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CASK DROP TESTING AND ANALYSIS

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ABSTRACT

Packages designed to carry spent fuel within the United States must be approved and certified by the Nuclear Regulatory Commission (NRC). This is done by submitting an application to the NRC that describes the package design and provides a detailed technical evaluation of its performance under a variety of normal and accident conditions. These technical evaluations are often based on a combination of theoretical analysis and experimental testing that can be particularly important if it is necessary to corroborate specific analytical assumptions or confirm the methodology used. Tests can be applied to full-scale prototypes or scale model packages, either of which can frequently provide the necessary evidence to substantiate the conclusions. This report discusses two types of packages that were tested at the Oak Ridge National Laboratory — a scale model spent fuel cask and a full-scale canister designed to be carried inside a spent fuel cask. They were designed by two private companies. Both companies applied to the NRC for a Certificate of Compliance for their casks. In both cases, the combination of testing and analysis, and the way it was applied, formed a critical part of their application.

INTRODUCTION

All casks designed to carry irradiated fuel and high-level waste must be certified by the Nuclear Regulatory Commission (NRC). Once certified, the package will receive a Certificate of Compliance (C of C) that defines what the package can carry and any conditions that must be met during the shipping process. Application to the NRC is in the form of a Safety Analysis Report (SAR) for the package design, which presents a detailed technical analysis of the design and supports the conclusion of acceptability. That is, each design will be evaluated on the basis of an engineering assessment and supporting tests to ensure that it meets required regulations.

Federal regulations, promulgated by the NRC, identify a series of hypothetical accident conditions that any package designed to transport large quantities of radioactive material must be able to survive. The conditions, described in the form of tests (CFR, 1988), must all be applied to a single package in sequence and include a (1) 9-m free drop onto an essentially unyielding target, (2) 1-m drop onto a 15-cm-diam steel spike, and (3) 30-min fire. A fourth test, submergence under water, is required and may be performed on a separate package.

These hypothetical accident conditions may be applied analytically, by physical test, or by a combination of the two as the basis for requesting a C of C from the NRC. However, because of the type of performance tests the package is required to survive, most designers prefer to use an integrated program of testing and analysis to support their evaluations. This approach has the advantage of using actual tests to (1) corroborate some important analytic assumptions, (2) benchmark and confirm the methodology applied to predict results not specifically tested, and (3) provide experimental evidence that the package can withstand the severe accident criteria specified in the regulations.

If physical testing is carried out on a cask model, either to benchmark a code or to study the damage produced, it should be tested in such a way as to produce the maximum damage in the package. In some cases, analyses must be made in order to determine what orientation of the package during a 9-m drop test will produce maximum damage. If the damage produced in a test correlates well with predictions, the package designer will have a high degree of confidence that the most damaging orientation for the test was chosen, and that if the test orientation were changed (e.g., the drop angle of the cask relative to the impact pad), the analytic model would have a high probability of predicting the revised test.

This paper discusses some drop tests recently performed on packages at the Oak Ridge National Laboratory (ORNL).

TYPES OF PACKAGES TESTED

If physical testing of a particular package design is to be used, it is most often carried out on a scale model of the package because smaller models are less expensive and frequently can be fabricated more quickly than a prototype cask. However, there are practical limits, discussed below, as to how small a test model can be.

Laws of similitude indicate that by keeping the impact velocity the same (equivalent to keeping the 9-m drop height the same), deformation produced in the model upon impact will scale directly to the full-size cask for most package designs under consideration. The following scaling relationships have been developed for the testing of model shipping packages (McGovern and Thunborg, 1971; Duffey, 1970).

In the relationships that follow, "m" refers to the model and "p" the prototype (full-size) package; "n" refers to the linear scale factor, the ratio of the linear dimensions of the model to the prototype.

Velocity:	$V_m = V_p$,
Mass:	$M_m = n^3 M_p$,
Energy:	$E_m = n^3 E_p$,
Applied Force:	$F_m = n^2 F_p$,
Applied Acceleration:	$A_m = A_p/n$,
Time Duration:	$T_m = nT_p$,
Deformation:	$d_m = nd_p$.

