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Fracture Mechanics Based Design for Radioactive Material Transport Packagings Historical Review

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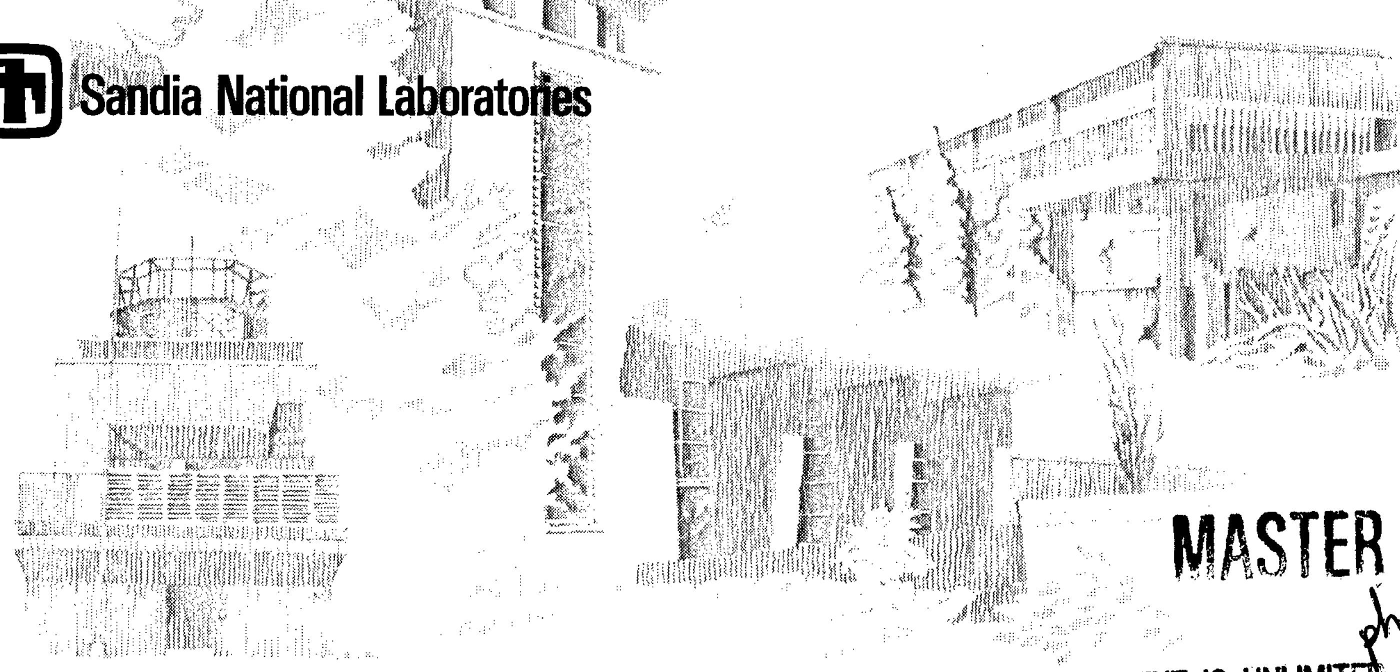

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Fracture Mechanics Based Design for Radioactive Material Transport Packagings
- Historical Review -

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Abstract

The use of a fracture mechanics based design for the radioactive material transport (RAM) packagings has been the subject of extensive research for more than a decade. Sandia National Laboratories (SNL) has played an important role in the research and development of the application of this technology. Ductile iron has been internationally accepted as an exemplary material for the demonstration of a fracture mechanics based method of RAM packaging design and therefore is the subject of a large portion of the research discussed in this report. SNL's extensive research and development program, funded primarily by the U. S. Department of Energy's Office of Transportation, Energy Management & Analytical Services (EM-76) and in an auxiliary capacity, the office of Civilian Radioactive Waste Management, is summarized in this document along with a summary of the research conducted at other institutions throughout the world. In addition to the research and development work, code and standards development and regulatory positions are also discussed.

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Executive Summary

This report is a compilation of materials and structural analysis research done at Sandia National Laboratories in recent years related to the design of radioactive material transport packaging containment.

Over a decade ago, in part in reaction to implications of the Nuclear Waste Policy Act, which mandated development of a repository for the disposal of spent nuclear fuel and vitrified high level waste, considerable activity among the Department of Energy and commercial vendors was directed towards innovative design concepts in radioactive material (RAM) packages for storage, transport, and disposal. The perceived need for large numbers of transport packages to accommodate DOE acceptance of commercial spent fuel and its subsequent disposal in a repository generated a surge in activity to design packagings with greater payload capacity and lower costs relative to existing Nuclear Regulatory Commission-certified packages. Among the innovations proposed, first by European vendors, was the use of ferritic materials for packaging containment (and shielding) instead of the traditionally used austenitic stainless steel. In particular, ductile iron storage and transport packagings were marketed (and are widely used in Europe). Domestic and international governmental and commercial entities, notably the Germans and the Japanese, citing potential cost savings and fabrication efficiencies with the use of ferritics for packages, investigated the merits of ductile iron and other materials, such as ferritic steels and titanium alloys, for containment applications. Materials, such as borated austenitic stainless steel for spent fuel baskets, were developed for RAM-package component applications.

The DOE/EM (and, to a lesser extent, /RW) engaged in modest research programs, primarily at Sandia, to evaluate ferritic materials for transport packaging applications. This research involved materials test programs, full-scale package drop testing, participation on codes and standards committees, international data exchanges, and forums at conferences and symposia.

The proposed use of ferritic materials for packaging containment has not been without controversy and critics. Ferritic materials, unlike austenitics, such as stainless steel, may exhibit a failure mode transition with decreasing temperatures and/or increasing loading rates from a ductile, high-energy failure mode to a brittle, low-energy fracture mode at below-yield stress levels. Regulators have thus been justifiably cautious regarding the use of ferritics for RAM package applications and have indicated that certification of such packages would require extensive confirmatory research and supporting data (although ferritic RAM packages for storage applications have been certified by the NRC). However, the general conclusion of the research reported herein is that appropriate engineering design methodologies exist which, when rigorously applied to RAM transport packaging conditions and environments, warrant the use of suitable ferritic materials for packaging containment. This report summarizes the Sandia work in support of that conclusion. The report also cites and references parallel research and conclusions of other institutions.

Nomenclature

ASME	American Society of Mechanical Engineers
ASTM	American Society for Testing and Materials
BAM	Bundesanstalt für Materialforschung und -Prüfung
CRIEPI	Central Research Institute of Electric Power Industry
CTOD	Crack Tip Opening Displacement
CVN	Charpy V-notch
DI	Ductile Iron
DOE	Department of Energy
EPFM	Elastic Plastic Fracture Mechanics
EPRI	Electric Power Research Institute
FAD	Failure Assessment Diagram
FEA	Finite Element Analysis
FMBD	Fracture Mechanics Based Design
FRG	Federal Republic of Germany
IAEA	International Atomic Energy Association
LEFM	Linear Elastic Fracture Mechanics
LWR	Light Water Reactor
MIDAS	Mobile Instrument Data Acquisition System
NDE	Nondestructive Evaluation
NDT	Nil-ductility Temperature
NRBT	Notched Round Bar Tension
NRC	Nuclear Regulatory Commission
QA	Quality Assurance
RAM	Radioactive Material
SNL	Sandia National Laboratories
YS	Yield Stress
UTS	Ultimate Tensile Stress
10CFR71	Code of Federal Regulations, Title 10, Part 71
a	Crack length
a_{cr}	Critical crack length
a_{NDE}	Crack length detected by nondestructive evaluation techniques
C	A parameter that depends on structure and crack geometry
J	J-Integral
J_c	J-Integral value at the onset of cleavage instability
J_{Ic}	J-Integral value at initiation of ductile tearing
J_{Id}	Dynamic value of J-Integral at initiation of ductile tearing
J_Q	Value of J-Integral calculated from a conditional K_Q value
$K_{applied}$	Applied value of stress intensity, K
K_{Ic}	Plane-strain fracture toughness

Nomenclature Cont.

K_{Id}	Dynamic plane-strain fracture toughness
K_{IR}	Material resistance stress intensity factor
K_{IR}^{*}	Lower bound fracture toughness at estimated service temperature
$K_{Ic,R}$	Plane-strain fracture toughness at a intermediate loading rate
K_{Jc}	Stress intensity factor calculated from a J_c value
K_{JIc}	Stress intensity factor calculated from a J_{Ic} value
$K_{resistance}$	Resistance value of stress intensity, K
K_Q	Conditional stress intensity factor according to ASTM E 399
$\dot{K}$	Rate of applied stress intensity factor
M_k	Membrane stress correction factor
M_B	Bending stress correction factor
Q	Shape factor
Δ_A	Graphite nodule spacing
δ	Crack tip opening displacement
σ	Stress
σ_M	Primary membrane stress
σ_m	Secondary membrane stress
σ_B	Primary bending stress
σ_b	Secondary bending stress

1.0 Introduction

The United States Department of Energy (DOE) is one of the largest shippers, on a total curie basis, of radioactive material (RAM). For example, the DOE has responsibility for approximately 200,000 spent-fuel assemblies of approximately 150 different types. Of these, approximately 20,000 are foreign research reactor assemblies which the United States has committed to retrieve and return to the United States in the near future. With the prospect of increasing needs for shipping RAM, there will be a growing need for safe and efficient transport packagings.

The current practice for the structural design of RAM transport packagings in the United States is based on the Code of Federal Regulations, Title 10, Part 71 (10CFR71), "Packaging and Transportation of Radioactive Material" [1]. This regulation defines specific loading criteria to qualify the structural integrity of a cask and identifies the Nuclear Regulatory Commission (NRC) as the licensing authority for transportation packagings.

The NRC has issued regulatory guides as aids to packaging designers in evaluating material response for packagings subjected to the loading conditions defined in 10CFR71. Specifically, NRC Regulatory Guide 7.6, "Design Criteria for the Structural Analysis of Shipping Cask Containment Vessels" [2], describes design criteria acceptable to the NRC for use in structural analysis. This regulatory guide reflects design considerations for austenitic stainless steels which remain ductile even at low temperatures and high strain rates; therefore, it does not consider structural materials which may have the potential to fail in a brittle mode.

The main licensing concern for using materials in transport packagings that can fail in a brittle manner is the potential of a catastrophic, brittle-type failure when the packaging is subjected to severe loading conditions. This concern is intimately associated with the behavior of such a material in the vicinity of a crack. A ductile material will absorb high energy values around stress concentrations, such as cracks or defects, through local plastic yielding. However, a material that has a ductile-to-brittle transition may dissipate the energy of loading by crack extension if the material is used within its brittle regime. Therefore, a fracture mechanics methodology is required to ensure that such a candidate material will respond to 10CFR71 loading conditions within its ductileregime.

The NRC has issued two regulatory guides that apply to materials that can fail in a brittle manner. These guides, NRC Regulatory Guide 7.11, "Fracture Toughness Criteria of Base Material for Ferritic Steel Shipping Containment Vessels with a Maximum Wall Thickness of 4 Inches (0.1 m),"[3] and NRC Regulatory Guide 7.12, "Fracture Toughness Criteria of Base Material for Ferritic Steel Shipping Cask Containment Vessels with a Wall Thickness Greater Than 4 Inches (0.1 m) but not Exceeding 12 Inches (0.3 m),"[4] only address ferritic steels. These regulatory guidelines were established to ensure that the materials selected have sufficient toughness to prevent brittle fracture at load levels near the dynamic yield stress. The selection of these ferritic steels is based on empirical relations between the nil ductility transition temperature and the fracture resistance of the material. Therefore, there is no regulatory guidance based on a design approach such as a fracture mechanics methodology for the design of RAM transport packagings.

Thus, current regulatory restrictions effectively limit the construction of RAM packagings to austenitic stainless or a limited class of high-grade ferritic steels. Based on fracture mechanics principals there may be significant economic benefit and technical justification for the use of other materials and designs for the containment boundary of RAM packagings. The economic benefits may accrue due to (1) lower raw material costs, (2) simpler fabrication methods, (3) multi-use functions (i.e. storage, transport, and disposal packagings), and (4) the possibility of savings through the use of lightly-contaminated recycled DOE-owned scrap steel.

Other countries are experiencing similar pressures in handling RAM inventories, which has resulted in the international community embracing a fracture mechanics based design (FMBD) of RAM packagings. This is illustrated by the International Atomic Energy Agency (IAEA) publication of TECDOC-717, entitled, "Guidelines for Safe Design of Shipping Packages Against Brittle Fracture"[5], of which Chapter 2 is now the draft of Appendix VI of Safety Series ST-2, "Advisory Material for the Regulations for the Safe Transport of Radioactive Material" [6]. The FMBD provides the RAM packaging developers the programmatic latitude to evaluate a wide range of structural materials for packaging construction while ensuring that the packaging containment boundary will not fail in a brittle manner.

The following sections provide a comprehensive overview of the research conducted at Sandia National Laboratories (SNL) and other institutions around the world to investigate the FMBD methodology as applied to RAM packaging construction. Extensive studies have been conducted at institutions throughout the world involving materials characterization, drop testing of actual RAM packagings, and computational analyses, all supporting the use of a fracture mechanics based methodology for the design of RAM packagings.

2.0 Fracture Mechanics Basis

One method of fracture control that has been implemented is to use only materials at temperatures above their transition temperature as determined by the Charpy V-notch (CVN) [7] or nil-ductility transition temperature (NDT) [8] test. Although this "transition temperature" method of design has been successful in preventing unexpected brittle failures, there is no analytical relationship between flaw size, stresses, and geometry. Brittle fracture is removed from design consideration by avoiding any temperature at which the material might behave in a brittle manner. Although the method does prove to be simple to implement, it unnecessarily eliminates many materials that have the fracture resistance to prevent brittle failure, despite the fact that under certain severe combinations of loading rate, temperature, and geometry they may fail by brittle fracture.

Advances in fracture mechanics have led to techniques for safe fracture-resistant design using FMBD approaches. Instead of merely avoiding temperatures that brittle failure of the material is possible under certain severe loading conditions (that are not necessarily present in a specific design case), a FMBD approach maybe used to relate the flaw size, loading conditions, and fracture resistance of the material to determine if brittle fracture is a possible failure mode. The

FMBD methodology enables the use of alternative materials (such as ferritic materials) in the design of the containment boundary of RAM packagings.

2.1 Linear Elastic Fracture Mechanics (LEFM)

The fundamental equation that describes linear elastic fracture mechanics in terms of the crack tip driving force as a function of applied stress and flaw depth is as follows:

$$K_{applied} = C\,\sigma\,\sqrt{\pi\, a} \qquad (2.1)$$

$K_{applied}$= applied stress intensity factor (MPa-m$^{1/2}$),

C = a parameter that depends on structure and crack geometry,

σ = applied nominal stress (MPa), and

a = flaw depth (m).

To prevent brittle fracture of a structure, the applied stress intensity factor must satisfy the followingrelation:

$$K_{applied} < K_{resistance} \qquad (2.2)$$

where $K_{resistance}$ is the resistance fracture toughness of the structure at the applied loading rate and temperature relevant to the loading conditions of the structure. The factor of safety is simply the ratio of the right-hand and left-hand side of eq. (2.2).

