and three Advanced Gas-cooled Reactor (AGR) stations have stopped producing electricity; they are now being decommissioned.

The long-term management policy of the UK Government is geological disposal in a Geological Disposal Facility (GDF). There is no GDF yet operating but the UK Government launched a site selection process in 2020 to find a volunteer host community with suitable geology.

The NDA's policy is waste from reprocessing overseas used fuel is to be returned to the country of origin as soon as practicable after vitrification. About 1 780 canisters of vitrified HLW and smaller quantities of other wastes are to be exported. All reprocessing contracts with overseas customers signed since 1976 include a provision to return packaged wastes or their equivalent back to the country of origin. NDA plans to complete the returns by around 2025.

7.4.8 United States (Department of Energy)

Responsibility for transporting UNF and HLW in the U.S. is divided between three U.S. DOE offices and the private nuclear power utilities. The U.S. DOE Office of Environmental Management (EM) is responsible for addressing WWII and Cold War environmental legacy materials resulting from decades of nuclear weapons production, foreign research reactor UNF return, and government sponsored nuclear energy research. This includes the transportation of UNF and HLW within and between DOE laboratories, and to waste management sites. EM transports UNF and radioactive waste using dedicated trains, road, leased barges, and ships.[18]

The second U.S. DOE office is a partnership between the Naval Nuclear Propulsion Program and U.S. DOE National Nuclear Security Administration (NNSA) [77]. These agencies supply the nuclear power plants used by the U.S. Navy, including the disposal of the UNF and reactor cores. This program primarily transports by rail using dedicated high-security trains.

The Office of Civilian Radioactive Waste Management (OCRWM) is the third U.S. DOE office and was established by the Nuclear Waste Policy Act of 1982. OCRWM is responsible for the construction and operation of a national DGR, and for the transport of civilian and U.S. DOE UNF and HLW to that national repository. In 2010, the U.S. DOE Office of Civilian Radioactive Waste Management, was defunded by Congress and the responsibility for directing and implementing the U.S. DOE's Nuclear Waste Policy Act activities related to Yucca Mountain were assumed by the U.S. DOE Office of Nuclear Energy.

Most of the UNF that would be shipped to a DGR is commercial UNF currently stored at 81 nuclear power plants in 34 states.[19] Almost all the UNF is currently stored in canisters that are housed in concrete overpacks. The current plan is to ship the canistered UNF in large Type B transportation packages that could weigh up to 100 -125 tons by rail for the cross-country movement. Some reactor sites lack rail access; therefore the U.S. DOE is planning to use barges and specialized heavy-haul trucks to transport the UNF to intermodal transfer sites where the transportation packages can be transferred onto special purpose rail cars [78].

The commercial UNF owners are considering the use of centralized interim storage facilities until the national repository becomes operational. Two privately owned storage facilities are currently

[18] The U.S. DOE Waste Isolation Pilot Plant (WIPP) transportation program is operated by US DOE Office of Environmental Management. WIPP is often referenced as a model program for future UNF and HLW shipments. Even though the waste being transported is TRU waste (plutonium or alpha radiation, see Appendix A), the program uses enhanced packaging and transportation requirements similar to those used for UNF packages. As of May 27, 2023, WIPP has completed 13 473 shipments safely and securely and traveled over 25 000 000 km. The Western States Technical Advisory Committee and U.S. DOE prepared and agreed to use the Western Governors' Association (WGA) WIPP Transportation Safety Program Implementation Guide (WIPP PIG) as the basis for transporting TRU waste to WIPP. The WIPP PIG has been accepted by all the other regions and has been used for other radioactive waste shipments including Cs-137 and Foreign Research Reactor Spent Fuel return programs, since 1998.

[19] Commercial UNF comprises approximately 6 300 MTHM of the anticipated maximum repository inventory of 7 000 MTHM. U.S. DOE UNF comprises approximately 2 268 MTHM, naval UNF comprises approximately 65 MTHM (for a total U.S. DOE allotment of 2 333 MTHM), and HLW comprises the balance of approximately 4 667 MTHM.

licensed by the NRC [79], [80].[20] The storage facilities are designed to store UNF that has been loaded into canisters and is currently stored at reactor sites. Due to the size and weight of these transportation packages, rail is the most likely mode for the cross-country movement to an interim storage facility [81]. For this case, the owners of the UNF would be responsible for the transportation to the private interim storage facilities. As with the U.S. DOE program, heavy-haul truck and barge may be required to move the UNF to an intermodal transfer facility to be loaded on to specialized rail cars [82].

[20] Interim Storage Partners LLC's Consolidated Interim Storage Facility in Andrews County, Texas, and Holtec International's (Holtec) Consolidated Interim Storage Facility (CISF) in Lea County, New Mexico.

8. FREQUENTLY ASKED QUESTIONS/COMMENTS

8.1 Will the package open during a transportation accident?

Type B packages, such as those utilized to transport used fuel, are required to meet strict regulatory standards that demonstrate a package's ability to withstand severe transportation accidents without a significant release of radioactive material. To meet the release criteria in the regulations, used fuel packages incorporate various design features that limit damage to the package body and lid. These design features include impact limiters to protect the lid and seal system during accident conditions, thick package walls and tightly secured lids that are either welded or bolted shut.

Bolted lids on used fuel packages are typically secured with a large number of highly torqued bolts that are closely spaced. The large number of bolts assures that the lid will remain in place even in the unlikely event that a few bolts are damaged. The highly torqued bolts compress the package seals and hold the lid tight to the package body. Bolted lids use double O-ring seals. Bolts and seals are inspected prior to each shipment. Seals are required to be changed periodically, and whenever damage is found during package loading. In addition, the package is leak tested prior each shipment. Some package designs, such as the DSC-TP, use welding as the closure system and the welds are tested to ensure the package is safely closed.

Section 3.4 describes the design of the bolts and seals on the UFTP and DSC-TP packages. Section 4 describes the tests that are used to demonstrate the effectiveness of the package safety standards and regulations.

In 2016, the U.S. Department of Energy (DOE) published *A Historical Review of the Safe Transport of Spent Nuclear Fuel* which is considered the most extensive effort to describe the worldwide record on the transport of used nuclear fuel [60]. In summary, the report estimated that at least 25 400 shipments of UNF were made worldwide, and that number could potentially be more than 44 400.

8.2 Will the package puncture during a transportation accident?

The three transport packages which NWMO is considering in their transportation program are the UFTP, DSC-TP and BTP. While the latter is still in development; the UFTP and DSC-TP have been designed and certified with a wall thickness of approximately 27 cm (stainless steel) for the UFTP and over 50 cm for the DSC-TP (carbon steel shell encased in high density concrete). Due to these thick walls and lids, these used fuel packages are unlikely to be punctured during severe accidents. As shown in Section 3.2.1.3, punctures have not been observed in severe historical puncture-type rail accidents for rail tank cars with wall thicknesses of at least one (1) inch. It is therefore highly unlikely that a used fuel package design being considered by the NWMO would be punctured during a severe transportation accident.

8.3 How many deaths have occurred as a consequence of accidents during the transportation of used nuclear fuel?

Used fuel has been shipped worldwide for over 60 years. During that time, there have been no deaths or serious injuries resulting from the release of radioactive material from used fuel packages during a transportation accident. Recent data from the U.S. Department of Transportation [83] shows that there were only 47 reported incidents for the approximately 30 million shipments of all types of radioactive material made between 2013 and 2022. None of these accidents resulted in a fatality or serious injury. Most of the 47 incidents involved small packages shipped by air or highway. In contrast, there were 63 reported fatalities during the same period involving other dangerous goods, mostly involving the shipment of gasoline by tanker truck.

The excellent safety record is due in large part to robust requirements for shipping radioactive material. Most of the incidents and fatalities that occurred in the shipment of dangerous goods resulted from breached containers carrying flammable, explosive, or toxic liquids or gases. In contrast, used fuel is an encapsulated solid, which is not readily dispersed, is not explosive or flammable and is shipped in packages designed and tested to withstand severe accidents.

The U.S. DOE's *A Historical Review of the Safe Transport of Spent Nuclear Fuel* [60] estimates that between 25 400 and 44 400 shipments of UNF have been made worldwide, and that all of these shipments were undertaken without any injury or loss of life caused by the radioactive nature of the material transported.

8.4 Will people along the transportation routes for used nuclear fuel be unknowingly exposed to high levels of radiation?

The regulatory requirement for radiation exposure from all radioactive material transport packages, including used fuel packages, is based on limiting the exposure of an individual to dose levels that would not impact their health or safety.

8.5 Are package certification tests adequate when conducted with scale models or simulations?

To demonstrate that a package design meets the regulatory requirements, the International Atomic Energy Agency (IAEA) regulations allow physical testing, and analytical calculations, or a combination thereof. Physical testing can include full-scale tests, scale model tests, or mock-ups of specific parts of a package. The intent is to allow an applicant to use accepted engineering practices to evaluate a package design. Regardless of the method used, documentation should be sufficiently accurate and complete to allow an approving authority (i.e., the Canadian Nuclear Safety Commission in Canada) to determine that all safety requirements have been met and all modes of failure considered. In practice, a package design for used fuel typically uses a combination of computer modelling, scale model testing and full-scale mock-ups of package components.

Scale model testing provides a number of benefits, such as allowing for evaluation from many drop angles to determine the orientation that results in the package suffering the maximum damage. The impact forces on the scale models can then be benchmarked or verified against computer simulations, as well as scaled up to predict the forces on a full-sized package. Scale model testing is a well understood and often practiced testing method. The regulations provide guidance on how to accurately perform scale testing. There is a robust body of knowledge and experience in industry with respect to scale model testing.

Other analytical tools (i.e., computer modelling) are also well suited to other aspects of package certification, such as assessing a package's response to the fire test. Thermal response can be accurately predicted by computer modelling because the thermal properties of materials used to fabricate used fuel packages are well documented and the dynamics of fires is well known. Computer modeling and analysis software are subjected to rigorous validation and verification testing before being used to simulate transportation package testing. For example, ANSYS, a popular analysis tool, meets the requirements of ASME NQA-1, a quality standard endorsed by the United States Nuclear Regulatory Commission. Computer modeling methodology and results must also be documented in detail as part of a transportation package's safety analysis report for review and approval by the relevant nuclear regulator.

The use of full-scale testing, while useful for validating computer models and analytical calculations, features its own disadvantages. There are very few test venues that can accommodate the full-scale testing of a large used fuel package. The costs of using full-scale packages to determine the most damaging orientation of tests are prohibitive and may require highly specialized facilities and testing equipment. In addition, full-scale testing may not always lead to the most robust design. The acceptance criteria for full-scale testing are pass-fail. On the other hand, when designs are based on computer modelling, safety margins or more stringent acceptance criteria are often applied. Design by computer modelling is an accepted engineering practice used in various other industries such as the aerospace and automobile industries.

The use of a particular method or combination of methods is left to the discretion of the approving authority who must make the ultimate decision that a used package design meets the safety regulations.

Additional information is provided in Section 3.3 and Appendix A.

8.6 Given Canada's limited experience in transporting used nuclear fuel when compared to other countries, how can you be sure it will be done safely?

The ability to ship used fuel safety in a country is not always closely correlated to the number of shipments that have historically been made in the country.

Used fuel has been transported worldwide for more than 60 years. Over that period of time, a stringent regulatory regime has been developed by the IAEA and applied internationally as well as to Canadian shipments of UNF. This has resulted in a specialized world-wide industry that has focused on the design and fabrication of transport packaging, as well as transportation logistics and safety. It has become a routine practice for countries and shippers to share processes and experiences. In addition, many facilities making UNF shipments rely on the use of international specialized service providers who routinely ship UNF. Canadian entities (including NWMO) work closely with each other as well as with these international service providers to ensure that expertise and best practices are applied to Canadian UNF and HLW shipments. Examples include NAC International (U.S.), HOLTEC (U.S.), Nuclear Transport Solutions (U.K.), Orano (France), Edlow International (U.S.), Hittman Transport Services (U.S.), GNS (Germany), and Nuclear Fuel Transport Co., Ltd. (Japan).

8.7 Do tests ensure that the package can perform in extreme cold conditions (e.g., -50˚C)?

Used fuel packages are tested to ensure they can perform safely in extremely cold conditions. The IAEA requires package designs to be evaluated for temperatures ranging from -40°C to +38°C, which represent the typical range of temperatures experienced during transport in most geographical regions. Approving authorities have the ability to require package designs to be evaluated for temperatures lower than -40°C and/or to require additional conditions during transport, such as limits on time of shipment.

8.8 What happens if the package rolls off a cliff, falls off a bridge, or rolls down a rock face?

The particular damage that a used fuel package experiences during an impact is determined largely by the drop height (kinetic energy), orientation, and relative “stiffness” of the package versus the impacted surface. The stiffness refers to an object’s ability to absorb force without deforming (i.e., fracturing or bending).

Compliance with the IAEA drop test (a 9 m drop test onto an unyielding surface) results in a used fuel package that is stiffer than almost any object that it would impact (including cement, rock, transport vehicles, etc.). This implies that most of the damage, should a package roll off a cliff, fall off a bridge, or roll down a rock face, would occur to the objects being impacted rather than the package itself.

It is also unlikely that a package would encounter an object that is stiffer than the unyielding surface - a surface engineered with infinite stiffness – used in the package drop testing. The unyielding target redirects all kinetic energy back into the package rather than the ground, resulting in a test that is more severe than even extreme accidents (such as a direct collision with a train). Section 3.2.1.2 provides further explanation of how the regulatory drop test bounds the impacts in severe accidents.

9. REFERENCES

[1] Ministry of Transportation and Ministry of Community Safety and Correctional Services, "Transportation of Radiaoctive Materials in Ontario - Information Package," [Online]. Available: http://ccnr.org/TRM_Transport_Ontario.pdf.

[2] Nuclear Waste Management Organization (NWMO), "Deep Geological Repository," [Online]. Available: https://www.nwmo.ca/en/A-Safe-Approach/Facilities/Deep-Geological-Repository.

[3] Canadian Nuclear Safety Commission (CNSC), "High-level radioactive waste," [Online]. Available: http://nuclearsafety.gc.ca/eng/waste/high-level-waste/index.cfm.

[4] International Atomic Energy Agency (IAEA), "About us," [Online]. Available: https://www.iaea.org/about.

[5] Government of Canada, "Packaging and Transport of Nuclear Substances Regulations," SOR/2015-145, 2015.

[6] International Atomic Energy Agency (IAEA), "Regulations for the Safe Transport of Radioactive Material," No. SSR-6 (Rev. 1), 2018.

[7] Canadian Nuclear Safety Commission (CNSC), "Types and sources of radiation," [Online]. Available: http://nuclearsafety.gc.ca/eng/resources/radiation/introduction-to-radiation/types-and-sources-of-radiation.cfm.

[8] Canadian Nuclear Safety Commission (CNSC), "Glossary of CNSC Terminology," REGDOC-3.6, 2023.

[9] United Nations, "Recommendations on the Transport of Dangerous Goods, Model Regulations," ST/SG/AC.10/Rev. 22., 2 vols, UN, New York and Geneva, Available at https://unece.org/transport/dangerous-goods/un-model-regulations-rev-22, 2021.

[10] Canadian Nuclear Association (CNA), "Backgrounder: Transportation of Nuclear Substances in Canada," https://cna.ca/wp-content/uploads/2014/12/Transportation-Backgrounder-English.pdf, 2015.

[11] Government of Canada, "Transportation of Dangerous Goods Regulations," SOR/2001-286, 2022.

[12] World Nuclear Transport Institute, "Package Types used for Transporting Radioactive Materials - Fact Sheet," London, 2021.

[13] Radiation Emergency Medical Management (REMM), "Understanding Shipping Labels and Placards for Radioactive Materials," [Online]. Available: https://remm.hhs.gov/transportation_hazard_id.htm.

[14] Container Products Corporation, "B-25 Waste Containers," [Online]. Available: https://c-p-c.net/products/containers/b-25-waste-container/.

[15] Energy Solutions, "Cask 14-170," [Online]. Available: https://www.energysolutions.com/waste-transportation/cask/.

[16] Nuclear Waste Management Organization (NWMO), "NWMO Transportation Technical Work Program," https://www.huronkinloss.com/en/townhall/resources/Documents/NWMOs-Technical-Transportation-Program.pdf, 2016.

[17] S. Komarov, A. Ivshkin, D. Derganov, O. Savina, A. Chernyshov, V. Shapovalov, A. Morenko, O. Alekseyev, L. Barabenkova, O. Amelicheva and S. Moses, "Description of Type C TUK-145/C Package Design - Certification in Russia," *Proceedings of the 17th International Symposium on the Packaging and Transportation of Radioactive Materials (PATRAM 2013),* 2013.

[18] American National Standards Institute (ANSI), "Radioactive Materials - Leakage Tests on Packages for Shipment," ANSI N14.5, 2014.

[19] Transport Canada, "Emergency Response Guidebook: A Guidebook for First Responders," https://tc.canada.ca/sites/default/files/2020-08/PDF%20English.pdf, 2020.

[20] Nuclear Waste Management Organization (NWMO), "Safe and Secure Transportation of Canada’s Used Nuclear Fuel," 2015.

[21] Nuclear Waste Management Organization (NWMO), "Why the Nine Metre Drop Test Bounds the Impacts from Most Severe Accidents," TR-2014-04, 2014.

[22] Proceedings of a Seminar held at the Institute of Mechanical Engineers, "The Resistance to Impact of Spent Magnox Fuel Tranaport Flasks - “Paper No. 14, Analysis of Primary Impact Forces in the Train Crask Collision”,page 163," London, 1985.

[23] Nuclear Regulatory Commission (NRC), "Reexamination of Spent Fuel Shipment Risk Estimates, Volume I: Main Report," NUREG/CR-6672, 2000.

[24] International Atomic Energy Agency (IAEA), "Advisory Material for the IAEA Regulations for the Safe Transport of Radioactive Material (2018 Edition)," No. SSG-26 (Rev. 1), 2022.

[25] D. Tsumune, T. Saegusa, H. Suzuki, N. Watabe, H. Asano, K. Maruyama and Y. Kinehara, "Dose Assessment for the Public due to Packages Shipping Radioactive Materials Hypothetically Sunk on a Continental Shelf," *International Journal of Radioactive Materials Transport,* pp. 11:4, 317-328, 2000.

[26] Pacific Northwest National Laboratories (PNNL), "Consequences of Postulated Losses of LWR Spent Fuel and Plutonium Shipping Packages at Sea," PNNL-2093 / UC-71, 1977.

[27] Nuclear Waste Management Organization (NWMO), "Preliminary transportation plan," 2021.

[28] H. Yoshimura, L. Shappert, R. Pope and M. Kubo, "Early structural testing of type B radioactive material packages in USA to environments beyond regulatory package structural test standards," J. Packag. Transp. Stor. Secur. Radioact.Mater., 2007a, 18, (3), 143–158.

[29] Sandia National Laboratories, "Analysis, Scale Modeling, and Full-Scale Tests of a Truck Spent-Nuclear-Fuel Shipping System in High Velocity Impacts against a Rigid Barrier," SAND77-0270, April 1978.

[30] Sandia National Laboratories, "Study and Full-Scale Test of a High-Velocity Grade-Crossing Simulated Accident of a Locomotive and a Nuclear-Spent-Fuel Shipping Cask," SAND79-2291, February 1983.

[31] Sandia National Laboratories, "Analysis, Scale Modeling, And Full-Scale Test of a Railcar And Spent-Nuclear-Fuel Shipping Cask in a High-Velocity Impact against a Rigid Barrier," SAND78-0458, June 1981.

[32] K. Sorenson, R. Salzbrenner and G. Wellman, "Results of the Sandia National Laboratories MOSAIK Cask Drop Test Program," Sandia National Laboratories, Albuquerque, NM, 1992.

