A CONCRETE CASK DESIGN FOR STORAGE, TRANSPORTATION AND DISPOSAL

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ABSTRACT

A program to assess whether concrete casks could store, transport and dispose irradiated CANDU fuel was undertaken at Ontario Hydro. In the process of developing a viable concrete cask, various stringent design criteria were met. The most stringent requirements were viewed to be the IAEA regulatory 9 m drop and fire tests for Type B packages. Two half-scale cask models were built and tested.

The test results confirmed that development of these concrete casks is feasible. During the tests, the cask models maintained their overall structural integrity and full containment with effective radiation shielding of an irradiated fuel payload would have been retained.

INTRODUCTION

The development of a concrete cask capable of storing, transporting and disposing fuel and/or HLW was undertaken in Ontario Hydro. This cask known as the concrete integrated cask (CIC), was shown to lead to overall cost savings and flexibility in the long-term management of irradiated fuel (Freire-Canosa, 1982). Since the cask is to be durable in the repository environment (upwards of 500 years), storage of the cask at the station site under significantly more benign conditions is expected to be maintenance free. After loading fuel into the cask, no further fuel handling is required as the cask remains ready for transportation and disposal. As a result, both transportation and disposal of the fuel can be scheduled on the basis of economics and convenience.

The modular nature of this type of storage also enhances strategy planning by:

(a) providing storage capacity as the need arises;

(b) decoupling decisions on storage needs from the implementation of the transportation and disposal phases;

(c) portability as the casks can be relocated both on-site or off-site in short notice.

Concrete simplifies the cask manufacture and offers:

(1) reduced material and fabrication costs;

(2) combined neutron* and gamma radiation shielding due to its hydrogen content and density.

* Shielding due to neutron radiation is not relevant to CANDU fuel.

CONCRETE INTEGRATED CASK: DESIGN REQUIREMENTS

The design requirements for a CIC prototype were determined from the expected conditions of storage, transportation and disposal. These requirements are summarized in Table 1 (Burnett, 1982). During the storage phase, the concrete cask mainly experiences thermal stresses and, possibly, freeze-thaw conditions. In the transportation phase, the cask would have to meet licensing regulations representative of Type B packages (IAEA, 1983). In particular, it would have to meet a drop from a 9 m height onto an unyielding surface, a 1 m drop onto a rigid pin and subsequently resist a 800°C fire for half-hour. During disposal, the cask would experience external loads of about 10 MPa due to the hydrostatic and equivalent lithostatic pressures.

TABLE 1: MAIN DESIGN REQUIREMENTS FOR THE CONCRETE INTEGRATED CASK

	Requirement
Storage	- storage of 5 year old fuel (approx. 3 kW for 192 CANDU fuel bundles) - fuel storage temperature below 150°C - freeze-thaw durability - fuel retrievability
Transportation	- IAEA transportation requirements for type B packages
Disposal	- long-term durability - resistance to ground water chloride and sulphate ions - concrete matrix compatible with disposal environment - concrete porewater pH of between 9-11 to reduce uranium solubility but not enhance corrosion - withstand hydrostatic pressures at the repository located 1000 m below ground level (10 MPa) - withstand lithostatic pressures of 10 MPa

In addition to these requirements the following was specified:

(a) transportable by road with capacity for two storage modules (192 bundles);

(b) fuel retrievability during the storage phase;

(c) stability to strong winds and tornado generated missiles;

(d) full-containment of the irradiated fuel payload; and

(e) ease of handling.

DEVELOPMENT PROGRAM

The development program for the CIC was divided into three phases:

(a) Engineering;

(b) Concrete materials development;

(c) Testing of two half-scale cask models.