By equating the applied fracture toughness (eq. 2.1), to the resistance fracture toughness, $K_{resistance}$, the critical flaw size can be determined. This is the flaw size that must exist for a given applied stress and material fracture toughness for crack initiation to occur. This yields:

$$a_{cr} = \frac{1}{\pi}\left[\frac{K_{resistance}}{C\,\sigma}\right]^2 \qquad (2.3)$$

Therefore, eq. (2.2) can be recast in terms of the crack depth:

$$a_{NDE} < a_{cr} \qquad (2.4)$$

Where a_{NDE} is the maximum flaw size that can go undetected by nondestructive evaluations (NDE) and a_{cr} is the flaw size that would result in the brittle fracture of the packaging.

Numerous codes, including those from the American Society of Mechanical Engineers (ASME), have implemented a FMBD approach for the nuclear power industry [9-14]. Although these cases are not directly applicable to the transportation industry they are example of fracture mechanics principles applied to the nuclear industry. Each of these cases are fundamentally linear elastic approaches. They provide the designer the opportunity to prevent fracture initiation and brittle fracture based on the materials resistance to fracture, stress levels and NDE limits.

2.1.1 Determination of the Material Resistance to Brittle Fracture ($K_{resistance}$)

There are several possible methods to establish a value of the material resistance to brittle fracture. The following three sections give several methods with varying degrees of conservatism.

2.1.1.1 Experimental Determination of the Material Resistance to Brittle Fracture

The most rigorous method to determine the material resistance to brittle fracture is to experimentally test for the material's fracture toughness. The relationship between the fracture toughness of the test specimen's geometry and the geometry of a structure must be understood, since for many materials the fracture toughness is dependent on the temperature, loading rate, and constraint. The results of a laboratory test can be used as the material resistance to brittle fracture if the laboratory specimen was tested at the same temperature and loading rate as the service temperature and loading rate of the RAM packaging, and if the constraint of the test specimen and the packaging are the same.

The difficulty associated with this method is the accurate measurement of the fracture toughness. At the elevated loading rates and the ductility levels of most of the candidate materials for RAM packagings, very large specimens are needed to measure valid LEFM fracture toughness values (valid according to ASTM E 399 [15], "Standard Tests Method for Plane-Strain Fracture Toughness of Metallic Materials," referred to as K_{Ic} for static rate and K_{Id} for the elevated rates). However, it is not practical to test or obtain large specimens from a RAM packagings because generally only a relatively small sample can be taken from a packaging and the test equipment and facilities for large specimens are limited. However, smaller test specimens may be employed by measuring a size independent value of the elastic-plastic J-Integral [16] parameter for fracture toughness and converting it to a size independent K_{Jc} using the following equation:

$$K_{Jc} = \sqrt{\frac{JE}{1-\nu^2}} \qquad (2.5)$$

Where J is the J-Integral, E is the modulus of elasticity, and ν is Poisson's ratio. This would be the most likely method to experimentally determine the material resistance to brittle fracture, K_{IR}, for RAM packaging materials (an ASTM standard for the measurement of a size independent cleavage value of J is being drafted.)

To ensure the fracture resistance of each packaging an estimate or measurement of the toughness must be made from each individual packaging. This requires fracture testing a small sample of the packaging or using some other method to estimate the toughness. Therefore, the fracture test specimens are either small or some other test is performed and a correlation to the fracture toughness is made. An example of this method is the correlation of fracture toughness with nodule spacing for ductile iron (DI), a proposed RAM packaging material (discussed in section 3.2.2 and ref. [17]).

2.1.1.2 Lower Bound Fracture Resistance

The next method of determining the value of the fracture resistance of a material used for the RAM packaging is to develop a lower bound fracture resistance curve for the material. Curves have been developed for certain grades of ferritic steel in the ASME code [18]. A lower-bound curve for DI was presented by Urabe and Harada [19]. With a lower-bound fracture resistance curve, the fracture resistance is determined as a function of service temperature. Therefore, the designer only has to determine the service temperature for the design and then identify the design fracture resistance from the curve. This provides an advantage over the first method proposed because fracture testing for each packaging is not required. However, the disadvantage is that a curve must be developed for the material and that the lowest bound curve will provide an uncertain level of conservatism. The exact factor of safety will not be known because the exact material resistance to brittle fracture is not determined.

2.1.1.3 Lower Shelf Fracture Resistance

Another, even more conservative method of establishing the fracture resistance for the design of the RAM packagings is to use a lower shelf fracture toughness value. Lower shelf values of fracture toughness are effected very little by temperature loading rate or constraint. Therefore, these factors would be eliminated and a standard size fracture test could be performed at a low temperature to determine a valid lower shelf fracture toughness value to use for the allowable fracture toughness. Once again, the exact factor of safety cannot be determined because a conservative value of fracture resistance is used in the design rather than the actual measured resistance to brittle fracture.

2.1.2 Determination of Applied Stress Intensity Factor (K_I) or Critical Crack Length (a_{cr})

In addition to the value of the fracture resistance, the value of the applied stress intensity factor must be calculated and compared as described in eq. (2.2). The value of the critical crack size can be calculated according to the proper relationship between stress intensity and crack size described by the general relation shown in eq. (2.1).

For a semi-elliptical part through surface flaw a relationship between crack size, stress, and geometry has been developed and implemented in the ASME Boiler and Pressure Vessel Code [18]. Some researchers have suggested this relationship be used for RAM packagings [20]. The relation is as follows:

$$K_I = (1.1\ M_k \sigma_M + M_B \sigma_B)\sqrt{\frac{a_{cr}\pi}{Q}} \qquad (2.5)$$

Substituting eq. (2.5) into eq. (2.2), and solving for a_{cr} (critical crack size):

$$a_{cr} = \frac{(K_{IR})^2\ Q}{\pi\{1.1 M_k \sigma_M + M_B \sigma_B\}^2} \qquad (2.6)$$

where,

Q=shape factor,

K_{IR}=Material Resistance Stress Intensity Factor (MPa-m$^{1/2}$),

M_k=Membrane stress correction factor,

M_B=Bending stress correction factor,

σ_M=Membrane stress (MPa), and

σ_B=Bending stress (MPa).

Therefore, using design stresses, the material resistance stress intensity factor, and the shape and correction factors (determined from graphs), the critical crack size can be determined and compared with the minimum size detectable by the quality assurance method (such as non-destructive evaluation). Other options, such as the method developed by Raju and Newman [21], are available to calculate the applied stress intensity factor for comparison with the material fracture toughness.

2.2 Elastic-Plastic Fracture Mechanics (EPFM)

In cases where there is no significant yielding of the structure, LEFM can be applied using a FMBD and the design will be conservative. However, for cases when the stress-strain conditions are largely elastic-plastic, eq. (2.1) must be recast in terms of elastic-plastic fracture parameters such as the energy line integral, J, and the crack tip opening displacement (CTOD), δ. Two methods to account for the elastic-plastic behavior of a structure have been incorporated into either codes [12,22] or handbooks [23,24]. The Electric Power Research Institute (EPRI) has developed handbooks [23,24] for the calculation of J for certain geometries and loading conditions. Although the exact geometries and loading conditions have not been developed specifically for RAM packagings, the method could be developed for RAM packagings. Researchers in the United Kingdom have developed the failure assessment diagram (FAD) to incorporate elastic-plastic behavior into their codes [12,22]. This method evaluates plastic failure parameters and brittle failure parameters to assess the safety of the structure.

3.0 Sandia National Laboratories Program

3.1 Introduction

Since the early 1980's, SNL has been investigating the use of a FMBD for packagings used for RAM transport. The purpose of the program has been to demonstrate the applicability of fracture mechanics to the design of RAM packagings to quantify the potential for fracture of the structural containment boundary. Current regulatory guidance provides acceptance criteria that are based on empirical materials tests and design methodology that does not quantify resistance to fracture.

The SNL program investigating the FMBD methodology consisted of two major areas. The first was material characterization of DI, chosen as an exemplary packaging material to demonstrate the FMBD methodology. Other materials which exhibit a ductile-to-brittle transition could have been chosen to demonstrate the applicability of the FMBD methodology to packagings.

However, DI has been the subject of extensive research as a possible candidate material for transport packaging construction. Further, DI packagings have been produced, tested, licensed, and are currently in use elsewhere in the United States and elsewhere in the world (not as transport casks in the United States), and DI packagings were available to SNL.

The other major area of research undertaken at SNL was the testing of an actual full-size DI packaging under conditions which met or exceeded the severe accident conditions specified in 10CFR71 [1]. This test program used a FMBD to size a flaw in the test packaging. The FMBD was used to predict crack initiation at the flaw tip resulting from the drop test. Although DI was demonstrated to be a suitable material for the application, the emphasis of each of the two major areas of the investigations was the development and application of the FMBD. Nonetheless, there is every indication that DI could be qualified as the containment boundary for Type B transport packages.

These two areas of the research were essential parts of the program to demonstrate the applicability of the FMBD methodology. The material characterization was used to predict the material response during the full-scale packaging tests and the full-scale tests demonstrated the ability to predict RAM packaging performance from lab-scale materials testing and finite element analysis.

3.2 Material Characterization of Ductile Iron

An understanding of the relationship between the mechanical properties and the composition and microstructure of any material is essential to its acceptability as a structural material for RAM transport packagings. Due to the international acceptance of the application of DI as a RAM packaging material. DI was chosen as a representative ferritic material for the SNL study. Sections 3.2.1 to 3.2.4 discuss the research conducted at SNL to quantify the material properties (including fracture toughness) and microstructure of DI.

DI is a form of cast iron in which the carbon precipitates from the melt as graphite and forms spherical nodules. Composition and cooling rate (of the melt) are critical factors in controlling the graphite nodule shape, spacing, and distribution. Composition and cooling rate are also important in controlling the matrix which can range from fully pearlitic (Fe_3C and ferrite) to fully ferritic. The spherical graphite nodules are primarily responsible for giving fully ferritic DI its combination of high strength and ductility compared to other forms of cast iron.

The potential brittle fracture material response of DI (and all ferritic material) to higher rate loadings, coupled with the low temperature service temperature, suggests that a thorough understanding of mechanical properties should be developed to ascertain the suitability of this material for RAM transport packaging construction.

3.2.1 Tensile Behavior

A basic understanding of the tensile behavior of DI was investigated to determine the relationship between composition and/or microstructure and strength and ductility of DI. The work was conducted to develop a data base that would be useful in design and licensing of DI RAM transport packagings. The results of the SNL study [25] is summarized below.

A series of eight heats of DI were produced and samples of each were tested in the as-cast and heat treated condition. The ingots were produced with varying microstructure and composition to study the effect of each on the tensile strength and ductility. Detailed chemical composition and microstructural measurements were made. Tensile tests and Charpy V-Notch tests were performed for temperatures ranging from -40°C to 175°C.

The effect of the heat treatment of the alloys was to reduce the pearlite content of the material. For the ingots that contained large amounts of pearlite prior to the heat treatment, the heat treatment improved tensile ductility and lowered the ductile-to-brittle transition temperature as measured by the CVN impact toughness. Comparison of the as-cast and heat-treated results show that the presence of pearlite in the DI degrades both tensile ductility and CVN toughness (see Figures 3.1 and 3.2).

Correlations between tensile properties and microstructure and/or chemical composition were investigated for the heat treated materials. A linear relationship was assumed between the dependent variable (e.g. yield strength) and independent variables (e.g. chemical composition, volume fraction graphite, graphite nodule spacing, and grain size). The strength (yield or ultimate) was found only to be dominated by chemical composition and was relatively independent of microstructural features. Correlations between strength and composition and/or microstructure are shown in Figures 3.3 and 3.4. No simple relationship was found to exist between ductility and composition/microstructure. The assumption of a linear relationship is thus invalid and a more complex model is needed to describe the microstructural/compositional basis for this behavior.

It is common in iron-based materials for ferrite grain size to be important with respect to strength. In this study, the measured variation in ferrite grain size was small and can be considered a constant. Its contributions to the linear equations developed was in the intercept value of the equations.

The most important determinant of strength in the alloys was found to be silicon content. Nickel content was also found to contribute to strength significantly. Since the linear model used was not found to describe a relationship between ductility and chemical composition and/or microstructural features, it is apparent that strength and ductility are not governed by the same variables and are not directly coupled. It is possible to increase the ductility of DI without significantly affecting the strength.

3.2.2 Static Fracture Toughness Testing

FMBD requires an understanding of the fracture toughness of the material to be used in the design. The studies at SNL have focused on measuring the material toughness of DI using the methods prescribed in ASTM standards and the possibility of determining fracture toughness by

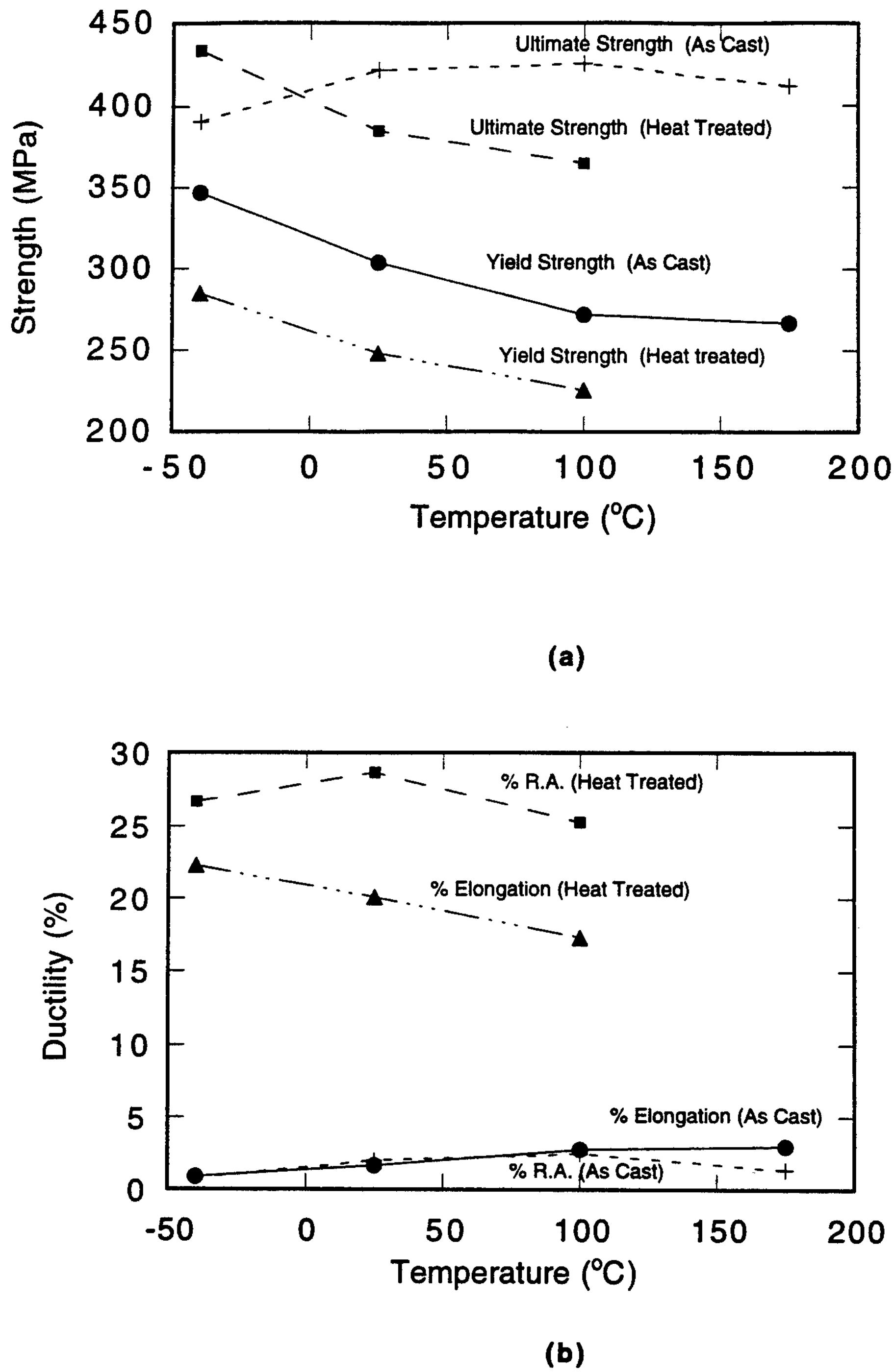


Figure 3.1 **The Effect of Heat Treatment on the (a) strength and (b) ductility.**

