DEVELOPING A BRITTLE FRACTURE ACCEPTANCE CRITERION FOR TRANSPORT CASKS FOR ADOPTION BY THE INTERNATIONAL ATOMIC ENERGY AGENCY (IAEA)*

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ABSTRACT

A significant effort has been underway in the international cask development community to write a brittle fracture acceptance criteria for structural components in nuclear material transportation casks. A proposal to develop such a criterion was formally introduced at PATRA '89 (1) and work has been underway to write a draft criterion for consideration by the International Atomic Energy Agency (IAEA).

The preliminary work is being performed by an Ad-Hoc group of engineers who have been active in ductile cast iron (DCI) research. The group is made up of representatives from Japan, France and West Germany, as well as the U.S. The draft criterion is being written early, at an unofficial capacity, in order to facilitate the review process when the draft criterion is submitted to the IAEA.

THE ISSUE

With increasing nuclear material transportation demands, new generation casks have included designs which propose the use of structural materials other than austenitic stainless steel. Motivation for using alternate materials include potentials for lower cost, easier fabrication, no welding and less weight (higher payload). Examples of candidate materials for structural components include ferritic steels and ductile cast iron (DCI) for the containment boundary and borated stainless steel for the basket.

The primary technical issue which separates these candidate materials from austenitic stainless steel is that they may, under certain combinations of mechanical and environmental loadings, fail in a brittle fracture mode. Design guidance and acceptance criteria for structural performance evaluated to brittle fracture standards are non-uniform and simply not applicable in many cases. Examples of U.S. criteria include a U.S. NRC draft regulatory guide [1] and ASME Sections III [2] and XI [3].

The NRC criterion is specific to ferritic steels only. The criterion places limits on the nil-ductility transition (NDT) temperature attained by NDT test measurements. The NRC criterion is material based. That is, reliance against brittle fracture is placed solely on a material property (NDT) which is statistically correlated to the material's ability to resist brittle fracture. No design latitude is allowed for mitigation of stresses using impact limiters or for limiting the amount of material inhomogeneity through the use of nondestructive examination (NDE) inspection methods. The result of this material-based criterion is a large conservatism that has the potential to exclude certain candidate materials which may be robust enough for this application.

By contrast, the ASME criteria is design-based in that the designer can limit applied stresses through the use of impact limiters and place strict limits on material inhomogeneity through NDE requirements. This allows a particular material to still meet the fracture toughness requirements with a somewhat lower margin of safety placed on the material properties. The ASME criteria allows a simplified qualification method for ferritic steels through the use of NDT testing because of the established correlation of NDT temperature to fracture toughness.

For both the ASME criteria and the NRC criterion, reliance on NDT measurements excludes materials other than ferritic steels for two basic reasons. First, the NDT/fracture toughness correlations for other materials have either not been established or have not been adopted by ASME. Second, the ASTM NDT test method [4] is specific to ferritic steels.

Brittle fracture evaluation also differs across national boundaries. This results in brittle fracture criteria development that is divergent among different countries, which implies that the "best" method for evaluating cask design for brittle fracture has not yet been established. The IAEA Safety Series 37, Appendix IX [5], discusses brittle fracture evaluation, but only in general terms and with little guidance.