[33] J. Miles, M. Shears, E. Tufton, R. Blythe, J. Hart, Central Electricity Generating Board and Ove Arup and Partners, "The Central Electricity Generating Board Flask Test Project," PATRAM 1986, Proceedings of the 8th International Symposium on Packaging and Transportation of Radioactive Materials, Davos, Switzerland.

[34] B. Droste, "A Survey on 35 Years of Packaging, Transport, and Storage of Radioactive Material," Bundesanstalt für Materialforschung und -prüfung (BAM), Berlin, Germany, 2013.

[35] B. Droste, "Testing of type B packages in Germany to environments beyond regulatory test standards," Bundesanstalt für Materialforschung und -prüfung (BAM), Berlin, Germany, 2014.

[36] H. -P. Weise, . H. Kowatewsky and R. Wenz, "Behaviour of Elastomeric Seals at Low Temperature," Bundesanstalt fur Materialforschung und -prufung (BAM), published in Vacuum, Volume 43, Issues 5-7, Pages 555-557, Elsevier Ltd., United Kingdom, 1992.

[37] B. Droste, H. Vo¨lzke, G. Wieser and L. Qiao, "Safety Margins of Spent Fuel Transport and Storage Casks Considering Aircraft Crash Impacts," Bundesanstalt fu¨r Materialforschung und -pru¨fung (BAM), Berlin, Germany, 2002.

[38] C. Ito, A. Kosaki, T. Arai and T. Saegusa, "Brittle Fracture Tests at Low Temperature for Transport Cask Materials," Central Research Institute of Electric Power Industry (CRIEPI), 1992.

[39] T. Kusakawa, T. Kishi, H. Ohtsubu, S. Shiomi, H. Takaku, C. Ito and T. Saegusa, "Full-Scale Tests and Evaluation for Quality Assurance of Ductile Cast Iron Casks," Central Research Institute of Electric Power Industry (CRIEPI), PATRAM 1989, Proceedings of the 9th International Symposium on Packaging and Transportation of Radioactive Materials, Washington, DC, U.S.A., CONF-890631-Vol. 1, 712-719, 1989.

[40] C. Itoh, T. Saegusa, H. Yamakawa and K. Shirai, "Testing of Type B Packages In Japan to Conditions Different From the Regulartory Packages Test Standard," Central Research Institute of Electric Power Industry (CRIEPI), 2007.

[41] Transportation Research Board and National Research Council, "Going the Distance? The Safe Transport of Spent Nuclear Fuel and High-Level Radioactive Waste in the United States," The National Academies Press, Washington, DC, 2006.

[42] United States Nuclear Regulatory Commission (USNRC), "Staff Actions Taken In Response To The National," SECY-07-0095.

[43] United States Nuclear Regulatory Commission (USNRC), "Spent Fuel Transportation Response to the Baltimore Tunnel Fire Scenario," NUREG/CR-6886, Rev. 2, 2006.

[44] United States Nuclear Regulatory Commission (USNRC), "Numerical Simulation of the Howard Street Tunnel Fire, Baltimore, Maryland, July 2001," NUREG/CR-6793, 2003.

[45] United States Nuclear Regulatory Commission (USNRC), "Analysis of Rail Car Components Exposed to a Tunnel Fire Environment," NUREG/CR-6799, 2003.

[46] United States Nuclear Regulatory Commission (USNRC), "Performance of Metal and O-Ring Seals in Beyond Basis Temperature Excursions," NUREG/CR-7115, 2012.

[47] United States Nuclear Regulatory Commission (USNRC), "Shipping Container Response to Severe Highway and Railway Accident Conditions," NUREG/CR-4829-Vol. 2, 1987.

[48] United States Nuclear Regulatory Commission (USNRC), "Spent Fuel Transportation Package Response to the Caldecott Tunnel Fire Scenario," NUREG/CR-6894, Rev. 1, 2007.

[49] United States Nuclear Regulatory Commission (USNRC), "Reexamination of Spent Fuel Shipment Risk Estimates," NUREG/CR-6672, 2000.

[50] United States Nuclear Regulatory Commission (USNRC), "Spent Fuel Transportation Package Response to the MacArthur Maze Fire Scenario," NUREG/CR-7206, 2016.

[51] United States Nuclear Regulatory Commission (USNRC), "Analysis of Structural Materials Exposed to a Severe Fire Environment," NUREG/CR-6987, 2009.

[52] United States Nuclear Regulatory Commission (USNRC), "Spent Fuel Transportation Package Response to the Newhall Pass Tunnel Fire Scenario," NUREG/CR-7207, 2016.

[53] United States Nuclear Regulatory Commission (USNRC), "Structural Materials Analyses of the Newhall Pass Tunnel Fire, 2007," NUREG/CR-7101, 2011.

[54] Association of American Railroads, "Performance Specification for Trains Used to Carry High-Level Radioactive Material," AAR Standard S-2043, 2017.

[55] Transport Canada, "Rules Respecting Key Trains and Key Routes," February 22, 2021.

[56] Association of American Railroads, "Recommended Railroad Operating Practices for Transportation of Hazardous Materials," Circular No. OT-55, 2019.

[57] Canadian Nuclear Safety Commission (CNSC), "Security of Nuclear Substances: Sealed Sources and Category I, II and III Nuclear Material," REGDOC-2.12.3, Version 2.1, 2020.

[58] National Academy of Sciences, "Going the Distance, Worldwide Transportation Experience," Pages 123-124, 2006.

[59] World Nuclear Association, "Transport of Radioactive Material," https://world-nuclear.org/information-library/nuclear-fuel-cycle/transport-of-nuclear-materials/transport-of-radioactive-materials.aspx, January 2022.

[60] K. J. C. a. R. B. Pope, "A Historic Review of the Safe Transport of Spent Nuclear Fuel," US Department of Energy, August 2016.

[61] Encyclopedia Britannica, "Zirconium Chemical Element," https://www.britannica.com/science/zirconium, 2023.

[62] Nuclear Waste Technical Review Board, "Survey of National Programs for Managing High-Level Radioactive Waste and Spent Nuclear Fuel: 2022 Update," (Table has been amended to reflect changes since publication.), July 2022.

[63] Nuclear Waste Management Organization (NWMO), "Implementing Adaptive Phased Management 2020 to 2024," 2020.

[64] Posiva, "Young maiden to replace a retiring lady," November 10, 2014.

[65] Cigeo, "The French Geological Repository Project," PATRAM 2013, 2013.

[66] International Atomic Energy Agency (IAEA), "France's Efficiency in the Nuclear Fuel Cycle: What Can 'Oui' Learn?," https://www.iaea.org/newscenter/news/frances-efficiency-in-the-nuclear-fuel-cycle-what-can-oui-learn, 2019.

[67] World Nuclear Association, "Japanese Waste and MOX Shipments from Europe," 2017.

[68] World Nuclear News, "Rokkasho reprocessing plant completion delayed again," 2023.

[69] Jenny Holmström, " Sigrid - the first part of the renewal of the Swedish transport system," PATRAM 2013.

[70] Nuclear Waste Management Organization (NWMO), "Planning framework for the transportation of used nuclear fuel," 2021.

[71] P. Shih, D. Sicard and L. Michels, "NUHOMS-MP197 Transport Cask," PATRAM 2004.

[72] W. Bracey, J. Li, P. Shih and J. He, "NUHOMS System for Storage and Transporation of VER Fuel," PATRAM 2019.

[73] From Power, "The Nuclear Fuel Cycle Facilities in Rokkasho, Aomori," Vol. 2, https://www.fepc.or.jp/english/library/power_line/detail/02/02.html, 1998.

[74] SKB, "The Swedish System," https://www.skb.com/our-operations/the-swedish-system/.

[75] NAGRA, "Where is the waste held today?," https://nagra.ch/en/knowledge-centre/where-is-the-waste-held-today/.

[76] World Nuclear News, "Reprocessing ceases at UK's Throp plant," 14 November 2018.

[77] United States Naval Nuclear Propulsion Program, "Operating Naval Nuclear Propulsion Plants and Shipping (rail) Naval Spent Fuel Safely for over 60 Years," US DOE NNSA, 2017.

[78] U.S. Department of Energy, "Draft Report on Transportation Planning for Shipment of Used Nuclear Fuel," 2013.

[79] Holtec International, "Holtec Receives U.S. NRC's License for Building and Operating America's First Below-Ground Consolidated Interim Storage Facility for Used Nuclear Fuel," 2023, (NRC approval documents for Holtec International, Issuance of Materials License SNM-2516 for the HI-STORE Consolidated Interim Storage Facility ISFSI, May 9, 2023, https://www.nrc.gov/docs/ML2307/ML23075A179.html).

[80] Nuclear Regulatory Commission, "Interim Storage Partners, Issuance of Materials License SNM-2515, WCS Consolidated Interim Storage Facility ISFSI," September 13, 2021, (The NRC approval documents for ISP's Consolidate Interim Storage Facility license (SNM-2125) can be found at: https://www.nrc.gov/docs/ML2118/ML21188A096.html).

[81] K. J. Conolly, L. S. Rodman and M. R. Feldman, "Route Readiness Elements in a Large-scale Spent Nuclear Fuel Transportation System," November 23, 2023.

[82] Pacific Northwest National Laboratory, "Nuclear Power Plant Infrastructure Evaluations for Removal of Spent Nuclear Fuel," PNNL-30429, 2021.

[83] United States Department of Transportation: Bureau of Transportation Statistics, "Transportation Accidents by Mode," https://www.bts.gov/content/transportation-accidents-mode.

[84] Canadian Nuclear Safety Commission (CNSC), "Introduction to radiation," [Online]. Available: http://nuclearsafety.gc.ca/eng/resources/radiation/index.cfm.

[85] Lawrence Livermore National Laboratory, "Guidelines for Conducting Impact Tests on Shipping Packages for Radioactive Material," UCRL-ID-121673, 1995.

[86] Sandia National Laboratories, "Spent Nuclear Fuel Transporation Package Performance Study Issues Report," NUREG/CR-6768, 2002.

[87] A. Rolle, V. Ballheimer, T. Neumeyer and F. Wille, "Application of Leakage Rates Measured on Scaled Cask or Component Models to the Package Containment Safety Assessment," PATRAM 2019, 2019.

[88] K. Muller, M. Minack and B. Droste, "The New BAM Drop Test Facility for Big Full Scale Casks," 14th International Symposium on the Packaging and Transportation of Radioactive Materials (PATRAM 2004), https://www.osti.gov/etdeweb/servlets/purl/20773340, September 20-24, 2004.

[89] CSA Group, "Quality assurance of analytical, scientific, and design computer programs," N286.7-16, Reaffirmed 2021.

[90] Justice Samuel Grange, Commissioner Supreme Court of Ontario, "Report of the Mississauga Railway Accident Inquiry," Appendix 2, December 1980.

[91] Ontario Ministry of the Solicitor General, "The Mississauga Evacuation: Final Report," November 1981.

[92] Jack Cahill, "Hot Box: The Mississauga Miracle," PaperJacks Ltd., Markham, ON, 1980.

[93] Commission of Inquiry Hinton Train Collision, "Report of the 'Commissioner the Honourable Mr. Justice Rene P. Foisy," December 1986.

[94] Transportation Safety Board of Canada, "Runaway and Main-Track Derailment Montreal, Maine & Atlantic Railway Freight Train," MMA-002 Mile 0.23, Railway Investigation Report R13D0054, Sherbrooke Subdivision Lac-Mégantic, Quebec, 2013.

[95] Bruce Campbell, "The Lac-Megantic Rail Disaster: Public Betrayal, Justice Denied," James Lorimer & Company Toronto, 2018.

[96] Transportation Safety Board of Canada, "Main-Track Derailment Canadian National Railway Company Freight Train U70451-10 Mile 111.7, Ruel Subdivision, Gladwick, Ontario," Railway Investigation Report R15H0013, 14 February 2015.

[97] Transportation Safety Board of Canada, "Main-Track Derailment Canadian National Railway Company Freight train U70451-02 Mile 88.75, Ruel Subdivision, Gogama, Ontario," Railway Investigation Report R15H0021, 7 March 2015.

[98] Transportation Safety Board of Canada, "Main-Track Derailment Canadian National Railway Company Freight train U73451-11 Mile 197.47, Rivers Subdivision, St. Lazare, Manitoba," Railway Investigation Report R19W0050, 16 February 2019.

[99] Transportation Safety Board of Canada, "Main-Track Derailment Canadian National Railway Company Freight Train X35041-18 Mile 108.25, Fort Francis Subdivision, Emo, Ontario," Railway Investigation Report R20W0031, 18 February 2020.

[100] David Giles, "19 cars 'involved in a pool of fire' after CP train derailment near Guernsey, Sask," Global News, February 14, 2020.

[101] B. Lewis, F. Iglesias, R. Dickson and A. Williams, "Overview of High Temperature Fuel Behaviour with Relevance to CANDU Fuel," Journal of Nuclear Materials, 394, pages 67-86, 2009.

[102] Dorofeev, S.B., et al., "Fireballs from Deflagration and Detonation of Heterogenous Fuel-rich Clouds," Fire Safety Journal, 25, 323-336, 1995.

[103] B. Droste, U. Probst and W. Heller, "Impact of an Exploding LPG Rail Tank Car onto a CASTOR Spent Fuel Cask," RAMTRANS, Volume 10, No.4, pp 231-240 , 1999.

[104] Calgary Herald, "Fireball closes portion of 401," Page B8, March 26, 1986.

[105] *The Ottawa Citizen,* p. 14, Wednesday April 1986.

[106] E. Easton, T. Mintiz and G. Adams, "Analyses of Historical Rail Accidents to Identify Parameters Impacting Transport of Spent Nuclear Fuel," Packaging Transport, Storage and Radioactive Material, March 2011.

[107] E. Easton and C. Bajwa, "Road Tunnels and Fires: Implications for the Transport of Used Nuclear Fuel," ASME 2011, Pressure Vessels and Piping Conference, Baltimore Maryland, July 17-21, 2011.

[108] E. Easton and C. Bajwa, "The Potential Impacts of Recent Transportation Accidents involving Severe Fires on the Safe Shipment of Spent Nuclear Fuel," ASME 2010 Pressure Vessels and Piping Conference, Bellevue, Washington, July 18-22, 2010.

[109] U.S. Nuclear Regulatory Commission, "The MacArthur Maze and Newhall Pass Fires and Their Implications for Spent Fuel Transport," 2010 Waste Management Conference, Phoenix Arizona, March 7-11, 2010.

[110] U.S. Nuclear Regulatory Commission, "The MacArthur Maze Fire: How Hot was It?," 2009 Waste Management Conference, Phoenix Arizona, March 1-2, 2009.

[111] James G. Quintiere, "Principals of Fire Behavior," Delmar Publishers, Page 141, 1998.

[112] United States Nuclear Regulatory Commission (USNRC), "Spent Fuel Transportation Package Response to the Caldecott Tunnel Fire Scenario, Table 8.2," NUREG/CR-6894, Rev. 1, 2007.

[113] U.S. Nuclear Regulatory Commission, "Spent Fuel Transportation Package Response to the MacArthur Maze Fire Scenario, Figures 8.2 and 3.," NUREG/CR-7206, 2016.

[114] U.S. Nuclear Regulatory Commission, "Spent Fuel Transportation Package Response to the Newhall Pass Tunnel Fire Scenario," Tables 8.3 and 8.4," NUREG/CR-7207, 2016.

APPENDIX A ADDITIONAL INFORMATION ON RADIATION TYPES

Four of the most common types of ionizing radiation emitted by radioactive materials are described in this appendix and shown in Figure A-1. Dose types as mentioned in the paragraphs below are illustrated in Figure A-2. More detailed information is available in [84].

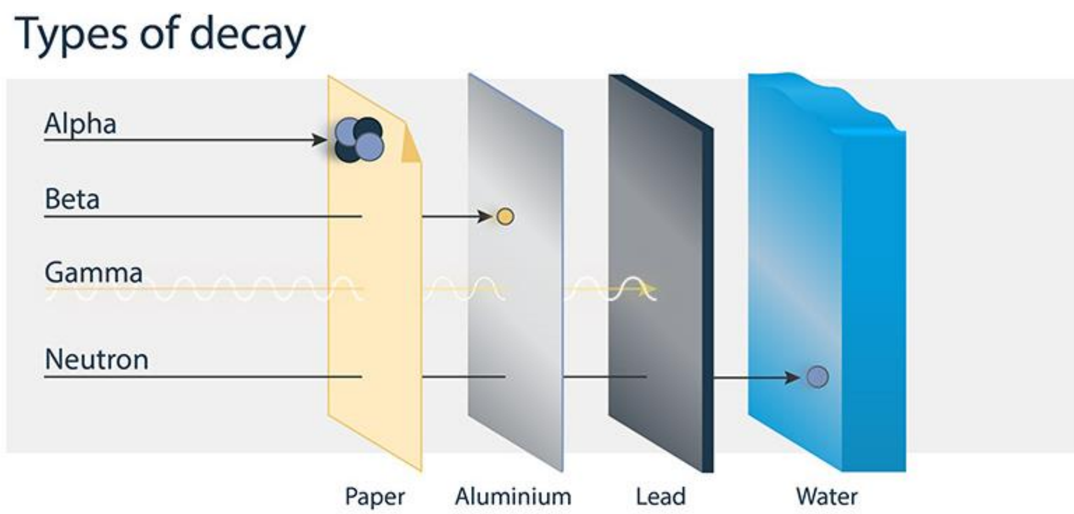


Figure A-1: The penetrating power of ionizing radiation based on radiation type [7]

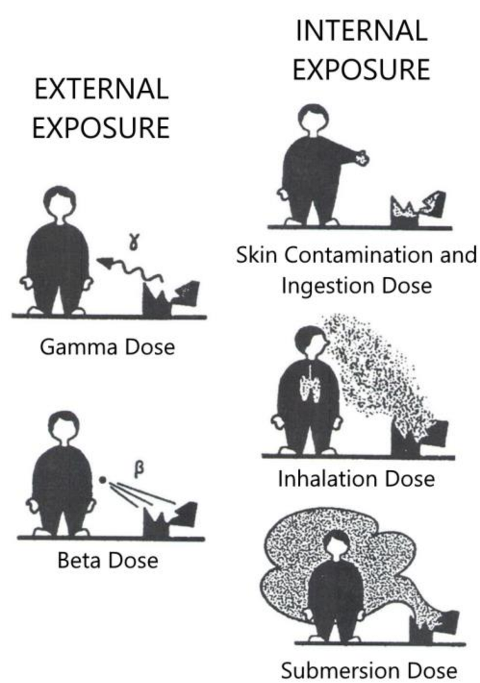


Figure A-2: Dose types for external and internal exposure

Alpha Radiation

Alpha radiation consists of two protons and two neutrons and is identical to the nuclei of a helium atom. Alpha particles are relatively heavy particles and carry with them an electric charge. As such, they will give up their energy within a very short distance (only a few centimetres in air) from the source mostly by causing ionization. The implications of this are that alpha radiation does not penetrate most materials very well - and thus can be easily shielded. In fact, most alpha particles cannot penetrate the dead layer of cells on the skin surface and therefore do not present any hazard while the alpha-emitting radionuclide remains external to the body.

However, if the material becomes ingested or inhaled into the body then the alpha particles can ionize atoms in living cells. The rate of ionization in this case is very high and significant cell damage can occur. Another implication of the lack of penetrating power is that it makes alpha radiation difficult to detect. Special instruments are required.

Beta Radiation

Beta particles are electrons emitted from a radionuclide. As such, they are much smaller and lighter than alpha particles. They are subsequently more penetrating, but their rate of ionization is much less than that of alpha particles. The penetration range of beta particles depends on their energy and the density of the material they are passing through. An average-energy beta particle will not penetrate a thin sheet of metal and will only travel about 10 mm in tissue. Hence, beta-emitting radionuclides are a hazard to skin and eyes as well as a hazard if they are inhaled or ingested. Ease of detection of beta radiation depends on the energy level. However, all but the lowest energies can be detected fairly easily.