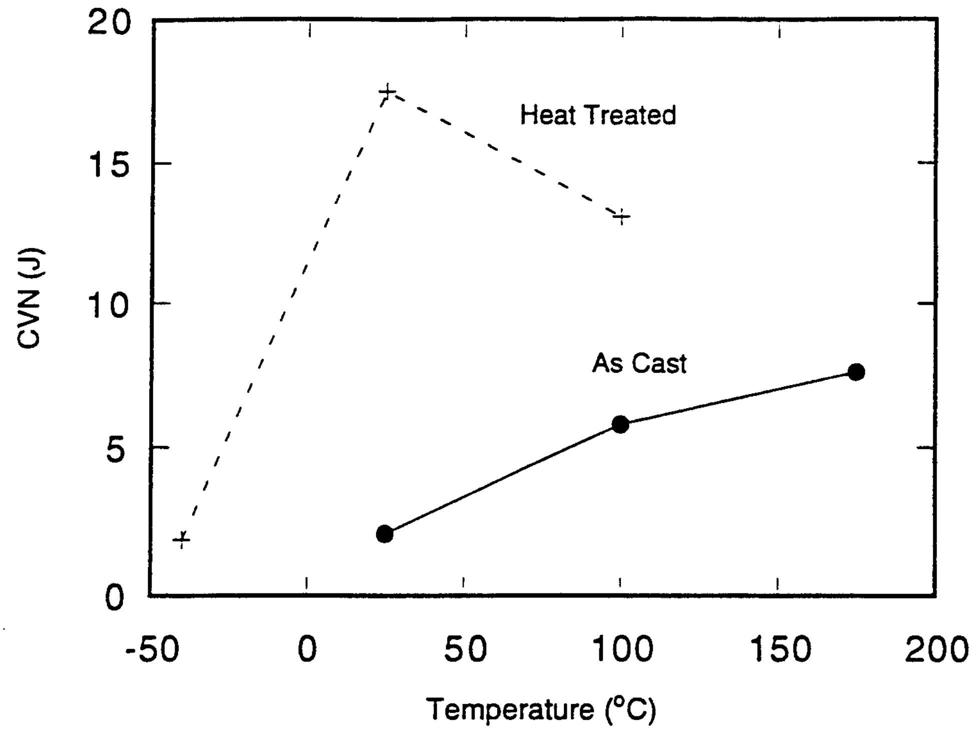
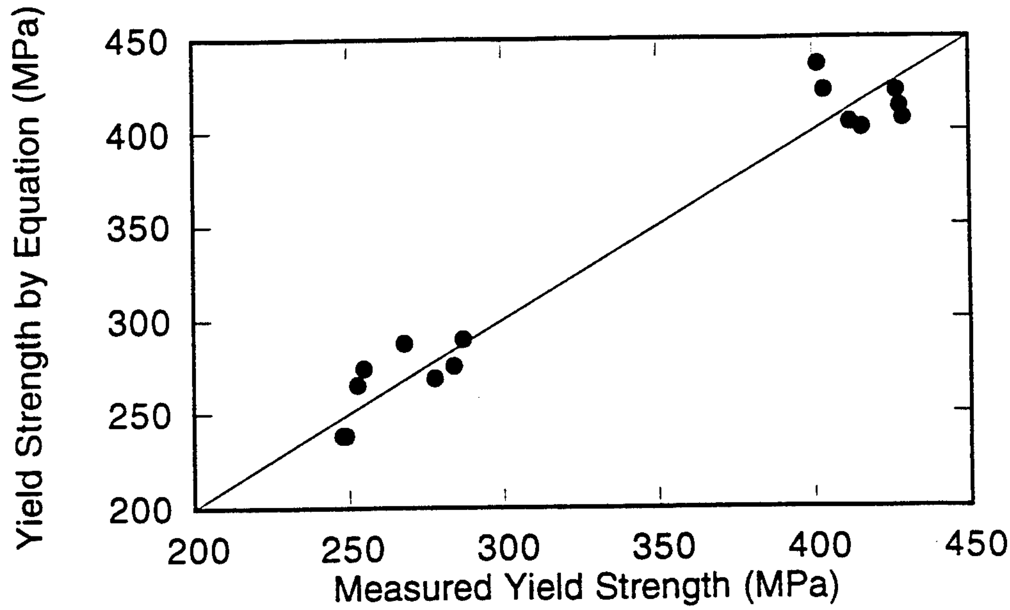


Figure 3.2 The effect of heat treatment on the CVN Impact Energy for the typical ingot with approximately 80% pearlite.

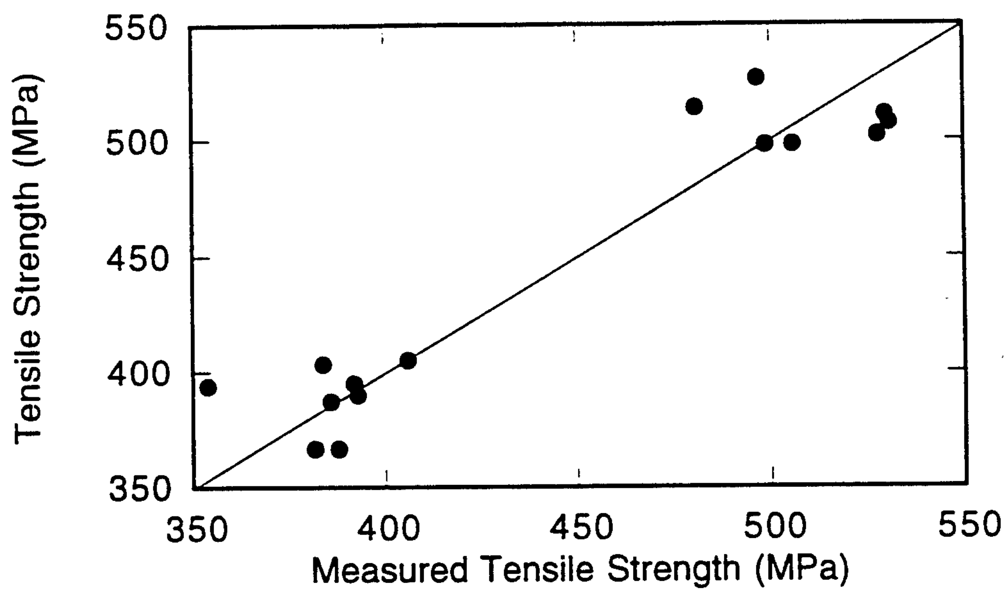
correlation with the result of a less costly test method. Many fabricators may not have the equipment and expertise necessary to conduct fracture toughness tests and could take advantage of a less costly method of certifying the fracture characteristics of the material they produce.

Analogous to yield strength, linear elastic fracture toughness (K_{Ic}) is an inherent material property. It can only be measured with very large specimens for many ferritic materials, including DI. The majority of the test results for DI have measured conditional fracture toughness, K_Q (i.e. specimens that are not valid according to ASTM E 399), or measured J-integral (J_{Ic}) using ASTM E 813 [26], "Standard Test Method for J_{Ic}, A Measure of Fracture Toughness," and converted them to K_{JIc} as described in Section 2.0. Since DI has microstructure that will vary though the thickness of very large specimens, to evaluate the effect of the microstructure of DI on the fracture toughness, smaller specimens must be tested. Thus, there is a dilemma between the smaller specimens needed to study the microstructure and the larger



ys = 135 + 118 (% Ni) + 105 (% Si)

Figure 3.3 Values of yield strength predicted by linear regression model (based on measured composition and microstructural features) versus yield strength measured by tensile test.



UTS = 286 + 85.6 (% Ni) + 84.6 (% Si)

Figure 3.4 Values of ultimate tensile strength predicted by linear regression model (based on measured composition and microstructural features) versus ultimate tensile strength measured by tensile test.

specimens needed to measure a valid K_{Ic}. However, as previous research has shown [27,28], it is possible to use a less strict size criteria and still have size independent results with specimens that do not meet the size requirements of ASTM E 399 (provided the specimens fail by cleavage).

Numerous previous studies on the fracture toughness of DI are summarized in both Motz et al. [29] and Bradley and Mead [30]. There are three primary reports discussing the work conducted at SNL on static rate fracture toughness over the past decade [17,31,32]. The studies investigated the effects of composition and microstructural features on the static rate fracture toughness of DI and correlations between composition and/or microstructure and static fracture toughness. In addition, the relationships between tensile strength, precracked Charpy toughness values, and static rate fracture toughness were investigated [32].

The first study [31] involved testing two different materials at temperatures ranging from -150°C to 25°C. One material was made to DIN specification 1693, Grade GGG-40 and the other was a DI referred to as S-45. The GGG-40 DI had highly spherical graphite nodules (Type I [33]) in a ferritic matrix that contained less than 1 percent pearlite while the S-45 material contained less spherical nodules (Type II [33]) and the ferritic matrix contained approximately 15 percent pearlite. The chemical composition of each material is shown in Table 3.1. The fracture toughness was measured according to ASTM E 813 and converted to K_{JIc} values. The material with the lower pearlite content, GGG-40, showed the higher fracture toughness and a lower ductile-to-brittle transition temperature (Figure 3.5).

Table 3.1. Chemical composition (weight percent) of the ductile cast irons

Alloy	C	Si	Ni	Mn	P	S
GGG-40	3.6	1.91	0.03	0.24	0.03	0.006
S-45	2.4	2.62	0.10	0.72	0.07	0.1

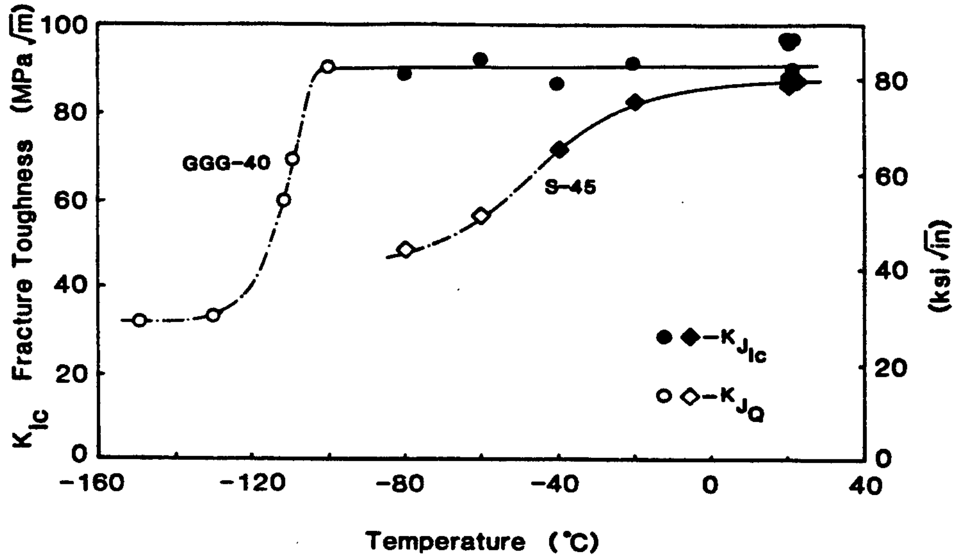


Figure 3.5 Fracture toughness as a function of temperature for alloys GGG-40 and S-45; K_{JIc} from valid J_{Ic} measurements; K_{JQ} from J values in tests with no stable crack growth.

The other studies investigated the relationship between (1) microstructure and/or compositional features and the fracture toughness of the material [17] and (2) tensile strength and precracked Charpy results and static fracture toughness [32].

Eight heats of ductile iron were tested in the heat-treated condition to remove most pearlite. The matrices were considered essentially fully ferritic (> 90%). The materials studied created an envelope that would include material similar to commercially produced DI at the time of the study and material that would meet current specifications required by ASTM A 874 [34], "Standard Specification for Ferritic Ductile Castings Suitable for Low-Temperature Service."

