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Generic Task No. A-11

Dr. R. E. Johnson
U.S. Nuclear Regulatory Commission
MS 440
Washington, D. C. 20555

Dear Dick:

Enclosed are five copies of the Quarterly Progress Report for the period ending June 30, 1980, for the NRC Program Reactor Vessel Materials Toughness Support. If there are any questions, please do not hesitate to call me.

Yours truly,

Gerry

G. M. Slaughter, Manager
Engineering Materials Section
Metals and Ceramics Division

GMS/bdk

Enclosures

cc: J. R. Weir
G. D. Whitman

cc/enc: R. G. Berggren
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Reactor Vessel Materials Toughness Support

Progress Report for Period Ending June 30,1980

G. M. Slaughter

Introduction

A few nuclear plants under licensing review have reactor vessels that have been identified as having the potential for marginal fracture toughness within their design life. To assist in the reevaluation of these vessels in the light of new criteria for long-term acceptability, an engineering method is needed to assess the safety margin for failure prevention. The Nuclear Regulatory Commission is sponsoring an inter-disciplinary effort at several sites (Task Action Plan A-11) encompassing various aspects of materials and fracture technology; this will permit the determination of appropriate licensing criteria for low toughness reactor vessel materials and the evaluation of material degradation from neutron irradiation.

The scope of the ORNL program includes three tasks. The first is material evaluation wherein available experimental results will be reviewed to establish relevant fracture mechanics parameters and the effect of size and neutron radiation on them. The second is reactor vessel analyses wherein existing elastic-plastic fracture mechanics concepts will be used to develop a crack instability predictive method applicable to the reactor vessel beltline region and compared to available vessel test data. The third is evaluation wherein the results of the other two tasks will be compared to the criteria of existing codes (ASME and 10 CFR 50).

Subcontracts with P. C. Riccardella (Nutech), W. E. Cooper (Teledyne Engineering Services), and H. T. Corten (Univ. of Illinois) are in effect to provide additional technical assistance on this program.

Technical Progress

Meetings: Meetings of program participants have been held at the Nuclear Regulatory Commission offices at Bethesda, Maryland on February 27, April 9-10, and May 15-16. These meetings have been very valuable for making technical plans and reviewing progress.

On June 19, a meeting was held at Bethesda to review progress in the analytical aspects of the program.

On April 16, A Mid-Year Review of the progress to date was held at Bethesda.

Materials Evaluation - (R. G. Berggren, D. A. Canonico, and F. J. Loss*)

The goal of this task is to provide mechanical properties data for materials relevant to nuclear reactor pressure vessels and in a form that can be applied in structural analysis methods developed in the Analysis Task. The present analytical effort is aimed at predicting ductile tearing behavior and tearing instability and we are therefore assembling, analyzing, and correlating elastic-plastic fracture toughness data on the ductile-tearing mode of failure in steels.

It is widely recognized that the J-integral method provides a valid general solution to the problem of crack tip singularity fields under large-scale yielding, even up to fully plastic conditions for some geometries. Although standard test methods are being established for measuring J to initiate crack extension (J_{Ic}), methods for describing crack propagation by ductile tearing are still experimental. These experimental methods apparently can be used to provide curves of $J = f(\Delta a)$, the so-called J-R curves, and therefore measure the tearing modulus T, which is proportional to dJ/da.

The specimen usually used in the J-integral method, the "compact tension" specimen, is adequate for measuring elastic fracture toughness and often adequate for measuring J_{Ic} for small-scale crack extension. However, large-scale yielding occurs in the region of the intersection of the crack with the specimen surface when tests are conducted in the plastic tearing regime. This surface effect increases the work done in propagating a tear and therefore increases J and the measured tearing modulus, T. In addition, this surface effect results in crack "tunneling," a condition that cannot be analyzed by present methods. Increasing the specimen thickness would reduce the contribution of this surface effect to the measured J-integral, but specimen sizes become impractical. However, side-grooving of the specimen (20% in a 1T compact specimen) has been shown to result in uniform propagation of the crack front and, inferentially, elimination of the surface effect.

