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QA: N/A

SEP 27 2002

OVERNIGHT MAIL

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TRANSMITTAL OF REPORT ADDRESSING KEY TECHNICAL ISSUE (KTI) ITEM CONTAINER LIFE AND SOURCE TERM (CLST) 2.03

This letter transmits a report entitled *Agreement CLST 2.03* which satisfies the subject KTI agreement. The content of this transmittal was discussed in a teleconference with the U.S. Nuclear Regulatory Commission (NRC) on September 24, 2002. Specifically, the KTI agreement states:

> CLST 2.03: "Demonstrate how the Tresca failure criterion bounds a fracture mechanics approach to calculating the mechanical failure of the drip shield.
> DOE stated that it believes its current approach of using ASME Code is appropriate for the application. Additional justification for this conclusion will be included in the next revision of AMR ANL-XCS-ME-000001, Design Analysis for the Ex-Container Components, to be completed prior to LA."

Agreement item CLST 2.03 concerns mechanical failure criteria for the drip shield. The U.S. Department of Energy (DOE) agreed to provide justification for the use of the Tresca failure criteria as a bounding approach. The justification was originally planned to be documented in future revisions of the relevant Analysis and Model Reports prior to submittal of a License Application. However, as agreed during the NRC/DOE Technical Exchange and Management Meeting on April 15-16, 2002, the information in the enclosure addressing the underlying concerns and basis for closure of this agreement item is being submitted early to facilitate the NRC staff review.

The enclosure analyzes three types of loaded material specimens of Ti-7 and Alloy C-22. The analysis demonstrates that the failure of these materials is dominated by plastic collapse and not by brittle fracture. The ultimate failure conditions for these materials were determined using a failure assessment diagram (FAD). Based on the FADs, it is shown that the strength-of-materials

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approach (Tresca failure criteria) is appropriate for both materials. The DOE considers this enclosure to fully address the agreement item CLST 2.03, and pending the NRC review and acceptance, recommends that the agreement be closed.

There are no new regulatory commitments in the body or enclosure to this letter. Please direct any questions concerning this letter and its enclosure to Timothy C. Gunter at (702) 794-1343 or Paige R.Z. Russell at (702) 794-1315.

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OL&RC:TCG-1777

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Agreement CLST 2.03

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AGREEMENT CLST 2.03

September 2002

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ENCLOSURE

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1. AGREEMENT ITEM CLST 2.03

This enclosure provides information to address the Key Technical Issue (KTI) agreement related to the Container Life and Source Term (CLST) KTI agreement item 2.03. Each CLST KTI agreement item addresses phenomena or considerations related to the performance of the waste package and allied materials in a repository environment and the ability of U.S. Department of Energy (DOE) to model these phenomena accurately and adequately.

The information in this enclosure is provided in four sections. Section 1 provides the background and summarizes the technical issues of interest to the U.S. Nuclear Regulatory Commission (NRC) and DOE identified in the KTI agreement; Section 2 provides the wording of the agreement; Section 3 provides the information called for by the KTI; and Section 4 lists references.

1.1 BACKGROUND FOR AGREEMENT CLST 2.03

The primary focus of the KTI related to CLST is the adequacy of the technical basis for the models describing the degradation of the engineered barrier system design in order to assure that models capture the range of expected processes and process interactions. The CLST KTI is focused on evaluating the adequacy of the methodology, testing, and modeling used by the DOE in the investigations related to the drip shield, waste package (container and waste form), and the potential for criticality inside the waste package.

The CLST KTI covers six related subissues, one of which is directly related to agreement item CLST 2.03 and is addressed in this enclosure. The technical bases and the rationale for agreement item CLST 2.03 are explained in the NRC's Issue Resolution Status Report, Key Technical Issue: Container Life and Source Term, Revision 3, January 2001 (NRC 2001). Subissue 2, effects of phase instability and initial defects on the mechanical failure and lifetime of the containers.

Agreement item CLST 2.03 was reached during the Technical Exchange and Management Meetings on the CLST KTI between the NRC and DOE on September 12-13, 2000 (DOE/NRC 2000). Agreement item CLST 2.03 is concerned with how the Tresca failure criterion bounds a fracture mechanics approach to calculating the mechanical failure of the drip shield.