The results of the studies revealed no correlation between yield strength or ductility and fracture toughness (Figs. 3.6b and 3.6c) nor between precracked Charpy results and fracture toughness (Figure 3.6a). However, a correlation was found between precracked Charpy results and ductility (Figure 3.6d). In addition, fracture toughness was found to depend on graphite nodule spacing. A

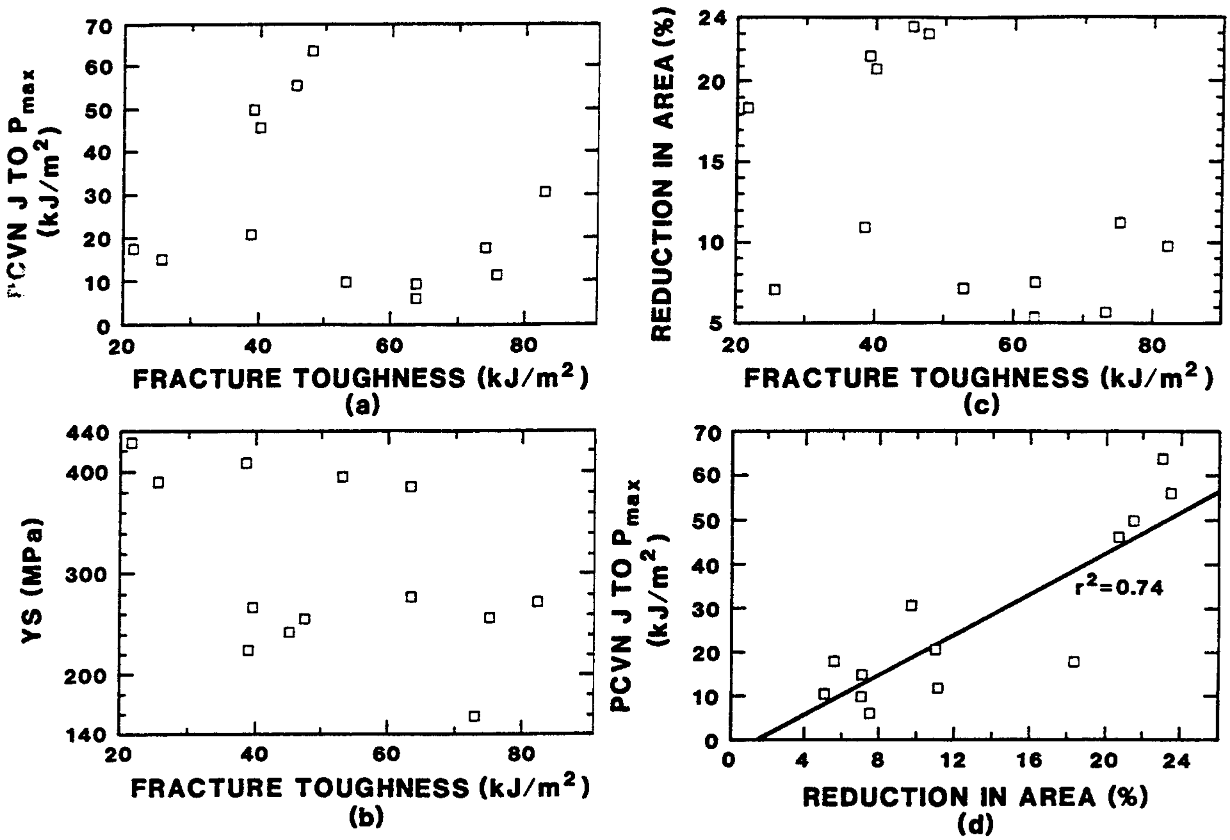


Figure 3.6 **Cross plots of common mechanical properties measured on the DCI alloys. (a) Precracked Charpy V-Notch J-values vs J_{Ic}. (b) Yield strength vs J_{Ic}. (c) Tensile ductility (%R.A.) vs J_{Ic}. (d) Tensile ductility (%R.A.) vs Precracked Charpy V-Notch J-Values.**

linear regression technique similar to the one used in the previous tensile study [25] was performed and it was found that J_{Ic} was linearly related to the spacing of the graphite nodules in fully ferritic DI.

Both two and three-dimensional methods for measuring the graphite nodule spacing were investigated [17]. Geometric considerations indicate that these measurements are essentially equivalent and this was confirmed experimentally. The two-dimensional spacing method was shown to predict the toughness well and is much easier to measure than the three-dimensional method. The equation describing the relation between J_{Ic} and two-dimensional graphite nodule spacing (Δ_A) is:

$$J_{Ic} = 12.5 + 517 (\Delta_A) \qquad (kJ/m^2, mm) \quad (3.1)$$

As can be seen from the equation, for the alloys studied there is a linear relationship between the fracture toughness and the graphite nodules and not the other microstructural features or the chemical composition of these materials investigated. Figure 3.7 graphically shows the relationship between the measured toughness and the predicted toughness using eq. (3.1). Also shown on the figure, are results for two commercially produced ductile irons (labeled "T" and "B"). As can be seen in Figure 3.7, the toughness of the commercially produced ductile irons validates the previously determined equation. The ability to predict the fracture toughness by measuring the graphite nodule spacing is much more cost effective than performing fracture toughness tests. Such a method may be very effective in qualifying the fracture behavior of each individual packaging manufactured in a serial fashion. The realization that nodule spacing dominates the fracture toughness also provides valuable insight with respect to process control. The solidification rate and graphite inoculation can be controlled to ensure appropriate levels of fracture toughness.

3.2.3 Rapid-Load Rate Fracture Toughness Testing

Packagings designed for the transportation of RAM must be designed for severe accident conditions which occur at loading rates considerably higher than a quasi-static rate. Regulations for certifying packagings require the packaging to withstand a nine meter drop on an unyielding surface [1]. Thus, the rapid-load rate fracture toughness of the material must be known. Two studies were conducted at SNL [35,36] to investigated the rapid-load rate fracture toughness of DI and methods to calculate J_{Id} (the rapid-load rate elastic-plastic fracture toughness) .

A method for rigorously implementing ASTM E 813 for rapid-load rates was developed. The rapid load rates were comparable to those existing in packagings during a severe accident

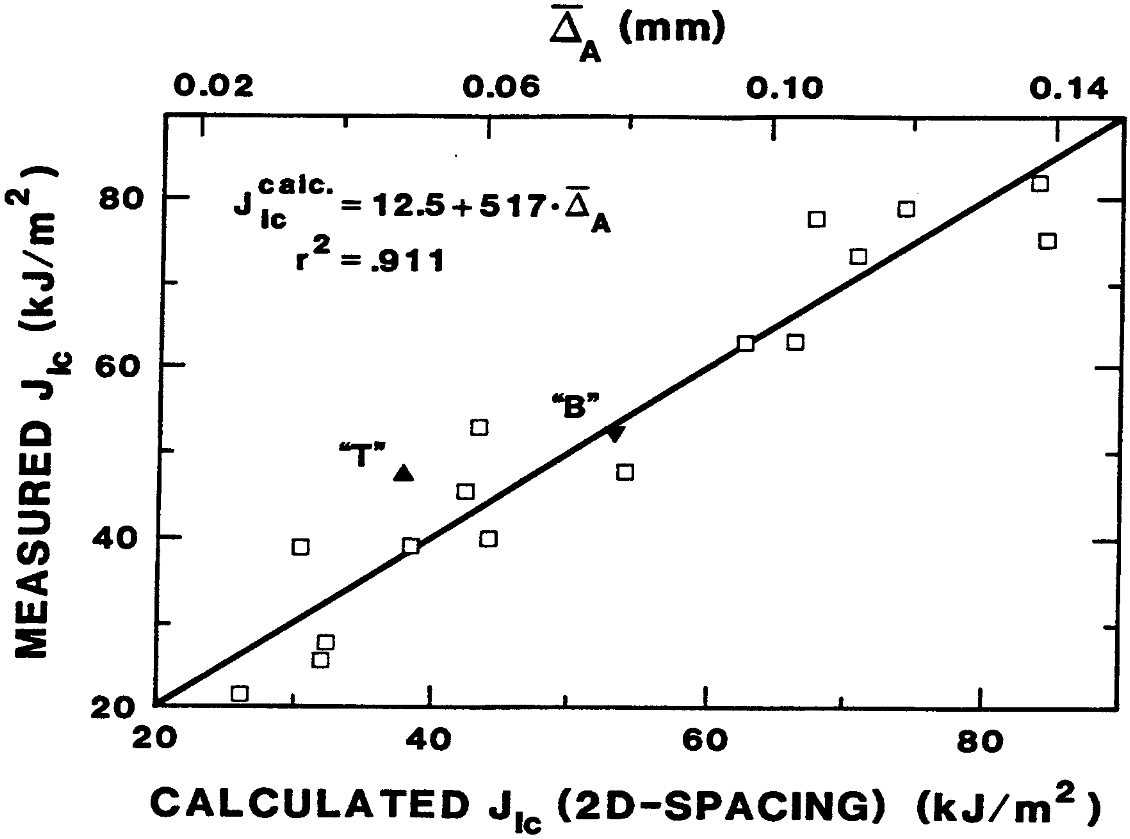


Figure 3.7 **Measured values of inititation fracture toughness versus values predicted by the linear regression model based on the average ("2D") graphite nodule spacing.**

condition [36]. Previous studies [37] had used the precracked Charpy results to estimate the rapid load fracture toughness. The precracked Charpy tests do not meet the requirements of ASTM E 813, and therefore should not be used to estimate fracture toughness. Combining these results with static results from a previous study at SNL [31] indicated that there is a drop in the upper shelf fracture toughness for the dynamic rate fracture results (Figure 3.8). Bend specimens were tested [38] at the same loading rate as the precracked Charpy tests to verify this drop in upper shelf toughness for rapid load rate fracture toughness of DI. As shown in Figure 3.8 the precracked Charpy and bend test results supported each other. However, as pointed out in reference [35], there are several shortcomings of the precracked Charpy tests and the bend tests that provide enough error to significantly under estimate the rapid-load fracture toughness.

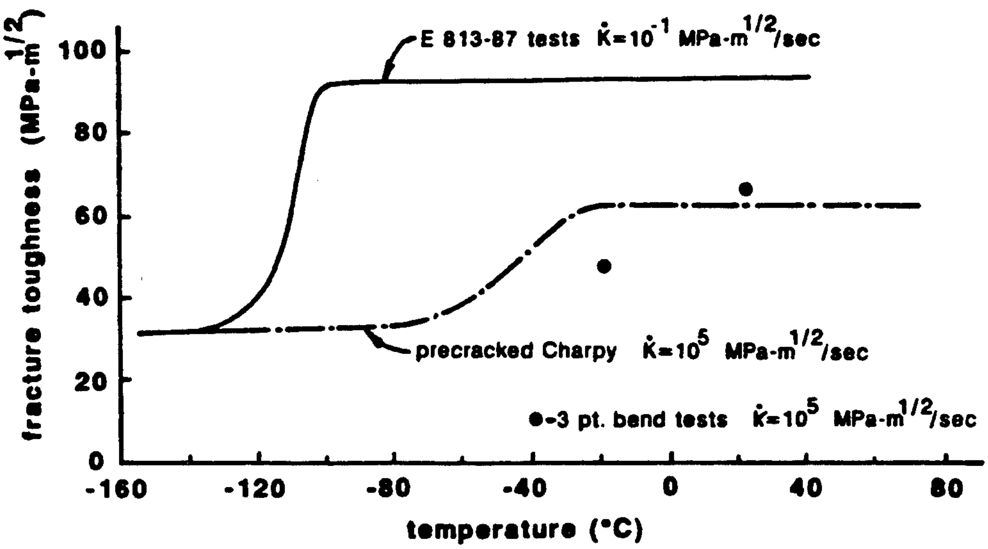


Figure 3.8 **Comparison of static rate fracture toughness (as per ASTM E 813-87) as a function of temperature, with toughness values estimated from precracked Charpy impact and three point bend drop tower tests.**

Tests were conducted at SNL [35] on compact specimens that rigorously followed ASTM E 813 and accurately measured the load line displacement of the test specimen, allowing an accurate assessment of the rapid load fracture toughness. A detailed description and analysis of the testing method used is described in reference [36].

The testing of the compact specimens were performed at three different stress intensity rates ($\dot{K}$), between 4 X 10^2 and 3 X 10^4 MPa-$m^{1/2}$/s [35]. All tests were conducted at -29°C to meet the licensing requirements of hypothetical accident conditions [1]. The initiation toughness was found to be independent for the rates tested which were above what could be expected in an accident condition. There was no decrease in fracture toughness as a result of the loading rates tested, and the higher rate fracture toughness was found to be comparable to the static fracture toughness. That is, for these loading rates, temperatures, and specimen sizes the fracture toughness remained on the upper shelf. The lower toughness reported for the precracked Charpy and bend specimens was likely a result of limitations inherent in the testing method [35].

3.2.4 Constraint Effects

For DI, the fracture toughness is dependent on temperature, loading rate, and constraint (where constraint is basically defined by the triaxial state of stress ahead of the crack tip). Geometry such as specimen thickness, width, crack depth, and crack depth to width ratio (a/W) are all factors that influence constraint. For an accurate estimate of fracture resistance in an engineered structure it is necessary to understand the influence of constraint on the fracture toughness of the component as compared with that measured in the laboratory. Ferritic steel fracture toughness typically decreases as specimen thickness increases. Previous studies [39,40] have suggested that the toughness of DI appears to either increase or remain the same as the thickness increases. A study at SNL [41] investigated the effects of sample size and loading rate and found that as the specimen thickness increased the toughness decreased at temperatures near the static rate transition region (Figure 3.9).

The effect of thickness for the specimens tested was also found to be more pronounced at the elevated loading rates [41]. Testing was conducted at $\dot{K}$ between 10^{-3} and 10^{+5} MPa $m^{1/2}$/s. As the thickness of the specimens was increased from 1 to 2 centimeters the toughness decreased approximately 25 percent at 25°C and 40 percent at -29°C. The specimens failure surfaces initiated as cleavage and changed to ductile tearing during crack growth. This behavior may be due to test methodology in which the sample displacement and the time duration of the loading were controlled in the laboratory testing.

The results of all the tests were examined with respect to the size criteria suggested by Anderson and Dodds [27,28]. The results from the largest specimens tested at the static loading rate should be sufficient to establish the size independent fracture toughness. Similarly, the largest specimen tested at -29°C for the high loading rate, should be large enough to provide a valid toughness value. If the fracture toughness measured at the high loading rate at -29°C is size independent, this value of toughness can be used in the fracture mechanics based evaluation of the fracture

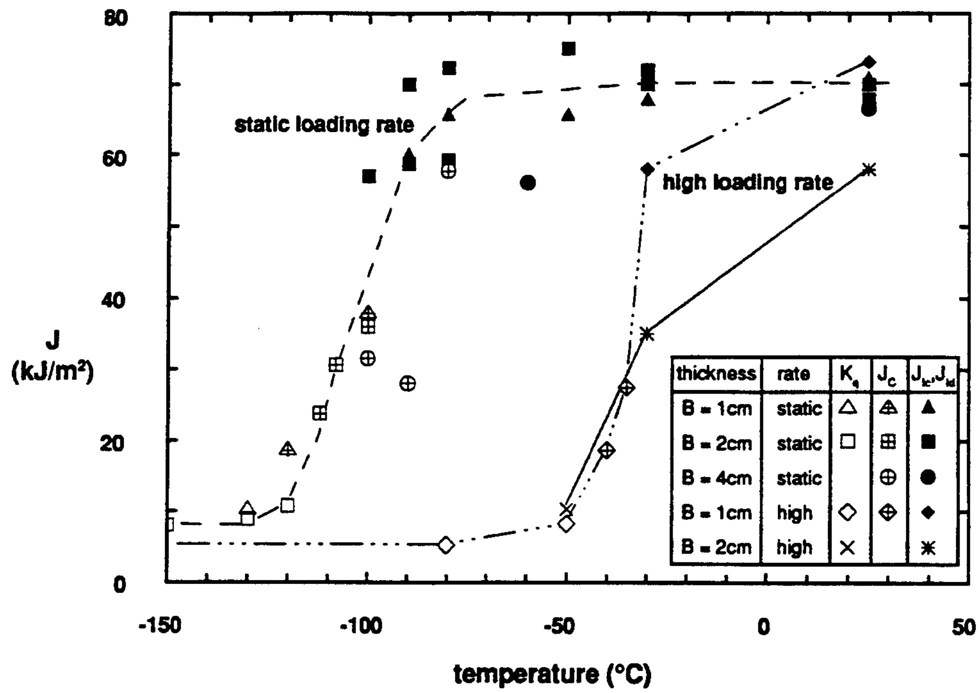


Figure 3.9 **The measured fracture toughness behavior of a ferritic ductile iron alloy as a function of temperature (loading rate and specimen thickness are noted in the legend).**

resistance of RAM packagings.

