



UNITED STATES  
NUCLEAR REGULATORY COMMISSION

WASHINGTON, D.C. 20555-0001

September 15, 1994

Mr. Raymond Burski  
Combustion Engineering Owners Group  
c/o Entergy Operations  
Highway 18  
Kilona, LA 70066

SUBJECT: SAFETY ASSESSMENT OF REPORT CEN-604 REVISION 01, "FINAL EVALUATION OF LOW UPPER SHELF ENERGY FOR COMBUSTION ENGINEERING NUCLEAR STEAM SUPPLY SYSTEMS REACTOR PRESSURE VESSELS, FINAL REPORT," SEPTEMBER 1993

Dear Mr. Burski:

By letter CEOG-93-479 dated September 27, 1993, the Combustion Engineering Owners Group (CEOG) submitted a report entitled "Evaluation of Low Upper Shelf Energy for Combustion Engineering Nuclear Steam Supply Systems Reactor Pressure Vessels, Final Report," CEN-604 Revision 01. This report was provided to the NRC for information only with regard to Generic Letter (GL) 92-01, and no request for review and approval was made. The stated objective of the report was to present a bounding analysis for all CEOG reactor pressure vessel beltline materials which may be expected to have upper shelf energy (USE) values below the NRC screening criteria of 50 ft-lb before the end of license (EOL). As set forth in Title 10 of the Code of Federal Regulations, Part 50 (10 CFR 50), Appendix G, the existence of margins of safety against fracture equivalent to those required by Appendix G to ASME Code Section III must be demonstrated for materials which exceed these screening criteria. A request for additional information (RAI) was made by the NRC staff in a letter dated November 19, 1993, and the response to the RAI, dated February 21, 1994, was received by the staff on March 3, 1994.

The staff has completed a safety assessment of the equivalent margins analysis presented in the report, as enclosed. The staff assessment supports the following conclusions: (1) the methodology employed for the analysis was consistent with the guidelines in ASME Code Case N-512 and, with some modification in the values selected for the evaluation parameters, is acceptable to the staff; (2) the report demonstrates margins of safety equivalent to those of the ASME Code, Section III, Appendix G for CEOG beltline plate materials; (3) an equivalent margins analysis based on weldment properties was not performed because the CEOG concluded that all of the beltline welds would be above 50 ft-lb at EOL; and (4) individual licensees desiring to reference CEN-604, Revision 01, as the basis for addressing the USE requirements of 10 CFR 50, Appendix G must confirm its plant-specific applicability by either demonstrating that all beltline welds will have EOL USE above 50 ft-lb or that the bounding plate used in the report has a lower

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J-R curve than any other beltline material in the vessel. Further, individual licensees must request review and approval of referencing CEN-604, Revision 1 in accordance with 10 CFR 50, Appendix G.

If you have any questions, please contact Edwin M. Hackett of my staff at 301-504-2751.

Sincerely,

*[Signature]*  
Original signed by

Brian W. Sheron, Director  
Division of Engineering  
Office of Nuclear Reactor Regulation

Enclosure: As stated

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## ENCLOSURE

### SAFETY ASSESSMENT BY THE OFFICE OF NUCLEAR REACTOR REGULATION REACTOR VESSEL UPPER SHELF BOUNDING EQUIVALENT MARGINS ANALYSIS FOR COMBUSTION ENGINEERING OWNERS GROUP PRESSURIZED WATER REACTORS CEN-604, REVISION 01

#### 1.0 REVIEW SUMMARY

By letter CEOG-93-479 dated September 27, 1993, the Combustion Engineering Owners Group (CEOG) submitted a report entitled "Evaluation of Low Upper Shelf Energy for Combustion Engineering Nuclear Steam Supply Systems Reactor Pressure Vessels, Final Report," CEN-604 Revision 01 [1]. This report was provided to the NRC for information only with regard to Generic Letter (GL) 92-01, and no request for review and approval was made. The stated objective of the report was to present a bounding analysis for all CEOG reactor pressure vessel beltline materials which may be expected to have upper shelf energy (USE) values below the NRC screening criteria of 50 ft-lb before end of license (EOL). As set forth in volume 10 of the Code of Federal Regulations Part 50 (10 CFR 50), Appendix G, the existence of margins of safety against fracture equivalent to those required by Appendix G to ASME Code Section III must be demonstrated for materials exceeding this screening criteria. A request for additional information (RAI) was made by the NRC in a letter dated November 19, 1993 and the response to the RAI, dated February 21, 1994, was received by the staff on March 3, 1994 [2].