Gamma Radiation

Gamma radiation is electromagnetic radiation similar to radar, radio, TV, microwave, light, ultraviolet, and infrared radiation. However, gamma radiation has higher energy, higher frequency, and shorter wavelength than these similar forms of radiation. X-rays can be generally regarded as lower energy gamma rays that are machine-produced instead of stemming from a radioactive atom.

Gamma radiation can penetrate much further when compared to beta or alpha radiation. Consequently, it is relatively easy for gamma radiation to completely penetrate through the body. Gamma radiation is an external and internal hazard but can be shielded by dense materials such as lead, steel, or uranium. It is easily detected, even at very low levels.

Neutron Radiation

In addition to existing in the nucleus, it is possible to have free neutrons as a form of radiation. Neutrons are unique among the types of radiation in that they only have interactions with other nuclei (nuclear reactions). Neutrons are very penetrating and the ease with which they can be shielded and detected depends heavily on their energy. They can cause significant cell damage as they pass through the body. They are an external and internal hazard but can be shielded by hydrogenous material (such as water) or materials including elements such as cadmium or boron. They are detected only with special instruments.

APPENDIX B THE Q-SYSTEM FOR THE CALCULATION OF A_1 AND A_2 VALUES

An important concept embedded in the International Atomic Energy Agency (IAEA) transport safety regulations [6] is the establishment of A_1 and A_2 values. These values determine the maximum quantity (activity) of a radionuclide that can be shipped in a package that is not designed to withstand a severe accident (Type A package).

The $\mathbf{A_1}$ value is the activity limit based on radioactive materials in indispersible special form (encapsulated) where the main hazard is from direct exposure.

The $\mathbf{A_2}$ value is the activity limit based on radioactive materials in normal form where the hazards can result from direct exposure, inhalation, ingestion, or submersion.

In the 1985 edition of its Transportation Safety Regulations (now called SSR-6), the IAEA developed the Q system to update the dosimetric models used in the derivation of Type A package contents limits. The goals were to develop more realistic accident scenarios and to strengthen the relationship between the transportation safety standards and internationally accepted radiation exposure limits. Since then, the Q-system has been the basis for calculating A_1 and A_2 values for individual radionuclides and mixtures of radionuclides. These limits, A_1 and A_2, in addition to defining the content limits of a Type A package, are also used for several other purposes in the regulations, such as specifying package leakage limits, specifying the package limits for excepted quantities, low specific activity material, and surface contaminated objects.

The content limits of a Type A package, A_1 and A_2 values, are set to ensure that the radiological consequences of severe damage to a Type A package are acceptable, and design approval by the CNSC is not required, except for packages containing fissile material. Activities in excess of the Type A package limits must be transported in a package whose design requires CNSC approval (called a Type B package). The design requirements for Type B packages are designed to reduce the probability of a significant release of radioactive material or increased external dose during a severe accident to a level that would not significantly affect public health and safety.

The dosimetric Q system considers a series of exposure pathways (see Figure A-1 in Appendix A). In particular, it looks at pathways which might lead to radiation exposure, either external or internal, to persons in the vicinity of a Type A package involved in a severe transport accident. In evaluating the accident doses, the model assumes that 10^{-3} to 10^{-2} of a Type A package's content would be released in an accident, and 10^{-4} to 10^{-3} of the material released would be taken up by an individual. The model assumes that the individual would be exposed for 30 minutes at a distance of 1 meter.

The doses for individual radionuclides are evaluated for each of the exposure pathways to determine the A_1 and A_2 values for each scenario that would limit the doses to:

- Whole body effective dose less than or equal to 50 mSv
- Dose to individual organs less than or equal to 0.5 Sv
- Dose to eyes less than 0.15 Sv

The final A_1 value assigned to an individual radionuclide in special form is the greater of doses calculated for the external gamma and beta doses. This is because special form material is not dispersible, and the hazard consists solely of direct exposure. Radioactive material in normal form is considered as readily dispersible and therefore the A_2 value assigned to an individual radionuclide is based on the largest dose calculated for all exposure pathways.

The A_1 and A_2 values for individual radionuclides are listed in Section IV, Table 2 of SSR-6 [6]. An extract from Table 2 is reproduced in Figure B-1. The table illustrates the following points:

1. The activity that can be shipped in a Type A package for an individual radionuclide when as normal and special form. For example, for Americium-241 (Am-241), a Type A package is limited to 1×10^1 TBq when shipped as special form (indispersible) and 1×10^{-3} TBq as normal form (dispersible). Quantities greater than these must be transported in accident-resistant Type B packages.
2. For Am-241 to qualify as an exempt material, the activity concentration limit must not exceed 1×10^0 Bq/gram.
3. The total activity for all exempt packages in a consignment (shipment) for Am-241 must not exceed 1×10^4 Bq.

The A_1 and A_2 values are used to:

- Classify package contents based on form (normal or special), activity (quantity) and specific activity (concentration).
- Define package types and content limits for each classification of radioactive material.
- Define acceptance criteria for package evaluations under routine, normal and severe accident conditions.
- Limit the number of packages that can be shipped together.

Using the A_1 and A_2 values in this manner relates these activities directly to internationally-accepted radiation exposure limits.

TABLE 2. BASIC RADIONUCLIDE VALUES

Radionuclide (atomic number)	A_1 (TBq)	A_2 (TBq)	Activity concentration limit for exempt material (Bq/g)	Activity limit for an exempt *consignment* (Bq)
Actinium (89)				
Ac-225 (a)	8×10^{-1}	6×10^{-3}	1×10^{1}	1×10^{4}
Ac-227 (a)	9×10^{-1}	9×10^{-5}	1×10^{-1}	1×10^{3}
Ac-228	6×10^{-1}	5×10^{-1}	1×10^{1}	1×10^{6}
Silver (47)				
Ag-105	2×10^{0}	2×10^{0}	1×10^{2}	1×10^{6}
Ag-108m (a)	7×10^{-1}	7×10^{-1}	1×10^{1} (b)	1×10^{6} (b)
Ag-110m (a)	4×10^{-1}	4×10^{-1}	1×10^{1}	1×10^{6}
Ag-111	2×10^{0}	6×10^{-1}	1×10^{3}	1×10^{6}
Aluminium (13)				
Al-26	1×10^{-1}	1×10^{-1}	1×10^{1}	1×10^{5}
Americium (95)				
Am-241	1×10^{1}	1×10^{-3}	1×10^{0}	1×10^{4}

Figure B-1: Tabulation of A_1 and A_2 values from Table 2 of the IAEA's SSR-6 [6]

APPENDIX C MATERIAL CLASSIFICATIONS BASED ON LOW SPECIFIC ACTIVITY OR CONTAMINATION

As noted in Table 2-1 in Section 2.3.2, industrial packages are used to transport certain low specific activity (LSA) materials and surface contaminated objects (SCOs). There are three types of industrial packages (Type IP-1, Type IP-2, and Type IP-3) that are used for LSA and SCO shipments. Below is a simplified definition of the classes of LSA materials and SCO.

Low Specific Activity (LSA)

LSA materials are materials that have a low specific activity and in which the activity is uniformly distributed throughout. LSA material is considered a low hazard material because a person could not physically breathe in or ingest enough material to cause serious harm. As such, these materials are not shipped in package types that are designed to withstand severe accident conditions.

There are three classes of LSA materials:

LSA-I includes unirradiated natural or depleted uranium and thorium compounds and ores, and other radioactive material with unlimited A_2 values or with a specific activity which reaches only a very low level.

LSA-II includes water with a tritium concentration of up to 0.8 TBq/L and other material in which the activity is distributed throughout, and the estimated average specific activity does not exceed 10^{-4} A_2/g for solids and gases, and 10^{-5} A_2/g for liquids.

LSA-III includes solids (e.g., consolidated wastes, activated materials), excluding powders, in which the radioactive material is distributed throughout a solid or a collection of solid objects, or is essentially uniformly distributed in a solid compact binding agent (such as concrete, bitumen and ceramic) and the estimated average specific activity of the solid, excluding any shielding material, does not exceed 2×10^{-3} A_2/g.

Detailed requirements for LSA materials are outlined in paragraphs 408-411 of SSR-6 [6].

Surface Contaminated Object (SCO)

SCOs are solid objects that are not them selves radioactive, but which have radioactive material in the form of non-fixed contamination distributed on their surface. The hazard associated with these materials arises from surface contamination that can be scraped off in an accident. Like LSA materials, SCOs are considered a low hazard material because a person could not physically breathe in or ingest enough material from an accident to cause serious harm. As such, SCOs are not shipped in package types that are designed to withstand severe accident conditions.

There are three classes of SCOs:

SCO-I material includes solid objects which have the lowest levels of non-fixed contamination, fixed contamination, and non-fixed plus fixed contamination. Examples of these could include large items associated with decommissioning of nuclear plants, such as building rubble, structural steelwork, pipes, machine tools and other scrap.

SCO-II material includes solid objects on which either the fixed or non-fixed contamination on the surface exceeds the applicable limits specified for SCO-I and on which objects have the highest levels of fixed, non-fixed, and non-fixed plus fixed among both categories. Examples of these could include equipment and decommissioning wastes, described earlier, when the contamination level exceeds the values authorized for SCO-I. They must also comply with the other requirements for SCO-II.

SCO-III material includes large solid objects that cannot be transported in a type of package described in SSR-6 due to their size. The openings must be sealed, the inside must be dry and specific contamination limits must be met.

Detailed requirements for SCO materials are outlined in paragraphs 412-414 of SSR-6 [6].

APPENDIX D REGULATORY REQUIREMENTS BASED ON CONDITIONS OF TRANSPORT

As described in Section 2.3.1, a graded approach is applied to the regulatory requirements for transportation packages based on the conditions of transport. All radioactive materials are subject to general requirements. In addition, the following severity levels are applied according to the package type:

(a) Routine conditions of transport (incident free)
(b) Normal conditions of transport (minor mishaps)
(c) Accident conditions of transport

Table D-1 presents the applicability of general requirements under routine conditions of transport for each package type. General requirements are provided in paragraphs 607-618 of SSR-6 and additional requirements for air transport are provided in paragraphs 619-621 of SSR-6 [6].

Table D-1: General design requirements for all packages under routine conditions of transport

	EXCEPTED PACKAGE	IP-1	IP-2	IP-3	TYPE A	TYPE B	TYPE C
General Requirements							
As they relate to: Handling, lifting, protrusions, water retention, vibrations, acceleration for routine conditions of transport, ageing mechanisms, material compatibility, valves, ambient temperature, and pressure, shielding	x	x	x	x	x	x	x
Additional Requirements for Air Transport							
As they relate to: Temperature and pressure	x	x	x	x	x	x	x

Table D-2 presents the applicability of test requirements under normal conditions of transport for each package type. Package test requirements for normal conditions of transport are provided in paragraphs 719-725 of SSR-6 [6].

Table D-2: Package tests requirements for normal conditions of transport

	EXCEPTED PACKAGE	IP-1	IP-2	IP-3	TYPE A	TYPE B	TYPE C
Drop test 0.3-1.2 m			x	x	x	x	x
Stacking			x	x	x	x	x
Water Spray				x	x	x	x
Penetration							
1.0 m				x	x	x	x
1.7 m					Liquids Gases		

Table D-3 presents the applicability of test requirements under accident conditions of transport for each package type. Package test requirements for accident conditions of transport are provided in paragraphs 726-737 of SSR-6 [6]. Note that the drop/crush test, penetration and thermal tests must be done on the same specimen in the most damaging orientation.

Table D-3: Package test requirements for accident conditions of transport

	EXCEPTED PACKAGE	IP-1	IP-2	IP-3	TYPE A	TYPE B	TYPE C
Drop Test 9 m					Liquids Gases	HHD[1]	x
Penetration 1 m						x	
Crush Test 9 m						LLD[2]	x
Thermal Test						x	
Water Immersion 15 m						x	x
Water Immersion 200 m						LQ[3]	x
Puncture-Tearing Test							x
Enhanced Thermal Test							x
Impact Test							x
Water Leak Test for Criticality	All packages that contain fissile material						

Notes:

1. High Weight/High Density Package
2. Light Weight/Low Density Package
3. Large Quantity Packages (> 10^5 A_2)

Finally, Table D-4 displays the graded approach applied to all radioactive material packages.

Additional details regarding the requirements are provided in SSR-6 [6].

Table D-4: Graded approach to radioactive material packages

	EXCEPTED PACKAGE	IP-1	IP-2	IP-3	TYPE A	TYPE AF	TYPE B	TYPE BF	TYPE C
Air Accident Conditions									X
+Fissile								X	
Accident Conditions							X	X	X
+Fissile						X		X	
Normal Conditions			X	X	X	X	X	X	X
Routine Conditions	X	X	X	X	X	X	X	X	X
SSR-6 Paragraphs	607-618	607-618 636	607-618 636 722-723	607-618 636-649 722-723	607-618 635-651	607-618 635-651 673-675	607-618 636-649[1] 653-666	607-618 636-649[1] 653-666 673-675	607-621 636-649[1] 653-657 661-666 670-672

[1] *Except as specified in paragraph 648(a)*

APPENDIX E ADDITIONAL INFORMATION ON TESTING METHODS

As described in Section 3.3, testing to demonstrate Type B package compliance with regulatory requirements can be performed using full-scale physical testing, scaled physical testing, computer modelling, and/or calculations. The choice of method for each test is determined by several factors which are discussed in this appendix. Information on the methods is provided in Appendix E.1 to E.3 and the use of each method for each regulatory test is described in Appendix E.4.

E.1 PHYSICAL TESTING

Physical testing is a common method of assessing package design performance and has been utilized in many countries with used nuclear fuel transportation programs. Testing of Type B package designs is typically conducted in designated testing facilities which feature the capability for testing packages weighing upwards of 100 tonnes. Physical testing can be performed with full-scale models (see Appendix E.1.1) or scale models (see Appendix E.1.2). Testing facility characteristics are discussed in Appendix E.1.3.

Physical testing may also be utilized for a variety of reasons beyond just verification of design, verification of fabrication, and inspection methods. Physical testing also provides validation of values which can be used to enhance computer modelling. Moreover, the documentation of these physical tests during the licensing process (i.e., pictures and videos) is also used as safety demonstrations to provide the public with a visual demonstration of the safety of the Type B packages. A list of various physical tests across the world and their specifics are found in Section 4.

E.1.1 Full-Scale Physical Testing

The most common full-scale physical tests conducted are the *Free-Drop Test* and *Puncture Test* as the setup requirements are straightforward, and containment integrity following the tests can be validated via a standardized leak test. The *Thermal Test* has also been conducted on full-sized packages, whether through the use of controlled burns or utilizing large industrial ovens to achieve similar heat flux conditions. Additional information on the test methods used for each regulatory test is provided in Appendix E.4.

E.1.2 Scale Model Physical Testing

The *Free-Drop* and *Puncture* tests are often performed with scale models to facilitate package handling, facility capabilities, and the ability to perform the tests using multiple orientations to determine the sequence that results in the package suffering maximum damage. Scale model testing is a proven and accepted practice across engineering disciplines, including for testing airplanes, ships, buildings, and other large engineered structures. SSR-6 permits scale models to be used if appropriate adjustments to certain parameters are accounted for. Table E-1 outlines the testing outputs that may be obtained from scale model testing.

Table E-1: Parameters gained from scale model testing

Aims of Tests	Use of Scale Models
Quantification of stresses and deformations	Recommendable
Verification of calculations (methods, models)	
Identification of construction weak points	
Stresses and Strains	
Acceleration	
Bolt Forces	
Design verification	Achievable, with additional setup and test methods
Verification of manufacturing and inspection methods (with test specimen first)	
Quantification of leakage rates	

For impact tests (e.g., *Free-Drop Test and Puncture Test*), the scale model must be made of identical materials as specified for the package design. Additionally, the drop conditions (i.e., the drop height, velocity and orientation angle) must be identical to that which would be used in a full-scale physical test. The scale model must have only one independent scaling factor – this means that, for example, a scale model cannot scale some parameters to a 1/2 scaling factor and others to a 1/3 scaling factor. Additional details for designing scale model tests are provided in *Guidelines for Conducting Impact Tests on Shipping Packages for Radioactive Material* [85]. The *Thermal Test* is not conducted with scale models because the input and output variables cannot be scaled accurately.

As discussed above, scale model tests must have one independent scaling factor. Based on this scaling factor, the output values (i.e., the information that the test is designed to provide) can be determined based on scaling relationships. These scaling relationships are well understood and firmly based on the equations of physics [86]. Table E-2 compiles the scaling relationships for various values that scale model tests are typically designed to measure.

Table E-2: Values obtained by scaling factors

Scaling Factor of Test	Values Measured
Full-Scale	Impact Velocity, Pressure, Density
Scale with Scaling Factor	Length, Time, Deformation
Scale with Inverse of Scaling Factor	Acceleration, Strain Rate
Scale with Square of Scaling Factor	Force, Area
Scale with Cube of Scaling Factor	Mass, Volume, Energy, Moment

Parameters that introduce challenges to scale model testing include scaling small package components (fabrication may not be possible at a scaled size) and elastomeric seals. Components may not be available at exact scaling factors, whereupon conservative component scaling must be exercised. For these cases, the adequacy of scale model testing is to be confirmed experimentally or with computer modelling. If confirmed experimentally, the test could be performed with different independent scaling factors and compared to ensure they correlate using established scaling laws. Computer modelling can be used to confirm that the scale model tests consider all parameters controlling the results. Additionally, different scale model tests can be used to demonstrate the performance of different package components.

Regarding the scaling of elastomeric seals and package leak rates, many factors must be considered to predict leakage rates on the basis of scale model test results [24]. Adequate safety factors must also be used for scale model testing of package leakage rates and often a combination of test methods may be the most efficient way to demonstrate compliance with leakage rate limits. Additional information is provided in *Application of Leakage Rates Measured on Scaled Cask or Component Models to the Package Containment Safety Assessment* [87].

E.1.3 Testing Facility Characteristics

Around the world, there exist testing facilities specifically designed to test Type B packages. However, each facility may have been constructed with different goals or characteristics in order to conduct physical testing safely and accurately. The testing facility should maintain a controlled environment with appropriate certified testing equipment, such as drop towers, dynamometers or pendulum impact testers, to simulate real-world transportation scenarios. The International Atomic Energy Agency's (IAEA) SSG-26 document provides design guidance for testing facilities [24].

BAM operates a drop test facility in Horstwalde, Germany [88]. The BAM drop test facility was constructed in 2004 for performing drop tests of full-scale packages up to a total mass of 200 000 kg. Figure E-1 shows a Type B package being subjected to the 9 m drop test at the BAM drop test facility. The main construction features are:

- 36 m high drop tower as steel pipe construction.

- 200 ton hoist on top of the drop tower, with a maximum hook height of 30 m.
- A 24 m x 20 m closed test hall below the drop tower with moveable roof and rolling gates.
- An 80 ton overhead crane inside the test hall.
- The unyielding target is realized by a reinforced concrete block with the dimension 14 m x 14 m x 5 m depth, with a mass of 2,450,000 kg, and with an impact pad made of anchored mild steels plates 10 m x 4.5 m x 0.22 m.

The impact pad consists of a center steel plate 2.5 m x 10 m x 0.22 m and two side steel plates 1.0 m x 10 m x 0.22 m, also embedded and fixed on the concrete block.

Figure E-1: Full-scale 9 m drop testing at the BAM drop test facility

Canada previously operated testing facilities at Chalk River Laboratories in Deep River, Ontario. A special facility was designed to conduct the *Free-Drop*, *Puncture* and *Thermal* tests. The facility had been used to conduct drop tests in the past on a half-scale model of the UFTP. Images of these tests are shown in Figure E-2.

