Scale Testing of Battelle Energy Alliance (BEA) Research Reactor Cask (BRRC) in Support of Nuclear Regulatory Commission (NRC) Licensing - 10459

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ABSTRACT

Scale model testing was used to support the Nuclear Regulatory Licensing of a new package for the shipment of irradiated research reactor fuel. The package is a legal weight truck cask designed specifically to interface with the research reactor facilities. The one-half scale testing was done to confirm the performance of the impact limiters and attachments. The confirmatory testing provided baseline data that was used in the structural evaluation of the package. The scale testing also was used to demonstrate the design capabilities of the impact limiters and attachments. The scale testing program provided physical evidence of the performance capabilities of the impact limiters on which to base the design and license. The reduction in risk by performing the testing permitted an expedited schedule where the full scale cask was fabricated in parallel with licensing activities.

INTRODUCTION

Battelle Energy Associates (BEA) Research Reactor Cask (BRRC) is a replacement cask for an older cask for which the license expired due to recent regulatory changes. The need to replace this cask in a timely manner required the BRRC to be designed, licensed and fabricated expeditiously. To move forward with this endeavor with minimum risk necessitated large margins in the design that could be demonstrated easily. Demonstration of the compliance of the BEA Research Reactor Cask package design with the requirements of 10 CFR §71.73 of the US Code of Federal Regulations was achieved primarily by analysis. Minimizing the use of complex analysis by using a simplified licensing approach reduced the risk unnecessary delays in the licensing. Therefore, one-half-scale testing was used to demonstrate the performance of the polyurethane foam-filled impact limiters. The tests used prototypic, half-scale test impact limiters and a dummy cask with prototypically scaled weight. Both the impact limiters and the attachments (including the limiter attachment components and the cask attachment components) were of prototypic materials and construction.

The objectives of these tests were to demonstrate the general structural integrity of the impact limiters and attachments in free drop and puncture events, to confirm the maximum impact magnitudes, and to verify that the maximum damage to the impact limiters was bounded by the assumptions used in the thermal and criticality analyses.

PACKAGE DESCRIPTION

The BEA Research Reactor Cask or BRRC is a small truck-mounted cask designed for the shipment of research reactor fuel. The cask fully loaded weighs approximately 14,515 kg (32,000 lb). The overall height of the package with impact limiters is 3.04 m (119.5 in). The outer diameter (OD) of the body is

0.97 m (38 in). The OD of the impact limiters is 1.52 m (60 in) and each weighs approximately 1,043 kg (2,300 lb). The cask body is shielded with 20.3 cm (8 in) equivalency of lead.

The inner cavity of the BRRC is 0.46 m (16 in) in diameter and 1.70 m (67 in) in height. It currently is designed to hold four different baskets for the different fuel families. The baskets are for the Missouri University Reactor Fuel, the Massachusetts Institute of Technology Reactor Fuel, the Advanced Test Reactor Fuel and theTraining, Research, Isotopes, General Atomics (TRIGA) fuels. The baskets have the capability to accommodate the various lengths within each family of fuels through different length spacers. The fuels are of plate type, either aluminum or stainless cladding.

