DISCLAIMER

This report was prepared as an account of work sponsored by an agency of the United States Government. Neither the United States Government nor any agency thereof, nor any of their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States Government or any agency thereof. The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States Government or any agency thereof.

UCRL 15496

P.O. 1062605

E-3965

Project 1026

UCRL--15496

DE84 002775

VALUE/IMPACT OF DESIGN CRITERIA FOR CAST DUCTILE IRON SHIPPING CASKS

July 15, 1983

Report Prepared by
Transnuclear, Inc.
for
University of California
Lawrence Livermore National Laboratories

Contract W-7405-ENG-48

Transnuclear, Inc.
One North Broadway
White Plains, NY 10601

MASTER

DISTRIBUTION OF THIS DOCUMENT IS UNLIMITED

20B

TABLE OF CONTENTS

	<u>Page</u>
1.0 Introduction	1
2.0 Summary	2
2.1 Ductile Failure	2
2.2 Brittle Failure	2
3.0 Ductile Failure Design Criteria ..	4
3.1 Background	4
3.2 Selection of Design Stress Intensity Value, S_m	5
3.3 Other Comments on Ductile Failure Design Criteria	8
3.3.1 Primary Membrane and Bending Stress ..	8
3.3.2 Fatigue Strength Reduction Factors ..	8
3.3.3 Range of Primary Plus Secondary Stresses	9
3.3.4 Ductility	9
4.0 Brittle Failure Design Criteria	9
4.1 Materials Approach	10
4.2 Linear Elastic Fracture Mechanics	10
4.2.1 Yield Stress Levels	14
4.2.2 Stresses Below Yield	15
4.3 Drop Test Acceptance Criteria for Resistance to Brittle Fracture	16
5.0 Safety Margins and Costs	19
5.1 Ductile Failure Design Criteria	19
5.1.1 Safety Margins	19
5.1.2 Costs	20
5.2 Fracture Initiation Brittle Fracture Criterion Based Upon Yield Stress Levels ...	21
5.2.1 Safety Margins	21
5.2.2 Costs	21
5.3 Fracture Initiation Brittle Fracture Criterion Based Upon Stresses Below Yield ..	21
5.3.1 Safety Margins	21
5.3.2 Costs	22
5.4 Drop Test Acceptance Criteria for Resistance to Brittle Fracture	22
5.4.1 Safety Margins	22
5.4.2 Costs	23
References	25

	<u>Page</u>
Table 1 Summary of Different Basis for Determining Design Stress Intensity, S_m	28
Table 2 Allowable Stress Levels for Three Different Stress Intensity Values	29
Table 3 Margins of Safety for a Typical TN Rail Cask With Different S_m Criteria	30
Table 4 Safety Margins in Terms of Flaw Size	31
Figure 1 Stress Distribution in Rectangular Beam Cross Section	32
Figure 2 Applied Stress vs. Material Critical Flaw Size	33

1.0 INTRODUCTION

Lawrence Livermore Laboratory (LLL) performed a study (Base Report⁽¹⁾) with the objective of determining the applicability of U.S. Nuclear Regulatory Commission (NRC) Regulatory Guide 7.6 (Reg. Guide 7.6⁽²⁾) as the basis for ductile failure design criteria and developing criteria for preventing brittle failure in nodular (ductile) iron shipping containers.

Transnuclear, Inc. (TN) was requested to review the results of the LLL study to determine the impact of design and acceptance criteria for cast ductile iron spent fuel shipping casks upon safety margins and costs that might be incurred by adopting the LLL proposed criteria.

Prior to performing the value/impact evaluation it was necessary to review and evaluate the proposed criteria. For ductile failure design criteria the selection of the design basis and stress intensity value, S_m , could effect thickness requirements which in turn would effect safety margins and cost. The selected brittle failure acceptance criteria would also greatly effect safety margins and cost. Factors such as nondestructive examinations (NDE), stress analysis, model testing, etc. could vary considerably depending on the criteria selected.

The proposed ductile failure design criteria are evaluated and compared with other possible criteria in Section 3.0. The impact on safety margins and cost is presented in Section 5.0.

The brittle failure acceptance criteria are reviewed and evaluated to determine first, their applicability to cast ductile iron and second, whether the criteria will demonstrate acceptance of this material for shipping casks. The results of this evaluation are presented in Section 4.0. Their impact on safety margins and cost are also presented in Section 5.0.

2.0 SUMMARY

2.1 DUCTILE FAILURE

The ductile failure criteria proposed in the Base Report appear appropriate except that stress intensity values, S_m should be based on lower safety factors and ductility should be added as a criterion.

A safety factor for stress intensity, S_m of 4 is recommended rather than 3 on minimum ultimate tensile strength, S_u in accordance with ASME Code philosophy of assigning higher safety factors to cast ductile iron than to steel. This more conservative approach has no impact on costs since the selection of wall thickness is controlled by shielding rather than by stress considerations.

The addition of a ductility criterion is recommended because of the problems associated with the selection of appropriate brittle failure criteria and the potential for cast ductile iron to have extremely low elongation at failure.

2.2 BRITTLE FAILURE

Neither a "materials" nor a linear elastic fracture mechanics (LEFM) approach appear to be viable for demonstrating the prevention of brittle failure in cast ductile iron shipping casks.