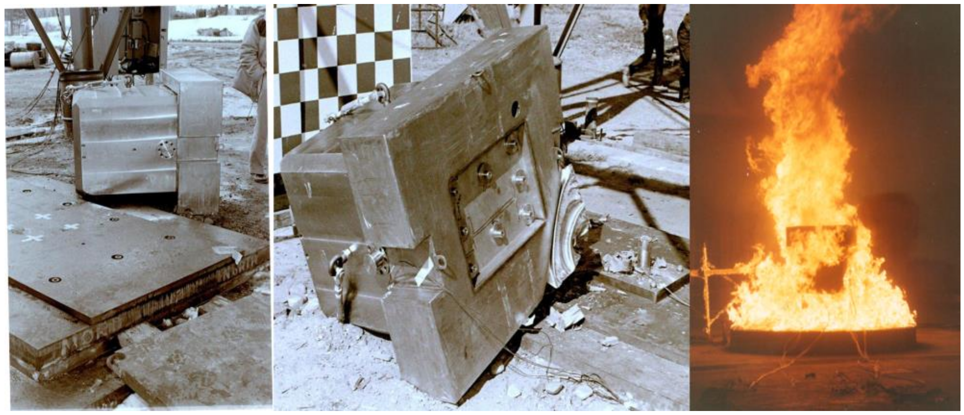


Figure E-2: Impact and thermal tests on the UFTP at the Chalk River Laboratories testing facility

E.2 COMPUTER MODELLING

Although the IAEA SSR-6 packaging standards are described as physical tests, the standards allow alternative methods to demonstrate compliance. These alternative methods include calculations such as computer modelling (IAEA's SSR-6, Paragraph 701). Computer modelling can be applied to simulate and predict the behavior of a package under various conditions, such as during transportation or in the event of an accident. The analysis models represent the complete package, including the impact limiters, the package body, the contents and any overpacks. All of these items are explicitly modelled in three dimensions.

For *Impact and Immersion Tests*, structural analysis can be performed using computer modelling (e.g., with the use of Finite Element Analysis (FEA)). FEA is a method that uses computation to simulate how an object would behave under various physical conditions, such as the conditions experienced during an *Impact or Immersion Test*. A major advantage of using computer modelling is that it allows the package to be analyzed for many different drop angles to determine the most damaging orientation, especially for large packages where it may be impracticable to conduct multiple physical drop tests. Advancements in computational modelling and the use of conservative values and code margins for design features have supported the use of computer modelling for *Impact and Immersion Tests*. The factors of safety (i.e., how much margin for the calculation) should be selected and justified by the package designer, with acceptance by the competent authority, taking into account confidence in the validation of methods used and uncertainties. Verification and validation of codes is discussed in Appendix E.2.1.

Computer modelling can also be used to perform or confirm the *Thermal Test*. Computer modelling is typically completed using Computational Fluid Dynamics (CFD) which uses numerical methods to simulate the behaviour of liquids and gases, such as the behaviour of fire and air during the *Thermal Test* conditions. Fire parameters are modelled according to the regulations and the heat flux is applied as would be the case in a physical test.

Computer modelling for testing package leakage rates is not typically performed given the challenges associated with modelling the properties and behaviour of elastomeric seals in Type B packages.

Computer modelling can also be used to optimize the package design, identify potential issues and vulnerabilities, and inform improvements to the package's safety and efficiency. Computer modelling is a useful tool for enhancing the safety and effectiveness of transport packages.

Margins of error are used in computer modelling to ensure that results are conservative – this means that in many cases, results from computer modelling exceed the minimum safety requirements in the regulations and have a bigger design safety factor than results from physical testing can provide. The safety margins represent the degree to which a package's design, and its performance during testing, exceed the minimum safety requirements as laid out in the regulations.

E.2.1 Verification and Validation of Computer Codes

Computer codes are validated for their intended uses and verified prior to their use. Based on the definitions provided in CSA N286.7-16, *Quality assurance of analytical, scientific, and design computer programs* [89], *verification* is the process of determining whether or not the computer code fulfills the applicable requirements. *Validation* meanwhile is the process to assess fitness and quantify computer code accuracy for its intended applications. Validation is performed by comparing results calculated using the computer code with relevant measured data or known solutions.

E.3 COMBINED USE OF COMPUTER MODELLING AND PHYSICAL TESTING

Using computer modelling has proven to yield reliable results, even for dynamic impacts. As with all computer modelling methods, it is imperative that the modelling be conducted in accordance with appropriate materials/material laws and contact parameters. While the regulations allow for the use of computer models to demonstrate the safety of a design, reliable physical tests can be used to supplement information that is harder to extract from computer models.

Developing force-deflection curves for a package impact limiter and target is a challenge in computer modelling but can be obtained through physical tests or analyses. Computer modelling should be used if impact loads are near limits, based on real material properties from physical testing.

E.4 METHODS COMMONLY USED FOR EACH REGULATORY TEST

The following subsections describe the methods commonly used for each regulatory test. Regardless of the method used, documentation should be sufficiently accurate and complete to allow an approving authority (i.e., the Canadian Nuclear Safety Commission in Canada) to determine that all safety requirements have been met and all modes of failure considered. In practice, a package design for used fuel typically uses a combination of computer modelling, scale model testing and full-scale mock-ups of package components. It is up to the applicant to choose the appropriate methods for each regulatory test and up to the approving authority to verify that the selected methods are appropriate.

E.4.1 Impact Tests

While physical testing is often used to verify results, computer modelling is often used as the first step in the assessment. This is due to it being more efficient and the ease of testing the same package in different scenarios without having to build a new package every time it is damaged. Computer modelling makes it easier to find the most damaging orientation by testing impacts at various locations on the package and various package orientations. When computer analysis is done, it is verified that the solution method is appropriate for the evaluation and that the computer program used to conduct the analyses is reliable. When using these methods, the solution methods, benchmarking results and quality assurance program for maintaining and using the computer codes is documented and submitted for approval.

While computer modelling is more practical than physical testing, it often requires additional full-scale or scale model testing to analyse the force-deflection curve of the impact limiter. The dynamic response of O-rings during an impact test also may not be accurately modeled by computer analysis as the O-ring fits into a groove formed by the package and lid surfaces. The O-ring groove may not have totally smooth surfaces which may result in multiple small leak paths between the O-ring and groove surfaces. To assure that the O-ring maintains a proper seal, a physical leak test has to be done on the O-rings during certification testing to show that the package can meet the regulatory requirements for containment.

E.4.2 Thermal Test

The *Thermal Test* can be performed using either computer modelling or physical testing, or by a combination of both. Physical testing of the *Thermal Test* is difficult since it requires a large amount of fuel (to sustain the fully engulfing fire), intricate instrumentation, and ambient wind conditions. Only a few specialized facilities are available that can do these tests for large packages, such as a UNF package. Due to this, computer modelling (often using Computational Fluid Dynamics (CFD)) is used most of the time. The use of computer modelling for the *Thermal Test* also allows a margin of safety to be applied. Scale model testing is not used for the *Thermal Test* for the purposes of certification by a competent authority.

E.4.3 Immersion Tests

The *Immersion Tests* are most often conducted using computer modelling as it is the most cost effective and the data/variables can be obtained and controlled easily. The effects of increased pressure on package materials are well understood and computer modelling software is capable of effectively assessing the package performance.

APPENDIX F PACKAGES USED FOR USNRC ACCIDENT RECONSTRUCTIONS

F.1 HOLTEC HI-STAR 100 SNF TRANSPORTATION PACKAGE

The HI-STAR 100 is a Type B package designed to ship used fuel by rail. The design (Figure F-1) features an outermost containment boundary in the form of the package shell, lid and lid seals. It provides an additional containment boundary in the form of a welded multi-purpose canister (MPC) enclosing the used fuel. Holtec uses MPC designs to accommodate three different used fuel loading configurations: up to 24 PWR assemblies, up to 32 PWR assemblies, or up to 68 boiling water reactor (BWR) assemblies.

The package inner shell is stainless steel, and six layers of carbon steel plates comprise the gamma shield. The next layer is a polymeric neutron shield, strengthened by a network of carbon steel stiffening fins. The outer shell of the package is carbon steel, with a painted surface. Aluminum honeycomb impact limiters with stainless steel skin are installed on the ends of the package prior to shipping. These impact limiters protect the closure lid, MPC, fuel basket, and contents from damage in the event of a package drop accident. The impact limiters also provide thermal insulation to the lid and port cover components in the event of a fire exposure. This package weighs approximately 277 300 lbs (125 781 kg) when loaded for transport.

The MPC-24 configuration was selected for the Baltimore Tunnel fire study. This configuration of design has an integral fuel basket that accommodates 24 PWR used fuel assemblies with a maximum total decay heat load of 68 240 BTU/hr (20 kW). The MPC is placed in the transportation packaging for shipment after it has been loaded with used nuclear fuel and welded shut.

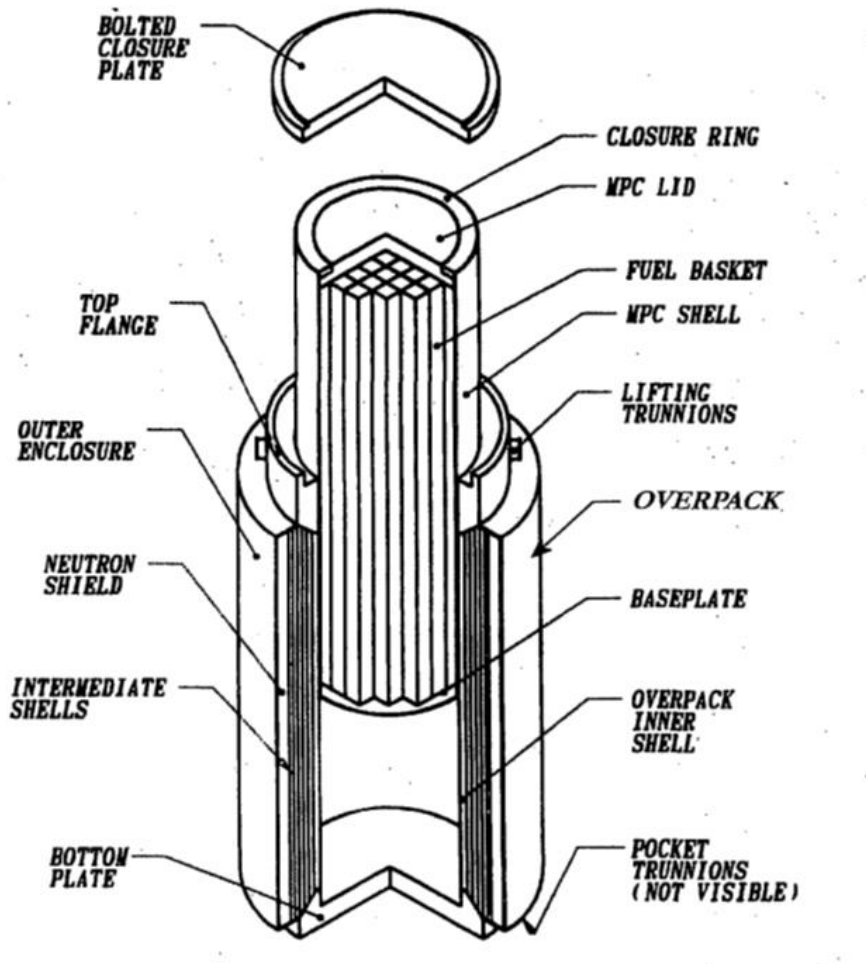


Figure F-1: Exploded view of the Holtec Hi-Star 100

F.2 TRANSNUCLEAR TN-68 TRANSPORTATION PACKAGE

The TN-68 is a Type B package used to ship BWR used fuel assemblies (Figure F-2) by rail. The basic design is similar to that of the Holtec HI-STAR 100, except that the TN-68 package does not include an inner seal-welded canister.

The containment boundary is provided by the package shell and lid seals. The TN-68 package holds up to 68 BWR assemblies, with a maximum total decay heat load of 72 334 BTU/hr (21.2 kW). The fuel assemblies are contained within a basket structure consisting of 68 stainless steel tubes that have aluminum and borated aluminum (or boron carbide/aluminum composite) neutron poison plates sandwiched between the steel tubes. The basket structure is supported by aluminum alloy support rails bolted to the inner carbon steel package shell, which also serves as the inner gamma shield. This inner steel shell is shrink-fitted within an outer carbon steel shell that serves as the outer gamma shield. The gamma shielding is surrounded by the neutron shielding, which consists of a ring of aluminum boxes filled with borated polyester resin.

The outer shell of the package is carbon steel. The package bottom is carbon steel with an inner steel shield plate. The package lid is also carbon steel with a steel inner top shield plate. During transport, the ends of the package are capped with impact limiters made of redwood and balsa and covered in stainless steel plate. The TN-68 weighs approximately 260 400 lbs (118 115 kg) when loaded for transport.

The TN-68 was one of the three packages used to evaluate the potential effects of an accident of the magnitude and severity of the Baltimore Tunnel Fire.

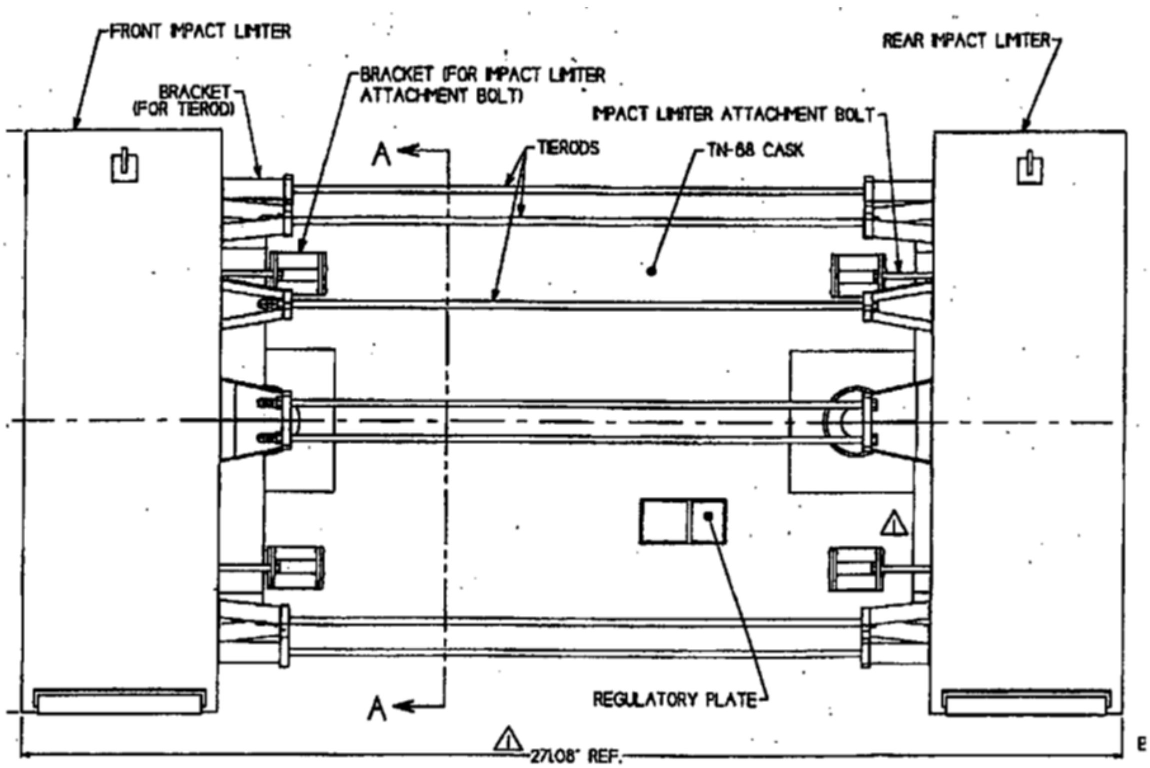


Figure F-2: Engineering drawing of the TN-68 transportation package

F.3 NAC-LWT TRANSPORTATION PACKAGE

The NAC-LWT (Figure F-3) is a Type B package certified for transport on a standard tractor trailer truck, and which can also be transported by rail. The NAC-LWT is typically enclosed within an International Organization for Standardization (ISO) shipping container when shipped by rail. This package is designed to transport a variety of commercial and test reactor fuel types with widely varying maximum decay heat load specifications. For the purpose of the Baltimore Tunnel study, the package was assumed to contain a single PWR used nuclear fuel assembly, with a maximum decay heat load of 8 530 BTU/hr (2.5 kW). The loaded package weighs approximately 52 000 lbs (23 586 kg).

The containment boundary provided by the stainless-steel package consists of a bottom plate, outer shell, upper ring forging, and closure lid. The package has an additional outer stainless-steel shell to protect the containment shell, and also to enclose the lead gamma shield. Neutron shielding is provided by a stainless-steel neutron shield tank containing a water/ethylene glycol mixture. An additional annular expansion tank for the mixture is provided, external to the shield tank. This component is strengthened internally by a network of stainless-steel stiffeners. Aluminum honeycomb impact limiters covered with an aluminum skin are attached to each end of the package.

The NAC-LWT package was also used to evaluate the potential effects of the Caldecott Tunnel Fire.

Figure F-3: NAC-LWT transportation package on display

F.4 GA-4 LEGAL WEIGHT TRUCK TRANSPORATION PACKAGE

The General Atomics GA-4 legal weight truck (LWT) Type B package can carry a relatively large payload for a legal weight truck package, and therefore the potential consequences of package failure could be more severe than for packages with smaller payload capacities. The GA-4 package is designed to transport up to four intact PWR used fuel assemblies with a maximum decay heat load of 2 105.4 BTU/hr (0.617 kW) per assembly, for a total package decay heat load of 8 423 BTU/hr (2.468 kW). The GA-4 can carry zircaloy-clad UO_2 fuel with maximum initial enrichment of 3.15% U-235, in 14x14 assemblies with maximum average burnup of 35 GWd/MTU (minimum cooling time of 10 years), or 15x15 assemblies with maximum average burnup of 45 GWd/MTU (minimum cooling time of 15 years).

The stainless-steel package body encloses the gamma shield, which consists of an inner shell of depleted uranium (DU). Neutron shielding is provided by a stainless-steel neutron shield tank external to the package body, containing a water/propylene glycol mixture. Aluminum honeycomb impact limiters, completely enclosed in a thin stainless steel outer skin and inner housing, are attached to each end of the package.

This transportation package (Figure F-4) was selected to evaluate the potential effects of an accidents of the magnitude and severity of the Newhall Pass Tunnel and MacArthur Maze fires on an NRC-certified UNF Type B transportation package.

For the purpose of the Newhall Pass Tunnel fire analysis, the package was assumed to contain four Westinghouse Electric 14x14 PWR used nuclear fuel assemblies at the maximum decay heat load. The payload capacity is 6 648 lbs (3 015 kg), and the fully loaded package weighs approximately 55 000 lb. (24 948 kg). The package containment boundary is provided by the stainless-steel package body wall, the stainless-steel bottom plate, the stainless-steel package closure lid secured by Inconel fasteners and dual O-ring seals for the closure lid, gas sample port, and drain valve.

