Activities in Support of Licensing Ontario Hydro's Dry Storage Container for Radioactive Waste Transportation

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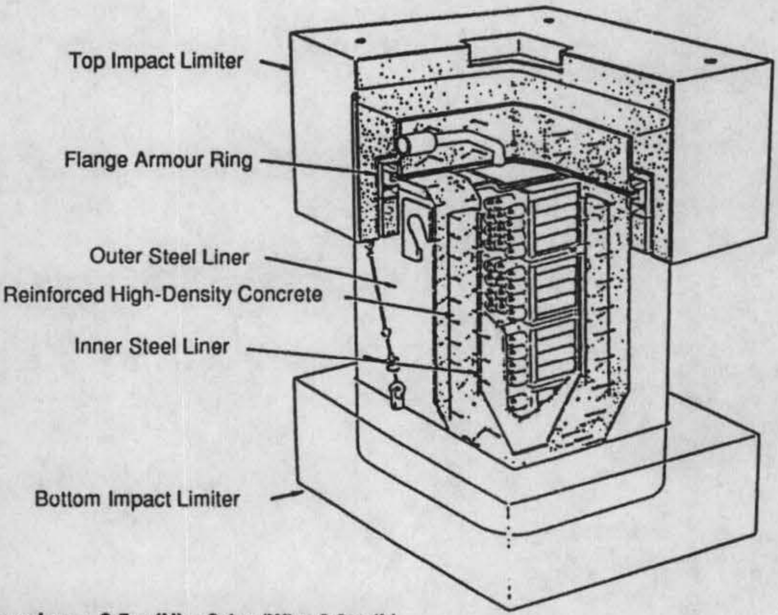
INTRODUCTION

The Dry Storage Container (DSC) is being developed by Ontario Hydro for the on-site storage and possible future transportation of used fuel. The DSC, as shown schematically in Figure 1, is essentially rectangular in shape and has a total weight of approximately 68 Mg when loaded with used fuel. The container cavity is designed to accommodate four rectangular fuel modules (each module contains 96 CANDU fuel bundles). The space between the inner and outer steel liners (each about 12.7 mm thick) is filled with high-density reinforced shielding concrete (approximately 500 mm thick). Polyurethane foam-core steel-lined impact limiters will be fitted around the container during transportation to provide impact protection. In addition, an armour ring will be installed around the flanged closure weld (inside the top impact limiter) to provide protection from an accidental pin impact.



Dimensions: 3.5m (H) x 2.1m (W) x 2.2m (L)

Figure 1 - Schematic of DSC with Impact Limiters

Analyses using in-house developed impact and thermal computer codes and testing of scaled models to simulate accident conditions as specified by the Canadian Atomic Energy Control Board (AECB) in their regulations governing the safe transport of radioactive materials have been carried out to ensure that the DSC can be transported from the on-site storage facility. As part of this process, it is desirable that both testing and analyses correlate in order to facilitate the acquisition of a transport license.

ACCIDENTAL IMPACT

Drop testing of a 1/2 scale DSC model to prove compliance with the regulations was performed at the Ontario Hydro Research Division (OHRD) Wesleyville site (Boag et al. 1991). A 9 m top corner drop and a 1 m pin impact at the flange armour ring (through the impact limiter) were performed without sustaining any structural damage to the model. Helium leak testing of the model after both drop tests demonstrated that the container remained leak tight.

In addition to the DSC drop tests, a parallel effort involving structural analyses has been undertaken (Lee 1991 and Nadeau 1991). Analyses have been carried out using the in-house finite element program H3DMAP (Sauvé 1991). H3DMAP is an explicit time-integration three dimensional program which is applicable to the large deformation transient response of inelastic continua.