We are assembling available data for side-grooved specimens for conditions of large-scale yielding and large-scale ductile crack extension. Since this method of testing is relatively new, there are relatively few data presently available and some of the suitable data are proprietary. An additional requirement is that tensile data and Charpy upper-shelf energy (USE) data are available for the material.

We are assembling data from several institutions such as the U.S. Naval Research Laboratory (NRL), Hanford Engineering Development Laboratory (HEDL), Electric Power Research Institute (EPRI), Naval Ships Research and Development Command (NSRDC), Babcock and Wilcox Company, and Westinghouse Research Laboratory. Not all of this data have been integrated into the analysis at this time. However, some comments can be made on the basis of the data presently analyzed.

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*Naval Research Laboratory.

The experimental J-Δa data are corrected for crack extension (Δa correction) and, where possible, for specimen rotation. The resulting J-R curves examined to date at ORNL and NRL seem to fit a power law expression and are therefore amenable to analytical expression. The tearing modulus T is then determined and J versus T is plotted. The Naval Research Laborotory has plotted J versus T for a number of tests on several steels, some being irradiated steels. These J versus T plots appear to be ordered with regard to Charpy-V upper-shelf energies. Materials and conditions with lower Charpy-V upper-shelf energies have lower J values for a given tearing modulus T. If J values for a given J/T are plotted against Charpy-V upper-shelf energy, the relationship can apparently be expressed by a power law function:

$$J = aW^n ,$$

where

J = J-integral (lb/in.) for given J/T, e.g., $J/T = 50$,

W = Charpy-V upper-shelf energy (ft-lb), and

a and n are constants.

The data presently available yielded values for these constants of: $a = 3.6$ and $n = 1.34$ with a data scatter of about ±30%. This relatively small scatter level is surprising when we consider the differences in J-R testing and Charpy-V impact testing. The J-R tests were conducted at low strain rates with side-grooved specimens (little or no surface effect) and the Charpy-V upper-shelf tests are conducted at very high strain rates and no side grooves (large surface effect and gross shear lips).

We are presently integrating additional data into the materials analyses and attempting to secure release of proprietary data in order to publish the results. In addition, we will attempt to correlate material toughness (J and T) with other material toughness measures such as Charpy-V lateral expansion, irradiation levels, and flow stress and will also attempt correlations with non-side-grooved J-R test data.

Analysis - (J. G. Merkle, J. R. Dougan, P. C. Paris*, and P. C. Riccardella)

Introduction

Light water reactor pressure vessel steels are chosen so that upper shelf toughness conditions will prevail at vessel operating temperatures. This means that at operating temperatures, if a crack begins to extend, the fracture toughness of the vessel steel will not decrease because of the high strain rates near the crack tip caused by the crack advance, but instead will increase because of the crack advance, thus facilitating stable rather than unstable crack growth. Below the upper shelf temperature range, fractures may initiate either by rapid cleavage or by slow tearing, but unstable cleavage crack propagation is always possible. Therefore, only in the upper shelf temperature range is it correct to take credit for an increase in toughness with crack extension in a vessel fracture safety analysis. It is therefore necessary to be able to identify the upper shelf temperature range from surveillance specimen data. Because fracture mechanics specimens may either not exist in a given surveillance capsule, or must be reserved for toughness measurements, the upper shelf temperature range should be identifiable from Charpy impact energy data alone. It is recommended that Charpy testing be done with an instrumented machine, and that as many as possible of the following criteria be used jointly to define the beginning of the upper shelf temperature range.

1. Fracture appearance is 100 percent shear;
2. Impact energy has reached a maximum;
3. No sudden load drops occur in the instrumented load record;[1]

Tearing Resistance

The relation between toughness and crack extension is commonly called a tearing resistance curve. Relatively small specimens can be used for measuring the tearing resistance of a material. Toughness values are calculated as J integral values by elastic-plastic analysis, and crack length changes are measured indirectly by measuring changes in the elastic unloading compliance. Several factors influence the measured resistance curve, and to obtain a curve that can be reasonably treated as a plane strain resistance curve, the test specimens should be at least one inch thick and be side grooved in the net section about 20 percent. In addition, the equation for calculating J values should include the effects of prior crack extension,[2] and the elastic unloading compliance should be corrected for the effects of prior plastic specimen arm rotation during loading.[3]

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*Washington University, St. Louis, MO.