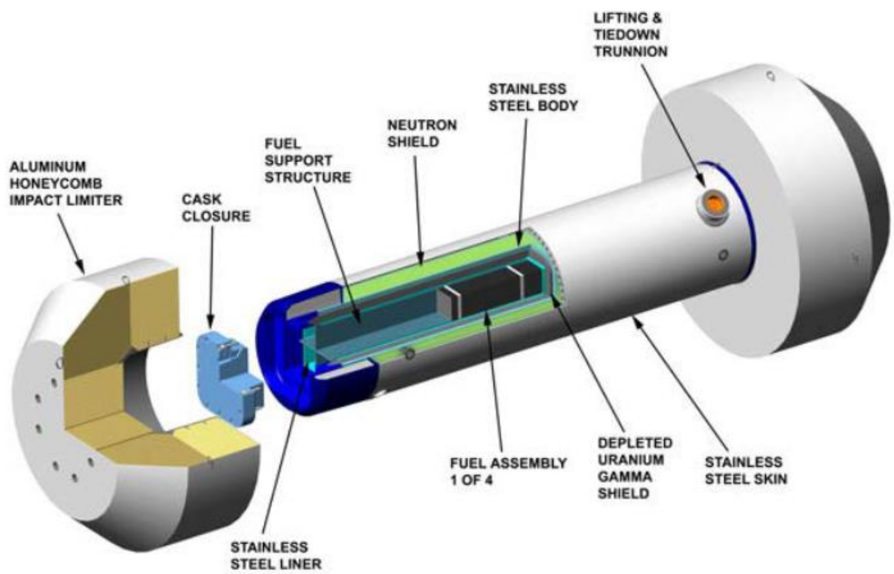


Figure F-4: Exploded view of the GA-4 legal weight truck transportation package

APPENDIX G SURVEY OF SEVERE CANADIAN ACCIDENTS (1979-2022)

Location	Date	Type	Deaths	Dangerous Goods		Number of Vehicles		Notes
				Good	Released (liters)	Train Total	Derailed	
Mississauga, ON [90], [91], [92]	1979	Train Derailment (72 km/h)	0	Caustic Soda Propane Styrene Toluene Chlorine	Release occurred from all derailed tank cars, except for one toluene tank car	3 locomotives 106 railcars	24 railcars Caustic soda (4) Propane (12) Styrene (3) Toluene (3) Chlorine (2)	Three propane tank cars exploded. Fires lasted 48 hours. Chlorine gas was released causing major evacuations.
Hinton, AB [93]	1986	Train Collision/ Derailment (95 km/h freight train, 79 km/h passenger train)	23	Caustic Soda Ethylene dichloride	None	3 locomotives 114 railcars 1 caboose	35 grain cars 7 flat bed - (pipe) 45 hopper cars (Sulphur)	Fire was fueled by the spilled locomotive diesel oil. Fire engulfed the lead units of each train, the baggage car and day coach. On Train 413 the 3 diesel locomotives, the high-speed spreader, 35 grain hopper cars, 7 flat cars carrying large pipes and 33 hopper cars carrying sulphur were destroyed or damaged.

Location	Date	Type	Deaths	Dangerous Goods		Number of Vehicles		Notes
				Good	Released (liters)	Train Total	Derailed	
Lac Mégantic, QC [94], [95]	2013	Train Derailment (105 km/h)	47	Crude Oil	6 000 000	72 tank cars 1 boxcar 5 locomotives 1 caboose	63 tank cars (DOT Class 111) 1 box car	40 buildings destroyed, 2000 people evacuated.
Gladwick, ON [96]	2015	Train Derailment (61 km/h)	0	Crude Oil (68 tank cars) Petroleum Distillates (32 tank cars)	1 700 000	100 railcars 2 locomotives	29 tank cars (19 breached)	Crude oil pooled and ignited. 19 tank cars were breached in the initial derailment. 5 tank cars subsequently suffered thermal tears. Fires burned for 5 days.
Gogama, ON [97]	2015	Train Derailment (69 km/h)	0	Crude Oil	2 600 000	94 tank cars 2 locomotives	39 tank cars (TC/DOT Class 111, CPC-1232) (33 breached)	33 tank cars were breached and released crude oil. Fire reached about 275 meters in diameter.
St. Lazare, MB [98]	2019	Train derailment (79 km/h)	0	Crude Oil	815 000	108 tank cars	37 tank cars (TC/DOT Class 117R) (17 breached)	Following the derailment, crude oil pooled near a culvert on the north side of the rail line. No fire.

Location	Date	Type	Deaths	Dangerous Goods		Number of Vehicles		Notes
				Good	Released (liters)	Train Total	Derailed	
Emo, ON [99]	2020	Train derailment (71 km/h)	0	Crude Oil	319 731	144 freight cars	29 tank cars (Mix of TC/DOT Class 111, CPC-1232, and DOT 117 R) 28 crude oil 1 asphalt 4 non-DG (8 breached)	No fire reported.
Guernsey, SK [100]	2020	Train derailment (67 km/h)	0	Crude Oil	1 200 000	108 cars	32 tank cars DOT 117J100-W (19 breached)	Following the derailment, crude oil pooled and caught fire.

APPENDIX H POTENTIAL HAZARDS FROM BREACH OF A TANK CAR TRANSPORTING DANGEROUS GOODS

Most severe transport accidents in Canada involved the rupture (breach) of tank cars carrying flammable liquids. Two examples are the 1979 Mississauga and 2013 Lac Mégantic accidents. This appendix briefly describes the ways that tank cars fail in rail accidents and the consequences of such failures. For context, a comparison is made between the characteristics of shipments of flammable dangerous goods by tank car shipments and UNF shipments.

H.1 DANGEROUS GOODS SHIPPED IN TANKS CARS

Table H-1 shows the characteristics of several dangerous goods that are commonly shipped in tank cars, along with the characteristics of used fuel and radioactive material. The primary accident hazards in shipping these dangerous goods in tank cars are fire, explosion and release of toxic chemicals from tank car containment failure.

Table H-1: Characteristics of some dangerous goods

Type	Shipment Frequency	Physical Form	Primary Hazard(s)	Dangerous Goods Class
Gasoline	High	Liquid	Fire, Explosion	Class 3
Chlorine	High	Gas	Poison, Inhalation	Class 2.3 Class 8
Flammable Gas	High	Gas	Fire, Explosion	Class 3
Flammable Liquid	High	Liquid	Fire, Explosion	Class 3
Diesel Fuel	High	Liquid	Fire, Explosion	Class 3
Used Nuclear Fuel	Low	Solid	Radiation Exposure	Class 7
Radioactive Material	Low	Solid	Radiation Exposure	Class 7

As Table H-1 shows, there are numerous types of dangerous goods that are commonly shipped as flammable liquids or gases. For example, the Lac Mégantic accident involved shipping large quantities of flammable liquids, and the primary hazard in the Mississauga accident was the rupture of a chlorine tank car. A significant release of dangerous goods that are in liquid or gaseous form can occur if the tank car is breached or ruptured.

H.2 FAILURE MODE FOR TANK CARS IN ACCIDENTS

The various ways that a tank car can rupture are shown in Figure H-1. Although these illustrations (taken from the Lac Mégantic accident) are for U.S. Department of Transportation (DOT) Class 111 tank cars, they are typical for most other tank car types. The breaches fall into two major categories involving either the failure of the tank car inlet and outlet or a breach in the tank wall. Some of the breaches, such as the failure of the inlet/outlet valves, cause slow or moderate leaks resulting in the pooling of flammable liquids and subsequent fire or vapor detonation explosions. The wall of the tank car can be breached by puncture, burn-through or a thermal tear. Thermal tears can involve a more rapid release as a result of BLEVE.

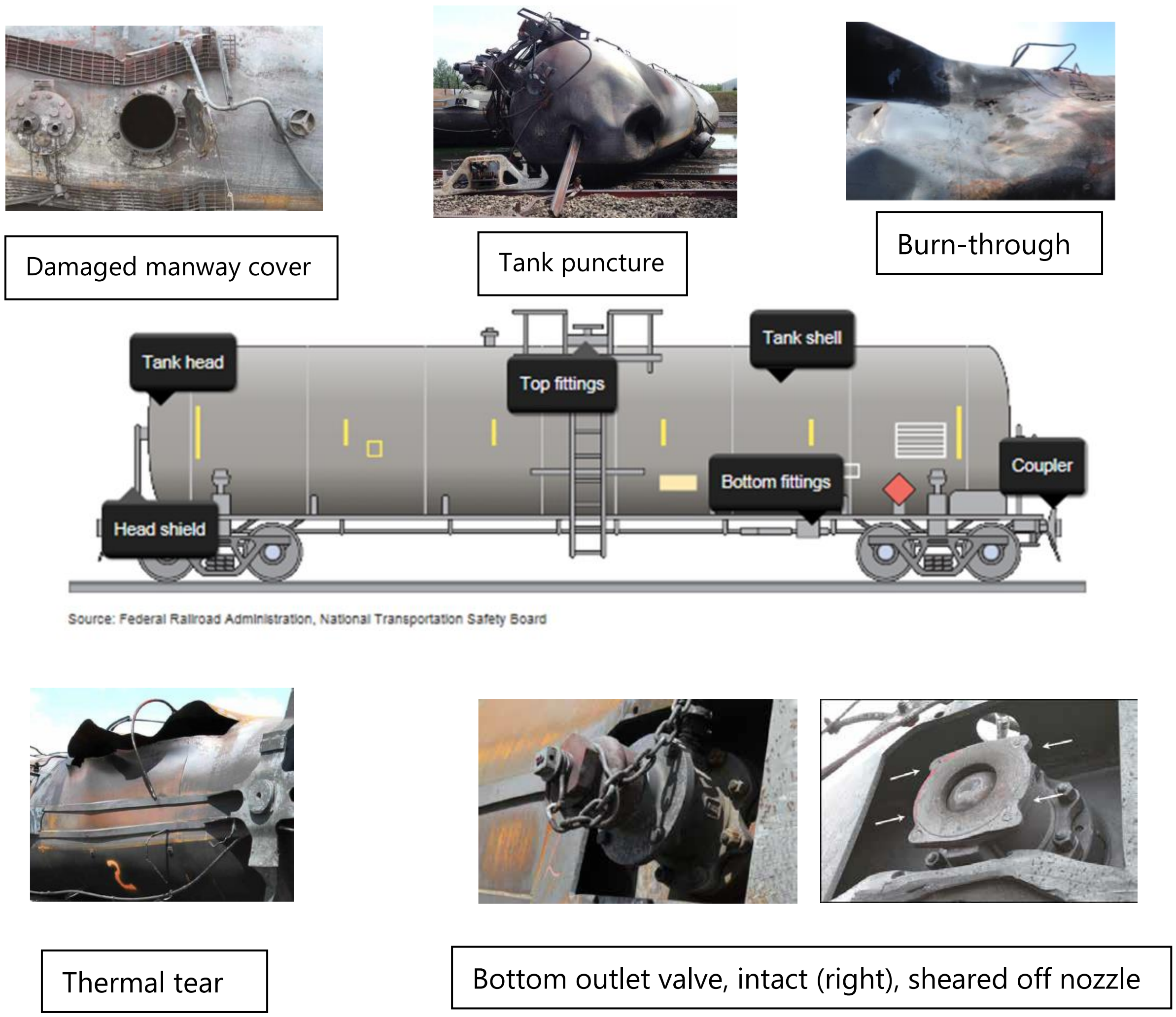


Figure H-1: Rupture modes for DOT class 111 tank cars

H.3 CONSEQUENCE OF A TANK CAR FAILURE

The consequences of a tank breach can vary for each tank car, depending on the type of breach. Figure H-2 shows the possible pathways that accidents involving a breach can follow. The most severe consequences result from BLEVEs, vapor cloud detonations (VCDs) and severe pool fires.

A BLEVE results in a tank car being burst apart, and can cause large tank fragments to be ejected at high speeds. The potential impact of a BLEVE on a UNF package was demostrated in 1999 by the German Federal Institute for Materials Research and Testing (BAM) using a tank car with liquified propane gas that BLEVEs next to a CASTOR used fuel package (see Section 4.4.1 of the report). BAM demonstrated that a UNF package could withstand the shockwave from a BLEVE with very little damage. VCDs are explosions that have blastwaves that are generally of the same order of magnitude as those occuring in a BLEVE. The main difference between a VCD and a BLEVE is that no tank fragments are ejected in a VCD as the explosion occurs external to the tank car. The potential impact of a pool fire on a UNF package depends on many variables, such as temperature, duration and location of the fire, position of the UNF package within the fire, mass (i.e., thermal inertia) of the package, and design of the lid sealing area or welded closure area.

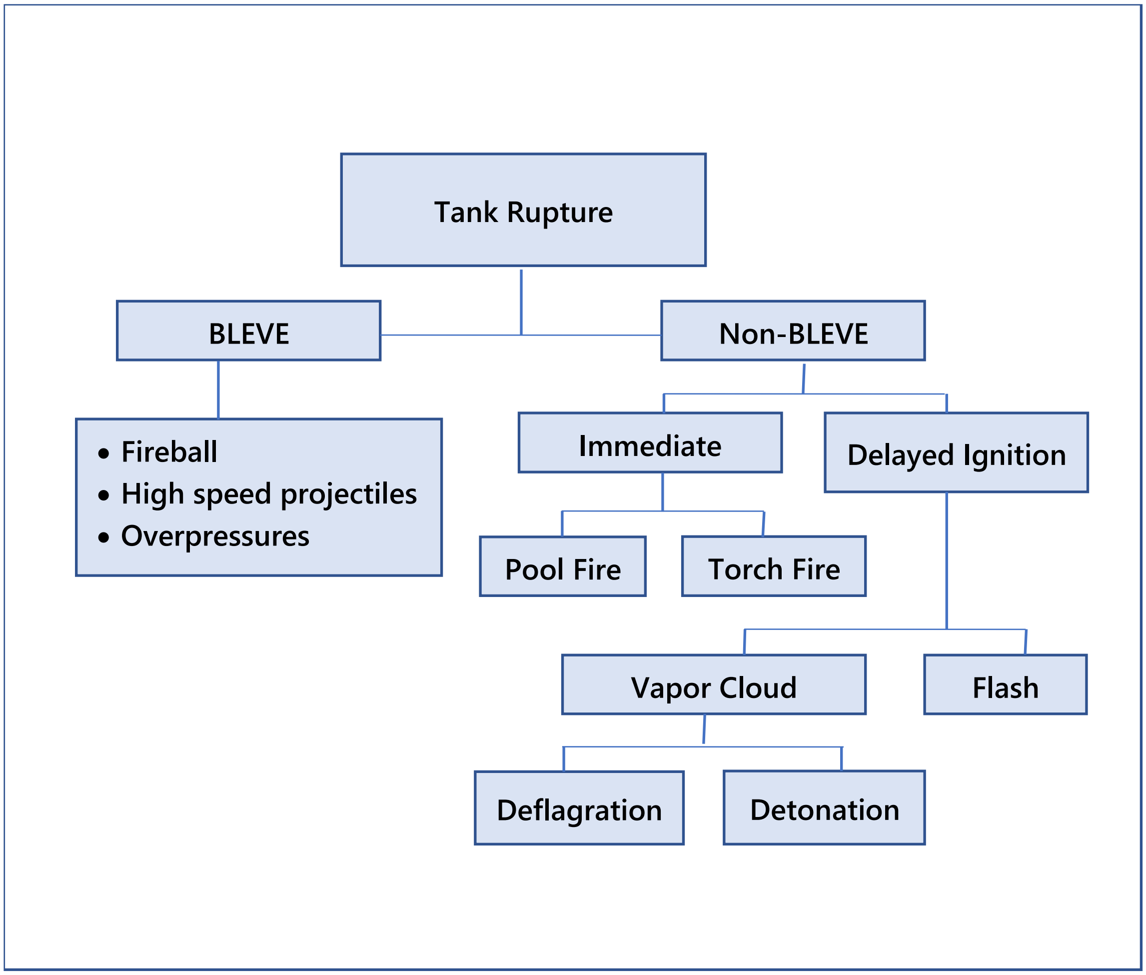
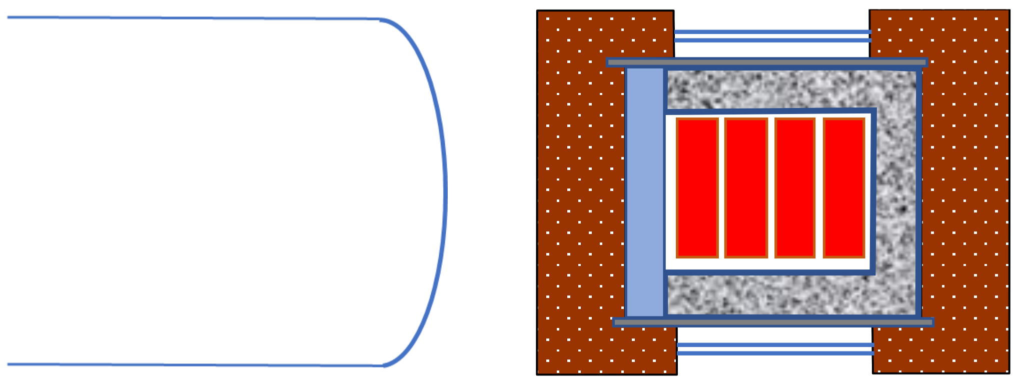


Figure H-2: Accident pathways resulting from the rupture of tank car

H.4 COMPARISON OF SHIPMENTS MADE IN TANK CARS VERSUS UNF SHIPMENTS

Figure H-3 shows a comparison of the characteristics of a shipment of a flammable liquid or gas made in a tank car versus the shipment of UNF made in a Type B package.

Flammable liquids and gases are frequently shipped in tank cars with relatively thin walls ranging from 1 to 2.5 cm thick. This often results in tank punctures and ruptures leading to fires and explosions in severe accidents. A used fuel package certified to Type B safety standards is designed to withstand severe transport accidents. Demonstration tests (Section 4) and analyses based on accident reconstructions (Section 5) have consistently shown that certified UNF package designs can resist the most severe real-world accidents, including severe accidents involving the derailment of trains carrying flammable dangerous goods.



Cross section of Tank Car

Cross section of UNF Package

Materials with high frequency of shipments Highly dispersible materials – primarily gases and liquids Poisonous, flammable, or explosive properties	Materials with low frequency of shipments Low dispersible materials – primarily solids Not flammable or explosive

Figure H-3: Comparison of shipment made in tank cars versus UNF shipments

In contrast, a UNF package contains a solid low dispersible material that will not explode or cause a fire and has a low frequency of shipments. UNF packages designed to meet Type B package standards result in thick-walled packages (see Section 3.2.1.3) that contain no exposed openings and lids that are welded or bolted shut.

APPENDIX I RELEASE PATHWAYS FOR RADIOACTIVE MATERIAL IN SEVERE TRANSPORTATION ACCIDENTS

There are two main barriers to the release of radioactive material from used fuel packages during a severe transportation accident. The first barrier is the design of the transportation package itself. Used fuel is transported in a Type B package that is designed to withstand severe accidents without a significant loss of containment or an increase in external radiation that would endanger first responders or the general public. In meeting the Type B design standards, the package designer must demonstrate that a package can prevent puncture and protect the lid or welded closure from being significantly damaged or displaced, thus showing that radioactive material is being adequately contained.

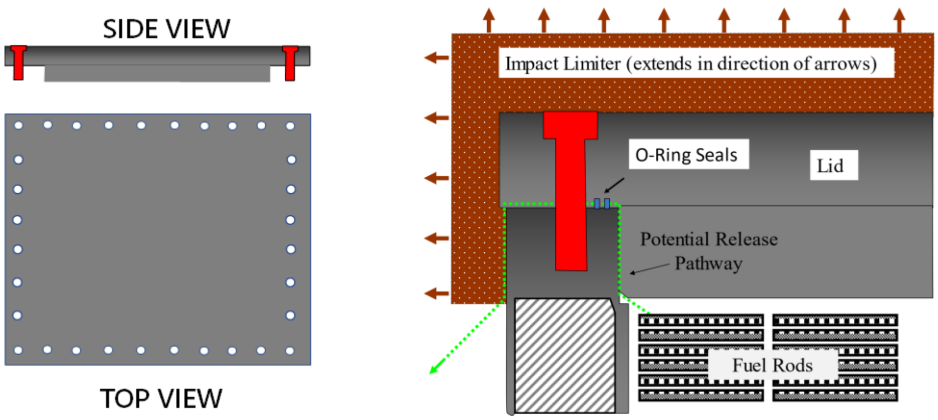
The second barrier is the fuel rod cladding or sheathing. The sheathing for most commercial nuclear fuel is made from zirconium metal alloy, which is fabricated into metal tubes. These tubes contain uranium dioxide pellets. The tubes are pressurized to resist collapse or leaks when used in the high-pressure operating environment of a nuclear reactor core. Fuel rods are grouped together in bundles using metal structural supports. These supports help prevent fuel rods from buckling in a severe transportation accident. The intact sheathing provides a containment barrier that prevents used nuclear fuel particles from escaping from within the tubes to the inside of the package. CANDU fuel sheath failure may occur if the internal gas pressure inside a fuel tube causes the sheathing to strain. The sheathing for CANDU fuel approaches the onset of ballooning (a precursor to sheath failure due to overstrain) once its temperature surpasses approximately 650°C [101].

