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HSST CRACK-ARREST STUDIES OVERVIEW*

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ABSTRACT

An overview is given of the efforts underway in the Heavy-Section Steel Technology (HSST) Program to better understand and model crack-arrest behavior in reactor pressure vessel steels. The efforts are both experimental and analytical. The experimental work provides K_{Ia} data from laboratory-sized specimens, from thick-wall cylinders which exhibit essentially-full restraint and from nonisothermal wide-plate specimens. These data serve to define toughness-temperature trends and to provide validation data under prototypical reactor conditions. The analytical efforts interpret and correlate the data, plus provide LEFM, elastodynamic and viscoplastic methods for analyzing crack run-arrest behavior in reactor vessels. The analysis methods are incorporated into finite element computer programs which are under development at three separate laboratories.

1. INTRODUCTION

Understanding crack-arrest behavior is important to assessing the integrity of light-water reactor (LWR) pressure vessels. In pressurized-thermal-shock scenarios, inner surface flaws have the greatest propensity to propagate because they are in the region of highest thermal stress, lowest temperature and greatest irradiation damage. If such a flaw begins to propagate radially through the vessel wall, it will extend into a region of higher fracture toughness due to higher temperatures and less irradiation damage. Although thermal stresses may decrease with the propagation depth, the stress-intensity factor due to the pressure loading will be increasing. Assessment of the integrity of a reactor vessel under a crack run-arrest event includes the prediction of arrest location, of potential reinitiation,

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stable and unstable ductile crack growth, and structural instability of the remaining vessel wall. The Heavy-Section Steel Technology (HSST) Program is carrying out experimental and analytical studies to extend available data bases to higher temperatures and additional materials, to validate the understanding of crack run-arrest behavior in structural specimens, and to establish appropriate analytical methods for performing static, dynamic and inelastic fracture analyses.

This paper is intended to serve as an introduction to several of the ongoing activities that contribute to the overall HSST crack-arrest studies. These studies are integrated by the Oak Ridge National Laboratory (ORNL) and carried out by the Battelle Columbus Laboratory (BCL), the University of Maryland (U. Md), the National Bureau of Standards (NBS), ORNL, and the Southwest Research Institute (SwRI). The technical efforts can be grouped in three categories as illustrated in Fig. 1. (The H.5 designation in Fig. 1 is a result of the crack-arrest studies being the fifth of the ten tasks that make up the total HSST research program.) The following papers cover work underway at the latter three organizations cited above.

2. ANALYTICAL METHODS AND COMPUTER PROGRAMS

The task of predicting the arrest of a propagating crack in a reactor pressure vessel steel is generally approached by considering that arrest occurs when the driving force (e.g. stress intensity factor K_I) reaches a critical toughness value, K_{Ia}. Figure 2 illustrates that K_I depends on the applied stress, σ, and the crack size, a. Additionally, the critical toughness value for arrest is dependent on temperature and irradiation exposure. The principal ingredients in the analytical technology to quantitatively predict crack run-arrest behavior are (1) constitutive equations to predict the stress-strain-time response of the material, (2) stress-strain-time-temperature data to implement the constitutive equations in stress analyses, (3) critical driving force parameters (e.g. initiation and arrest toughness values, K_{Ic} and K_{Ia}, respectively) that are compatible with the stress-analysis methods used, and (4) computer programs (e.g. finite element programs) capable of employing the constitutive equations and fracture criteria.

To date, major techniques for dynamic fracture analysis have been based on classical linear-elastic fracture mechanics. The following papers by Bass[1] and Kanninen[2] include descriptions of the state-of-the-art in this area. The most general fracture analysis codes used at ORNL are based on linking a mesh generator (ORMGEN[3]) and a fracture mechanics postprocessor (ORVIRT[4]) to the general purpose program ADINA.[5] Until recently, dynamic fracture analyses in the HSST program were carried out at SwRI and ORNL using the SWIDAC computer code[6] and at the U. Md. using the SAMCR code.[7] Bass[1] describes the recent extension of the ADINA fracture analysis system to include elastodynamic fracture capabilities. The resulting code is referred to as ADINA/EDF. Kanninen[2] describes the development of an improved 2-D elastodynamic code at SwRI. Figure 3 gives a sample prediction of crack-velocity during propagation of a crack and the influence of dynamic effects on the stress intensity factor.