Material Property Correlations

As mentioned previously, fracture mechanics specimens are few in number or nonexistent in some surveillance capsules. Furthermore, current regulatory criteria[4] specify lower limits on vessel fracture toughness in terms of the Charpy V-Notch impact energy. Therefore, it is necessary to develop correlations between Charpy impact energy and tensile properties, and the tearing resistance of a pressure vessel steel. These correlations are needed to perform fracture safety analyses for upper shelf toughness conditions in the absence of direct measurements of tearing resistance and to determine the significance of the presently specified lower limits on Charpy impact energy. Three types of correlations have been proposed for application to the A-11 problem. P. C. Paris has proposed a graphical correlation between the toughness, J, and the Charpy V-Notch upper shelf impact energy, CVN. The value of J/T is specified for this correlation, where

$$T = \frac{dJ}{da} \cdot \frac{E}{\sigma_o^2} \qquad \text{Eq. (1)}$$

Paris has also proposed a graphical correlation between J and CVN in which the value of T corresponding to the value of J determined by the correlation is specified. This correlation is therefore not applicable to a material having a bilinear tearing resistance curve.

The third correlation is an empirical relationship between the Charpy V-Notch impact energy, the flow stress and the parameters of a power law approximation to the tearing resistance curve. F. J. Loss and B. H. Menke at the Naval Research Laboratory (NRL) measured resistance curves for several different nuclear pressure vessel steels and weld metals in both the unirradiated and irradiated conditions. Most of the tests were performed at 200°F, and the specimens were 1T CT specimens with 20% side grooving. The measured tearing resistance curves were corrected for both crack extension and arm rotation effects. The Charpy V-Notch impact energies of the materials tested ranged from 35 to 141 foot pounds. Each measured resistance curve was fit with a simple power law equation. J. G. Merkle and J. R. Dougan of ORNL then developed a correlation between the power law parameters of the R curve, and the Charpy V-Notch impact energy and flow stress.* The power law equation for the R curve was written in the form

$$J = 1000\,c \left(\frac{\Delta a}{1.0}\right)^n, \qquad \text{Eq. (2)}$$

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*This correlation was developed under the Fracture and Irradiation Effects Task, which is sponsored by the Structures and Components Standards Branch of the U.S. Nuclear Regulatory Commission.

in which J and the factor (1000) have the units of in.-lbs./in.^{2}, Δa and the factor (1.0) are in inches, and both the coefficient c and the exponent n are dimensionless. As shown in Fig. 1, the values of the coefficient c were plotted versus the values of the Charpy V-Notch impact energy, CVN, and a parabolic curve having the equation

$$c = -0.114 \left(\frac{CVN}{100}\right) + 5.382 \left(\frac{CVN}{100}\right)^2 \qquad \text{Eq. (3)}$$

was fit to the data. In Eq. (3) the term CVN and the factor (100) both have the units of ft.-lbs., so that the other factors in the equation are dimensionless. Then, after some trials, the exponent n was plotted versus a function of both the Charpy V-Notch impact energy and the flow stress, defined by

$$x = c + 1.5 \left(\frac{\sigma_o}{100}\right) \qquad \text{Eq. (4)}$$

where c is the multiplying coefficient determined from Eq. (3) and σ_o is the flow stress, defined as the average of the yield and the ultimate tensile stresses. In Eq. (4) the term σ_o and the factor (100) both have the units of ksi, and the other terms in the equation are dimensionless. Then, as shown in Fig. 2, the plotted data were fit with a curve having the equation

$$n = \frac{0.473\, x^3}{14.42 + x^3} \quad . \qquad \text{Eq. (5)}$$

Eqs. (3), (4), and (5) make it possible to estimate a power law approximation for the R curve, based only on Charpy and tensile data.