The release of a significant quantity of radioactive material from a loaded Type B used fuel transport package during a severe accident would occur only if the package and one or more fuel rods were breached. A breach in a fuel rod could occur from either mechanical or thermal rupture.

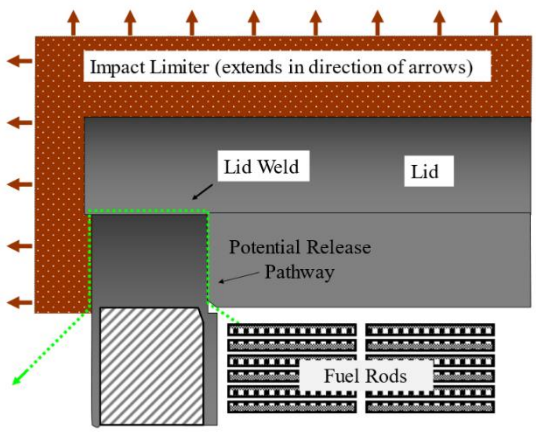
Figure I-1 illustrates the pathways from which radioactive material could be released from a UNF package having both bolted and welded lids. The potential release path for a package with a bolted lid leads from inside the package through the tight clearance between lid and the inner wall of package, passes by double O-ring seals, then through the clearance between lid and package's lid sealing surface. The clearance between the lid and the lid sealing surface is very narrow, plugs easily, and prohibits all but the tiniest particles from passing. The clearance is very narrow because the lid is clamped down by a large number of highly torqued (tightened) bolts.

The package will only leak when the lid is somehow dislodged or distorted, and the fuel sheathing is breached.

The potential release path for a package with a welded lid leads from inside the package through the tight clearance between lid and the inner wall of package, then through a crack in the weld. The package will only leak when the lid weld is cracked, and the fuel sheathing is breached.



Release Pathway for Bolted Lid



Release Pathway for Welded Lid

Figure I-1: Pathways for release of radioactive material

APPENDIX J MISSISSAUGA TRAIN DERAILMENT

J.1 THE ACCIDENT

The Mississauga train derailment was a railway accident that occurred a few minutes before midnight on November 10, 1979, in Mississauga, Ontario, Canada. The accident involved a Canadian Pacific Railway (CPR) freight train carrying a variety of dangerous goods, including propane, toluene, styrene, and chlorine. At the point of derailment, the train was traveling about 80 km/h. In total, 24 cars derailed. Fire spread through most of the derailed cars, and three tank cars that were loaded with propane exploded causing considerable property damage. A tank car carrying chlorine suffered a 76 cm (2½ foot) diameter hole, and because of concern of the health effects of escaping chlorine, approximately 218 000 people were evacuated from the city of Mississauga and its surrounding areas for periods of up to five days. Fortunately, there were no fatalities resulting from the accident, but over 200 people were injured, mostly due to exposure to toxic chemicals. The cause of the accident was determined to be a broken rail, which caused the train to derail.

J.2 THE TRAIN AND ITS CARGO

At the time of the derailment, the freight train consisted of 3 engines and 106 cars. Eighty-four cars were loaded (38 with dangerous goods) and 22 were empty. Twenty-four of the 106 cars derailed. These cars were in the 33rd through 56th positions in the train. Figure J-1, taken from the Grange Accident Inquiry [90], shows the contents and final positions of the 24 derailed cars. In Figure J-1, the derailed cars are numbered from 1 through 24. The derailed train cars were carrying the following dangerous goods:

- Cars 1,16 and 24 : Toluene – colorless flammable liquid (boiling point: 110 °C) shipped in 18 400-gal (69 651 L) DOT 111 tank cars.
- Cars 3,4,5 and 6 : Caustic Soda - sodium hydroxide solution (boiling point: > 142 °C)
- shipped in 18 400-gal (69 651 L) DOT 111 tank cars.
- Car 7 : Chlorine – toxic gas (boiling point: -34 °C) shipped in 17 360-gallon (65 715 L) DOT-105 tank cars.
- Cars 8,12,13,14, 17-23: Propane – flammable liquid (boiling point: -42 °C) shipped in DOT-117 tank cars.
- Cars 9, 10 and 11 : Styrene monomer – clear pale yellow oily liquid (boiling point: 145 °C) shipped in 26 000-gallon (98 421 L) DOT-111 tank cars.

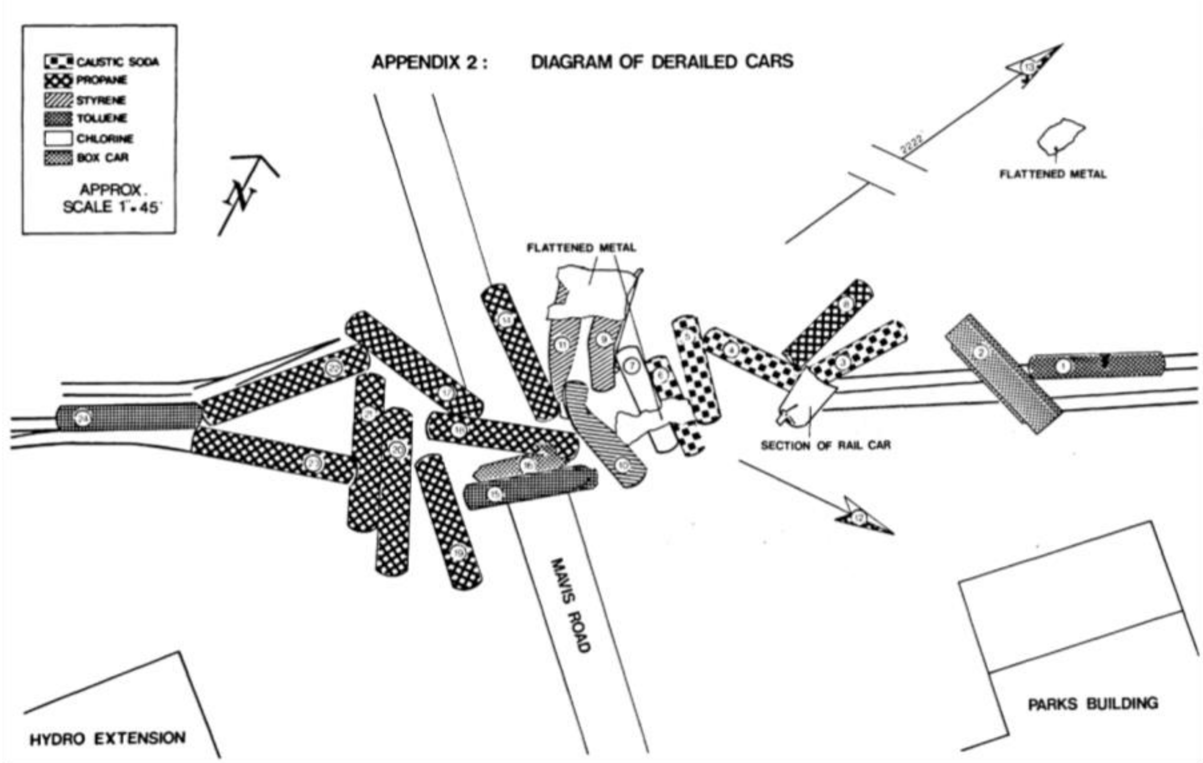


Figure J-1: Derailment diagram from Accident Inquiry [90]

J.3 THE TIMELINE AND CONSEQUENCES

The derailment occurred at appoximatelly 11:56 p.m. on November 10, 1979. An explosion and fireball occurred shortly thereafter. This explosion and fireball were the result of a propane tank car (car 8) undergoing a boiling liquid expanding vapour explosion (BLEVE) [21].

A second explosion was reported at 1:09 a.m (November 11), followed by a third explosion at 1:16 a.m. Both of these explosions were attributed to propane tank cars (Cars 12 and 13) undergoing BLEVEs. During a BLEVE, a tank car will fragment into pieces forming projectiles that travel at high speed and can be thrown large distances (~1 km). Shock waves from a BLEVE can lead to damaging overpressures resulting in structural damage to buildings, etc. Simultaneously, the liquid/vapors are ignited to form a spherical partially pre-mixed flame termed a fireball. As much as one third of contents of a propane tank car can be consumed in a fireball. A typical fireball from a railcar carrying hydrocarbons will last from 10 to 30 seconds and can have a diameter of 200 to 300 meters [102]. Figure J-2 illustrates a fireball from the Mississauga derailment.

[21] BLEVE - an explosion resulting from the failure of a vessel containing a liquid at a temperature significantly above its boiling point at normal atmospheric pressure. BLEVEs can be caused by structural damage to a tank car, or by pool fire impinging on a tank car increasing its temperature and pressure causing the tank to rupture.

Figure J-2: Mississauga derailment - Left: Fireball, Right: Propane tank car fires

After the initial fireball, a fire from a propane tank car will generally be confined to or near the point of release from the tank car. Propane will generally not form liquid pools because it vaporizes rapidly at or above room temperature.

The police were the first to respond arriving shortly after midnight. The fire department responded within eight minutes of the derailment (12:04 a.m.) and deployed fire fighting equipment. In fighting a propane fire, it is not always necessary to extinguish the fire. The main objective is to cool the tank car to avert a BLEVE. In fact, if a propane tank car fire is extinguished without being able to seal the leak, a subsequent explosion could result. In most accidents involving propane tank cars, the remaining propane in a tank car is subsequently flared off as it represents the safest way to remove it. Figure J-3 depicts a flaring operation that was undertaken during the aftermath of a propane train derailment in Weyauwega, Wisconsin (March 8-16, 1996). This flaring operation can result in a precautionary evaluation of surrounding areas and often results in accidents being reported with a long duration when the immediate danger is long past.

Figure J-3: Tank flaring in Weyauwega, Wisconsin

At 2:35 a.m., the fire was reported to be contained. The contained fire for the Mississauga derailment is shown in Figure J-4. Note that the fires are located at the points of release from the tank cars and that none of the railcars are “fully engulfed” by fire. Beyond this point, there were no explosions or periods where the fire was not firmly under contol.

Figure J-4: Fire containment in the Mississauga derailment

After the fire was contained, the focus of the accident response was on preventing the further release of chlorine and moving people beyond harm’s way. As stated in the Accident Inquiry report:

> “*The main problem, however, was not with the propane explosions however spectacular and potentially dangerous they may have been. What most concerned the authorities was that it was apparent almost from the beginning that some Chlorine was escaping into the air and it became known at least by the early morning of Monday, November 12, that Car 7 in the derailment, the Chlorine car, had a hole between 2 and 3 feet in diameter. No one could make an exact measurement of the amount of Chlorine remaining in the car and no one could give a guarantee that what remained would not be released in either the process of sealing the hole or in the process of removing the Chlorine from the sealed tank. As a result, a large portion of Mississauga together with a small part of Oakville to the west and isolated pockets of Etobicoke, a Borough of Metropolitan Toronto to the east, was evacuated on Sunday, November 11, and the area of Mississauga from Burnhamthorpe Road south to Lake Ontario, and from Highway 10 on the east to Erin Mills Parkway and Southdown Road on the west-an area of about 45 square kilometers (17.4 square miles) involving close to 75 thousand people remained evacuated until Friday, November 16 . Even then, however, the Chlorine car was not completely empty . The draining of Chlorine and the clean-up of the site continued for some days, once again fortunately without casualty.*”

J.4 POTENTIAL IMPACT ON A USED NUCLEAR FUEL PACKAGE

Several aspects must be considered when evaluating the performance of a used fuel package, such as the Dry Storage Container Transportation Package (DSC-TP), had it been in an accident such as the Mississauga train derailment. These include the potential damage to the package body or welded closure area from direct impact, puncture, explosions and long duration severe fires. The release of radioactive material will only occur if the DSC-TP side wall is breached or the lid (welded closure area) is severely damaged.

J.4.1 Direct Impact

The train was traveling approximately 80 km/h when it derailed. This speed represents an upper bound on impact speed. The impact to a DSC-TP would result from the DSC-TP colliding with an adjacent railcar, most likely in a side to side impact. This results from the tendancy of railcars to end up in accordion-like patterns in derailments.

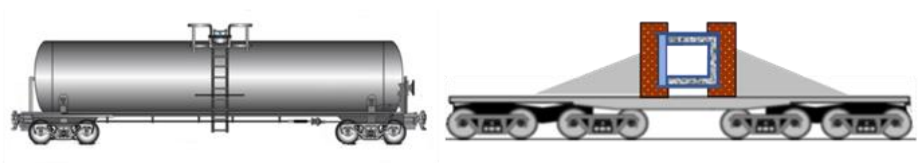


Figure J-5: Tank railcar (left) and used fuel railcar (right) – note that the DSC-TP is shipped horizontally

In addition, some of the impact force would be absorbed by the used fuel package transport railcar. Unlike tank railcars, used fuel packages are attached to the railcars using tie-downs. (Figure J-5). The SANDIA tests, described in Section 4.2, are an example of the ability of used fuel package railcars to absorb the forces of direct impact. The impact limiters for the DSC-TP also provide protection to the lid area during impact, and the side protection shield provides additional resistance to a side impact. The body of the DSC-TP is approximately 54.9 cm thick (i.e., a 52.3 cm concrete shell encased in two 1.27 cm carbon steel shells). The lid is sealed using multiple weld passes.

The impact forces experienced by the DSC-TP during the Mississauga train derailment would be several orders of magnitude lower than the forces measured in the 160 km/h train collision decribed in Operation Smash Hit (described in Section 4.3). Operation Smash Hit simulated a rail accident that consisted of a 140 metric ton locomotive traveling at 160 km/h colliding directly with a stationary 47 metric ton Magnox flask attached to a 13 metric ton railcar. The flask and railcar were oriented so that the locomotive would strike directly on the package lid edge at the most vulnerable orientation. The orientation of the flask was chosen to represent the most vulnerable location, near the lid seal region which consisted of a bolted lid and O-rings. The full-scale simulation demonstrated that the Magnox package could survive a severe rail accident with surficical surface damage, minimal damage to the lid seal region, and no significant release of radioactive materials.

In comparison, the DSC-TP is a heavier package (100 metric tons when loaded), and has a welded lid. The impact speeds and forces during the Mississauga derailment (which derailed at 80 km/h) are much smaller than the forces involved in a direct collision of a locomotive traveling at 160 km/h (such as Operation Smash Hit). The impact forces on the DSC-TP that would have occurred during the Mississauga train derailment would be not be sufficient to either breach the package wall or severely damage the package’s welded closure area.

J.4.2 Puncture

The DSC-TP has thick walls that are made of carbon steel encased concrete. The total wall thickness consists of a 52.3 cm (20.6 in) thick layer of concrete encased by two 1.27 cm (0.5 inch) thick carbon steel shells. The 52.1 cm (20.5 in) thick package lid consists of concrete encased in a carbon steel shell. The top and bottom of the package are protected by polyurethane foam impact limiters encased in stainless steel shells. The DSC-TP uses double layered side protection during transportation. The side protection consists of two layers – an inner stainless steel shell that is 1.3 cm (0.5 in) thick and an outer stainless steel shell that is 0.95 cm (0.375 in) thick. The shells extend downward from the top impact limiter and upward from the bottom impact limiter and overlap around the circumference of the DSC-TP.

Data from the U.S. Nuclear Regulatory Commission (NRC) and Association of American Railroads (AAR) (presented in Section 3.2.1.3) show that rail tank cars with thicknesses greater than one inch (2.54 cm) are highly unlikely to be punctured in severe rail accidents. Contrasting the AAR data to the wall and lid thicknesses of UNF packages, it is not expected that a breach of the package wall or severe damage to the package's welded closure area would take place in a derailment scenario, such as the Mississauga accident. Design features of the DSC-TP are shown in Section 3.4 of the report.

J.4.3 Explosion

The Mississauga train derailment resulted in the BLEVE of three propane tank cars. The impact damage from a BLEVE results from the shock waves created and the fragments of the exploding tank car that may be projected with great force and over long distances. Because the occurrence of BLEVEs is not uncommon in severe transportation accidents, the ability of used fuel packages to withstand the effect of a BLEVE has been studied by multiple research and regulatory bodies.

One study of particular relevance to the Mississauga train derailment is the physical demonstration test of a propane tank car BLEVE next to a CASTOR THTR/AVR used fuel package conducted by the German Federal Institute for Materials Research and Testing (BAM) [103]. The demonstration test is described in more detail in Section 4.4.1.

During the test, the propane tank BLEVE resulted in a severe impact of rail tank car fragments with the CASTOR package and caused the 22 450 kg package to be flipped over, landing 7-10 meters from its original location. The BLEVE caused only superficial damage (deep scratches and imprints from the impacting railcar fragments) to the package body and did not significantly affect the integrity of the package's bolted lids. The integrity of the package's lids was confirmed as the measured leak rate from the lid seals was the same before and after the test. The impact on the package was determined to be on the same order of magnitude from the regulatory drop test (9 meters onto an unyielding surface).

In comparison, the DSC-TP is a heavier package (100 metric tons when loaded) and has a welded lid. The impact forces from a BLEVE during the Mississauga derailment would be similar to those experienced in the BAM test since they both involved exploding propane tanks. The impact forces on the DSC-TP that would have occurred during from a BLEVE in the Mississauga train derailment would not be sufficient to either breach the package wall or severely damage the package's welded closure area.

J.4.4 Fire

The fires that occurred during the Mississauga derailment involved the burning of propane, toluene and styrene monomers. These fires burn at an average of approximately 800°C. In addition, the fire only lasted about 2 ½ hours before it was fully contained.

The impact of the fire on the DSC-TP would depend on the package's location in the fire. As a condition of approval, the DSC-TP was evaluated in a fully engulfing fire – this means that 100% of the package surface is exposed to the fire's heat flux. From the accident diagram (Figure J-1) and photos (Figure J-4) of the Mississauga train derailment, it is evident that one or more sides of the DSC-TP would likely be protected by the transport vehicle involved in the accident, or the fire would be only on one side of the package. The package would also rest on the ground which would reduce the surface area exposed in an accident as compared to the fully engulfing fire required in the regulations. In addition, the lid area is covered by impact limiters that act as insulators or heat shields.

Given the large thermal interia of the 100 metric ton DSC-TP, the relatively short duration of the fire (2 ½ hours) and the fact that the fire would not be fully engulfing, the package would be unlikely to experience temperatures that would adversely affect the integrity of the package body or lid seal region.

J.4.5 Summary

None of the forces (impact, puncture, or explosion), or the fire that occurred in the Mississauga train derailment would be sufficient to either breach the DSC-TP package wall or severely damage the package's welded closure area.

APPENDIX K HINTON TRAIN COLLISION

K.1 THE ACCIDENT

The Hinton train collision was a railway accident that occurred on February 8, 1986, near the town of Hinton, Alberta, Canada. The accident involved a westbound freight train and an eastbound passenger train, which collided head-on on a single-track section of the Canadian National Railway (CN) mainline. The passenger train was the Via Rail Canadian, enroute from Vancouver to Toronto, traveling at 79 km/h and was carrying 170 passengers and 2 crew. The freight train consisted of three locomotives and 114 loaded cars traveling at 95 km/h carrying a crew of three. The collision resulted in the deaths of 23 people, including two crew members on the freight train, and 19 passengers and two crew members on the passenger train. The freight train derailed. The cause of the accident was determined to be a breakdown in communication between the two trains and a failure of the automatic block signal system. After the crash, diesel fuel spilled from the locomotives and ignited, engulfing the locomotives, the baggage car, and the day coach.