2. APPLICABLE NUCLEAR SAFETY STANDARDS, REQUIREMENTS, AND GUIDANCE

10 CFR 63, Subpart B, Licenses, provides the requirements for pre-application review. These pre-application reviews include informal conferences between a prospective applicant and the NRC staff, as described in 10 CFR Part 2, paragraph 2.101 (a)(1). Consistent with these requirements and in accordance with the memorandum of understanding between the two federal entities, Agreement between DOE/OCRWM and NRC/NMSS Regarding Prelicensing Interactions (Brownstein 1999), a series of interactions was undertaken to identify information

needed for a prospective license application. At these meetings, agreements for the DOE to provide the NRC with information were recorded as KTI agreements.

2.1 APPLICABLE REQUIREMENTS

The Yucca Mountain disposal regulations include requirements to describe the capability and provide technical basis for the engineered barrier system to isolate waste, taking into account parameter ranges and bounding values used in the performance assessment (10 CFR 63.114(b), 10 CFR 63.115(b) and 10 CFR 63.115(c)). Agreement item CLST 2.03 is related to the use of a strength-of-materials approach (Tresca criterion) versus a toughness-of-materials approach (fracture mechanics based) in design and evaluation of the drip shield.

2.2 KTI AGREEMENT

Quoted below is the text of the CLST KTI agreement that is the subject of this enclosure. The purpose of the agreement is to assure that sufficient information is available on the subject KTI to enable the NRC to docket a license application. Wording of the CLST agreement item 2.03 is documented in the summary highlights of the DOE and NRC Technical Exchange and Management Meeting held on September 12-13, 2000 (DOE/NRC 2000):

> "Demonstrate how the Tresca failure criterion bounds a fracture mechanics approach to calculating the mechanical failure of the drip shield. DOE stated that it believes its current approach of using ASME Code is appropriate for the application. Additional justification for this conclusion will be included in the next revision of AMR ANL-XCS-ME-000001, Design Analysis for the Ex-Container Components, to be completed prior to LA".

2.3 STATUS OF AGREEMENT

Prior to the NRC/DOE Technical Exchange and Management meeting on CLST KTI in September 2000, Subissues 1, 2, 3, 4, and 6 were considered open. At the conclusion of the meeting, these subissues were designated as "closed pending," with the DOE providing additional information on various technical issues. NRC staff and DOE staff have discussed subsequently the work covered by the various CLST KTI agreement items, including this agreement item. The DOE proposed an approach to satisfy the intent of the agreements, and prioritized the work related to the KTI agreement items using a risk-informed approach. The approach was presented to the NRC during the Technical Exchange and Management Meeting on April 15 and 16, 2002 (DOE/NRC 2002). At this meeting, the DOE proposed submitting information that would enable closing a number of agreement items in fiscal year 2002. However, this agreement item CLST 2.03 was scheduled for delivery to the NRC during the fiscal year 2003-2004 time frame. The work for this agreement item is now complete, and is able to be submitted ahead of schedule.

3. TECHNICAL BASIS FOR THE DOE PROPOSED RESOLUTION

3.1 PURPOSE

As mentioned earlier, the purpose of this enclosure is to show that the use of the traditional strength-of-materials approach to the drip shield design is bounding and appropriate when compared to the fracture mechanics approach. In addition, a similar analysis is provided for the waste package material, Alloy C-22. The failure assessment diagrams for the two materials at issue: Ti-7 and Alloy C-22 are developed and discussed.

3.2 METHOD

A closed-form solution (Anderson 1995, BSC 2002) for determination of the failure characteristics of brittle and ductile materials is used to assess the failure mechanisms of Ti-7 and Alloy C-22. A quasi-static solution for failure assessment is obtained for both materials. This approach considers three different closed-form solutions: compact specimen, single-edge notched bend specimen, and single-edge notched tension specimen. The specimens characterize both the membrane stresses and bending stresses. The combination of these stresses can be used to describe stress contours in a structure. Hence the three specimen geometries represent the loading conditions and the ensuing stress profiles in plate and shell materials resulting from a design basis event of a rockfall onto a drip shield or a waste package. The results of the calculations on these specimens demonstrate that the strength-of-materials approach (Tresca criterion) is appropriate for the design of drip shield and waste package.

