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Extrapolation of the J–R Curve for Predicting Reactor Vessel Integrity

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Prepared for
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ABSTRACT

The work in this report was conducted in support of the issues studied by the U.S. Nuclear Regulatory Commission (NRC) J_D/J_M Workers Group during the period 1987-1989. The major issues studied were the *J-R* curve extrapolation techniques for using small-specimen test results to predict ductile instability in larger structures where the extent of crack extension from the small-specimen test was not sufficient. This included the choice of parameter in characterizing the *J-R* curve, deformation *J*, or modified *J*, J_M. These issues are studied both by comparing small- and large-specimen *J-R* curves and by using *J-R* curves from smaller specimens to predict the behavior of larger specimens and pressure vessel models.

An additional issue was raised during the course of this work by the testing of a low-upper-shelf A 302 steel. The results from these tests were not typical of ductile fracture in many steels and suggested that small-specimen *J-R* curves may not predict the behavior of large structures in some cases. The causes of this behavior were studied as well as the consequences of using the *J-R* curve results from small specimens of this kind of material.

Finally, a discussion and recommendations are given relating to the use of extrapolated *J-R* curves.

CONTENTS

Page

LIST OF FIGURES

LIST OF TABLES

FOREWORD

The work reported here was performed at Oak Ridge National Laboratory under the Heavy-Section Steel Technology (HSST) Program, W. E. Pennell, Program Manager. The program is sponsored by the Office of Nuclear Regulatory Research of the U.S. Nuclear Regulatory Commission (NRC). The technical monitor for the NRC is M. E. Mayfield.

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1. INTRODUCTION

The prediction of ductile fracture behavior in large structures requires a methodology that incorporates a fracture criterion along with the material deformation properties. The fracture criterion can be incorporated in a number of ways. For example, a single value of toughness such as J_{IC}, the fracture toughness of materials near the onset of stable tearing, can be used. A second way to use toughness in a fracture methodology is in the form of a curve such as the *J-R* curve, which plots *J* vs ductile crack extension. The former criterion often tends to be too restrictive; hence a fracture methodology based on the *J-R* curve may be more desirable.

The fracture methodology based on the *J-R* curve often uses crack extension from small specimens to predict the stability behavior of larger structures. The small specimens may not produce enough crack extension to develop a sufficient *J-R* curve for the large structure; hence, extrapolation of the small-specimen *J-R* curve may be necessary. Attempts to establish rules for allowing *J-R* curve extrapolation led to some discussion between groups involved in ductile fracture testing and applications. These groups included the Elastic Plastic Fracture Subcommittee of the American Society of Testing and Materials (ASTM E24.08) and the American Society of Mechanical Engineers (ASME) Section XI Task Group on Reactor Vessel Integrity Requirements. Several issues relating to the use of *J-R* curves were raised, including the proper parameter to use in characterizing the *J-R* curve, *J* or J_M; the reasons for the limits in the ASTM test methods, which severely restrict the amount of ductile crack extension allowed in a *J-R*-curve test; and the methods for extrapolating the *J-R* curve when necessary.

In order to address these issues, a Working Group (WG) was established by M. E. Mayfield of the U.S. Nuclear Regulatory Commission (NRC) with the goal of solving many issues relating to the use of small-specimen *J-R* curves for ductile fracture prediction in larger structures such as reactor pressure vessels. The group was led by E. M. Hackett of the David Taylor Research Center (DTRC) in Annapolis, Maryland. This group, known as the J_D/J_M Working Group, first met in August 1987 and subsequently met regularly until September 1989. At least eight group meetings were held during this time. The University of Tennessee (UT) participated in this group through the support of the NRC-sponsored Heavy-Section Steel Technology (HSST) Program at Oak Ridge National Laboratory (ORNL).

The work conducted at UT was focused on the issues raised by the J_D/J_M WG, namely the ones listed above. This was done by both examining the basic character of the *J-R* curves themselves and by constructing structural models through which these issues could be further examined. In addition, new issues were raised during the course of the WG meetings, and additional work was done to examine these new issues. This included work done under the support of the above projects and unsupported work done to solve problems raised by the WG. This report is a final summary of all of the work done at UT in support of the issues raised by the J_D/J_M WG.

2. BACKGROUND

The establishment of requirements for reactor vessel integrity requires a methodology for ductile fracture. Many ductile fracture methods are based on the *J-R* curve fracture toughness. The laboratory test method to develop the *J-R* curve is ASTM Standard E 1152-87 (Ref. 1), which is based on an elastic unloading compliance method of crack extension measurement. It has strict requirements for establishing a valid experimental J-R curve, among them being a limit on the total crack extension allowed during the test. Theoretically, tests on specimens that do not meet validity requirements can be repeated with larger specimens; the size of the specimen would be increased until validity is satisfied. Practically, however, the tests to establish reactor vessel integrity are often conducted on irradiated specimens for which the size is predetermined. Tests that fail validity cannot be repeated.

One major issue in developing adequate *J-R* curves for vessel integrity is the total crack extension in the *J-R* curve, especially when the fracture methodology is based on ductile instability prediction. For a large structure such as a reactor vessel, the ductile instability will often occur at a point on the *J-R* curve which has significant crack extension, something much greater than the crack extension that can be generated on a valid ASTM *J-R* curve test for the small-size irradiated specimens. Hence, for reactor pressure vessels, adequate material fracture toughness data often cannot be generated by the standard test method to use in a methodology based on a ductile instability prediction.

There are several approaches to solving this problem. One is to use a different methodology; the fracture point can be based on a measure of toughness before the ductile instability point. The point of ductile fracture initiation, J_{IC}, has been used in the past. As an alternative, a fixed point on the *J-R* curve which presumably occurs before instability can also be used. These are sometimes unsatisfactory because they do not allow a quantitative margin of safety to be established. A fracture prediction based on an arbitrary point may range from unconservative to overly conservative.

To use a fracture criterion based on instability, something must be done about the restrictive validity requirements. The present requirements of ASTM E 1152 were largely based on numerical results and did not have experimental verification. A series of tests was conducted to determine the consequences of developing *J-R* curves that went beyond the validity limit on crack extension.[2] These tests were conducted on various sizes of specimens to try to determine at what value of crack extension the smaller-specimen tests failed to predict the behavior of larger specimens. These results showed that the E 1152 validity limits did not represent the point where test results gave inconsistent *J-R* curves. *J-R* curves could be developed well beyond these limits with no apparent problem. The tests did raise a question about the proper parameter to use in developing the *J-R* curve beyond the E 1152 limits. This method uses a measure of *J* called deformation *J*, J_D. It is the *J* related to the *J* integral of Rice[3] and is the characteristic strength of the crack-tip singular stress and strain fields for nonlinear analysis.[4] Studies by Ernst[5] had suggested an alternate parameter, the modified *J*, J_M, as a more appropriate parameter for characterizing *J-R* curves at crack extensions that exceed those allowed by the test standards.

The results of Ref. 2 showed that the J_D rather than the J_M appeared to correlate the *J-R* curves of the various sizes of specimens that were tested to large crack extensions. These results also suggested that the crack extension from small laboratory specimens, the type that would be tested for a reactor vessel integrity evaluation, could be taken beyond the present limits of ASTM E 1152. However, the longest crack extensions would not be sufficient to develop a full ductile fracture methodology to predict instability in large structures. Therefore, in addition to allowing longer crack extension from the *J-R* curve, an extrapolation would be required to develop the full extent of the *J-R* curve needed.

In order to develop a reactor vessel integrity requirement based on a ductile instability analysis method, a number of questions had to be answered.

- Can the ASTM E 1152 validity requirement on total crack extension be relaxed to allow longer crack extension to be developed in the *J-R* curve test for all materials of interest?
- If so, what is the new limit on crack extension that should be allowed?
- What parameter should be used to characterize the longer *J-R* curves—J_D or J_M?
- When a *J-R* curve extrapolation is needed, what should the basis for extrapolation be?

The NRC Working Group on J_D/J_M Issues organized by M. E. Mayfield and led by E. M. Hackett was assembled to address these issues. The initial thrust was to use existing data to reevaluate all of these issues. Additionally, a test program was planned on a low-upper-shelf (LUS) A 302 steel which would be conducted on a range of specimen sizes such that the values of crack extension in the test would exceed the E 1152 limits. This set of data was to supply the final calibration to the answers suggested by the J_D/J_M WG.

The University of Tennessee participated in the activities of this group with the support of Martin Marietta Energy Systems through the HSST Program at ORNL. At the time the group was organized, they had recently developed a new method for analyzing *J-R* curves from test-specimen load vs displacement records. This method, based on the normalizing properties of plastic flow, could provide more accurate *J-R* curves than the conventional elastic, unloading-compliance method, particularly at larger crack extension. This would be useful in evaluating the proper parameter for characterizing the *J-R* curve at longer crack extensions and could provide a better basis for *J-R* curve extrapolation. In addition, they were working on a ductile fracture methodology based on the work of Ernst and Landes[6] which could provide a format based on structural evaluations for assessing use of the J_D/J_M parameters as well as the methods for extrapolating the *J-R* curve.

The areas addressed at UT in support of the J_D/J_M WG included

1. Study of the J_D vs J_M issue. This work took data from the literature as well as the new data being generated by the WG and reevaluated all *J-R* curve results using the method of normalization. The *J-R* curves at long crack extension from small specimens were compared with those from larger specimens using both J_D and J_M. *J-R* curves generated with both parameters were used in the ductile fracture methodology to predict behavior of other specimens and structures.

2. Study of *J-R* curve extrapolation techniques. *J-R* curve extrapolation was studied, starting with the load vs displacement curve itself. Methods for extrapolating this curve

were used to infer an extrapolation of the *J-R* curve. This approach was unsuccessful; so further extrapolation studies were concentrated on the *J-R* curve itself. Extrapolation based on simple fits were done. The range of crack extension over which extrapolation could be made was also studied. The extrapolation techniques were further evaluated by using structural models in a ductile fracture methodology to assess their predictive qualities.

3. Use of V8A weldment *J-R* curves for predicting structural behavior. Data generated by Babcock and Wilcox (B&W) on V8A vessel weldment material was used to study the predictive capabilities of the ductile fracture methodology applied to reactor vessels. A method based on the ASTM A11 Committee analysis was used, along with a method for predicting the V8A test vessel behavior. The A11 Committee approach was used in a sensitivity study to look at the effect of various input variables on the prediction of fracture behavior.

4. Evaluation of A 302 steel LUS data. The A 302 steel LUS data that were generated as a final calibration of the work in support of the J_D/J_M controversy and *J-R* curve extrapolation techniques were not as successful as hoped. In addition, these test results raised some new issues regarding the extrapolation of *J-R* curves from small-specimen test data for prediction of behavior in larger structures. The method of normalization was used to reexamine the *J-R* curve results for the A 302 steel. Various methods to explain the results were attempted on the basis of ratios of elastic to plastic deformation, test instability, and sampling position.

5. Evaluation of results relative to NRC LUS guidelines. The results from this work were used to evaluate an NRC LUS position for vessel integrity. The work from the above tasks was presented in the following sections. This represents a final report of the work conducted at UT in support of the J_D/J_M WG concerns. This report combines results of work conducted under two contracts by UT for the HSST Program and the work conducted under no outside support. This unsupported work accounts for more than half of the overall effort and is an integral part of the overall findings. It is included here so that this report will have technical completeness.

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*Available for purchase from National Technical Information Service, Springfield, VA 22161.

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3. DUCTILE FRACTURE METHODOLOGY

A fracture methodology is an integral part of a structural integrity evaluation. For materials like those used in nuclear reactor vessels, the range of service temperatures is such that any potential fracture would be by a ductile mode at a high value of fracture toughness. For this, a ductile fracture methodology is needed. A ductile fracture methodology based on the *J-R* curve and ductile instability was originally proposed by Paris et al.[1] This used the normalized *R*-curve slope called material tearing modulus, *T*, as the resistance to fracture. The material *T* taken from the *R* curve was compared with the applied *T*, the crack driving force, to determine the condition for stability (Fig. 3.1). This approach is often used in a format where *J* is plotted as a function of *T* in a *J-T* diagram.[2] An intersection between the material and applied *J-T* curves marks instability (see Fig. 3.2).

The *J-T* approach, although commonly used, does not present the stability point in terms of parameters familiar to engineers. An approach originally proposed by Ernst and Landes[3] was based on the *J-R* curve but presented the stability analysis in terms of more familiar parameters such as load and displacement or strain. This approach was further developed at UT in cooperation with the U.S. Navy's David Taylor Research Center to provide an easy-to-use ductile fracture methodology.[4] Although this approach was not developed under the program, it is included briefly in this report because it is used frequently as a tool for examining the various issues related to choice of parameters and *J-R* curve extrapolation techniques.

The ductile fracture methodology combines two separate pieces of information to determine the total response (Fig. 3.3). The first is information on the deformation character of the material; this is often called the calibration functions. It relates the various parameters used in the analysis, usually load, *P*, displacement, *v*, crack length, *a*, and fracture parameter, *J*. The calibration functions provide two equations to relate the four parameters. For a complete description of the behavior, a third equation is needed. This comes from the fracture behavior. For ductile fracture, the *J-R* curve is a usual way to supply this relationship. The methodology is shown graphically in Fig. 3.4. The first calibration equation gives the relationships between load and displacement for a fixed crack length. This represents a family of *P-v* curves, each for a fixed crack length. The second calibration equation gives the relationships between *J* and load at a fixed crack length. The criterion for changing crack length comes from the *J-R* curve fracture toughness and provides the third equation to describe the relationship between the four parameters. A fourth equation or condition, namely, an instability criterion, describes the behavior of the structure being analyzed.

The deformation properties used in the calibration functions can be determined experimentally or numerically. Experimentally, a load vs displacement can be developed for a fixed crack length by testing a blunt-notched specimen for the geometry of interest. Numerically, the load vs displacement behavior can be developed using finite-element analysis with the flow properties of the material as determined from a tensile test. For certain standard geometries, these numerical solutions exist in a handbook.[5] Methods for best using these handbook solutions in a ductile fracture methodology have recently been outlined.[6]

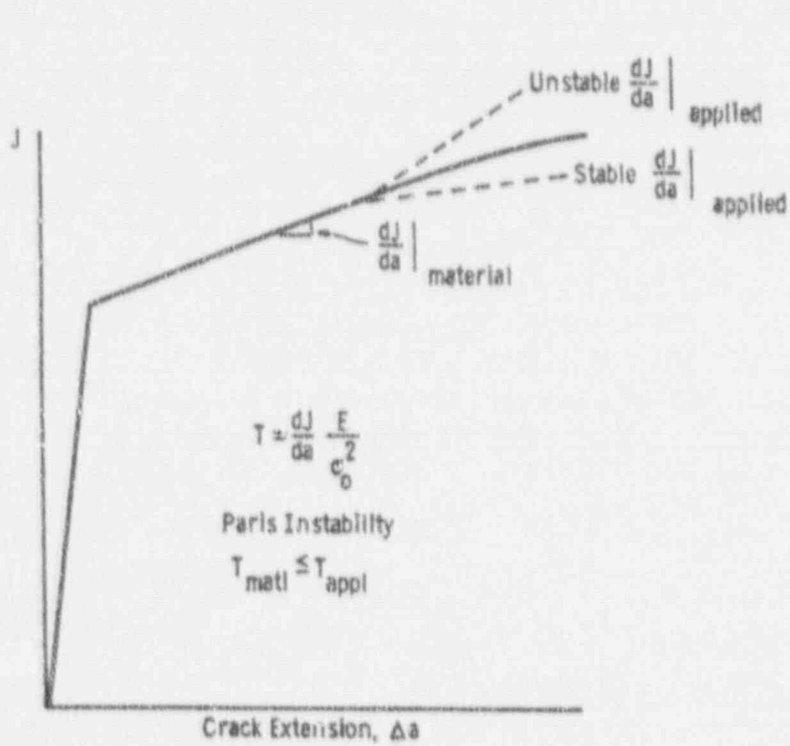

Fig. 3.1 Ductile instability based on the tearing modulus approach of Paris et al.

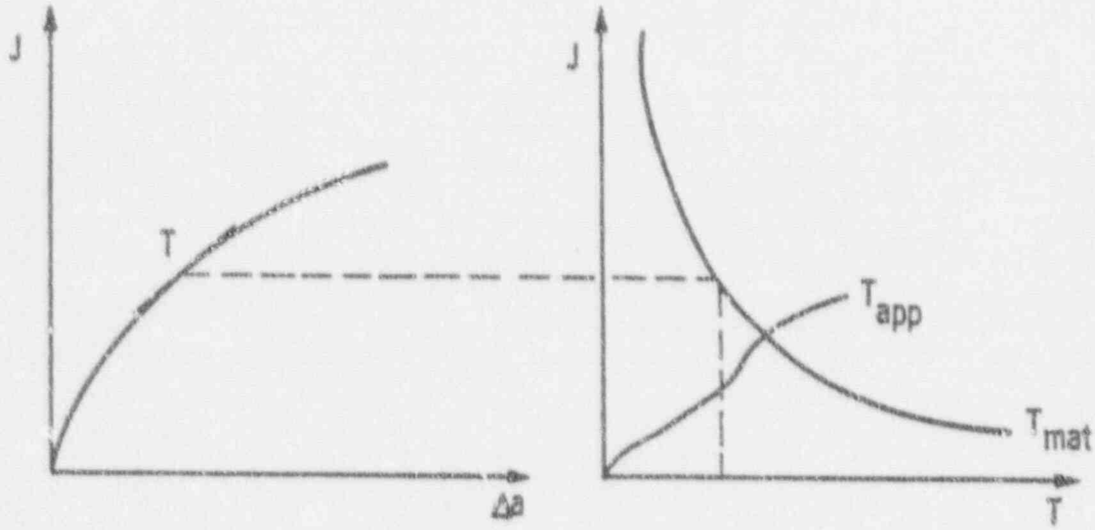

Fig. 3.2 J-T diagram approach to instability prediction.

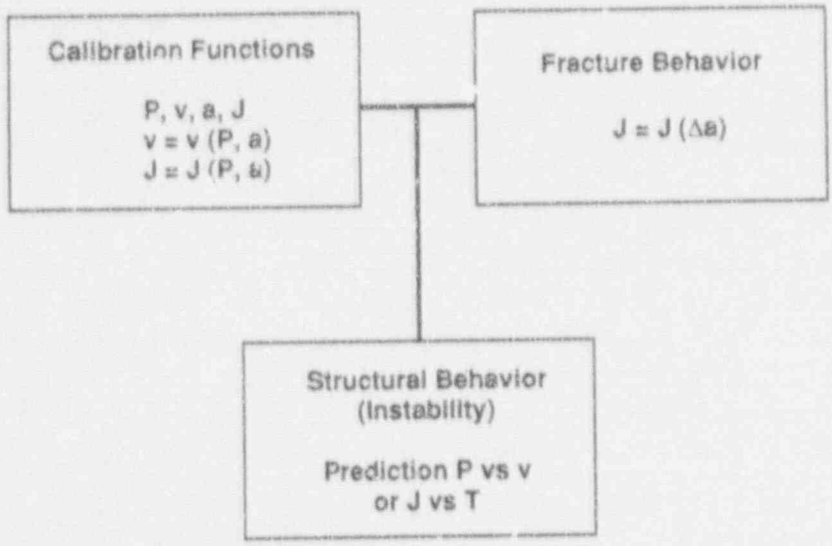

Fig. 3.3. Schematic of ductile fracture methodology based on combining calibration functions with fracture behavior.

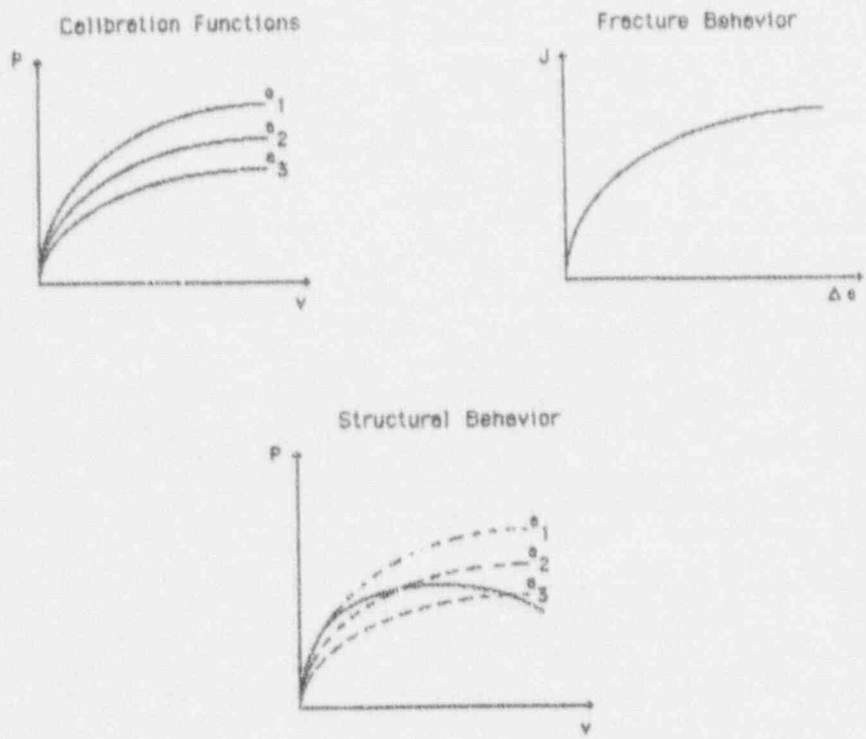

Fig. 3.4. Graphical representation of ductile fracture methodology.

The fracture toughness in the J-R curve format forms the second part of the methodology. Fracture toughness may be a function of structural size, geometry, and thickness.[7] Care must be taken in determining the correct toughness for the material and structure being analyzed. Of particular concern is having enough of an R curve to complete the analysis of structural behavior. When a small specimen is used to develop the material toughness property, it often does not contain sufficient crack extension to completely analyze a larger structure.

The methodology as originally proposed by Ernst and Landes[3] used the J-R curve as characterized by the modified J, J_M (Ref. 8), rather than the standard deformation J. This was thought to take care of some of the size and geometry effects observed, especially at the longer crack extensions.[9] The work in these contracts shows that the deformation J, J_D, will give a more conservative analysis. Also, it is easier to use in the methodology because deformation J is given in the calibration functions.

The steps involved in using the methodology are shown in Fig. 3.5. An initial defect length, a, is chosen. The independent variable is the plastic displacement, v_{pl}. As this is incremented, all other parameters can be determined by combining the calibration curves with the J-R curve. When it is not appropriate to use displacement for a structure, a strain value or J can be used as the independent variable. An example of the predictive capabilities is given in Figs. 3.6 and 3.7. It is worth noting that the choice of v_{pl} as the independent variable is arbitrary. Another parameter such as crack length could be chosen as the independent variable. All other variables are determined as a function of crack length

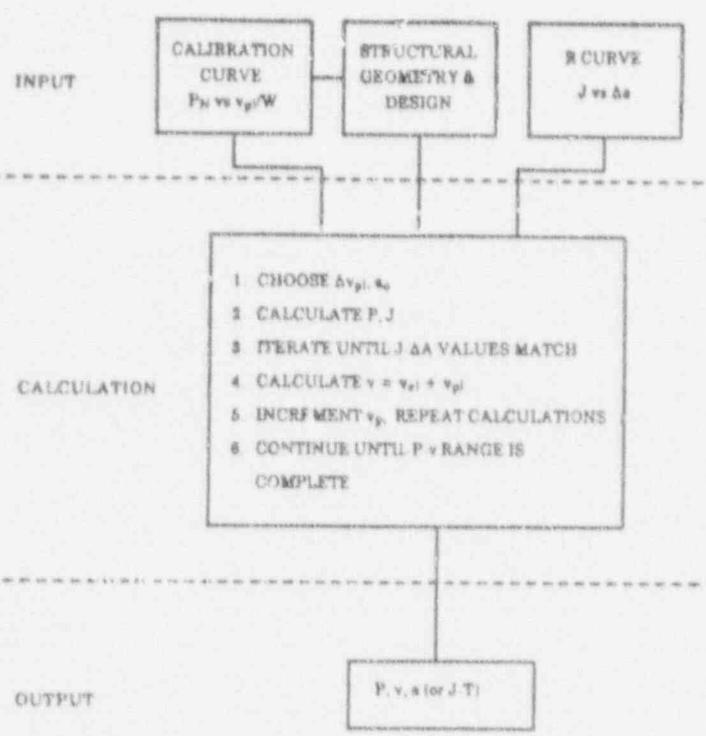

Fig. 3.5 Flow diagram of steps involved in ductile fracture methodology calculations.

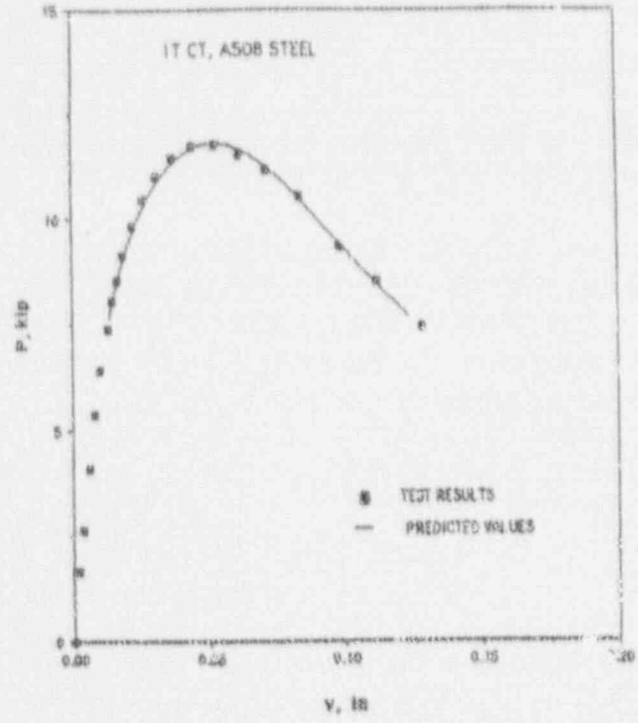

Fig. 3.6. Predictive capability of ductile fracture methodology for A 508 steel.