Figure K-1: Hinton train collision – freight train (left) and passenger train (right)

Eighteen of the 36 occupants on the day coach were killed. The contents of a grain car were propelled on top of the day coach, helping to smother the fire. The observation dome car behind the day coach suffered serious damage and was also hit by a freight car. One of its occupants was killed. The others were able to escape either through a broken window in the dome or through the hole left by the freight car. The two sleepers following the dome car derailed and were thrown on their sides. There were no deaths in these cars, but there were several injuries. The three passenger cars at the rear of the train did not derail, but there were some injuries.

As the accident unfolded, the cars on the freight train piled up on each other, resulting in a large pile of rolling stock. The three freight locomotives and the first 76 cars of the freight train were either destroyed or damaged.

K.2 THE TRAINS AND THEIR CARGO

The freight train consisted of three locomotives, 114 loaded freight cars and a caboose as described in Table K-1. None of the railcars carrying dangerous goods derailed or released contents.

Table K-1: Composition of freight train

Freight Train Consist			
Position	**Type of Car**	**Contents**	**Accident Status**
1-3	Locomotives	2 crew	Derailed
4	Highspeed spreader	-	Derailed
5-39	Hopper cars	Grain	Derailed
40-46	Flat cars	78 Inch Diameter Pipe	Derailed
47-91	Open top hopper cars	Sulphur	33 Derailed
92-103	Tank cars	Caustic Soda	Did Not Derail
104-111	Tank cars	Ethylene Dichloride	Did Not Derail
112-117	Hopper cars	Grain	Did Not Derail
118	Caboose	1 crew	Did Not Derail

The composition of the passenger train is given in Table K-2. Ten cars from the passenger train derailed, including a day coach and dome car. The fatalities that occurred were in the first five cars.

Table K-2: Composition of passenger train

Passenger Train Consist			
Position	**Type of Car**	**Fatalities**	**Accident Status**
1-2	Locomotives	2 Fatalities (crew)	Derailed
3	Baggage Car	-	Derailed
4	Day Couch/ Lounge	18 Fatalities	Derailed
5	Dome Car/ Lounge	1 Fatality	Derailed
6	Sleeper	-	Derailed
7	Sleeper	-	Derailed
8	Locomotive	-	Derailed
9	Steam Generator Car	-	Derailed
10	Baggage Car	-	Derailed
11	Day-Nighter Coach	-	Did Not Derail
12	Café/Lounge Car	-	Did Not Derail
13	Sleeper	-	Did Not Derail
14	Steam Generator Car	-	Did Not Derail

K.3 POTENTIAL IMPACT ON A USED FUEL PACKAGE

Several aspects must be considered in order to evaluate the performance of a used fuel package, such as the Dry Storage Container Transportation Package (DSC-TP), in accidents such as the Hinton train collision. These include the potential damage to the package body or welded closure area from (1) direct impact, (2) puncture, (3) explosions and (4) long duration severe fires. The release of radioactive material will only occur if the DSC-TP body wall is breached, or the welded closure area is severely damaged.

K.3.1 Direct Impact

The passenger train (travelling at 79 km/h) and freight train (travelling at 95 km/h) collided at a combined speed of approximately 184 km/h. This speed represents an upper bound on impact speed. The combined impact speed of 184 km/h would only be experienced by the locomotives at the front end of the two trains. The cars that derailed on the freight train derailed at a much lower speed (< 95 km/h). In general, the speed of collision and impact forces of a railcar decrease with the distance of the railcar from the front or back of a train (i.e., point of collision).

The impact to a DSC-TP in a derailment would result from the DSC-TP colliding with an adjacent railcar, most likely in side-to-side impacts. This results from the tendency of railcars to end up in accordion like patterns in derailments. This accordion like pattern can be seen in Figure K-1 (left).

In addition, some of the impact force would be absorbed by the used fuel package transport railcar. Unlike rail tank cars, used fuel packages are attached to the railcars using tie-downs (Figure K-2). The SANDIA tests, described in Section 4.2, are an example of the ability of used fuel package railcars to absorb the forces of direct impact. The impact limiters for the DSC-TP also provide protection to the lid area during impact, and the side protection shield provides additional restistance to a side impact.

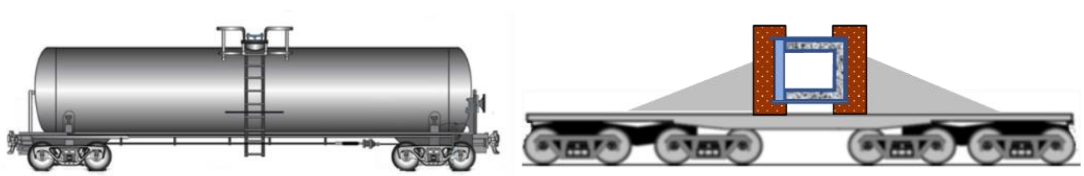


Figure K-2: Tank railcar (left) and used fuel railcar (right) – note that the DSC-TP is shipped horizontally

The impact forces experienced by the DSC-TP during the Hinton train collision and derailment would be significantly lower than the forces measured in the 160 km/h train collision described in Operation Smash Hit (described in Section 4.3). Operation Smash Hit simulated a rail accident that consisted of a 140 metric ton locomotive traveling at 160 km/h colliding directly with a stationary 47 metric ton Magnox flask attached to a 13 metric ton railcar. The flask and railcar were oriented so that the locomotive would strike directly on the package lid edge at the most vulnerable orientation. The orientation of the flask was chosen to represent the most vulnerable location, near the lid seal region which consisted of a bolted lid and O-rings. The full-scale simulation demonstrated that the Magnox package could survive a severe rail accident with superficial surface damage, minimal damage to the lid seal region, and no significant release of radioactive material.

In comparison, the DSC-TP is a heavier package (100 metric tons when loaded), and has a welded lid. The impact speeds and forces during the Hinton derailment (which derailed at 95 km/h) are much smaller than the forces involved in a direct collision of a locomotive traveling at 160 km/h (such as Operation Smash Hit). The impact forces on the DSC-TP that would have occurred during the Hinton train derailment would be not be sufficient to either breach the package wall or severely damage the package’s welded closure area.

K.3.2 Puncture

The DSC-TP has thick walls that are made of carbon steel encased concrete. The total wall thickness consists of a 52.3 cm (20.6 in) thick layer of concrete encased by two 1.27 cm (0.5 inch) thick carbon steel shells. The 52.1 cm (20.5 in) thick package lid consists of concrete encased in a carbon steel shell. The top and bottom of the package are protected by polyurethane foam impact limiters encased in stainless steel shells. The DSC-TP uses double layered side protection during transportation. The side protection consists of two layers – an inner stainless steel shell that is 1.3 cm (0.5 in) thick and an outer stainless steel shell that is 0.95 cm (0.375 in) thick. The shells extend downward from the top impact limiter and upward from the bottom impact limiter and overlap around the circumference of the DSC-TP.

Data from the U.S. Nuclear Regulatory Commission (NRC) and Association of American Railroads (AAR) (presented in Section 3.2.1.3) show that rail tank cars with thicknesses greater than one inch (2.54 cm) are unlikely to be punctured in severe rail accidents. Contrasting the AAR data to the wall and lid thicknesses of UNF packages, it is not expected that a breach of the package wall or severe damage to the package's welded closure area would take place in a derailment scenario such as the Hinton train collision and derailment. Design features of the DSC-TP are shown in Section 3.4 of the report.

K.3.3 Explosion

No explosions occurred in the Hinton rail collision. The only dangerous good on the freight train that could be involved in an explosion was ethylene dichloride – a flammable liquid. There are two types of explosions possible. The first is a boiling liquid expanding vapour explosion (BLEVE)[22]

[22] BLEVE - an explosion resulting from the failure of a vessel containing a liquid at a temperature significantly above its boiling point at normal atmospheric pressure. BLEVEs can be caused by structural damage to a tank car, or by pool fire impinging on a tank car increasing its temperature and pressure causing the tank to rupture.

resulting from the sudden vaporization of a liquid. The second type is a vapor cloud detonation (VCD) caused by the ignition of a flammable vapor cloud.

Ethylene dichloride has a boiling point of 83.5°C. Because the boiling point of ethylene dichloride is significantly higher than ambient temperature, a tank car carrying ethylene dichloride cannot undergo a BLEVE.

A VCD will only occur when the following five conditions are met: fuel, oxidizer, ignition source, dispersion and confinement. It is the lack of dispersion and confinement that keeps most flammable materials from exploding in VCDs. Therefore, the most likely result from the rupture of a tank car containing ethylene dichloride is a leak and subsequent fire.

If a VCD would have occurred, the impacts would likely be bounded by the physical demonstration test conducted by the German Federal Institute for Materials Research and Testing (BAM) of a propane tank car BLEVE next to a CASTOR THTR/AVR used fuel package [103]. The demonstration test is described in more detail in Section 4.4.1.

During the test, the propane tank BLEVE resulted in a severe impact of rail tank car fragments with the CASTOR package and caused the 22 450 kg package to be flipped over landing 7-10 meters from its original location. The BLEVE caused only superficial damage (deep scratches and imprints from the impacting railcar fragments) to the package body and did not significantly affect the integrity of the package’s bolted lids. The integrity of the package’s lids was confirmed as the measured leak rates from the lid seals was the same before and after the test. The impact on the package was determined to be on the same order of magnitude from the regulatory drop test (nine meters onto an unyielding surface).

In comparison, the DSC-TP is a heavier package (100 metric tons when loaded) and has a welded lid. The impact forces from a VCD during the Hinton train collision would be bounded by those experienced in the BAM test. The major difference between a BLEVE and VCD is that VCD does not involve the fragmentation and projection of tank fragments from the tank car. The shockwaves are similar. Based on the BAM test, it is likely that the explosive impact forces on the DSC-TP that would have occurred from a VCD in the Hinton train derailment would not be sufficient to either breach the package wall or severely damage the package’s welded closure area.

K.3.4 Fire

The fire that occurred during the Hinton collision and derailment involved the burning of diesel oil fuel leaking from the locomotives. Diesel oil fires burn at an average of approximately 800°C. Figure K-1 (left) and Figure K-3 show the localized nature of the fire. As such, the fire would not have impacted a used fuel package carried on the train.

If the fire had been more widespread[23], the impact of the fire on the DSC-TP would be determined by its location in the fire. As a condition of approval, the DSC-TP was evaluated in a fully engulfing fire – this means that 100% of the package surface is exposed to the fire's heat flux. From the accident photo in Figure K-1 (left) of the Hinton train collision, it is evident that the railcars ended up in accordion like patterns. This would likely result in one or more sides of the DSC-TP being shielded from the fire by an adjacent railcar. The DSC-TP would be shielded by the transport vehicle on which it is being transported. The package would also rest on the ground which would reduce the surface area exposed in an accident as compared to the fully engulfing fire required in the regulations. In addition, the lid area is covered by impact limiters that act as insulators or heat shields.

Figure K-3: Hinton collision showing the aftermath of a fire involving locomotives diesel fuel

Given the large thermal inertia of the 100 metric ton DSC-TP, and the fact that the fire would not be fully engulfing, the package is unlikely to experience temperatures that would adversely affect the integrity of the package body or lid seal region.

K.3.5 Summary

Neither the impact or puncture force that occurred in the Hinton train collision and derailment would be sufficient to either breach the package wall or severely damage the package's welded closure area. The Hinton collision resulted in a very localized diesel fire that would not have seriously impacted a used fuel package. There were no explosions. No release of radioactive

[23] The freight train was carrying eight tank cars of ethylene dichloride – a flammable liquid.

material or increase in external radiation would have occurred under the conditions actually experienced in the Hinton collision.

It is also highly unlikely that a release of radioactive material or increase in external radiation would have occurred had the collision resulted in a larger fire or vapor explosion from damage to one or more of the eight tanks cars of ethylene dichloride.

APPENDIX L JAMES SNOW PARKWAY

L.1 THE ACCIDENT

The James Snow accident occurred on March 24, 1986, when a gasoline tanker truck on Highway 401 near Milton, Ontario, collided with a flatbed truck. The gasoline tanker which was carrying 51 000 liters of gasoline rolled onto its side and slid down the highway to the James Snow Parkway overpass. The tanker then exploded and erupted into a fireball [104]. The Calgary Herald reported that the resulting fire caused concrete to burn away, exposing the inner steel reinforcing cables of the overpass[24] [104]. The tanker truck was reported to be an upside-down unrecognizable skeleton of a truck. The Ottawa Citizen reported that the intense heat from the fire melted the reinforcing rods in the concrete bridge [105].

L.2 POTENTIAL IMPACT ON A USED FUEL PACKAGE

Several aspects must be considered to evaluate the performance of a used fuel package, such as the UFTP, in accidents such as the James Snow Parkway collision. These include the potential damage to the package body or lid sealing area[25] from (1) direct impact, (2) puncture, (3) explosions and (4) long duration severe fires. The release of radioactive material will only occur if the package wall is breached, or the lid (sealing area) is severely damaged.

L.2.1 Direct Impact

The impact forces experienced by a UNF package during a tanker truck collision would be significantly lower than the forces measured in the 160 km/h train collision described in Operation Smash Hit (described in Section 4.3). Operation Smash Hit simulated a rail accident that consisted of a 140 metric ton locomotive traveling at 160 km/h colliding directly with a stationary 47 metric ton Magnox flask attached to a 13 metric ton railcar. The flask and railcar were oriented so that the locomotive would strike directly on the package lid edge at the most vulnerable orientation. The orientation of the flask was chosen to represent the most vulnerable location, near the lid seal region which consisted of a bolted lid and O-rings. The full-scale simulation demonstrated that the Magnox package could survive a severe rail accident with superficial surface damage, minimal damage to the lid seal region, and no significant release of radioactive materials.

[24] The reinforcing cables are steel cables and bars (rebars) used to reinforce concrete structures in the overpass. They are embedded in the concrete.
[25] The lid sealing area includes the lid, O-ring seals, and lid mating surface.

L.2.2 Puncture

The UFTP is a UNF package designed primarily for road transport. It has nearly 30 cm (11 inch) thick stainless steel walls and lid. During transport, the top of the UFTP is protected by an impact limiter consisting of a redwood core enclosed within a stainless steel shell.

Data from the U.S. Nuclear Regulatory Commission (NRC) and Association of American Railroads (AAR) (presented in Section 3.2.1.3) show that rail tank cars with thicknesses greater than one inch are unlikely to be punctured in severe rail accidents. Contrasting the AAR data to wall and lid thicknesses of UNF packages, it is not expected that a breach of the package wall or severe damage to the package's sealing area would take place in a derailment scenario such as the James Snow Parkway accident. Design features of the UFTP are shown in Section 3.4 of the report.

L.2.3 Fire

The James Snow accident involved a fire that occurred in a “partially enclosed” space. Fires occurring in enclosed spaces generally involve higher temperatures, and are more engulfing than pool fires that occur in the open [106], [107], [108], [109], [110]. In an open pool fire, a significant amount of heat is transferred to the environment by the buoyancy of the flames. As the heated combustion products rise, the fire draws in fresh cooler air creating a turbulent air flow. This process is referred to as air entrainment. For hydrocarbon fuels, the turbulent flame temperature is independent of the fuel and can be approximated by 800°C [111]. In contrast, in an enclosed or partially enclosed fire, much of the heat from the rising hot gases is transferred to the surface of the enclosure where it is reradiated back to the package surface. This results in higher flame temperatures in enclosed spaces than those that are characteristic of open pool fires.

Table L-1 shows several highway accidents that have been evaluated to determine what impact a fire occuring in an enclosed space might have on a used fuel package. The temperatures generally range about 200 to 300 degrees centigrade higher than the 800°C found in open pool fires. In the first two accidents, the fire was caused by a ruptured gasoline tanker. The third accident involved multiple trucks carrying common goods, mostly food stocks. The fire durations were determined from accident reports. The MacArthur Maze accident was modeled as a two part fire: a 37 minute fire at 1040°C followed by a 71 minute fire at 900°C.

Table L-1: Accidents involving fires in enclosed spaces

Accident	Type	Fuel Source	Used Fuel Package	Maximum Fire Temp.	Fire Duration
Caldecott Tunnel [112]	Enclosed highway tunnel	33 310 liters gasoline	NAC-LWT	1040°C	40 min
MacArthur Maze [113]	Highway underpass	32 554 liters gasoline	GA-4	1100°C 900°C	37 min 71 min
Newhall Pass [114]	Highway underpass	Common Goods	GA-4	1088°C	33 min

The James Snow accident involved an overturned tanker truck carrying approximately 51 000 liters of gasoline. Thus, it would be possible that the flame temperature in an accident similar to the James Snow accident could exceed the fire test temperature of 800°C, and could be as high as 900-1100°C (similar to the MacArthur Maze fire described above).

As described in Appendix I, there are two main barriers that prevent the release of radioactive material in severe accidents: the package lid seals and the used fuel sheathing. Both must fail to result in the release of radioactive material from the package. When the lid is bolted, the seal comes from two O-rings that are compressed between the lid and package body by the clamping forces of highly torqued bolts. Thus, in a severe fire the operating temperature of the O-rings becomes important. If the operating temperature is exceeded, the lid seals are assumed to have lost the ability to provide a seal. Even if the lid seals are assumed to have failed, the clearance between the lid and package body remains tight and prevents the release of all but the very smallest particles.

Table L-2 shows the characteristics of the packages used in the fire studies previously described and the UFTP envisioned for use in the NWMO's transportation program. The UFTP is heavier than the GA-4 and NAC-LWT packages. This implies that it has a similar or greater thermal inertia; i.e., it can absorb a similar or greater amount of heat per change in temperature.

Table L-2: Characteristics of used fuel packages used in accident evaluations

Accident	Package	Package Weight, kg	Package Contents	Lid Closure	Shielding	Package Walls
Caldecott Tunnel [112]	NAC-LWT	23 586	1 PWR	Bolted	Lead	Stainless steel
MacArthur Maze [113]	GA-4	24 948	4 PWR	Bolted	DU	Stainless steel
Newhall Pass [114]	GA-4	24 948	4 PWR	Bolted	DU	Stainless steel
James Snow	UFTP	34 800	192 Bundles CANDU	Bolted	Monolithic stainless steel	

Table L-3 shows the lid seal temperatures calculated for the Caldecott Tunnel, MacArthur Maze and Newhall Pass fires. In all cases, the temperatures exceeded the operating temperatures for the lid, drain and vent ports seals. The drain and vent ports are small openings that allow packages to be drained and gas samples to be taken. The drain and vent ports are recessed and are covered by bolted lid plates sealed with O-rings. This can create a release pathway to the interior of the package. However, as previouly stated, the clearance between the lid and package body is very small and would prevent the release of all but the very smallest particles. However, the analyses for the three accidents show that enclosed fires can produce temperatures hot enough to affect the performance of Type B package seals in a severe fire – especially those seals made of polymeric elastomers.