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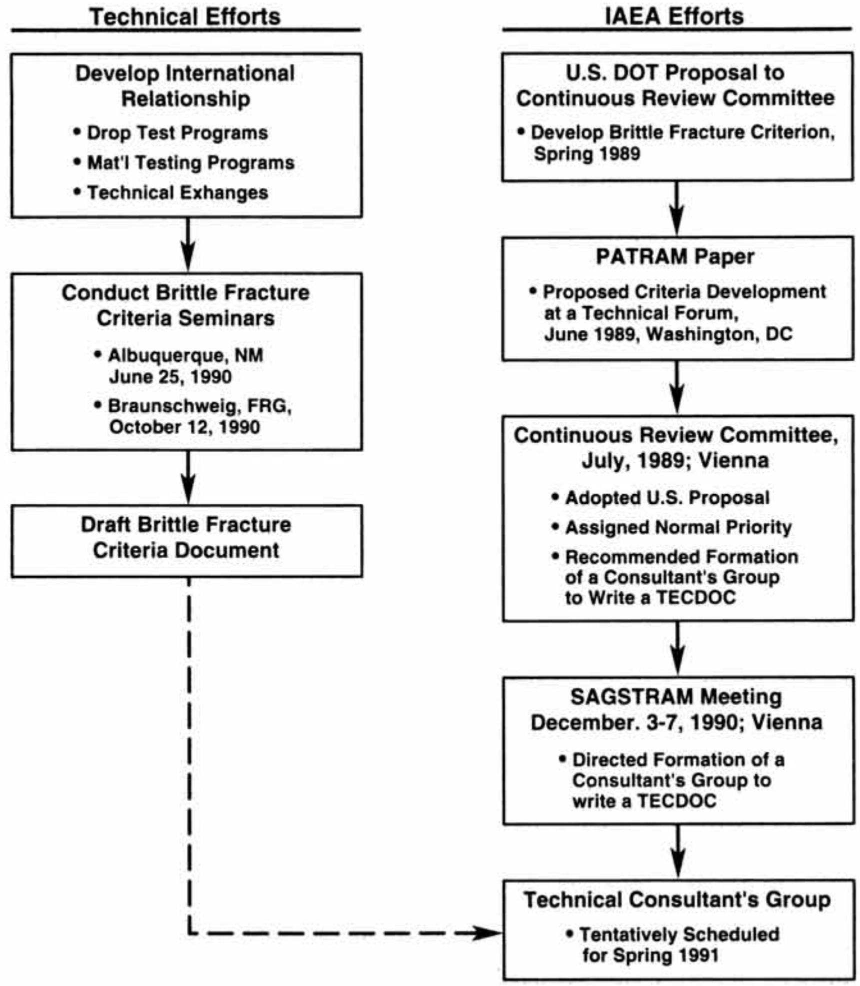

Fig. 1. Status of brittle fracture criterion development.

There is a clear need to develop a consensus criterion that will encompass a broad range of materials and provide a consistent method for evaluating candidate materials with respect to brittle fracture. Adopting such a criterion through the auspices of the IAEA has distinct advantages. An international consensus would provide assurance to regulators and the public that the most appropriate method is used, and countries developing packages using candidate materials could work with a single criterion without concern that another country is setting precedent using a different criterion.

The development of such a criterion has been in progress for two and one-half years. There are two major efforts which are being pursued in parallel. There is the technical effort to write a draft document and the formal effort to facilitate adoption of a criterion by the IAEA. These two efforts are being pursued in parallel in order to accelerate the adoption process. Figure 1 illustrates the basic components of these two efforts.

TECHNICAL APPROACH

As Fig. 1 illustrates, there has been a significant amount of work in recent years to qualify candidate materials for use in transport casks. Japan, France, the Federal Republic of Germany, England and the U.S. are examples of countries who have or have had active programs to qualify candidate materials.

Through technical exchanges associated with drop test programs, materials testing programs, and technical conferences, a consensus among the technical participants for evaluation of brittle fracture formed around the discipline of fracture mechanics. Although there are differences of opinion such as to where factors of safety should be placed, it is generally agreed that the design approach should be based on fracture mechanics.

The fundamental linear-elastic fracture mechanics equation is defined as;

$$K_I = C\sigma(\pi a)^{1/2} \quad \text{(Eq. 1)}$$

Where,

K_I = applied stress intensity (MPa-√m)

C = a constant that is function of flaw geometry

σ = nominal applied tensile stress (MPa)

a = depth of a pre-existing flaw or defect (m)

Further, in order to preclude brittle fracture;

$$K_I < K_{Ic} \quad \text{(Eq. 2)}$$

Where,

K_{Ic} = material fracture toughness (MPa-√m)

The critical flaw size, a_{cr} (depth of flaw at which brittle fracture is imminent), can easily be calculated from Eqs. (1) and (2);

$$a_{cr} = \frac{1}{C^2\pi}\left\{\frac{K_{Ic}}{\sigma}\right\}^2 \quad \text{(Eq. 3)}$$

This is a design-based approach that will allow the designer the flexibility to adjust the pertinent parameters (material fracture toughness, applied stress, and NDE detection capability) and still satisfy the conditions of Eq. (3). This approach can be applied to a wide range of materials in a consistent manner.