3.3 MOSAIK Cask Program

A significant portion of the research conducted at SNL has been directed to the full-scale testing of actual packagings and the verification of the applicability of FMBD to RAM packagings. Following the characterization of the material chosen for the packaging design (DI in this case), full scale testing was the next logical step. Two DI casks donated to SNL by Gesselschaft für Nuklearservice (GNS) of Germany were tested. Packagings of this type are currently used in Europe to transport low and intermediate level radioactive wastes. The first cask, MOSAIK I, was primarily used to verify test conditions, apparatus, and instrumentation. The MOSAIK I cask results were reported as "break/no break" observations of the cask's performance. The

MOSAIK KfK cask was rigorously tested and a detailed investigation of the results was conducted. The next three sections discuss the material characterization, structural analysis and drop testing of the MOSAIK Casks.

3.3.1 Cask Characterization

3.3.1.1 Materials Characterization

Material characterization of the MOSAIK KfK cask was required for the analysis and interpretation of the cask drop tests. Results of the material characterization are reported in detail in references [42,43]. A coring was extracted from the bottom of the cask and used to conduct the material characterization. The dimensions and mass of the cask are shown in Figure 3.10. The coring was taken from the bottom of the cask to best preserve the structural integrity of the cask and produced a minimal impact on the results of the drop test. As shown in Figure 3.11 this coring was divided into 5 layers to investigate the variation of composition and properties through the greater than 210 cm wall thickness.

The composition did not vary substantially through the thickness. Table 3.2 lists the chemical composition of various layers. However, the microstructure did vary significantly through the thickness, as shown in the micrographs in Figure 3.12. The average nodule spacing decreased

Table 3.2. Compostion measurements at various locations through the bottom coring of the MOSAIK KfK cask

Sample Location	C (wt %)	Si (wt %)	Ni (wt %)	S (wt %)
Plane 1	3.56	1.72	0.06	0.006
Plane 3	3.39	1.74	0.05	0.005
Plane 5	3.32	1.7	0.06	0.005

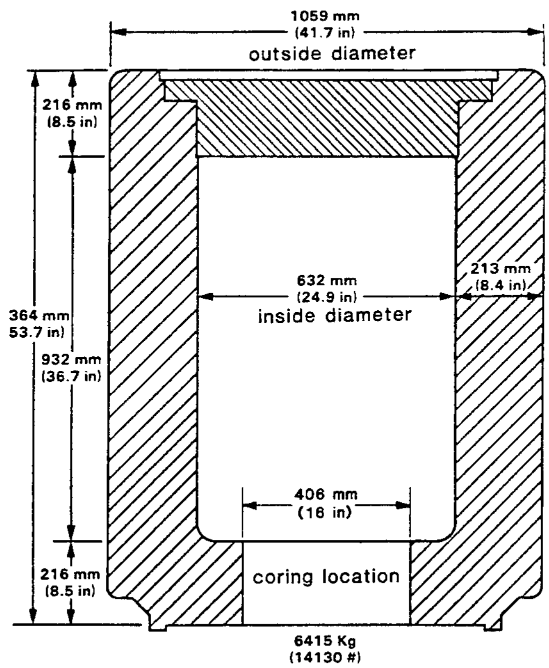


Figure 3.10 A cross sectional sketch of the MOSAIK KfK cask showing the location of the bottom corring.

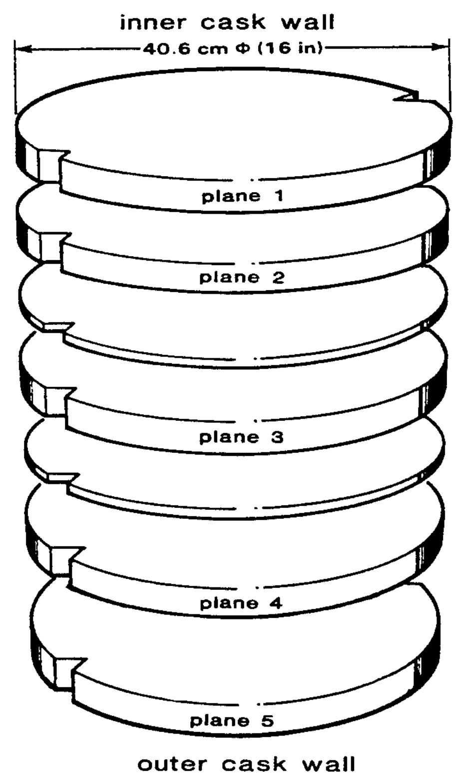


Figure 3.11 An exploded view sketch of the bottom coring from the MOSAIK KfK cask, showing the plane locations with respect to the inner and outer cask surfaces.

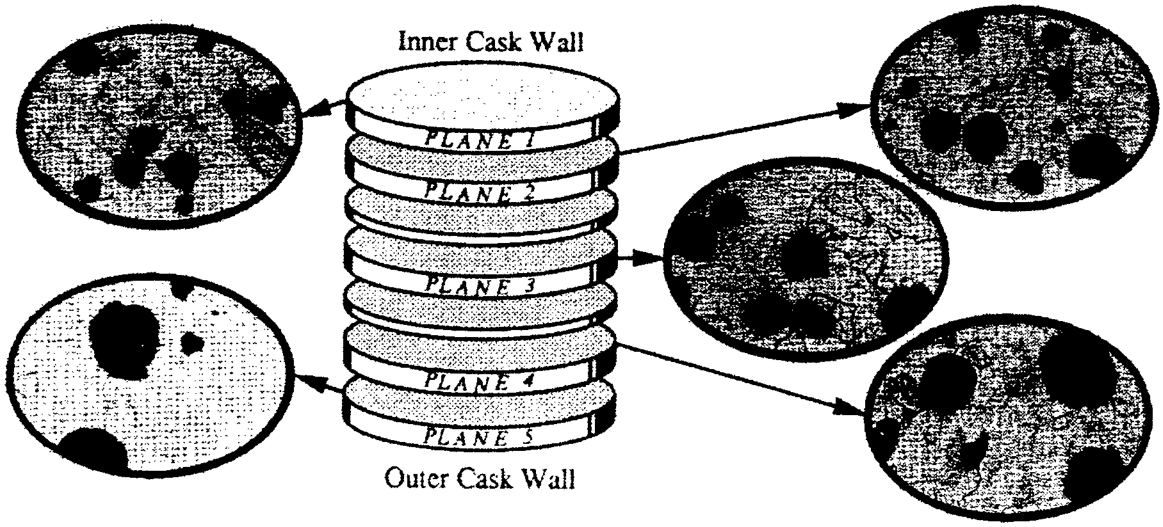


Figure 3.12 The variation of microstructure with location for the bottom coring from the MOSAIK KfK cask.

toward the inner surface. The sphericity of the graphite nodules deteriorated somewhat and the pearlite content increased toward the outside surface.

The elastic constants (Young's modulus, shear modulus, and Poisson's ratio), tensile strength and ductility, and CVN toughness were measured for the five layers through the thickness. There was a small decrease in the elastic constants from the inside to the outside surface of the cask. However, this slight variation was insignificant in engineering terms. Previous work [25] suggested that the strength of DI is predominately controlled by composition. Since there was very little change in chemical composition through the thickness of the cask it follows that there was also very little change in the tensile strength through the thickness as shown in Figure 3.13. However, the strain rate did have a small effect on the tensile strength. An increase in tensile strength with increased strain rate is commonly observed in many ferritic alloys [44].

Although CVN impact results for DI cannot be directly correlated to fracture toughness their results are useful for comparing relative toughness and the ductile-to-brittle transition temperature. Therefore, CVN impact tests were performed for each of the five layers of the cask

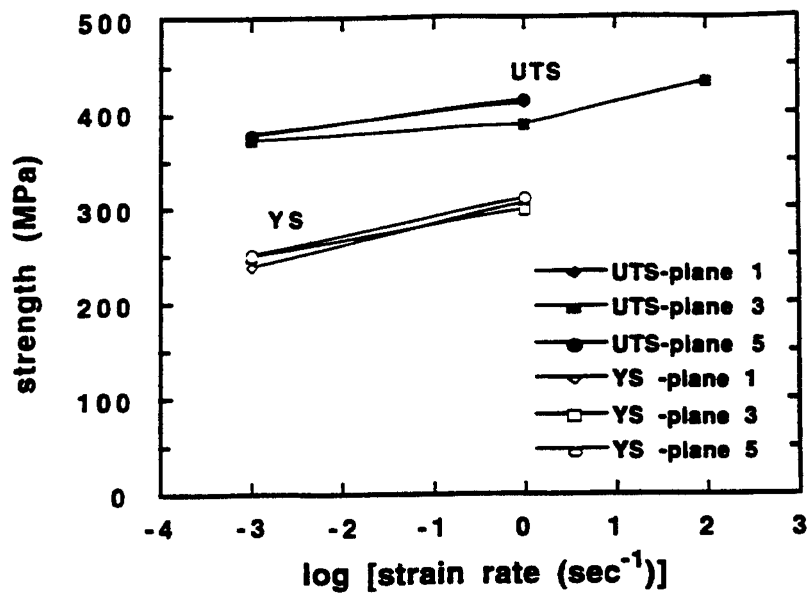


Figure 3.13 The variation of strength (at -29°C) with strain rate for the bottom coring of the MOSAIK KfK cask.

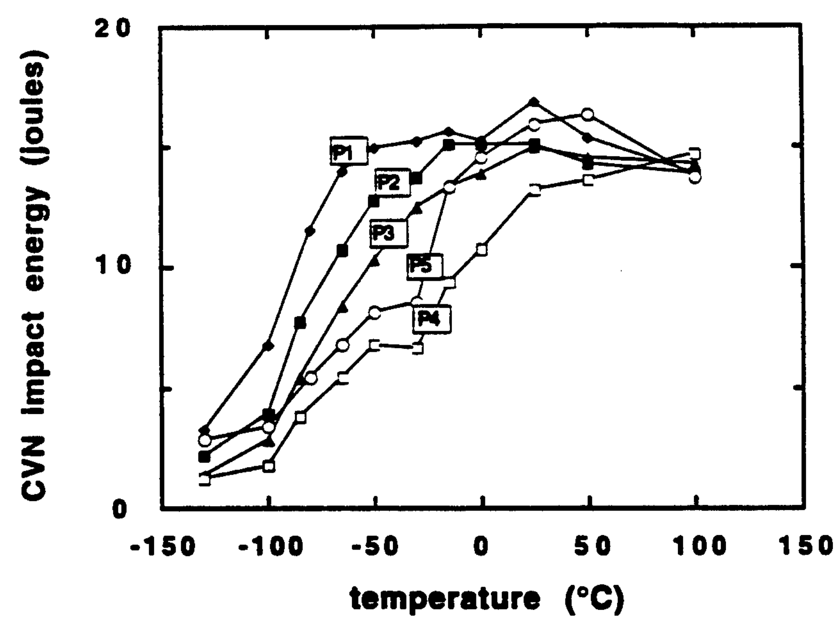


Figure 3.14 The Charpy "V" notch behavior as a function of temperature for the bottom coring of the MOSAIK KfK cask.

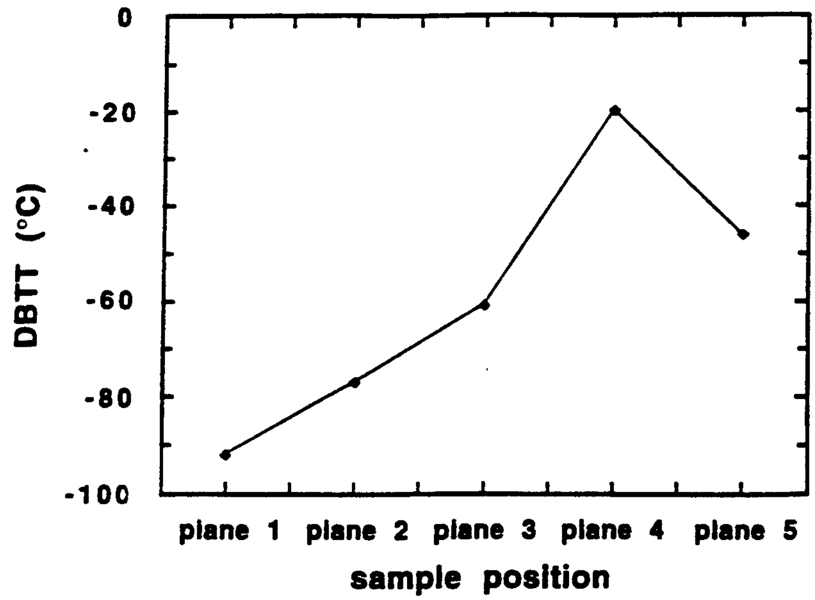


Figure 3.15 The variation of the ductile-to-brittle transition temperature (estimated from CVN measurements) with location, for the bottom coring of the MOSAIK KfK cask.

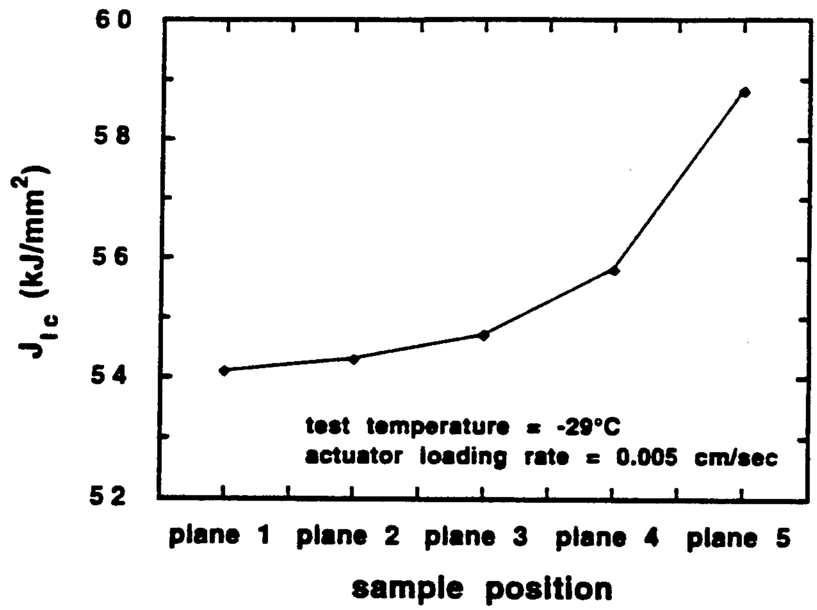


Figure 3.16 The static-rate fracture toughness as a function of location for the bottom coring of the MOSAIK KfK cask.