The "materials" approach is unacceptable for two reasons. The first is related to the fact that the desirable properties of cast ductile iron are destroyed by welding which is required for the preparation of a drop weight test specimen which has to be used with the standard (ASTM E-208⁽³⁾) drop weight test for establishing the nil ductility transition temperature (NDTT). Secondly, the lowest allowable service temperature would be much higher than the -20°F specified in NRC Regulatory Guide 7.8⁽⁴⁾ based on estimates of NDTT from other test data and adding a thickness correction factor.

LEFM approaches are not acceptable because of limits in the capabilities of existing NDE methods to detect small flaws. The smallest detectable flaw size is in the 1/4 to 1/2 in. range under laboratory conditions. Allowing for at least a doubling of that size for an undetected flaw under production conditions and for crack extension during service results in design critical flaw sizes of 1.5 in. minimum. If cask stresses reach yield values, LEFM predicts brittle failure with flaws as small as 1/8 in. Only, if maximum tensile stresses will not exceed approximately 17 ksi could a 1.5 in. flaw be accommodated without brittle failure. It is neither practical nor cost effective to limit maximum stresses to such low values.

Probabilistic approaches or model testing could be used to demonstrate the acceptability of cast ductile iron casks from a brittle failure point of view.

Before probabilistic methods can be used, the NRC would have to be persuaded to accept the approach of the Competent Authority in West Germany or more formalized methods for probabilistic risk assessments (PRA).

It is possible that the analytic methods predict brittle failure because of extremely conservative assumptions whereas real casks may not fail. Model drop tests could be used to demonstrate containment integrity. It is estimated that a risk commitment of at least \$1,000,000 would be required for engineering, design, model fabrication and testing. Before taking such risks, a mechanism should be found to obtain concurrence from NRC that the results of the test would be acceptable.

3.0 DUCTILE FAILURE DESIGN CRITERIA

3.1 BACKGROUND

The ductile failure design criteria presented in the Base Report are for the most part based on the design stress intensity values, S_m as used in the ASME Boiler and Pressure Vessel Code (ASME Code). S_m values are generally obtained by applying safety factors to the minimum ultimate tensile or minimum yield strength of the material for temperatures below 600°F-800°F which is the lower limit of the creep range. It is anticipated that the maximum temperature of a cask would not exceed 300°F during normal operation. Only during and after a fire would the cask body temperature be expected to exceed 600°F. The length of time at such elevated temperatures would be too short for creep effects to be important.

It should be noted that the ASME Code and other Regulatory Guides do not permit the use of cast iron materials in the construction of equipment for containment of radioactive substances. Regulatory Guide 1.143,⁽⁵⁾ which is applicable to radwaste systems, states that material for pressure-retaining components should conform to the requirements of the specifications for materials listed in Section II of the ASME Code, except that malleable, wrought, or cast iron materials should not be used.

Part UCD of Section VIII, Division 1⁽⁶⁾ which provides rules for construction of cast ductile iron pressure vessels states that such vessels shall not be used for services in which lethal substances are to be contained. Section III⁽⁷⁾ of the ASME Code does not permit the use of cast ductile iron as a material except for Code Case N-205⁽⁸⁾ which allows the use of SA-395 for pipes and fittings containing service water.

Thus, while the ASME Code philosophy seems to provide a logical approach to the selection of design criteria, as was done in the Base Report, it should be recognized that this is not tantamount to ASME Code acceptance. Since spent fuel transport casks are not presently covered by the ASME Code, it is not possible to obtain a timely ruling on the acceptance of cast ductile iron as a material for such casks. This matter could be introduced into the deliberations of the Code bodies through the NUPACK Committee (Special Working Group on Containment Systems for Nuclear Spent Fuel and High Level Waste Transport Packagings) which is presently writing such rules and requirements under the auspices of the ASME Code, Section III.⁽⁷⁾

3.2 SELECTION OF DESIGN STRESS INTENSITY VALUE, S_m

The bases for the selection of the design stress intensity value, S_m are summarized in Table 1.

The ASME Code assigns different safety factors to different types and classes of components as well as to components made by casting or other processes. As shown in Table 1 for Section VIII, Division 1 components, ⁽⁶⁾ cast iron and cast ductile iron have significantly higher safety factors for S_m values than steel. Part UCI, ⁽⁶⁾ which gives requirements for construction of (grey) cast iron pressure vessels, specifies a safety factor of 10 on the minimum ultimate tensile strength.

The S_m value listed in Table UCD-23, Part UCD⁽⁶⁾ for the construction of cast ductile iron pressure vessels is based on a safety factor of 5 on the minimum ultimate tensile strength. Although not explicitly stated the latter value is based on a design by formula approach. A casting quality factor must be applied to the stress value obtained from Table UCD-23.⁽⁶⁾ Section VIII Para. UG-24(a)(1)⁽⁶⁾ specifies a quality factor of 80%. The latter requires no impact tests or NDE. Other parts of Section VIII, Division 1⁽⁶⁾ which cover pressure vessels made of steel assign a lower safety factor of 4 on minimum ultimate strength.

An even lower safety factor of 3 is used for Section VIII, Division 2⁽⁹⁾ steel components because a design-by-analysis approach (i.e. extensive structural analysis of the component) is required compared to a design by formula approach required by Section VIII, Division 1.⁽⁶⁾

Nuclear steel components covered by Section III, Class 1⁽⁷⁾ also require design by analysis and therefore have the same safety factors as Section VIII, Division 2⁽⁹⁾ steel components. Class 2 and 3 nuclear steel components, following a design by formula approach, also have the same safety factors as Section VIII, Division 1⁽⁶⁾ steel vessels.