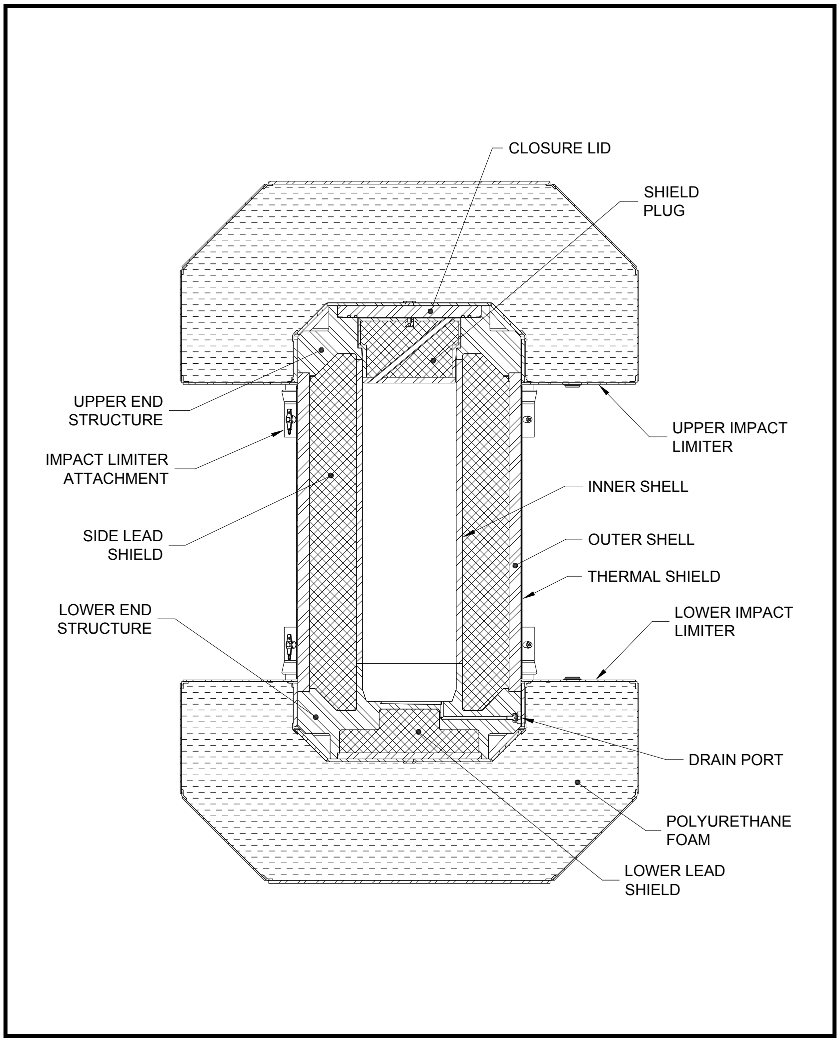

Fig. 1 BEA Research Reactor Cask Cross Section

DESIGN

The basic package design was based on a previously licensed package, the Sterigenics Eagle, NRC Docket (71-9287). The Eagle was licensed for handling irradiation sources. The Eagle package had approximately the same cavity size and shielding requirements as the BRRC. Therefore, the size and basic structural requirements were similar. The major difference was that the decay heat load was far greater for the Eagle sources than what appeared to be required for the research reactor cask. Due to the lower heat load for the BRRC, the more traditional foam and shell impact limiter design was used to facilitate licensing.

The fragility of the contents of a package is something over which the designer usually has little control and, in many cases, is an undefined factor that must be addressed. The structural integrity of the contents is usually counted on in some form for criticality control, shielding and, in some cases, containment. As seen in the commercial fuel, higher burn ups lead to higher irradiations of the structural material. This brings into question the integrity of materials that cannot be readily addressed. A large margin of conservatism is invoked when the structural integrity cannot be addressed and it must be assumed that the contents will be reduced to a rubble state. This conservatism significantly diminishes the efficiency of the shipping package.

The research reactor fuel to be shipped in the BRRC is fairly robust by design due to its small size and plate configuration. The basic fuel designs have also been in service for a number of years. The anticipated shippers of the fuel were able to come up with some reasonable fragility limits of 120 g's for the design basis of the package.

Polyurethane foam and shell impact limiters have been used in a variety of radioactive material shipping packages over the last 40 years. Both the material and various configurations have been tested extensively providing a very detailed design basis. Polyurethane foam as an energy absorbing material changes properties, as do all materials with temperature. The changes in properties, although well known, must be accounted for in the design process. As in all cases, the designer must devise an impact limiter that not only provides adequate protection for the contents and package at cold temperatures where the foam is the stiffest but also keeps the impact limiters from running out of energy absorbing capacity at high temperatures.

