A Proposal for an International Brittle Fracture Acceptance Criterion for Nuclear Material Transport Cask Applications*

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INTRODUCTION

The use, or proposed use, of materials other than stainless steel for structural components of transportation casks is becoming increasingly common. Examples of structural cask components which may be manufactured from alternate materials include the containment boundary as well as the internal spent fuel basket. Specific alternate materials include low alloy ferritic steels, titanium, depleted uranium, aluminum, borated stainless steel and ductile cast iron (DCI). The technical issue which separates these alternate materials from the austenitic stainless steels is that they can, under certain environmental and mechanical loading conditions in combination with a flaw, fail in a low-energy fracture mode at stresses below yield level. Cask designers and regulators are responsible for assuring that these cask components are designed such that low-energy fracture is precluded.

Current practices for qualifying these alternate materials vary between countries. In general, however, qualification is primarily design based and is linked to a linear-elastic fracture mechanics approach. Because of the performance-based history of cask development, many cask design organizations supplement fracture mechanics analysis with demonstration proof testing. The proof test becomes the actual acceptance criterion for a specific cask design/candidate material. From a practical standpoint, the implementation of the proof test and defining the criteria for a successful test is the area which has the largest amount of variability between different cask developers. Examples of issues which arise when evaluating drop tests include:

i. Should impact limiters be used? If so, should they be the same temperature as the cask metal temperature?
ii. Should a flaw be introduced into the cask wall as part of the drop test? If so, should the flaw be a sharp fatigue flaw, or mechanically machined or cut?
iii. What analytical method should be used to calculate the depth of the flaw for the drop test?
iv. Is flaw growth, resulting from the drop test, allowed?
v. What factor of safety should be applied to the design? Should the factor of safety be applied to the stresses, material properties, nondestructive examination, or a combination of the three?

In addition to the design-based approaches, the U.S. Nuclear Regulatory Commission (USNRC) has issued a draft regulatory guide, "Fracture Toughness Criteria for Ferritic Steel Shipping Containers with a Wall Thickness Greater Than 4 Inches (0.1m)" (1986), which gives brittle fracture acceptance criteria for ferritic steels with wall thicknesses greater than 100 mm (4 inches). This draft regulatory guide is material based, as opposed to design based, and imposes very severe requirements on the Nil-Ductility Transition (NDT) temperature of the steel. The NDT temperature for a particular ferritic steel is the temperature at which complete brittle fracture occurs in a specimen tested according to the ASTM E 208 test procedure. The NDT temperatures recommended in the draft regulatory guide are

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established on the premise that a through-wall propagating flaw will arrest at temperatures above -40 C. The specified NDT temperatures in the U.S. Nuclear Regulatory Commission's draft regulatory guide, "Fracture Toughness Criteria for Ferritic Steel Shipping Containers with a Wall Thickness Greater Than 4 Inches (0.1m)," (1986) provide an unquantified level of conservatism. The level of conservatism established by this approach avoids the practical issues raised above. The NDT criteria is however, severe to the point of excluding materials that may be robust enough to satisfactorily meet a fracture toughness design approach.

The acceptance approach which relies on the measurement of NDT temperatures has been developed specifically to apply to only one class of alloys--namely, ferritic steels. The NDT temperature is a materials characteristic, which by itself cannot be used directly in design calculations. Design must ultimately be based on fundamental, inherent materials properties, such as strength, fracture toughness, thermal conductivity, etc. In the case of ferritic steels, the conservative (or lower bound) relationship between NDT temperatures and fracture toughness has been developed to the point where measurement of the NDT temperature can be statistically correlated to the fracture toughness. The American Society of Mechanical Engineers Boiler and Pressure Vessel (ASME) Code employs these NDT temperature/fracture toughness relationships to allow a simplified qualification method, which directly applies only to ferritic steels. Methods for determining NDT temperatures for other classes of alloys do not, in general, exist. The concept of NDT behavior does not apply to all the candidate materials listed (e.g., aluminum and titanium alloys). It is also problematic that the existing procedure for NDT measurements can be directly applied to materials such as DCI which exhibit a ductile-brittle transition. The NDT test procedure involves the introduction of a brittle weld as the crack initiator. This has a dramatically different effect on the parent microstructure of DCI compared to its effect on ferritic steels. The relationship between fracture toughness and NDT temperature has not been established for any materials except fcr ferritic steels and should not be assumed to apply to other material classes such as DCI. The use of NDT temperature measurements as the primary method of assuring against brittle fracture thus will effectively exclude all metals except ferritic steels.