The previously mentioned state-of-the-art techniques for dynamic fracture analysis include, in addition to inertial effects, fracture toughness measures that are crack-speed dependent. Concerning the latter of these effects, Kanazawa[8] showed data over a range of crack speeds and temperatures that support the type of toughness response shown in Fig. 4. In addition, however, the propagation of a crack gives rise to high strain rates in regions near the crack front, and this effect is not included in present state-of-the-art techniques. Freund and Hutchinson[9] show that these strain rates exceed 10^3 s^{-1} for crack velocities over about 1/10 of the Rayleigh wave speed in structural steels. This level of strain rate is known to have a pronounced effect on the yield and flow properties of pressure vessel steels as shown schematically in Fig. 4. Correspondingly, investigations are underway to establish fracture analysis capabilities based on viscoplastic material behavior. SwRI is developing a system based on the Bodner-Partom formulation of constitutive equations.[10] Kanninen[2] discusses the goals and status of this effort. ORNL is extending the ADINA fracture analysis system to include a viscoplastic capability based on constitutive equations formulated by Perzyna.[11] Bass[1] references this effort which is resulting in a code referred to as ADINA/ VPF. This latter formulation is similar to that used by Brickstad.[12] Scoping studies using these viscoplastic approaches are to reveal the sensitivity of quantitative arrest predictions to the inclusion of viscoplastic features. From that point, the merits of evaluating other choices of constitutive equations and fracture criteria relative to improved behavioral representations can be established. SwRI and ORNL are performing exploratory laboratory experiments to characterize HSST plate 13A of A 533 grade B class 1 steel to support this study.

3. SPECIMEN AND TEST RECOMMENDATION

One major objective of the HSST program has been to obtain reliable fracture toughness data, provide means for interpreting size effect,[13] and to assist in establishing standard test practices.[14] In the case of crack-arrest (K_{Ia}) data, most tests have been performed with laboratory-size specimens, and available K_{Ia} data have been entered into a data bank at BCL.[15] Additionally, the toughness properties for each major material studied in the HSST program are characterized individually to provide bases for analyses of large specimen tests. For example, small-specimen crack-arrest data obtained for the first HSST pressurized-thermal-shock experiment (PTSE-1) material are shown in Fig. 5. These and other characterization data for PTSE-1 material are discussed by Bryan.[16,17]

The currently used laboratory crack-arrest specimen has evolved over the past several years, with a strong emphasis on minimizing dynamic effects. A typical specimen configuration is shown in Fig. 6. An ASTM standard has been proposed by Task Force E 24.01.06 on Crack Arrest and a round-robin test program has been undertaken to validate the proposed test method and to establish lab-to-lab variability. The round-robin is administered by the University of Maryland (Dr. W. L. Fourney) through a subcontract with the HSST program. There are twenty-seven laboratories in eleven countries participating in the round robin, and results had been received from twenty laboratories as of September 1, 1985. Three steels, A 533 grade B class 1, A 588 and A 514, are employed in the round-robin.

The irradiation effects studies in the HSST program are concerned with the effects of neutron exposure on all fracture properties. In particular, the Sixth HSST Irradiation Series is examining the shift and change of shape in the crack-arrest toughness vs temperature curve with accumulated neutron exposure. This study is carried out on the same two relatively high-copper welds that are used in the Fifth Series for similar studies of the effects on initiation toughness. McGowan and Nanstad[18] discuss these studies and associated properties evaluations in a subsequent paper.

