Development of a Brittle Fracture Acceptance Criterion for the International Atomic Energy Agency (IAEA)*

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Introduction

Radioactive material (RAM) shipments are increasing in importance because of heightened level of awareness by the general public. Public scrutiny of RAM shipments demands that meticulous attention be given to compliance to all rules and regulations that may apply to a specific payload and shipment. The appearance of any impropriety, or incompleteness in meeting both the letter and the spirit of the rules and regulations must be avoided if public acceptance is to be gained. Regulators that certify transport casks also require exacting verification of compliance with all pertinent rules and regulations. At times, a particular regulator may require demonstration of package integrity above and beyond the regulatory requirements to assure that the transport package is safe.

Given the volume of shipments crossing international boundaries, the plethora of rules and regulations that a transport package must comply with, and the certification philosophy of individual regulators, it is imperative that uniform, consensus regulations be developed and adopted to assure that RAM transport operations can continue in an efficient and safe manner. This philosophy is embodied in the International Atomic Energy Agency (IAEA) regulations in the form of the Type B(U) certification. The "U" stands for unilateral certification. This certification is given by the competent authority in the country of origin. Separate transport certification from each country that a particular cask may enter is not required since the Type B(U) certification is a verification that the cask has met all IAEA rules and regulations. This process obviates the need for redundant (and expensive) certification from each country that a cask is transported through during a RAM shipment.

Although the Type B(U) certification is designed to allow transport of RAM materials in certified casks across international boundaries of IAEA signatory countries, individual competent authorities may still deny entry due to misgivings about the integrity of a particular cask. Such misgivings may arise from gaps in the IAEA regulations, or may be due to differences in the level of risk accepted by separate competent authorities. The methods by which competent authorities evaluate cask designs for susceptibility to brittle fracture of the containment boundary provides a relevant example in which Type B(U) certification is not uniformly applied or accepted. The existing guidance in the IAEA, as provided for in Appendix IX of Safety Series #37, is limited and dated. Several nations involved in the transport of RAM have individually developed criteria to meet specific needs. However, the lack of an international consensus criterion limits the applicability of these criteria.

An effort is underway to develop a consensus brittle fracture evaluation criterion that would have international technical consensus and that would be adopted into the IAEA Safety Series. This criterion would provide a clear and consistent approach to evaluating the potential for brittle fracture of a wide range of structural materials for cask construction.

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

The Issue

New candidate materials are being proposed for the construction of the structural components of RAM transport casks. Candidate materials include ferritic steel, ductile iron, borated stainless steel, titanium, and depleted uranium. The motivations for proposing new materials over more traditional metals such as austenitic stainless steel include lower cost and greater ease of fabrication. The main structural issue associated with these materials is that they may, under certain combinations of mechanical and environmental loading, fail in a brittle fashion. Clearly, this is not acceptable for a RAM transport cask. Design criteria must be established that assure the cask owner, the regulator, and the public that brittle fracture is not a possibility with a particular cask material and design.

Existing brittle fracture criteria in general, cannot be applied to a wide range of structural materials and do not enjoy international consensus. As an example, the brittle fracture criteria which have been proposed in the U. S. for ferritic steels (U. S. NRC Guide, 1991) cannot be extended to the full range of structural materials and are not accepted internationally. These U.S. criteria are empirically based and are not directly associated with fundamental (inherent) materials properties. Their use is suitable only for a restricted range of composition and thickness of ferritic steels; the margin of safety against brittle fracture cannot be quantified by this approach. Such technical limitations (within individual countries) coupled with country-to-country variations, underscore the need to develop a brittle fracture criterion through an international consensus standards body. Given the advancements in fracture mechanics analysis in recent years, such a criterion can be written that will be applicable to a wide range of structural materials. It is most appropriate to write this criterion under the aegis of the IAEA in order to achieve international technical consensus.