It has long been recognized that some parameters do not scale correctly when a model package is subjected to structural assaults (Blythe et al., 1987; IAEA, 1987). These parameters include strain rate, fracture/tearing, and gravity; the first two are the most important. The modeling of features such as seals, welds, and fasteners, as well as tolerances used in the fabrication of models, must also be considered when determining the proper scaling factor to be applied to a test model.

Another difficulty that must be recognized when considering the use of a reduced scale model is that it could not be used to obtain direct temperatures of the full-size package if the model were subjected to the hypothetical thermal accident condition specified in the CFR (1988). However, if the model was placed in a high-temperature environment, the resultant time-temperature data might be used to benchmark the thermal code that could, in turn, be used to predict the behavior of the full-scale cask. Because of these factors, it is important to understand how the results of the tests are to be used when considering whether to test a model or a prototype.

In part, because of the factors described previously, the NRC recommends that if model tests are to be used to support the structural conclusions in the SAR, nothing smaller than a quarter-scale model of the prototype should be tested. Because the package weight scales as the cube of the linear dimension, the quarter-scale model of a 100-ton cask (1) weighs about 1.56 tons, (2) is far cheaper to build than a prototype, and (3) can be tested in a number of facilities. For full-size casks, depending on the type of tests needed, the number of available testing facilities is significantly smaller.

Most large casks today are equipped with energy absorbers. These devices can be built from wood, foam, or metal honeycomb materials encased in a metal sheath. They are generally designed to reduce the shock load on a cask from many hundreds to around 60 *g* when subjected to a 9-m impact on a solid, unyielding surface; they are also expected to protect the cask body from deformation, particularly in the area around seals and valve penetrations. If these areas are not damaged from an impact, a high probability exists that none of the contents of the package will be released, even under extremely severe accident conditions. If they are properly designed, reduced-scale models of energy absorbers can be tested to develop knowledge of full-scale behavior.

MODEL CASK DROP TESTS

The Nuclear Assurance Corporation (NAC) is developing a legal-weight truck cask to carry a single pressurized water reactor (PWR) fuel assembly. This cask has two stainless steel shells between which the lead gamma shield is poured. A solid, hydrogenous neutron shield, contained within a third stainless steel shell, is placed just outside of the gamma shield. The lid is built completely out of stainless steel, is recessed into the body of the cask, and is held in place with 12 bolts. It is sealed with an elastomeric gasket.

To verify that the design is structurally adequate and that the package meets the requirements specified in the CFR (1988), a number of drop and impact tests were performed on a quarter-scale model of the cask (see Fig. 1). The model had steel blocks welded to the outer shell to simulate the weight of a neutron shield. It was built with a valved penetration between the inner cavity and the outside, thus permitting potential leakage from the cavity during impact to be assessed. The model cask was loaded with a steel bar to simulate the weight of a PWR fuel assembly. The package was equipped with energy absorbers designed to reduce the shock loading to the cask to acceptable limits. The model was equipped with an elastomeric O-ring seal and pressurized to 2×10^5 Pa (30 psig). Two triaxial accelerometers were attached to the outer shell to measure cask decelerations from an impact; strain gages were bonded to the cask at several locations. Before the tests, a number of precise measurements were made to determine the original dimensions of the model; they were then compared with similar measurements after the tests were completed.

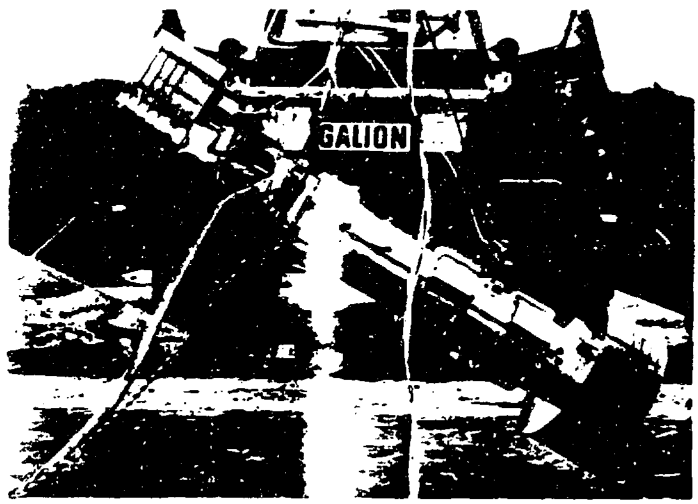

Fig. 1. Model of the NAC single-element shipping cask.