4. CRACK-ARREST EXPERIMENTS

The small laboratory crack-arrest specimens discussed in the previous section provide limited constraint of deformation in the crack-plane region and permit only the generation of data at temperatures below those where arrest is likely to occur in some PTS scenarios. Figure 5 shows a typical range of K_{Ia} data generated by small laboratory specimen tests. These data extend to temperatures about 60°C above the RTNDT for that (PTSE-1) material and to a value of about 150 $MPa \cdot \sqrt{m}$. However, since the driving force under PTS scenarios can be high, it is desirable to understand the crack-arrest behavior at temperatures up to or beyond the onset of Charpy upper-shelf energy. The HSST program has been and is continuing to provide crack-arrest data over an expanded temperature range through tests of thermally shocked cylinders, PTS vessels, and wide-plate specimens. The wide-plate tests allow a significant number of data points to be generated at affordable costs, while the thermal-shock and PTS tests provide validation data under full-constraint, transient, multiaxial loading conditions.

While the HSST thermal-shock experiments (TSEs) have produced a significant number of data points, the driving force in those experiments is thermal stress only, and consequently, crack-arrest data have been below about 150 $MPa \cdot \sqrt{m}$. As Fig. 7 illustrates, an important conclusion from the HSST TSEs is that the K_{Ia} data from these highly-restrained propagations fall well within the range of K_{Ia} data from laboratory specimens and above the ASME K_{IR} curve. Most of the TSE data shown in Fig. 7 are reported by Cheverton in Ref. 19.

The pressurized-thermal-shock experiments (PTSEs) have the capability of providing higher K_{Ia} values under similar highly-restrained conditions. To date, one three-part experiment (PTSE-1) has been performed and is discussed by Bryan.[16,17] PTSE-1 has provided K_{Ia} data as high as 300 $MPa \cdot \sqrt{m}$ and at temperatures up to 30°C above the onset of the Charpy upper shelf as illustrated in Fig. 8.

Most recently the HSST program has initiated a program to investigate the crack run-arrest behavior in large plates with steep toughness gradients. These tests use wide-plate specimens that possess a single-edge notch (crack) that initiates at low temperature and arrests in a region of increased fracture toughness. The toughness gradient is achieved through a linear transverse temperature profile across the plate. The experiments require the application of large tensile loads and are being conducted by the NBS in Gaithersburg, Md. The first objective is to provide K_{Ia} data above the ASME K_{IR} curve upper-limit criterion for prototypical pressure vessel steels. The steels include typical base metals and low-upper shelf materials representative of degraded weld materials. Other objectives include providing data for which dynamic facture analyses can be performed. Figure 9 shows a wide-plate specimen under test. Fields[20] discusses the performance of and data interpretation efforts for these tests. To date four tests have been performed on A 533 grade B class 1 steel.

A consistent trend is formed when the crack-arrest data from the three types of HSST large specimen tests mentioned above are combined on a plot of K_{Ia} versus T — RTNDT. Figure 10 illustrates that this is still the case when one includes the results of thermal-shock tests from France[21] and wide-plate (ESSO) tests from Japan.[22] Collectively, these tests are showing that arrest occurs at temperatures up to and above that which corresponds to the onset of Charpy upper-shelf behavior, and the measured K_{Ia} values extend above the limit included in Section XI of the ASME code. It is important to note that the data in Fig. 10 are for materials with RTNDT values that differ by at least 115°C.

5. CONCLUSIONS

In conclusion, the HSST program has a comprehensive and integrated effort underway concerning crack-arrest technology. The effort addresses the analytical tools necessary for making quantitative calculations, establishing laboratory test methods, and generating data for method validation and range extension. The goal is to develop the range of applicability of current state-of-the-art practices and to develop alternatives where improvements are needed.