TOP CORNER IMPACT (9 M DROP)

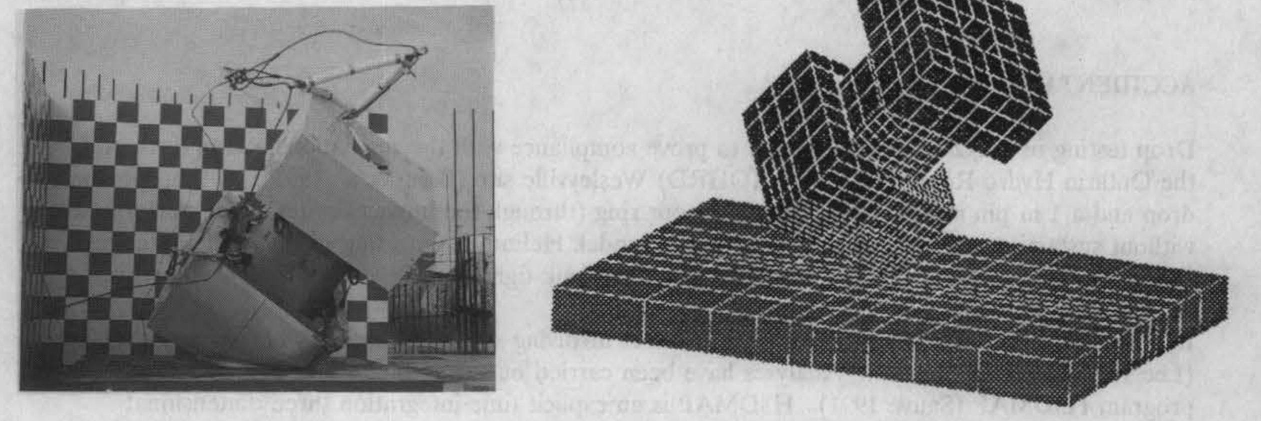
One type of regulatory transport accident scenario was a 9 m container top corner drop onto an unyielding surface. The DSC model was dropped so that the package's centre of gravity was directly above the impact point. The DSC model struck the target plate in the intended orientation with no visible in-flight rotation (see Figure 2a).

The top impact limiter deformed locally at the point of impact and split along a vertical steel liner attachment weld. The average deceleration of the 1/2-scale DSC model on impact measured with four accelerometers was approximately 44 g (which corresponds to 22 g for the full-scale container).

Figure 2b shows the assembled finite element model of the full-scale DSC in the drop orientation prior to impact onto a rigid surface. The impact limiter is modelled using shell elements to represent the stainless steel skin and hydrodynamic solid elements to represent the polyurethane foam core. The region of the impact limiter in the vicinity of the impact is modelled using a refined mesh in order to capture the detailed response at impact. The main body of the DSC is comprised of solid hydrodynamic elements for the concrete and shell elements for the steel liners surrounding the concrete. A rigid target surface is provided by solid elements which are restrained from movement during impact.

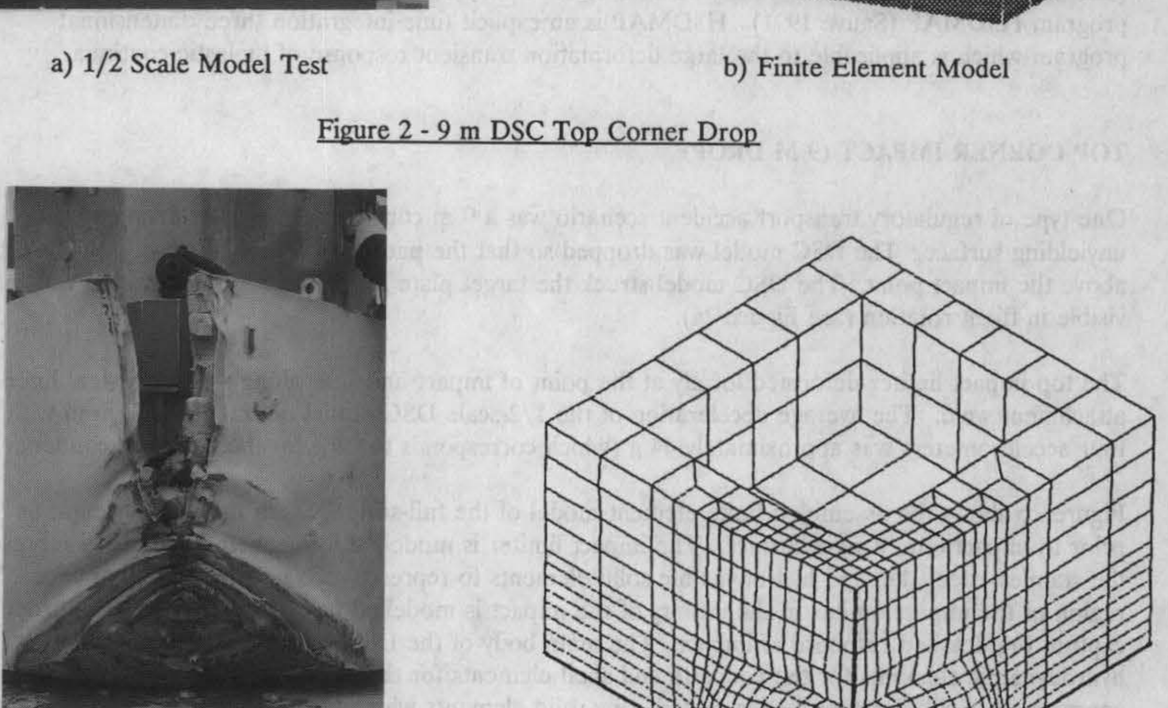
Analyses have predicted a maximum deceleration on impact of 26.5 g for the full-scale DSC. A comparison of the predicted full-scale and 1/2-scale model impact limiter damage is shown in Figure 3. In contrast to the impact limiters, analysis has shown that the DSC concrete body experiences relatively low stresses.