The Regulatory Guide 7.6⁽²⁾ has adopted the design-by-analysis approach for Class 1 components for design criteria for shipping cask containment vessels. The Base Report ⁽¹⁾ recommends using the same criterion as a basis for S_m values, i.e. a safety factor of 3 on the minimum ultimate tensile strength, S_u .

Based on the foregoing, it would appear that this safety factor of 3 is too low and not consistent with the ASME Code philosophy of using greater conservatism for cast iron materials compared to steel.

A safety factor of 4 appears to be more appropriate based on a safety factor of 5 and a quality factor less than one for cast ductile iron components under Section VIII, Division 1⁽⁶⁾. The safety factor is reduced from 5 to 4 by performing design by analysis rather than by formula. The quality factor is increased to one since casting soundness will be assured by extensive nondestructive examinations to prevent brittle failure.

Table 2 presents a summary of the allowable stress levels for different stress categories for three different bases for design stress intensity, S_m . The values of S_m are obtained using the minimum ultimate tensile strength of A-536, Grade 60-40-18⁽¹⁰⁾ and the material used by Transnuklear, GmbH (TNF) for the TN-1300 cask design⁽¹¹⁾. For both materials, the ultimate tensile strength rather than yield strength are controlling in establishing the S_m values.

A-536, Grade 60-40-18 is used here because it is referenced in the Base Report. It should be noted that this is not an ASME Code accepted material. The corresponding ASME Code material is SA-395⁽¹²⁾ whose minimum tensile properties are the same. Presumably the ASME Code material has been characterized sufficiently to provide confidence that the tensile properties of production castings are not lower than the "minimum" values if the material meets the requirements of SA-395.

The TNF material quality is GGG 40.3 as described in the German Standard DIN 1693, Part 2⁽¹³⁾. According to this Standard acceptance criteria have to be agreed upon between the casting manufacturer and the client for wall thicknesses greater than 200 mm. The TNF material criteria for the TN-1300 which have been agreed upon by Thyssen, TNF and the German Competent Authority are 46.4 ksi tensile strength, 26.1 ksi yield strength and 20% elongation, as determined with test coupons from cast-on blocks⁽¹¹⁾.

3.3 OTHER COMMENTS ON DUCTILE FAILURE DESIGN CRITERIA

3.3.1 Primary Membrane and Bending Stress

A statement is made in the Base Report⁽¹⁾ that there is a 50% margin against collapse for a rectangular beam if S_m is $2/3$ yield strength and the combined primary membrane (P_m) and bending (P_b) stress is less than $1.5 S_m$. This statement is correct only if the primary membrane stress (P_m) is zero and the stress distribution is as shown in Fig. 1.a. However if P_m stresses reach the allowable limit of S_m (per ASME Code Section III, Class 1⁽⁷⁾) or $2/3$ yield strength as shown in Figure 1.b then there is not a 50% margin against collapse.

It should be noted that for other shapes the margin against collapse is less. The margin against collapse for a pipe would be approximately 30% if the stress distribution was as shown in Figure 1(a) (i.e. $P_m = 0$).

3.3.2 Fatigue Strength Reduction Factors

Fatigue strength factors for nodular cast iron, if used, would result in a greater allowable alternating stress amplitude, S_a , than fatigue design curves since its notch sensitivity is less than one. That is, the application of a stress concentration factor to nominal stresses will result in peak stresses which produce a fatigue life of less cycles than using fatigue strength reduction factors.

3.3.3 Range of Primary Plus Secondary Stresses

The position 4 of Regulatory Guide 7.6⁽²⁾ is basically identical to the simplified Elastic-Plastic analysis proposed by the ASME Code (NB-3228.5⁽⁷⁾). It allows the $3 S_m$ limit for primary plus secondary bending stresses to be exceeded if certain requirements are met. If all the stress limits are met, the above method is not used. At any rate the maximum value for K_e for carbon steel would be five (5). A fatigue strength reduction factor or a stress concentration factor greater than 5 would not be expected for any material including ductile cast iron. On a preliminary basis the values listed for carbon steel would seem acceptable for ductile cast iron.

3.3.4 Ductility

Both, the ASME Code, Section III⁽⁷⁾ and Reg. Guide 7.6⁽²⁾ emphasize S_m as the principal criterion to prevent ductile failure. Implicit in both documents is that only steels with high ductility will be utilized for nuclear components or cask containment. Because of the lower ductility of ductile cast iron and the potential of extremely low values, ductility should be added to the Base Report⁽¹⁾ as an important criterion especially in view of the problems associated with establishing criteria to prevent brittle failure, as discussed in the following Section 4.

4.0 BRITTLE FAILURE DESIGN CRITERIA

A shipping cask must be designed so that it does not fail in a brittle manner when subjected to the hypothetical accident condition of 10CFR71 Appendix B⁽¹⁴⁾ at the lowest service temperature. To demonstrate that a cask design has sufficient toughness against brittle failure three approaches can be considered, (1) a materials approach, (2) linear elastic fracture mechanics and (3) testing. Each of these approaches is considered in the following.

4.1 Materials Approach

This would be the most conservative, most direct, simplest and least expensive approach. It assures that brittle failure will not occur by demonstrating that the material will be on the "upper shelf" of the impact energy transition curve at the lowest service temperature.