TEST PROGRAM

To support the design and licensing of the BEA Research Reactor Cask (BRRC) a half-scale test program was determined to be the best path forward. The test program was designed to validate the design parameters of the impact limiters, demonstrate the calculated values of the applied loads to the cask, conservatively bound the actual loads, and demonstrate adequacy of the impact limiter attachments. In validating the design parameters, it was necessary to show that the impact limiters had adequate energy absorbing capability to protect the package and contents during the drop event. In addition, it was necessary to demonstrate that the skin of the impact limiters was adequate but not so strong as to make the impact limiters too stiff. The skin or shell of the impact limiter protects the foam in the fire event as it chars. The foam insulates the package, protecting the seals and the contents of the package. It is recognized that a shell compliant enough to allow the foam to crush may be punctured in the pin puncture portion of the tests. The only means to demonstrate that the shell is not so weak as to allow major portions of the foam to either become removed or exposed excessively to fire, is to perform a series of puncture tests attacking the impact limiter in various locations.

The bounding case for the impact limiter performance is a series of cold free drops where the foam becomes stiff. Therefore, for benchmarking purposes and to demonstrate bounding conditions, cold impacts were chosen to validate the analytic analysis of the impact limiter performance. Three basic drops were chosen for the 9 m (30 ft) drops, end drop, slap down, and center of gravity (c.g.) over the impacted corner. The orientations for the various drops can be seen in the schematic in Fig. 2.

TEST FACILITIES

The drop pad had a total weight of approximately 22,680 kg (50,000 lb). The embedded steel plate target had a thickness of 6.35 cm (2.5 in). The pad therefore constituted an essentially unyielding surface for the test package, which weighed somewhat less than 1814 kg (4,000 lb).

In accordance with the requirements of 10 CFR §71.73(c)(3), the half-scale puncture bars were fabricated from solid, 7.62-cm (3-in) diameter mild steel bars. Puncture bars of two lengths were used: 63.5 cm (25 in) and 172 cm (50 in) long, measured from the top of the base plate, which were welded firmly to the impact surface during the drops. The length of each bar was designed to allow the puncture event to proceed to completion before the test package gained any support from the unyielding surface, but without excessive length.

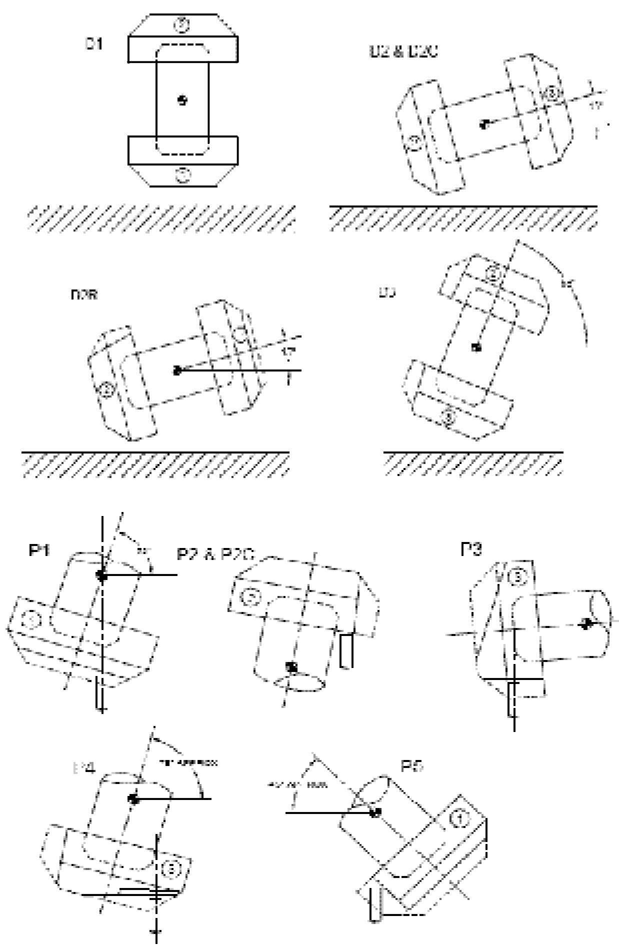

Fig. 2 Test Orientations

The dummy cask was a steel cylinder which represented the BRRC in half-scale. It consisted of a thick-walled carbon steel outer cylinder with an OD of 48.2 cm (19 in). The inner cavity was occupied by a lead-filled pipe. The cask impact limiter attachments were prototypic and made of Type 304 stainless steel. The cask attachments were welded to stainless steel plates which were embedded in the surface of the dummy cask, thus ensuring that the entire impact limiter attachment load path was fully prototypic.