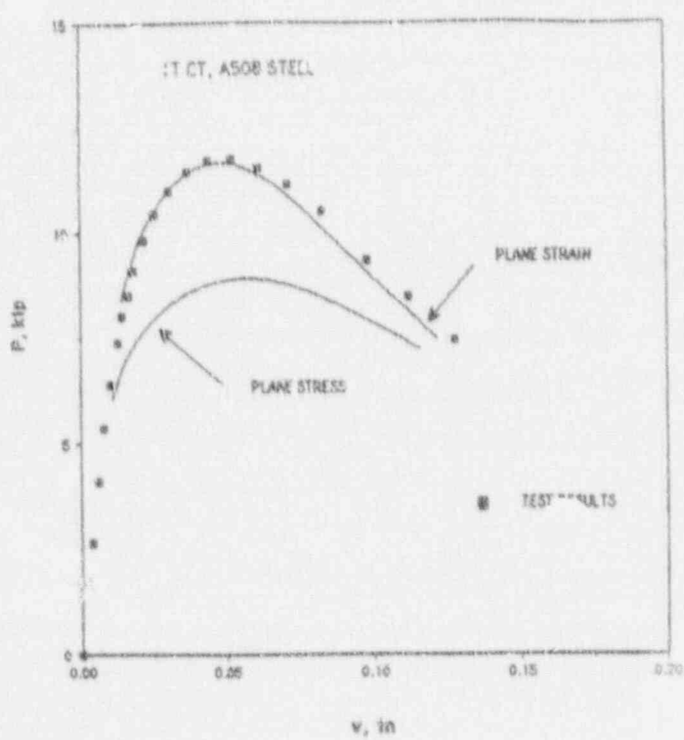

Fig. 3.7. Example of plane strain vs plane stress predictive for ductile fracture methodology.

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4. NORMALIZATION ANALYSIS AND *J-R* CURVE TWIST

A new method for analyzing the *J-R* curve from an experimental load displacement record labeled normalization analysis was developed at UT.[1-3] This method was based on the key curve approach.[4] It uses the ductile fracture methodology of Fig. 3.3 in reverse. The methodology takes the calibration functions and the *J-R* curve to determine the structural load vs displacement relationships. The normalization method starts with the load vs displacement record and separates that into a calibration curve and a *J-R* curve. With this method the *J-R* curve can be developed without the usual crack length monitoring equipment. In using the methodology of Fig. 3.3, two of the curves must be known to predict the third. To use the normalization method, the calibration curve must be developed from calibration points in the test. The method assumes a functional form with unknown constants.[1] These constants can be determined at points where load, displacement, and crack length are all known, namely, at the beginning and end of the test, where crack lengths are measured on the fracture surface.

Using a calibration point at the end of the test based on a physically measured crack length forces the *J-R* curve to go through that point. That means that the final *J-R* curve point is at the correct crack extension as determined physically. This is an important factor for the extrapolation of the *J-R* curve. Automatic crack-length monitoring systems can give some error in crack-length measurement. This error in crack length influences the *J* calculation. The total effect is a twisting of the *J-R* curve[5] (see Fig. 4.1) when a given point has an error in crack-extension measurement. Errors in several successive points can lead to an incorrect trend. When the *J-R* curve is to be used for extrapolation, this incorrect trend at the end of the curve can give a large error in the extrapolated *R* curve (see Fig. 4.2). Examples of R curves with incorrect end trends along with the normalization correction are shown in the following two figures. Figure 4.3 shows the result of incorrect compliance measurement for an A 508 steel *J-R* curve, along with the corrected *J-R* curve from normalization. Here, an overestimate of the compliance crack extension resulted in a negative *J-R* curve slope. Extrapolation of this *J-R* curve would give a continuing negative slope, which would be grossly overconservative. Figure 4.4 shows a *J-R* curve for a high-strength low-alloy (HSLA) steel where the crack-extension estimate was too short. Here, the final trend is too steep and would lead to an unconservative extrapolation. Considering these examples, it is advisable to use the normalization analysis to reanalyze *J-R* curves that will be used for extrapolation.

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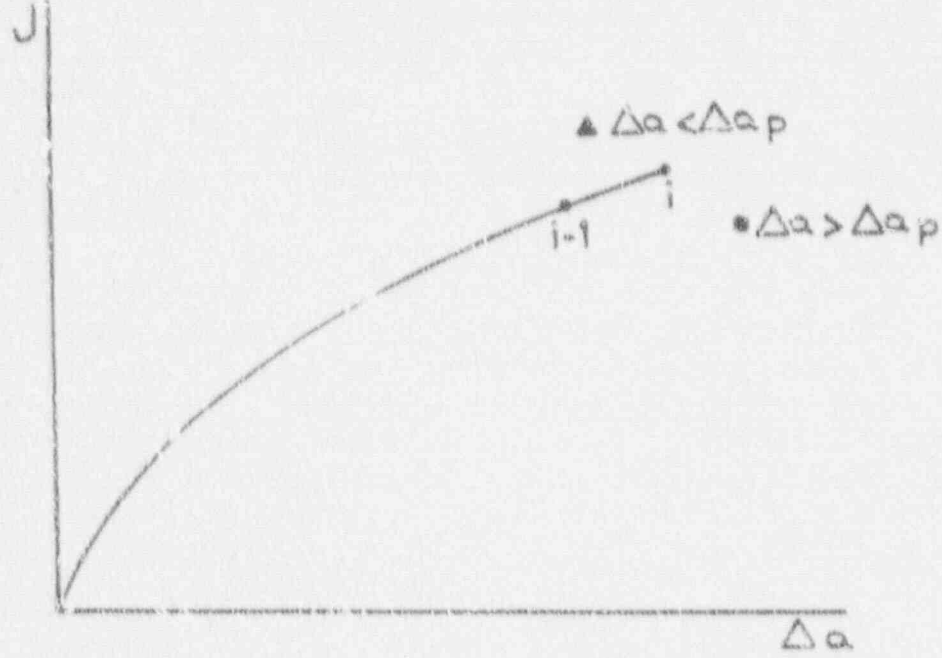

Fig. 4.1 Schematic showing effect on J-R curve of incorrect crack length measurement.

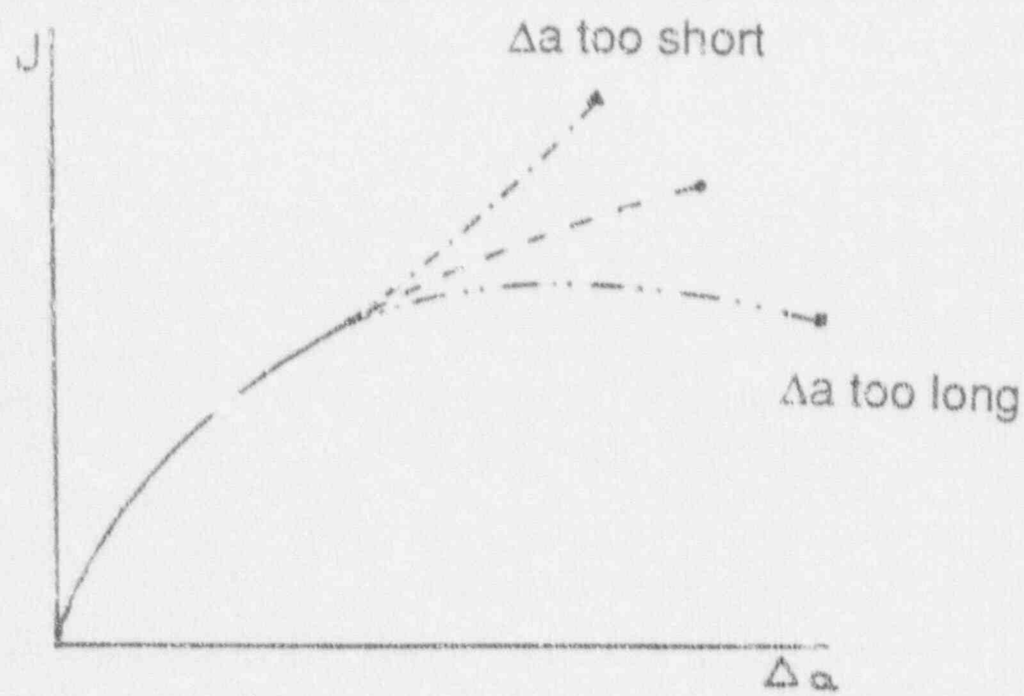

Fig. 4.2 Schematic showing cumulative effect of incorrect crack length measurements.

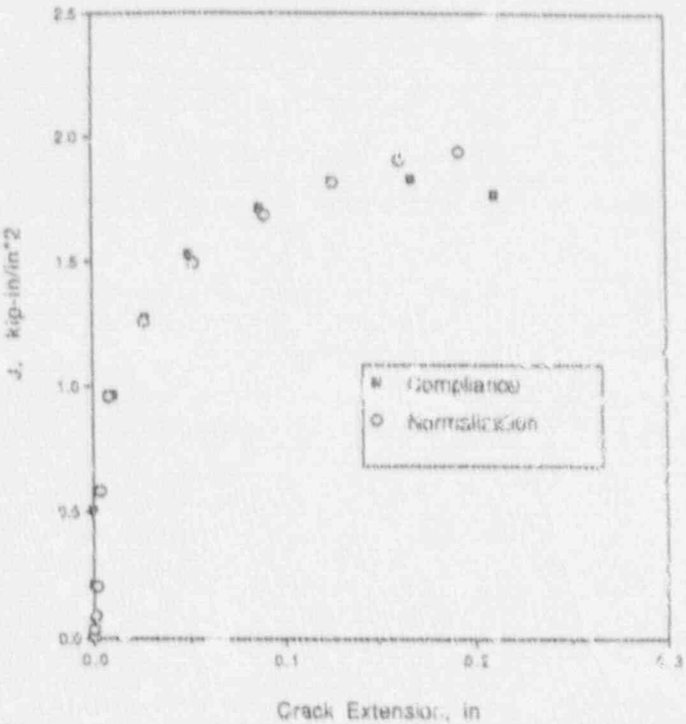

Fig. 4.3. J-R curve for an A 508 steel comparing compliance and normalization measurement of Δa.

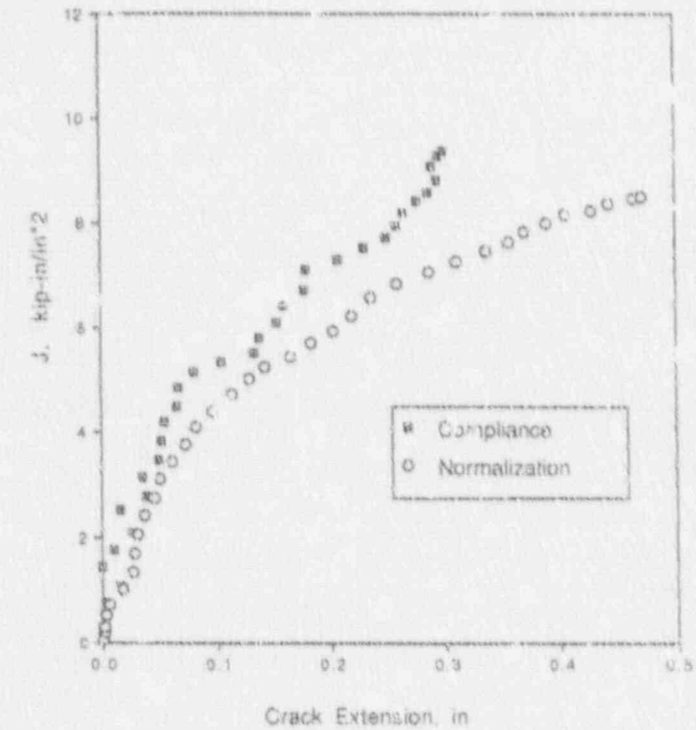

Fig. 4.4. J-R curve for an HSLA steel comparing compliance and normalization measurement of Δa.

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5. MODIFIED *J*

The *J-R* curve approach to fracture toughness characterization was originally based on deformation *J*.[1] These results often showed some evidence of size and geometry effects.[2] A ductile fracture methodology, which uses the *J-R* curve from a laboratory specimen to predict the behavior of a structure of much larger size and different geometry, must have a specimen *J-R* curve that is appropriate for the structure. A modified *J* parameter, J_M, was proposed by Ernst as a parameter that could help eliminate size and geometry effects.[3] Size effects were eliminated by J_M in the *J-R* curve for an aluminum alloy where the tests were conducted on three sizes of compact specimens. Figure 5.1 shows the *J-R* curve for the three specimen sizes plotted with deformation *J* (simply labeled *J*); these show a size dependence at longer crack extension. Figure 5.2 shows the same result plotted with modified *J*, J_M. The size dependence is eliminated.

A series of tests sponsored by the Electric Power Research Institute (EPRI) was conducted at Westinghouse R&D Center in which an A 508 steel was tested using various sizes of compact specimens (see Fig. 5.3).[4] The results, when plotted with *J*, showed a size dependence somewhat like that of the aluminum data. At longer crack extension, the *R* curve in the smaller specimen goes below that of the larger one. Again, J_M appeared to eliminate this size dependence (Fig. 5.3). Upon reexamination of the results, it was discovered that the *J-R* curves, evaluated by the standard elastic unloading compliance method, had an error in the final crack length which caused a mismatch twist.[5] This twist gave a trend in the *J-R* curve behavior which is an artifact of the test technique and analysis method rather than a true physical effect. The method of normalization was applied to the data, and the *J-R* curves were reevaluated with *J* (Fig. 5.4) and J_M (Fig. 5.5). The reanalysis showed that there was some remaining size dependence for deformation *J*, although not so severe. The same data plotted with J_M showed a size dependence in an opposite way, with the smaller specimens having a higher trend in the *R* curve than the larger ones.

To study this further, the normalization analysis was applied to all available sets of *J-R* curve data generated on specimens of different sizes. In general, there was some scatter; sometimes *J* correlated the data better, and sometimes J_M was better. An example for an HSLA steel shows a good correlation with *J*, as given in Fig. 5.6. The same set of data plotted with J_M showed some size dependence (Fig. 5.7).

Results from tests conducted by Hackett and Joyce examined *J* and J_M correlations for *R* curve data conducted to very long crack extensions[6] (crack extension of about 70% of the initial uncracked ligament) (Fig. 5.8). The correlation with *J* was acceptable over this range, but J_M always gave a severe size dependence at longer crack extension.

All of these results cast some doubt upon the original conclusions that J_M was better than *J* as a parameter that eliminated size effects. Since the goals of this program were to extend ASTM limits on crack extension and to use these results for *J-R* curve extrapolation, it was important to get a parameter that would eliminate the size effect. The *J-R* curve testing for vessel integrity would be focused on small specimens; therefore, it is equally important that the small specimens do not give unconservative results, that is, a higher *J-R* curve or higher toughness than actually found for a pressure vessel geometry.

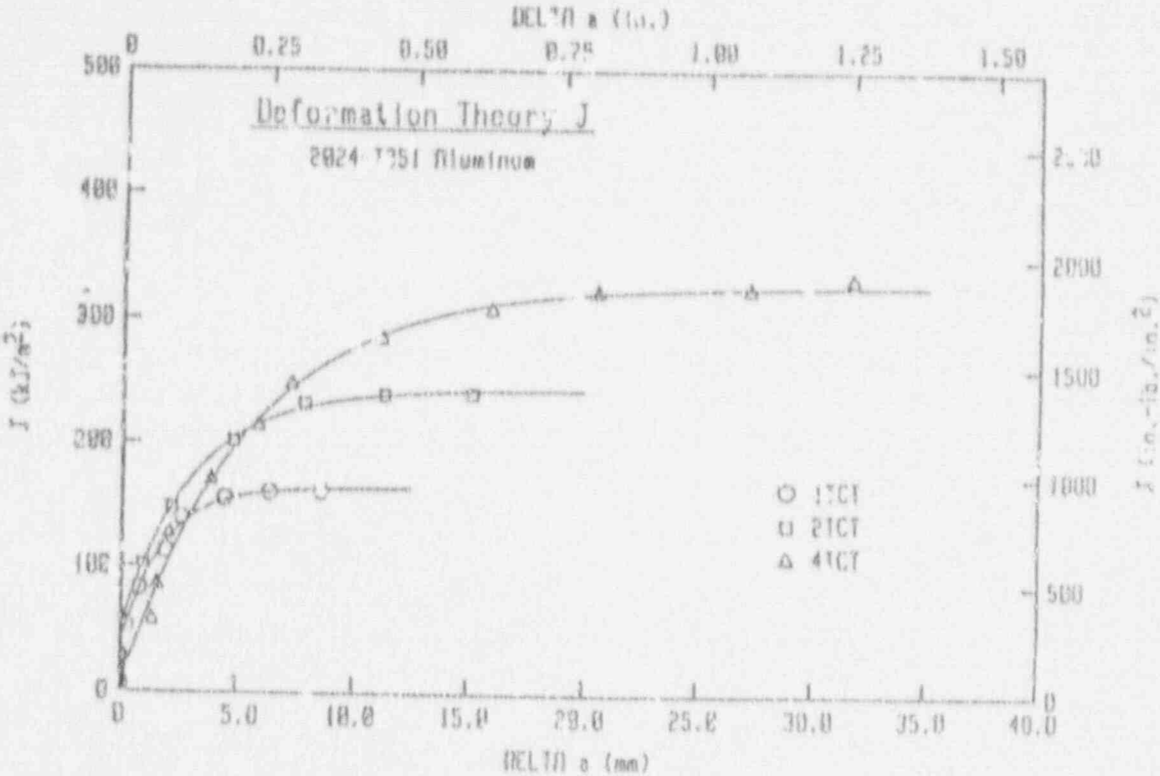

Fig. 5.1 Deformation J-R curves for an aluminum alloy showing size effect.

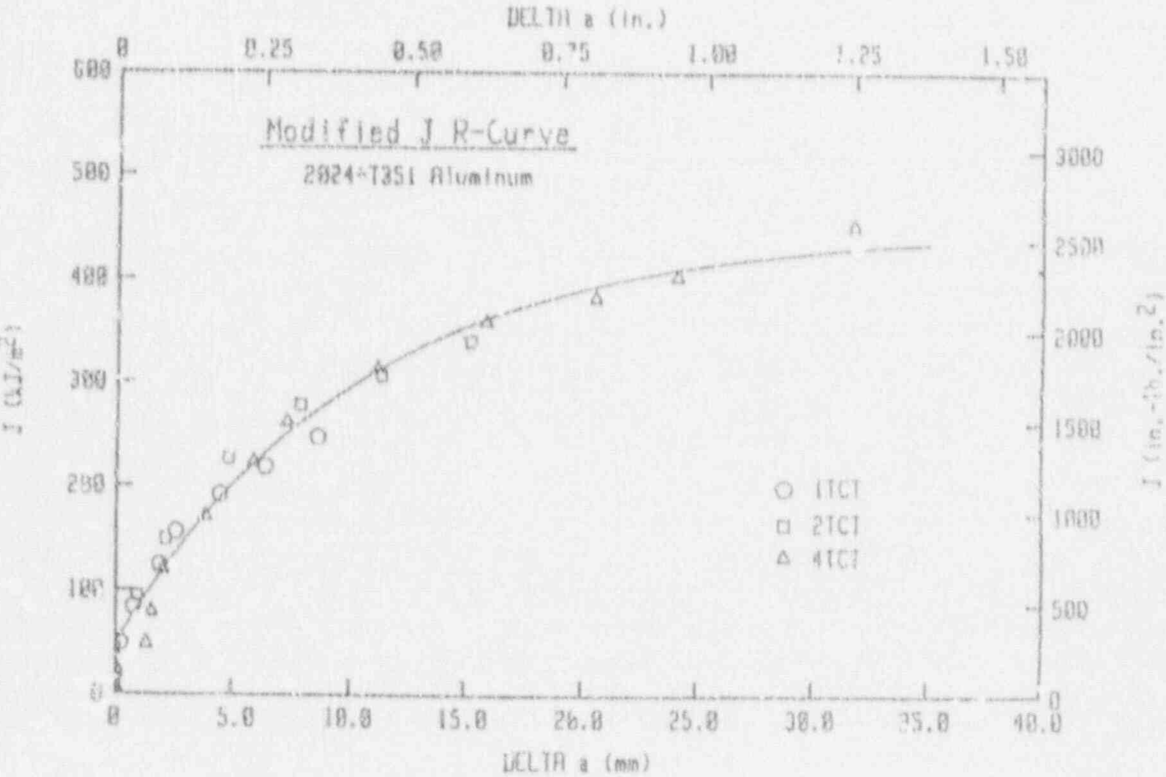

Fig. 5.2 Modified J-R curve for an aluminum alloy eliminating size effect.

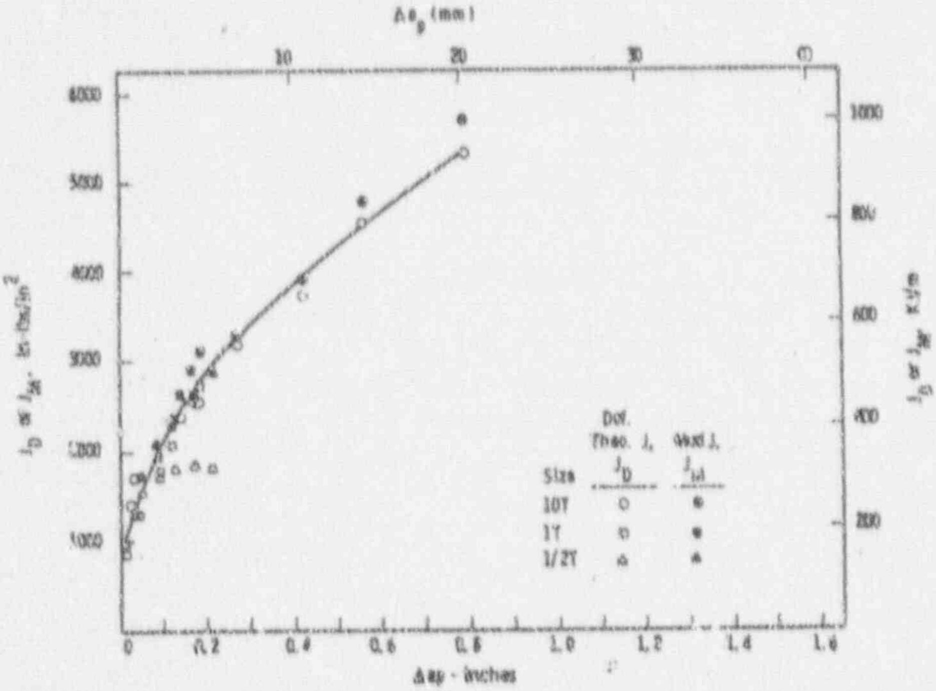

Fig. 5.3 J-R curve for an A508 steel, including J_D and J_M, Compliance measured Δa.

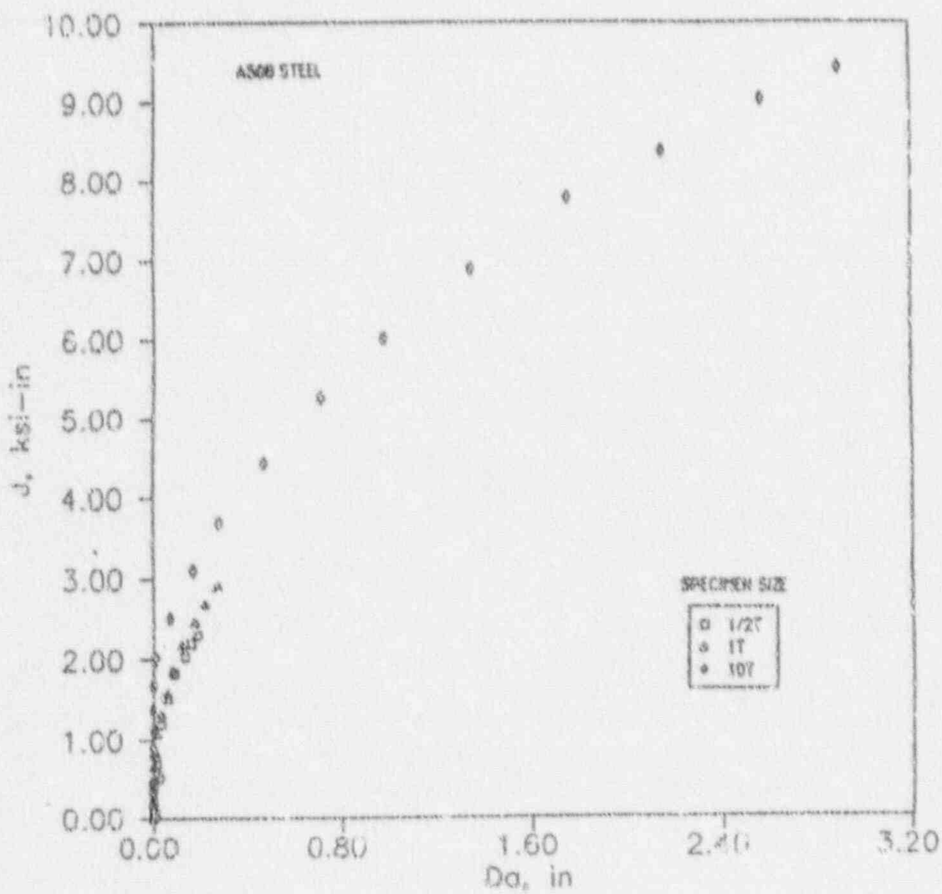

Fig. 5.4 Deformation J-R curve for an A508 steel using normalization analysis.

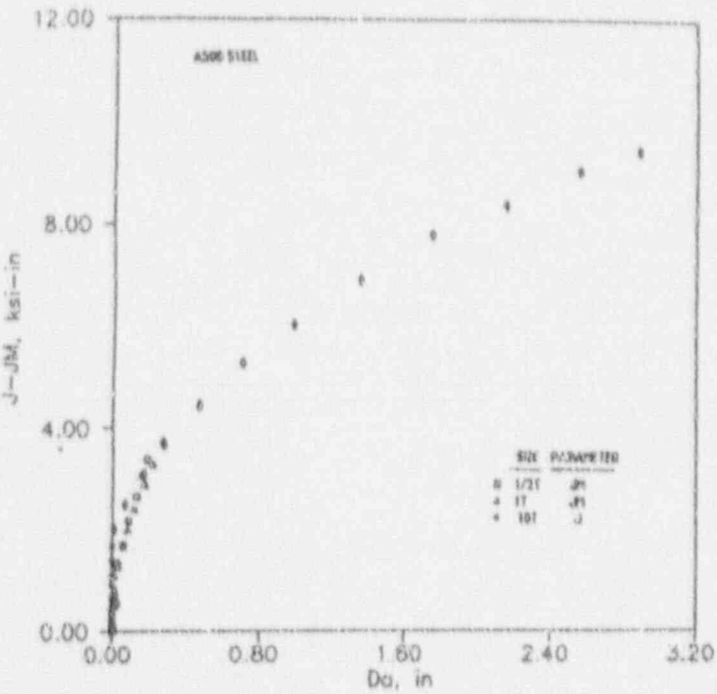

Fig. 5.5 Modified J-R curve for an A508 steel using normalization analysis.