The calculations are developed using failure assessment diagrams (FADs). FADs are used to assess the material behavior at failure and to ascertain whether the material experiences a brittle fracture, ductile collapse, or a combination of both. The criterion for the determination of which design approach is bounding depends upon the material failure mode. If the failure mode of these two materials is dominated by the ductile collapse, then the use of the traditional strength-of-materials approach for the failure determination of the drip shield and waste package designs is bounding and appropriate when compared to the fracture mechanics approach.

After the CLST KTI agreement items were instituted, the drip shield design was modified to incorporate additional load resistance capability for the drip shield. This design uses Ti-24 material rib stiffeners. The new design is able to withstand large size rock fall without failure of the drip shield. The evaluation presented here does not specifically address the failure aspects of the Ti-24 material. It is expected that the failure behavior of Ti-24 will be similar to that of Ti-7 based on the mechanical properties of titanium materials. It should also be noted that the Ti-24 material is not exposed to the drip fluid from the unsaturated zone and stress corrosion cracking of the material is not significant.

The analysis presented here uses base material properties. Weldment and environmental effects on the materials failure mechanisms will continue to be evaluated as part of our materials testing and modeling efforts. Failure analyses and criteria will be appropriately modified if the results of these efforts show these changes to be appropriate.

3.3 DESIGN METHODOLOGY ASSESSMENT

An impact load on the drip shield or the waste package may occur due to rockfall. Such dynamic loads might induce rapid crack propagation in brittle materials and might result in ductile collapse in ductile materials, or might result in any combination of these two extreme cases. This section first discusses the two basic design approaches used in solid mechanics. For completeness, additional aspects of dynamic fracture mechanics are described that are not considered in quasi-static fracture mechanics evaluation.

3.3.1 COMPARISON OF TWO DESIGN APPROACHES

There are two basic design approaches in solid mechanics: the traditional strength-of-materials approach and the fracture mechanics approach. The former involves a comparison of the applied stress with a design criterion, which is usually based on the material tensile strength. The latter contains a three-way comparison between the applied stress, flaw size, and the material toughness. Any two of these parameters can be fixed to determine the third one, which is then compared to an allowable value for the design.

In order to design a structure, the determination of the mode of failure is imperative. The failure of structures is governed by the behavior of the specific material used in the design, under prescribed loading conditions. An overloading of a brittle material results in fractures, whereas overloading of a highly ductile material causes a plastic collapse. For the materials that fall between the two characteristics, the point of failure may be reached by the combination of both fracture and collapse.

The expected failure mode of a specific material is determined by developing a FAD and plotting the failure path on the FAD. The FAD is developed using the following equation:

$$K_r = S_r \left[\frac{8}{T^2} \ln \sec\left(\frac{T}{2} S_r \right) \right]^{-1/2}$$ (Page 475, Anderson 1995)

where:

K_r = stress intensity ratio = K_I / K_{Ic}
S_r = stress ratio = σ / σ_c
K_I = stress intensity
K_{Ic} = fracture toughness
σ = applied stress
The work hardening of materials can be taken into account by using an average of yield and tensile strength:
σ_c = collapse stress = σ_{flow} = flow stress = (yield strength + true ultimate strength) / 2

A point on the FAD is defined by two parameters: the stress intensity ratio and the stress ratio. Any point that falls inside the curve defined by the above equation indicates that there will be no failure. However, any point outside the subject region indicates a failure.

A quasi-static solution for failure assessment has been performed for both Ti-7 and Alloy C-22. The analysis was performed for: compact specimen, single-edge notched bend specimen, and single-edge notched tension specimen geometries.

The point of possible failure is determined by plotting a line extending from origin to the failure curve, with an angle measured from horizontal. The slope of the line is defined by the ratio of the stress intensity ratio to the stress ratio. A critical value of this angle is observed on the failure curve at the point where the curve starts to take an asymptotic approach to the axis of the stress ratio (Anderson 1995). This angle is calculated as 31°. Hence, angles less than 31° are indicative of a plastic collapse. Figures 1 through 3 show the FADs for Ti-7; Figures 4 through 6 show the FADs for Alloy C-22. Each FAD includes a failure curve and two separate lines. The dashed line and the dotted line indicate the solution for the plane stress and the plane strain cases, respectively. The dash-dotted lines in Figures 1-6 indicate the 31° line. The plane stress and plane strain cases provide the lower and upper bound respectively, for the real three-dimensional problem. Additional details of the analysis is provided in BSC (2002).