Both testing and analyses have demonstrated that the impact limiter is effective as a sacrificial energy absorbing structure. The tests and analyses compared well in terms of both deceleration on impact as well as impact limiter damage.


a) 1/2 Scale Model Test

b) Finite Element Model

Figure 2 - 9 m DSC Top Corner Drop


a) Testing

b) Analysis

Figure 3 - DSC Impact Limiter Damage

FLANGE PROTECTION ARMOUR PIN IMPACT (1 M DROP)

The 1/2 scale DSC model was oriented so that a cylindrical low-carbon steel pin (76 mm in diameter) would directly impact the flange armour ring through the impact limiter as shown in Figure 4. A schematic of the armour flange ring cross-section is shown in Figure 5a. The DSC armour flange was designed to provide protection of the welded containment flange. The height of the drop was measured to be 1 m from the bottom of the impact limiter to the top of the pin.

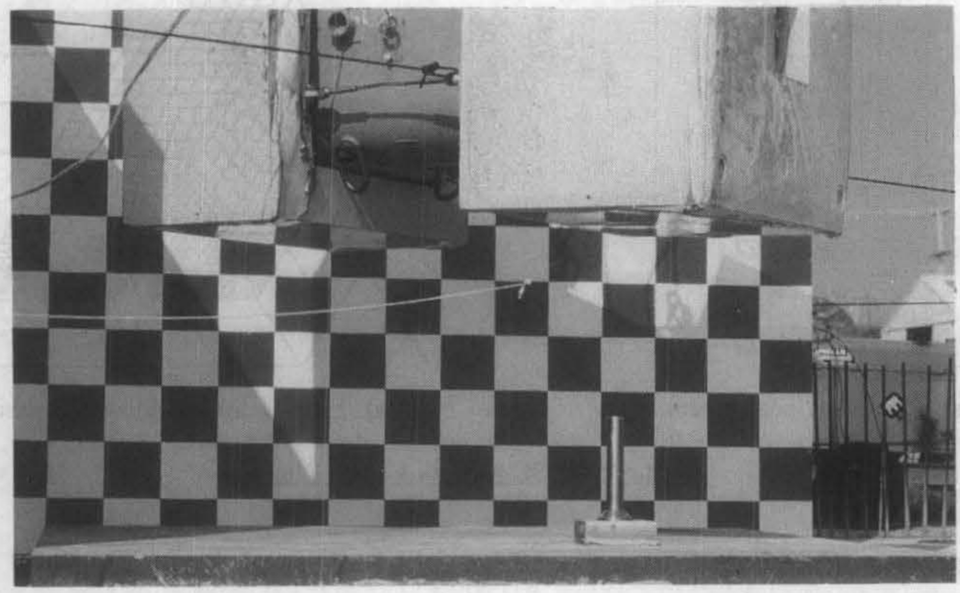


Figure 4 - DSC Armour Flange Pin Impact (1/2 Scale Model Test)