The implications of a power law equation for the resistance curve can be examined by considering a simplified example, to which LEFM is assumed to be applicable. The value of J is given by

$$J = \frac{K^2}{E} = C^2 \frac{\sigma^2}{E} \pi a. \qquad \text{Eq. (6)}$$

Taking logarithms on both sides of Eq. (6), assuming a constant value of C, and then differentiating gives

$$\frac{d \ln J}{d \ln a} = 1. \qquad \text{Eq. (7)}$$

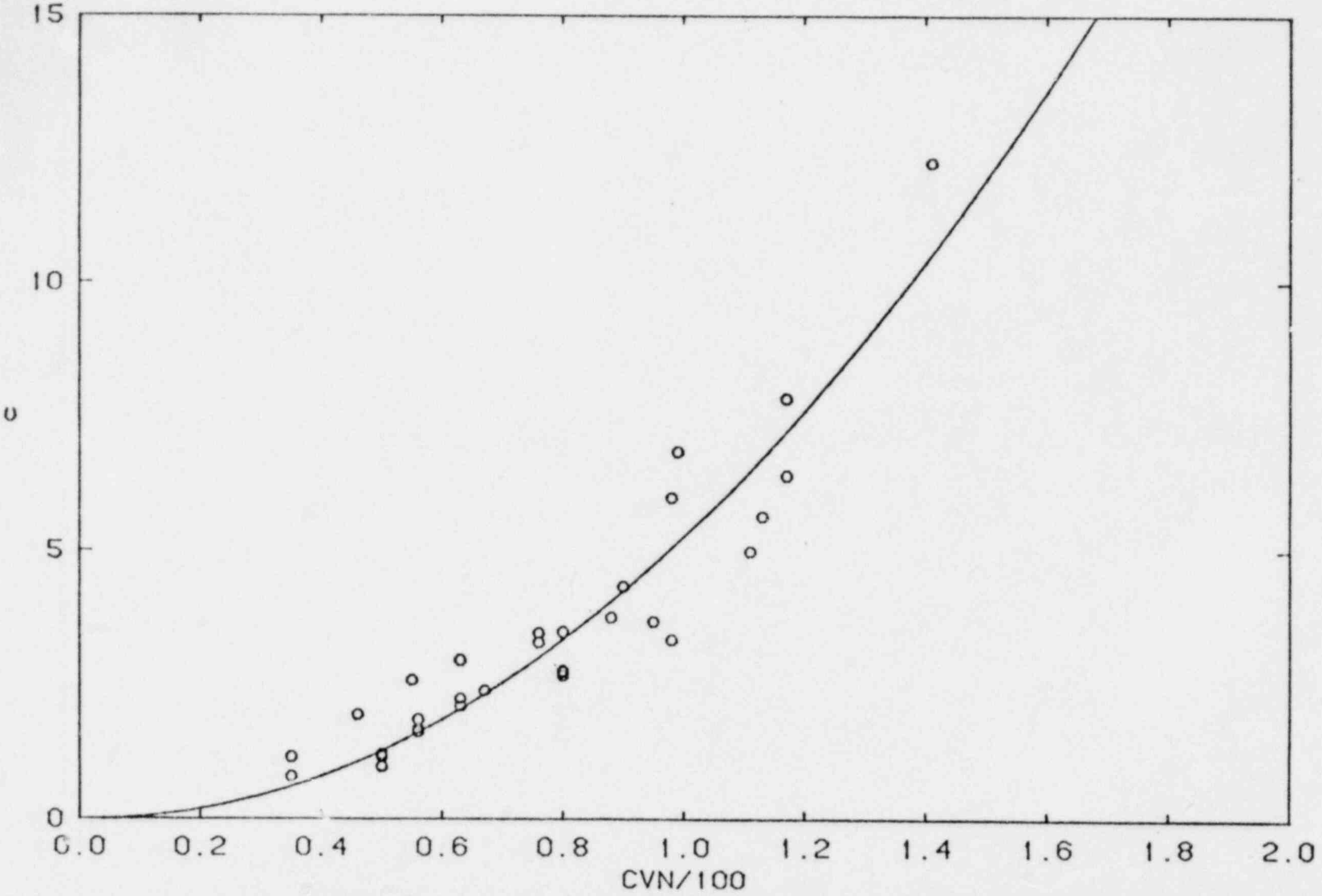

Fig. 1. Correlation of c with CVN, using NRL data from 1T-CT specimens with 20 percent side grooving tested at 200°F; resistance curve data were corrected for crack extension and arm rotation effects.