The principal reason for the variety of different methods which are being used to qualify candidate materials is that an internationally recognized brittle fracture acceptance criterion does not exist. Although the International Atomic Energy Agency (IAEA) provides drop test requirements for Type B transport containers, as described in International Safety Standards, Safety Series 6, "Regulations for the Safe Transport of Radioactive Material" (1987), it does not address the issue of brittle fracture. Although practical issues such as those discussed previously must be resolved, the primary focus should first be on establishing a fundamental design approach. Therefore, it is reasonable to propose that an international brittle fracture acceptance criterion be developed. The advantages to having such a criterion are clear:

i. The significant amount of research and development effort currently being expended on multiple approaches could be better focused on a single design methodology.
ii. The criterion could be formulated such that a wide class of materials could be addressed for all cask structural applications. Current U. S. practice limits evaluation to specific materials applied to specific cask functions (e.g., the U.S. Nuclear Regulatory Commission's draft regulatory guide, "Fracture Toughness Criteria for Ferritic Steel Shipping Containers with a Wall Thickness Greater Than 4 Inches (0.1m)," [1986] pertains to ferritic steels used in containment vessels).
iii. A unified technical approach provides assurance to the public that the best possible method for evaluating the cask has been applied.

The remainder of this paper will present a fundamental basis for a brittle fracture acceptance criterion, examine several existing criteria and propose examples for consideration as international brittle fracture acceptance criteria. The proposed criteria are intended to stimulate discussion in order to advance the development of a consensus approach.

BASIS FOR BRITTLE FRACTURE ACCEPTANCE CRITERIA

For material which can fail in a brittle manner, the fundamental equation which describes the structural behavior for a given stress state in the presence of a flaw is:

$$K_{app} = C\sigma\sqrt{\pi a} \tag{1}$$

where

K_{app} = applied stress intensity at the tip of a sharp flaw (MPA-m)

C = a constant which is a function of the flaw geometry

σ = maximum nominal stress (MPa)

a = depth of an existing flaw (m)

When the applied stress intensity exceeds the material fracture toughness, K_{Ic}, crack initiation is predicted. K_{Ic} is a measurable materials property which specifically quantifies the fracture sensitivity. If K_{Ic} is substituted for K_{app} in Eq. (1), the equation becomes:

$$a = \frac{1}{C^2 \pi} \left\{ \frac{K_{Ic}}{\sigma} \right\}^2 \tag{2}$$

From the equations, it can be seen that the material response to a given loading is a function of design. Specifically, structural response is related to the pertinent material property (fracture toughness, K_{Ic}), the level of applied stress (σ), and the flaw characteristics (quantified by nondestructive examination (NDE) techniques). Brittle fracture acceptance criteria can then be based on one or more of these parameters. As fewer of the parameters are used for a given acceptance criterion, the factor of safety (or level of conservatism) must increase. A method which involves all parameters is a design-based criterion and provides considerable flexibility in satisfying Eq. (1).

In contrast, a method which is based on a single parameter, such as the material's toughness, requires no knowledge of the state of stress or flaws. In order to cover all the possible combinations of stress and flaw characteristics, the allowed toughness must be extremely conservative. Thus, this type of criterion may be so restrictive that many materials are excluded which are robust enough to satisfy a design-based criterion (Eq.1).

EXAMPLES OF EXISTING BRITTLE FRACTURE ACCEPTANCE CRITERIA

Table 1 provides a comparison of three selected U. S. brittle fracture criteria. The first two have been incorporated in the ASME Codes, "Protection Against Nonductile Failure," Sec. III, Appendix G (1986) and "Analysis of Flaw Indications," Sec. XI Appendix A (1986) for nuclear power plant components. The third criterion is the previously mentioned USNRC draft regulatory guide "Fracture Toughness Criteria for Ferritic Steel Shipping Containers with a Wall Thickness Greater Than 4 Inches (0.1m)," (1986).