Engineering Phase

A full scale CIC was designed as a cylindrical structure with a carbon steel lined inner cavity with capacity for two (CANDU) fuel storage modules (Figure 1) (Mammolitti, 1986). The cask walls are made of high-density concrete. The dose on contact at the surface of the cask is specified at 200 mrem/hr (2×10^3 μSv/h) and 1 mrem/hr (10 μSv/h) at 1 m distance from the cask surface in keeping with IAEA transportation regulations. Concrete samples taken during pouring of the half-scale models measured compressive strengths in the range 58.9 - 65.8 MPa after 28 curing days, well above specifications. The walls of the cask were reinforced with two steel cages and the ratio of reinforcement to concrete was moderate at a value of about 0.013. The entrance to the cask was provided with a step-wise opening to provide a seat or shoulder for the cask-lid. The lid was also made of reinforced concrete and was attached to the cask by bolts. Three removeable lifting lugs were provided on the lid for handling. Containment of the inner cavity was maintained by seal welding a carbon-steel lid to the carbon-steel lined cavity (as shown in Figure 1). Protection of the steel lining from the ingress of water was achieved by grouting the concrete lid to the cask concrete wall.

Concretes Development

A number of cement pastes tailored to meet the combination of high strength (>45 MPa), high density (>3.5 Mg/m^3) low permeability ($<10^{-13}$ m/s), pH (9-11) and chemical inertness to the groundwater chemistry were tested (Hooton and Burnett, 1984, Hooton, 1986). The impact of various cementing materials on the ability of the paste to show good performance and durability were evaluated by changing:

(a) cement type (portland and aluminous);

(b) supplementary cementing materials (fly-ash, blast furnace slag, silica fume and silica flour);

(c) the amount of superplasticizer; and

(d) water/cementing materials ratios (W/CM).

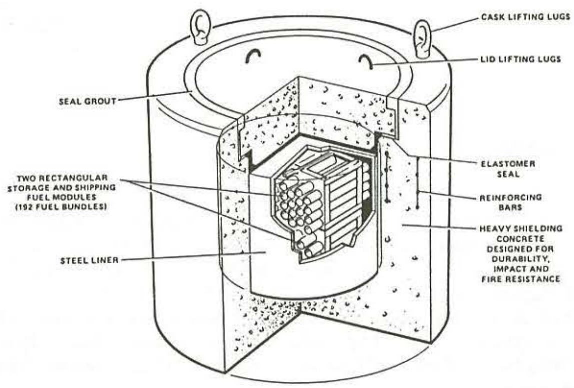

FIGURE 1
CONCRETE CASK

The supplementary cementing materials (SCM) tend to reduce permeability and the leachable CaOH content of the concrete mix. Various W/CM ratios with the use of superplasticizing admixtures were evaluated. Lower W/CM ratio usually reduces permeability and increases strength. The paste chemical stability in the disposal environment was simulated by exposing it to a highly saline, sulphate bearing groundwater at 70°C. A CSA Type 50 sulphate resistant portland cement (ASTM Type V) was chosen as the reference cement as it remains stable in the presence of sulphate ions found in the Canadian Shield granitic groundwaters. Since the groundwater also has a high chloride content, the resistance of the cement paste to chlorides was improved by replacing cement with supplementary cementing materials. The objective was both to reduce the amount of calcium hydroxide available for leaching and the pore size of the hardened cement paste. The results showed a 20 percent replacement by silica fume to be the preferred alternative. The calcium hydroxide levels were reduced to zero after only 28 days curing of the cement paste.

In developing an optimum concrete mix for the CIC, various concrete mixes were developed based on high density specularite (fine) and magnetite (coarse) aggregates and the most promising sulphate resistant cement pastes. Both replacements with silica fume and fly-ash were tested. The results confirmed that the 20 percent silica fume replacement paste gave best overall performance with a permeability below the detection limit of the test equipment ($<10^{-15}$ m/s) after 28 days curing. This value was confirmed by measurements of very small mortar phase porosities. Equally important, this concrete mix also showed the highest compressive strength (80.5 MPa after

91 days curing), tensile strength (≈ 4.8 MPa) and elastic modulus (≈ 82 GPa). In all the concrete mixes, the water/cement ratio (≈ 0.35-0.39) was kept low by the use of superplasticizing admixtures.