IAEA Charter

A proposal was submitted by the U.S. Department of Transportation (DOT) to the IAEA in 1989 to develop a brittle fracture acceptance criterion. The IAEA Continuous Review Committee officially responded through action TC-405.3, which recommended that a Consultant's Services Meeting be convened to expand IAEA regulations to include brittle fracture evaluation criteria. Action TC-405.3 provided five specific instructions:

1. Review the paper by Sorenson, et al.; "A Proposal for an International Brittle Fracture Acceptance Criterion for Nuclear Material Transport Cask Applications" (Sorenson et al. 1989).
2. Consider all packaging materials with "brittle" characteristics.
3. Address issues of "catastrophic flaw, failure prediction and NDT methods for significant flaws."
4. Prepare proposed advisory material for inclusion in Safety Series #37.
5. Submit a Consultant's Report to the Agency.

These recommendations were forwarded to the Standing Advisory Group on the Safe Transport of Radioactive Materials (SAGSTRAM) for implementation. At its December 1990 meeting, SAGSTRAM voted to convene a group of international experts for a Consultant's Services Meeting (CSM) to address the five issues of TC-405.3.

The nine delegates comprising the Consultant's Services Meeting (CSM) represented transportation and fracture mechanics experts from IAEA-member countries France (L. Tanguy and D. Moulin), Germany (K. Wieser), Japan (N. Urabe and C. Ito), the Confederation of Independent States (V. Ershov), the United Kingdom (T. Webster), and the United States (R. Nickell and K. Sorenson).

The CSM has met two times: Oct 9-11, 1991 and April 1-3, 1992. The focus of these meetings has been to revise Appendix IX of Safety Series #37 (Appendix IX provides guidance on brittle fracture evaluation). Technical consensus has been achieved using a fracture mechanics methodology. An IAEA Technical Document (TECDEC) has also been written by the delegates that provides technical justification for the positions adopted in revised Appendix IX.

Brittle Fracture Evaluation Criteria

The basis for the brittle fracture evaluation criterion in revised Appendix IX is linear-elastic fracture mechanics (LEFM). The fundamental equation that defines LEFM is:

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

where,

K_I = stress intensity factor (units: MPa $\sqrt{m}$)
C = geometric constant
σ = maximum nominal tensile stress (units: MPa)
a = depth of an existing flaw (units: m)

Further, in order to prevent crack initiation (or extension) from the existing flaw:

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

where,

K_{Ic} = fracture toughness material property (units: MPa $\sqrt{m}$).

Equation 1 computes the stress intensity factor that results from mechanical loads at the location of an existing flaw. Equation 2 ensures that if the applied stress intensity factor is less than the material's fracture toughness, that brittle fracture will not occur. Crack initiation and/or brittle fracture become imminent when a flaw reaches a critical size for a specific cask design, material, and loading. Combining Equations 1 and 2 allows the critical flaw size (a_{cr}) to be estimated.

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

Applying Equation 1 to a transportation cask requires the calculation of stress intensity for a specific cask design subjected to regulatory loading at the location of an existing flaw (e.g., slag inclusion, porosity, cold shut, etc.). For conservatism of design, an existing flaw is assumed to be at the location of highest stress and in the most damaging orientation. Application of LEFM through Equation 1 may further require that a nondestructive examination (NDE) of the cask be performed to assure that all flaws are less than the critical flaw size calculated in Equation 3 (in some cases however, the critical flaw size is so large that requirements concerning NDE may be greatly relaxed).

Independent mechanical testing is generally required in order to determine that the fracture toughness of the structural component is greater than the applied stress intensity (Equation 2). Therefore, it can be seen that the LEFM methodology involves a combination of engineering analysis, cask inspection and materials testing. Results of the evaluation are specific to the cask geometry, the loading criteria, and the structural material. A full LEFM approach allows the cask designer the latitude to appropriately adjust the design parameters (e.g., applied stress, allowed flaw size, material fracture toughness) to maintain the relationship required by Equation 2. Specifically, abnormally high material properties need not required to compensate for unrealistic expectations for applied stresses or flaw dimensions.

Application of LEFM in Appendix IX

The criterion in revised Appendix IX allows for three approaches to satisfying Equation 2. These approaches are based on different methods for determining the value of K_{Ic} to be used in Equation 2. Approaches 1 through 3 sequentially increase the conservatism of the value of fracture toughness that is used (in Equation 2), as the complexity and requirements associated with the direct determination of the material's fracture toughness decrease.