6. ACKNOWLEDGEMENTS

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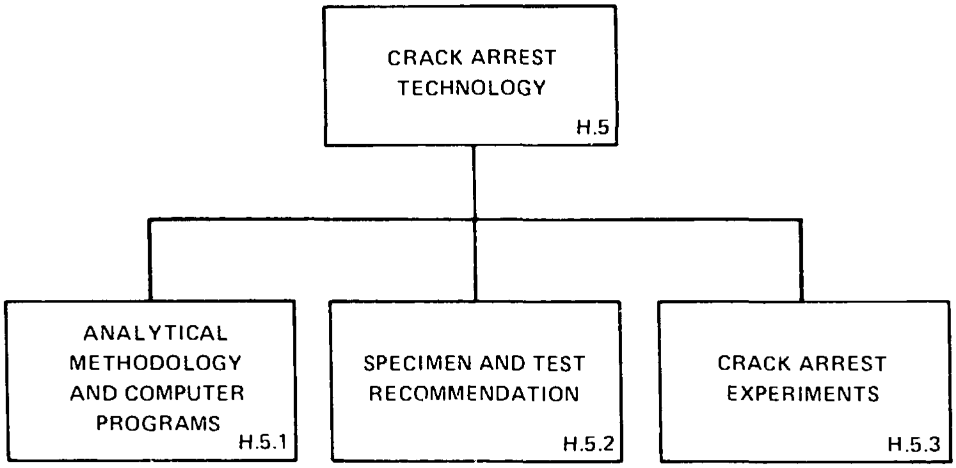

Fig. 1. Three basic elements of the HSST crack-arrest technology studies.

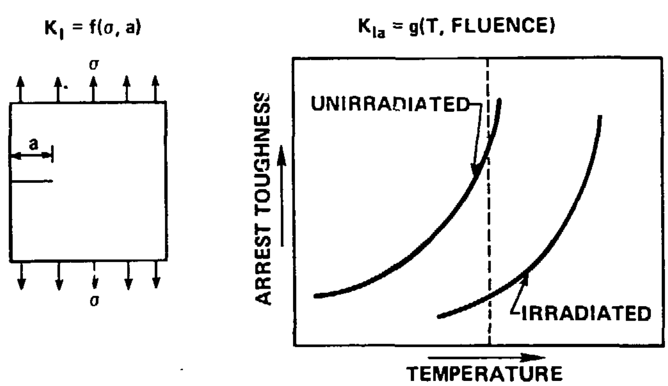

Fig. 2. Schematic illustration that crack arrest occurs when the driving force (K_I) reaches a critical toughness value (K_{Ia}) which is dependent on temperature and irradiation exposure.

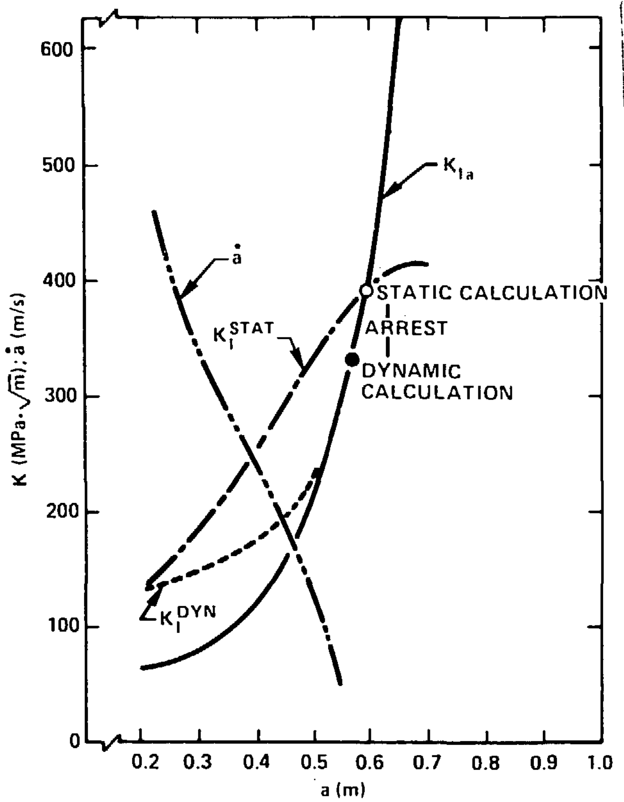

Fig. 3. Schematic of dynamic effects during a crack run-arrest event in a wide-plate specimen where the crack-tip temperature increases with crack depth.