The purpose of this evaluation is to determine the failure mode (i.e., whether the material behavior is brittle or ductile). If the lines of the plane stress and plane strain have a slope that is close to the vertical, then the material shows a brittle behavior, and a fracture occurs. On the other hand, if the lines extend into the region of failure with a slope closer to the horizontal (less than 31°), then the material is said to be ductile and the failure occurs by plastic collapse. The specific structural behavior of both Ti-7 and Alloy C-22 under increased loading is determined by the use of FADs; the results are discussed in Section 3.3.3.

3.3.2 ROCKFALL IMPACT ON FRACTURE

Falling rocks provide a dynamic load on the drip shield. This may result in a fracture or a material yielding phenomenon. For dynamic fracture conditions to prevail over a quasi-static fracture, three aspects need to be assessed:

- **Inertia effects**–Inertia effects are important if there is potential for a rapid crack growth. Rapid crack growth does not occur in highly ductile materials such as Alloy C-22, or in moderately ductile materials such as Ti-7 at temperatures and strain rates that are of interest in this study. It is known that dynamically loaded materials, in general, show two different phases in their time-history response diagrams. The first phase is the short-term transitional period where inertia effects, such as kinetic energy, dominate prior to the transition time. However, the deformation energy dominates at times significantly larger than the transition time, which is also called the long-term response. For a three-point bend specimen, a quasi-static approach can be used as long as the fracture occurs at times longer than the transition time. This requirement is relatively easy to meet in impact tests on ductile materials. Thus, inertia effects are eliminated for the materials considered in this study.

- **Reflected stress waves**–Quasi-static formulations of fracture mechanics do not include the effects of discrete stress waves; therefore, this formulation is only valid after stress waves have traversed the width of the specimen several times. The calculations indicate that the elastic stress waves will travel 120 times and 83 times through the thickness of

Ti-7 and Alloy C-22 shells, respectively, before the transition time is reached from inertial effect dominance to strain energy dominance. Hence, the effect of reflected waves could also be eliminated for the purpose of this analysis; a quasi-static approach is appropriate.

- **Strain rate effect**–The fracture behavior of ductile metals is primarily strain controlled. Therefore, the fracture toughness of these metals, such as Ti-7 and Alloy C-22, shows a tendency to increase at high loading rates because more energy is required to reach a given strain value. Furthermore, most metals are not sensitive to moderate variations in strain rate near ambient temperature. Hence, the effect of strain rate is considered to be small for the materials of concern in this study.

Regardless of the three complicating aspects stated above, this calculation considers the effect of strain hardening. When strain hardening is taken into account, the shape of the FAD changes such that the safe region for the design increases along the axis of the stress ratio. A linear formulation approach to the problem is conservative in this case because a shell made from a strain-hardened material can withstand greater stresses. Therefore, the FAD used in this analysis is slightly conservative and appropriate for the design.

3.3.3 RESULTS

The results of the calculation are provided in Figures 1 through 6. These figures depict the FADs for both Ti-7 and Alloy C-22, which were used in determining the drip shield and the waste package material failure characteristics. In these diagrams, the horizontal axis represents the stress ratio; the vertical axis represents the stress intensity ratio. The solid curve indicates the threshold for failure, which encloses the region of safety. The point of possible failure is determined by plotting a line extending from origin to the failure curve, with an angle measured from horizontal. A critical value of the angle between this line and the horizontal is 31° (indicated by dash-dotted lines). Any angle less than 31° are demonstrated by calculation to indicate a ductile collapse. Figures 1 through 3 (Ti-7) and Figures 4 through 6 (Alloy C-22) indicate the range of possible failure between the plane stress and plane strain cases, which are represented by straight lines. These two cases provide lower and upper bounds for the problem; the real solution for a three-dimensional case lies between them.