Table I. Test Unit Weights

Component	Weight, kg(lb)
Dummy Cask	1443kg (3,181lb)
Impact Limiter Serial No. 1	126kg (278lb)
Impact Limiter Serial No. 2	125kg (276lb)
Impact Limiter Serial No. 3	125kg (276lb)

The dummy cask, which modeled the cask, shield plug, closure lid, and maximum contents, weighed 1,443 kg (3,181 lb). In full-scale, that weight would be eight times larger or 11544 kg (25,448 lb). This is approximately 7% less than the estimated upper bound weight of the full-scale cask body, less impact limiters, of 12,428 kg (27,400 lb). The attachment ball-lock pins used in testing were made of carbon steel with a lower breaking strength than the full scale stainless pins. These differences were not considered significant.

INSTRUMENTATION

Accelerometers

Accelerometers were used to record the impact of each free drop, except drop D2C, which was a confirmatory test for the revised impact limiter attachments. Accelerations of the puncture drops were not recorded. The accelerometers mountings were changed depending on the orientation of the drop to obtain the correct loading on the package. When the angle was not in line with the axis of the accelerometer, the output was corrected for the geometry.

Four axial and four transverse mounting positions were provided at each end of the cask. The measurement axes were as close to the cask surface as possible, and the mounting blocks were welded rigidly to the cask.

Thermocouples

A refrigerated trailer was present onsite to cool the certification test articles prior to assembly onto the dummy cask for testing. Thermocouples were inserted in each test article. Two thermocouples were used for each test article, located 180º apart. Since the minimum temperature which could be set on the chiller unit was -28.9 ºC (-20 ºF), the test articles were generally between -23.3 ºC (-10 ºF) and -28.9 ºC (-20 ºF) at the time of test. The temperature of the foam in tests D3, P2, P2C, P3, P4, and P5 was not required to be cold. Temperature of the foam was recorded just prior to the test for the impact limiter(s) experiencing impact or puncture.

TEST RESULTS

Results of the scale testing are summarized below. The tests were performed in the order D1, P1, D2, D2R, P2, D3, P4, P5, and P3. The accelerometer data reported was an average from the multiple accelerometers, and the component was taken perpendicular to the impact pad. These values were then scaled and compared to the calculated full-scale values as discussed later. The performance of the impact limiters and attachments for each test are discussed below.

All puncture drop tests were performed from a height of 1 m (40 in) above the top of the puncture bar. All puncture tests, except P2 and P2C, were performed using a 63.5-cm (25-in) long puncture bar. Tests P2 and P2C utilized the127-cm (50-in) long bar. The puncture bars remained securely attached to the steel drop pad in all cases.

According to the laws of scaling, the full-scale linear measurements are twice those recorded here, and the full-scale accelerations are half of those recorded here. The tests are documented in the order in which they were performed.

Free Drop, Vertical (D1)

Test D1 was performed using a drop height of 9 m (30 ft) oriented with the cask axis vertical. The lower impact limiter was serial number 1. The impact limiter attachment pins for this test were 0.64 cm (1/4 in) diameter carbon steel pins. The pins were in matching drilled holes.

The impact limiter was attached securely following the test. Of the six impact limiter attachment pins, one failed by bending and shear, and others showed signs of bending without failure. At least two had no noticeable damage. The shells of the limiter deformed without any tearing or exposure of foam.

Puncture Drop Test P1

Puncture test P1 was performed immediately after drop test D1. The test was a c.g.-over-corner impact on the thicker bottom plate of the impact limiter, near the outer edge of the thicker plate. The impact took place on the crush damage from free drop test D1. The angle of the cask axis was 73º ±3º to the horizontal. The ball lock attachment pins were 0.64 cm (1/4 in) diameter carbon steel pins.

The bar impact was located approximately 2.5 cm (1 in) from the outer edge of the thicker bottom plate. The impact created a dent approximately 4.4 cm (1.75 in) deep. One or two rebound impacts having negligible deformation also occurred. There were no signs of cracking in the dent or in the nearby weld seam.