The first criterion shown, ASME Section III, Appendix G, is meant to be applied during the design of the component. The calculated stresses are combined with an assumed flaw size to determine the applied stress intensity (Eq. 1). The applied stress intensity, K_{app}, is then compared with an allowable fracture toughness determined from the K_{IR} curve. The K_{IR} curve is the lower bound of a data base of measured fracture toughness values (static, dynamic, and arrest) for four grades of ferritic steels and has been related to the NDT temperature. Thus, the determination of fracture toughness has been reduced to simple NDT temperature measurements. An explicit Factor of Safety (FOS) of 2 is applied to the calculated stresses. Implicit FOSs are also included by assuming a 1/4 t flaw (i.e., the flaw depth is 1/4 of the wall thickness) and selecting the allowable fracture toughness by using the K_{IR} curve as related to the NDT temperature.

The criterion for ASME Section XI, Appendix A, is also design based and is meant to be applied for actual flaws which are detected during in-service inspection. The allowable fracture toughness material value can be determined from the K_{IR} curve (i.e., NDT temperature measurements) or can be measured directly. The actual flaw size and location, along with design stresses, provide the information necessary to calculate the applied stress intensity. K_{app} must be less than the allowable fracture toughness.

The NRC approach is material based and limits the material NDT temperature to specified minimums, as a function of section wall thickness. The NDT temperatures are established using the assumption that a running crack initiated from a through-wall flaw at yield level stresses will arrest at temperatures above -40 C. The FOS is unquantified but is presumed to be very large because of the assumptions applied to the stress and flaw parameters.

The main differences between the two ASME methods are centered on the assignment of assumptions between the parameters in Eq. (1). Section III, Appendix G requires an explicit FOS on stresses, uses the K_{IR} curve, and assumes a 1/4t flaw. The Section XI, Appendix A approach allows for actual measurement of K_{Ic} and does not apply an explicit FOS on calculated stresses. The main difference between the ASME and NRC NDT approach is that the ASME implements a design method whereas the NRC places the entire burden for fracture resistance on the material.

The similarity between the three approaches is that they all relate fracture toughness to the material's NDT temperature. These approaches are therefore limited to ferritic steels.

Examples of international criteria are similar to the ASME approaches in that they relate material behavior to brittle fracture temperatures determined from NDT or Charpy tests. Representative criteria include: the British Standards Institute Pressure Vessel Code BS 5500, Appendix D, the French Pressure Vessel Code, Appendix ZG and the Japanese Code JEAC 4206. The French Code is novel in the respect that it allows for elastic-plastic analysis.

PROPOSED INTERNATIONAL BRITTLE FRACTURE ACCEPTANCE CRITERIA

Three proposed brittle fracture acceptance criteria are presented in this section. The proposed criteria are designed based and reference actual material behavior at -40 C. The basic approach for all three proposed criteria most closely follows an ASME Section XI, Appendix A evaluation. The criteria vary in the selection of the allowable fracture toughness. All three proposed criteria differ from the ASME approach in that the fracture toughness is not referenced to a NDT temperature. This permits broader applicability. All three criteria provide acceptable assurance against brittle fracture. However, the level of difficulty in implementing the criteria varies. As the level of conservatism increases, the difficulty of implementing the criterion decreases.

For illustration, DCI which meets the ASTM material specification A 874 is used. The yield stress is 200 MPa and the tensile strength is 300 MPa. For this example, the cask component is assumed to have a constant stress distribution across the wall (i.e., a pure membrane stress with no bending stress). This conservative assumption results in the highest possible K_{app}. The three proposed criteria are all design based; therefore, stresses must be calculated, while a reference flaw depth (based on NDE capabilities) and an allowable material fracture toughness measure are selected. In all three cases, a reference flaw is selected based on a FOS of two on NDE inspection sensitivity. A 5mm deep by 30mm long (1 to 6 aspect ratio) surface flaw is easily detectable by conventional methods and is chosen as the minimum sized detectable flaw for this example. Therefore, the NDE detection limit will be established at 10mm deep. It should be pointed out that the calculation of stresses and determination of the NDE inspection limits are not insignificant and have a direct influence on K_{app}. Conservatisms used in these parameters should be balanced with the selection of K_{Ic}. Given a calculated stress intensity (which will be the same for each criterion), the difference between the three approaches arises from the allowable fracture toughness measures selected. Relative advantages and disadvantages are discussed below.

i. Proposed Criterion 1. This criterion uses as its measure of allowable applied stress intensity the actual fracture toughness at the lowest use temperature, -40 C. The stresses must be calculated, based on design conditions, with a hypothetical reference flaw placed at the location of highest penalizing stress. In Fig. 1, a measured dynamic fracture toughness value of 55 $MPa\sqrt{m}$ was used. This corresponds to the lowest measured dynamic fracture toughness in recent Sandia test programs as described in "An Investigation of the Dynamic Fracture Toughness Transition Temperature of Ferritic Ductile Iron," McConnell, et al., Sandia National Laboratories, (draft) and "Upper-Shelf Dynamic Fracture Toughness of Ferritic Ductile Iron From a MOSAIK Cask," McConnell, et al., Sandia National Laboratories, (draft). As can be seen in Fig. 1, yield level stresses would be acceptable for this design using a measured fracture toughness of 55 $MPa\sqrt{m}$ and a reference flaw depth of 10mm.