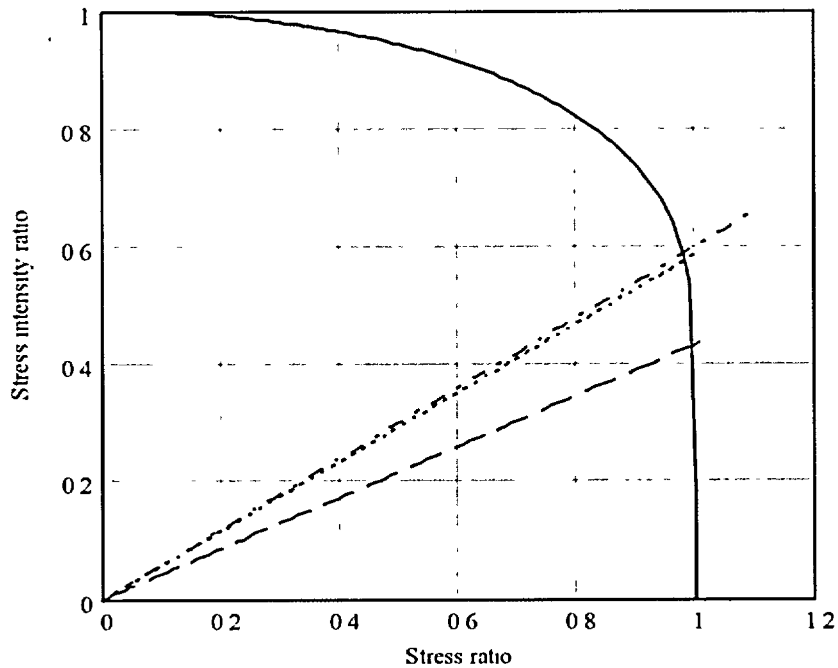

Figure 1. Failure Assessment Diagram for Ti-7 (compact specimen)

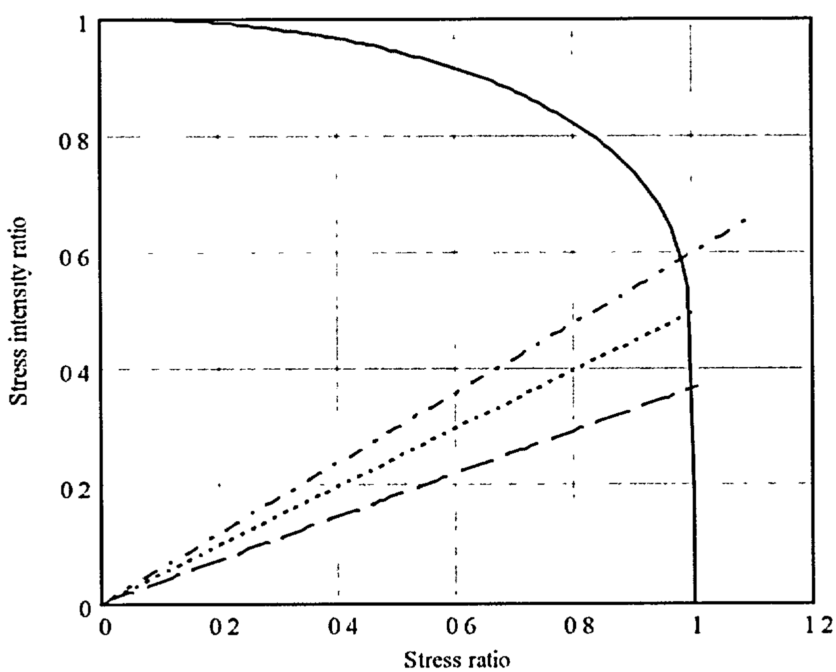

Figure 2. Failure Assessment Diagram for Ti-7 (SENB specimen)