Oblique Slap Down Free Drop Test D2

Test D2 was performed using a drop height of 9 m (30 ft) oriented with the cask axis at 16º to the horizontal. The primary (lower) impact limiter was serial number 2, and the secondary (upper) impact limiter was serial number 3.

In the test, all of the attachment pins on the primary impact limiter sheared off. The limiter remained attached to the cask. None of the pins failed on the secondary impact limiter. There was some incipient cracking of the weld seam on the secondary limiter, but the cracks were of insignificant size and no foam was exposed.

Repeated Oblique Slap Down Free Drop Test D2R

Test D2R was designed as a repeat of test D2, made after increasing the size of the attachment pins from the original diameter of 0.64 cm (1/4 in) to 1.3cm (1/2 in) which had four times the strength. The hole through the cask attachment lugs was increased to 1.3cm (1/2 in), and the hole in the impact limiter blade was increased to 1.6 cm (5/8 in). The effect of increasing the hole size was to reduce the ligament width on both sides of the hole, but especially on the inner side (toward the cask body). In some cases, the ligament was increased with a weld overlay. These changes were made to all three impact limiter test articles.

In the test, none of the attachment pins failed, but four out of six of the blades of the primary limiter failed by tensile failure of the inner ligaments. The limiter remained attached to the cask. None of the pins or ligaments failed on the secondary impact limiter.

In addition, the corner joint between the top annular plate and the outer cylindrical shell of the secondary impact limiter failed in the impact region. The tear appeared in the weld as well as in the leg of the corner angle located on the top surface.

Confirmatory Drop and Puncture Tests of Modified Design of Attachments

The D2 and P2 tests were rerun with impact limiters with strengthened attachments The strengthening of the test articles resulted in attachments which, in full-scale, were not stronger than the attachments used on the production hardware. None of the other tests were invalidated by the increase in the strength of the attachments. In all of the other tests, the attachments did not fail. Therefore, making the attachments stronger had no effect on the prior tests.

Description of Design Changes

The configuration of the attachments was increased in capacity as much as possible given the limitations of the existing hardware. In no case did the revised test hardware have a greater strength than the revised full-scale design. The nominal thickness of the blades, made of ASTM Type 304 material, was 0.95 cm (3/8 in). The width of the blades was increased to 3.81 cm (1.5 in). The new blades were attached to the original blade roots using a full penetration weld.

Oblique Slap down Free Drop Test D2C Results

Test D2C was performed using a drop height of 9 m (30 ft) oriented with the cask axis at 17º to the horizontal. The crush deformations were very similar to those obtained in tests D2 and D2R on the same limiter. All of the attachments, both primary and secondary, remained completely intact. The accumulated damage to the impact limiters, including the results of test D2C, can be seen in the photograph at the end of this paper.

Puncture Drop P2C Results

Puncture test P2C was performed immediately after drop test D2C. The longer puncture bar was used to impact the top annular surface of the damaged primary impact limiter. The orientation could not be over the center of gravity due to the desired impact location. The impact caused the long puncture bar to bend somewhat, but the attachment to the steel drop pad plate remained intact. The impact dent on the annular plate was negligible, without any cracking or tearing of the steel shell, and no exposure of foam. The attachments all appeared to be in good shape following the test. There was little deformation to the impact limiter attachments and only minor damage to the welds that spread the loads into the impact limiter shell annular plate that deformed around the attachments.

Table II. Summary of Certification Tests

No.	Test Description [a]	Test Limiter	Acceleration (g's) Primary/Secondary	Crush cm(in) Primary/Secondary
D1	End drop	#1	116	8.6(3.4)
D2	Slap down oblique drop, 15º	#2 & #3	140/107	9.9(3.9)/10.2(4.0)
D2R	Slap down oblique drop, 15º	#2 & #1	113/114	10.2(4.0)/9.9(3.9)
D2C	Slap down oblique drop, 15º	#2 & #3	Not recorded	
D3	C.G.-over-corner drop	#3	117	14.0(5.5)
P1	Oblique through c.g. on thicker end plate on test D1 damage	#1	Not recorded	
P2	Approx. parallel to package axis, on test D2 primary-end damage	#2	Not recorded	
P2C	Approx. parallel to package axis, on test D2 primary-end damage	#2	Not recorded	
P3	Approx. perpendicular to package axis, on test D2 primary-end damage	#2	Not recorded	
P4	On test D3 damage, on thick/thin joint, near c.g.	#3	Not recorded	
P5	Oblique to package axis, on test D3 secondary-end damage	#3	Not recorded	

[a] All free drops (Dx) are from 9 m (30 ft), and all punctures (Px) are from 1 m (40 in).

