Results of the Sandia National Laboratories MOSAIK Cask Drop Test Program*

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Introduction

There has been a significant international effort over the past ten years to qualify structural materials for construction of radioactive material (RAM) transportation casks. As *total life cycle cost* analyses argue the necessity for more efficient casks, new candidate structural materials are evaluated relative to the historically accepted austenitic stainless steels. New candidate cask containment materials include ferritic steels, ductile iron, depleted uranium, and titanium. Another material, borated stainless steel is being considered for structural cask internals because of its neutron absorption properties. The mechanical performance of the borated stainless steels is a function of the boron content and metallurgical processing conditions. A separate paper in this symposium (Stephens et al. 1992) deals with the properties of a range of borated stainless steels. A major technical issue involved with the qualification of all these candidate materials is that they may, under certain combinations of mechanical and environmental loading, fail in a brittle fashion. Such a failure would of course not be acceptable for a RAM transport cask involved in an accident. The cask designer must assure cask owners, regulators as well as the general public that the cask will not undergo brittle fracture for all regulatory loading conditions.

Qualification of ferritic metals, and in particular ductile iron, has progressed on a number of fronts. Standards development and analyses and testing programs have been pursued through a number of international organizations. Two companion papers are also being presented at PATRAM '92; the first paper (Sorenson et al. 1992) deals with developing a brittle fracture evaluation criterion through the IAEA and the second paper (Salzbrenner et al. 1992) describes the materials characterization program for the MOSAIK casks.

This paper summarizes the drop tests that were conducted using the MOSAIK casks to verify the fracture mechanics cask design approach and to demonstrate that ductile iron could be subjected to severe loading conditions without failing in a brittle manner.

Engineering Basis

The fundamental engineering discipline of linear-elastic fracture mechanics (LEFM) is being applied to the qualification of ferritic materials for structural components in RAM transport casks. The basic formulas that describe material behavior are;

$$K_I = C\sigma(\pi a)^{1/2} \qquad \text{Equation 1}$$

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* This work performed at Sandia National Laboratories supported by the U. S. Department of Energy under contract number DE-AC04-76DP00789.

** A U. S. Department of Energy Facility.

where,

K_I = applied stress intensity {MPa-m$^{1/2}$}
C = geometric constant
σ = maximum applied tensile stress {MPa}
a = depth of flaw at location of maximum applied tensile stress {m}

Further, to preclude brittle fracture behavior, the materials fracture toughness value, K_{Ic}, must be less that the applied stress intensity value, K_I;

$$K_{Ic} > K_I \qquad \text{Equation 2}$$

Equations (1) and (2) can be used to predict the critical flaw depth, a_{cr}, at which brittle fracture is imminent for the set of design conditions under consideration;

$$a_{cr} = \pi^{-1}(K_{Ic}/C\sigma)^2 \qquad \text{Equation 3}$$

This set of equations allows the cask designer to adjust the design parameters (i.e. applied stress, material properties, and inspection procedure) in order to satisfy Equation (2). Applying these equations to cask design, the potential for brittle fracture is precluded.

The above Equations 1-3 assume the cask will behave in a linear elastic manner. Under linear elastic conditions, the applied stress causes negligible plastic deformation, and all of the applied energy is available to extend the flaw. This is a conservative assumption, in actuality plastic deformation in the vicinity of the flaw will often occur. Extensive plastic deformation has at least two effects: the first is that the crack tip is blunted and thereby becomes less potent; the second is that since some of the "energy" from the applied stress has been "absorbed" by the plastic deformation processes, that less is available to propagate the flaw.

The situation in which significant plastic deformation precedes (or accompanies) flaw extension is appropriately treated by elastic-plastic fracture mechanics (EPFM). The engineering application of EPFM is somewhat more complex, but its basic steps are comparable to those described above for LEFM. The applied driving force to extend the flaw is designated J_I, which is a measure of the elastic-plastic stress-strain field ahead of the flaw tip. This can be calculated (using finite element methods for complex geometries) as the path-independent line or surface integral that encloses the crack front from one crack surface to the other. A method for doing this is described elsewhere (Wellman, 1990). The applied J_I is compared to the material's inherent resistance to crack initiation, called J_{Ic}. J_{Ic} is a material property which can be measured in the laboratory (and can be related to K_{Ic} which is the material's resistance to crack initiation in linear elastic terms). When J_I is less than J_{Ic} no crack initiation from the flaw will occur. When J_I is greater than J_{Ic}, at least some crack initiation from the flaw will occur.