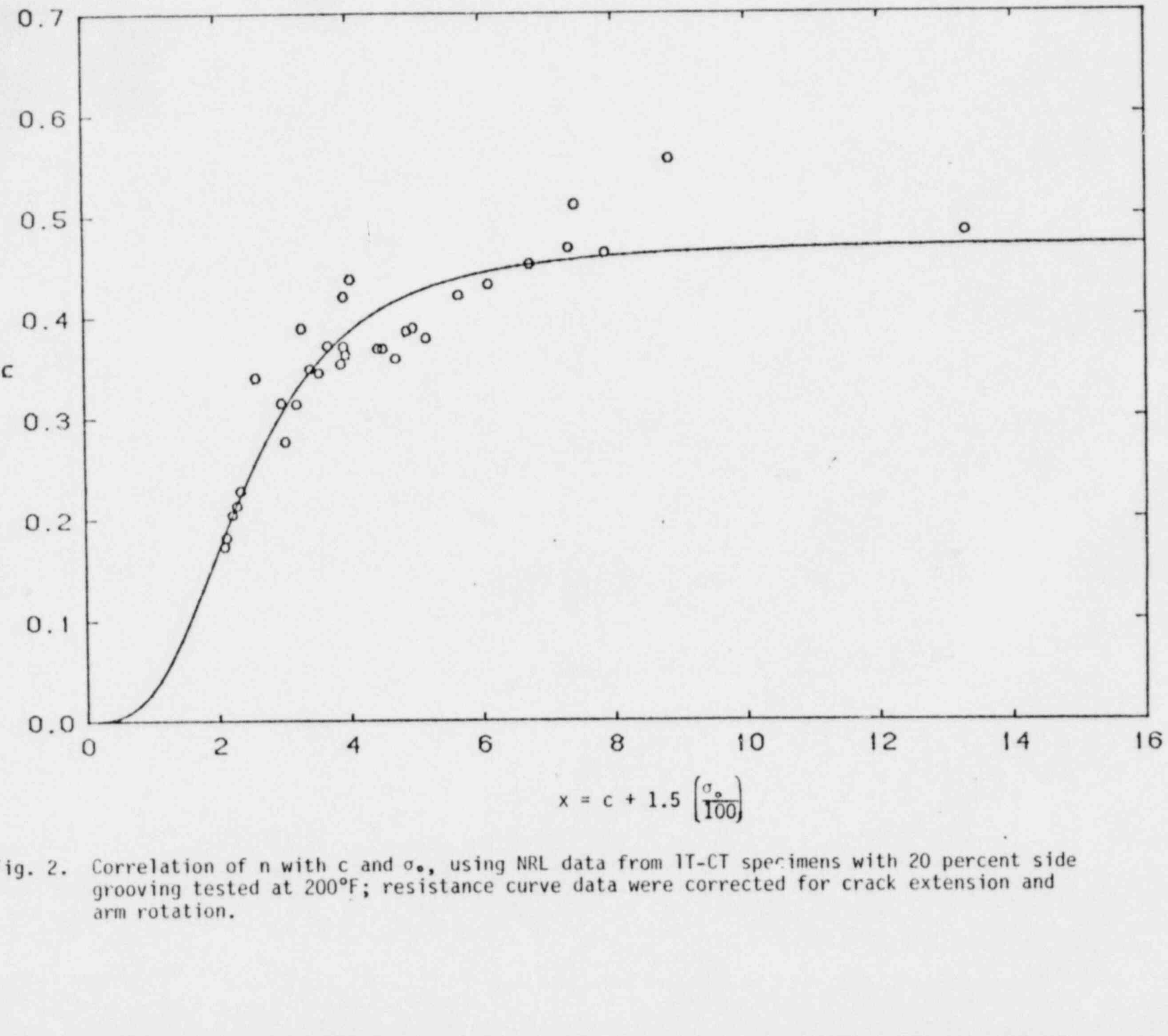

Fig. 2. Correlation of n with c and σ_o, using NRL data from 1T-CT specimens with 20 percent side grooving tested at 200°F; resistance curve data were corrected for crack extension and arm rotation.

Tearing instability must occur when the slope of the resistance curve satisfies Eq. (7). Taking logarithms on both sides of Eq. (2) and differentiating gives

$$\frac{d \ln J}{d \ln a} = n \frac{d \ln \Delta a}{d \ln a} . \qquad \text{Eq. (8)}$$

Since $\Delta a = a - a_o$, Eq. (9)

$$\frac{d \ln \Delta a}{d \ln a} = \frac{a}{a - a_o} . \qquad \text{Eq. (10)}$$

Thus, combining Eqs. (7), (8), and (10), tearing instability occurs when

$$\Delta a = na , \qquad \text{Eq. (11)}$$

or, by using Eq. (9),

$$\Delta a = \left(\frac{n}{1 - n} \right) a_o . \qquad \text{Eq. (12)}$$

Referring to Fig. 2, it can be seen that for high toughness materials, n is approximately 1/2. For n = 1/2, Eq. (12) indicates that tearing instability will occur when the flaw has grown to double its original size. Thus the amount of flaw growth at tearing instability may not be small compared to the original flaw size. This conclusion has already been demonstrated by the results of several of the HSST Program intermediate pressure vessel tests.

Analysis Methods and Results

Thus far the major efforts of the A-11 task group have been devoted to formulating analysis procedures based on existing theories, and to developing material property correlations consistent with these procedures. Problems of flaw evaluation in the upper shelf temperature range can be approached on two different levels. On the simplest and most conservative level, linear elastic fracture mechanics, with or without a plastic zone size correction, can be used to ensure that tearing instability will not occur under elastic conditions, within specified ranges of flaw size and load. This method can be used to determine a conservative margin of safety in terms of load, using a specified part-through crack size and the initial yield load based on the unirradiated yield stress.