The staff has completed a safety assessment of the equivalent margins analysis presented in the report. The staff assessment supports the following conclusions: (1) the methodology employed for the analysis was consistent with the guidelines in ASME Code Case N-512 [3] and, with some modification in the values selected for the initial parameters, is acceptable to the staff; (2) the report demonstrates margins of safety equivalent to those of the ASME Code, Section III, Appendix G for CEOG beltline plate materials; (3) an equivalent margins analysis based on weldment properties was not performed because the CEOG concluded that all of the beltline welds would be above 50 ft-lb at EOL; and (4) individual licensees desiring to reference CEN-604, Revision 01 as the basis for addressing the USE requirements of 10 CFR 50, Appendix G must confirm its plant-specific applicability by either demonstrating that all beltline welds will have EOL USE above 50 ft-lb or that the bounding plate used in the report has a lower J-R curve than any other beltline material in the vessel. Further, individual licensees must request approval of CEN-604, Revision 1 in accordance with 10 CFR 50, Appendix G.

#### 2.0 APPLICABLE REGULATORY REQUIREMENTS AND GUIDELINES

Regulatory requirements for the USE of RPV beltline materials are contained in Appendix G of 10 CFR 50. The appendix requires that the unirradiated USE determined by Charpy V-Notch (CVN) methods be no less than 75 ft-lb and that the vessel materials maintain an USE of no less than 50 ft-lb throughout the

service life of the vessel. If it is believed that any vessel material may fall below the 50 ft-lb criteria before EOL, an analysis must be submitted to the NRC which demonstrates, "margins of safety against fracture equivalent to those required by Appendix G of the ASME Code." This analysis will be subject to the approval of the Director, Office of Nuclear Reactor Regulation.

The guidelines that the staff has determined to be acceptable for the demonstration of equivalent margins of safety are contained in ASME Code Case N-512 [3], Appendix K to ASME Code Section XI [4], and in Draft Regulatory Guide DG-1023 [5]. DG-1023 incorporates the criteria of ASME Code Case N-512 while providing additional guidance on the determination of material properties and on the selection of transients.

Since fracture toughness data is often not available for the limiting beltline materials in licensee vessels, CVN data may be used to provide an estimate of the fracture toughness. NRC Regulatory Guide 1.99, Revision 2 [6] provides a conservative methodology for determining the percent decrease in USE for either base metal or weld materials based on the initial copper weight percent and the neutron fluence. NUREG/CR-5729 [7] presents empirically derived modeling results for the production of material fracture toughness (J-resistance or J-R) curves from the available CVN data, neutron fluence data, and copper content.

Additional guidance has been provided in NRC Branch Technical Position MTEB 5-2 [8] which provides for the estimation of the CVN data for the transverse orientation (T-L) from longitudinal (L-T) test data for base metal materials. The 50 ft-lb criterion in 10 CFR 50, Appendix G has been established for the consideration of transverse orientation properties in base metal materials. For welds, the fracture toughness and CVN properties are not dependent on test sample orientation.