Given agreement among the technical members as to the basic approach, it was decided to informally draft, without any IAEA association, a brittle fracture acceptance criteria document. Knowing that the IAEA process was on-going, but that committee action may occur infrequently, it was felt that having a draft document for the IAEA committees to review at the appropriate time would facilitate the adoption process.

The forum for developing the draft document was two brittle fracture criteria seminars; one was held in Albuquerque, New Mexico on June 25, 1990 and the second was held in Braunschweig, FRG on October 12, 1990. Main discussions at these seminars centered on the appropriate application of safety factors and techniques for measuring K_{Ic}. The draft document was completed in the late fall of 1990 and is a compilation of input from technical experts representing Japan, France, FRG, Great Britain and the U.S. It is intended that this draft document be used as a resource for the IAEA Technical Consultant's Group when they draft the TECDOC, which will be the basis for the IAEA brittle fracture acceptance criteria.

It is important to note that the input for this draft document comes from a limited number of technical experts. The draft document does not constitute an official position by any particular country. It is felt however, that it does represent the position of a wide cross-section of international technical experts. Therefore, it should be a useful reference document for the IAEA Consultants Group.

IAEA EFFORTS

Formal efforts to develop the brittle fracture acceptance criteria began with the U.S. Department of Transportation (DOT) submitting a proposal for revising the IAEA Safety Series in the Spring of 1989. The proposal was submitted by the DOE to the DOT. The DOT accepted the DOE recommendation and forwarded it to the IAEA as a U.S. proposal.

Prior to formal acceptance of the U.S. proposal by the IAEA, a paper was presented at PATRAM '89 [6] in Washington D.C. in June, 1989. This paper outlined one possible approach to evaluating brittle fracture and suggested that development of a brittle fracture criterion be considered by the IAEA. PATRAM '89 provided a forum to suggest to the international technical community that such a criterion be developed through the IAEA.

In July, 1989, the Continuous Review Committee 405.3 met in Vienna. It accepted the U.S. proposal as a "normal" priority with attached recommendations. First, the development of this criterion should address the "brittle" characteristics of all packaging materials. Second, a Technical Committee (TC) should be convened to prepare a TECDOC (technical document) as guidance for Safety Series 37. Third, issues of "catastrophic" failure, failure prediction and NDE methods for significant flaws should be addressed. The Continuous Review Committee recommendation was forwarded to the SAGSTRAM (Standing Advisory Group for the Safe Transport of Radioactive Material) committee.

The SAGSTRAM committee met Dec. 3-7, 1990 to address the Continuous Review Committee recommendations. The recommendations were accepted by SAGSTRAM. SAGSTRAM will convene a group of experts nominated by member countries to serve on the Technical Committee that will write the TECDOC. This meeting is tentatively planned to occur in the Spring of 1991. The draft document discussed previously can be used as a reference for development of the TECDOC. Since a number of technical experts already agree with the approach in the draft document, development of a consensus TECDOC should be facilitated.

The criterion, once adopted by the IAEA, will likely replace the guidance given Appendix IX of Safety Series 37. Safety Series 37 is advisory material on how to meet the requirements of Safety Series 6 [7] and is the appropriate place to provide guidance on brittle fracture evaluation.

CONCLUSION

Development of an IAEA brittle fracture acceptance criterion will provide the radioactive material (RAM) transportation community with an effective, consistent method to evaluate brittle fracture for a wide range of materials. Further, by developing the criterion as a consensus document that has been reviewed and agreed to by the international technical community, it provides assurance to the cask designer, owner, regulator and the public that the best method was used to evaluate the cask for brittle fracture.

REFERENCES

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