On the other level, the determination of a condition of tearing instability for either a specified load or a specified flaw size requires analytical methods developed for the purpose. P. C. Paris has suggested a graphical method of solving tearing instability problems, based on a plot of the toughness J versus the tearing modulus T. Two curves are plotted in these coordinates, the first being a material property curve and the second being a curve of J versus the value of T required for crack stability. The intersection of the two curves defines a condition of tearing instability. This method has the advantage of graphical simplicity, but the disadvantage of either neglecting the amount of stable crack growth that preceeds failure, or requiring additional steps to account for it.

Other methods of analysis are being considered and evaluated by means of comparing calculated failure strains and pressures with the measured results from the HSST Program intermediate pressure vessel tests. Methods for estimating the relation between applied strain, flaw size and the value of J required for flaw stability are numerous. Two such methods currently being considered are LEFM based on strain and the tangent modulus method. The former method appears to be applicable up to the point of gross yielding, beyond which it becomes increasingly conservative. The latter method shows promise of maintaining accuracy into the strain hardening range, and is currently being evaluated by making posttest calculations for HSST Program intermediate test vessels, V-1, V-3, and V-6, in which substantial amounts of stable crack growth developed before failure.

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3. J. R. Hawthorne (editor), *The NRL-EPRI Research Program (RP886-2), Evaluation and Prediction of Neutron Embrittlement in Reactor Pressure Vessel Materials, Annual Progress Report for CY 1978*, NRL Report 8326, U.S. Naval Research Laboratory, Washington, D.C., August 30, 1979.

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