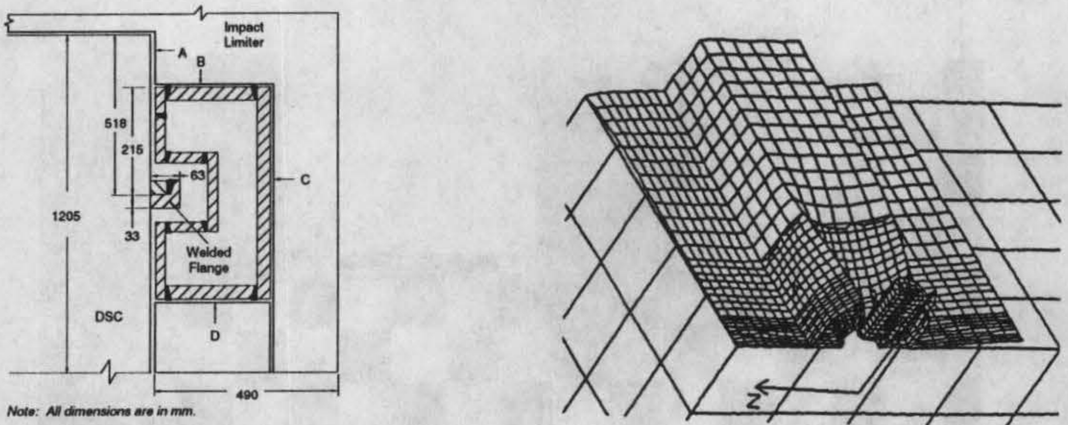
On impact, the pin penetrated the top impact limiter and struck the flange armour ring in the desired location. The pin locally deformed both the outer and inner channels of the armour flange ring, bulging the inner channel towards but not damaging the DSC welded containment flange. The indentation of the outer channel and the bulge on the inner channel was measured to be 48 mm and 9 mm (or 96 mm and 18 mm for the full-scale armour flange ring), respectively.

In the finite element analysis of the full-scale pin impact, the DSC main body and the pin were modelled using solid elements and the armour flange ring was represented by shell elements. One of the design criteria specified that any contact between the armour flange ring and the welded flange would be unacceptable. Since only the deformation of the armour flange ring was allowed, the welded flange was not modelled. The DSC main body was modelled mainly to capture the rigid body motion of the package due to inertia. Symmetry was exploited so that only one half of the package, armour flange ring and pin assembly were modelled with the appropriate boundary conditions. To simplify the analysis, the foam was not modelled and it was assumed that the pin would directly strike the outer channel.

The energy absorption of the foam, however, was estimated using simple calculations and was taken into account in the model by modifying the initial container potential energy. Three contact interfaces were used to model the interaction between various surfaces in the model. One contact interface was between the pin and the outer channel while the second interface provides for the interaction of the two protective channels. The third interface was between the shell of the inner protective channel and the DSC. These interfaces were modelled using the 3-D contact algorithm (Sauvé 1991) available in H3DMAP.

Figure 5b shows the final deformation of the armour flange ring after the pin impact. Outside channel deformation and inner channel bulge were determined to be 110 mm and 24 mm, respectively. Analyses have also shown that a 9 mm gap remains between the DSC containment flange and the inner protective channel after impact.

Both testing and analysis have correlated well in predicting damage and both have demonstrated that the flange armour ring provides adequate protection for the welded flange.



Note: All dimensions are in mm.

a) Cross-Sectional Schematic b) Final Deformed Shape-Analysis

Figure 5 - DSC Armour Flange Ring

ACCIDENTAL FIRE

A thermal analysis was performed on the full-scale DSC to simulate the transport accident conditions of a 30 minute fully engulfing fire (800°C). The purpose of this analysis was to obtain fuel sheath and container wall temperatures.