While the methods of LEFM may be applied via a straightforward hand calculation, the EPFM procedure in most cases requires finite element analysis (using a material model which accurately captures the plastic regime of the stress-strain behavior) performed on large computers. While the EPFM methods describe the structural response more accurately, the LEFM method can be used as a conservative, easy-to-apply approximation. The MOSAIK cask drop tests were analyzed using both the LEFM approximation and the more exact EPFM procedure. The MOSAIK cask test program was used to demonstrate the validity of this approach and to quantify the factor of safety that can be expected when designing casks using LEFM.

Physical Description of the Test Casks

Two casks were used in this test program; the MOSAIK KfK and the MOSAIK I. These casks were donated to Sandia National Laboratories by Gesselschaft für Nuklearservice (GNS) of Germany. The casks were constructed of ductile iron and are currently used in Europe to transport low-level radioactive wastes. The MOSAIK KfK was the cask that was used for the rigorous testing. The MOSAIK I was used primarily as a device to verify test conditions, rigging procedures, instrumentation, etc., prior to a drop of the MOSAIK KfK. Table 1 details the main physical features for each cask.

Table 1. Mass and dimensions of the two MOSAIK casks used in the Sandia National Laboratories MOSAIK Drop Test Program.

Cask	Mass (Kg)	Height (mm)	Outside Ø (mm)	Inside Ø (mm)	Wall Thick, (mm)
MOSAIK KfK	5402	1365	1060	632	214
MOSAIK I	2960	1150	900	600	150

Material Description of the Test Casks

Both the MOSAIK I and the MOSAIK KfK casks were manufactured in the early 1980's and utilize a ductile iron that is not as advanced as the materials currently produced by GNS (and others) using the most recent casting procedures. More advanced, later generation materials generally possess higher ductility and have a lower variation in mechanical properties through the wall thickness. The ductile iron used in the casks tested in this program does not meet the ASTM A-874 specification on ductile iron for composition. Therefore, these casks tests can be considered as lower bound test case for ductile iron. A complete description of materials testing and properties (material composition and microstructure) is provided in another PATRAM '92 paper (Salzbrenner et al. 1992).

The testing revealed that the cask material had the following "average" (Salzbrenner et al. 1992) characteristics:

- Young's Modulus = 16.5 x 10^5 MPa
- Yield Strength = 243 MPa
- Ultimate Strength = 378 MPa
- Tensile Elongation = 24.3% (25mm gage)
- Reduction in Area = 20.6%
- Static Rate Frac. Toughness @–29°C = 95.3 MPa-m$^{1/2}$ (LEFM) ↔ 54.4 kJ/m^2 (EPFM)
- Dynamic Rate Frac. Tough. @–29°C = 74.7 MPa-m$^{1/2}$ (LEFM) ↔ 33.1 kJ/m^2 (EPFM)
- Microstructure — High nodularity of the graphite (>95% Types I & II)
  — Low pearlite (<5%)

Nondestructive Examination Procedures

Before the drop tests were conducted, a comprehensive set of nondestructive examination tests were performed to fully characterize the soundness of the casks. The casks were inspected using dye penetrant, ultra-sonic, and radiographic examinations. The dye penetrant and ultra-sonic testing procedures were performed in accordance with ASTM and ASME standards. The radiography testing was performed in accordance with ASME procedures. No flaws were detected in the castings. These three independent procedures provided a high probability of identifying all material flaws (e.g., casting voids, cracks, and other defects) large enough to constitute a flaw size approaching a_{cr}.

Test Parameters

The drop test program used the hypothetical accident conditions specified by US regulations (10CFR71 1984) as a basis for drop criteria. Parameters that were held constant for each drop were:

1. a 9 meter cask drop height (with one exception),
2. a drop onto an unyielding surface,
3. the cask was dropped without impact limiters (steel rails on the cask ends were used to increase the tensile component of the applied stress in the vicinity of the artificial flaw),
4. the cask metal temperature was = –29°C, and
5. an artificial flaw was placed in the cask wall in the location of the highest applied tensile stress.