K_{Ic}, as shown in Equations 2 and 3, is the fracture toughness value that represents the linear-elastic fracture behavior of a material tested at a static loading rate. For many cask applications, the structural material will behave in an elastic-plastic fashion. This may require the measurement of an elastic-plastic fracture toughness parameter, such as

J, which can, under certain circumstances (Salzbrenner et al. 1990) be used to determine an equivalent K_{Ic} value. In addition, during accident scenarios, cask loading conditions are dynamic, not static. The dynamic fracture toughness may thus be required (and is designated as K_{Id} or J_{Id}). The full range of conditions results in four test measurements which could be required to define a material's fracture toughness; K_{Ic},.K_{Id}, J_{Ic}, and J_{Id}. Depending on which of the three approaches is selected for evaluating brittle fracture, one or more of these measurements may be required. To avoid confusion, revised Appendix IX refers to all four of these parameters as $K_{I(material)}$. The selection of structural material and the approach in Appendix IX will dictate the type of fracture toughness testing that will be required.

Approach 1

Approach 1 requires that the actual fracture toughness of the structural material be determined for the most severe loading and environmental conditions. These conditions are defined by regulatory requirements that a cask must demonstrate an ability to withstand specified (hypothetical) accident scenarios. This generally requires that the fracture toughness be determined for elevated loading rates at –40°C. This value of fracture toughness is then chosen for $K_{I(material)}$ and is compared with the maximum applied stress intensity for a specific cask design/material/flaw (see Equation 2). The ratio of the fracture toughness to the (maximum) applied stress intensity allows a brittle fracture safety margin to be quantified.

Approach 1 demands the least conservatism in terms of selecting the fracture toughness behavior to be used in Equation 2. The rigorously determined fracture toughness is measured and applied in Equation 2. Since the relevant fracture toughness is directly determined, there is no need to add indirect levels of conservatism by assuming a lower-than-actual fracture toughness for the material. A direct control over the level of conservatism is afforded through application of Equations 1 through 3. The appropriate safety margin (level of conservatism) against brittle fracture that is agreed upon by the competent authorities and designers/manufacturers can then be explicitly demonstrated. Approach 1, in which the most rigorously determined fracture toughness is directly determined and compared to the (maximum) applied stress intensity, allows the most precise determination of the actual margin of safety. A cask designer can employ changes in material, design (to control applied stress), and NDE (to limit the maximum flaw size) to meet a specified margin of safety.

Approach 1 is (potentially) the least conservative of the three approaches in terms of the material's fracture toughness which must be used in calculations, but this is compensated for with an increase in the requirements for determining the fracture toughness. As the requirements and confidence in the fracture toughness test measurements increase, the absolute level of conservatism in choosing $K_{I(material)}$ can be reduced. For Approach 1, the fracture toughness parameter must be measured for the specific structural material at the most severe design temperature and loading rate. These test data must be demonstrated as being statistically significant, and must be proven to be representative of production material (for all serially produced casks).

Approach 2

The $K_{I(material)}$ that is allowed for Approach 2 is the lowest bound value from a statistically significant set of data for a specific class of material. These data may, for example, be comprised of static, dynamic, and fracture arrest measurements as a function of temperature. The most important characteristic of the data is that they must be demonstrated as enveloping the fracture behavior for the material of interest. The data set may be pre- existing for a well-characterized material or may need to be generated (through data gathered from manufacturers, and the literature and/or from direct measurement) by the cask designer. The $K_{I(materials)}$ value selected must be the lowest-bound toughness value at the -40°C design temperature. The use of this $K_{I(material)}$ over the direct measurement in Approach 1 will normally yield a lower, more conservative, estimate of the fracture toughness of the material.