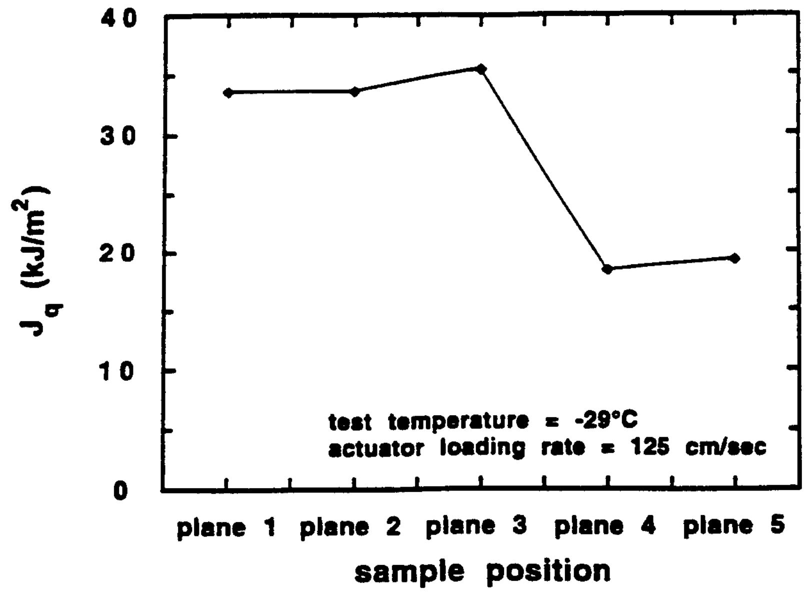


Figure 3.17 The elevated loading rate fracture toughness as a function of location for the bottom coring of the MOSAIK KfK cask.

Table 3.3. Microstructural measurements taken as a function of position through the bottom coring of the MOSAIK KfK cask

Sample location	Graphite vol. fract. (%)	Pearlite vol. fract. (%)	Nodule count (no./mm^2)	Nodule spacing (mm)	Nodule type	Ferrite grain size (mm)
Plane 1	10.5	0	123	0.045	100% Type I	0.030
Plane 2	13.8	0	122	0.045	100% Type I	0.029
Plane 3	10.8	3	74	0.058	100% Type I	0.029
Plane 4	18.4	3	41	0.079	90% Type I 10% Type II	0.034
Plane 5	18.0	5	48	0.073	75% Type I 25% Type II	0.037

material and the results are plotted in Figure 3.14. In general, the CVN toughness decreased toward the outside surface except that layer 5 (the outermost layer) had higher toughness than layer 4. Figure 3.15 shows the ductile-to-brittle transition temperature as a function of layer. The interior layer had the lowest ductile-to-brittle transition temperature and the value increased as the outer layer was approached. However, this temperature was highest for layer 4 and then decreased for the outermost layer (layer 5).

Both static and rapid-load rate fracture toughness tests were performed on each of the five layers. The results of the static tests are shown in Figure 3.16. The fracture toughness increased from the inner to the outer layer. However, the difference in toughness between the outer and the inner layer was only approximately 9 percent. Despite this small variation, this is in agreement with previous research [17] that showed an increase in static fracture toughness with increasing nodule spacing.

The rapid-load rate toughness results can be separated into two categories (see Table 3.3 and Figure 3.17). The first group consists of the results for the three interior layers. These tests resulted in elastic-plastic tests and the toughness was calculated as J_Q results, since there are currently no valid tests for a rapid-load rate testing. The tests for layers 4 and 5 were linear elastic and the toughness values were calculated using ASTM E-399. However, these specimens did not meet the size requirements of the standard and are therefore reported as conditional K_Q values. Within each of the two categories the values are consistent with previous research [17], showing increased fracture toughness with nodule spacing. However, as can be seen in Figure 3.17 the outer two layers have lower toughness then the inner three layers, despite having larger nodule spacing.

In addition to the coring from the bottom of the cask, corings were removed from the side wall of the cask [43,45]. The side wall coring displayed a chemistry similar to the coring removed from the bottom of the cask, but the variation of the microstructure was more limited. The total sidewall microstructural variation is limited to that found in planes 1 through 3 in the bottom coring (Figure 3.11 and 3.12). The difference in microstructure between the bottom and sidewall corings is due to the manufacturing methods used to cast and cool the cask. The mechanical properties (strength, ductility, and fracture toughness) of the side wall (which control the structural response for the side-drop orientation) has been estimated from the properties of planes 1 through 3 of the bottom coring.

3.3.1.2 Cask NDE (Nondestructive Evaluation)

Prior to conducting the drop tests, the casks were examined using nondestructive ultrasonic and radiographic techniques to inspect for pre-existing flaws. The ultrasonic examination used ASTM A 609 [46] "Standard Practice for Castings, Carbon, Low-Alloy, and Martensitic Stainless Steel, Ultrasonic Examination Thereof," for guidance with the sensitivity calibrated to a 6 mm diameter flat bottom hole. Both axial and circumferential scanning was conducted. The radiographic examination used an x-ray linear accelerator. The exam was performed in accordance with ASTM E 142 [47], "Standard Method for Control of Radiographic Testing." The sensitivity was calibrated to 2 percent of the wall thickness (4.3 mm). A single wall technique was implemented with 100 percent coverage. There were no indications above the established sensitivity using either procedure, indicating that there were no preexisting defects of significant size within the cask wall. These results demonstrate the high quality of the casting process used to fabricate these casks.

3.3.2 Structural Analysis

Finite element analyses (FEA) were conducted on the MOSAIK KfK cask in conjunction with a sequence of drop tests. These analyses were used to help establish drop test parameters and flaw sizes to be introduced into the cask wall for the drop tests. Specific details of the FEA are given in references [48-54] and a general discussion of the structural analyses of the MOSAIK KfK cask is given below.

The FEA was used to accurately predict flaw sizes to produce factors of safety (for crack extension from a pre-existing flaw) varying from 1.5 to 0.9. For the case with the factor of safety of 0.9, crack initiation was predicted by the FEA and confirmed in the experimental drop test. The combined results of the FEA and experimental drop test program confirm the capability of FEA to be used accurately as a predictive and analysis tool for the casks.

3.3.2.1 Modeling and Drop Orientation

The MOSAIK KfK cask shown in Figure 3.10 was modeled with FEA by utilizing planes of symmetry and building a model of a quarter of the cask (shown in Figure 3.18). Impact limiters were replaced by steel rails attached to the ends of the cask to increase the tensile component of the applied stress in the vicinity of the artificial flaw and to provide a tensile component through the entire wall thickness. Although one end of the cask had a coring removed, both ends were considered to be geometrically equivalent; therefore, a plane of symmetry could be taken between the two ends. A rigid surface was placed under the steel rails and the entire model was given an initial velocity based on the drop height.

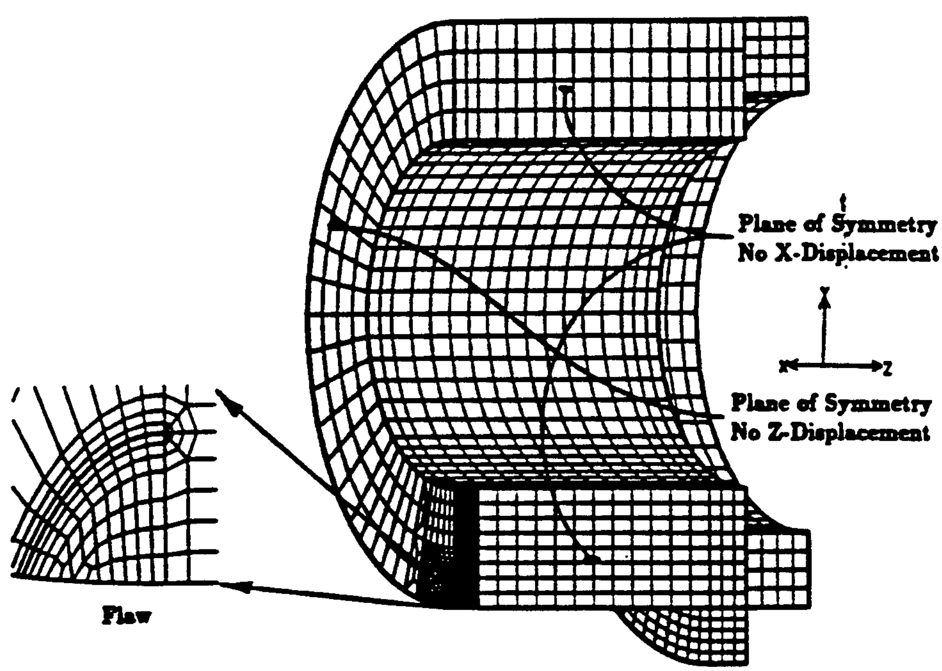


Figure 3.18 Finite element mesh for the MOSAIK cask drop test.

PRONTO 3D [55] was used to perform the nonlinear transient dynamic analyses of the simulated drop tests. The FEA code is a Lagrangian finite element program that uses explicit time integration to integrate the equations of motion. The elastic and plastic response of the material was represented using the Johnson-Cook material model [56]. The model characterizes the strain hardening behavior by a power law while incorporating strain rate dependency and thermal softening.

Standard 8-node hexahedral (brick) elements were used in the analyses. Four elements were used around the 180° arc from the flaw face to the plane of symmetry. One face of the notch tip elements was collapsed at the crack tip resulting in a fan shaped mesh around the flaw. The coincident nodes were free to displace as deformation occurred. A transition from the relatively fine mesh near the flaw to the remaining coarser mesh was accomplished using tied surfaces. Tied surfaces maintain the relative locations of the nodes from one surface to the other. This technique permits rapid transitions in mesh refinements without allowing gaps, overlaps, or relative translation. The impact enhancing rails were also attached using this technique.

3.3.2.2 J-Integral and Stress Analysis

Using the FEA, both the stresses and the J-Integral levels resulting from the drop tests were computed. The applied J-integral was compared with the measured toughness from laboratory specimens [57]. The FEA of drop tests 1 through 4 showed that even with extremely large flaw depths (up to 36% of the wall thickness), tensile stresses were still below yield stress levels. The calculated J-Integral driving force was found to be below the J_{Ic} of the material, implying that no crack initiation should occur during the drop event. For drop test 5 FEA predicted a driving force J value that would result in a factor of safety of 0.9. Examination of the flaw after the drop test revealed that the crack initiated and arrested.

3.3.3 Drop Test Verification Program

3.3.3.1 Drop Criteria

The drop criteria for the MOSAIK casks was based on the conditions specified by U. S. regulations (10CFR71 [1]). In each case (except for a single drop from approximately 18 m), the casks were dropped from a height of 9 meters onto an unyielding surface. The casks were cooled to a temperature of -29°C. A circumferential part through-wall artificial flaw was placed in the casks at the location of the highest tensile stress. Impact limiters were replaced by steel rails attached to the ends of the cask to increase the tensile component of the applied stress in the vicinity of the artificial flaw and to provide a tensile component through the entire wall thickness. The use of the steel rails in place of impact limiters, the placement of a artificial flaw, and the 18 meter drop test were all extra-regulatory criteria that made the drop tests substantially more severe then the requirements of 10CFR71 [1].

3.3.3.2 Flaw Construction/Measurement

U. S. regulations do not address the potential existence or consequences of flaws. However, to demonstrate the FMBD technique, artificial flaws were introduced into the casks. The flaws were machined into the casks and sharpened using either a machining technique or using laser embrittlement. The shallower flaws were machine sharpened resulting in a notch root radius of less than 0.08 mm. The deeper flaws did not allow the machine sharpening technique to provide a sufficiently sharp radius. Therefore, a laser embrittlement technique was employed. The laser embrittlement technique uses a laser welder to remelt the material at the tip of the notch. When the remelted material solidifies, it consist of a high carbon martensite (with an inherently low toughness) which has fractured during resolidification. Metallographic examination of the brittle zone revealed that the zone was approximately 3.8 mm extending from the root of the machined notch. Therefore, the total flaw depth for the laser embrittled flaws was the machined notch depth plus the 3.8 mm embrittled zone. Figure 3.19 shows a laser sharpened flaw with the laser embrittled zone.

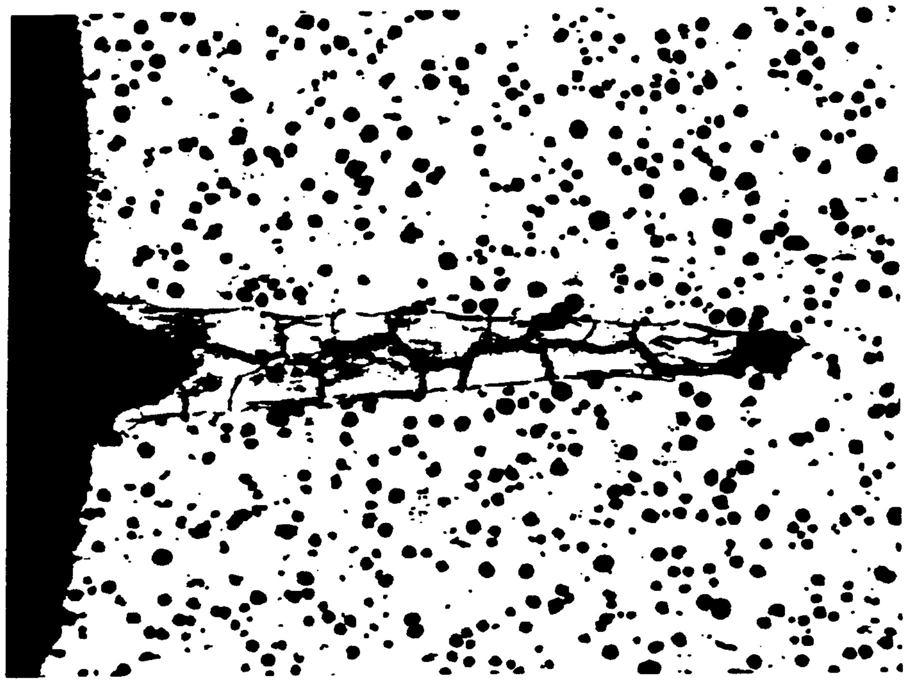


Figure 3.19 Micrograph of the laser sharpened flaw removed from the MOSAIK KfK cask after the 4th drop test.

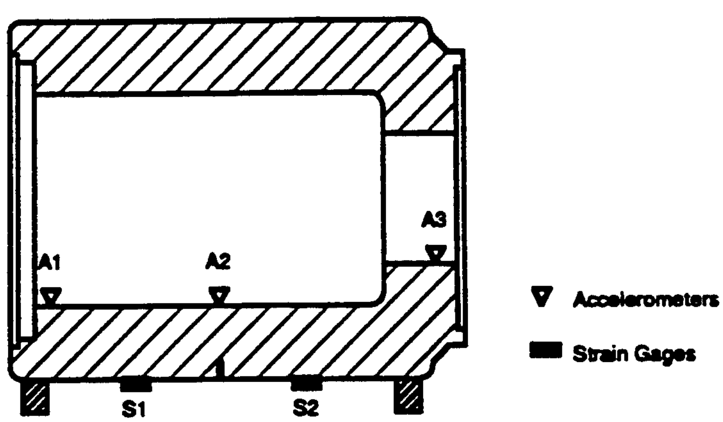


Figure 3.20 Instrumentation for the MOSAIK KfK cask.

SNL laboratory tests conducted at room temperature and at static loading rate showed that the measured fracture toughness for specimens with the laser embrittled flaws possessed a lower initiation toughness than standard fatigue cracked specimens. The combination of the high carbon martensite with fine solidification cracks is more severe than a fatigue induced crack of equivalent dimensions. Testing a component with the laser embrittlement flaw should thus provide a conservative estimate of the response of a component with a severe production defect. The flaw depths, which were much larger than could go undetected by NDE (greater than 99% reliability of detection [19,57]), ranged from 35.4 mm to 127.0 mm.