The primary test variable in sequential drop tests was the depth of the artificially induced flaw. Successive tests were performed with deeper flaws in order to increase the applied (LEFM) stress intensity in the cask wall as shown in Equation 1. Flaws were introduced by radial cuts from the cask exterior; all flaw tips were subsequently sharpened either by machine or laser techniques. The machine sharpening technique produced flaw tips with a root radius smaller than 0.08 mm. The laser sharpening method produced a small region of remelted material in which small cracks (with a tip radius <0.01 mm) were formed during resolidification. Laboratory tests (room temperature, static loading rate) showed that the measured fracture toughness of ductile iron specimens with the laser induced flaw decreased from the values measured on fatigue precracked specimens. In linear elastic fracture toughness units, the fatigue precracked specimens produced an average value of 120 MPa-m$^{1/2}$ while the laser flawed specimen yielded a value of 78 MPa-m$^{1/2}$. The laser technique was successful in producing an artificial flaw which is more severe than the crack induced by fatigue-type loading.

Figure 1 shows a photograph of a laser-sharpened flaw. This micrograph highlights the graphite nodules imbedded in the ferritic matrix, and also shows the cracks formed during solidification. High carbon martensite is formed in the remelted zone, and possesses a very low toughness. A small volume of embrittled material is thereby placed at the tip of the artificial flaw. The induced cracks and the zone of embrittled material are both effective in lowering the resistance to cracking during an impact loading event. This laser flaw is much more severe than naturally occurring flaws formed by casting defects.

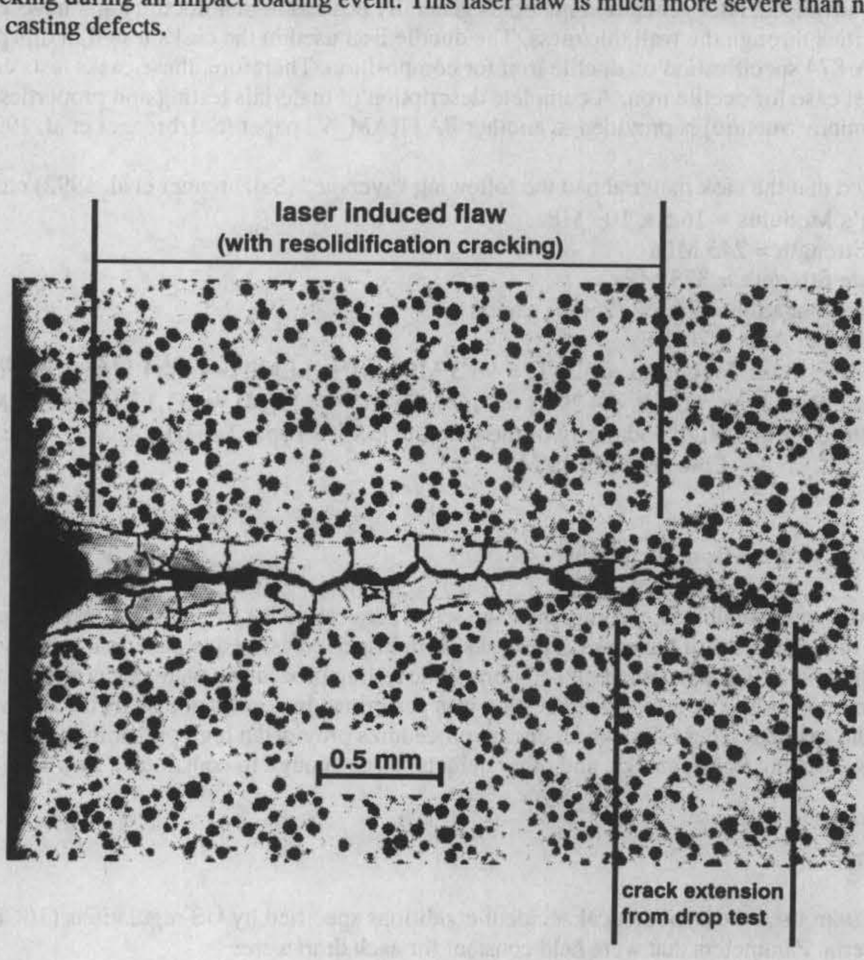

Figure 1. Micrograph of the laser sharpened flaw removed from the MOSAIK KfK cask after the 5th drop test. A small amount (<1 millimeter) of ductile crack extension occurred. A length of approximately 137 mm of uncracked material remained from the furthest extent of crack extension to the inner cask wall.