This criterion has the advantage of being the most rigorous. The FOS can be precisely determined. The ability to adjust the three parameters in Eq. 1 provides the greatest opportunity to safely qualify more materials.

The principal disadvantage of using this criterion is the need to measure K_{Ic} at dynamic rates at -40 C. Currently, an approved dynamic fracture toughness test for highly ductile materials (such as DCI) does not exist. Fracture toughness testing is very difficult at elevated rates and has not been standardized.

Additionally, as in the case of DCI, valid K_{Ic} measurements are difficult to obtain using "standard" sized specimens. Either very large specimens must be used (difficult experimentally) or standard specimens must be tested at very cold temperatures (does not relate to the cask environment). In order to make use of standard specimens, an elastic-plastic test can be performed and the resultant value can be converted to K_{Ic}. However, stringent requirements must adhered to and explicitly demonstrated if such a conversion is to be regarded as valid. Therefore, this proposed criterion may be difficult to implement due to the issues concerning the measurement of valid fracture toughness at the appropriate rate for the candidate cask materials.

ii. Proposed Criterion 2. This criterion makes use of an existing data base of fracture toughness properties for the specific material. For ferritic steels, the K_{IR} curve in Section III, Appendix G, is available. This curve is a lower bound of all fracture toughness measurements made on selective grades of ferritic steels. For DCI, a K_{IR} curve is shown in Seminar Proceedings from the Containers for Radioactive Materials Made from Nodular Cast Iron, B. Droste and R. Rodel, Bundesanstalt fur Materialforschung und Prufung, 1987, which provides a lower bound fracture toughness as a function of temperature. Results of the SNL test program as described in "An Investigation of the Dynamic Fracture Toughness Transition Temperature of Ferritic Ductile Iron," P. McConnell, et al., Sandia National Laboratories, draft; "Upper-Shelf Dynamic Fracture Toughness of Ferritic Ductile Iron from a MOSAIK Cask," P. McConnel, et al., Sandia National Laboratories, draft; and work done at the Japanese Central Research Institute of Electric Power Industry (CRIEPI), as described in the CRIEPI report "Research on Quality Assurance of Ductile Cast Iron Casks," (1988)--all provide K_{IR} curve fracture toughness measurements above those described in Seminar Proceedings from the Containers for Radioactive Materials Made from Nodular Cast Iron. A K_{Ic} value of 47 $MPa\sqrt{m}$ is identified at -40 C and is used as the allowable fracture toughness value in Fig. 1 for this criterion.

As with the first criterion, yield level stresses would be acceptable for an allowable fracture toughness of 47 $MPa\sqrt{m}$ and with a reference flaw depth of 10mm. The principal advantage of this criterion is that fracture toughness measurements by the designer are not required, provided that a data base for the candidate material is available. By not requiring material testing and using a lower bound K_{IR} value, design requirements are simplified. The principal disadvantage to this approach is that a comprehensive data base must be generated and verified for individual materials. An additional disadvantage may arise from using the lower bound K_{IR} curve which may result in disqualification of some suitable materials due to the conservative assumptions placed on the allowable fracture toughness.

iii. Proposed Criterion 3. A final criterion, and most conservative of the three, would establish a lower shelf value of fracture toughness as the allowable value. The lower shelf represents complete brittle fracture behavior. This criterion has some attributes which are not provided for in the preceding criteria. By specifying a valid, lower shelf K_{Ic} value as the allowable, linear-elastic fracture toughness testing can be performed with standard-sized test specimens at low temperatures for materials which exhibit transition behavior. Dynamic rates do not substantially affect the lower shelf toughness so that static testing will be satisfactory. Since the lower shelf toughness is a lower bound, specimen size effects relating to the conversion from elastic-plastic to linear-elastic toughness are eliminated. In effect, choosing the allowable fracture toughness value as the lower shelf value for a particular material establishes a worst case allowable toughness value. Questions pertaining to rate, temperature, and material variability would be effectively eliminated.