The "design margin of safety" against brittle fracture remains defined as the $K_{I(material)}$ divided by the (maximum) applied stress intensity (from Equation 1). The "actual margin of safety" (as opposed to the "design margin of safety") cannot be determined as accurately (as for Approach 1) since there is increased uncertainty in the real behavior of the material (i.e., its real fracture toughness may fall in a range from the lower-bound to values significantly higher). The difference between the lowest bound fracture toughness and the real fracture toughness adds to the "actual margin of safety," but this increase cannot be quantified nor credited to the design. The designer must meet the requisite "design margin of safety" by controlling the applied stress intensity (by limiting the applied stress through design considerations, and/or limiting the flaw sizes through NDE requirements) to remain below a specified fraction of the lowest bound fracture toughness (at -40°C). The designer is not allowed credit (in this approach) for improved material behavior brought about by advances in fabrication, processing, etc. The benefit of Approach 2 lies in the (potentially) reduced requirements (compared to Approach 1) for fracture toughness testing and qualification of individual heats of material. This may result in significant overall cost savings, particularly when the value of lower bound $K_{I(material)}$ does not result in excessively restrictive requirements concerning NDE or applied stress reduction during accidents.

Approach 3

The value of fracture toughness that is used in Approach 3 is the lower shelf value that represents full linear-elastic brittle behavior. Such a value is generally determined at a temperature below the lowest design temperature of -40°C. This is shown schematically in Figure 1. Using this lower shelf value for $K_{I(material)}$ incorporates the most restrictive assumptions concerning the resistance of the material to brittle fracture. Since the conservatism in selecting the $K_{I(material)}$ is greatest for this approach, the "actual margin of safety" is generally higher (as compared to Approaches 1 and 2). However the increase cannot be quantified and cannot be applied to the "design margin of safety" that must be satisfied to demonstrate the acceptability of a specific cask.

The primary incentive for using Approach 3 for the designer is that the test procedure for measuring a lower-shelf fracture toughness value is straightforward. The ease of establishing the value for $K_{I(material)}$ allows less cost to be directed towards material testing and qualification. This option can be very desirable for those cases where the applied stress intensity is small with respect to even the most conservative value for $K_{I(material)}$. Approach 3 is appropriate when the designer finds that an acceptable "design margin of safety" against brittle fracture can be demonstrated without creating undue difficulties in design (to lower applied stresses) or in inspection (for NDE requirements): credit for a higher level of fracture toughness inherent in Approaches 1 and 2 is not required to make the design viable.

Figure 1 shows the relative differences in the selection of $K_{I(materials)}$ using the three different approaches. The curves shown represent an example material response. Testing of specific materials will yield different curves.

Factor of Safety

As discussed above, the "design factor of safety" is the ratio of the $K_{I(material)}$ to the (maximum) applied stress intensity, ($K_{I(applied)}$). This overall factor of safety is achieved through an integrated process of material selection, design, and inspection. This allows the designer to manage three parameters that directly affect the "design factor of safety": $K_{I(material)}$, σ, and a. Selection of different materials (and/or whether Approach 1, 2, or 3 is chosen) gives the designer control over the value of $K_{I(material)}$. The overall design (e.g., section thicknesses, shape, impact limiters,...) allows the designer to control the level of applied stress. The inspection process permits the designer to determine the size of flaws which will be allowed in the cask. The overall "design factor of safety" can thus be met by applying "individual safety factors" to one or more of these parameters. In order to maintain generality of the criterion, Appendix IX guidance suggests that the factors of safety be justified by the cask designer and agreed to by the regulator.

Status

The TECDOC is nearly complete with the revised Appendix IX to Safety Series #37 included as a chapter. The TECDOC provides the justification for the technical positions adopted in the revised Appendix IX. The IAEA Safety Series will not be revised until 1995. It is therefore the intent of the CSM to publish the TECDOC so that guidance is available until Appendix IX can be formally incorporated into Safety Series #37. Publication of the TECDOC is anticipated in early 1993.

Conclusion

The revised Appendix IX of Safety Series #37 satisfies the list of five criteria that SAGSTRAM established for the CSM. The revised Appendix IX provides a general evaluation criterion that has been adopted through a technical consensus process and that is applicable to a wide range of materials. It is recommended that the approach outlined in the revised Appendix IX be incorporated into member nation design rules to further solidify the Type B(U) certification process with regard to brittle fracture evaluation.