Figure 2 depicts the drop test set-up. The casks were dropped with two steel rails attached to the ends to produce through-wall tensile stresses in the proximity of the artificial flaw. The laser flaw in combination with the steel rails on the ends of the cask provides favorable conditions to reveal whether brittle fracture can be induced (at −29°C) in the cask material. The test conditions used for the drop tests of the MOSAIK casks are significantly more severe than those required by the U. S. regulations (in which potential consequences of flaws are not treated). Figure 3 shows the generalized instrumentation employed during the MOSAIK KfK drop tests. Instrumentation included accelerometers, strain gages, and thermocouples (two thermocouples were located in small diameter (~1.6 mm) holes at 2.5 and 10 cm wall depths). The accelerometer and strain gage results are used to benchmark the finite element analyses.

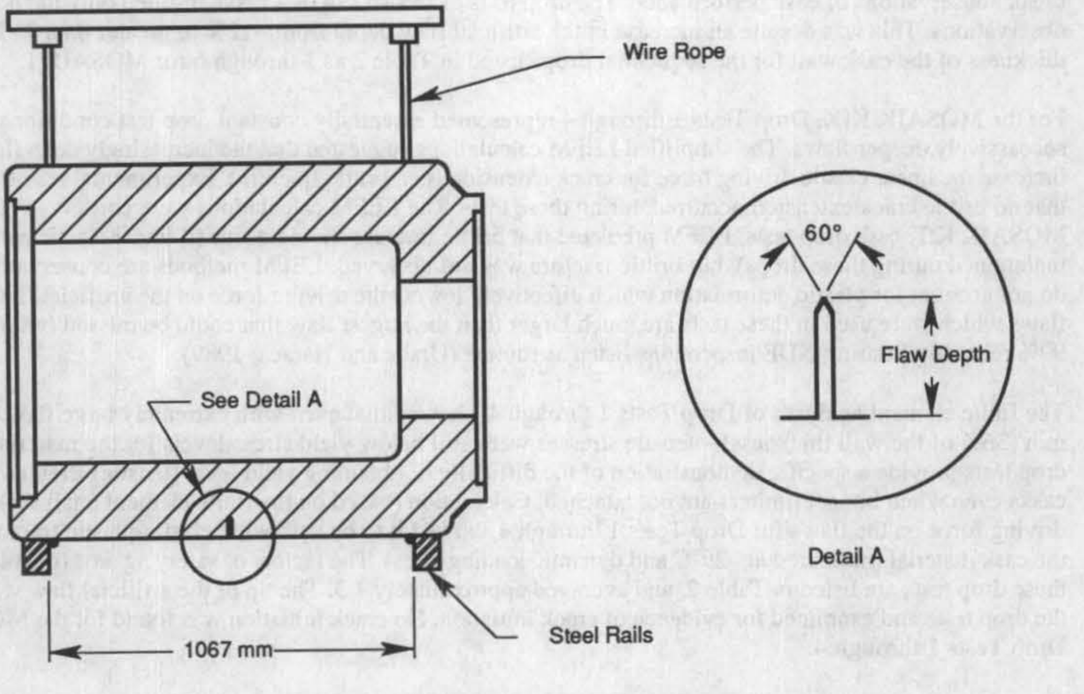

Figure 2. MOSAIK KfK Drop Test Set-up.

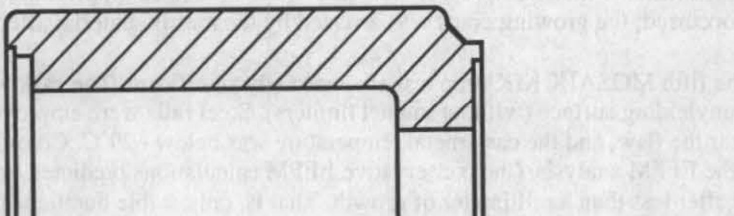

Figure 3. Instrumentation for MOSAIK KfK.