### 3.0 EVALUATION

For service Levels A and B as specified in the ASME Code, the CEOG performed an analysis for the limiting normal operation cooldown rate (100°F/hr). The analysis is consistent with the guidelines provided in Code Case N-512 [3]. In accordance with the Code Case, the CEOG assumed a flaw with a depth of one-quarter of the base metal wall thickness (1/4 T) for Levels A and B and a flaw depth of up to one-tenth of the base metal wall thickness plus cladding for Levels C and D. The flaw geometry considered for all service conditions was a semi-elliptical surface flaw with a 6:1 aspect ratio (length/depth). The RPV beltline base plate materials covered by the CEOG report included:

- (1) A302 Grade B Modified (Plate)
- (2) A533 Grade B, Class 1 (Plate)

The CEOG has concluded that the USE values for the RPV beltline base plate materials for all of the member plants are not predicted to decrease to below 50 ft-lbs before EOL. However, the CEOG stated that use of the Regulatory Guide 1.99 [6] methodology with estimated transverse orientation USE yielded values in one vessel which were as low as 48.5 ft-lbs for an A302 Gr B

Modified plate. The equivalent margins analysis was undertaken to bound this condition.

The RPV beltline welds covered by the CEOG included those produced using the following fluxes:

- (1) Linde 1092
- (2) Linde 0091
- (3) Linde 124
- (4) ARCOS B-5

Based on an evaluation of GL 92-01 and surveillance data, the CEOG concluded that there was "reasonable assurance that the USE values of CEOG reactor vessel beltline welds will be maintained above 50 ft-lbs at EOL." As such, the bounding equivalent margins analysis was based on plate properties as described previously.

The adequacy of the equivalent margins analysis can be determined from the following considerations: (1) selection of mechanical properties, (2) the determination of predicted EOL USE value, (3) selection of the model for generating the fracture toughness data (J-R curves), (4) selection of the limiting transients, (5) the calculation for applied fracture driving force ( $J_{\text{applied}}$ ) and (6) the bounding nature of the analysis.

### 3.1 Mechanical Properties

The elastic modulus and yield strength for the bounding A302 Gr B Modified plate material as a function of temperature were obtained from data tabulated in the ASME Code [9].

The CEOG used the following values for the material properties required for the equivalent margins analysis:

Elastic Modulus (E) =  $29.0 \times 10^6$  psi  
 Poisson's Ratio = 0.3  
 Yield Strength = 50.0 ksi

The material yield strength at 550°F obtained by interpolation from Table 5.5 of the report [1] (44 ksi) was adjusted for the increase due to irradiation by a statistical analysis of RPV base metal data from the power reactor embrittlement database and additional surveillance data. A mean trend curve was fit to the data to enable a prediction of the percent increase in yield strength as a function of fluence. While the staff agrees that an increase in yield strength with irradiation may be expected in RPV materials, the methodology employed by the CEOG was not acceptable. The degree of scatter in the data effectively precluded the use of a mean trend curve to accurately predict the increase in yield strength due to irradiation. The staff believes that an adequate statistical approach would bound 95% of the data with 95% confidence. Since such an analysis was not presented, 44 ksi was used for the yield strength in the independent analysis performed by the staff.

The elastic modulus used by the CEOG does not agree with the value obtained for 550°F by interpolation from Table 5.4 of the report [1]. The staff analysis used this interpolated value ( $26.7 \times 10^6$  psi) for the elastic modulus.

### 3.2 Predicted EOL USE Values

As stated previously in Section 3.0, the CEOG has concluded that the USE values for the RPV beltline base plate materials for all of the member plants are not predicted to decrease to below 50 ft-lbs before EOL. However, using the Regulatory Guide 1.99 [6] methodology with an estimated transverse orientation USE, the CEOG obtained a value of 48.5 ft-lbs at EOL for one plant with an A302 Gr B Modified plate. This value was obtained for a plate with 0.19% Cu subjected to a 1/4T fluence of  $1.615 \times 10^{19}$  n/cm<sup>2</sup> at EOL. The equivalent margins analysis was undertaken to demonstrate that this limiting condition would be bounded.