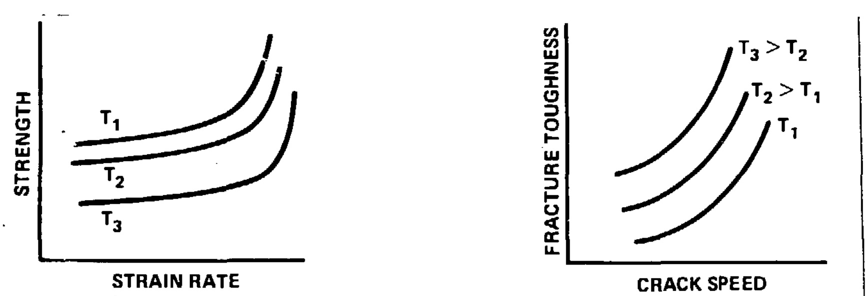

Fig. 4. Schematic illustration that strength and fracture toughness measures are temperature and rate dependent.

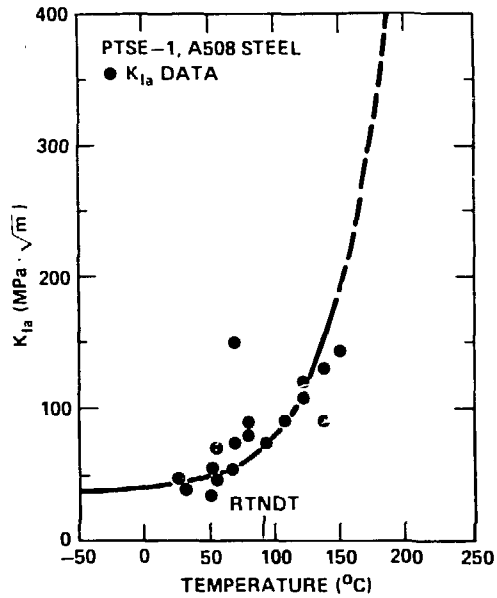

Fig. 5. Crack-arrest data for HSST PTSE-1 material from tests at Battelle Columbus Laboratories using laboratory-size specimens.

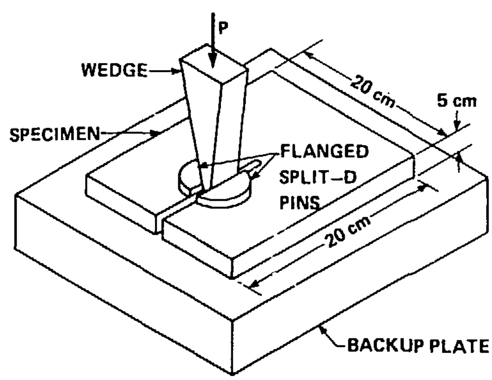

Fig. 6. Schematic of side-wedge-loaded compact specimen used in laboratory crack-arrest tests.