All MOSAIK drop tests were conducted with the parameters shown above, with one exception: in a single drop test, the drop height was increased from 9 to 18 meters. This test was performed to dramatize the integrity of the ductile iron cask when subjected to (extreme) extra-regulatory testing. The drop test was also performed in order to increase the applied tensile stresses, thereby increasing the driving force on the artificial flaw above initiation levels. This test was designed to cause crack propagation from the laser flaw.

Results and Discussion of the Drop Tests

Table 2 shows the results of the drop tests for both the MOSAIK I and the MOSAIK KfK casks. Instrumentation and structural analyses were not performed for the MOSAIK I drop tests. The MOSAIK I drop tests were "break / no break" observations of cask performance. The drop tests of the MOSAIK I casks resulted only in "no break" observations. This was despite an increase in the artificial flaw depth from ~12% to greater than 75% of the thickness of the cask wall for the sequential drops listed in Table 2 as 1 through 6 for MOSAIK I.

For the MOSAIK KfK, Drop Tests 1 through 4 represented essentially constant drop test conditions with successively deeper flaws. The simplified LEFM calculations suggested that the increasingly deep flaws would increase the linear elastic driving force for crack extension (i.e., brittle fracture). Experimental results demonstrated that no brittle crack extension occurred during these tests. The LEFM calculations were conservative for the MOSAIK KfK cask drop tests. LEFM predicted that brittle fracture should occur (if linear elastic conditions could be maintained during these drops), but brittle fracture was **not** observed. LEFM methods are conservative because they do not account for plastic deformation which effectively lowers the driving force on the artificial flaw. The gross flaws which were used in these tests are much larger than the largest flaw that could be missed (with greater than 99% reliability) during NDE inspections listed as routine (Urabe and Harada, 1989).

The finite element analyses of Drop Tests 1 through 4, showed that even with extremely large flaw depths – up 76.2 mm (36% of the wall thickness) – tensile stresses were still below yield stress levels for the material. The MOSAIK drop tests provide a specific demonstration of the difficulty of obtaining yield level (tensile) stresses in thick-walled casks even when impact limiters are not attached. Calculation (based on the finite element analyses) of the EPFM driving force on the flaws for Drop Tests 1 through 4 showed it to be below the elastic-plastic fracture toughness of the cask material (measured at –29°C and dynamic loading rates). The factors of safety against (ductile) fracture for these drop tests are listed in Table 2, and averaged approximately 1.3. The tip of the artificial flaw was removed after the drop tests and examined for evidence of crack initiation. No crack initiation was found for the MOSAIK KfK Drop Tests 1 through 4.

In order to achieve yield level stresses and increase the applied J_I above the level of J_{Ic} (the material's fracture toughness), the fifth KfK drop test was performed from a height of 18 meters. The experimental results showed that this drop did cause the applied stress to exceed the yield strength of the material. The calculated value of the EPFM driving force exceeded the laboratory measurement (Salzbrenner et. al. 1992) of elastic-plastic fracture toughness. The factor of safety was computed as 0.9 (i.e., the flaw depth was greater than the calculated critical flaw depth). Metallographic examination of the flaw tip region confirmed that crack initiation did in fact, occur. A crack extended from the tip of the remelted zone of the laser flaw into the cask matrix. Approximately 0.25 – 0.31 mm of cracking into the matrix occurred; the growing crack was arrested by the matrix material after this small amount of growth.

The results of the fifth MOSAIK KfK drop test are especially significant. The cask was dropped from a height of 18 meters onto an unyielding surface (without impact limiters). Steel rails were employed to enhance the through-wall driving force near the flaw, and the cask metal temperature was below –29°C. Crack initiation did occur, as was predicted from the EPFM analysis, (the conservative LEFM calculations predicted brittle fracture), but the crack growth arrested after less than a millimeter of growth. That is, only stable ductile tearing occurred. This test verified that the material did indeed behave as an elastic-plastic material, in a manner consistent with that demonstrated by laboratory specimens of the same material. For this material and design configuration, the test parameters could not induce a change in the fracture behavior from ductile tearing to brittle cleavage even when crack initiation (ductile) is intentionally introduced. The entire MOSAIK Drop Test Program on the MOSAIK KfK and the MOSAIK I demonstrate that brittle fracture will not occur for accelerations up to 1150 gs at a temperature of –29°C.