This approach is exemplified by the fracture toughness requirements for ASME Class 2 nuclear components (Section III, Subsection NC⁽⁷⁾). Specifically, a nil ductility transition temperature NDTT is determined by the standard drop weight test method (ASTM E-208⁽³⁾). The lowest service temperature (LST) is then established by adding to NDTT a value A which is a function of the material thickness.

Unfortunately, this approach does not appear to be viable for cast ductile iron spent fuel transport casks for two reasons.

First, the standard drop weight method for establishing NDTT uses a weld bead on the test specimen as a crack initiator. The application of such a weld bead to a cast ductile iron specimen test will leave a significant effect on the material properties of the specimen and thus invalidate the results.

Secondly, if one bases estimates of NDTT on available data from other types of tests (e.g. Charpy) and corrects for thickness, the resulting LST is substantially higher than the minimum -20°C specified in Reg. Guide 7.8⁽⁴⁾.

4.2 Linear Elastic Fracture Mechanics

Since prevention of brittle fracture cannot be demonstrated using a materials approach, linear elastic fracture mechanics (LEFM) methods are considered in the following.

The stress level must be considered in terms of the critical flaw size in order to determine the critical stress intensity, K_{ID} , which defines the fracture toughness of the material. In order to do this, the data in the Base Report⁽¹⁾ given in Table 7 and Fig. 19 were used with Equation 4 to obtain the curve of applied stress versus critical flaw size as shown in Fig. 2 herein. The curve is based on the following:

$$a_i = \frac{Q (K_{ID}/\sigma_{yD})^2}{1.21 \pi (\sigma/\sigma_{yD})^2} \quad \text{Eq. 4 from Ref. 1}$$

As stated in the Base Report⁽¹⁾, the ratio of K_{ID}/σ_{yD} will be in the range of 0.5 to 0.6 at the NDTT. Therefore the ratio of K_{ID}/σ_{yD} of 0.59 was used which is based on a $K_{ID} = 37 \text{ ksi}\sqrt{\text{in.}}$ and $\sigma_{yD} = 63 \text{ ksi}$ at -20°F . These are the values upon which Fig. 19 (Ref. 1) is based and are probably the most appropriate values for cast ductile iron.

There are two fracture initiation criteria proposed in the Base Report⁽¹⁾, one for yield stress levels and the other for stresses below yield. In order to evaluate these two criteria it is necessary to establish a reference design flaw size which would be based on considerations of the smallest detectable flaw size, acceptable flaw sizes and the probable maximum undetected flaw size.

Smallest Detectable Flaw Size

Based on contacts with several organizations it appears that the smallest detectable known flaw size is between 1/4 in. and 1/2 in. This is based on knowing the size of a reference round bottom hole used in ultrasonic testing (UT) inspection methods. TNF in their material qualification program of the TN 1300 transport and storage cask determined that a hole smaller than 10 mm diameter and 50 mm deep could not be detected by UT even when the location of the hole was known.

Acceptable Flaw Size

Section VIII, Appendix 7⁽⁶⁾ of the ASME Code allows a flaw, i.e. linear indication, of 0.75 in. for thicknesses over 2.5 in. without repair.

Section XI⁽¹⁵⁾, which contains inservice requirements for nuclear components provides acceptance standards for flaws in welding. The standards depend on the category of the weld. For pressure retaining welds in the reactor vessel or nozzle to vessel the acceptable surface indication is 2.5 percent of the wall thickness or for a 12 in. wall 0.3 in. For pressure retaining welds between dissimilar metals or in piping, the acceptable surface indication is 5 percent of the wall thickness or for a 12 in. wall, 0.6 in. These numbers are based on an aspect ratio of 1/6. Flaws greater than the acceptance standard must be repaired or analytically evaluated to determine whether the component can remain in service to the next inspection period.

TNF, based on their experience with the TN-1300, cask suggests a maximum acceptable flaw of 0.8 in. (20 mm) in a cask lid and 1.6 in. (40 mm) in all other areas of the ductile iron casting.

Undetectable Flaw Size

The design flaw should really be the maximum size flaw which might not be detected during the routine examination of production casks. One method for arriving at such a flaw size is to apply a factor of conservatism to the smallest detectable flaw size. At Patram 83⁽¹⁶⁾,⁽¹⁷⁾ it was suggested that the factor should be two (2). Using the smallest detectable flaw of 0.4 in. (10 mm) and applying a factor of two gives a

flaw size of 0.8 in. (20 mm). As stated above, Section VIII(6) would accept a flaw of 0.75 in. without repair. This would be an absolute lower bound and would require the use of the best present state-of-the-art flaw detection technology.

Section III of the ASME Code for welds assumes an undetected flaw size of $1/4 T$, i.e. one-fourth the wall thickness of the component. For a 12 in. thick casting this would be a flaw of 3 in. in depth and 18 in. in length if a depth-to-length ratio of six (6) were used. This results in a factor of safety of approximately 10 on the smallest detectable flaw size using radiographic examination method(18). This is certainly an upper bound.

For a typical rail cask, TN has estimated that crack growth of 0.7 in. could be expected in the vicinity of the front trunnions due to cyclic loadings caused by pressure, bolting, temperature and inertia during manual handling and transport. Adding this to the smallest detected flaw size of 0.8 in. at the end of fabrication yields a minimum critical flaw size of 1.5 in. As shown in Fig. 2 herein for flaw sizes greater than 1.5 in. a small incremental change in stress results in a large increase in critical flaw size. Therefore a 1.5 in. flaw is almost an infinite flaw in terms of allowable stress levels.