Fig. 1 shows the results of applying proposed criteria 3 for DCI with a lower shelf K_{Ic} of 30 $MPa\sqrt{m}$. This value was chosen from the K_{Ic} curve provided in Seminar Proceedings from the Containers for Radioactive Materials Made from Nodular Cast Iron, B. Droste and R. Rodel, Bundesanstalt fur Materialforschung und Prufung, 1987. For this case, with a reference surface flaw depth of 10mm, the allowable stresses would be limited to 3/4 of the yield strength.

The advantages of this proposed criterion lies in the relative ease of determining the allowable fracture toughness. The determination and interpretation of this value is straightforward and not ambiguous. The disadvantage is associated with the high level of conservatism that may under some circumstances eliminate many candidate materials.

Once the brittle fracture acceptance criterion has been adopted, the practical considerations associated with the demonstration drop (if warranted) test can be addressed. The drop test acceptance criteria should address the questions raised at the beginning of this paper. The following points are suggested as recommended drop test criteria and follow directly from the approaches outlined above:

i. The cask should be dropped with impact limiters. The limiters and the cask metal should both be cooled to -40 C.

ii. The cask should have a flaw induced in the highest stressed region of the wall. A machined flaw is acceptable provided that the flaw tip radius is < 0.1mm. CRIEPI has reported the results from recent tests which validate the conclusion that the fracture toughness is not affected by using "blunt" flaws with such a small tip radius, as described in the CRIEPI report "Research on Quality Assurance of Ductile Cast Iron Casks," (1988). This conclusion is supported for DCI only. Similar tests would have to be conducted to support the conclusion for other materials.

iii. The flaw for the drop test should be sized according to one of the three proposed criteria. For a given cask design stress level and an allowable fracture toughness value, the flaw should be sized according to Eq. (2).

iv. Acceptance of the drop test should be based on no crack initiation from the flaw tip. Issues such as these should be addressed in detail as part of the development of a fully formulated brittle fracture acceptance criterion.

CONCLUSIONS

The three proposed criteria presented here form a hierarchy of approaches with varying levels of conservatism. The basis for developing a criterion should include an evaluation of the ease of implementation as well as the adaptability of the criteria to various materials and applications.

The IAEA should sponsor the development of an international brittle fracture acceptance criterion which would be adopted by the technical community as well as the regulatory community. The criteria presented in this paper may serve as a starting point for international technical group discussions aimed at developing an acceptable criterion.

REFERENCES

ASME Boiler and Pressure Vessel Code, Section III, Appendix G, "Protection Against Nonductile Failure," (1986).

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TABLE 1

Comparison of Selected Brittle Fracture Acceptance Criteria

Criteria Basis	Approach	Acceptance Criteria	Assumptions	Factors of Safety
1. ASME B&PVC Sec. III, App G	Design	$K_I=2\{M_m rm\}+2\{2/3M_m rb\}$ $K_I < K_{IR}$	1/4t flaw	a. Two on calculated stresses b. Unquantified on toughness using K_{IR}
2. ASME B&PVC Sec. XI, App A	Design	$K_I=rmM_m!pa/Q+r_bM_b!pa/Q$ $K_I < K_{Ic}$		No explicit factor of safety
3. NRC Draft Regulatory Guide	Material	Nil-ductility transition (NDT) temperature must meet specified limits	A running crack initiated from a through-wall; flaw will arrest	Unquantified on NDT toughness

Notes:
1. K_I = stress intensity value (MPa-!m)
2. $M_{m,b}$ = stress correction factor for membrane (m) and bending (b) stresses
3. rm,b = membrane and bending stress (MPa)
4. K_{IR} = lower bound fracture toughness value defined in Sec. III, App G (MPa-!m)
5. t = section thickness (m)
6. a = flaw depth (m)
7. K_{Ic} = material fracture toughness as measured from testing (MPa-!m)