Table 2. Test conditions and measured values for the Sandia National Laboratories MOSAIK Drop Test Program of the MOSAIK I and the MOSAIK KfK ductile iron casks (FS = Factor of Safety).

		date	drop hght. (m)	metal temp. (°C)	flaw depth (mm)	flaw tip radius (mm)	flaw aspect ratio	strain$^+$ (10^{-6})	tensile stress$^\#$ (MPa)	fracture toughness K_{Ic}^{++} (MPa-m$^{1/2}$)	LEFM applied K_I (MPa-m$^{1/2}$)	estimated LEFM FS (K_{Ic}/K_I)	F.E. applied $K_I^\#$ (MPa-m$^{1/2}$)	FS$^\#$ (K_{Ic}/K_I)	max. gs$^+$ [at 1 kHz]
MOSAIK I															
(2960 Kg	#1	3/14/90	9	-26	25.4	laser	4.5 : 1	**Not Determined**							
150 mm	#2	3/21/90	9	-31	45.2	laser	3.1 : 1								
wall	#3	5/23/90	9	-32	76.2	.0762	3.2 : 1								
thickness)	#4	8/29/90	9	-32	76.2	laser	3.1 : 1								
	#5	7/10/91	9	-31	101.6	laser	4.0 : 1								
	#6	7/12/91	9	-31	127.0	laser	3.2 : 1								
MOSAIK KfK															
(5402 Kg	#1	6/25/90	9	-26	19.1	.0762	6.8 : 1	1100	179	74.8	51	1.5	50.6	1.5	950
214 mm	#2	2/2/91	9	-29	50.4	.0762	6.0 : 1	750	124	74.8	70	1.1	62.3	1.2	600
wall	#3	8/1/91	9	-29	57.1	laser	6.2 : 1	1100	179	74.8	78	<1	53.9	1.4	800
thickness)	#4	9/5/91	9	-31	76.2	laser	6.0 : 1	900	179	74.8	102	0.7	58.7	1.3	710
	#5	11/14/91	18	-31	57.1	laser	6.2 : 1	1850	**	74.8	**	**	83.6	0.9	1150

$^+$ by field measurements
$^\#$ by finite element (elastic-plastic) calculation
$^{++}$ by laboratory measurement
** not determined

Conclusions

The MOSAIK Drop Test Program at Sandia National Laboratories provides a rigorous demonstration that an LEFM approach to cask design is conservative. Further, it shows that ductile iron is an appropriate material of construction for structural components of RAM transport casks. Results of this test should be used in a complementary fashion with programs from other organizations to provide a background of engineering data that will assure cask owners and regulators alike that LEFM is an appropriately conservative method for designing casks and evaluating cask structural components for the risk of brittle fracture.

References

10CFR71, *Title 10, Code of Federal Regulations, Part 71*, Office of the Federal Register, Washington, DC, (1984).

Sorenson et al., "Development of a Brittle Fracture Acceptance Criterion for the International Atomic Energy Agency," *The 10th International Symposium of the Packaging and Transportation of Radioactive Materials, PATRAM '92* Yokohama, Japan, September 13-18, (1992).

Salzbrenner, R., et al., "Mechanical Properties Used for the Qualification of Transport Casks: Prototype Development and Extension of Serial Production," *The 10th International Symposium of the Packaging and Transportation of Radioactive Materials, PATRAM '92*; Yokohama, Japan, September 13-18, 1992.

Stephens, J. J. et al., "Elevated Temperature Tensile Properties of Borated 304 Stainless Steels: Effect of Boride Dispersion on Strength and Ductility," *The 10th International Symposium of the Packaging and Transportation of Radioactive Materials, PATRAM '92*; Yokohama, Japan, September 13-18, 1992.

Urabe, N., and Harada, Y., "Fracture Toughness of Heavy Section Ductile Iron Castings and Safety Assessment of Cast Casks," Proceedings of *The 9th International Symposium of the Packaging and Transportation of Radioactive Materials, PATRAM '92*; Washington, D.C., June 11-16, 1989, pp. 743-752.

Wellman, G.W., "First Drop of the MOSAIK Cask," *Sandia National Laboratories Memo* to K. B. Sorenson, March 19, 1990.