Another consideration is the size of surface versus subsurface flaws. Surface flaws are of more concern because they are more likely to be sharp tipped, at least initially, than subsurface flaws. Subsurface flaws such as gas voids, porosity, etc. would be expected to be more rounded in shape.

In terms of size on shape factor (not applied stress or stress intensity) a subsurface flaw would be equivalent to twice the dimensions of a surface flaw. Thus the subsurface critical flaw depth (i.e. in thickness direction) could be twice 1.5 in. or 3 in. For a 12 in. thick walled cask this would be equivalent to the Section III criteria. Also it would be desirable to allow a larger subsurface flaw because it will be harder to detect or conversely it could more easily go undetected than a surface flaw.

Based upon the above one would obtain critical flaw sizes of 1.5 in. and 3.0 in. respectively for surface and subsurface flaws. These would be the reference or design critical flaw sizes to be used for design to prevent brittle failure.

4.2.1 Yield Stress Levels

Brittle failure is of greatest concern for the regulatory free drop occurring at the lowest service temperature. The stress levels which would be allowed based on ductile failure criteria are shown in Table 2 for different stress intensity criteria. Obviously it would be desirable to be able to achieve these stress levels and not be limited by brittle failure.

For a stress criterion based on $S_m = 1/3 S_u$ the maximum allowable stress for a ductile failure design criteria under an accident condition would be 60 ksi. This would result in a σ/σ_{yp} of almost 1.0 and a corresponding critical flaw size limited to 0.1 in. (2.5 mm). If the design stress intensity S_u were based on $1/5 S_u$ the maximum allowable stress level for an accident condition would be limited to 43 ksi. The corresponding critical flaw size would be 0.22 in. respectively. This critical flaw size is larger than the one based on $S_u = 1/3 S_u$ but it is still very small.

The static yield stresses for A-536, Grade 60-40-18 and the TNF material are 40 ksi and 26.1 ksi respectively. If these are used with Fig. 2 the corresponding critical flaw sizes are 0.25 in. and 0.8 in. respectively. Applying a safety factor of two would reduce the acceptable flaws to 0.125 in. and 0.4 in. respectively. Both are smaller than the design critical flaw size of 1.5 in.

It is, therefore, concluded that flaw sizes which may be permitted at yield stress levels are much smaller than the design critical flaw size and that a fracture initiation brittle fracture criterion based on yield stress levels is not acceptable.

4.2.2 Stresses Below Yield

For a critical flaw size of 1.5 in., and a K_{ID} value of 37 ksi $\sqrt{\text{in.}}$ the maximum stress which could be allowed to prevent brittle failure is 17 ksi. This is an intolerable low stress level, especially for accident conditions. Even for normal conditions of cask handling and transport, stresses of 25 ksi can be expected in the areas of support attachments of typical rail casks. For a packaging without fuel and therefore no thermal stress, maximum stress levels of TN casks are approximately 17 ksi for normal transport conditions. As shown in Table 2 the allowable stress levels based on ductile failure design criteria are significantly greater than 17 ksi.

It should be anticipated, that under the regulatory 30 ft. free drop accident, stresses will reach yield levels somewhere in the cask. For example, elastically calculated stresses in the body of a typical TN rail cask exceeds 100 ksi near the point of impact. Stresses also exceed yield at the lid flange, body shell-bottom junction and other structural discontinuities at which stress distributions are intensified.

The only approach for increasing the 17 ksi stress limit for cast ductile iron is to increase the K_{ID} value. Based on the existing data as summarized in Ref. 1, this is not likely. The material which gave the value of 37 ksi $\sqrt{\text{in.}}$ is material developed by Thyssen for the TNF 1300 cast ductile iron shipping cask. Based on contacts with TNF/Thyssen it is their judgement that the material fracture toughness cannot be improved significantly for production casks with the present technology and understanding of brittle fracture of cast ductile iron.

Therefore a brittle fracture initiation criterion based on stresses below the yield stress is not acceptable. It is concluded that the only alternative to demonstrate that a cast ductile iron cask has acceptable fracture toughness is a drop test program.

4.3 Drop Test Acceptance Criteria for Resistance to Brittle Fracture

Based on the data presently available and using a material approach or linear elastic fracture mechanics one would predict that a cast ductile iron cask with a design critical flaw would fail in a brittle manner if subjected to the regulatory free drop accident at a temperature of -20°F .

Bundesanstalt für Materialprüfung (BAM) has performed regulatory free drop tests at -40°F ⁽¹⁹⁾ with scaled and full scale models constructed of ductile cast iron. The fact that no brittle failures occurred demonstrates that cast ductile iron has excellent fracture toughness properties. However, these tests were performed without having sharp tipped flaws

introduced at points of highest stress. As was brought out during open discussions at PATRAM '83, the Competent Authority in Germany (i.e. BAM) considers the probability that a cask with a critical flaw in the most adverse orientation at points of maximum stress to be involved in an accident as severe as the regulatory accident conditions at -40°F to be so low that an applicant for a license does not have to address such an event.

If the U.S. Nuclear Regulatory Commission (NRC) could be persuaded to take a similar position one could demonstrate the acceptability of cast ductile cask by testing programs similar to those carried out in Germany. Probabilistic risk analysis (PRA) might be used as an additional step in judging the acceptability of a potential failure, if the state-of-the-art would permit reaching meaningful results. Recognizing that the NRC has not accepted probabilistic approaches to licensing of spent fuel transport casks in the past, it is assumed for the remainder of this section that the NRC will not make an exception of their previous position for cast ductile iron.