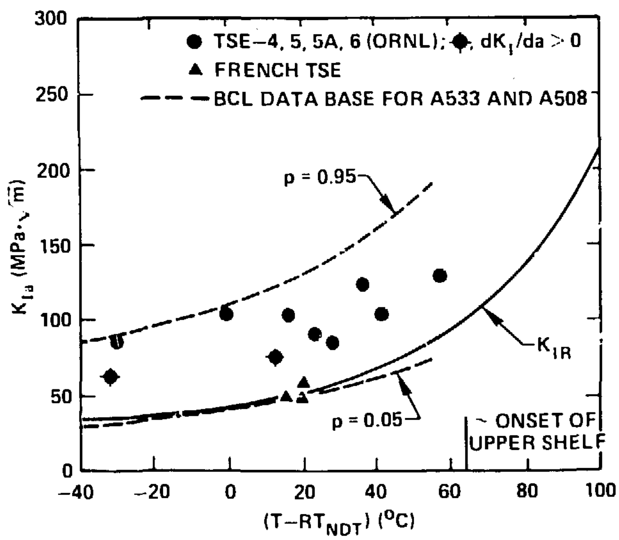

Fig. 7. Crack-arrest toughness data from thermal-shock experiments of thick-cylindrical specimens.

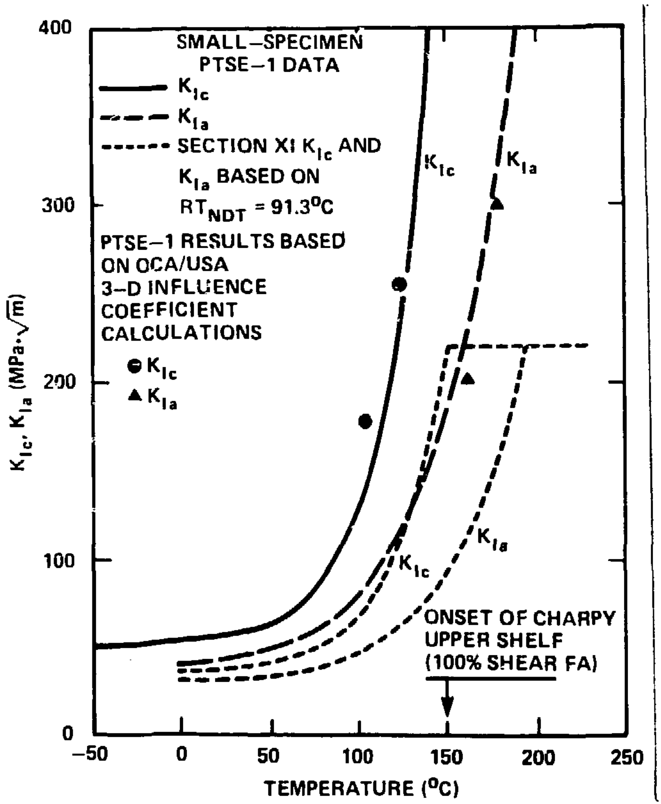

Fig. 8. Initiation and arrest toughness data from the first HSST pressurized-thermal-shock experiment (PTSE-1).