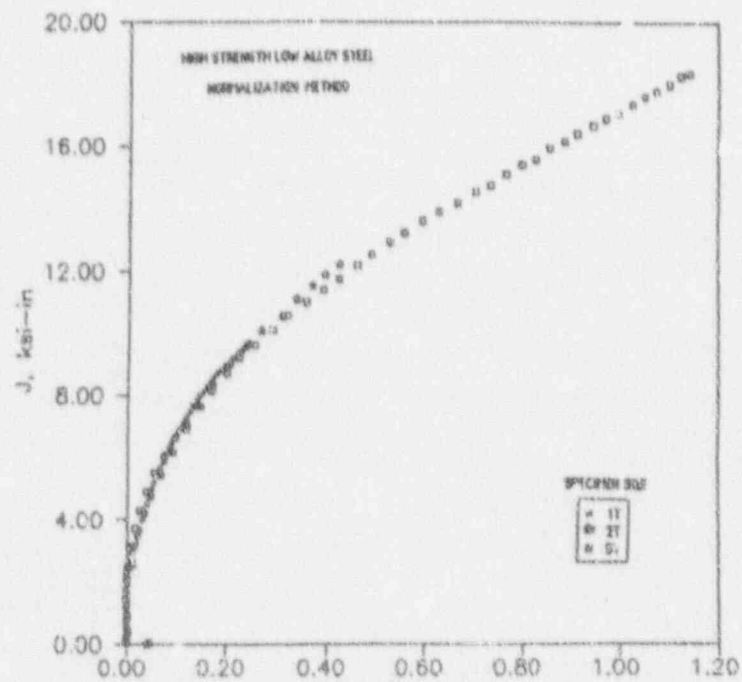

Fig. 5.6 Deformation J-R curves for an HSLA steel using normalization analysis.

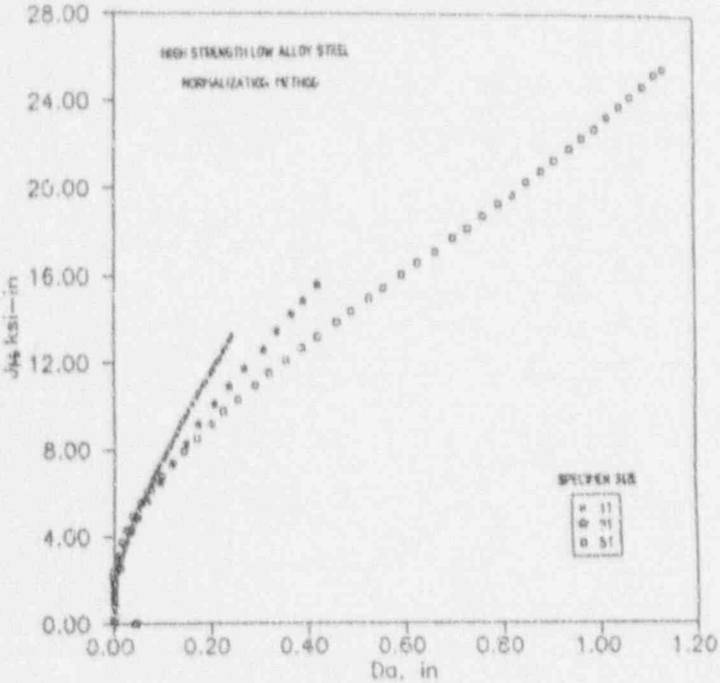

Fig. 5.7 Modified J-R curves for an HSLA steel using normalization analysis.

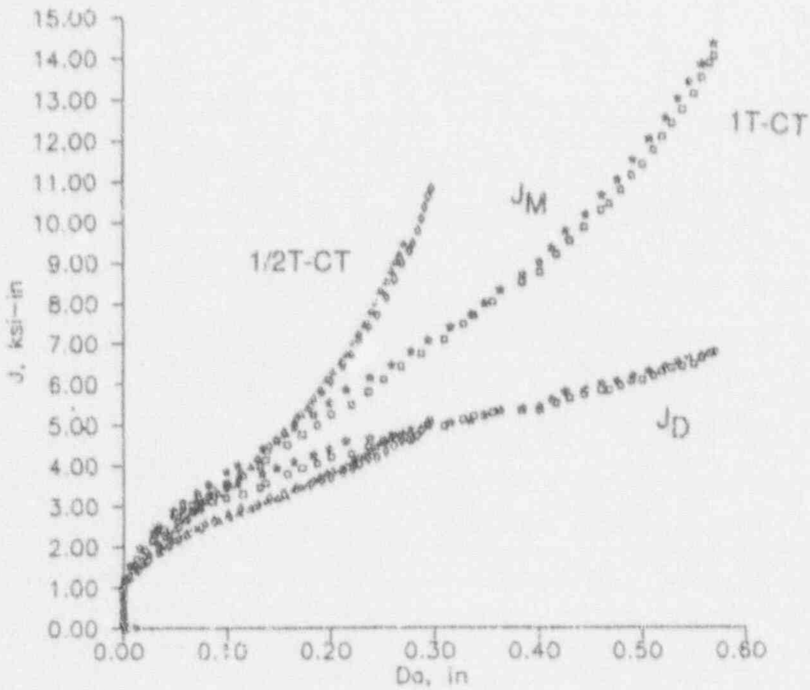

Fig. 5.8 J, J_M-R curves for an A533B steel showing size effect of J_M.

The uncertainty about whether to use J or J_M was one of the major issues addressed by the NRC WG. That and the development of m thods for extrapolating the J-R curve became the first set of tasks to be addressed. In the following sections, the issue of J-R curve extrapolation is treated as the primary one. However, this issue is examined with both J and J_M as the characterizing parameters of the R curve so that the issue of how to extrapolate the J-R curve can be evaluated relative to the correct parameter to use.

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6. *J-R* CURVE EXTRAPOLATION

The methods for *J-R* curve extrapolation are presented in this section. In order to present a complete picture of the work, the unsuccessful ideas are presented along with the successful ones. The section focuses on the basic ideas of extrapolation. These include (1) extrapolation assumptions on the load vs displacement (*P-v*) curve, (2) extrapolation on the *J-R* curve, (3) comparisons of *J-R* curve extrapolation, and (4) a set of guidelines for *J-R* curve extrapolation. After the guidelines were established for this program, they were used along with the ductile fracture methodology to make predictions of structural behavior. These predictions were used to give confidence to the extrapolation guidelines as well as to further examine the J-J_M issue. The work on structural predictions is presented in later sections.

6.1 *P-v* EXTRAPOLATION

The first examination of *J-R* curve extrapolation was centered on the behavior of the load vs displacement (*P-v*) records of the test specimens. Typically, the *P-v* curve from a *J-R* curve test has a characteristic shape (Fig. 6.1). The curve has an initial linear portion before significant yielding begins and becomes nonlinear as the yielding begins to spread. Ductile stable crack extension usually begins on the nonlinear region somewhere before maximum load. However, as the crack extension becomes significant, the load-bearing capacity of the specimen is greatly reduced, maximum load is reached, and the load begins to drop. With increased stable crack extension, the load continues to drop as displacement increases, giving a negative and often nearly straight-line slope to the *P-v* curve. If the test has been run to very large amounts of crack extension relative to the initial uncracked ligament, the *P-v* curve begins to show a decrease in negative *P-v* slope. Any test conducted with enough crack extension to develop an *R* curve has usually reached the unloading region of the curve.

Since this curve is so nearly reproducible from one test to another, it was thought that the *J-R* curve could be extrapolated by extrapolating the *P-v* curve. This is shown schematically in Fig. 6.2. The first idea was to do a linear extrapolation of the end of the *P-v* curve (Fig. 6.3). The unloading portion of the *P-v* curve appears to be linear over a significant region; so it was believed that a linear extrapolation of *P-v* would give a reasonable extrapolation on the *J-R* curve. The result was not good. The method of *P-v* extrapolation was important; it was, in fact, not linear. When the curve was fitted from just below maximum load until the end, the resultant *J-R* curve extrapolation was different from the one obtained from just fitting the last 10%. An extrapolation of a short amount was not bad; however, when further straight-line extrapolation on *P-v* was made (e.g., enough to extrapolate *J-R* another 50%), the trends in the *J-R* curve were not characteristic. A typical *J-R* curve as shown in Fig. 6.4 could have a number of results from *P-v* extrapolation. The points may alternately go up and down, giving an oscillating character (Fig. 6.5), or they could take a sharp turn up or down. The sharp turn up is shown in Fig. 6.6 as the high-rise *J-R* curve.

Since the linear extrapolation of *P-v* was not successful, a second idea based on load vs displacement manipulation was tried. This was based on an idea in which *P-v* records for

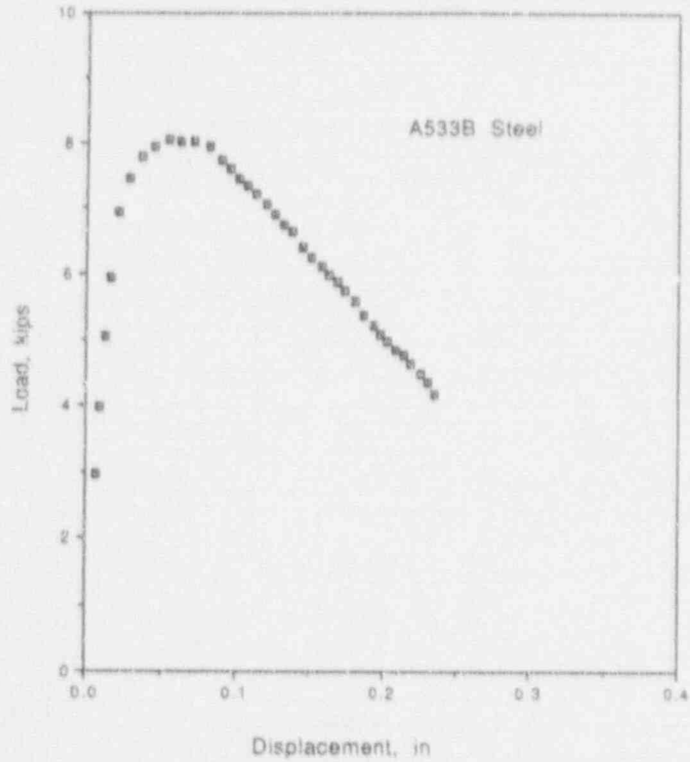

Fig. 6.1 Load vs displacement record, P-v for a J-R curve test.

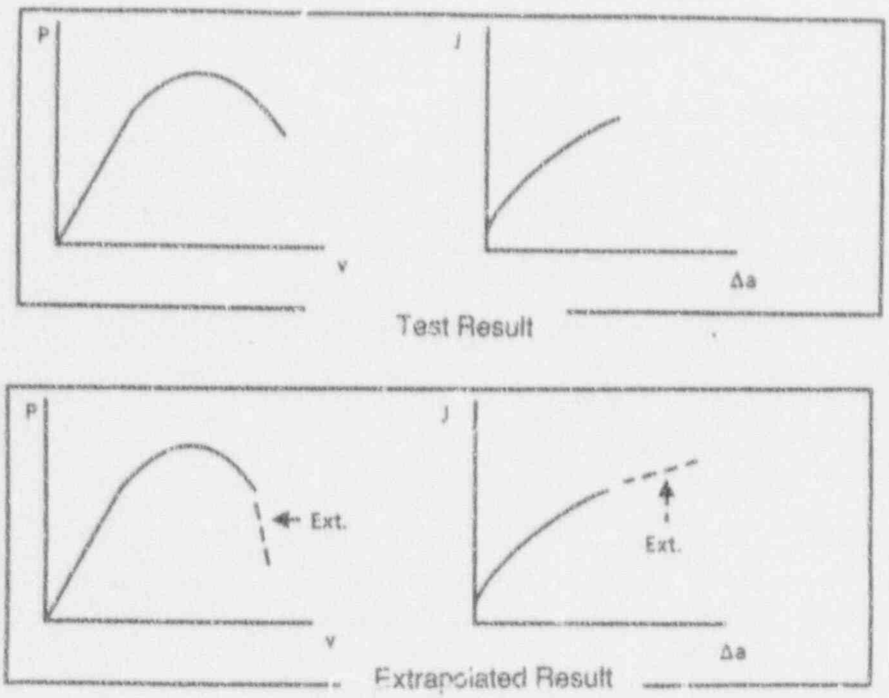

Fig. 6.2 Schematic of J-R curve extrapolation using P-v extrapolation.

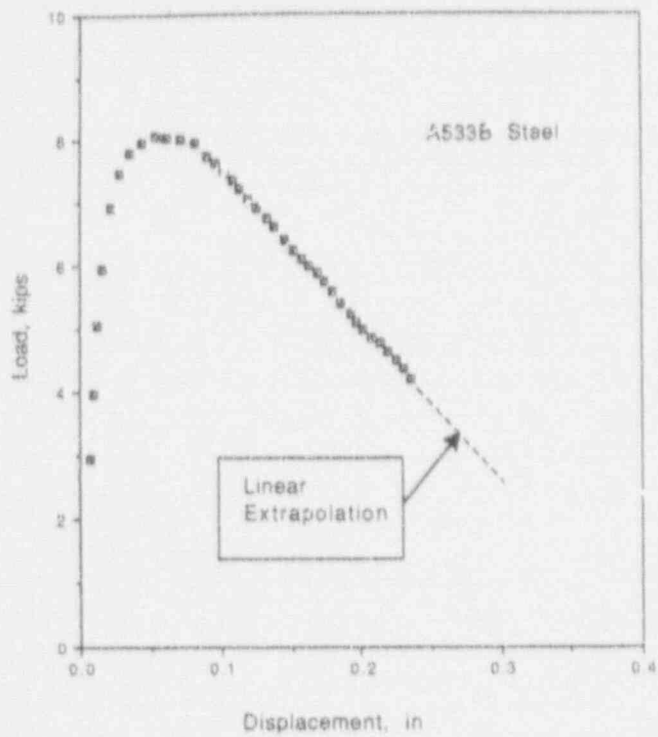

Fig. 6.3 Linear extrapolation of P-v curve.

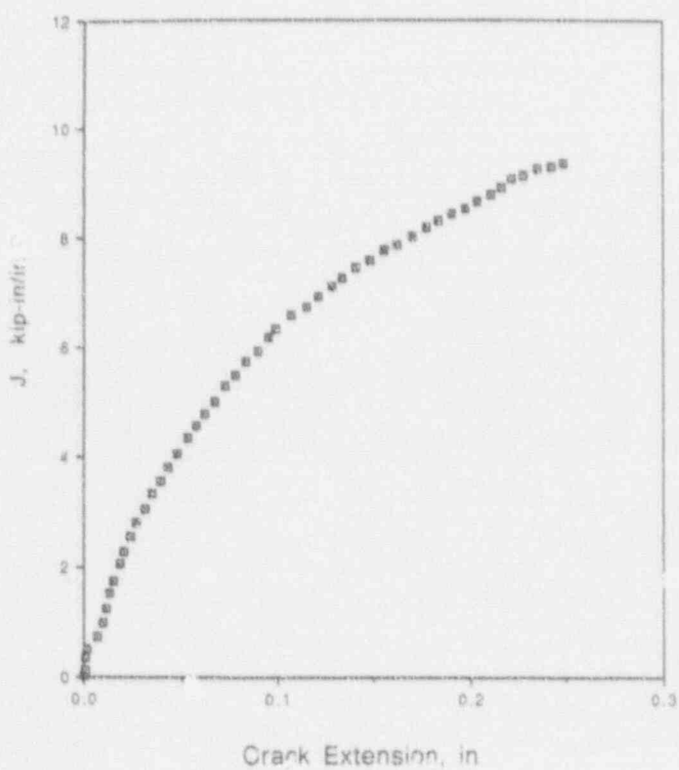

Fig. 6.4 Typical J-R curve from P-v record.

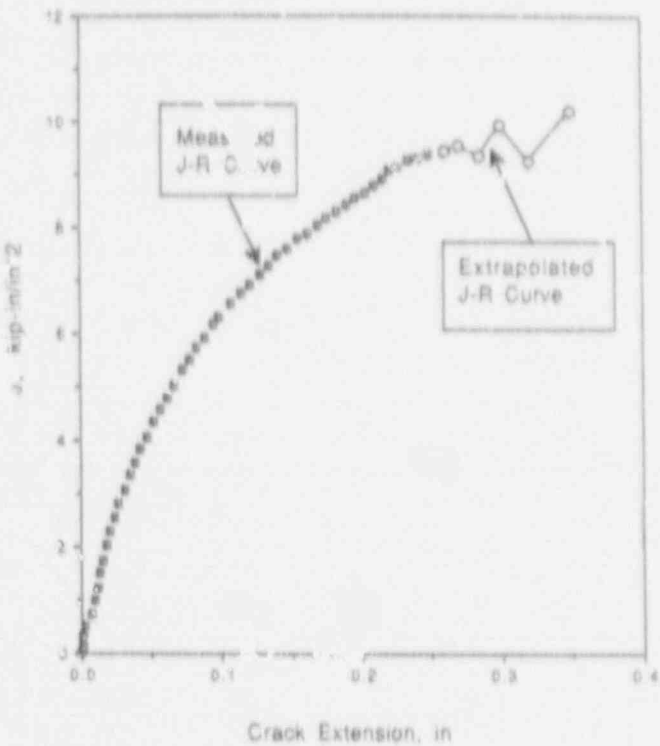

Fig. 6.5 Examples of results from P-v extrapolation; oscillating J-R curve.

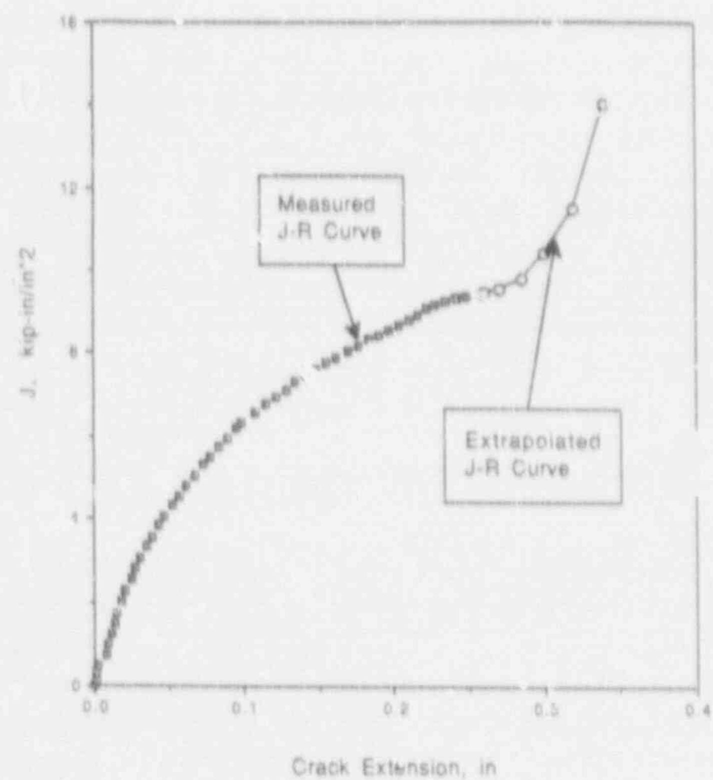

Fig. 6.6 Examples of results from P-v extrapolation high rise J-R curve.

different specimen sizes are compared. Larger specimens reach a higher value of the toughness parameter before yielding than the smaller specimens do. At any level of plastic deformation, the larger specimens have a higher J value than the smaller ones. Since the J-R curve is only slightly size dependent, the larger specimen generates much more J-R curve for equivalent amount of plastic deformation than does the smaller specimen. The idea of prediction of J-R curve extrapolation from a small specimen assumed that the shape of the P curve for a larger specimen could be inferred from that of the smaller one. If a small specimen is tested in a standard manner so that the final load is on the negative P-v portion well beyond the maximum load, a reasonable amount of crack extension would occur. If a specimen that is much larger were tested to the same point on the P-v curve, much greater crack growth would have occurred. Therefore, if the smaller and larger specimens have the same P-v shape, a small specimen can be tested, the shape of the P-v curve can be transferred to a larger specimen, and the J-R curve can be analyzed from the larger-specimen P-v curve in the usual manner. This method (Fig. 6.7) is a way to effectively extrapolate a J-R curve by assuming a P-v curve shape for the larger specimen.

Methods to do this were attempted; these centered around a way to normalize the P-v curve from the test so that the experimental result from the small specimen could be used to generate the larger-specimen P-v curve without the test. The load, P, was generally normalized by maximum load, P_{max}. The displacement was normalized by a variety of parameters, including a maximum displacement, P_{max}, and a specimen dimension such as uncracked ligament, b. The normalization with maximum load and plastic displacement was reasonable (Fig. 6.8); however, this was not sufficient to infer the large-specimen P-v record without a test. The problem came from the fact that a test was required on the larger specimen to measure the normalizing parameter (maximum load in this case) so that the normalized P-v record could be unnormalized in order to analyze it.

The use of P-v extrapolation to extrapolate the J-R curve was not successful. Although it seemed like a reasonable idea on one hand, on the other hand, it appears to violate the basic premise of the ductile fracture methodology—that is, that structural behavior under loading has two components of behavior. The deformation behavior (calibration functions) relates load to the elastic and plastic displacement. The fracture behavior relates the loading to the crack extension. The fracture and deformation behaviors are different and must be measured separately. Without a proper fracture toughness measurement, attempts to infer fracture toughness from deformation behavior fail.

6.2 *J-R* CURVE EXTRAPOLATION

The second approach to J-R curve extrapolation worked directly with the J-R curve itself. The choices that need to be made were what parameter to use for characterizing the R curve and what functional form to use for the extrapolation. Two parameters were used to look at extrapolation; deformation J (labeled J) and modified J (labeled J_M).

The extrapolation technique was formulated by getting data from materials where more than one size specimen was tested. The R curve from the smaller specimens would be extrapolated; the result would be judged by comparing this extrapolated J-R curve with one from a larger specimen of the same material. (Later structural models were used to further

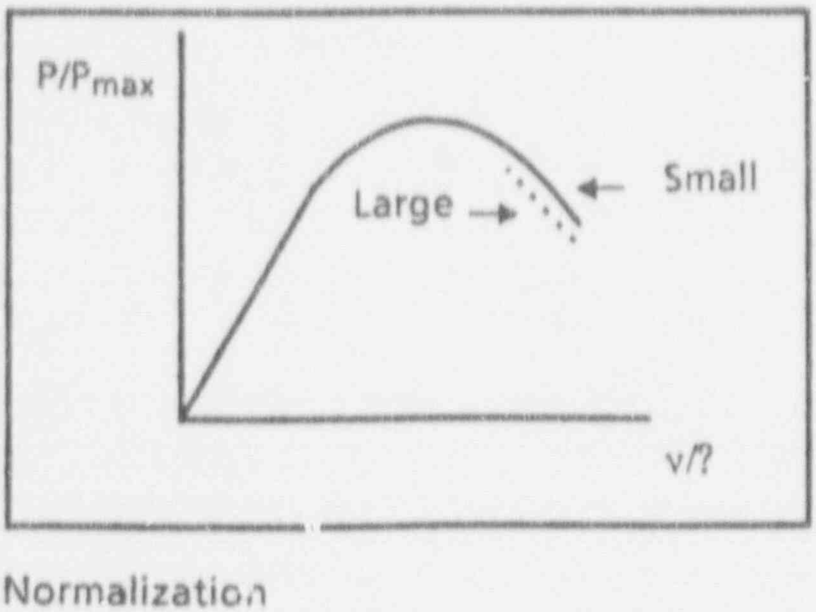

Fig. 6.7 Schematic of load displacement normalizatio.n for size extrapolation.

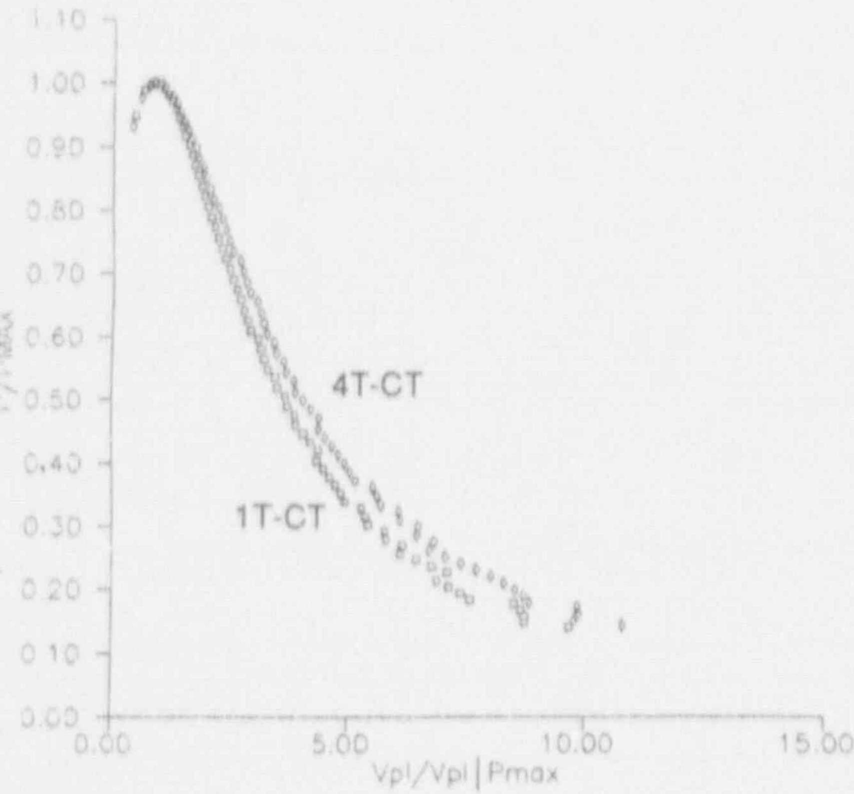

Fig. 6.8 Load vs plastic displacement normalized with maximum load.

evaluate the extrapolation techniques.) Initially, four steel alloys were found which would be suitable to use in the extrapolation analysis. They were an A 508 steel,[1] an HSLA steel, a 5Ni steel,[2] and an A 533 B steel.[3] The A 508 steel had *J-R* curves for compact specimens ranging from 1/2T (W = 1.0 in.) to 10T (W = 20 in.). The *J-R* curve from the smallest specimen (1/2T) had about 0.2 in. of crack extension, whereas the curve from the largest (10T) had more than 3 in. of crack extension. This would allow an assessment of extrapolation over more than an order of magnitude. The extrapolation in the other steels ranged from five times to two times in crack extension.