IMPACT LIMITER EVALUATION

The acceleration data was used not only to demonstrate the adequacy of the impact limiters by test but also to bench mark the analytic tools used to evaluate the impact limiters. As noted, the impact limiters are filled with polyurethane foam that absorbs energy by crushing. The force required to crush the foam is dependent on the strain rate, the temperature of the foam, the orientation of the foam, the manufacturing tolerance of the foam and the percentage of crush. Analytic tools have been developed that can provide force deflection curves for the various orientations of the cask impacts taking into consideration the orientation of the foam at the various impact orientations. These force deflection curves are then used in applying a force to the cask for the structural response of the package at the different orientations and temperatures.

Bounding values for each crush percentage are developed that take into consideration the temperature and the manufacturing tolerance. The highest crush strength comes from the cold foam with the greatest density permitted. The softest foam is the foam at the highest temperature and the lowest density. Of course it takes less crush of the stiff or cold foam to absorb the same amount of energy. On the other extreme, the soft foam must be checked at the maximum strain where it gets very hard as well. These two bounding conditions also are affected by the impact limiter shells which add crush strength to that provided by the foam. These force deflection curves are used to predict loadings on the cask in various orientations. These analytic values are compared to the accelerations seen in the scale testing and the crush distances in the scale testing when corrected for the scale factors. The values calculated, as seen in the table below, show that the calculated values are conservative compared to the test values in all orientations.

Table III. Test Unit Values as a Percentage of Predicted Results (Full-Scale)

		Acceleration (g)			**Crush Distance (in)**		
Test #	**Location**	**Calc**	**Actual***	**% Less**	**Calc**	**Actual**	**% Less**
D1	Primary	72.4	58.0/54.5	-19.9/-24.7	7.3	6.8	-6.8
D2R	Primary	71.0	69.0/63.5	-2.8/-10.6	10.7	8.0	-25
	Secondary	86.8	71.8/66.3	-17.3/-23.6	12.1	7.8	-36
D3	Primary	69.6	58.5/50.5	-15.9/-27.4	13.3	11.0	-17

*The actual accelerations are given as the data from 1019 Hz cutoff and the estimate for the rigid body response.

As a result of testing, several modifications were made to the full-scale unit. The closure weld for the impact limiters was moved from the outer edge of the impact limiter shell to the inner edge where less deformation occurred. The impact limiter attachments were strengthened by increasing the plate thickness and the pin diameter which was confirmed in test D2C and P2C. The diametrical clearance between the cask and the impact limiters was decreased, and the number of attachments was increased to eight.

CONCLUSION

The half-scale test program used in the design and licensing activities for the BEA Research Reactor Cask successfully proved several aspects of the impact limiters. It showed that the impact limiter attachments, which are difficult to size by calculation, needed to be strengthened. The redesign of the attachments, which increased the strength by doubling the attachment plates on the impact limiters and doubling the size of the attachment pins, was demonstrated to be adequate in confirmatory testing. Likewise, the attachments were confirmed to be adequate by puncture bar confirmatory testing. The half-scale tests also uncovered a potential flaw in the location of the closure joint in the impact limiter shell. This joint was relocated and a stronger joint used in the higher deformation region. Accelerometers and detailed measurements provided force deflection data for a series of drops. The half-scale tests demonstrated that the analytically developed applied loads for the different drop orientations were conservative under all conditions as compared to the test data.

These demonstrations and hard physical data allowed for expedient licensing of the BEA Research Reactor Cask package. The half-scale test program provided a firm basis to demonstrate significant margins of safety for the design. Furthermore, it provided confidence in the design permitting at risk fabrication of the package in parallel with the licensing process.

Fig. 3 Puncture Test P5 Damage

Fig. 4 Scale Package after D2C Test showing Accumulated Damage