The optimum concrete chosen for the full scale prototype cask is described as consisting of:

(1) 20 mm magnetite coarse aggregates;

(2) specularite (hematite) fine aggregates;

(3) sulphate resistant portland cement (SRPC);

(4) 20 percent partial replacement of the SRPC with silica fume;

(5) low W/CM ratio achieved through the use of superplasticizing admixtures.

The sulphate resistant cement gave the concrete an increased resistance to sulphate ions in granitic ground waters. The silica fume was found to increase the durability of the concrete by enhancing its resistance to chloride and sulphate ion attack. Much of the increase in durability is attributed to the secondary hydration of silica fume with calcium hydroxide resulting in a reduced permeability, a finer pore structure, and practical elimination of the leachable calcium hydroxide phase.

<u>Structural Tests</u>

Based on the full-scale design for a CIC, two half-scale models were built by appropriate scaling of the cask dimensions, reinforcement and concrete mix. The half-scale prototype size was 1.21 m in height, 1.37 m outer diameter and 0.82 m inner diameter and weighed about 6 Mg (see Figure 2). One model was used in the structural and fire test, and the other in thermal tests. For the structural tests, fuel was simulated with scaled mock-up weights. In the thermal tests, fuel was simulated with electric heaters.

FIGURE 2: CASK MODEL

<u>Drop and Fire Tests</u>

To assess the cask performance during a transportation accident, a half-scale model was subjected to the drop and fire tests in accordance with IAEA guidelines for Type B packages. The tests were done at the AECL-Chalk River facilities and included (Sato and Vecchio, 1986):

(a) 9 m corner drop on the lid side of the cask;

(b) 1 m drop onto a steel pin;

(c) exposure to a 961°C fire lasting 7.5 minutes (scaled fire).

The 9 m drop test caused some minor damage to the cask both at the point of impact and 180° from the impact (see Figure 3). Damage at the impact point was as expected resulting mainly in superficial concrete spalling with breakage of two outer reinforcing bars and bending of some outer loop bars. A crack about 20 mm wide on the surface of the cask formed on the opposite side but arrested at the shoulder of the cask/lid interface. During impact, the cask deceleration was 119 g indicating desirable energy absorbing properties. The cask was dropped along its centre of gravity (2° off vertical), and did not bounce on impact.

Post-test inspection of the cask revealed that the inner liner remained intact during the tests. There was no failure of the welding of the liner cover/interface and no visible plastic deformation. The mock-up payload was easily retrieved.

An examination of the cask/lid interface showed the cask concrete lid moved out of position during the impact striking the concrete wall where the crack formed. This free movement of the lid was found to have been caused by inadequate grouting of the lid to the cask wall. The grouting failed to fill the depth of the 3 mm wide gap between the cask wall and the lid in accordance to specifications.

After the 9 m drop test, the cask was subjected to the puncture test by dropping it from a 1 m height onto a steel pin. The steel pin was designed to comply with IAEA guidelines and was long enough to penetrate the concrete wall to the steel liner. The orientation and location of impact were identical to the previous 9 m drop in order to obtain the most accumulative damage possible as required by the IAEA regulations. During this impact, the pin failed to penetrate the cask and buckled (Figure 4). No further cracks or spalling was observed as a result of this impact, suggesting good performance for the concrete mix. The concrete mass loss due to spalling during both drop tests was about 2 percent of the total mass of the cask and was mainly due to the 9 m drop test.

After completion of the drop tests, the cask was tested for its fire resistance in keeping with IAEA regulations. The scaled-down fire was specified for a temperature of 961°C and 7.5 minutes duration. However, the cask was exposed to a more serious fire lasting about twelve minutes with temperatures in the 1000°C range (see Figure 5).

Significant spalling of the cask concrete surface occurred. However the loss of concrete was rather uniform about the cask, with the worst case amounting to 19 percent of the cask wall thickness. The main result was the loss of concrete cover over the outer reinforcing bars without the formation of cracks. The process of spalling of the concrete cover was not catastrophic but uniform and steady in that small pieces of concrete would dislodge from the concrete mass in a random fashion. The phenomena is due to a hydrothermal effect caused by the sudden formation of steam in the concrete matrix. The concrete was cured only for about 28 days and sufficient moisture would still be present to lead to its spalling as the temperature front penetrated. The cask inner cavity during the fire and approximately one hour and a half after fire extinguishing experienced a 2°C temperature increase suggesting the concrete cask provides an effective shield to the thermal effects of the fire. This aspect is beneficial as it would protect the radioactive payload from degradation during a fire following a transportation accident.