The initial work was done with the A 508 steel because it gave an opportunity for the longest crack extension extrapolation. All of the data from the various specimens were reanalyzed using the normalization procedure to get the correct final region of the *J-R* curve. Results were plotted on log-log paper to see if a power law relationship might fit the J-Δa curve. The idea is shown schematically in Fig. 6.9. The *J-R* curve extrapolation for three different sizes—1/2T, 1T, and 10T— are plotted in a log-log format in Fig. 6.10. This was done again for J_M in Fig. 6.11. The typical result is given by the plot in Fig. 6.10. A power law relationship (straight line on a log-log plot) fits over an intermediate region of the curve. There is an initial region for small crack extension which does not fit the straight line and a final region for longer Δa that may not fit. The intermediate region does fit. The same was true for J_M. Not only were the J vs Δa plots on log-log axes nearly a straight line, they also agreed reasonably well between the different sizes. This was true for curves plotted by J and J_M (Figs. 6.10 and 6.11).

Since the *J-R* curves were consistent between the sizes, the extrapolation procedure was simply an extension of the straight line on the log-log plot. That is, a power law relationship was assumed graphically for extrapolation. The extrapolated results are also shown for J in Fig. 6.10 and for J_M in Fig. 6.11. The J-Δa extrapolation gave estimates from the small specimen that are slightly lower than those of the large specimen (conservative), and the extrapolation of J_M-Δa gave results that showed a slightly higher or unconservative trend at longer extrapolations of crack extension.

To make the same assessment for the other materials, log-log plots were made for the various sizes of specimens of HSLA steel (see Fig. 6.12 for J and Fig. 6.13 for J_M). The 5Ni steel and A 533 B steel were analyzed, but the results are not shown here. The trends for all of these are consistent; the extrapolated J-Δa curves from small specimens are all exact or slightly conservative with respect to the larger specimens. The J_M-Δa are slightly to considerably unconservative. In each case, however, there is a region of linear J-Δa behavior on the log-log plots, meaning that the power law assumption is valid over part of the J-Δa curve. The worst result came from the 5Ni steel.

Since a power law extrapolation of small-specimen J-Δa curves always matched the J-Δa from larger speci[illegible] was conservative, this was chosen as the method for *J-R* curve extrapolation. The J_M-[illegible]trapolation tended to be unconservative. In order to develop guidelines for extrapolation, the log-log plots of J-Δa were examined to determine the consistent region of power law behavior. Results from this are given in Table 6.1. This table shows that power law behavior develops consistently over a middle range of the J-Δa curve. The initial region does not fit the power law well. A final region did not fit well in some cases. In others, the test was terminated before the end of the power law region. In all cases (except for 5Ni steel), the region of crack extension to initial uncracked ligament $\Delta a/b_0$

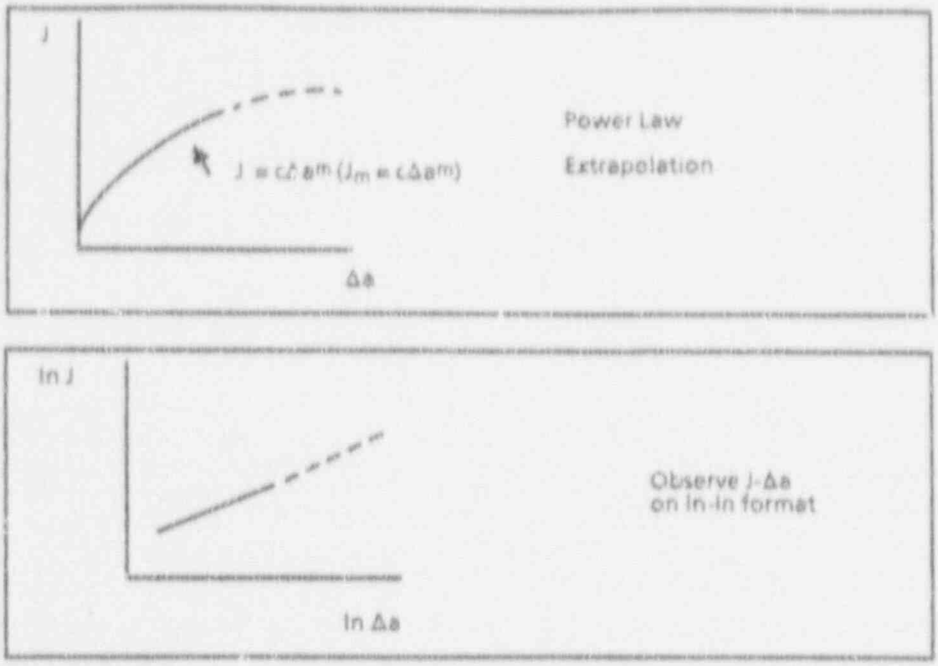

Fig. 6.9 Schematic of direct J-R curve extrapolation ideas.

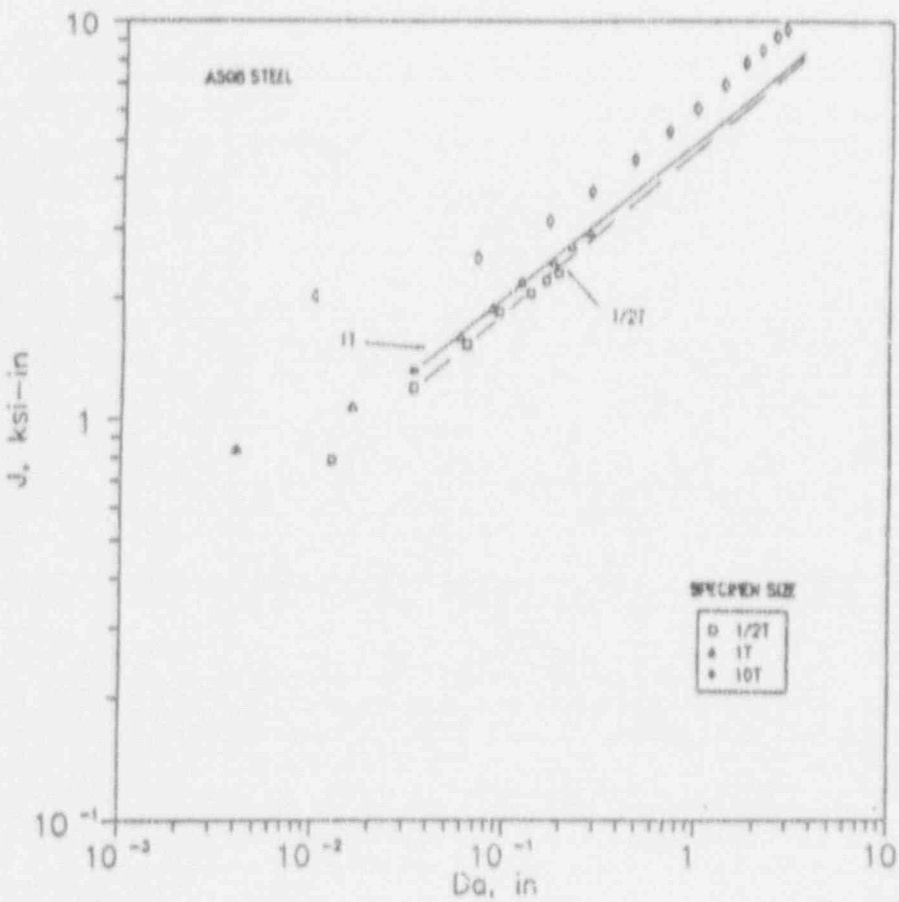

Fig. 6.10 J-R curve for A 508 steel on log-log format showing power-law extrapolation.

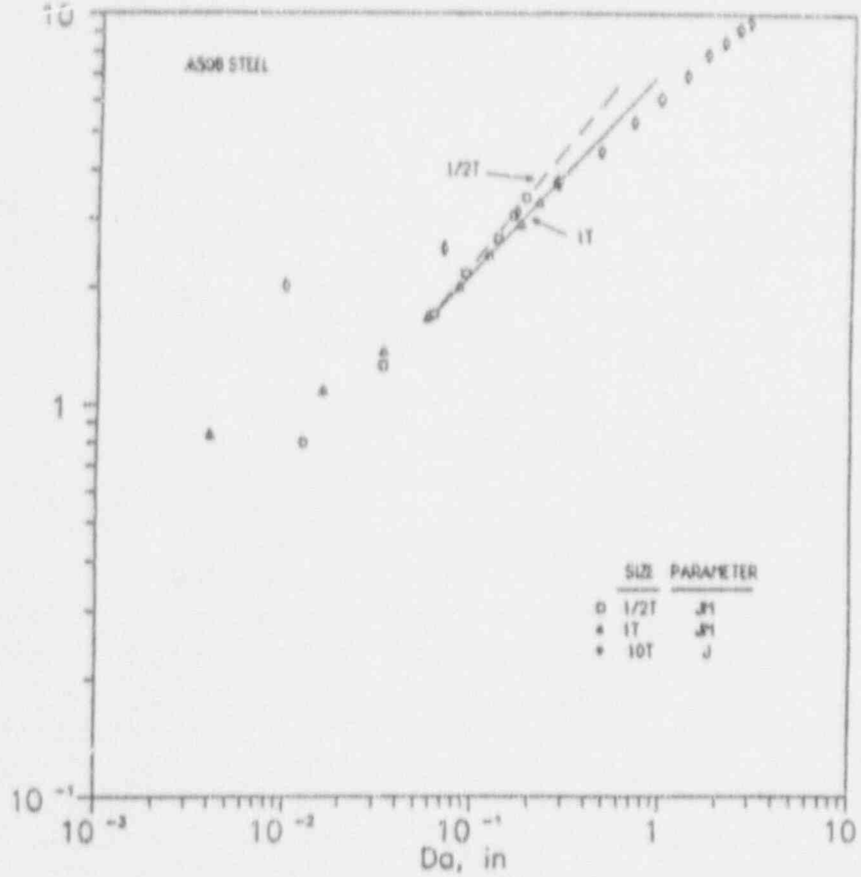

Fig. 6.11 J_M-R curve for A 508 steel on log-log format showing power-law extrapolation.

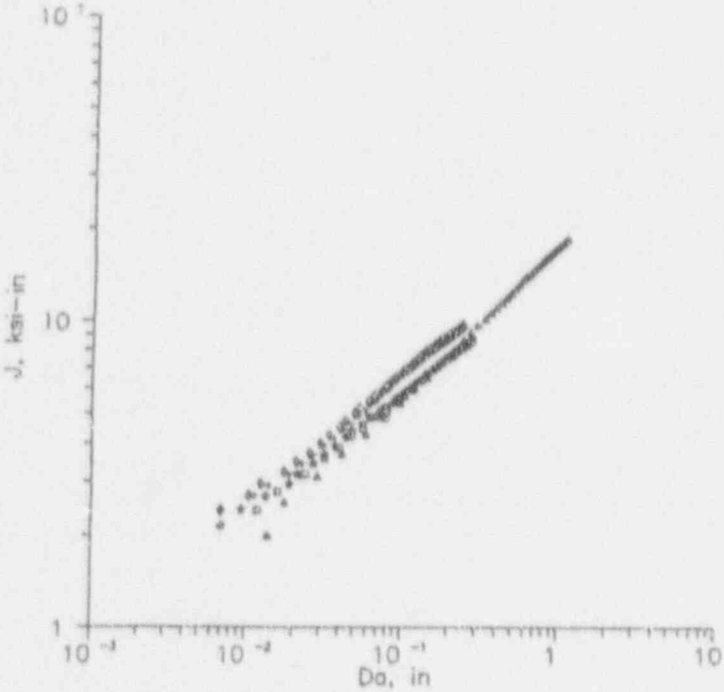

Fig. 6.12 J-R curve for HSLA steel on log-log format showing power-law extrapolation.

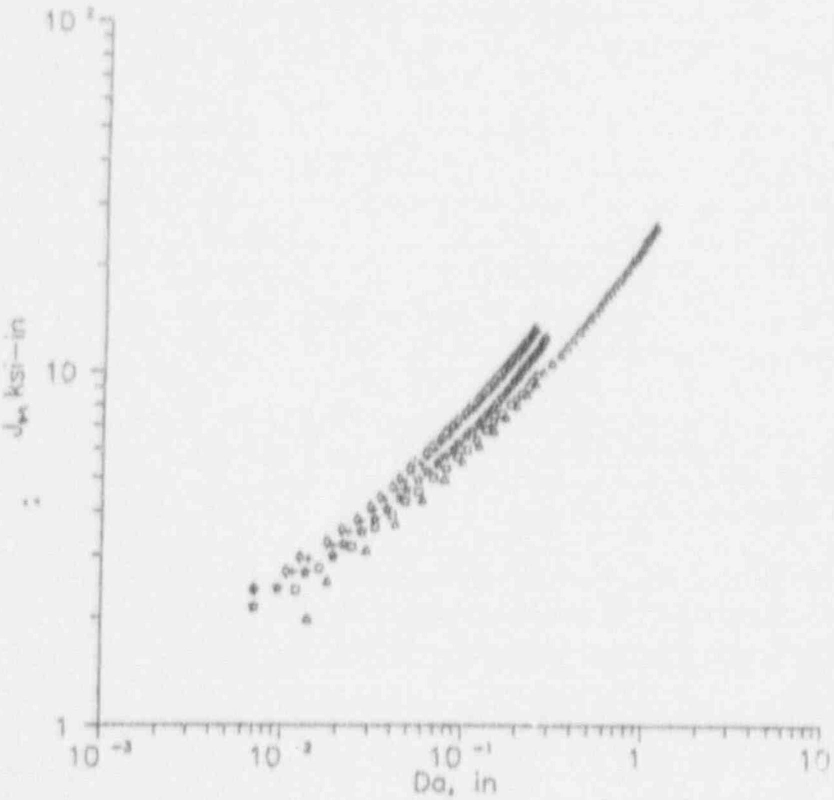

Fig. 6.13. J_M-R curve for HSLA steel on log-log format showing power-law extrapolation.

Table 6.1. Extrapolation of size analysis criteria for conservative extrapolation

Material	Specimen size	Initial $\Delta a/b_0$	Final $\Delta a/b_0$	End condition
A 508 steel	1/2T	0.10	0.45	End of data
A 508	1T	0.07	0.31	End of data
A 533	1/2T	0.07	0.55	End power law
	1T	0.025	0.58	End power law
HSLA	1T	0.03	0.41	End of data
HY130	1T	0.08	0.21	End power law[a]
HY130	1T (2nd fit)	0.11	0.26	End power law

[a]Power law never well-established.

between 0.1 and 0.3 gave good power law behavior. Therefore, extrapolation of this region was recommended. The guidelines for *J-R* curve extrapolation from this study are as follows:

1. The *J-R* curve should be reanalyzed using the normalization procedure.
2. *J-R* curves should be plotted with deformation *J* for a conservative extrapolation.
3. The *J-R* curve can be plotted on a log-log plot to get the best power law fit.
4. The power law fit should be taken over the region of crack extension to initial uncracked ligament, $\Delta a/b_0$, between 0.1 and 0.3 as a straight-line fit on the log-log plot.
5. This straight line can be extended to longer values of crack extension to achieve the *J-R* curve extrapolation.

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2. F. E. Link, J. D. Landes, R. Herrera, and Z. Zhou, "Something New on Size and Constraint Effects for *J-R* Curves," *Proceedings of the European Symposium on Elastic-Plastic Fracture Mechanics: Elements of Defect Assessment*, October 9–11, 1989, Freiburg, FRG, Institution of Mechanical Engineers, London, 1991.

3. J. A. Joyce et al., "Application of the *J*-Integral and the Modified *J*-Integral to Cases of Large Crack Extension and High Toughness Levels," pp. 85–105 in *Fracture Mechanics: Twenty-First Symposium*, ASTM STP 1074, J. P. Gudas, J. A. Joyce, and E. M. Hackett, Eds., American Society for Testing and Materials, Philadelphia, 1990.

7. EXTRAPOLATED *R* CURVES IN STRUCTURAL ANALYSIS

The guidelines for *J-R* curve extrapolation were based on the comparison of small- and large-specimen *R* curves. Since the ultimate goal is to use the extrapolated *J-R* curve to predict the behavior of a larger structure, it would be useful to use these extrapolated curves in the ductile fracture methodology to analyze some example structures. This was done in two steps. The first used the methodology to predict the behavior of various test specimens. The advantage of the specimen prediction is that there is a large choice of reasonably good experimental results to use for comparing with the actual results. The second step for modeling structural behavior was to use the pressure-vessel-type structures as examples. In this case, there are not the large number of experimental results for comparison, but the information is more relevant to vessel integrity assessment.

In the modeling of structural behavior, the load was predicted as a function of an independent variable related to strain or displacement. The load response could be applied load, stress, or, for the case of the vessel, pressure. The independent variable was a displacement-related variable that could be a displacement measured on the structure or an alternate strain-related parameter such as *J*. In predicting the load response, it is important to be able to first predict the maximum load accurately. Maximum load corresponds to ductile instability in a structure that is under load control or soft-loading conditions. The second region that should be predicted well is the unloading region after the maximum load. This region corresponds to the area where ductile instability could occur in a structure under displacement control or stiff-loading conditions. The first is more appropriate for a vessel under internal pressure. The second would be appropriate to a piping system that could be loaded, for example, by seismic displacements.

The examination of these structural models is done in two sections. The first is the specimen test result comparison where two materials, an A 508 steel and an HSLA steel, are used in the ductile fracture methodology. The main objective is to use the *J-R* curves from the smallest specimens to predict the behavior of the largest specimens. The second is an analysis of vessel structures. Again, the goal is to predict the behavior of the large structures from small test specimens. As part of this analysis, a sensitivity study was done by systematically varying important inputs in the methodology to observe the effect on the predicted loading behavior.

7.1 TEST SPECIMEN PREDICTION

To try to predict large-specimen behavior, the ductile fracture methodology as described in Sect. 3 was used along with the *J-R* curves from small specimens. The calibration functions were taken from two sources; one was from experiments, and the second was from the elastic-plastic handbook.[1] For the first case, the load vs displacement from a test record was used in a format that required the load to be normalized with respect to the current crack size. An alternative to this is to use a blunt-notch test record from the same material and structural type which has a constant crack length during the test.

The calibration function from the handbook[1] has the form

$$v_{pl} = \alpha \epsilon_0 a h_3 (P/P_0)^n \ , \tag{7.1}$$

where α and n are a constant coefficient and exponent from a Ramberg-Osgood fit of stress and strain, $\epsilon_0 = \sigma_0/E$, where σ_0 is a yield stress, a is a crack length, and h_3 is a tabulated constant. Generally, load, displacement, and crack length are related by

$$v = v_{el} + v_{pl} \ , \tag{7.2}$$

where

$$v_{el} = PC(a/W) \ . \tag{7.3}$$

$C(a/W)$ is an elastic compliance.

The J is calculated by

$$J = J_{el} + J_{pl} \ , \tag{7.4}$$

where

$$J_{el} = \frac{K^2}{E'} \ . \tag{7.5}$$

E' is effective modulus, and K is the elastic stress intensity factor.

$$J_{pl} = \frac{\eta_{pl}}{Bb} \int_0^{v_{pl}} P dv_{pl} \ , \tag{7.6}$$

where η_{pl} is a coefficient, B is thickness, and b is uncracked ligament $b = W - a$. Alternatively, a value of J_{pl} can be calculated from a handbook[1] equation.

When the calibration functions are taken from experimental results, the same basic equations are used except for Eq. (7.1). The load and plastic displacement relationship is given by the form

$$P = \left[BW \left(\frac{b}{W} \right)^{\eta_{pl}} \right] \frac{\left(L + M \dfrac{v_{pl}}{W} \right)}{\left(N + \dfrac{v_{pl}}{W} \right)} \left(\frac{v_{pl}}{W} \right) \ , \tag{7.7}$$

where L, M, and N are fitting constants and W is specimen width.

As can be seen from the above equations, the calibration functions determined from the handbook[1] require material property input as well as some decisions on how to handle interpolations. The material property inputs are yield strength (or flow stress), σ_0, an equivalent yield strain, ϵ_0, and the hardening exponent, n, and coefficient, α, form a Ramberg-Osgood power-hardening law. Most tensile tests do not determine ν and n for a material. In cases where these are not available, the Bloom approximation from yield strength and ultimate tensile strength was used.[2] The interpolations required in using the handbook[1] involve crack length, hardening exponent, and plane strain vs plane stress. The methods for handling these interpolations are outlined elsewhere.[3]

The J-R curves used from the small specimens did not have enough crack extension to predict the behavior of the larger specimens through the entire load range desired; often, the prediction did not go as far as the maximum load reached by the larger specimens. Therefore, the extrapolation procedures outlined in Sect. 6.2 were used. The small-specimen J-R curve was extrapolated far enough to cover the entire range of P-v on the large specimen; sometimes this required an extrapolation of more than an order of magnitude on the J-R curve. Both J-Δa and J_M-Δa R curves were used in the analysis to compare the results from each.

Results from two materials were used in this study. One was the A 508 steel with a 20 to 1 difference in size,[4] and the second was an HSLA steel with a 5 to 1 difference in size.[5] To use the methodology, a program was written which incremented the plastic displacement, v_{pl}. For the given v_{pl} and initial crack length, a_0, the load, P, was determined. The value of J was then calculated, and the corresponding crack extension Δa was added to a_0. The calculations were repeated for the initial v_{pl} and new crack length a. This procedure was repeated until values of load, P, and crack length, a, converged to a stationary value. The plastic displacement was then incremented, and load, P, and crack length, a, were determined again. This was continued until a sufficient range of P and v were calculated. Since the J-R curve was extrapolated, the process could have been continued until the crack grew through the remaining ligament. To make the calculations easier, the P_N vs v_{pl}/W and the extrapolated J-Δa curves were fitted. To make certain that the computational procedures were working, a closed-loop analysis was first performed. The load vs displacement, P-v, curve was predicted for an A 508 1T-CT specimen using the data (both calibration functions and J-R curve) that resulted from its own test record (Fig. 7.1). This prediction was very good.

The predictions were made for a variety of cases. For example, the 2T-CT P-v curve was predicted from the 1T-CT J-R curve (both J and J_M) and a handbook[1] calibration curve in Fig. 7.2; and the same prediction was made using the 1/2T-CT J-R curve in Fig. 7.3. In both cases, the J-based R curve gave a conservative prediction, and the J_M-based R curve gave an unconservative prediction. To study the effect of the various inputs, the same prediction was made using a calibration function from the handbook[1] and various experimental calibration curves (Fig. 7.4). The predictions fit the experimental result very closely. The same prediction was made with the correct calibration curve and the 10T, 1T, and 1/2T J-R curves (Fig. 7.5). The results are similar to those in Figs. 7.2 and 7.3. This shows that the difference between prediction and experiment is a result of the conservatism in the J-R curve extrapolation (Fig. 7.6). All of the A 508 cases analyzed are tabulated in Table 7.1; here, the ratio of predicted maximum load to experimental maximum load is given for the various inputs of calibration curves and J-R curves. All results are similar; the maximum load is

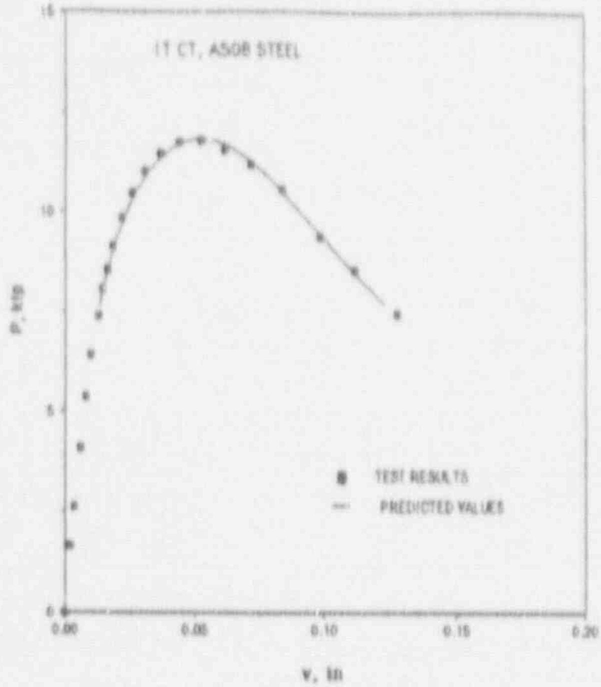

Fig. 7.1. Closed loop prediction of load vs displacement from specimen data for an A 508 steel.

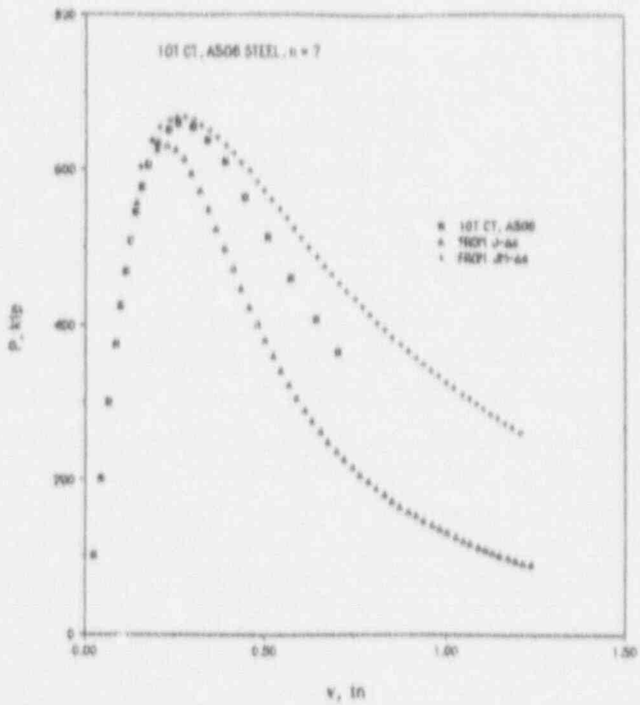

Fig. 7.2. Load vs displacement prediction of 10T-CT from 1T-CT J-R curve, A 508 steel.