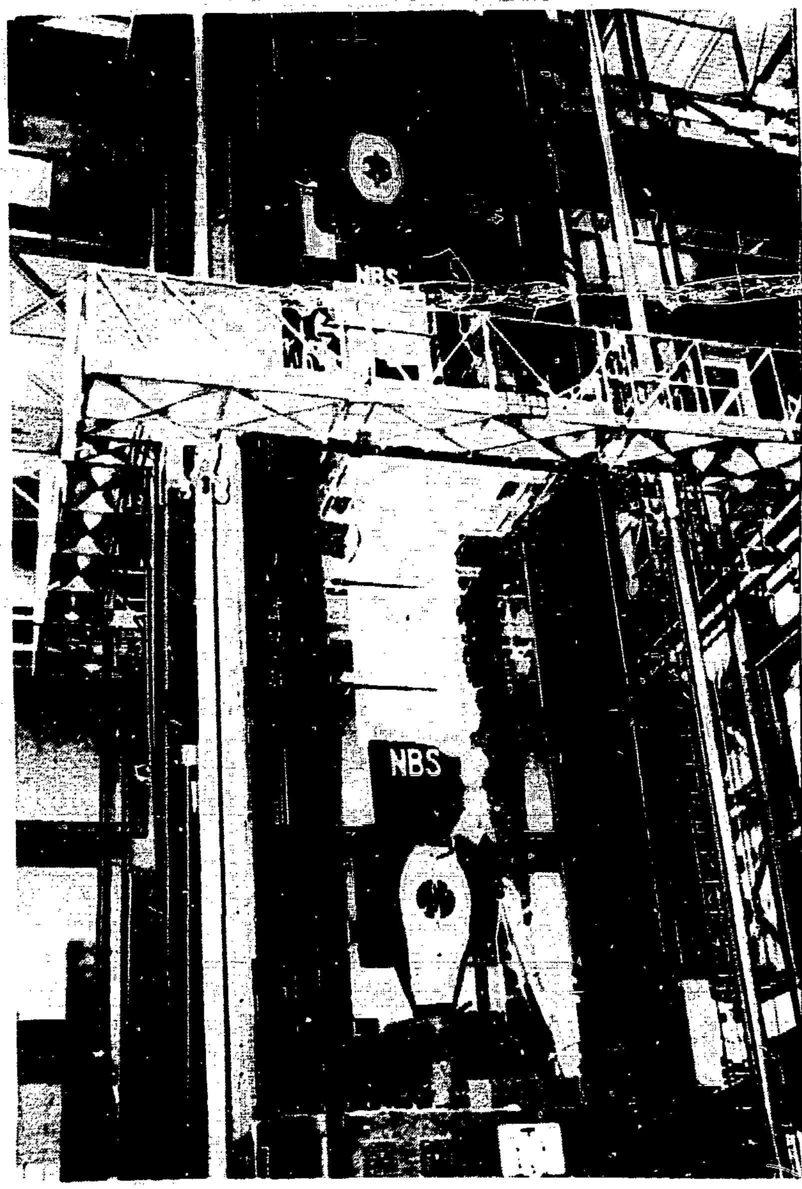

Fig. 9. Wide-plate crack-arrest test in progress in the 27 MN (6 million pound) tensile machine at the National Bureau of Standards, Gaithersburg, MD.

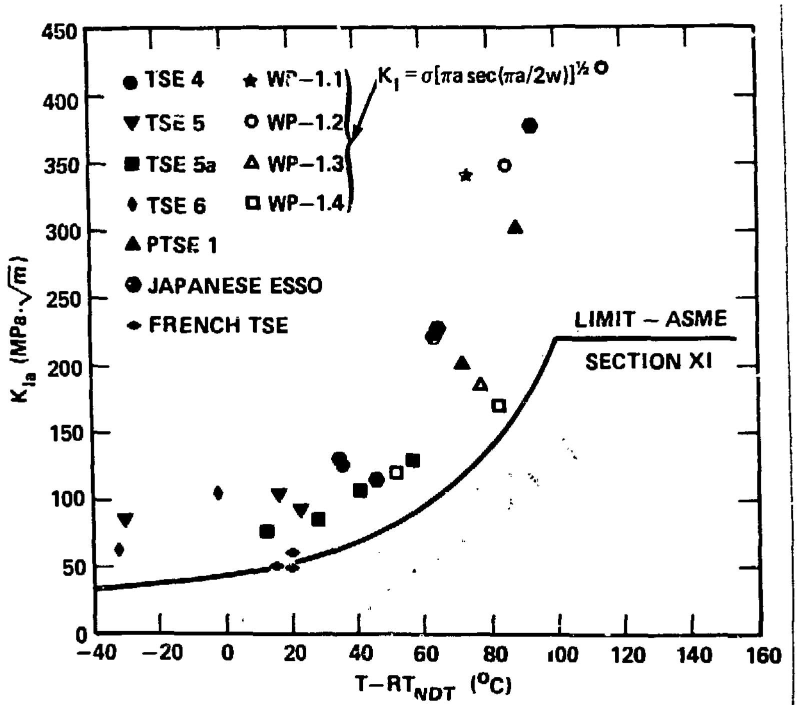

Fig. 10. Crack-arrest toughness data from large specimens show a consistent trend and extend above the ASME Section XI limit.