One may postulate some heretofore unexplored ideas which leave some hope that the containment integrity of a cast ductile iron cask can be maintained during a regulatory free drop test even if it contained critical flaws under the most adverse conditions. These ideas relate to:

- a. Differences in velocity of propagation of small disturbances and growth of finite cracks in multi-component matrices (graphite nodules in iron) vs. homogeneous metals.

- b. There is essentially zero energy stored in the cask prior to impact. The growth of a crack would have to be driven entirely by the limited energy available from the drop, which is further reduced by the energy absorbed in the deformation of other cask components.
- c. Highest tensile stresses result from bending of sections near points of impact and any crack growth within such sections has to propagate through regions which are initially under extremely high compressive loads. Crack growth may be arrested in such regions.

A test program with simplified models could be undertaken to demonstrate that brittle failures will not occur because of one or more of the reasons alluded to above. If such a demonstration was successful, one would still be confronted with designing a cost effective test program with scaled or full scale prototype casks which would demonstrate the acceptability of production casks. Some crucial items which will have to be considered are:

- a. Should the test model be full size since scaled models with thinner walls might have better fracture toughness properties than the production casks and through-thickness variations of material properties will be less pronounced?
- b. How does one determine the critical location and orientation of flaws that should be introduced prior to test?
- c. What method should be used to sharpen the crack tip to simulate fatigue extended cracks?

- d. Is limited crack growth acceptable during impact and if so, what method should be used to measure crack growth?
- e. What material properties and/or casting process variables should be controlled to assure that the fracture toughness of the production cask material will be as good or better than that of the test model?
- f. How many models should be tested under what conditions to establish margins of safety?

Costs and risks for such a program are addressed in the following section.

5.0 SAFETY MARGINS AND COSTS

5.1 DUCTILE FAILURE DESIGN CRITERIA

5.1.1 Safety Margins

Safety margins, $S_a/\sigma - 1$ are determined by comparing actual or applied stresses, under different loading conditions with allowable stresses, S_a . In turn, the allowable stresses depend primarily on the design stress intensity value, S_m .

In Section 3.2, it is proposed to use a more conservative approach for established S_m values than that given in the Base Report, i.e. increase the safety factor for S_m from 3 to 4. The resultant lower values of S_m lead to lower margins of safety. As long as the margins of safety are positive, a design is acceptable.

Table 3 lists the margins of safety for a typical 100 ton TN rail cask. The applied stresses are given for the highest stressed areas during normal handling, normal transport and regulatory accident conditions. As can be seen, the margins of safety remain positive for a safety factor of 4 or even 5 (barely).

The principal reason for the large margins of safety is that wall thicknesses are controlled by shielding rather than by strength considerations.

This also applies to fatigue. Using the fatigue curves in the Base Report (Figs. 8 and 9 Ref. 1) and cyclic stress data for a typical TN rail cask, the cumulative fatigue damage is calculated to be less than 1, i.e. it is acceptable.

It should also be noted that the ASME Code, does not assign any ductile failure stress limit to local bending stresses during an accident. As stated above, elastically calculated stresses exceed 100,000 psi in the regions of impact of a typical TN rail cask under the regulatory free drop conditions. Containment integrity is assured by the P_m and P_L limits, while local yielding and deformation are permitted. This approach would be acceptable for cast ductile iron only if high ductility can be assured (See Section 3.3.4).

5.1.2 Costs

Based on the foregoing, there is no cost impact due to the more conservative selection of a higher safety factor or lower S_m value than those given in the Base Report (See Section 3.2). The cask body thickness is dependent on shielding requirements and the body thickness does not have to be increased for structural considerations.

The selection of a safety factor lower than that specified for Section VIII cast ductile iron vessels has also no impact on costs because: first, a design-by-analysis approach would be required for the spent fuel cask containment to demonstrate actual stresses are less than allowable regardless of the ductile failure criteria used, and second, extensive nondestructive examinations would be required to establish that actual flaws meet the criteria specified to prevent brittle failure.

5.2 Fracture Initiation Brittle Fracture Criterion Based Upon Yield Stress Levels

5.2.1 Safety Margins

Table 4 summarizes safety margins for flaw sizes for A-536 and TNF material with yield stresses of 40 ksi and 26.1 ksi, respectively. The critical material flaw size is obtained from Fig. 2. The minimum acceptable and undetected flaw size is 0.8 in. from Section 3.2. Adding to this a predicted crack growth of 0.7 in. results in a design critical flaw size of 1.5 in. As can be seen from the table, all margins of safety with or without crack growth are negative or zero at best, indicating that the use of this criterion predicts brittle failure if stresses reach yield loads.

5.2.2 Costs

There is no cost impact for this criterion since it is not acceptable.

5.3 Fracture Initiation Brittle Fracture Criterion Based Upon Stresses Below Yield

5.3.1 Safety Margins

No attempt was made to determine safety margins since the stress level must be limited to 17 ksi to use this criterion.

This is highly restrictive and means all stresses, including those due to the regulatory free drop accident, would have to be limited to 17 ksi. As stated above, stresses in the body of a typical TN rail cask near points of impact would be in the 100 ksi range. Eighty (80) percent of this stress results from bending. Since the bending stress is inversely proportional to the square of the thickness, the body wall thickness of approximately 1 ft would have to be more than doubled to approximately 2 ft to 3 ft to reduce the stress level below 17 ksi. The resultant outside dimensions and weight of the cask would be unacceptably large.