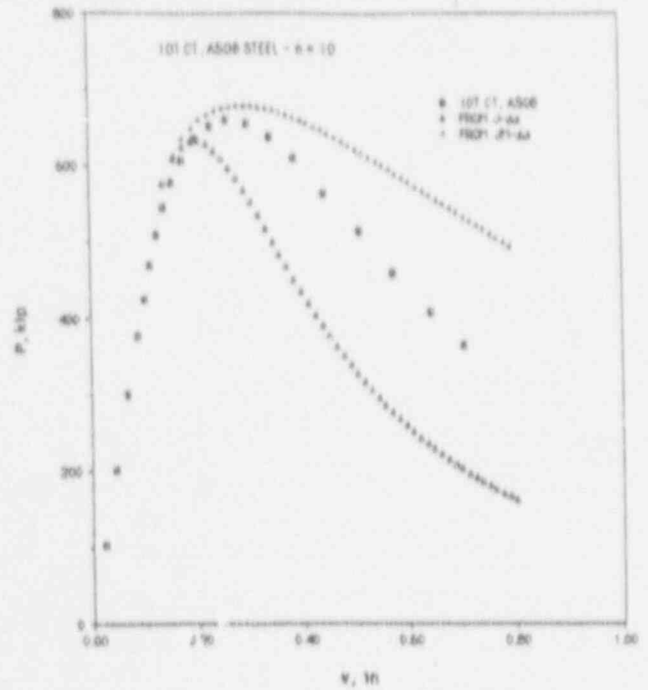

Fig. 7.3. Load vs displacement prediction of 10T-CT from 1/2T-CT J-R curve, A 508 steel.

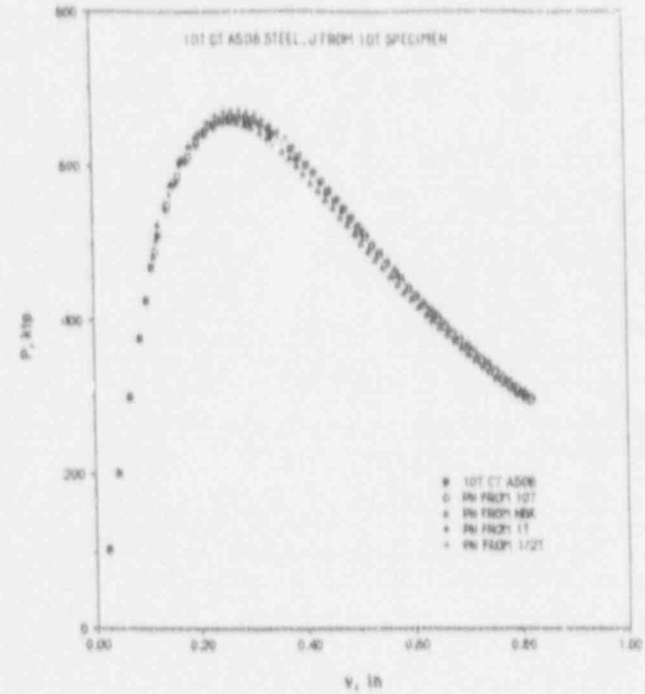

Fig. 7.4. Load vs displacement prediction of 10T-CT varying calibration functions, A 508 steel.

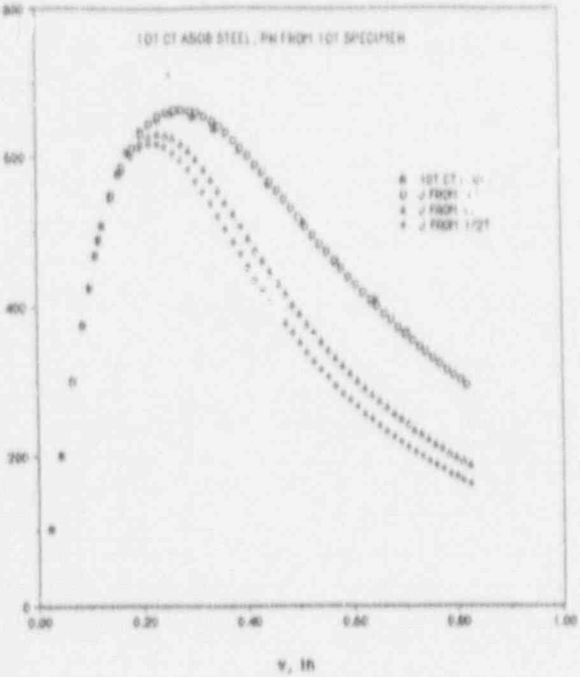

Fig. 7.5. Load vs displacement prediction of 10T-CT ying J-R curves, A 508 steel.

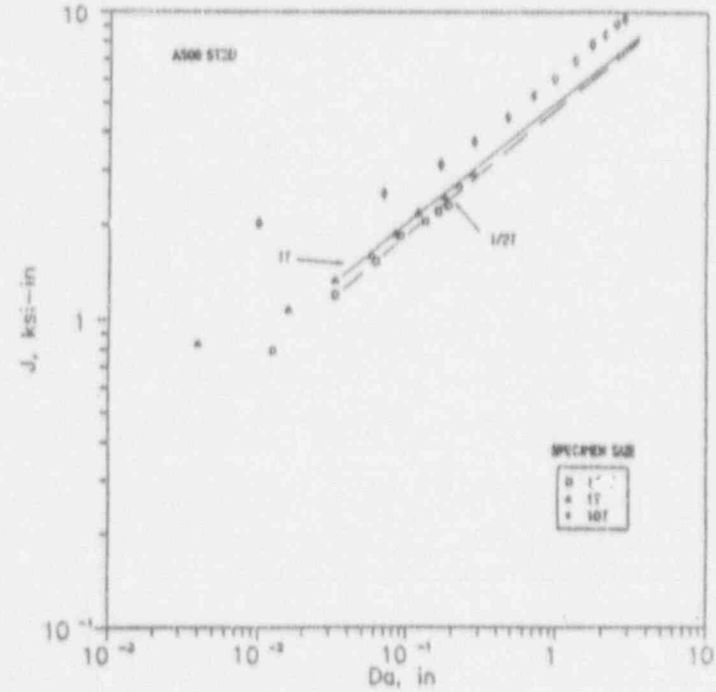

Fig. 7.6. Log-log plot of A 508 J-R curves showing conservative extrapolation.

Table 7.1 Summary of A 508 steel results

Input			Prediction/test result		
Size	Calibration curve	J-R curve	Size	P_{max}	Slope
1/2T	Test	J	10T	0.95	1.26
1/2T	Test	J_M	10T	1.07	0.41
1/2T	HBK n = 7	J	10T	0.94	1.30
1/2T	HBK n = 7	J_M	10T	1.04	0.45
1/2T	HBK n = 10	J	10T	0.96	1.23
1/2T	HBK n = 10	J_M	10T	1.03	0.53
1T	Test	J	10T	0.95	1.30
1T	Test	J_M	10T	1.02	0.63
1T	HBK n = 7	J	10T	0.96	1.28
1T	HBK n = 7	J_M	10T	1.01	0.73
1/2T	Test	J_M	10T	1.07	0.48
1/2T	Test	J_M	10T	1.07	0.60
1/2T	Test	J_M	4T	0.96	1.02
1/2T	Test	J_M	4T	1.02	0.44
1T	Test	J	4T	0.96	1.02
1T	Test	J_M	4T	0.98	0.60

underpredicted by a J-R curve extrapolation and overpredicted by the J_M-R curve extrapolation. All of the predictions of maximum load, however, are within 10% of the experimentally measured maximum load. This would correspond to a prediction of instability under a soft-loading situation such as a pressurized vessel. The prediction of the P-v slope after maximum load is also compared with the experimental result. This has more error. Again, J gives conservative predictions, and J_M gives unconservative predictions.

The study for the HSLA steel used 1T-CT J-R curves (both J and J_M) to predict a 5T-CT P-v curve. When the handbook[1] calibration functions were used, predictions from both J and J_M were unconservative, particularly for the prediction of maximum load (Fig. 7.7). When the experimental calibration curve is based on a straight line rather than a power law, the J-R curve extrapolation was nearly exact (Fig. 7.8). For this case, the J_M-R curve did not work as well. The conclusion was that the handbook[1] calibration curves based on power law hardening will not work for some materials. In fact, further work showed that all calibration curves have essentially an initial power law hardening region and a final straight-line hardening region (Fig. 7.9).[3] Materials that have limited plastic deformation remain in the power law hardening region and can be predicted well with the power law-based handbook[1] solutions. Materials that are more ductile get into the straight-line hardening region, and the handbook[1] will not predict correct calibration curves. Therefore, care should be taken on choosing the deformation information for a structural analysis. The HSLA results are summarized in Table 7.2. The errors in prediction are greater here. However, when the experimental straight-line calibration functions are used, the maximum load can be predicted within a few percent.

7.2 STRUCTURAL PREDICTIONS

The same approach used in Sect. 7.1 was applied to structures more representative of reactor vessels. The two cases studied were a model suggested by the ASME Section XI Working Group on Flaw Evaluation and V8A pressure vessel model.[6] To make the predictions, calibration curves from various sources were used. These will be detailed in the following sections. The J-R curve results were taken from a set of V8A weld metal specimen tests described in the next section.

7.2.1 V8A Weld Metal J-R Curves

The V8A weld metal J-R curves were generated by W. A. Van Der Sluys at B&W Research Center. The J-R curve results from seven 1T-CT specimens were reanalyzed using the normalization procedure. These are plotted in Fig. 7.10. These show some scatter in the J-R curves. To look at the extrapolation of the data, these were plotted in a log-log format (Fig. 7.11). Three of the seven specimens were chosen, representing an upper bound, V8A-7 (high); lower bound, V8A-6 (low); and medium, V8A-3 (mid) (Fig. 7.12). These three curves were used in subsequent structural analysis and were given to the J_M/J_D WG to use as the standard J-Δa R curves in future benchmark analyses. In Fig. 7.12, it can be seen that some of the points at longer Δa fall above the upper-bound fit. These are points that go beyond

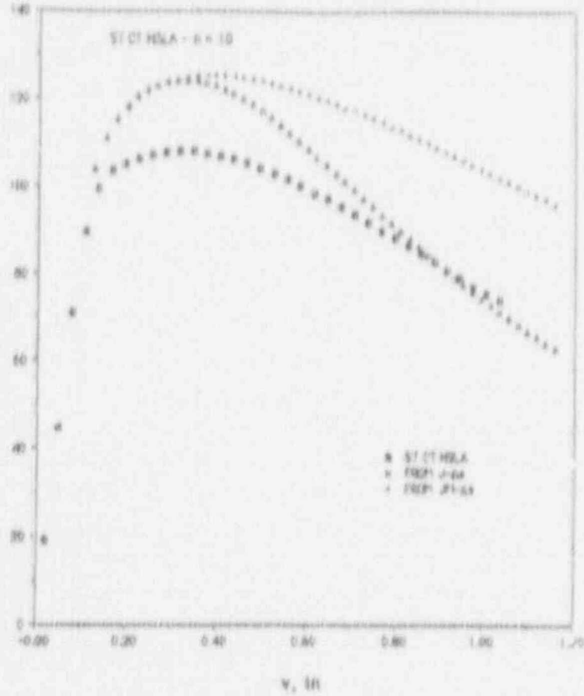

Fig. 7.7. Load vs displacement prediction of 5T-CT from 1T-CT J-R curve, power-law calibration functions, HSLA steel.

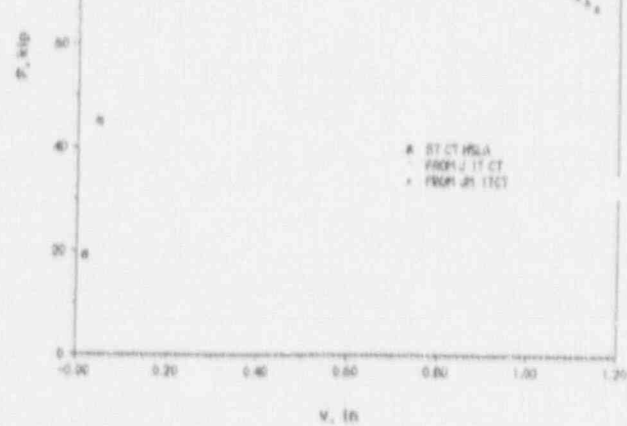

Fig. 7.8. Load vs displacement prediction of 5T-CT from 1T-CT using straight-line calibration functions, HSLA steel.

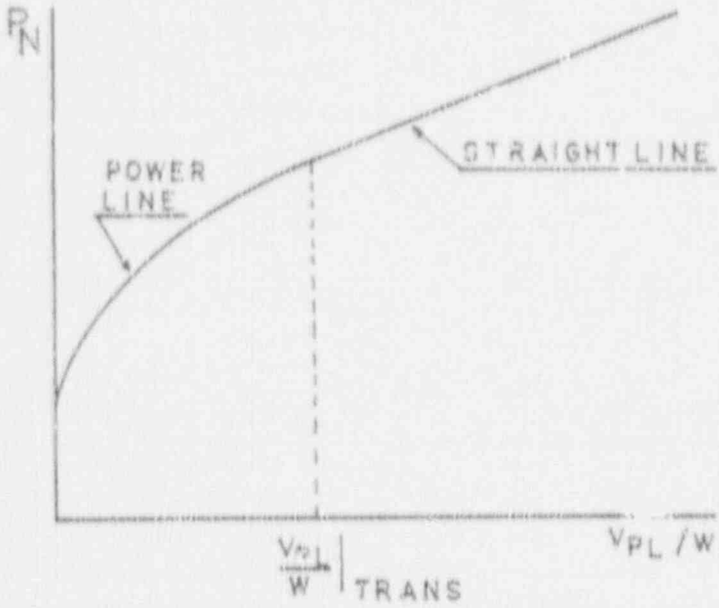

Fig. 7.9. Schematic of normalized load vs plastic displacement showing power-law and straight-line regions.

Table 7.2. Summary of HSLA results

Input			Prediction/test result		
Size	Calibration curve	*J-R* curve	Size	P_{max}	Slope
1T	HBK n = 13	J	5T	1.12	1.59
1T	HBK n = 13	J_M	5T	1.12	1.08
1T	HBK n = 10	J	5T	1.14	1.78
1T	HBK n = 10	J_M	5T	1.16	0.69
1T	HBK n = 7 (α = 11)	J	5T	0.95	0.99
1T	HBK n = 7 (α = 11)	J_M	5T	0.97	0.23
5T	Test power law	J	5T	1.07	0.63
1T	Test straight line	J	5T	1.00	1.00
1T	Test straight line	J_M	5T	1.01	0.24

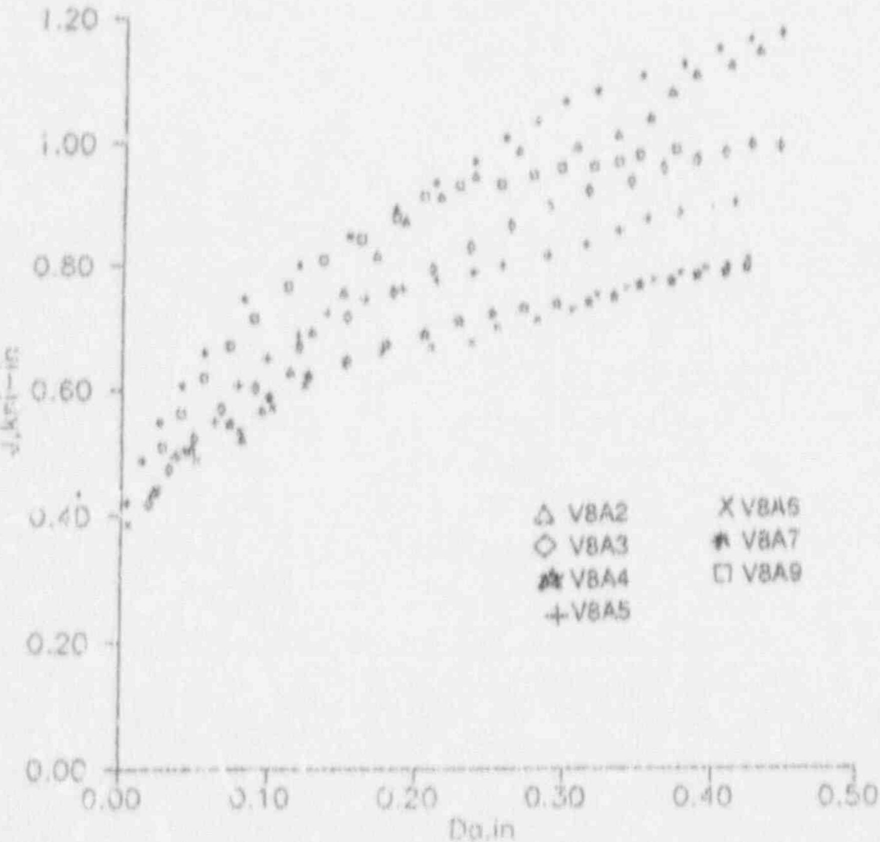

Fig. 7.10 J-R curves for V8A weld data.

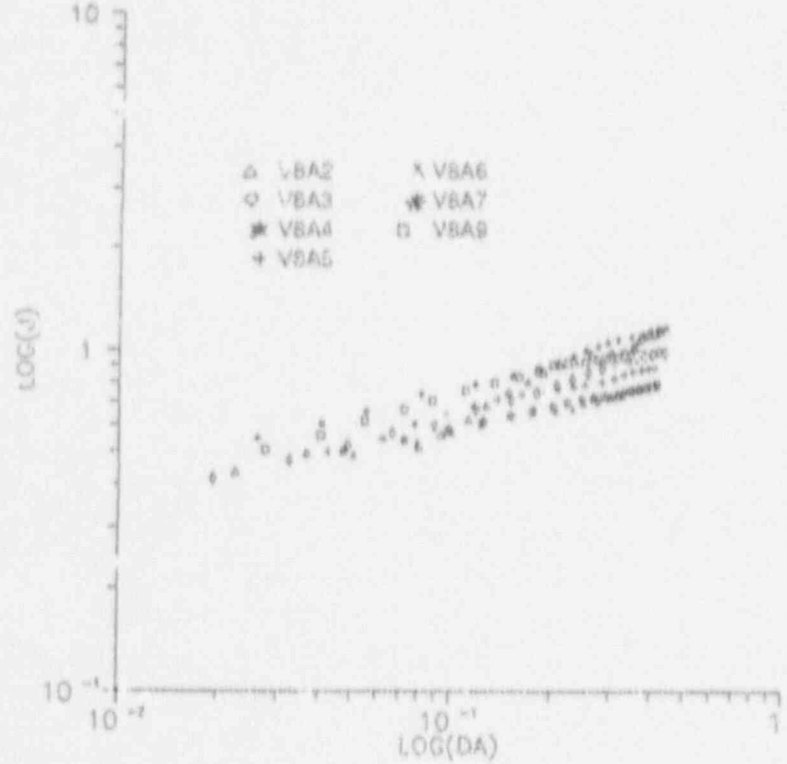

Fig. 7.11. J-R curves for V8A weld data in log-log format.

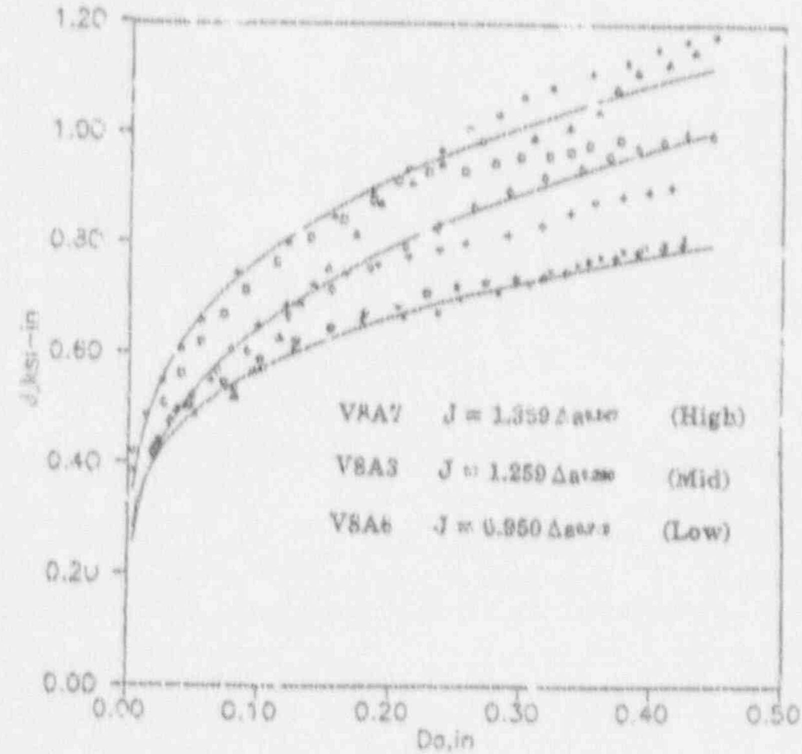

Fig. 7.12. J-R curves for V8A weld data with power-law fits to high, medium, and low data.

the $\Delta a/b$ limit of 0.3 given in the extrapolation rule fit of Sect. 6. The same approach was applied in the J_M-Δa format (Fig. 7.13). Here, it is obvious that the longer Δa points are not following the extrapolated lines. The data used, then, in predictive models was the J-Δa R curve. This is shown in its extrapolated form in Fig. 7.14.

7.2.2 A11 Model and Sensitivity Study

The results from the V8A weld metal J-R curve tests were used in the model suggested by the ASME Section XI Group.[7] It is referred to here as the A11 model. There were not any experimental results to compare with the predictions generated here. The predictions were made, first, to demonstrate the approach and, second, to use in a sensitivity study of input variables.

The model is briefly described below. For pressure vessels, there is not a clear measure of displacement like there is on a test specimen. Therefore, the ductile fracture methodology of Sect. 3 was revised so that J could be the independent variable rather than displacement. A schematic representation of the ductile fracture methodology for pressure vessels is given in Fig. 7.15. The result of the analysis is pressure, p, vs J. Instability occurs at the maximum pressure because a pressure vessel corresponds to a soft-loading system.

The A11 calibration function equations are given in Table 7.3. J is determined from calibration equations that have a similar format to those in the handbook.[1] The calibration constant h_1 follows the Bloom modification for the part through the crack, and the limit load, P_0, uses the Central Electricity Generating Board (CEGB) modification. The J-R curves used were those from the V8A weld data. The three J-R curves that were fit and extrapolated were used; they are identified as high, medium, and low.

The first analysis was made simply to develop plots of pressure, p, vs J. This is done for deformation J in Fig. 7.16 and for modified J in Fig. 7.17. Since there is no experimental result to use for comparison, all that can be done is to observe trends. As expected, the pressure rises with increasing J and then falls as crack growth ensues. The highest J-R curve predicts a high maximum pressure. The J_M predicts higher maximum pressure for a given J-R curve (see Fig. 7.18, where predictions based on J and J_M are compared).

To use the A11 model further, a sensitivity study was conducted in which the significant input variables were systematically varied. These included variables from the calibration functions and variables from the J-R curve. The variables included are listed in Table 7.4, along with the range considered. The analysis was done by choosing a median value for all parameters except one. That one was then varied through the listed range. An example of the pressure vs J is given in Fig. 7.19 for variation of the J-R curve coefficient C_1. Generally, the maximum load is of greatest interest because it represents the instability point. This is plotted as maximum pressure, p_{max}, vs C_1 in Fig. 7.20, where a percent variation from the p_{max} at median C_1 is plotted vs C_1. The variation of p_{max} with J is nearly linear. This is not generally true for the other variables. An example of the p_{max} vs flow stress, σ_0, is given in Fig. 7.21 with actual values of p_{max} and in Fig. 7.22 with percent variation from the median.

The sensitivity study was conducted for each variable in Table 7.4. The results of the sensitivity study are given in Table 7.5, where the variation in the input parameter is listed along with the maximum error in the prediction of p_{max}. Notice that p_{max} does not vary directly with the input parameter; the percent variation in p_{max} is smaller than the variation

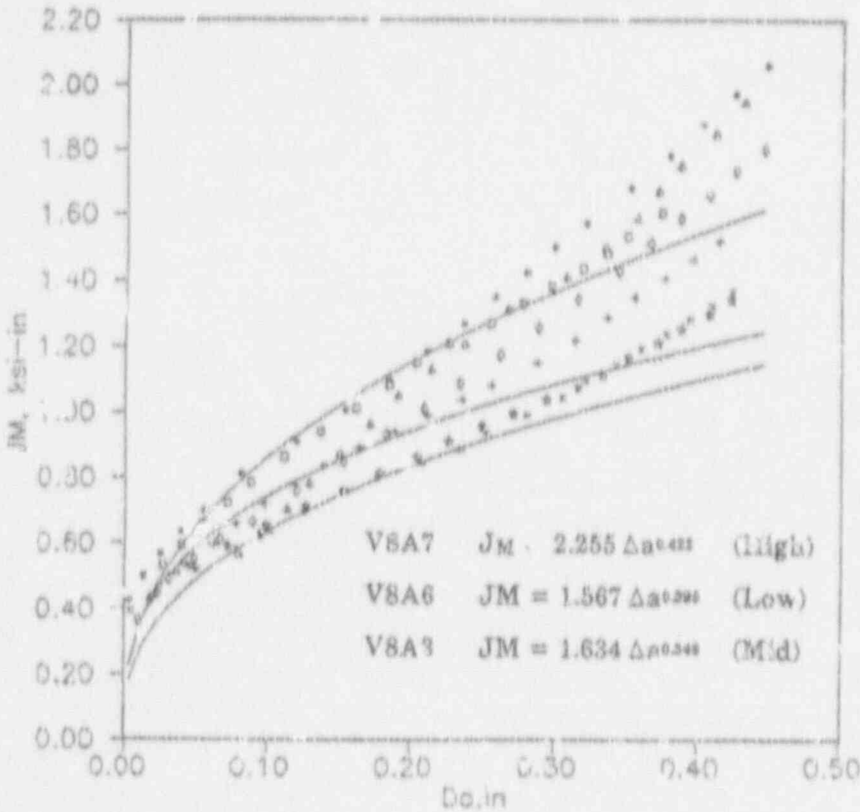

Fig. 7.13. J_M-R curves for V8A weld data with power-law fits to high, medium, and low data.