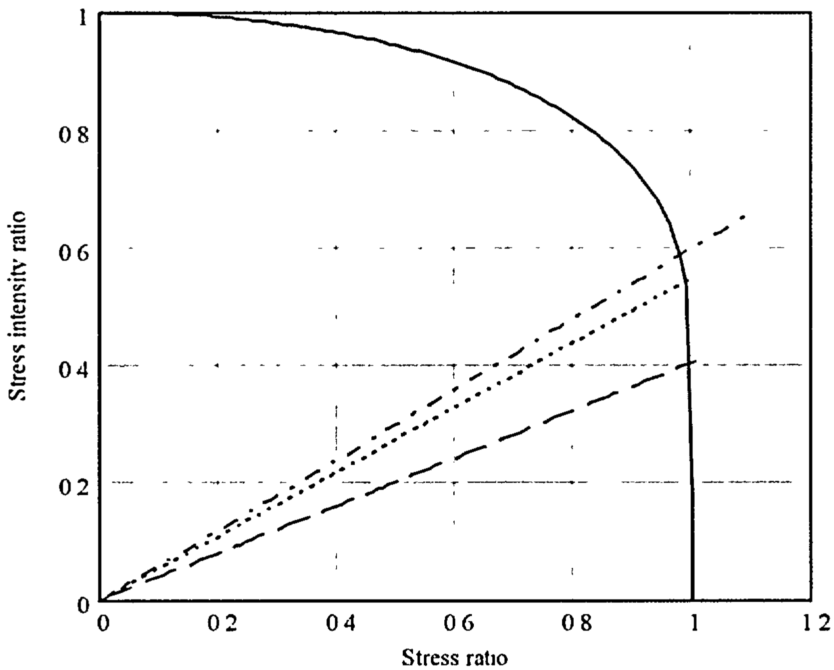

Figure 3. Failure Assessment Diagram for Ti-7 (SENT specimen)

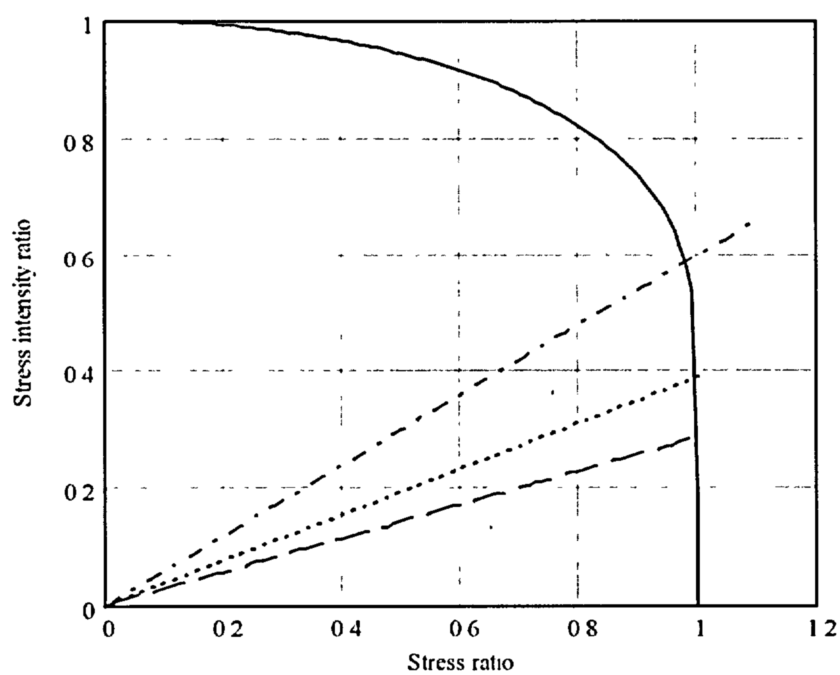

Figure 4. Failure Assessment Diagram for Alloy C-22 (compact specimen)