3.3.3.3 Cask Instrumentation, Cooling, and Data Acquisition

The general layout of the cask instrumentation is shown in Figure 3.20. Strain gages and accelerometers were used to monitor the test and benchmark the finite element analysis. Two thermocouples were located at two depths (2.5 and 10 cm) in the cask wall to monitor the cask temperature. The cask was cooled to -29°C using a carbon dioxide cooling chamber.

The SNL Mobile Instrument Data Acquisition System (MIDAS) was employed to collect strain gage, accelerometer, and thermocouple data. MIDAS is a fully automated, self-contained data acquisition system capable of collecting data from a variety of piezoresistive measurement devices. It is capable of processing 72 channels of piezoresistive or voltage-based transient structural data and up to 200 channels of temperature data. Quality assurance and documentation are an integral part of the MIDAS system which has been developed and documented meeting current regulatory drivers to ensure accurate and reliable response measurements. An overview of SNL's RAM packaging testing capabilities is provided in reference [58].

3.3.3.4 Drop Test Results

A total of eleven drop tests were performed on the MOSAIK I and MOSAIK KfK casks. The drop test parameters and results are shown in Table 3.4. The first six drop tests were performed on the MOSAIK I cask and the results were reported as "break/no break." All six tests resulted

Table 3.4. Test conditions and measured values for the Sandia National Laboratories drop test program of the MOSAIK I and the MOSAIK KfK ductile iron casks

	date	drop height (m)	metal temp. (°C)	flaw depth (mm)	flaw tip radius (mm)	flaw aspect ratio	strain[a] (10^{-6})	tensile stress[b] (MPa)	fracture toughness [c] K_{Ic} (MPa-$m^{1/2}$)	LEFM applied K (MPa-$m^{1/2}$)	estimated LEFM FS[d] (K_{Ic}/K_I)	Finite Element applied K_I (MPa-$m^{1/2}$)	FS[b,d] (K_{Ic}/K_I)	max gs[a] (at 1 kHz)
MOSAIK I (2960 Kg, 150 mm wall thickness)														
1	3/14/90	9	–26	25.4	laser	4.5:1								
2	3/21/90	9	–31	45.2	laser	3.1:1								
3	5/23/90	9	–32	76.2	0.0762	3.2:1								
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, 214 mm wall thickness)														
1	6/25/90	9	–26	19.1	0.0762	6.8:1	1100	179	74.8	51	1.5	50.6	1.5	950
2	2/2/91	9	–29	50.4	0.0762	6.0:1	750	124	74.8	70	1.1	62.3	1.2	600
3	8/1/91	9	–29	57.1	laser	6.2:1	1100	179	74.8	78	<1	53.9	1.4	800
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

a By field measurements.
b By finite element calculations.
c By laboratory measurement.
d FS=factor of safety.
Note: shaded areas represent values not determined.

in "no break" tests. The MOSAIK KfK cask had five highly instrumented drop tests with substantial test results recorded and reported. All tests, except for one, were dropped from 9 meters at a temperature of approximately -29°C. In one test, the MOSAIK KfK cask was dropped form a height of 18.4 meters at -29°C.

The results of the drop test program confirm the FMBD methodology and the use of ferritic materials for the construction of radioactive transportation packagings. None of the drop tests from the 9 meter height resulted in crack initiation. All of these tests were substantially more severe than the accident conditions required by 10CFR71. Test results on the MOSAIK cask demonstrate that the FMBD is a viable option for ensuring the integrity of transport packagings. The low stresses (from the large wall dimensions of the cask and impact limiters), the possibility of only very small flaw sizes (as per NDE results), and a relatively high fracture toughness all combine to increase the conservatism of the demonstration which shows the use of DI materials in cask construction to be a safe and reasonable design alternative (i.e. to stainless steel/lead casks).

The program showed that the finite element technique is an accurate method for predicting and analyzing a packaging's behavior under severe accident conditions. The FEA used for this study accurately predicted the stresses, strains, and the onset of crack initiation. Using the fracture mechanics methodology and FEA crack initiation was predicted to initiate for the 18.4 meter drop. The results of the test showed that crack growth had initiated and arrested.

3.4 Alternative Materials

Ductile iron is not the only proposed alternative to stainless steel for structural components of transportation packagings. Low alloy ferritic steels, titanium, depleted uranium, aluminum, and borated stainless steel are all possible construction materials that might be considered for either the containment boundary or internal spent fuel basket of RAM transportation packagings. However, just as with ductile iron, some of these materials can, under certain environmental and mechanical loading conditions in combination with a flaw, fail in a low-energy fracture mode.

Therefore, fracture mechanics methodology is required to ensure that these materials meet the design requirements for packaging components. Research at SNL [59,60] has shown that depleted uranium is a possible candidate material for both structural integrity and the containment boundary of RAM packagings and that borated stainless steel [61] could be used for the internal fuel baskets of the transportation packagings.

4.0 Results from Similar International Programs

The growing need for safe and economical storage and transportation of RAM has led other international organizations to investigate the use of the fracture mechanics based design for RAM transportation packagings and alternative materials for construction (such as ductile iron). In Japan the Central Research Institute of Electric Power Industry (CRIEPI) has conducted substantial research on the development of a brittle fracture design criteria and DI. In the Federal Republic of Germany, Bundesanstalt für Materialforschung und -Prüfung (BAM) has also conducted extensive research on DI. Additional research has been conducted by organizations in the United Kingdom, France, Finland and other programs in the United States. These programs are summarized in the following sections.

4.1 Central Research Institute of Electric Power Industry (CRIEPI) -Japan

Extensive has been work conducted in Japan on the use of ductile iron and a fracture mechanics based design methodology for application to RAM transport packagings. References [62-72] discuss some of the research conducted prior to the work sponsored by the CRIEPI Quality Assurance (QA) Committee of Ductile Cast Iron Casks [20]. This committee was formed after it was recognized that there was a need for intermediate storage of light-water reactor (LWR) spent fuel. Since the development of the QA committee and its initial report [20] further testing has been conducted including drop testing, development of brittle failure design criteria and the prediction of packaging toughness using small specimens. The next four subsections briefly discuss this research.

4.1.1 "Research on Quality Assurance of DI Casks"

In 1987 the "Long Term Plan of Nuclear Power Utilization" prepared by the Atomic Energy Commission of Japan suggested that LWR spent fuel would require intermediate storage [20]. This suggestion initiated the development of the QA committee and their research investigating the use of DI and a FMBD methodology for application to RAM transport packagings. The objective of the research was to generate material property data on DI and develop a structural design criteria for the packagings.

Extensive material characterization was conducted on six DI packagings from six different manufacturers. There were different combinations of molds, cooling methods, and standing conditions of the molds for the castings. Chemical and physical properties of the material were measured. CVN and instrumented Charpy tests were conducted. Both static and rapid-load rate fracture toughness was measured on either large (6TC(T)) or small (1TC(T)) specimens. The results show material properties that were equal to or greater than values reported by researchers in the United States and Germany. A summary of the material values is shown in Table 4.1.

In reference [20] the QA committee provided a draft of a ductile failure and brittle failure design criteria. There were two options provided for the ductile failure design criteria. One option was the evaluation by maximum shear stress theory and the other option was the evaluation by maximum principal stress theory. Maximum shear stress theory defines failure when the maximum shear stress reaches the shear yield strength (tensile yield strength/2) and the maximum principal stress theory defines failure when the maximum principal stress reaches the tensile yield strength [73].

The draft of the brittle failure design criteria was based on fracture mechanics methodology and referred to the ASME Code Sec. III, Appendix G and Sec. XI, Appendix A [14,18]. A critical flaw size is determined using the primary and secondary bending and membrane stresses along with the lower bound fracture toughness of the material at the service temperature.

Table 4.1. Results of round robin material testings (summary)[a]

Items		Test Results		Reference Values	
		Average	Minimum	United States	West Germany
0.2 % offset yield strength (kgf/mm^2) (room temperature)		22.4	20.5	20 (CASTOR-V)[b]	18 (TN-1300)[c]
Tensile strength (kgf/mm^2) (room temperature)		35.3	33.6	23 (CASTOR-V)	33 (TN-1300)
Elongation (%) (room temperature)		15.1	12.2	12 (NUREG/CR-3760)	12 (TN-1300)
Fracture Toughness ($kgf/mm^{3/2}$) (-40°F)	K_{Ic}[d]	220	214	160 (CASTOR-V)	-
	K_{Id}[e]	174	170	-	-

a From The Quality Assurance Committee on Ductile Iron Casks, "Research on Quality Assurance of Ductile Iron Casks," CRIEPI Report EL 87001, Tokyo, April 1988.
b Topical Safety Analysis Report for the CASTOR V/21 Cask Independent Spent Fuel Storage Installation (Dry Storage), Rev. 1, GNSI, Jan. 1985
c Sicherheitsbericht Behälter TN-1300/1-12, TN GmbH, Nov. 1982
d ASTM E 399 (6 TCT)
e ASTM E 24.03

4.1.2 Packaging Drop Testing

The QA committee undertook directing full scale packaging drop testing to demonstrate the ability of the DI packagings to withstand the IAEA requirements [75] and the verification of the brittle failure criteria. A design for the packaging was chosen such that the tests were applicable to any of the various DI packagings produced. Pre-drop finite element analyses were conducted to find the drop orientation that produced the most severe accident condition. Artificial flaws were introduced into the packagings with a radius of 0.1 mm. Fracture toughness specimens (6TC(T)) were also tested with both the 0.1 mm tip radius flaws and fatigue cracks to verify the equivalency of the 0.1 mm tip radius artificial flaw and fatigue cracks. The two flaw sizes chosen to verify the brittle failure design criteria were (1) twice the minimum flaw size detectable by ultrasonic testing and (2) a flaw that analytically would provide a factor of safety of 1.5 against brittle fracture [76]. A drop height of 9 m and test temperature of approximately -40°C were implemented. Conventional impact limiters at atmospheric temperature were placed on the packagings prior to each test.

The two 9 meter drop tests were performed along with a horizontal drop of 1 meter onto a mild steel pin (puncture test). After the tests, the artificial flaws were examined using an optical fiberscope. No crack growth was observed and in each test containment was maintained.

4.1.3 Brittle Failure Design Criteria

The QA committee recommended an initial brittle failure design criteria [20] that was investigated and updated in subsequent work by CRIEPI researchers [77-83]. The design criteria is based on linear elastic fracture mechanics concepts and is similar to the ASME code [18,74]. The essential concept behind the brittle fracture criteria is to keep the applied stress intensity factor, K_I, times some factor of safety, α, less then the reference fracture toughness, K_{IR}. Or:

$$a\, K_I < K_{IR} \qquad (4.1)$$

CRIEPI suggested a factor of safety of 2.0 in contrast to ASME which uses a factor of safety of 1.4. Writing this equation in terms of critical flaw size:

$$\alpha\, a_{NDE} < a_{cr} \qquad (4.2)$$

where a_{NDE} is the minimum value of crack depth detectable by the inspection technique and a_{cr} is the critical crack size calculated using linear elastic fracture mechanics methodology. Based on the ASME code the QA committee recommended [76]:

$$a_{cr} = \frac{(K_{IR}^{*})^2 Q}{\pi\{1.1M_k(2\sigma_M + \sigma_m) + M_B(2\sigma_B + \sigma_b)\}^2} \quad (4.3)$$

where,

Q=shape factor,

K_{IR}^{*}=Lower bound fracture toughness at estimated service temperature,

M_k=Membrane stress correction factor,

M_B=Bending stress correction factor,

σ_M,σ_m=Membrane stress (primary, secondary), and

σ_B,σ_b=Bending stress (primary, secondary).

This brittle failure design criteria was verified as being conservative during the drop testing [76-78]. Using eq. (4.3) and applying stress values measured from the packaging instrumentation the actual factors of safety (α) were calculated for the two drop tests conducted with the artificial flaws. A factor of safety of 2.67 was found for the flaw size that was twice the minimum size detectable for the ultrasonic testing and a factor of safety of 1.32 was found for the larger flaw size. Therefore, even with flaw depth of 20 percent of the packaging thickness the factor safety against brittle fracture was considerably greater than one.

4.1.4 Prediction of Fracture Toughness from Small Specimens

Determining the fracture toughness of a material is essential when applying a fracture mechanics based design. To apply linear elastic fracture mechanics an estimate of K_{Ic} is required. As with many materials, very large specimens must be tested to get valid linear elastic fracture toughness values. It is not realistic to test a large specimen from each packaging to determine the fracture toughness. Therefore, CRIEPI conducted studies [20,81,84] to determine the K_{Ic} of DI from small laboratory specimens.

Arai et al. [84] investigated correlations between small specimens machined from larger test specimens and the larger specimens test results. The correlations related J_c (J integral value at the onset of cleavage instability) for the small specimens to K_I of the larger 6TC(T) specimens. Both the large and small specimens were tested at a similar temperatures and loading rates ($\dot{K} > 300\ MPa \cdot m^{1/2}/s$). Correlations between 1TC(T), NRBT (notched round bar tension), and U-notched Charpy impact specimens were investigated. Evaluations from the results from all the specimens showed good correlations between the small and large specimens.

The correlation developed between the small 1TC(T) and larger 6TC(T) specimens was:

$$K_{Ic,R} = 12.91\ J_c^{0.48} \qquad (4.4)$$

where $K_{Ic,R}$ denotes the fracture toughness K_{Ic} at the higher loading rate. Since 12.91 is nearly equal to the square root of the elastic modulus of DI and the exponent is nearly equal to 0.5, the equation developed is nearly equal to the theoretical relationship between K and J [85]:

$$K = \sqrt{\frac{JE}{(1 - \nu^2)}} \qquad (4.5)$$

Therefore, the experimental toughness results obtained from the 1TC(T) specimens, despite not meeting the size requirements of ASTM E 399, appear to give size independent estimates of the linear elastic fracture toughness.

Another study by Urabe and Arai [81] developed equations to correct small test specimen results for either the constraint based effects of size (due to the loss of stress triaxiality [27,28]) or the probability based constraint loss described by the weakest link theory (the concept that smaller specimens have a less likely chance of sampling a defect (i.e. weakest link)). However, the equations were not verified by comparing the small specimen test results corrected by these equations and the large specimen test results.

4.2 Bundesanstalt für Materialforschung und -Prüfung (BAM) -Germany

BAM has been conducting research since the early 1980's to demonstrate the possibility of using DI as a packaging material. The motivating factor associated with this research was that the need for a large number of intermediate waste storage and transportation packagings that were simple and inexpensive to construct [86]. After extensive testing and research the majority of the packagings tested and licensed in Germany by the late 1980's were DI packagings and their numbers were in the hundreds [86]. Besides Germany, DI packagings have been approved for use in Belgium, the Czech Republic, Finland, France, Hungary, Poland, Russia, Sweden, Switzerland, and the United Kingdom (and for storage in the United States). An overview of the status of the program in the Federal Republic of Germany (FRG) as of the late 1980's is given in references [86-88]. The extensive work conducted by BAM is summarized in the sections 4.2.1 to 4.2.4.