The model was dropped onto a steel-surfaced, reinforced-concrete pad from 9 m. It was subjected to the following tests in the order shown.

1. a vertical end drop;
2. an edge drop with the center of gravity of the cask over the edge;
3. a side drop; and
4. an angle (slapdown) drop, with the cask body initially oriented at 60 deg from vertical.

A fifth test was made in which the model was dropped in a horizontal attitude from 1 m onto a mild steel punch. The package impacted at the midpoint along its length.

The results of the tests are as follows. With the exception of the fifth test, all drops affected one of the two, or both, attached energy absorbers. These particular absorbers were built from an aluminum honeycomb material and designed so that the energy absorbed per unit volume of material crushed is independent of the direction of impact.

The energy absorbers performed the task they were designed for: namely, to crush from an impact and protect the model cask from high impact forces. In most cases, the loadings suffered by the cask were reduced to approximately 250 *g* as measured by piezoelectric accelerometers attached to the body of the quarter-scale model. From the scaling laws described earlier, this measurement is equivalent to about 60 *g* in the full-scale cask.

The dimensions of the test model were measured at the ORNL Metrication Laboratory. The inner diameter was measured in a number of directions and locations along the cavity length. The outer diameter measurements were taken at three locations along the length of the cask. In addition, external longitudinal dimension measurements were made to monitor any permanent bending that might occur as a result of the cask hitting the impact pad at an oblique angle. Similar measurements were made following each of the tests.

Results indicate that very few dimensional changes occurred in the model, except in the fifth test. In this last test, both the inner and outer steel shells bent slightly in a very localized way, with the inner cavity bulge reducing the inner diameter by about 0.5 cm if scaled to the prototype cask (equivalent to a change of approximately 1.5% in the cavity diameter at that point).

This information has been used by the NAC in its application and request for a C of C from the NRC.

CANISTER DROP TESTS

To demonstrate how the combination of tests and analysis can be used to shorten the time required to obtain regulatory approvals, the recent development of a new spent fuel shipping system is described below. A cask developed by Nuclear Packaging Inc. (NuPac) was designed to transport debris from the damaged Three Mile Island Unit II core in sealed canisters to the Idaho National Engineering Laboratory. The canister, shown in cross section in Fig. 2, incorporated neutron poison rods for criticality control.

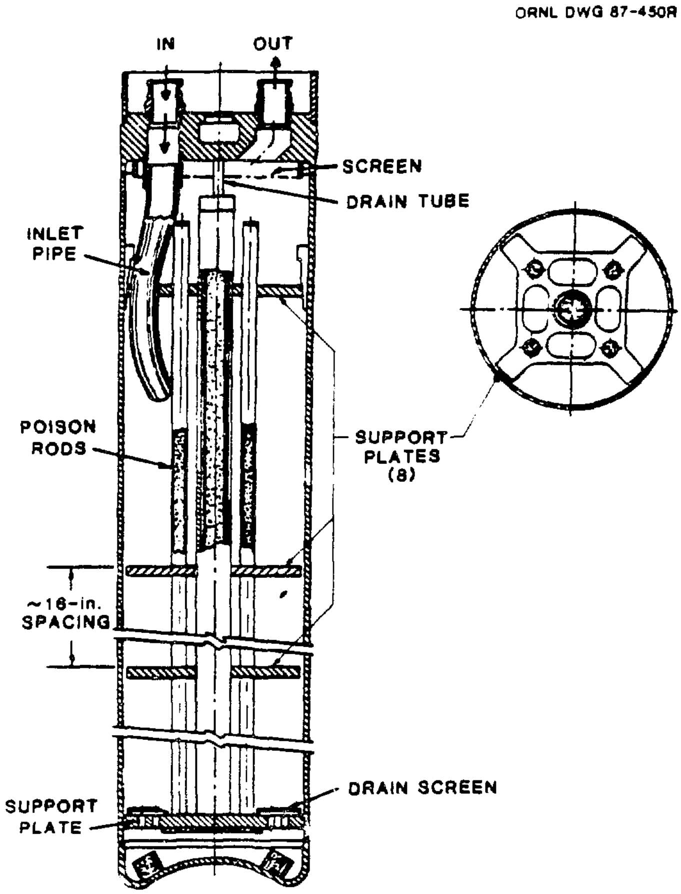

Fig. 2. Defueling canister.