THERMAL ANALYSIS

The thermal analysis of the DSC containing 6-year old used CANDU fuel has been carried out using an in-house 3-D heat transfer code FD-HEAT which was specially developed for this purpose.

The main results of the fire accident analysis (Taralis 1990) at the end of the 30 minute fire are presented in Table 1. The temperature of the hottest computational cell (which is equivalent to a tube/fuel bundle assembly) was determined to be 134.1°C. By adding a temperature correction of 3°C obtained from previous experimental results (Taralis 1986), a fuel sheath temperature of 137.1°C was obtained. The cavity pressure was determined to be 133.4 (kPa)a assuming an average predicted cavity gas temperature of 114°C and that dry conditions exist within the DSC cavity. These temperatures and pressure will increase slightly after the fire and then decrease as the DSC wall cools down.

Table 1- Summary of DSC Fire Accident Temperature Results

External Surface Temperature	502.9°C	
Internal Surface Temperature	78.0°C	
Cavity Fluid Temperature	114.3°C	
Maximum Fuel Sheath Temperature	137.1°C	
	Absolute	Gage
Cavity Pressure (Dry)	133.4 kPa	32.1 kPa

Ambient Temperature = 38°C
Decay Heat = 7.4 W/Bundle (6 years old fuel)
Cavity Fluid = Air

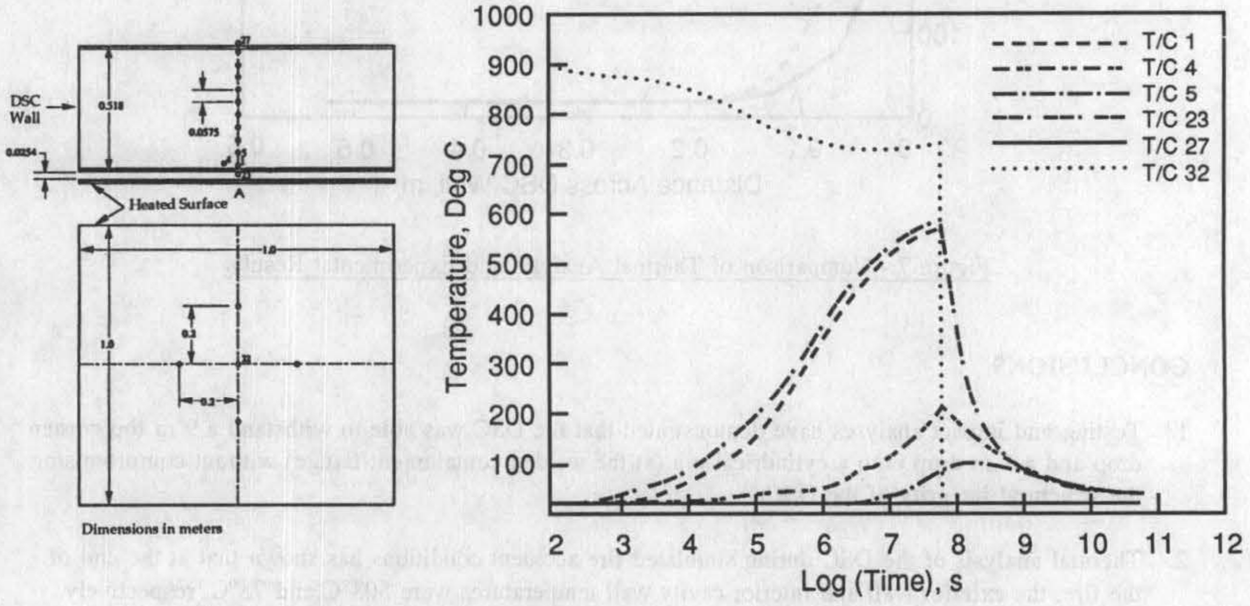
THERMAL CODE VERIFICATION

The validation of the FD-HEAT thermal code for the heat conduction through the DSC wall has also been performed. (The validation of the convection within the DSC cavity was previously performed (Taralis 1990). To accomplish this, thermal tests have been carried out on an actual DSC wall section to measure the transient temperature distribution across its thickness.