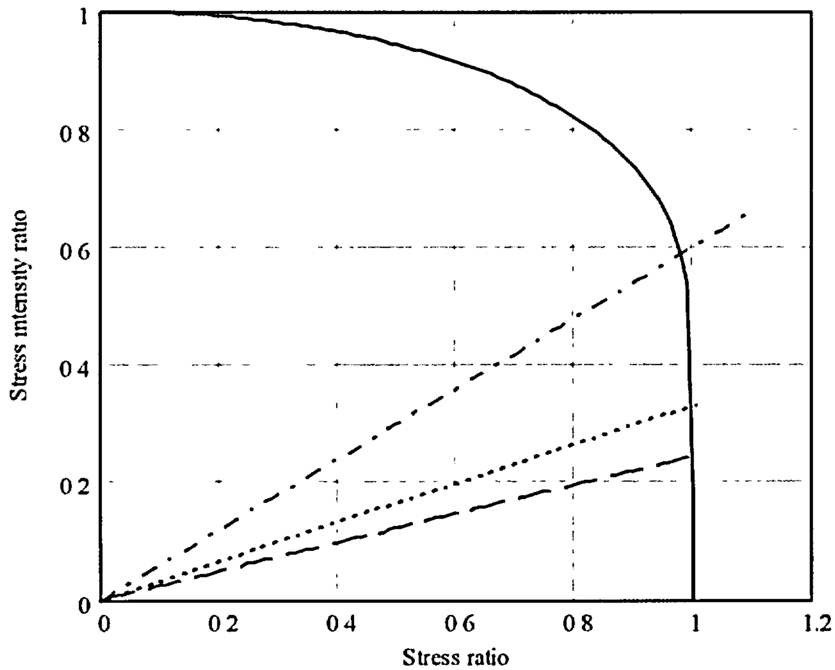

Figure 5. Failure Assessment Diagram for Alloy C-22 (SENB specimen)

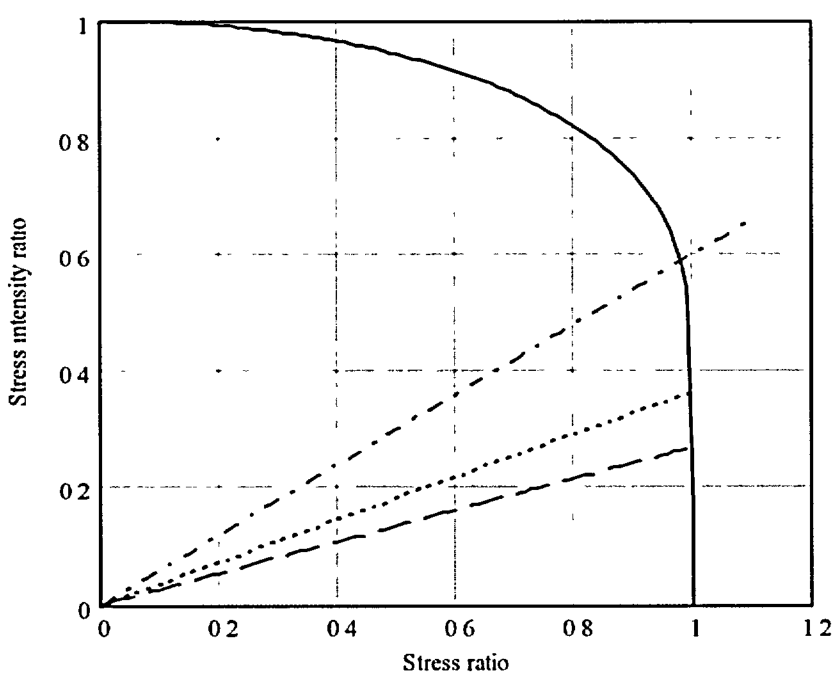

Figure 6. Failure Assessment Diagram for Alloy C-22 (SENT specimen)

3.3.4 CONCLUSIONS

The FADs of both Ti-7 and Alloy C-22 (Figures 1 through 6) indicate that the angles of all straight lines for both the plane stress and the plane strain cases are less than 31°. Therefore, any failure due to excessive loading is dominated by ductile collapse. This conclusion was reached by consideration of the fact that the failure lines cross the failure curve within a range of the limit angle (0° to 31°), which represents a ductile material behavior under external loading (FAD curve asymptotically approaches the plastic collapse limit). As noted, the failure mode is dominated by the ductile collapse. It is concluded that the use of the traditional strength-of-materials approach for the failure determination (such as the Tresca criterion) due to mechanical loading of the drip shield and the waste package designs is bounding. It is, therefore, appropriate to use the strength-of-materials approach used in American Society of Mechanical Engineers codes when compared to the fracture mechanics approach.

4. REFERENCES

Anderson, T. L. 1995. *Fracture Mechanics, Fundamentals and Applications*, 2nd Edition. Boca Raton, Florida. CRC Press. TIC: 246278.

Brownstein, A. B., to Reamer, C. W. 1999. Agreement Between DOE/OCRWM and NRC/NMSS Regarding Prelicensing Interactions.

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