A post-test radiation shielding analysis based on the location of the crack networks and the mass loss due to the fire test indicated the cask would have maintained an adequate shielding within the IAEA post accident requirements of 1 rem/h (10^4 µSv/h). Thirty percent of the concrete cask wall thickness would have to be lost before exceeding this requirement. In addition, the formation of the cracks was not critical to the overall performance of the cask and improvements could be readily obtained by redesigning the reinforcing arrangement about the cracked zones and modifying the cask/lid interface grouting procedure.

Thermal Tests

The cask structural response to thermal stresses was investigated at the Ontario Hydro Research Laboratories (Sato and Vecchio, 1986). The half-scale model was placed in an environmentally controlled room where ambient temperatures in the range -20 to +30°C could be readily obtained. The decay heat from irradiated fuel was simulated with electrical heaters placed inside the cask. Three tests were performed:

(a) heat transfer under constant heat load;

(b) power-cycling; and

(c) accelerated weathering (freeze-thaw).

Tests under item (a) above were designed to study the thermal gradients in the cask wall and the cask heat dissipation characteristics during constant heat load and changing ambient temperatures. The internal heat load of the cask was maintained constant at 0.75 kW corresponding to a full scale 3 kW load as generated by 192 five year old CANDU fuel bundles. The outside ambient temperature was varied in the range -20 to +30°C. The temperature gradient across the cask wall remained constant for the various ambient temperatures with a temperature difference of about 17°C. The cask surface remained unchanged and no cracks formed during the tests.