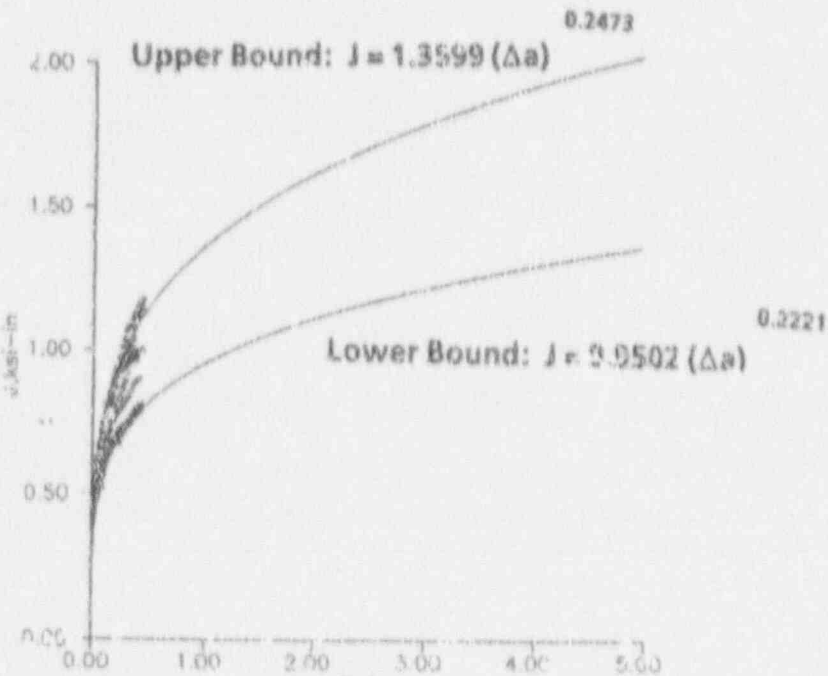

Fig. 7.14. J-R curves for V8A weld data showing extrapolated high and low curves.

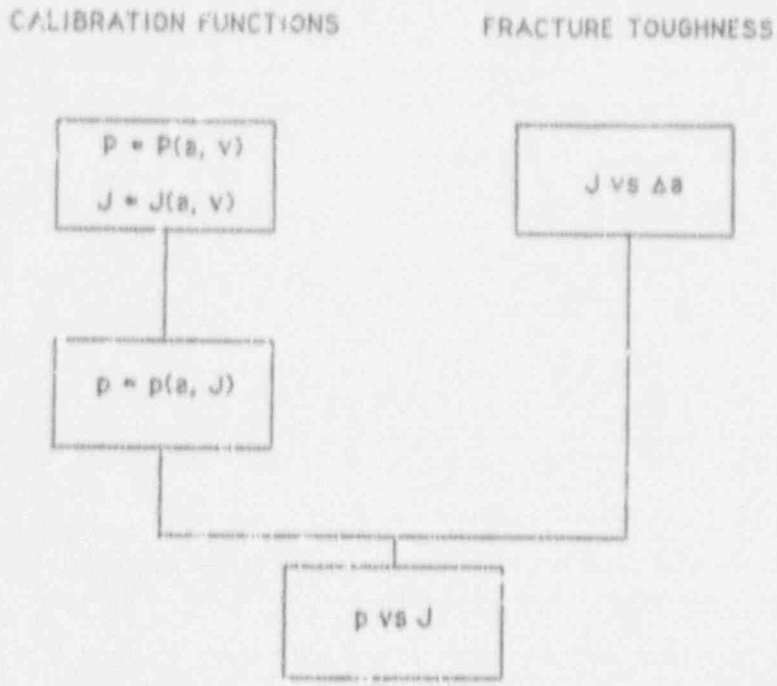

Fig. 7.15. Schematic of ductile fracture methodology for prediction of pressure based on J as the independent variable.

Table 7.3. A11 model *J* calibration

$J = J_{el} + J_{pl}$

where

$J_{el} = K^2/E'$

$J_{pl} = \alpha \, \epsilon_0 \, \sigma_0 \, a \, h'_1 \, (a, n) \, (P/P_0)^{n+1}$

h'_1 = Bloom's Part Through Crack (PTC) Modification

$P_0 = P_0(a^*)$

a^* = CEGB PTC Modification

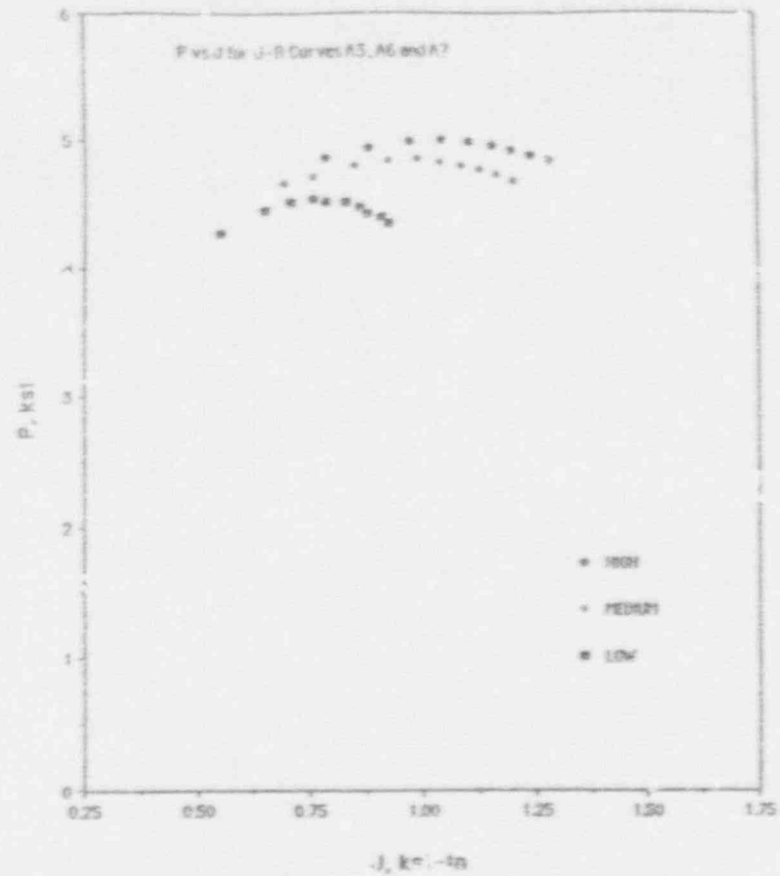

Fig. 7.16. Plot of pressure vs J for A11 model and three weld data J-R curves.

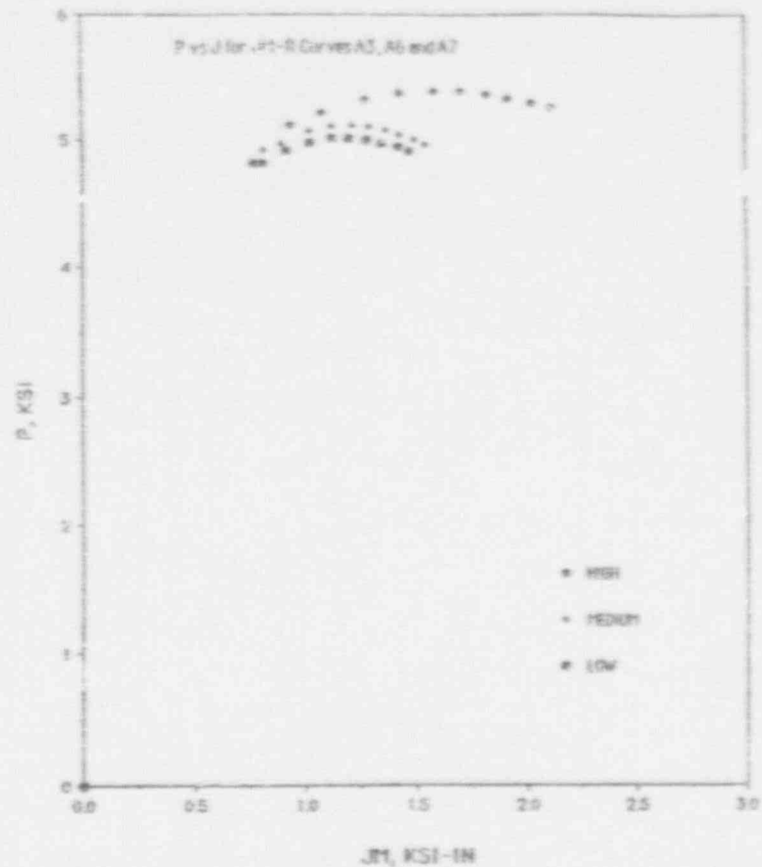

Fig. 7.17. Plot of pressure vs J_M for A11 model and three weld data J-R curves.

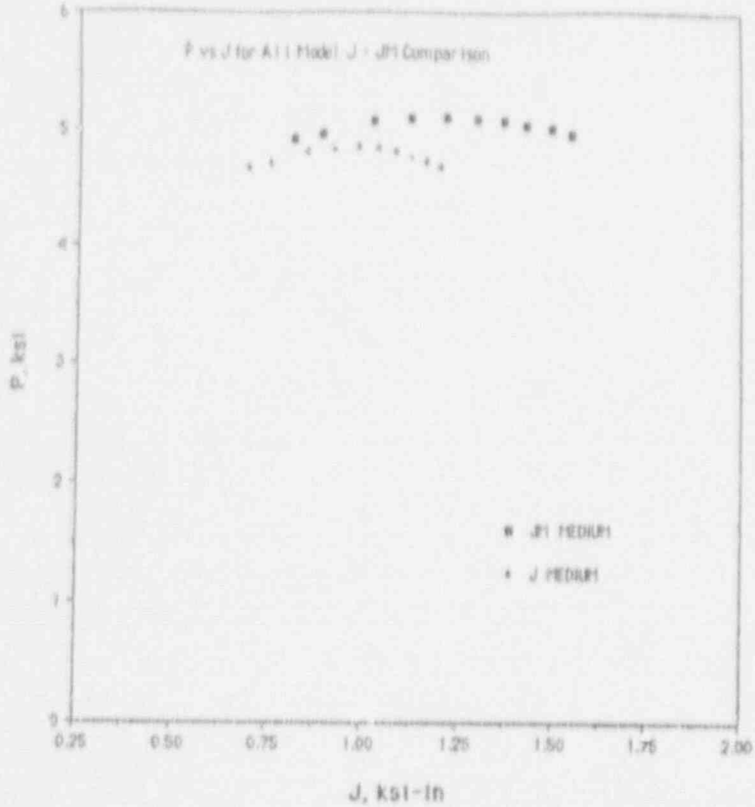

Fig. 7.18. Plot of pressure vs J for A11 model comparing J with J_M predictions for medium J-R curve.

Table 7.4. A11 sensitivity study

Parameter [$J = C_1 \Delta a^{c_2}$]	Range
C_1	1.0 to 1.4
C_2	0.2 + 0.4
E	27,000 to 33,000 ksi
σ_{yt}	50 to 90 ksi
n	5 to 10
α	1 to 4
a_0	2 to 2.5 in.

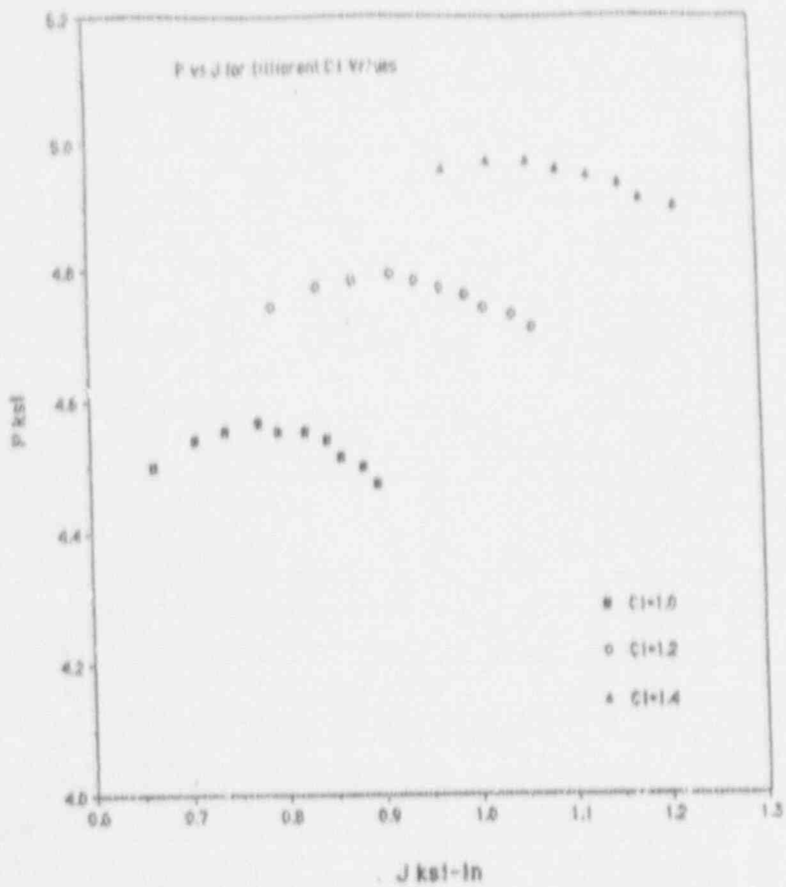

Fig. 7.19. Plot of pressure vs J for A11 model varying C_1 on the J-R curve.

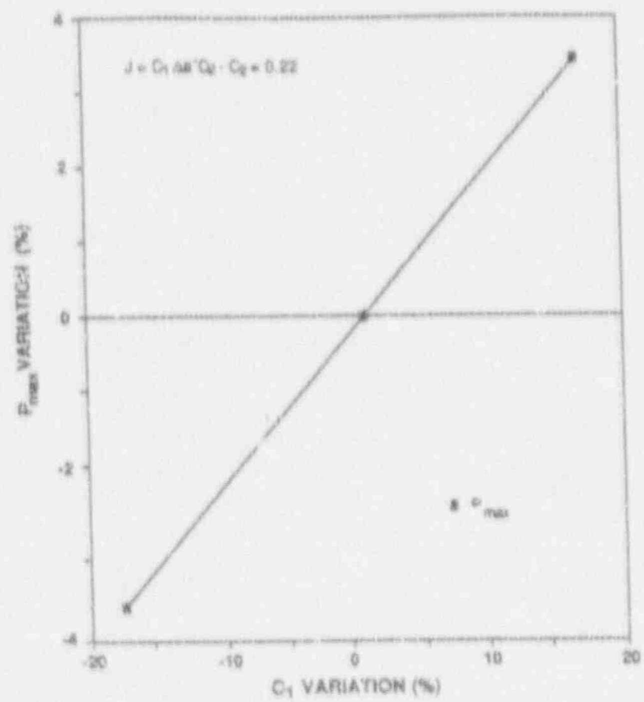

Fig. 7.20. Plot of maximum pressure variation vs C_1 for A11 model and medium J-R curve.

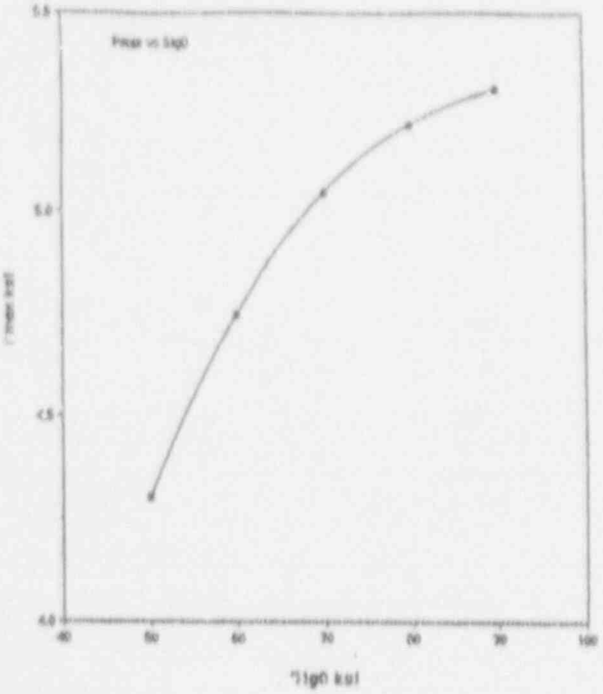

Fig. 7.21. Plot of maximum pressure vs flow stress for A11 model and medium J-R curve.

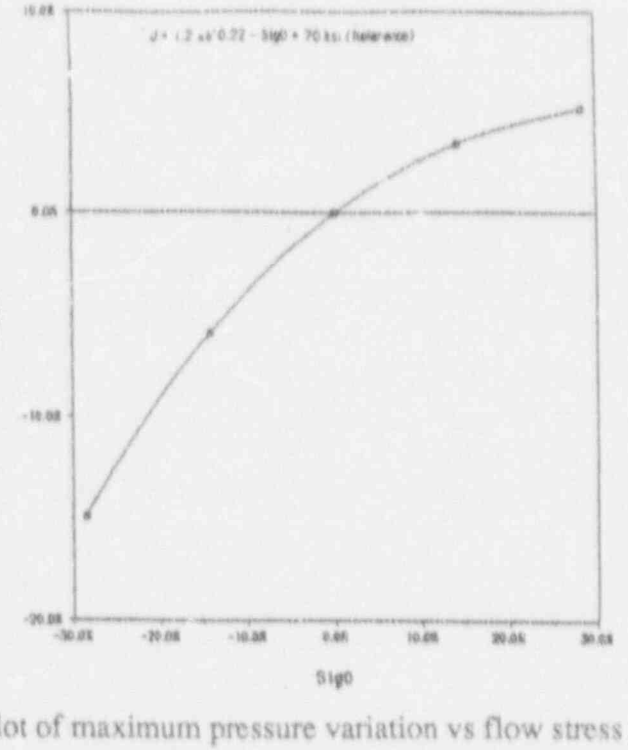

Fig. 7.22. Plot of maximum pressure variation vs flow stress for A11 model and medium J-R curve.

Table 7.5. Summary of A11 sensitivity study

Parameter	Reference value	Parameter variation (%)	Error for P_{max} (%)
C_1	1.2	10	+2
C_2	0.30	20	-1
E	30,000	10	2
σ_{ys}	60	10	4
n	7	20	3
α	1.78	25	-1
a_0	1/4T	10	-5

in the input parameter. It is also interesting to note that the parameters associated with the *J-R* curve, C_1 and C_2, do not cause as much error in p_{max} as the parameters associated with the calibration functions. The choice of flow stress σ_0 and initial defect size has the most influence on p_{max}. What was not assessed in this sensitivity study is what level of variation might be expected for each input variable. Whereas one parameter may never vary by more than ±10%, another may vary regularly by ±50%. The study does illustrate that not all concern must be placed upon the variation in the *J-R* curve. The material flow properties that influence the calibration functions also play a role in the variation of predicted maximum pressure. An important result from this study is that maximum pressure never varies by more than 10% for the range of the input parameters used in this study.

7.2.3 V8A Vessel Model

A V8A vessel model was used to evaluate the ductile fracture methodology and the J vs J_M issue. This model corresponds to one of the test vessel series, V8A, so that results are available to compare with predicted results. The model vessel experiment is documented in Ref. 6. The approach used was the one used in the A11 model in that calibration functions were developed as a function of J. Two different sets of calibration functions were used; both were taken from Ref. 6. One was a linear elastic model (LEFM), and the second was based on an ORVIRT finite-element analysis of the vessel. In both cases the calibration functions may not have predicted the vessel deformation behavior very accurately. The *J-R* curves used were the three cases from the V8A weld tests. Results are presented here in terms of maximum predicted pressure.

An example of the plot of pressure vs J is shown in Fig. 7.23 for the ORVIRT model for three *J-R* curves. The plot of maximum pressure is given in Fig. 7.24 for the LEFM model, where the *J-R* curve result is compared with the J_M-R curve result. The same

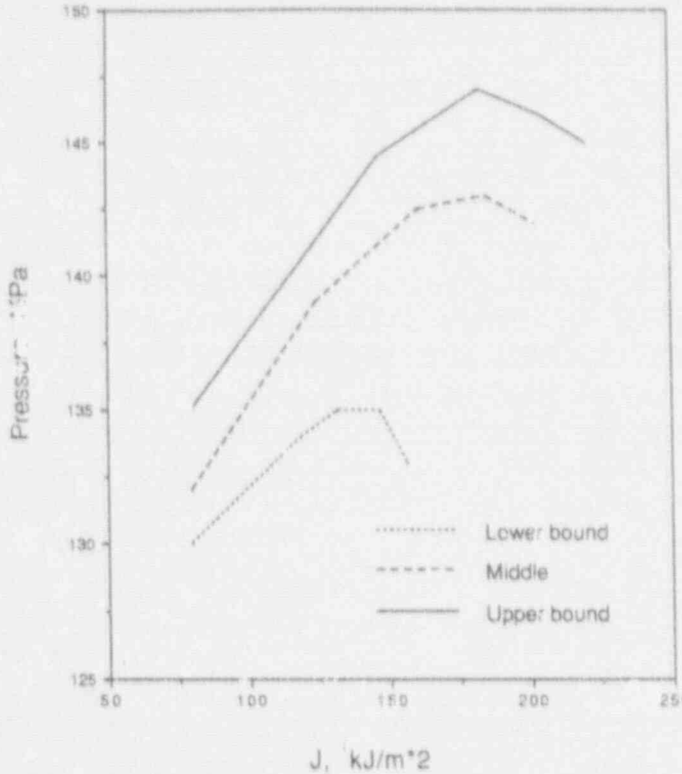

Fig. 7.23. Plot of pr[illegible] vs J for the V8A ORVIRT model and the three J-R curves.

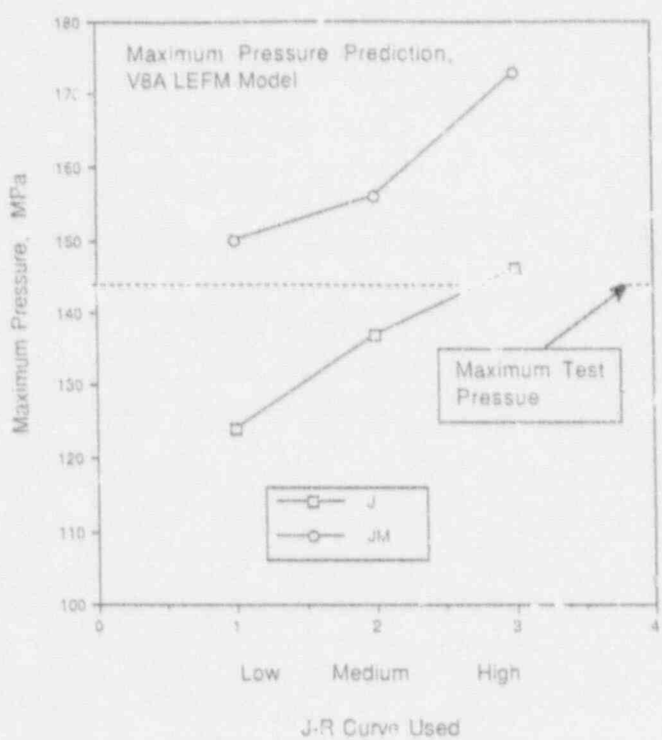

Fig. 7.24. Maximum predicted pressure as a function of J-R curve for V8A LEFM model.

comparison is made for the ORVIRT model in Fig. 7.25. The result from the finite-element calibration functions was sensitive to the manner in which the part through the crack in the vessel was allowed to extend. For Fig. 7.25, the crack was extended proportionally. That means that an increment of growth in crack depth, Δa, was accompanied by twice that increment in surface crack length, $\Delta(2c)$, that is, $\Delta(2c) = 2\Delta a$. This did not exactly fit the observed pattern of growth, which was too complicated to model for the approach used here.

The results can be compared in terms of the test pressure at failure on the test vessel, which was 143 MPa at its maximum point. This value of pressure is indicated on the figures containing the V8A prediction. However, since the calibration functions may not have been quite accurate, it is more interesting to compare the effect of inputs on the results. The *J-R* curve analysis again appears to be slightly conservative, whereas the J_M-*R* curve analysis is slightly unconservative. The variation in maximum predicted pressure between the upper- and lower-bound *J-R* curves is about ±10% for the LEFM model and ±5% for the ORVIRT model.

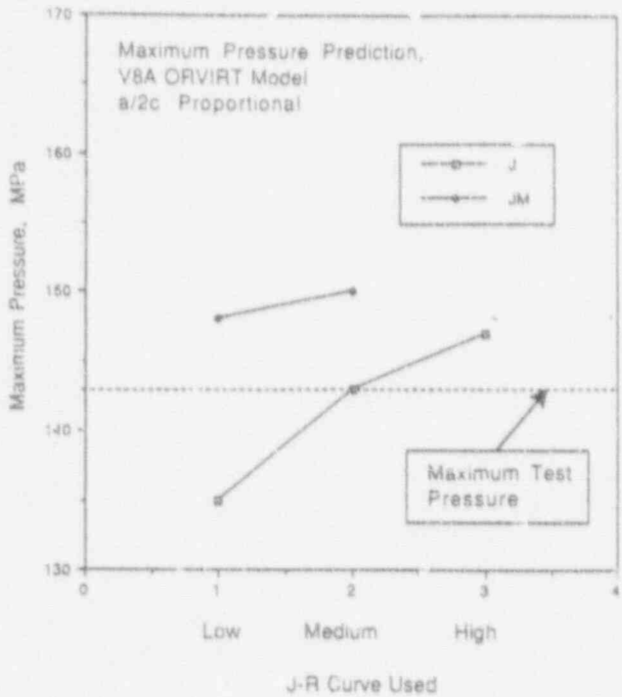

Fig. 7.25. Maximum predicted pressure as a function of J-R curve for V8A ORVIRT model.

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8. A 302 STEEL ANALYSIS

As part of the overall effort of the working group, a series of tests on various sized specimens of an LUS A 302 steel was to be conducted. These test results were to serve as a benchmark calibration on all of the analyses and rules for extrapolation that were made. However, when the results became available to the group, they caused confusion rather than providing a final answer to the issues of *J-R* curve extrapolation and the J_D/J_M controversy. The results showed some size effects that were unusual. Unlike the typical conservative results from small specimens, the A 302 steel small-specimen results gave grossly unconservative *J-R* curves. To examine these data further, three tasks were conducted. First, the data were reanalyzed using the method of normalization; and these results were analyzed to determine the exact nature of the resulting *J-R* curves. Second, reasons for the unexpected nature of the results were postulated and examined. Third, structural models were analyzed with the ductile fracture methodology to see what the consequences might be of using the unconservative results in structural analysis.

8.1 REANALYSIS OF A 302 STEEL *J-R* CURVES

The A 302 steel test matrix contained five sizes of compact specimens with proportional dimensions ($W = 2B$). They ranged from 1/2T (W = 1 in.) to 6T (W = 12 in.). The tests were conducted at Materials Engineering Associates (MEA), Lanham, Maryland.[1] These tests were conducted using the standard elastic unloading compliance method of crack length measurement. These *J-R* curve results are given in Fig. 8.1 for all sizes tested. The unusual and disturbing aspect of the results is that the small specimens gave relatively high and steep *J-R* curves, whereas the large specimens gave low and flat *J-R* curves. All the results were reanalyzed using the method of normalization. These are presented in Fig. 8.2. They show no essential difference from the results analyzed by the compliance method. For these materials, J_M was not used because it would cause the small-specimen results to show even more difference from the large-specimen results.