Specific defueling schedules of the reactor resulted in the need to produce a licensed cask within 18 months after NuPac received the contract for the system (Haelsig et al., 1987). As a result, the accelerated development of the cask system required an integrated approach to analysis and testing that used conservative analytical methods in the design of the package, followed by the testing of models to prove their adequacy to meet the regulations with no need to revise the design and retest.

Both a quarter-scale model of the cask and a full-scale prototype of a fuel canister were built and tested as part of this effort. The primary concern of the canister tests carried out at ORNL (Box et al., 1986) was to demonstrate that neutron poison rods located in the central region of the container would remain in place even under the severe accident conditions required by the regulations.

Disassembled parts of a prototype defueling canister were sent to ORNL. The canister was then assembled and measured to determine the exact location of various components. These dimensions became the basis for comparing subsequent measurements made of the canister following the various drop tests. Because of the need to ensure that the central poison rods remained in place following the tests, the canister was initially X-rayed from a number of predetermined angles in order to document the exact position of the rods.

This canister is designed to contain 800 kg (1770 lb) of debris from the core. The fuel is pumped into the canister as part of an aqueous slurry and is subsequently dewatered. Therefore, some water is expected to remain in the canister during shipment, which, under subzero temperature conditions, could freeze and create the potential for high torsional forces to be exerted on the internal poison rods during an impact. To simulate these conditions, a mixture of water and surrogate fuel (lead shot) was added to the test canister; excess water was removed until the total payload was approximately 820 kg (1800 lb). The canister was placed in a specific orientation and cooled to -30°C inside a refrigerator. With the canister at these subzero temperatures, several tests were run, during which the frozen mixture dynamically loaded its internal structure.

Previous analyses had determined that the canisters would be subjected to 60 to 80 *g* if the cask were exposed to the regulatory impact conditions. Therefore, ORNL designed a Cask Simulation Vessel (CSV), which is a pipe whose internal diameter is slightly larger than the outer diameter of the canister and has an attached energy-absorbing system that would restrict the decelerations experienced by the canister to approximately those shock levels.

Four drop tests of the canister in the CSV were carried out under conditions noted below:

Drop attitude	Canister orientation	Location of surrogate fuel	Canister internals
Vertical	Bottom down	Uniform along length of canister	Frozen
Horizontal	Side	Bottom of canister	Frozen
Vertical	Top Down	Top of canister	Ambient
Horizontal	Side	Side of canister	Frozen

Results of the tests indicated that little deformation of the internals was found. Details of the tests are in Box et al. (1986).

NuPac presented its SAR to the NRC and received a C of C within the time specified (NuPac, 1986). As a result of this effort, it was determined by Haelsig et al. (1987) that "integrated test and analysis demonstrations, when used together, can accelerate the design and licensing process."

CONCLUSIONS

In the case of NAC, the company determined that the testing of model energy absorbers was indepensable to their application for a C of C. The tests provided direct evidence that the energy absorbers would adequately protect the prototype cask if it were exposed to the

9-m drop test conditions specified in the regulations (CFR, 1988). In the case of NuPac, the company found that the integrated analysis/testing approach provided, in part, the following benefits (Haelsig et al., 1987):

1. Test results benchmarked and confirmed the applicability of analytic methods for the prediction of phenomena not directly tested.
2. All-important analysis assumptions were supported by physical tests.

It is apparent that drop testing of packages that are used to transport spent fuel is likely to remain a cornerstone of the regulatory approval process. As noted previously, there are many reasons for this probability, including the need to (1) develop material properties for some materials of construction, (2) corroborate specific analytic assumptions, and (3) demonstrate experimentally that certain package designs can withstand the severe accident criteria specified in the regulations.

While there are many benefits of testing scale models of spent fuel casks, there are also benefits of testing a prototype package, such as providing strong evidence to the public that the full-size cask can indeed pass the extremely severe regulatory tests and meet all necessary requirements. However, it remains to be seen whether the need to test full-scale prototype packages, including those weighing over 100 metric tons, will be necessary.

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