5.3.2 Costs

It is clear from the foregoing that cask body costs would more than double, if the increase in dimensions and weight would be acceptable. The use of other materials which are not susceptible to brittle failure such as stainless steel would triple the cost but would clearly be preferable since no increases in dimensions and weight would be required.

5.4 Drop Test Acceptance Criteria for Resistance to Brittle Fracture

5.4.1 Safety Margins

As indicated in Section 4.2, fracture mechanics theory would predict brittle failure of a cast ductile iron cask with a design critical flaw, if subjected to the regulatory free drop at -20°F. Therefore it would not be desirable to make initial drop tests more severe than necessary. In order to obtain some measure of safety margin, subsequent drop tests could be performed from greater heights, at lower temperatures with larger flaws or a combination of these.

5.4.2 Costs

A drop test program requires a commitment of funds which is estimated to be at least \$1,000,000. This estimate includes \$350,000 for engineering/design which would be applicable to the design of subsequent production casks, if the drop test program was successful. The fabrication cost of a 50-100 ton test model is estimated at \$300,000. Efforts associated with materials characterization, casting requirements, etc. are estimated at \$200,000. The cost of planning, performing and evaluating the drop tests, including the application of special instrumentation is estimated at \$150,000. These are minimum estimates and assume that a drop test facility is available for performing drops on non-yielding target surfaces from heights of 30 ft and greater.

The casting of the test model body will have to be done to special procedures under controlled conditions as those which will be used for subsequent production units to assure that the fracture toughness properties of the model material are no better. A detailed stress analysis will have to be performed using a three dimensional finite element program e.g. ANSYS, to determine the locations, magnitudes and directions of maximum tensile stress. Flaws would be introduced at these locations in the model.

All phases of the test program from design through materials procurement, fabrication, examination and testing will have to be performed under a full 18 criteria Quality Assurance Program.

The risks for undertaking such a test program are considerable considering that present theory predicts failure and that it is not known whether NRC would accept favorable results. As a minimum, it is recommended that the organization which applies for a certificate of compliance from the NRC for a ductile cast iron spent fuel cask obtain prior concurrence from the NRC not only with the general approach to the drop tests but also with critical details such as the analytic methods for identifying location and orientation of maximum tensile stresses and the methods for introducing flaws and measuring crack extension. It should be noted that there is no existing mechanism for obtaining such NRC concurrence prior to submitting an application.

REFERENCES

1. Schwartz, M. W. and Boyce, L., "Ductile and Brittle Failure Design Criteria for Nodular Cast Iron Spent Fuel Shipping Containers", Lawrence Livermore Laboratory, UCRL-53046, October 1982.
2. U.S. Nuclear Regulatory Commission, "Design Criteria for the Structural Analysis of Shipping Cask Containment Vessels", Regulatory Guide 7.6, Revision 1, March 1978.
3. American Society for Testing and Materials, "Standard Method for Conducting Drop-Weight Test to Determine Nil-Ductility Transition Temperature of Ferritic Steels", ASTM E-208.
4. U.S. Nuclear Regulatory Commission, "Load Combinations for the Structural Analysis of Shipping Casks", Regulatory Guide 7.8, May 1977.
5. U.S. Nuclear Regulatory Commission, "Design Guidance for Radioactive Waste Management Systems, Structures, and Components Installed in Light-Water-Cooled Nuclear Power Plants", Regulatory Guide 1.143, Revision 1, October 1979.
6. ASME Boiler and Pressure Vessel Code, Section VIII, Pressure Vessels, Division 1.
7. ASME Boiler and Pressure Vessel Code, Section III, Nuclear Power Plant Components.
8. ASME Boiler and Pressure Vessel Code, Code Cases, Nuclear Components, Case N-205, "Use of Ductile Iron SA-395, Section III, Division 1, Class 3", Approved July 13, 1981.

9. ASME Boiler and Pressure Vessel Code, Section VIII, Pressure Vessels, Division 2, Alternative Rules.
10. American Society for Testing and Materials, "Standard Specification for Ductile Iron Castings", ASTM A-536-80.
11. Anspach, W., Transnuklear GmbH and Walters, D., Thyssen GieBerei A.G. "TN-1300 Casting Process and Material Qualification" presented at the Seventh International Symposium on Transportation of Radioactive Materials, New Orleans, LA, May 15-20, 1983.
12. ASME Boiler and Pressure Vessel Code, Section II, Materials Specifications; Part A, Ferrous Materials, "Specification For Ferritic Ductile Iron Pressure Retaining Castings For Use at Elevated Temperatures", SA-395.
13. Federal Republic of Germany Material Specification, DIN 1693, "Cast Iron with Nodular Graphite".
14. U.S. Nuclear Regulatory Commission, "Packaging of Radioactive Material for Transport and Transportation of Radioactive Material Under Certain Conditions", Code of Federal Regulations, Title 10, Part 71.
15. ASME Boiler and Pressure Vessel Code, Section XI, Rules for Inservice Inspection of Nuclear Power Plant Components.
16. Van Den Avyle, V.A., Salzbrenner, R. and Trujillo, A. A., Sandia National Laboratories, "Assessment of Cast Iron for Structural Components in Nuclear Material Transportation Systems", presented at the Seventh International Symposium on Transportation of Radioactive Materials, New Orleans, LA, May 15-20, 1983.