When selected results are plotted separately, they do show some consistency. Figure 8.3 shows selected 1/2T and 1T results which form a reasonably close scatterband. When these selected results are plotted with the 2T and 6T sizes, they show the gradual reduction in the *J-R* curve slope with increasing specimen size (Fig. 8.4).

8.2 A 302 STEEL *J-R* CURVE EXPLANATIONS

The unconservative character of the *J-R* curve from the small-specimen tests is cause for concern and should be explained if possible. Three reasons for the behavior of the small specimens were proposed and studied here. They are (1) the sampling plan in the test plate, (2) the relative elastic-to-plastic behavior, and (3) the ductile instabilities (pop-ins) encountered during the test.

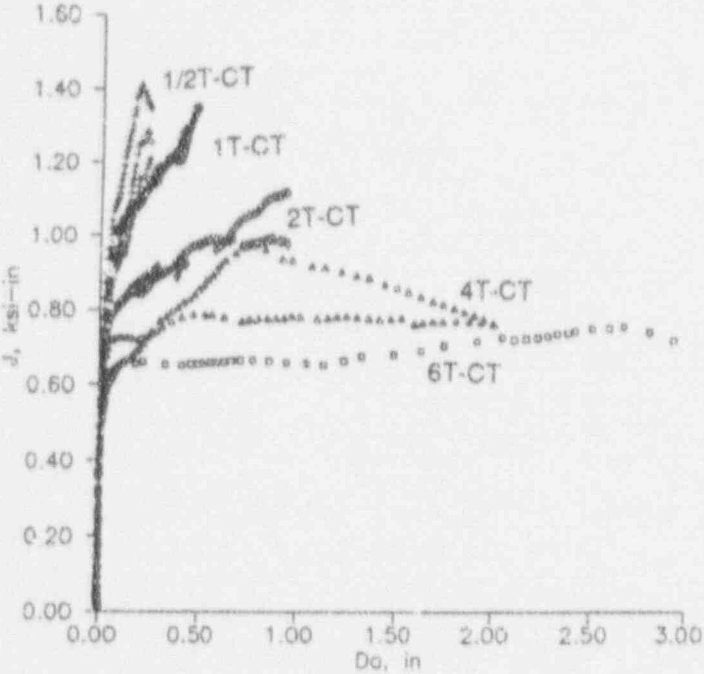

Fig. 8.1 J-R curves from elastic compliance for A30-2 steel, all sizes.

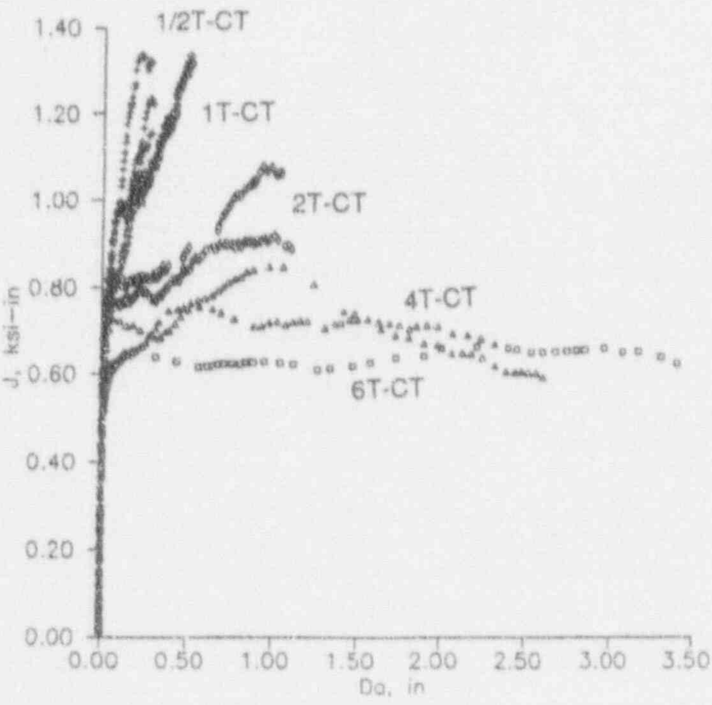

Fig. 8.2 J-R curves from normalization for A302 steel, all sizes.

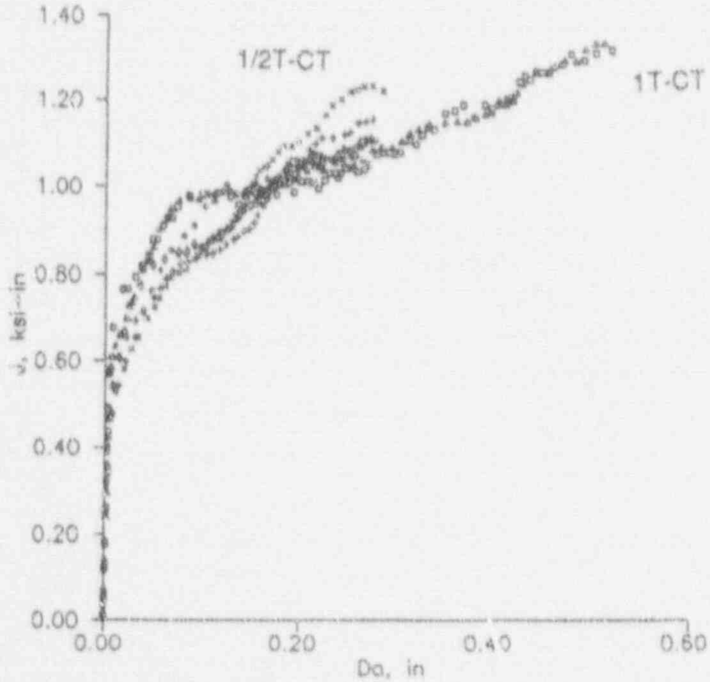

Fig. 8.3 J-R curves for A 302 steel showing 1/2T-CT and 1T-CT with consistent results.

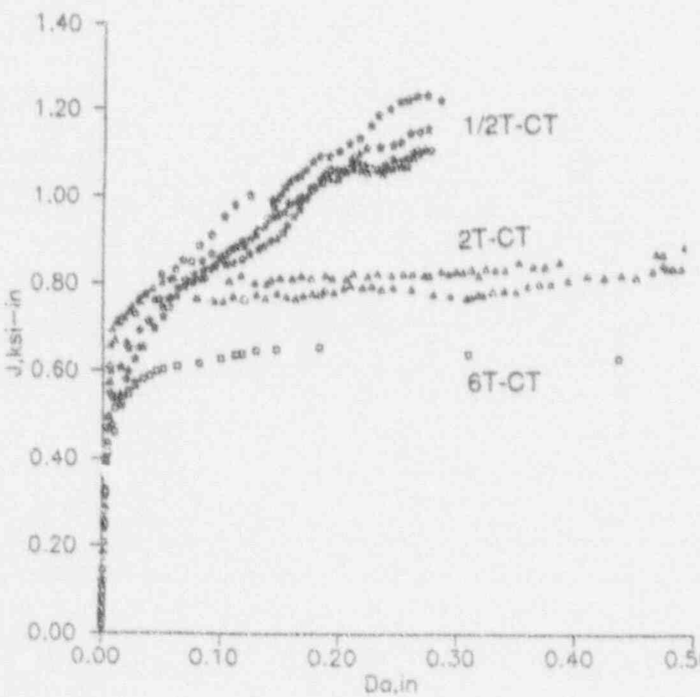

Fig. 8.4 J-R curves for A 302 steel showing 1/2T-CT with 2T-CT and 6T-CT.

The A 302 test plate was approximately 6 in. thick. The sampling plan is shown in Fig. 8.5. The larger specimens 6T and 4T were taken from a central location so that the plate centerline went through the middle of the specimen. The 2T specimens were taken just above and below the centerline. The 1T specimens were taken so that they were centered at 0.35 and 0.65 of the thickness, and the 1/2T specimens were taken at the 0.25, 0.50, and 0.75 thickness positions. Considering these locations, the consistent group of 1/2T and 1T specimen *J-R* curves came from the positions not touching the centerline (Figs. 8.3 and 8.6). The two 1/2T specimens from the centerline gave higher or lower *J-R* curves than the consistent group. All of the other specimens—2T, 4T, and 6T—at least touch the center plate position. Their *J-R* curves were all lower.

The observations relating to sampling plan merely suggest that specimens taken from the center plate position may not give results that are consistent with those taken from positions nearer the surface. There is no proof that the center region gives the lowest *J-R* curves.

The issue relating to the relative amounts of plastic and elastic deformation was proposed to explain this behavior.[2] The *J* value is generally calculated as a sum of an elastic and a plastic component from the expression.

The relative amounts of elastic-to-plastic contribution to *J* have been thought to possibly control the *J-R* curve behavior. The A 508 specimen data, which gave relatively consistent *J-R* curve behavior among the various specimen sizes, were used in comparison. Figure 8.7 shows a plot of the ratio of J_{el}/J_{pl} for both steels at a fixed point of crack extension. The A 508 generally has a much greater contribution from the plastic component of *J*. Even for the largest specimen, the ratio J_{el}/J_{pl} is about 1 to 1. The A 302 steel, on the other hand, has an increasing ratio of J_{el}/J_{pl} with increasing specimen size. For the largest specimen, the contribution is nearly all elastic. This looks convincing enough to conclude that the large elastic contribution could cause the low *J-R* curve. However, when compared with a set of 5Ni steel results, this conclusion is not clear. Figure 8.8 shows similar results for a 5Ni steel that, when smooth-sided, showed no size effect but, when side-grooved, showed a lower *J-R* curve with many ductile instabilities (Fig. 8.9). The J_{el}/J_{pl} ratios increased with side grooving; however, both side-grooved and smooth-sided had larger J_{el}/J_{pl} ratios than those observed for the A 302 steel. It appears from this that the large J_{el}/J_{pl} does not cause lower toughness. For the A 302 steel, it appears rather that the low toughness causes the high J_{el}/J_{pl} ratios. This interpretation also follows from Fig. 8.7 when the small-specimen results alone are analyzed. The 1/2T and 1T results from the A 302 steel have the same J_{el} to J_{pl} as the A 508 steel. From a predictive point of view, the small-specimen tests of A 302 steel would not indicate that a severe size effect would occur.

The last cause proposed to explain the A 302 size effect was the ductile instabilities observed during the test. A plot of load vs displacement, *P-v*, is given in Fig. 8.10 for the biggest specimen. Just after reaching maximum load, the load drops about 10% very suddenly, with no increase in displacement. This is a local instability caused by low *J-R* curve behavior. It had been observed with other material that low *J-R* curve behavior accompanied this type of local ductile instability behavior. In fact, the *J-R* curve could not be measured in a meaningful way when these instabilities were too large. However, these instabilities could likely be a result of low toughness rather than a cause.

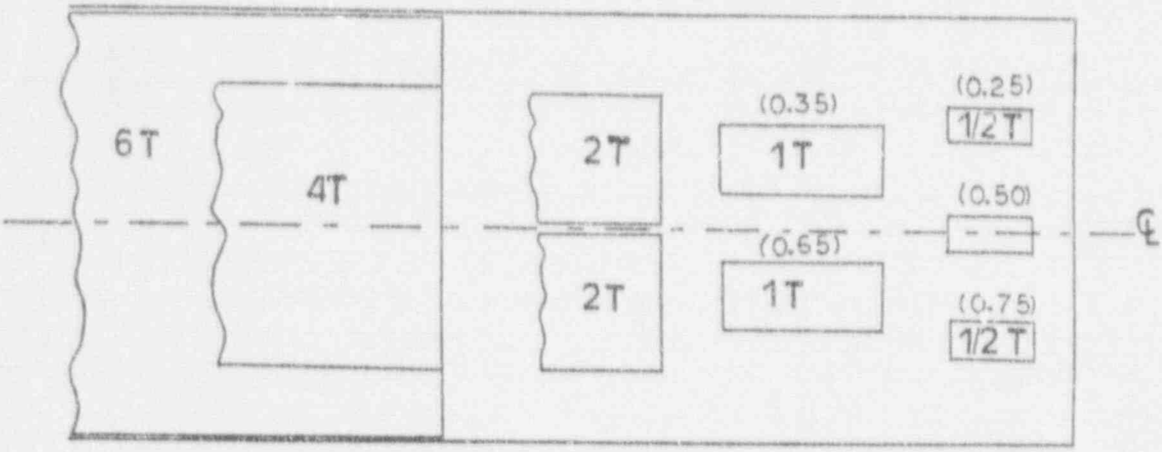

Fig. 8.5. Schematic of A 302 steel plate layout showing through plate thickness of specimens.

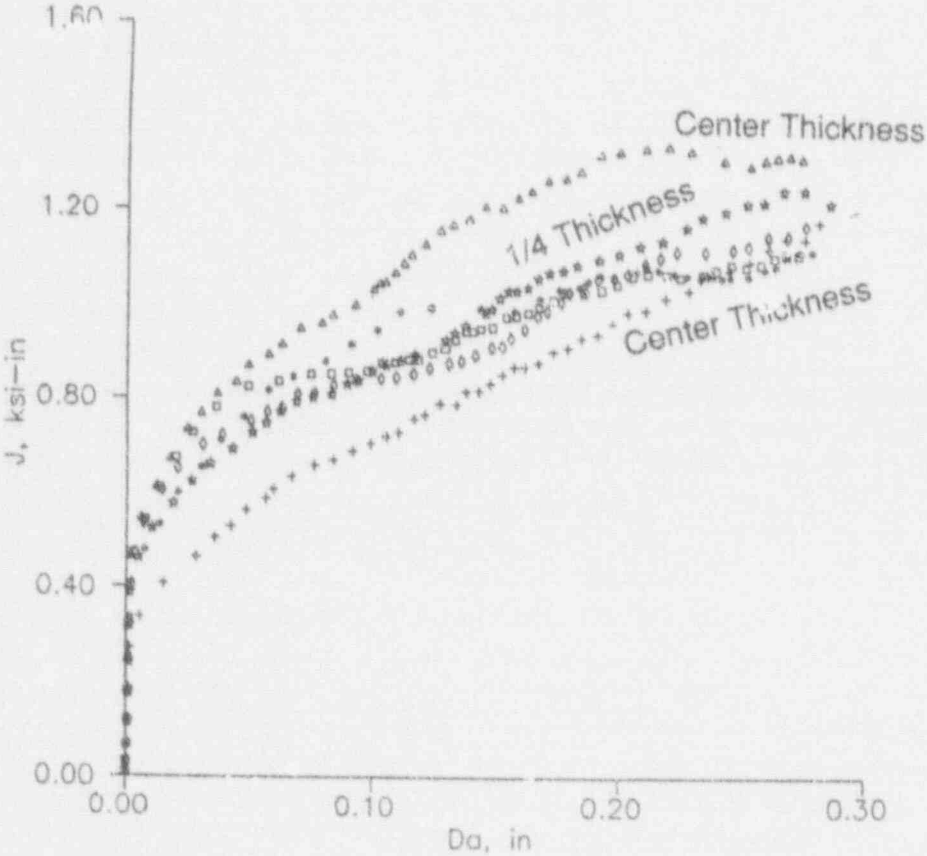

Fig. 8.6. J-R curves for A 302 steel, all 1T-CT and 1/2T-CT.

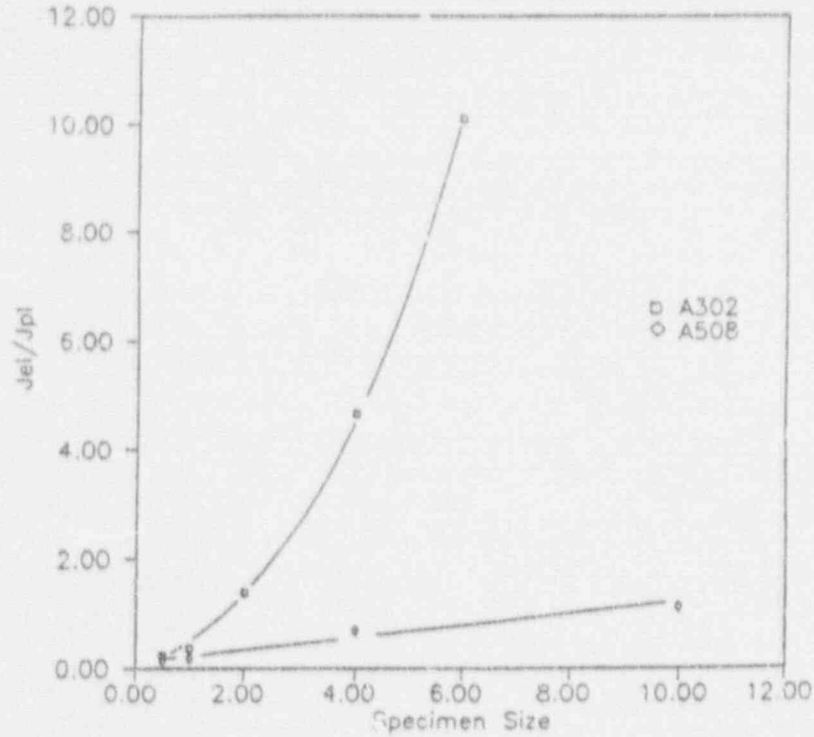

Fig. 8.7. Ratio of elastic to plastic J comparing A 302 and A 508.

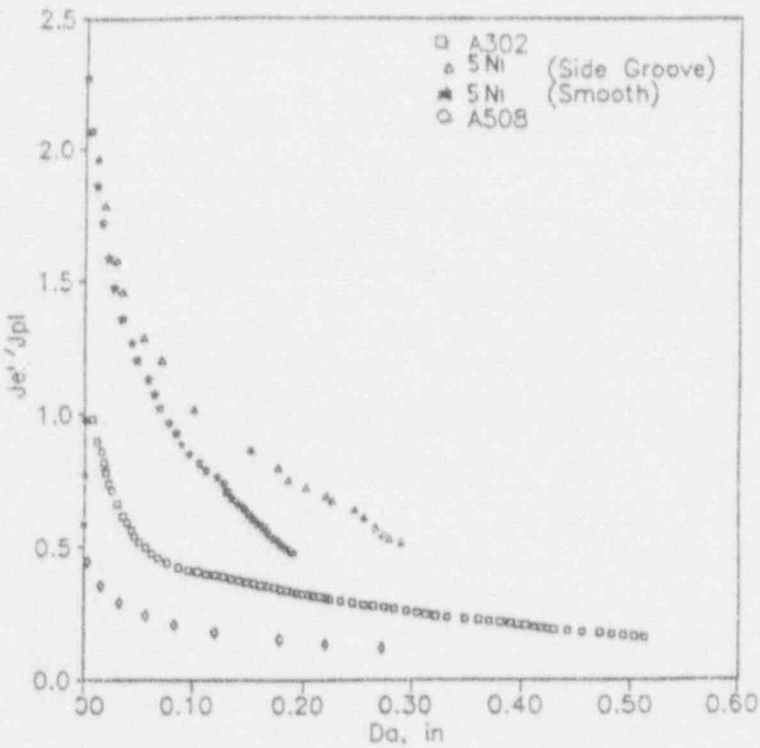

Fig. 8.8. Ratio of elastic to plastic J comparing A 302, A 508, and 5Ni steels (smooth sided and side grooved).

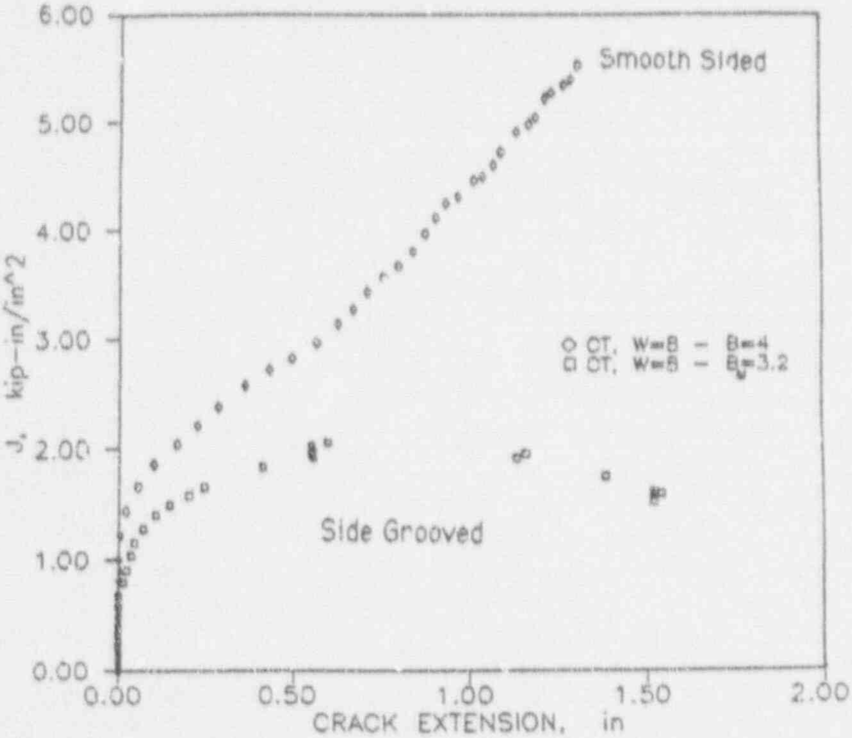

Fig. 8.9 J-R curve from 5Ni steel comparing side grooved with smooth sided.

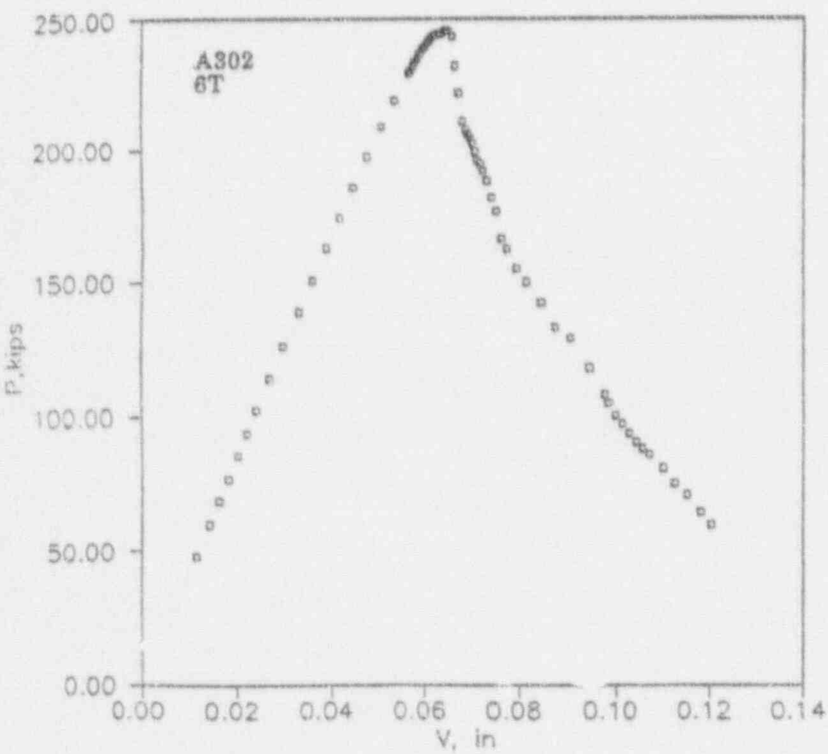

Fig. 8.10 Load vs displacement plot for A 302 steel 6T-CT.

The final conclusion of the analysis of cause is that no clear cause could be cited. The issues of J_{el} to J_{pl} ratio and local ductile instability could be a result rather than a cause of low *J-R* curve behavior. The sampling plan issue may be a cause, but this does not completely solve the problem of how to predict the large size effect observed here from small-specimen test results alone. Also, there was some evidence of longitudinal splitting in the larger test specimens. This behavior in the past often raised *J-R* curve toughness rather than lowering it. Again, this is not a behavior that could be predicted from small-specimen testing.

8.3 IMPLICATIONS TO STRUCTURAL ANALYSIS

The implication of the size effect observed for this material is that small-specimen tests cannot be used to predict the behavior of larger structures when this effect is present. To see if this implication is correct and to what extent for the A 302 steel, the ductile fracture methodology was used to predict behavior of specimens and pressure vessel geometries.

The first set of predictions used the small-specimen *J-R* curve with the *J*-based extrapolation scheme of Sect. 6 to predict the behavior of the larger specimens. This is done using the 1/2T *J-R* curve for prediction and both experimental and handbook-based calibration curves to predict the behavior of other specimens. First, the 1/2T was predicted from itself (Fig. 8.11). Next, the 1/2T data were used to predict the 2T (Fig. 8.12), the 4T (Fig. 8.13), and the 6T (Fig. 8.14). The 1/2T predicts itself exactly, as would be expected. Also, the 2T prediction from the 1/2T *J-R* curve is not so bad. The maximum load is predicted fairly well, but the unloading part of the *P-v* curve is not predicted well. The other specimens do not predict well. The maximum load estimate from the same 1/2T is much higher than the measured maximum load resulting in an unconservative prediction.

The second set of predictions used the models of Sect. 7 for the A11 prediction (Fig. 8.15) and the V8A vessel (Fig. 8.16). For this, both the extrapolated 1/2T and the 6T *J-R* curves were used. The 1/2T model would give the predicted behavior from a small-specimen *J-R* curve test that was extrapolated according to the guidelines established here in Sect. 6. The 6T *J-R* curve was an attempt to model actual pressure vessel behavior, assuming that it would behave more like the biggest specimen. The analysis predicted pressure vs crack extension so that a maximum pressure for failure could be evaluated. For the A11 model of Fig. 8.15, the maximum pressure from the 1/2T *J-R* curve is about 25% higher than that from the 6T *J-R* curve. For the V8A model, the difference is about 35%. If the assumption of the model is correct (i.e., the vessel would behave more like the larger and thicker test specimen), the small-specimen predictions are not good at all.