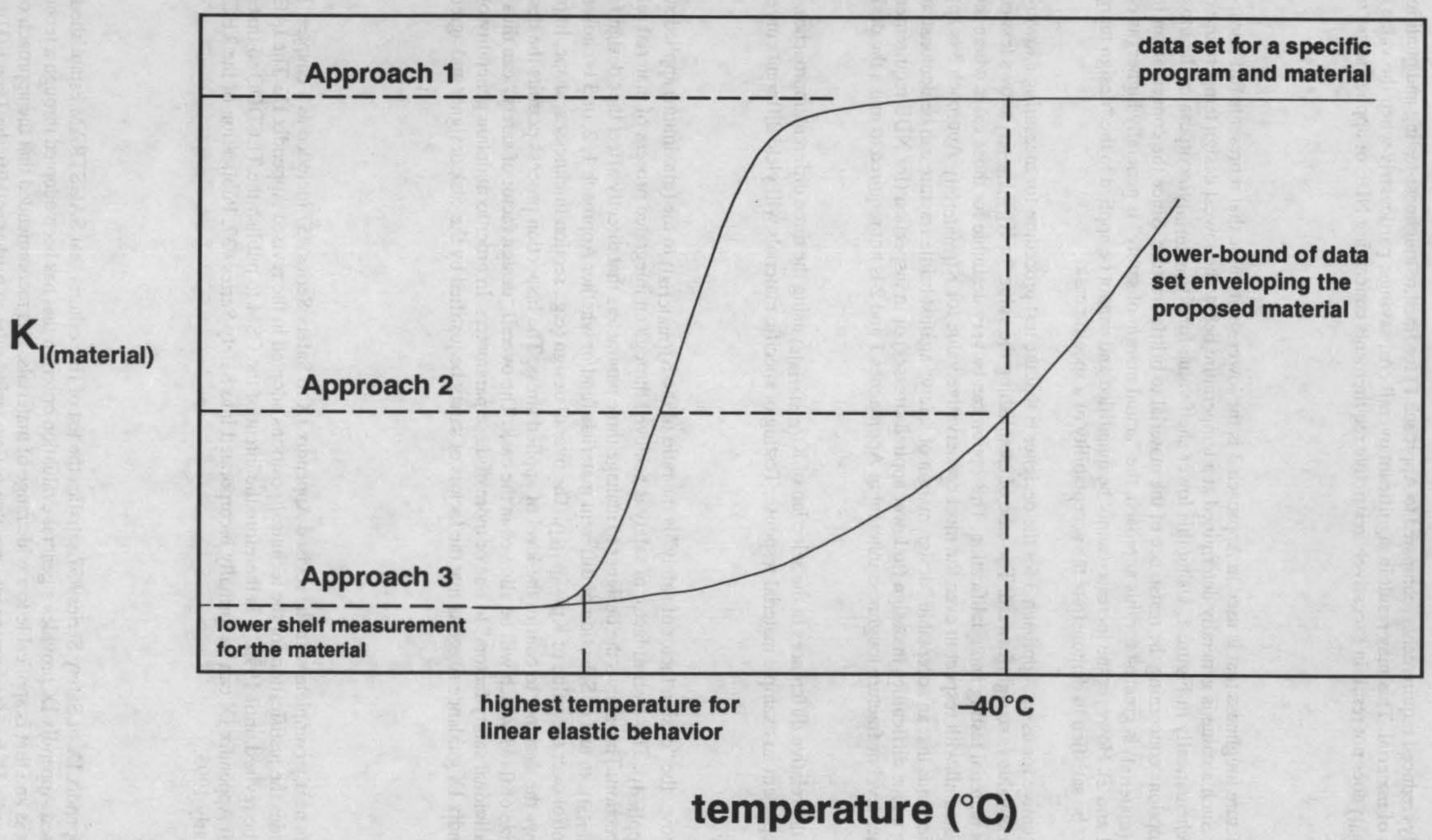

Figure 1. Schematic of the relative values allowed for $K_{I(material)}$ for Approaches 1, 2, or 3 for the IAEA revised Appendix IX of Safety Series #37.

References

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