The experimental apparatus used in conducting the tests consisted of a section of the DSC wall (including rebars) supported horizontally with a heated plate underneath. The plate simulates a heat source (equivalent to an 800°C fire) which is heated with electrical resistance heaters capable of delivering up to 100 kW power.

The DSC wall section was instrumented with approximately 30 thermocouples (Type K) at different locations through the section as shown in Figure 6a. In addition, the heated surface was also instrumented with 5 thermocouples. These five thermocouples were used to calculate the heat input to the wall by radiation (the effects of free convection were also included).

Once the heated surface was brought to the desired temperature, the test commenced by rolling the hot surface under the DSC wall. The temperature of the emitting surface started at about 950°C and dropped relatively quickly down to 725°C during the first part of the test. Subsequently the temperature rose slowly to a maximum of 750°C towards the end of the test. The temperature results of the benchmark thermal test are shown in Figure 6b.



a) Thermocouple Locations

b) Temperature Results

Figure 6 - DSC Wall Heat Conduction Test

As can be seen in Figure 6b, the outer steel liner reached a maximum temperature of about 580°C (which is similar to that predicted by the thermal analysis). Temperatures across the wall were much lower than this value. The large temperature difference of approximately 360°C observed between the steel liner and concrete (ie. thermocouples 23 and 4) was the result of an air gap (which may or may not be present at other locations). Post examination of the slab, by cutting through the section, revealed an air gap of up to 3 mm between the outer steel liner and the concrete wall although the plate contacted the concrete at some locations. The presence of this air gap is believed to have resulted from the differential thermal expansion of the plate and possibly from any air and steam pressure build-up.

The temperature measurements through the middle of the section have been compared with the FD-HEAT code predictions using available thermal properties of high density concrete. This comparison is shown in Figure 7. As this figure reveals, the thermal analysis and benchmark test correlate well and therefore the properties used in the analysis give satisfactory results.

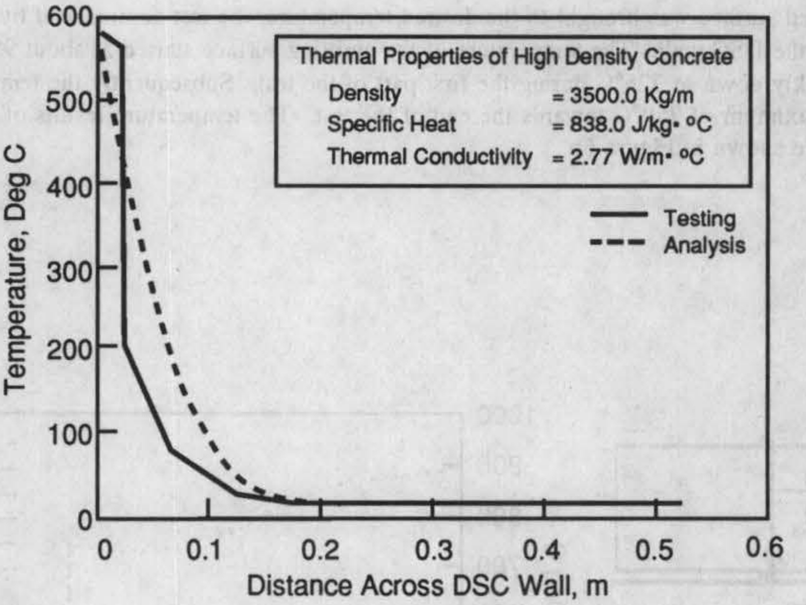


Figure 7 - Comparison of Thermal Analysis and Experimental Results

CONCLUSIONS

1. Testing and impact analyses have demonstrated that the DSC was able to withstand a 9 m top corner drop and a 1 m drop onto a cylindrical pin (at the welded containment flange) without compromising the structural integrity of the DSC.

2. Thermal analysis of the DSC during simulated fire accident conditions has shown that at the end of the fire, the exterior wall and interior cavity wall temperatures were 503°C and 78°C, respectively. The maximum fuel sheath temperature predicted was 137°C which was below the maximum allowable temperature for the used fuel. The FD-HEAT code used for this analysis was validated through a heat conduction test of an actual DSC wall section.

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