Table L-3: Lid seal temperatures for UNF packages in severe fires

Accident	Package	Max Fire Temp. (duration)	Max Lid Seal Temp	Lid Seal Operating Limit	Maximum Vent and Drain Port Seal Temp	Vent and Drain Port Seal Operating Limit
Caldecott Tunnel [112]	NAC-LWT	1040°C (40 min)	424°C	391°C (TFE) 288°C (Viton)	698°C	391°C (TFE) 288°C (Viton)
	NAC-LWT (within ISO Container)	1040°C (40 min)	393°C	391°C (TFE) 288°C (Viton)	557°C	391°C (TFE) 288°C (Viton)
MacArthur Maze [113]	GA-4	1100°C (37 min) 900°C (71 min)	621°C	421°C (ethylene propylene)	621°C	421°C (ethylene propylene)
Newhall Pass [114]	GA-4	1088°C (33 min)	560°C	421°C (ethylene propylene)	513°C (Vent) 520°C (Drain)	421°C (ethylene propylene)

The three accident scenarios were evaluated to determine the possible effects of enclosed fires on the performance of the used fuel transported. Table L-4 shows the maximum sheathing temperatures calculated for the Caldecott Tunnel, MacArthur Maze, and Newhall Pass fires. The maximum temperature calculated (MacArthur Maze: 753°C) exceeded the theoretical rupture limit for light water reactor fuel that it was certified to transport.[26] The maximum sheathing temperature for the Newhall Pass fire was 534°C which was within 30 degrees of the theoretical rupture limit for light water reactor fuel that it was certified to transport. The sheathing rupture temperature was not exceeded in the Caldecott accident scenario. Different used fuels have different rupture temperatures based on their different properites, such as burnup (i.e., time in a reactor) and aging (i.e. cooling time once the fuel is removed from a reactor). The analyses for the three accidents show that enclosed fires can produce temperatures hot enough to affect the performance of sheathing in a severe fire.

[26] The theoretical sheathing rupture temperatures used are temperatures at which the sheathing the onset of localized instability. This is the point that sheathing may experience rapid ballooning leading to failure.

Table L-4: Sheathing rupture temperatures for UNF packages in severe fires

Accident	Package	Maximum Temperature (Fire duration)	Maximum Sheathing Temperature	Sheathing Rupture Temperature
Caldecott Tunnel [112]	NAC-LWT	1040°C (40 min)	279°C	570°C
	NAC-LWT (ISO Container)	1040°C (40 min)	284°C	570°C
MacArthur Maze [113]	GA-4	1100°C (37 min) 900°C (71 min)	753°C	592°C
Newhall Pass1 [114]	GA-4	1016°C (78 min)	534°C	559°C

Note:

1. The Newhall Pass fire was analyzed for a series of potential fire scenarios. The maximum sheathing temperature is based on a 78-minute fire with a peak temperature of 1016°C.

There are three primary outcomes from a severe fire in an enclosed area. First, the lid seals can remain below their rated operating temperature, in which case there is no release of radioactive material. This is the most common result in an open (non-enclosed) pool fire. Second, the seals fail, but the cladding remains intact. There could be a minor release originating from the CRUD (i.e., corrosion products) on the surface of the used fuel sheathing. Third, the temperatures are high enough that both the package lid seals fail and the sheathing rupture temperature is exceeded. In this case, there can be a small release originating from the CRUD on the surface of the used fuel sheathing as well as very small particulates from the used fuel. The most probable outcome in the second and third cases is that there is no release given the small clearance between the lid and package body. These clearances remain small enough that they can be easily blocked or plugged by any particulates entering the clearance. Table L-5 shows the results from the Caldecott Tunnel, MacArthur Maze and Newhall Pass fires.

Table L-5: Results from accidents involving fires in enclosed spaces

Accident	Package	Seal Temperature Exceeded	Sheathing Temperature Exceeded	Source of Release	Estimated Release TBq	Fraction of Release Allowed by the Regulations A_2
Caldecott Tunnel [112]	NAC-LWT	x		CRUD adhering to fuel pin surface	0.0004	0.001
MacArthur Maze [113]	GA-4	x	x	Particulates released by sheathing rupture	0.91	0.24
Newhall Pass [114]	GA-4	x	x	Particulates released by sheathing rupture	0.91	0.24

The package seal temperature for the NAC-LWT for the Caldecott Tunnel accident scenario exceeds its operating limit, but the fuel sheathing remains intact. The release was estimated to be on the order of 0.0004 TBq which is about one-tenth of the amount that the regulations allow per week.[27] Both the seal temperature and sheathing rupture temperature are exceeded in the MacArthur Maze and Newhall Pass fires. The release for these scenarios is estimated to be on the order of 0.91 TBq, which is about 25% of the amount that the regulations allow per week.

Based on these results, the possibility of a small release from the UFTP cannot be ruled out. The Dry Storage Container Transportation Package (DSC-TP) would not suffer a release because of its welded lid. This conclusion for the UFTP is based in part on the packages having a similar mass, (i.e., thermal inertia) as the packages evaluated in the Caldecott Tunnel, MacArthur Maze and Newhall Pass fires. Also, the sheathing rupture temperature reported for used CANDU fuel is approximately 650°C, which falls within the range of maximum sheathing temperatures calculated for the MacArthur Maze and Newhall Pass fires [101].

L.2.4 Summary

Neither the impact or puncture force that occurred in the James Snow collision would be sufficient to either breach the package walls or severely damage the package’s sealing areas of the DSC-TP or UFTP.

A small release could be possible for the UFTP if the package seal operating temperature and fuel rupture temperature are exceeded in a severe fire. This could occur in an enclosed fire, such as one that might occur in a road tunnel or highway underpass. The package seal operating temperature and fuel rupture temperatures are unlikely to be exceeded in fires that occur in unenclosed areas such as open pool fires.

[27] The allowable release for a Type B package is A_2 per week.

APPENDIX M LAC MÉGANTIC TRAIN DERAILMENT

M.1 THE ACCIDENT

The Lac Mégantic train derailment was a railway accident that occurred during the early hours of July 6, 2013, in Lac Mégantic, Québec, Canada. The accident involved a Montréal, Maine and Atlantic Railway freight train carrying approximately 6.7 million liters of petroleum crude oil in 72 tank cars. At the point of derailment, the train was traveling about 105 km/h. Sixty-three of the 72 tank cars derailed spilling approximately 6 million liters. A schematic of the accident is shown in Figure M-1.

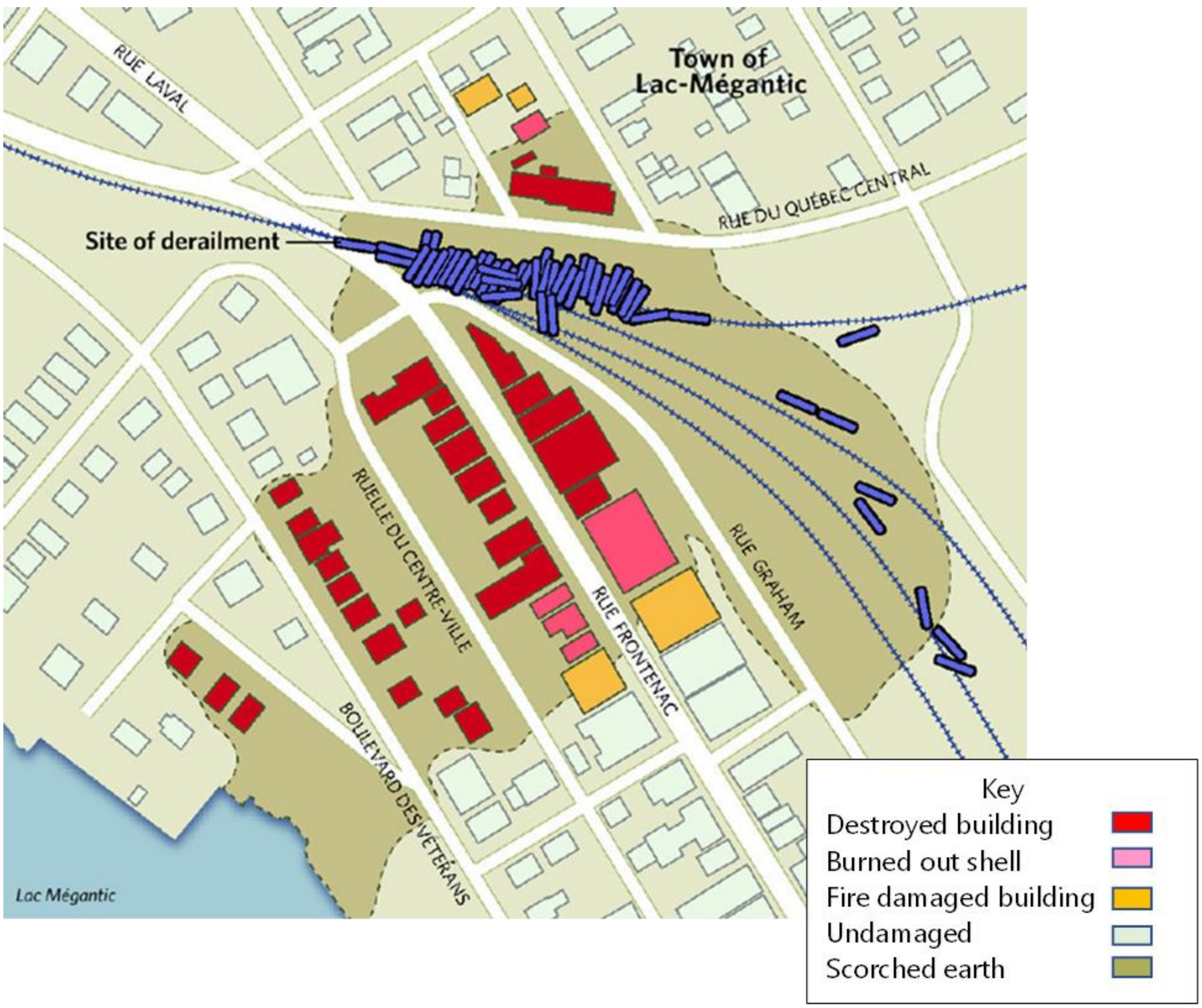


Figure M-1: The Lac Mégantic accident

Crude oil flowed downhill away from the derailment site towards the center of Lac Mégantic, with some of the crude oil entering manholes and flowing through the town's storm sewer system. An estimated 100 000 liters of crude oil ended up in Mégantic Lake and the Chaudière River by way of surface flow and the town's underground sewer system. As a result of the derailment and ensuing fires and explosions, 47 people died and about 2000 people were evacuated. Forty buildings and 53 vehicles were destroyed.

M.2 POTENTIAL IMPACT ON A USED NUCLEAR FUEL PACKAGE

Several aspects must be considered when evaluating the performance of a used fuel package, such as the Dry Storage Container Transportation Package (DSC-TP), in accidents such as the Lac Mégantic train derailment. These include the potential damage to the package body or lid welded closure area from (1) direct impact, (2) puncture, (3) explosions and (4) long duration severe fires. The release of radioactive material will only occur if the DSC-TP side wall and DSC-TP container side wall is breached, or the welded closure area is severely damaged.

M.2.1 Direct Impact

It was estimated that the train was going approximately 105 km/h (65 miles/h) when it derailed. This speed represents an upper bound on impact speed. The effective speed of impact for a UNF package would probably be much lower than 105 km/h because of the reduced speed at which some cars derailed, and the orientation of the package during impact. The speeds at which the tank indiviual cars derailed were predicted in the official accident report and are shown in Figure M-2.

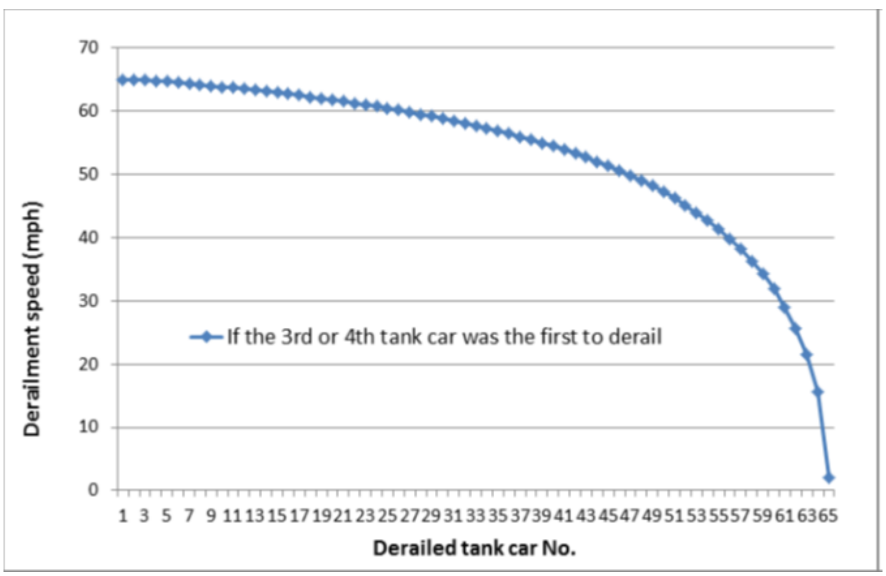


Figure M-2: Estimated speed of impact of derailed tank cars [94]

The derailment speeds ranged from 105 km/h to 5 km/h and decreased with distance from the first derailed car. In addition, the impact to a DSC-TP would most likely result from the DSC-TP colliding with an adjacent railcar, most likely in a side-to-side impact. This results from the tendancy of railcars to end up in accordion-like patterns in derailments. The accordion-like pattern can be seen in Figure M-3.

Figure M-3: Lac Mégantic accident aftermath

In addition, some of the impact force would be absorbed by the used fuel package transport railcar. Unlike tank railcars, used fuel packages are attached to the railcars using tie-downs. (Figure M-4). The SANDIA tests, described in Section 4.2, are an example of the ability of used fuel package railcars to absorb the forces of direct impact. The impact limiters for the DSC-TP also provide protection to the lid area during impact, and the side protection shield provides additional restistance to a side impact. The body of the DSC-TP is approximately 54.9 cm thick. (i.e., a 52.3 cm concrete shell encased in two 1.27 cm carbon steel shells). The lid is sealed using multiple weld passes.

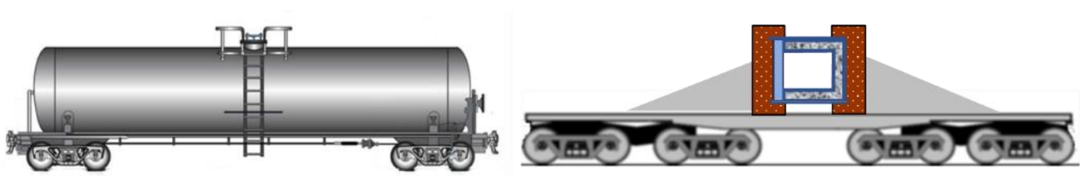


Figure M-4: Tank railcar (left) and used fuel railcar (right) – note that the DSC-TP is shipped horizontally

The impact forces experienced by the DSC-TP during the Lac Mégantic train derailment would be several orders of magnitude lower than the forces measured in the 160 km/h train collision decribed in Operation Smash Hit (described in Section 4.3). Operation Smash Hit simulated a rail accident that consisted of a 140 metric ton locomotive traveling at 160 km/h colliding directly with a stationary 47 metric ton Magnox flask attached to a 13 metric ton railcar. The flask and railcar were oriented so that the locomotive would strike directly on the package lid edge at the most vulnerable orientation. The orientation of the flask was chosen to represent the most vulnerable location, near the lid seal region which consisted of a bolted lid and O-rings. The full-scale simulation demonstrated that Magnox package could survive a severe rail accident with surficical surface damage, minimal damage to the lid seal region, and no significant release of radioactive material.

In comparison, the DSC-TP is a heavier package (100 tons when loaded), and has welded lids. The impact speeds and forces during the Lac Mégantic derailment (which derailed at 80 km/h) are much smaller than the forces involved in a direct collision of a locomotive traveling at 160 km/h (such as Operation Smash Hit). The impact forces on the DSC-TP that would have occurred during the Lac Mégantic train derailment would be not be sufficient to either breach the package wall or severely damage the package’s welded closure area.

M.2.2 Puncture

The DSC-TP has thick walls that are made of carbon steel encased concrete. The total wall thickness consists of a 52.3 cm (20.6 in) thick layer of concrete encased by two 1.27 cm (0.5 inch) thick carbon steel shells. The 52.1 cm (20.5 in) thick package lid consists of concrete encased in a carbon steel shell. The top and bottom of the package are protected by polyurethane foam impact limiters encased in stainless steel shells. The DSC-TP uses double layered side protection during transportation. The side protection consists of two layers – an inner stainless steel shell that is 1.3 cm (0.5 in) thick and an outer stainless steel shell that is 0.95 cm (0.375 in) thick. The shells extend downward from the top impact limiter and upward from the bottom impact limiter and overlap around the circumference of the DSC-TP.

Data from the U.S. Nuclear Regulatory Commission (NRC) and Association of American Railroads (AAR) (presented in Section 3.2.1.3) show that rail tank cars with thicknesses greater than one inch are highly unlikely to be punctured in severe rail accidents. The puncture forces on the DSC-TP that would have occurred during the Lac Mégantic train derailment would be not sufficient to either breach the package wall or severely damage the package’s welded closure area.

M.2.3 Explosion

No BLEVEs occurred in the Lac Mégantic train derailment because the crude oil in the tank car had a boiling point well above ambient temperatures. This was confirmed in the official accident report based on the lack of tank car fragments at the accident site [94]. The explosions that were reported would have resulted from the detonation of vapor clouds (vapor cloud detonation (VCD)). The blast waves from VCDs are of the same general magnitude as those occuring during BLEVEs.

One study with particular relevance to the Lac Mégantic train derailment is the physical demonstration test of a propane tank car boiling liquid expanding vapour explosion (BLEVE) next to a CASTOR THTR/AVR used fuel package conducted by the German Federal Institute for Materials Research and Testing (BAM) [103]. The demonstration test is described in more detail in Section 4.4.1.

During the test, the propane tank BLEVE resulted in a severe impact of rail tank car fragments with the CASTOR package and caused the 22 450 kg package to be flipped over, landing 7-10 meters from its original location. The BLEVE caused only superficial damage (deep scratches and imprints from the impacting railcar fragments) to the package body and did not significantly affect the integrity of the package's bolted lids. The integrity of the package's lids was confirmed as the measured leak rates from the lid seals was the same before and after the accident. The impact on the package was determined to be on the same order of magnitude from the regulatory drop test (9 meters onto an unyielding surface).

In comparison, the DSC-TP is a heavier package (100 tons when loaded), and has a welded lid. The impact forces from a BLEVE during the Lac Mégantic would be similar to those experienced in the BAM test since they both involved exploding propane tanks. The impact forces on the DSC-TP that would have occurred during from a BLEVE in the Lac Mégantic train derailment would not be sufficient to either breach the package wall or severely damage the package's welded closure area.

M.2.4 Fire

The fires that occurred during the Lac Mégantic derailment were caused when crude oil released from ruptured tank cars ignited. The resulting fires were widespread, burning both at the site of the derailment and at multiple locations within the town of Lac Mégantic, engulfing buildings and other structures. Most of the crude oil that was spilt flowed downhill through the streets and underground sewer system. Eventually over 100 000 liters reached the Mégantic and the Chaudière River.

The impact of the fire on the DSC-TP is determined by its location in the fire. As a condition of approval, the DSC-TP was evaluated in a fully engulfing fire – this means that 100% of the package surface is exposed to the fire's heat flux. From the accident photos (Figure M-3) of the Lac Mégantic train derailment, it is evident that if a UNF package was in the derailment it would be shielded from much of the fire by adjacent tank cars. In addition, the transport vehicle would likely shield one side of the DSC-TP from fire exposure.

The package may also come to rest on the ground, in which case it would reduce the surface area exposed in an accident as compared to the fully engulfing fire required in the regulations. The lid area is also encased by impact limiters that act as insulators or heat shields.

Given the large thermal inertia of the 100 metric ton DSC-TP, and the fact that the fire would not be fully engulfing, the DSC-TP would be unlikely to experience temperatures that would adversely affect the integrity of the package body or lid seal region.

M.2.5 Summary

None of the impact forces (impact, puncture and explosion), or the fire that occurred in the Lac Mégantic train derailment would be sufficient to cause either a breach in the DSC-TP package wall or severely damage the welded closure area.