8.4 DISCUSSION OF A 302 STEEL RESULTS

Of all of the work done on this study, the findings of this section have the most consequence to the prediction of reactor vessel integrity. The implications are that small specimens cannot be used in some cases to predict the integrity of larger structures. This is certainly true in the case when the severe size effect observed for the A 302 steel occurs in

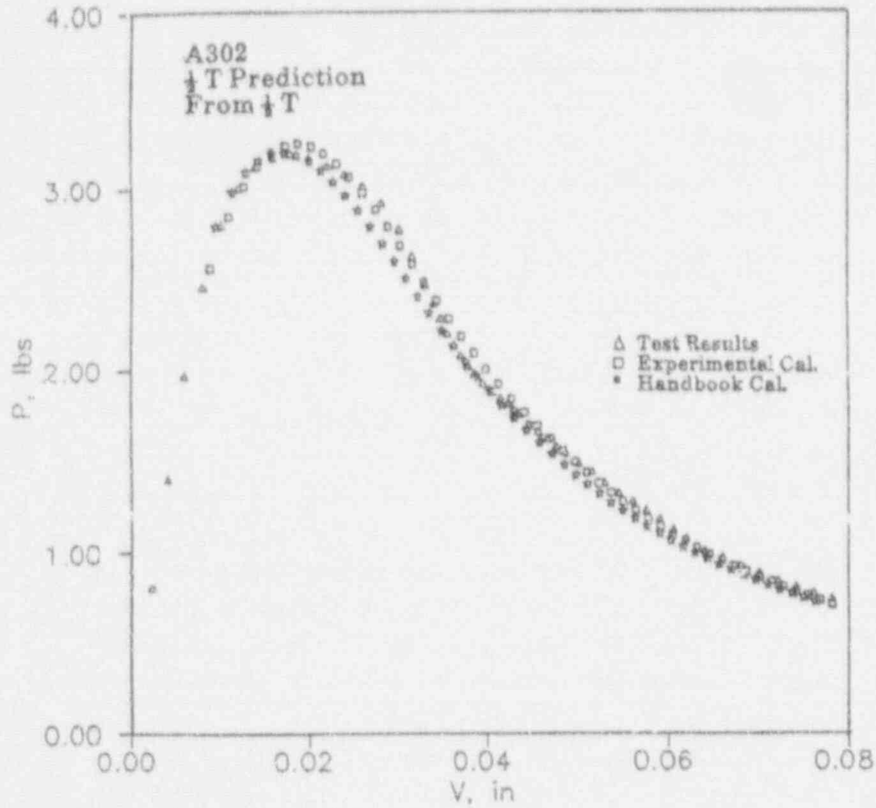

Fig. 8.11 Load vs displacement prediction for 1/2T-CT from 1/2T-CT J-R curve.

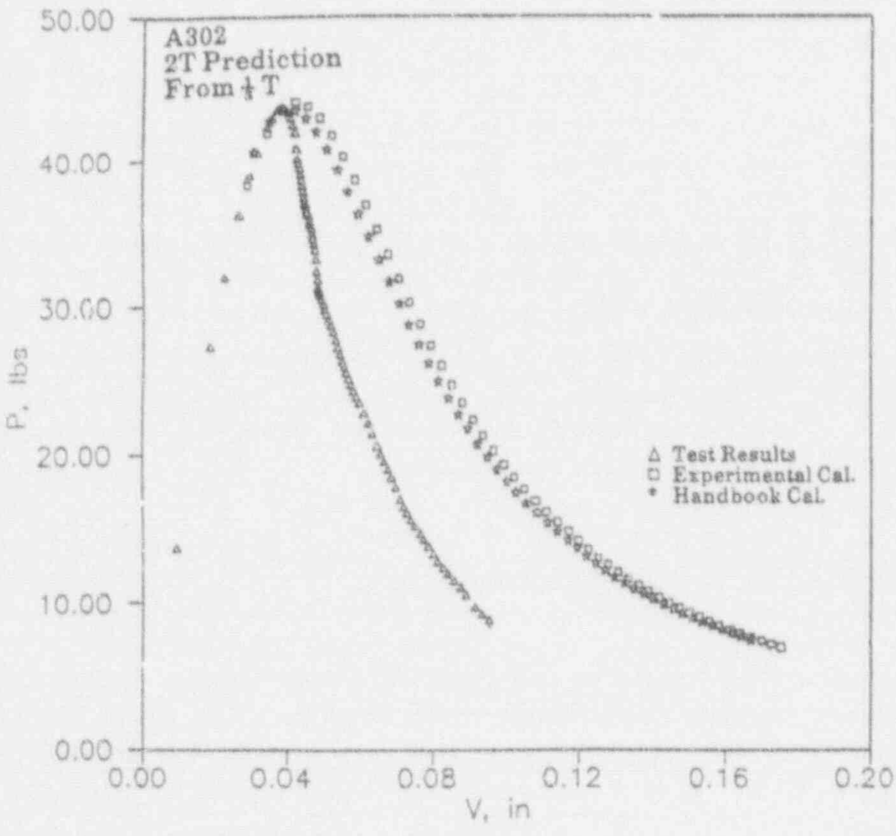

Fig. 8.12 Load vs displacement prediction for 2T-CT from 1/2T-CT J-R curve.

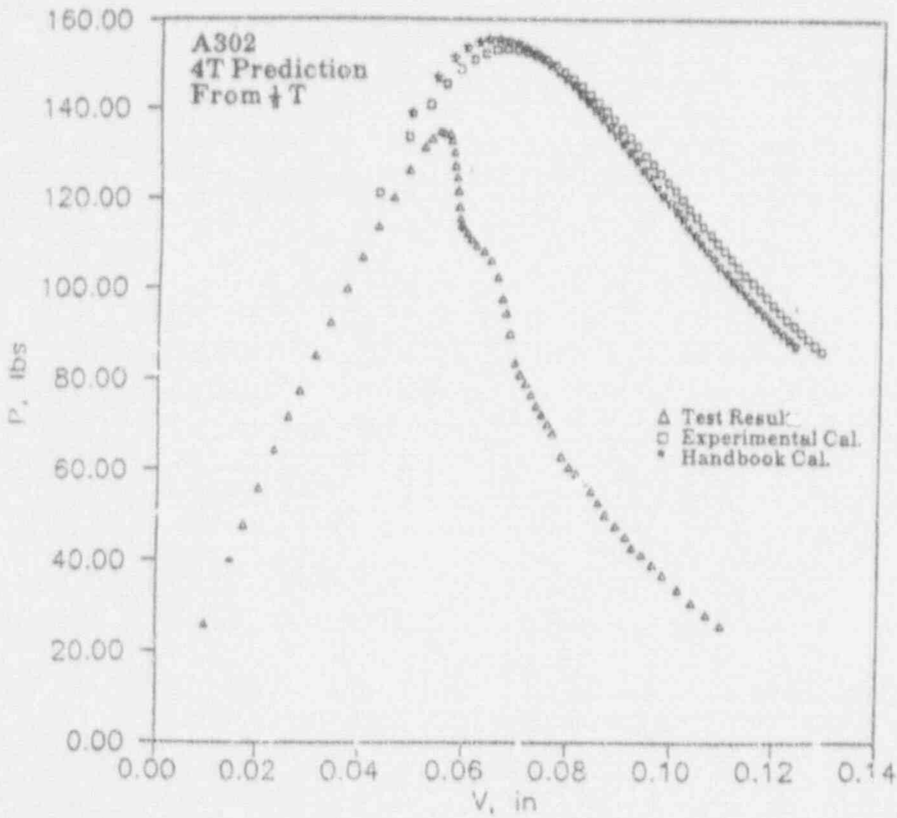

Fig. 8.13 Load vs displacement prediction for 4T-CT from 1/2T-CT J-R curve.

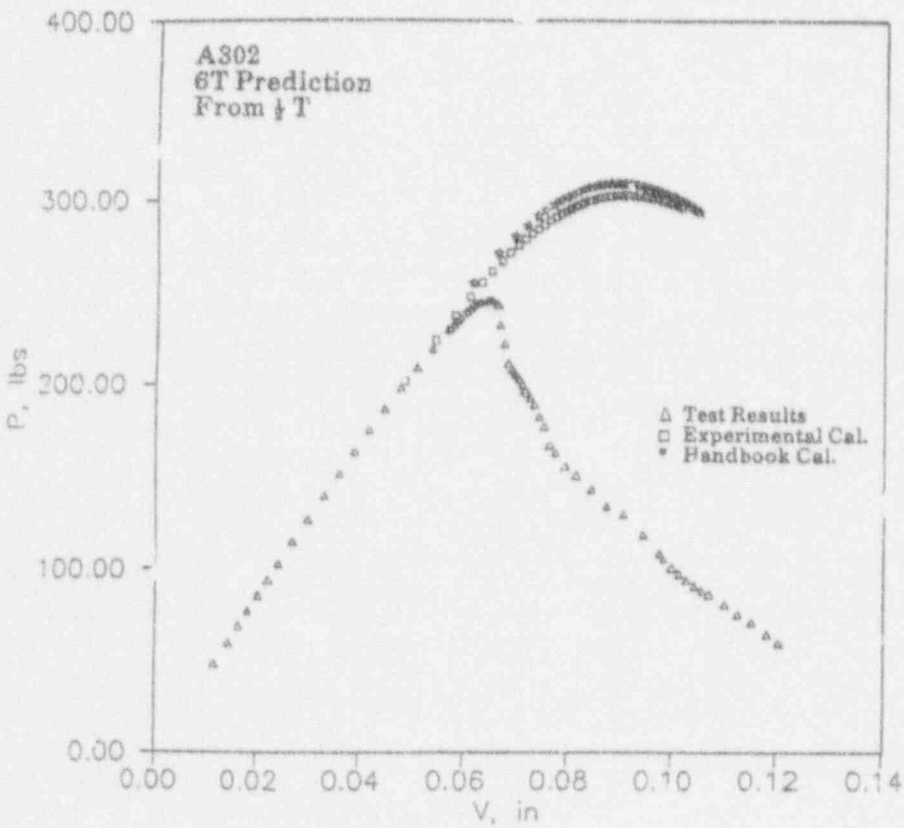

Fig. 8.14 Load vs displacement prediction for 6T-CT from 1/2T-CT J-R curve.

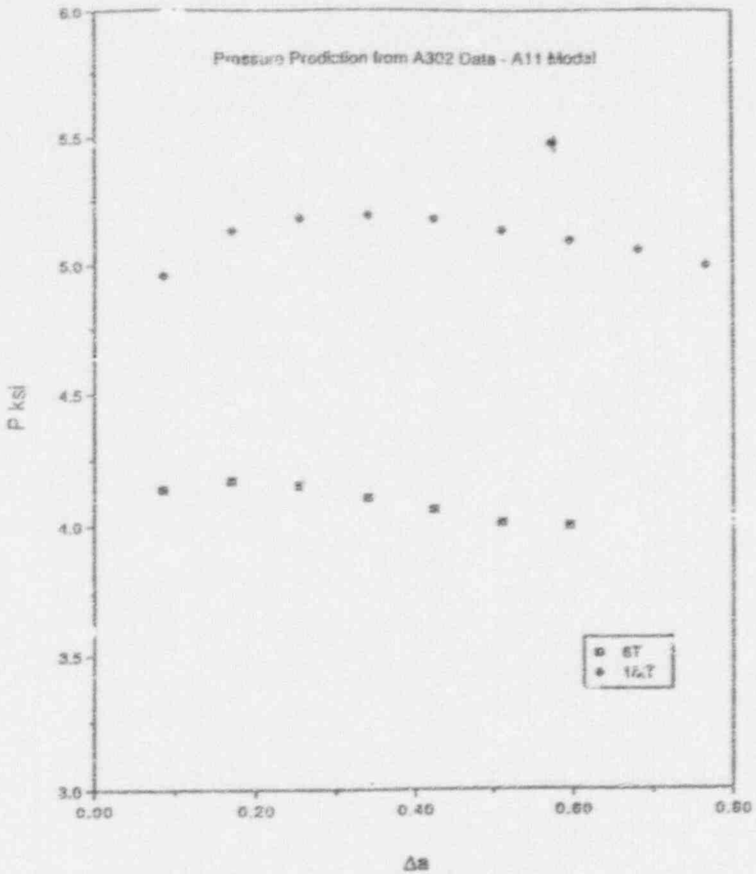

Fig. 8.15. Pressure vs crack extension comparing 1/2T-CT with 6T-CT J-R curve input, A11 model.

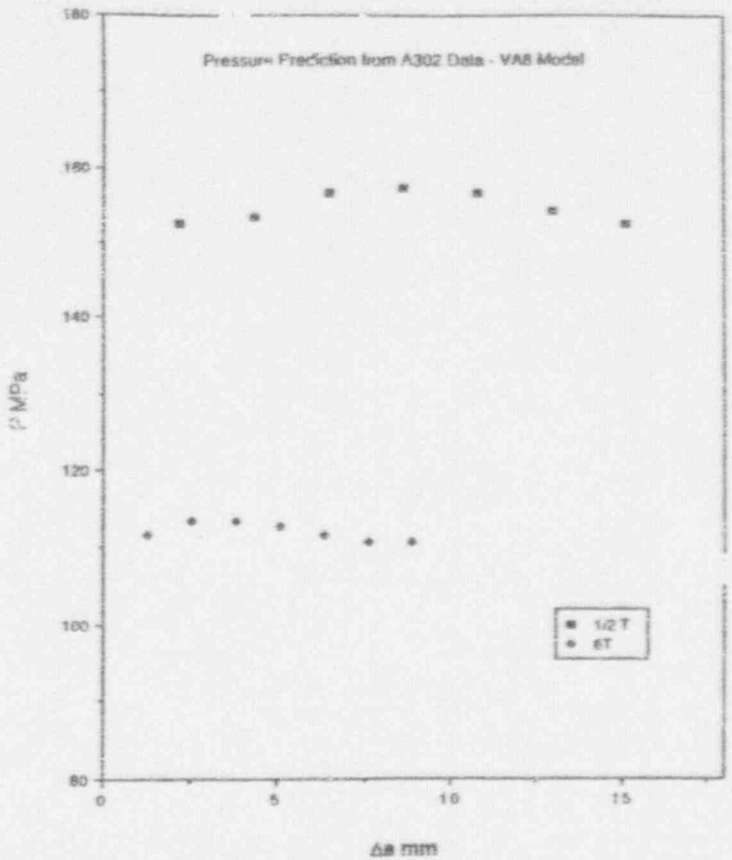

Fig. 8.16. Pressure vs crack extension comparing 1/2T-CT with 6T-CT J-R curve input, V8A ORVIRT model.

larger specimens, implying that this might also happen in large structures. Since this size effect does not generally occur, there is some hope for the development of a predictive methodology based on small-specimen results. The example materials used to study size effects in Sect. 6 did not show the severe loss of *J-R* curve toughness with increasing size that the A 302 steel did. However, having seen this one example, there is cause for concern. The size effect does not appear in the small-specimen results 1/2T and 1T. There is no warning that it should occur from the causes studied and no way to guess when it might occur from present knowledge. Therefore, prediction of behavior based on small-specimen results could be grossly unconservative.

Perhaps the cause of the size effect is related to some character of the material not yet studied, for example, microstructure, processing or aging, or some aspect of the testing [e.g., the relationship of test temperature to fracture appearance transition temperature (FATT)]. It does appear to be important to determine the cause of this behavior and the frequency of occurrence so that it can be recognized and predicted in other steels.

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9. LOW-UPPER-SHELF CRITERIA

Near the end of the tenure of the J_D/J_M Working Group, there was some discussion about various criteria for LUS prediction. In particular, one part of the discussion centered around the *J-R* curve criteria for prediction of behavior. One point of view advocated a limited use of the *J-R* curve so that crack extension never exceeded 0.1 in. The prediction of failure was related to the point where the *J-R* curve reached Δa = 0.1 in. This was examined for the various models chosen in the preceding sections. The A 508 steel specimen prediction of the large-specimen *P-v* behavior from small specimens is shown in Fig. 9.1. The point on the *P-v* curve where crack growth is 0.1 in. is marked, as well as the crack extension at maximum load. The point where Δa = 0.1 in. is well before maximum load. Maximum load corresponds to approximately Δa = 0.4 in. This represents an extrapolation of the *J-R* curves for both 1/2T and 1T specimens. The same indications of crack extension are given for the A11 model (Fig. 9.2) and for the V8A ORVIRT model (Fig. 9.3). In all cases, crack extension of 0.1 in. does not predict maximum load. The total crack extension at maximum

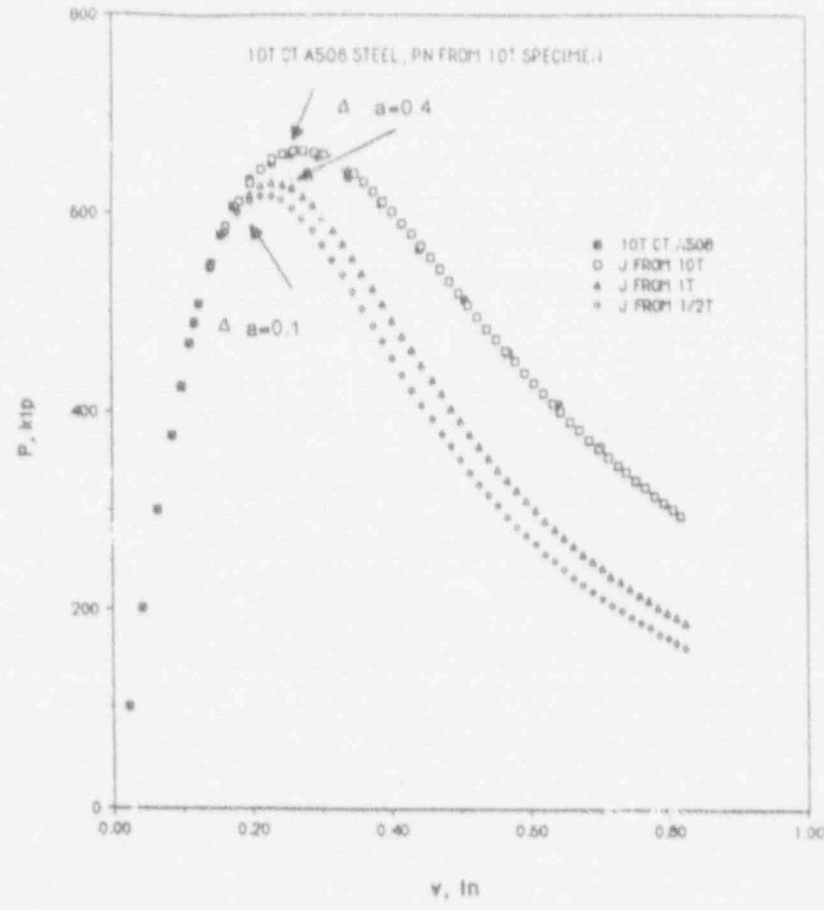

Fig. 9.1. Load vs displacement predictions for A 508 specimens showing 0.1-in. crack extension and crack extension at maximum load.

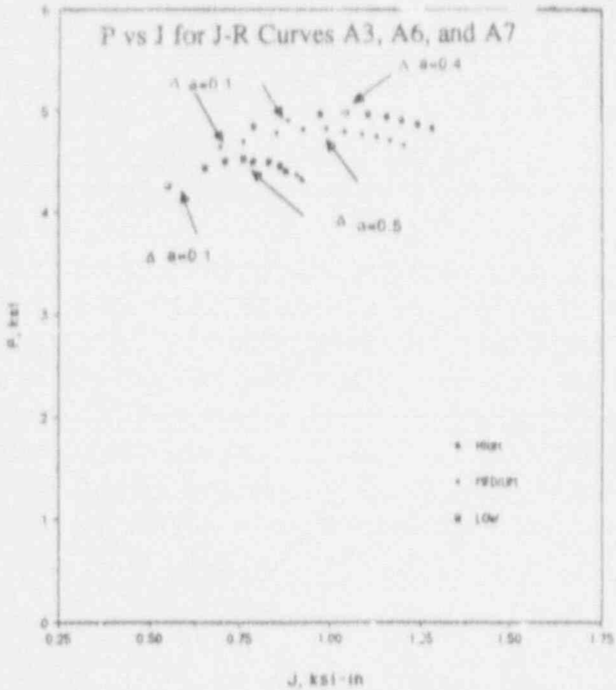

Fig. 9.2. Pressure vs J predictions for V8A weld J-R curves, A11 model showing 0.1-in. crack extension and crack extension at maximum load.

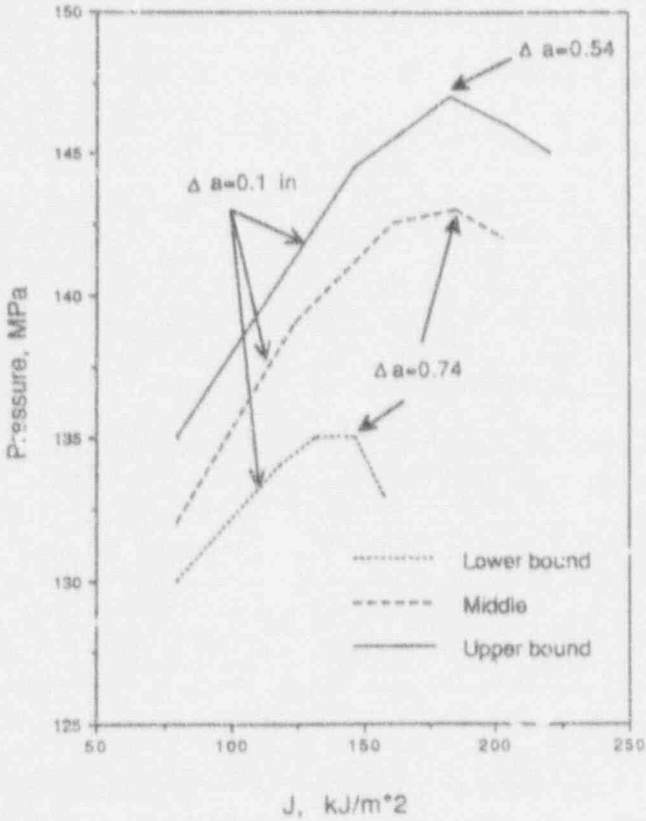

Fig. 9.3. Pressure vs J predictions for V8A weld J-R curves, V8A ORVIRT model showing, 0.1-in. crack extension and crack extension at maximum load.

load ranges from 0.4 in. to 0.74 in. This ranges from the maximum extent of the V8A weld data of Fig. 7.10 to about a two times extrapolation of the *J-R* curve.

In contr to the above, when the size effect of the A 302 steel is operating (Figs. 8.14 and 8.15), the maximum pressure is already reached before crack extension is 0.01 in. Using 0.1 in. as a standard could mean that the failure pressure is severely overpredicted at a crack extension 0.1 in. For these materials, crack extensions are often less than 0.01 in. at maximum load. Putting an arbitrary on crack extension limit does not assure that conservation will be maintained. Therefore, an arbitrary prediction of failure at a fixed point on the *J-R* curve does not seem to be a good criterion. It can range from too conservative in many cases to unconservative when there is an unexplained material size effect. A better picture of overall behavior can be obtained from a model like the ductile fracture methodology that predicts load or pressure as a function of an independent variable. This can predict a maximum load for instability which is more realistic than one based on an arbitrary point on the *J-R* curve. It also gives more information about behavior such as the unloading slope after maximum load, which relates to instability in a stiffly loaded structure.

10. DISCUSSION

Since this study was done on several different projects and contains results of studies organized with different objectives, it is good to try to relate everything in a general discussion. Two of the prevailing issues throughout the studies have been the method to use for *J-R* curve extrapolation and which parameter, J_D or J_M, to use for characterizing the *J-R* curve. For this study, the extrapolation worked well by graphically fitting the *J-R* curve with a power law by plotting results on log-log scales, fitting a straight line, and then extrapolating the straight-line fit. The use of *J* for the R curve always gave exact or conservative extrapolation when small- and large-specimen results were compared. The use of J_M for the R curve gave unconservative extrapolation. The same trends were observed when the ductile fracture methodology was used with the pressure vessel models, A11 and V8A.

The results from this study did show that extrapolation of the *J-R* curve is best done between the crack growth to initial remaining uncracked ligament ratio, $\Delta a/b_0$, of 0.1 to 0.3. Since 0.1 is the present limit of $\Delta a/b_0$ for the ASTM test method E 1152 for experimentally determining *J-R* curves, it appears that this limit should be relaxed when *J-R* curve extrapolation is necessary. All of the results studied in this work showed that the *J-R* curve could be developed in a consistent manner well beyond the limit of 0.1 $\Delta a/b_0$. Typically, inconsistencies between the various specimen sizes either in *J* or J_M first developed in the range of 0.3 to 0.4 $\Delta a/b_0$.

The ductile fracture methodology could be used to predict structural behavior reasonably well. The work done here showed that the choice of calibration functions, which relate load, displacement, crack length, and *J*, can be as critical to the prediction of instability as the proper choice of *J-R* curve. For the A11 sensitivity study, the greatest variation in predicted maximum pressure resulted from variations in the calibration function inputs such as yield stress rather than from variations in the *J-R* curve inputs. Also, the prediction of the HSLA steel large specimen was not very accurate when an incorrect (handbook power law) calibration function was used. Therefore, in the prediction of structural behavior and instability point, careful attention must be given to the deformation behavior that goes into the calibration curves as well as the fracture behavior resulting from the *J-R* curve.

An important observation from this work came from the analysis of the LUS A 302 steel *J-R* curves. These results showed a size dependence that is not typically seen. The small-specimen *J-R* curves were much higher than the large-specimen *J-R* curves. Any predictions made from these small-specimen results would be grossly unconservative if the structure to be analyzed had a fracture behavior like that of the large specimen. These results suggest that when such a size effect occurs, the small-specimen *J-R* curves cannot be used to predict the cracking behavior and instability of the larger structures. This observation is important. Although this size effect is not frequently observed, there appears to be no clue as to when it might happen. Even the test results from the small specimens do not warn of the impending problem encountered in the larger specimens. This is an area that requires further study if pressure vessel integrity is to be assured from small-specimen *J-R* curve results.

A final observation is that a criterion for fracture based solely on a selected point on the *J-R* curve, such as Δa = 0.1 in., is not sufficient. Depending on how the various inputs interact, this point could be either conservative or unconservative as a prediction of instability.

A criterion based on instability needs to be added. This method should relate instability in terms of design parameters like load, pressure, or displacement in the same way as does the ductile fracture methodology presented here.

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11. ABSTRACT (200 words or less)

The work in this report was conducted in support of the issues studied by the U. S. Nuclear Regulatory Commission J_D/J_M Workers Group during the period 1987-1989. The major issues studied were the J-R curve extrapolation techniques for using small-specimen test results to predict ductile instability in larger structures where the extent of crack extension from the small-specimen test was not sufficient. An additional issue was raised during the course of this work by the testing of a low-upper-shelf A 302 steel. The results from these tests were not typical of ductile fracture in many steels and suggested that small-specimen J-R curves may not predict the behavior of large structures in some cases. The cause of this behavior was studied as well as the consequences of using the J-R curve results from small specimens of this kind of material. Finally, a discussion and recommendations are given relating to the use of extrapolated J-R curves.

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