4.2.1 Material Characterization Program

Several early studies [29,89-91] investigated the material properties of DI. Later material characterization was done in conjunction with the packaging drop tests discussed in the next section [87,92,93]. Extensive material testing including tensile tests, CVN tests, fracture toughness testing, and metallographic tests were conducted on material removed from actual packagings. Initially, the licensing and approval of the packagings was done without a fracture mechanics based design. Assurance of the prevention of brittle fracture was provided by limiting the nominal stresses and specifying minimum ductilities. Table 4.2 lists the acceptance criteria for the DI containers. Emphasis was placed on improving the quality of the DI material and insuring enough ductility in the DI to prevent fracture in the 9 meter drop tests.

An extensive investigation into the mechanical properties of DI was discussed in reference [40]. The report was based upon research done by Dr. Frenz at the Technical University of Berlin (the work was translated to english while Dr. Frenz was on assignment at SNL.) The work consisted of a statistical analysis of the test results of 1100 transportation and storage packagings which was followed by a test program of 24 DI alloys investigating the mechanical and fracture

Table 4.2. Acceptance criteria for DCI containers[a]

1.	No fracture of prototype in IAEA-9 meter drop test at -40°C
2.	Stress level < 0.5 $R_{p0.2}$
3.	Safety relevant material properties: $R_{p0.2}$, R_m, A_5, K_{Ic}, pearlite content, graphite type
4.	NDE: Minimal detectable defect size smaller than flaw size corresponding to K_I = 50 MPa-$m^{1/2}$
5.	Specification and control of all measures relevant to quality of casting based on prototype fabrication

a From Sieser, K.E., Aurich, D., and Wüstenberg, H., "The Status of Ductile Cast Iron Shipping and Storage Containers in the Federal Republic of Germany," *Proceedings of the 8th International Symposium on the Packaging and Transportation of Radioactive Materials (PATRAM '89)*, 1989, pp. 701-711.

properties as a function of microstructure.

The program showed the strong effect of pearlite content and graphite nodule structure on the mechanical and fracture toughness properties of DI. Increases in pearlite content increased the strength and decreased the ductility. In the region of the lower shelf materials with small homogeneous graphite nodules showed higher fracture toughness while in the upper shelf region materials with larger graphite nodules showed higher fracture toughness.

4.2.2 Packaging Drop Testing

Extensive drop testing was conducted to qualify DI as a packaging material. The packaging tests were a major part of the approval process. As of 1989, there had been 44 packaging drop tests from the 9 meter drop height in accordance with IAEA standards [87]. In addition to these drop tests, additional precracked packaging drop tests were performed [92,93]. These tests were performed with the packagings dropped onto rails to enhance the tensile stresses at the crack location. The initial tests were conducted on a scale-model packaging to establish the test geometry. Three more drop tests were conducted at varying drop height and rail span to obtain a test with applied stress intensity below the predicted toughness, near the predicted toughness, and finally above the predicted toughness. The final test was conducted to initiate some crack growth and verify the analysis methods and material toughness. As predicted a small amount of crack growth did occur and was arrested. The final test which did initiate a crack consisted of a drop from a height of 14 meter onto the steel rails. The impact force in this case exceeded the type B package test condition by 650 percent [93] and included a flaw 46.5 percent through the wall thickness. These tests verified the fracture mechanics methodology applied to these packagings and demonstrated the large factor of safety that can be obtained using linear elastic fracture mechanics.

4.2.3 Structural Analysis

FEA has been an integral part of the research effort in the FRG. The use of FEA as a tool in the design and analysis of packagings is becoming more important as the technology advances and there is an interest to produce packagings of shapes other than those already tested and licensed. References [93-98] all contain details of the FEA work conducted in the FRG. Emphasis has been on demonstrating the ability to match the FEA work with drop tests [93-95,97,98] and applicability of material models. The more recent work has involved the dynamic aspects of the severe accident conditions. The research conducted has demonstrated the ability of the FEA to match the experimental packaging drop test results and quantified the high factor of safety involved in the DI packagings and the FMBD.

4.2.4 Fracture Criteria

Originally the BAM safety assessment concept for licensing ferritic packagings did not include a fracture criteria. The safety assessment was primarily based on the experimental drop tests and the requirements shown in Table 4.2. However, development of more sophisticated packaging designs and international interest in a FMBD has lead BAM to begin to develop a fracture mechanics based safety concept [92,99-102]. Using the IAEA-TECDOC criteria [74] it has been demonstrated that a DI packaging constructed in the FRG can indeed meet the requirements of a fracture mechanics safety assessment [99,100].

4.3 Other Related Efforts

SNL, CRIEPI, and BAM have had the largest research programs investigating the concept of FMBD methodology for RAM transport containers and the materials used for such containers. However, additional research has been conducted by other investigators that is pertinent to the issue of the FMBD and DI. A representative overview follows:

•USA: Work was conducted in the 1970's by Nanstad et al [103,104], Lazaridis et al. [105,106], Worzola et al. [107], and then by Bradley et al. [30,108-110] in the late 1970's and 1980's on the fracture mechanics properties of DI.

•United Kingdom: Early work conducted in the mid 1970's by Jolley and Holdsworth [111,112] and Holdsworth and Jolley [113] discussed the fracture toughness of DI and the influence of graphite nodules on the fracture toughness. More recently Gray et al. [114,115] and Smith et al. [116] investigated fracture assessment of packagings, fracture criteria, drop tests of packagings, and material properties of DI.

•France: The French have had a research program to investigate the risk of brittle fracture of transport packagings. An overview of the program can be found in references [117,118]. In addition to these references, Moulin et al. have investigated the toughness characteristics of large thickness components subjected to drop loads [119] and compared experimental drop test results to FEA results [120].

•Finland: DI packagings have been licensed for use in Finland for RAM transport. Reference [121] discusses the licensing requirements for the CASTOR TVO cask. An earlier study conducted by Oeberg and Wallin [39] investigated the fracture properties of various cast irons.

Theses studies all contribute to the overall international acceptance of the fracture mechanics based methodology for the construction of RAM transport packagings and the use of DI as a packaging containment boundary.

5.0 Standards and Code Development Work

Along with the strong international effort to develop a FMBD methodology for RAM packagings several organizations have made an effort to incorporate into their standards and guidelines a FMBD methodology and the use of DI material.

5.1 American Society for Testing and Materials (ASTM)

Within ASTM the "Standard Specification for Ferritic Ductile Iron Castings Suitable for Low-Temperature Service" ASTM A 874-89 [34] is applicable for RAM packagings. The DI described in this specification is essentially ferritic with spherical graphite nodules and possesses relatively high ductility and fracture toughness. Most DI packagings manufactured throughout the world adhere to this ASTM specification. The development of a standard for the material ensures a minimum level of material quality and supports the use of DI at service temperatures as low as -40oC.

5.2 American Society of Mechanical Engineers (ASME)

Although no section of the ASME Code [14,18,74,122] is directly applicable to RAM packagings, the code does contain several sections that implement a FMBD methodology in relation to the design of critical equipment such as nuclear reactor pressure vessels. The ASME is currently drafting a Code for Division 3 under Section III subgroup on Containment Systems for Spent Fuel and High Level Waste Transport Packagings [NUPACK] for transport packagings. As discussed in Section 2.0 the FMBD developed by SNL, BAM, and CRIEPI are at least partially based on Appendix G of Section III, Division 1, of the ASME Boiler and Pressure Vessel Code. The ASME code is a good example of the use of FMBD methodology for fracture critical members using ferritic steel and on components requiring a high level of safety because of the nuclear applications.

5.3 International Atomic Energy Agency (IAEA)

The IAEA has developed an international guideline for the prevention of brittle fracture of RAM shipping packagings that was issued as IAEA TECDOC 717 [5]. The document is anticipated to serve as a possible revision of Appendix IX of Safety Series No 37. The brittle fracture criteria in the TECDOC follow the provisions of the consensus codes and standards of the member states for nuclear power plants. Sections III and XI of the ASME code [14,18,74,122] were both referenced in the TECDOC.

The original version of the TECDOC contained only guidelines for LEFM. However, a subsequent revision [123] by F.M. Burdekin, engaged by the IAEA as an independent technical expert, contains specific guidelines for EPFM evaluation. More recently, there have been additional suggestions regarding the EPFM approaches [83].

6.0 U. S. Regulatory Position

There is no current United States regulatory guide for the fracture mechanics based design of RAM packagings. Guidance for the loading conditions that the containment boundaries for RAM packagings must withstand are contained in the Code of Federal Regulations Title 10, Part 71, "Packaging and Transportation of Radioactive Material" (10CFR71) [1]. One condition specified by the code is that the packaging (in addition to normal transport loadings) must be able to withstand a hypothetical accident condition of a 9 meter drop onto an unyielding target at a temperature of -29°C. However, the code does not explicitly provide design criteria and establish margins of safety for the design relative to the loading criteria of 10CFR71.

The main document used to evaluate RAM packagings with respect to the 10CFR71 loading criteria is the United States Nuclear Regulatory Commission, Regulatory Guide 7.6, "Design Criteria for the Structural Analysis of Shipping Cask Containment Vessels" [2]. The guide suggests that the material should have an applicable ASTM standard and should be listed as a Class I component as defined in Subsection NA in Section III of the ASME Boiler and Pressure

Vessel Code [74]. The guide states that it reflects recently licensed shipping packagings that were made of austenitic stainless steel, which is ductile even at low temperatures, and therefore does not consider brittle fracture. Thus, Regulatory Guide 7.6 excludes materials that may fail in a brittle fashion.

The possibility of an increased demand for RAM packagings has led the DOE to investigate structural materials other than austenitic stainless steel for the construction. Most of the alternative materials must address the possibility of brittle fracture. To address this problem the NRC has issued two regulatory guides for ferritic steels. These guidelines, Regulatory Guide 7.11, "Fracture Toughness Criteria of Base Material for Ferritic Steel Shipping Containment Vessels with a Maximum Wall Thickness of 4 Inches (0.1 m)," [3] and Regulatory Guide 7.12, "Fracture Toughness Criteria of Base Material for Ferritic Steel Shipping Cask Containment Vessels with a Wall Thickness Greater Than 4 Inches (0.1 m) but not Exceeding 12 Inches (0.3 m),"[4] are limited to ferritic steels which are selected based on empirical relations between the nil-ductility transition temperature [8] and the fracture resistance of the material. These documents are not based apon fracture mechanics principles as discussed in this report.

These NRC guides are guidelines and not regulations. Compliance with these guidelines are not required. Alternate approaches are acceptable if a basis for the findings are provided requisite to the issuance of a license by the NRC. However, alternate approaches are uncertain in the respect that there is no guarantee that the NRC will find the method acceptable. A more fundamental approach based on fracture mechanics methodology would create the opportunity to quantify safety margins for specific conditions. Such a method would not be material specific and would allow a more rational basis for design trade-offs to be considered in light of optimizing the safety and functionality of the overall packaging system. Therefore, the incentive is to develop a fracture mechanics based design methodology that is acceptable to the NRC.

7.0 Conclusions

Extensive research has been conducted throughout the world on the use of a FMBD and the use of DI to construct RAM packagings. The results have led to DI packagings being licensed in Europe and the release of the IAEA TECDOC-0717, "Guidelines for Safe Design of Shipping Packages Against Brittle Fracture." Recent studies [82,83,124] have shown that both linear elastic and elastic plastic FMBD can be used to evaluate RAM packagings. These studies evaluated packagings subjected to the drop test specified in 10CFR71 [1]. SNL, BAM, and CRIEPI all conducted packaging drop tests and used the results to verify the FMBD methodology.

Drop testing of RAM packagings has been a substantial part of the international effort to examine a fracture mechanics based methodology for the packagings. The material characterization of DI has also been an integral part of the research. To apply a FMBD methodology the material properties must be well understood. Therefore, in depth material characterization was conducted by SNL, BAM, and CRIEPI.

SNL conducted eleven drop tests with artificial flaws as part of the MOSAIK cask program [57]. The tests were more severe than regulatory drop tests specified in 10CFR71. In all cases the packagings withstood the drop test and in only one case, where the drop height was more than twice the regulatory height, was any crack growth observed (followed by immediate arrest after minimal extension). In Japan, CRIEPI, conducted several drop tests [77,79] with artificial flaws to verify the FMBD methodology. In Germany, as of 1989 BAM has conducted 44 packaging drop tests from the regulatory 9 meter drop height and in accordance with IAEA standards [87]. The results of these drop tests have demonstrated the credibility of DI as a RAM packaging material and how the FMBD approach can be applied to RAM packagings.

The FMBD methodology was used to evaluate packagings that were used in drop tests in Japan and at SNL [57,80]. The two drop tests evaluated in Japan found that for a 20 mm flaw there was a factor of safety of 2.67 and for a 83.5 mm flaw there was a factor of safety of 1.32. For the

MOSAIK cask an extra-regulatory drop test with a 19 mm flaw, the factor of safety was found to be 1.5. Studies [79,125] have shown that using nondestructive testing it is possible to detect flaws in the range of 6 to 9 mm. Therefore, these studies show that it is possible to design the RAM packagings to prevent brittle fracture and with allowable flaw sizes considerably larger then the minimum detectable flaw size of current NDE evaluation methods.

The numerous studies cited show that DI is a well characterized material that does have sufficient fracture toughness to produce a containment boundary for RAM packagings that will be safe from brittle fracture. All the drop tests discussed in this report were conducted using DI packagings and the studies indicate that even with drop tests exceeding the severity of those specified in 10CFR71 the DI packagings perform in an exemplary manner.

The requirements of 10CFR71 for the 9 meter drop test, model service conditions which are highly unlikely to occur. The acceleration due to the 9 meter free fall of the tests conditions is not likely to happen in a RAM packaging service. An unyielding surface is also not a naturel impact surface for a RAM packaging. Typical concrete or asphalt surfaces are much more forgiving then an unyielding surface. The -40oC service temperature specified by the IAEA is also not a likely condition for service. Even if the ambient temperature were -40oC, the heat from the RAM would make the temperature of the containment boundary considerably higher (resulting in a higher fracture toughness). Finally, there is no drop orientation that is likely to result in a through wall tensile stress. Without a completely through wall tensile stress, any crack that might initiate would likely arrest when it reached compressive stresses. Thus, it is extremely unlikely to encounter accident conditions as severe as the requirements of 10CFR71 and the IAEA, and having a flaw located in the packaging in the most severe orientation to result in a brittle fracture.

Despite the rigorous conditions stipulated by 10CFR71 and the IAEA, many of the drop tests such as the MOSAIK cask tests performed at SNL [45,57] were performed under conditions much more severe then required by these regulations. The MOSAIK casks were tested with flaws intentionally located in the most severe location and impact limiters were replaced with steel rails to insure that a very high through thickness tensile stress would occur where the flaw was located. The flaw sizes placed in the cask drop tests are considerably larger then the minimum size detectable by NDE methods. Using the current fracture mechanics methodology it is possible to show that the packagings are safe from brittle fracture.

References

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Appendix A

Additional References

During the writing of this document many references were collected that pertain to the fracture mechanics based design and the materials characterization of candidate materials applicable to radioactive material transport packagings. The following is an extensive list of additional resources collected but not referenced in the body of the text. Combined with the references in the body of the text, this list shows the vast body of work pertaining to these topics. The references are listed in chronological order.

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