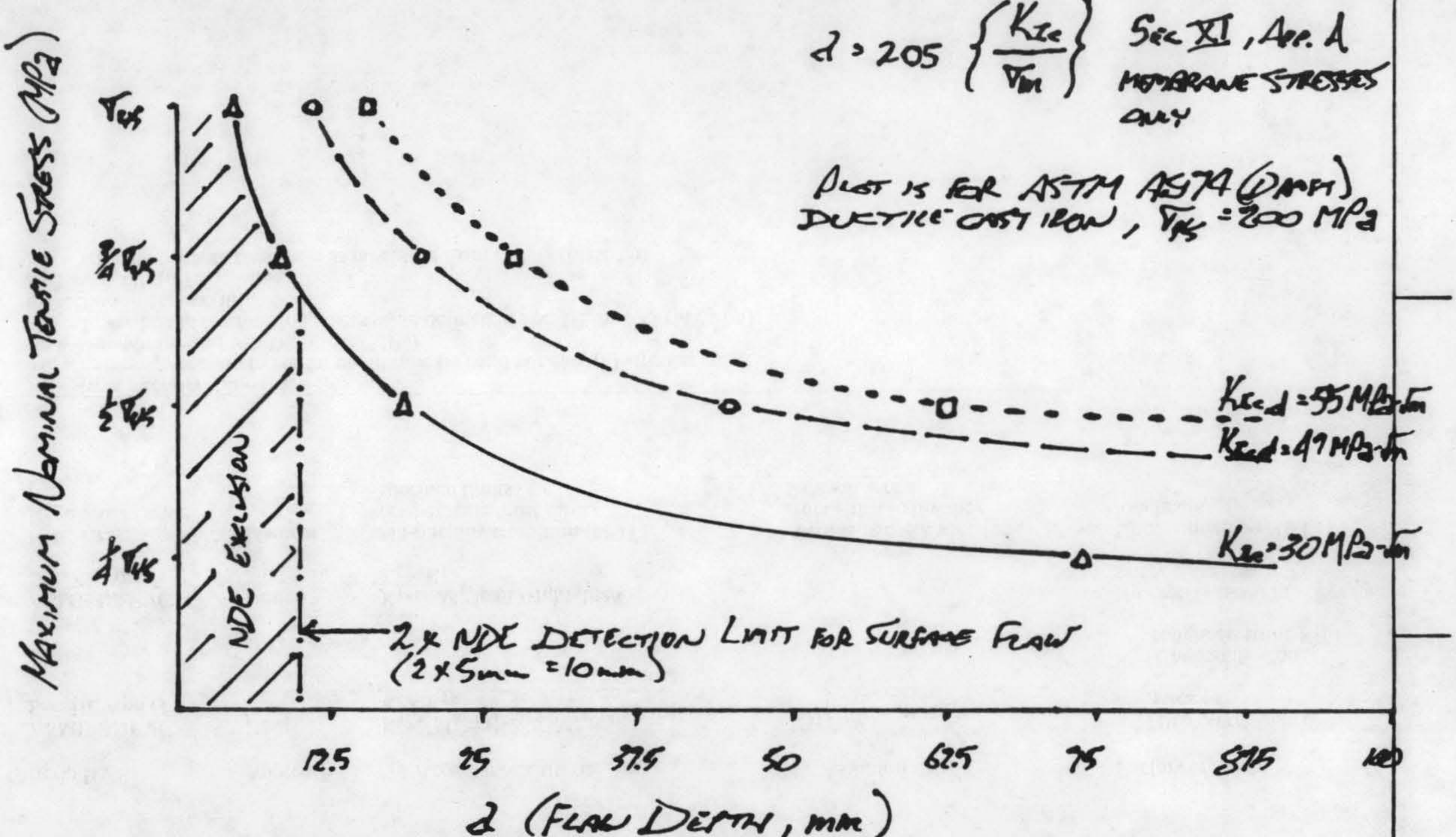
$a = 205 \left\{ \frac{K_{Ic}}{\sigma_m} \right\}$ Sec XI, App. A
MEMBRANE STRESSES ONLY
PLOT IS FOR ASTM A574 (DAMF) DUCTILE CAST IRON, σ_{ys} = 200 MPa
K_{Icd} = 55 MPa-√m
K_{Icd} = 49 MPa-√m
K_{Ic} = 30 MPa-√m
NDE EXCLUSION
2 x NDE DETECTION LIMIT FOR SURFACE FLAW (2 x 5mm = 10mm)
MAXIMUM NOMINAL TENSILE STRESS (MPa)
σ_{ys}
$\frac{3}{4}\sigma_{ys}$
$\frac{1}{2}\sigma_{ys}$
$\frac{1}{4}\sigma_{ys}$
12.5
25
37.5
50
62.5
75
87.5
100
a (FLAW DEPTH, mm)

FIGURE 1.

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