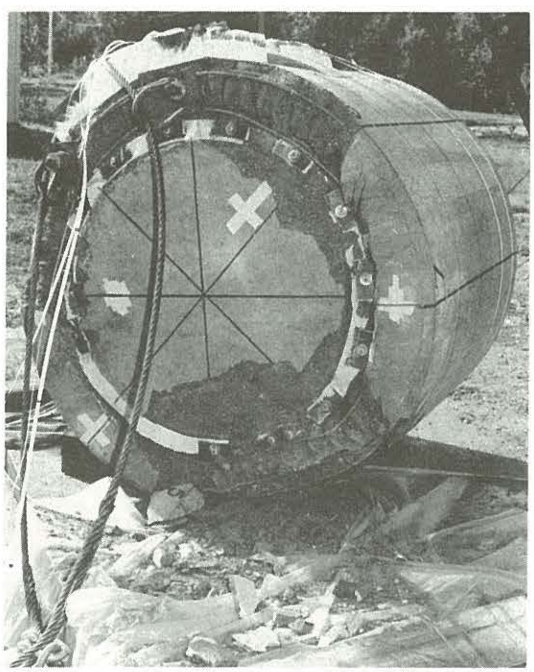

FIGURE 3: CASK MODEL AFTER 9 m DROP TEST

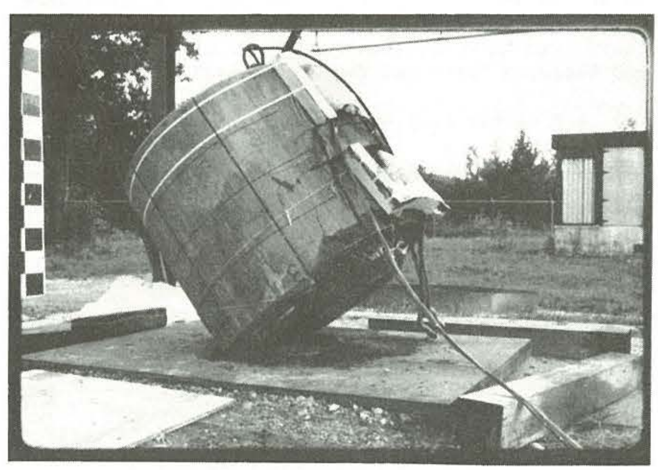

FIGURE 4: PIN DROP TEST

In terms of a full-scale cask, the temperature of the inner liner would be expected to remain about 50°C above ambient. Extrapolating from previously reported data (Ohta, 1978) on fuel temperatures within a closed square container (basket), the highest fuel temperature in the CIC will be below 110°C for 5 year old CANDU fuel. The actual temperature will be significantly below 110°C due to the open structure of the storage modules. At any rate, the fuel temperature during storage will not exceed 150°C as specified.

In the power cycling tests, the outside ambient temperature was constant while the cask internal heat source was ramped through a series of on-off cycles to assess the cask response to thermal shocks. As in the previous tests, the cask wall remained intact without the formation of cracks.

In the accelerated weathering tests, the ambient temperature was fluctuated about the freezing point while the prototype internal heat source remained constant. In this way, the impact of freeze-thaw conditions on the cask was assessed. The results indicated good performance and concrete resistance to freeze-thaw conditions.

After these tests were completed, the internal heat load was increased beyond the values expected under normal operation to assess the ultimate strength of the cask. For this purpose, the internal heat load was increased to an equivalent full scale loading of 4.0 and 6.0 kW beyond design specifications. At this latter loading, cracks appeared at the surface of the cask. However their widths did not exceed 0.2 mm.

CONCLUSIONS

Ontario Hydro completed a development and test program to assess the technical viability of using concrete integrated casks capable to store, transport and dispose irradiated fuel. The program included the development of high strength concretes and evaluated the structural performance of two-half scale CIC models under conditions relevant to transportation and storage. The program results suggest that development of concrete integrated casks is feasible and they could become an important alternative system for the management of irradiated fuel.

A high density concrete mix with 20 percent silica fume as replacement for CSA Type 50 sulphate resistant portland cement was developed. Drop and fire tests on a half-scale model built with this concrete showed overall good performance when subjected to the IAEA drop and fire test requirements for a Type B package. During the drop tests, the cask showed good energy absorbing properties and exhibited a peak deceleration of 119 g. The cask cavity temperature increased only by 2°C during the fire test showing the radioactive payload would not suffer damage as a result of the IAEA postulated fire.

Thermal tests were conducted on a second half-scale model to study the heat dissipation capacity of the cask and its resistance to thermal shocks during freeze-thaw cycles. These conditions were representative of normal operation and the results showed the cask remained intact and surface cracks did not form. Extrapolation of the test results indicated fuel temperatures are expected to remain below 110°C during the storage phase. The concrete will survive freeze-thaw conditions and resist thermal shocks.

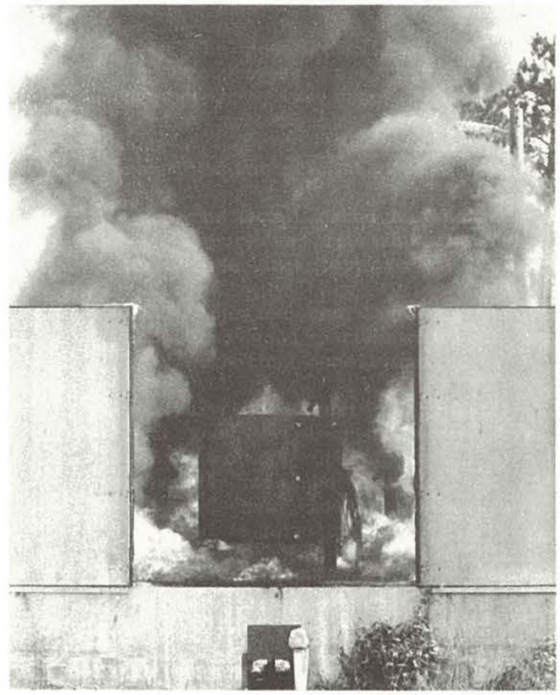

FIGURE 5: FIRE TEST IN PROGRESS

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