17. Schwartz, M. W. and Boyce, L., Lawrence Livermore National Laboratory, "Design Criteria for Nuclear Cast Iron Shipping Containers" presented at the Seventh International Symposium on Transportation of Radioactive Materials, New Orleans, LA, May 15-20, 1983.
18. Welding Research Council Bulletin 175, "PVRC Recommendations on Toughness Requirements for Ferritic Materials" prepared by the PVRC Ad Hoc Task Group on Toughness Requirements, August 1971.
19. Aurich, D., Helms, R. Ziebs, J. and Droste, B., BAM, "Mechanical Requirements for Material of Accident Proof Packagings of Radioactive Materials", presented at the Seventh International Symposium on Transportation of Radioactive Materials, New Orleans, LA, May 15-20, 1983.

TABLE 1 SUMMARY OF DIFFERENT BASIS FOR DETERMINING DESIGN STRESS INTENSITY, S_m

<u>REFERENCE DOCUMENT</u>	<u>BASIS FOR S_m</u>
Section VIII, Part UC1, Division 1 (Cast Iron)	$1/10 S_U$
Section VIII, Part UCD, Division 1 (Cast Ductile Iron)	$1/5 S_U \times F^{(1)}$
Section VIII, Parts, UCS, UHA, UHT Division 1 (Steel)	$1/4 S_U$ or $2/3 S_Y$
Section VIII, Division 2 (Steel)	$1/3 S_U$ or $2/3 S_Y$
Section III, Class 1 (Steel)	$1/3 S_U$ or $2/3 S_Y$
Section III, Class 2 or 3 (Steel)	$1/4 S_U$ or $2/3 S_Y$
Regulatory Guide 7.6	$1/3 S_U$ or $2/3 S_Y$
LLL Proposed Basis	$1/3 S_U$
TN Comment	$1/3 S_U$ is too high

(1) For iron castings-casting quality factor, F varies from 80-100%.

TABLE 2 ALLOWABLE STRESS LEVELS FOR THREE DIFFERENT STRESS INTENSITY VALUES

CONDITION	STRESS CATEGORY	SYMBOL	CODE LIMIT	ALLOWABLE STRESS LEVEL, S_a , KSI					
				$S_m=1/3S_u$		$S_m=1/5S_u$		$S_m=1/4S_u$	
				(1)	(2)	(1)	(2)	(1)	(2)
Normal Operation (Level A) (3)	Primary Membrane	P_m	S_m	20	15.5	12	9.3	15	11.6
	Primary Membrane Plus Bending,	P_m or P_L $+ P_b$	$1.5S_m$	30	23.2	18	13.9	22.5	17.4
	Primary Plus Secondary	P_m or P_L $+ P_b + Q$	$3.0S_m$	60	46.5	36	27.9	45	34.8
Accident (Level D) (3)	Primary Membrane	P_m	$2.4S_m$ or $0.7S_u$	42	32.5	29	22.3	36	27.8
	Primary Membrane Plus Bending	P_m or P_L $+ P_b$	$3.6S_m$ or S_u	60	46.4	43	33.5	54	41.8

(1) $S_u = 60$ ksi for material ASTM A-536 Grade 60-40-18

(2) $S_u = 46.4$ ksi, Acceptance Criteria for TNF⁽¹¹⁾ material.

(3) Level A and Level D as defined in the ASME B&PV Code Subsection NCA, General Requirements⁽⁷⁾

TABLE 3 MARGINS OF SAFETY FOR A TYPICAL TN RAIL CASK WITH DIFFERENT S_M CRITERIA

Loading	Stress Category Symbol	Applied Stress, ksi	Margin of Safety = $\frac{S_a}{S_m} - 1$					
			$S_m = 1/3S_u$		$S_m = 1/4S_u$		$S_m = 1/5S_u$	
			(1)	(2)	(1)	(2)	(1)	(2)
Normal During Handling	$P_L + P_b$	4	6.5	4.8	5.63	3.95	3.5	3.48
	$P_L + P_b + Q$	26	1.3	0.79	0.73	0.34	0.38	0.07
Normal During Transport	$P_L + P_b$	6	4.0	2.87	2.75	1.9	2.0	1.32
	$P_L + P_b + Q$	25	1.4	0.86	0.8	0.39	0.44	0.11
Accident at Midlength	P_m	17	1.47	0.91	1.12	0.64	1.69	0.31
Accident at Trunnion	P_L	19	2.16	1.44	1.84	1.2	1.27	0.76

(1) ASTM A-536, $S_u = 60$ ksi(2) TNF Material, $S_u = 46.4$ ksi

TABLE 4 SAFETY MARGINS IN TERMS OF FLAW SIZE

Material	Applied Stress σ_y , ksi	Critical Flaw Size from Fig. 2 a_i , in.	Minimum Acceptable and Undetected Flaw Size a_a , in.	Estimated Crack Growth During Normal Operation a_g , in.	Design Critical Flaw Size $a_d = a_a + a_g$, in.	Margins of Safety Without Crack Growth $\frac{a_i}{a_a} - 1$	Safety with Crack Growth $\frac{a_i}{a_d} - 1$
A-536, Grade 60-40-18	40	0.25	0.8	0.7	1.5	-0.69	-0.83
TNF Material	26.1	0.8	0.8	0.7	1.5	0	-0.47

Fig. 1 Stress Distribution in Rectangular Beam Cross Section

Fig. 2 - Applied Stress vs. Material Critical Flaw Size