### 3.3 Selection of the Fracture Toughness (J-R Curve) Model

The J-R curve information required for the equivalent margins analysis was generated by the CEOG for a range of CVN USE values using the RPV Base Metals model incorporating thickness corrections from NUREG/CR-5729 [7]. As stated previously, the CEOG has concluded that all of the CEOG beltline welds will be above 50 ft-lb at EOL and therefore did not develop J-R curve data for welds. Although not stated explicitly by the CEOG, for Levels A and B the staff originally assumed that the J-R curves (mean - 2 $\sigma$ ) for a temperature of 550°F were used in the report. However, an independent analysis by the staff could not specifically confirm the J-R curve data reported by the CEOG for 550°F. This discrepancy effectively made the CEOG reported values non-conservative in comparison with the staff calculations by approximately 5%. For Levels C and D the temperatures used for the J-R curves were from the appropriate transients (in the range of 400°F - 630°F).

### 3.4 Selection of Limiting Transients

The subject report used the 100°F/hr heatup and/or cooldown case as bounding for Levels A and B. This is consistent with the evaluation performed in NUREG/CR-6023 [10]. The input to the analysis included temperature and pressure profiles of the transients for Levels C & D. The steam line break (SLB) was found to be the most severe C/D cooldown and depressurization transient and was analyzed against the more stringent Level C requirements of Code Case N-512 [3]. The feed line break (FLB) transient was found to be the most severe heatup and pressurization transient and was evaluated against Level D requirements. Bounding pressure and temperature histories for both SLB and FLB events were provided.

### 3.5 Calculation of Applied Fracture Driving Force ( $J_{\text{applied}}$ )

The CEOG employed the procedures of Code Case N-512 in the determination of the fracture driving force ( $J_{\text{applied}}$ ) for Levels A and B. The staff performed an independent evaluation of the  $J_{\text{applied}}$  calculations for the limiting case using the material property values from Section 3.1. As the staff input

values differed from those used by the CEOG, the resulting  $J_{\text{applied}}$  calculations performed by the staff also did not concur with the CEOG calculations. The CEOG values for  $J_{\text{applied}}$  were non-conservative in comparison to the staff's values by approximately 2% to 5%. The pressure and temperature histories for the limiting Level C and D transients were input by the CEOG to a plasticity corrected linear elastic fracture mechanics (LEFM) analysis as per NUREG-0744 [11] to determine the applied fracture driving force. The stress distributions for the limiting transients included the contributions of the cladding to the thermal stress. Consistent with the results of the bounding analyses performed for NUREG/CR-6023 [10], the CEOG  $J_{\text{applied}}$  values for Levels A and B were found to be controlling in comparison with those for Levels C and D.

Although the fracture driving force calculations for Levels A and B could not be specifically confirmed by the staff's independent analysis, the methodology employed by the CEOG for calculation of the fracture driving force is acceptable.

### 3.6 Bounding Nature of the Analysis

The bounding results of the CEOG analysis are presented in Figures 1 through 4 [1]. The bounding Level A & B case was found to be for the largest reactor vessel (nominal inside diameter = 182 inches, wall thickness = 9.06 inches) with consideration of the axial flaw. The CEOG considered the material temperature at 550°F. Figure 1 presents the bounding Level A case evaluated against the flaw growth criterion (criterion 1) of Code Case N-512 [3]. The intersection of the  $J_{\text{applied}}$  and J-R curves at 0.1 inches of crack extension occurs for a USE of 35 ft-lbs. In Figure 2, a similar evaluation considering the flaw stability criterion (criterion 2) of the code case indicates a tangency (instability) point for a J-R curve at approximately the 38 ft-lb level. The CEOG therefore concluded that criterion 2 was controlling and that 38 ft-lbs was the bounding USE level for the equivalent margins analysis.

The bounding Level C & D transient (SLB) was considered against the flaw growth criterion of Code Case N-512 in Figures 3 and 4 [1]. An evaluation against the flaw stability criterion was not provided for either case as required by the Code Case. However, due to the extremely low  $J_{\text{applied}}$  values obtained for these the Level C & D transients, it is readily shown that Levels A & B are controlling for the equivalent margins analysis.

As the lowest calculated USE value at EOL for any of the CEOG vessels was reported to be 48.5 ft-lbs, and the minimum required USE level determined as described above is 38 ft-lbs, the CEOG has concluded that the equivalent margins analysis is bounding for all of their plants.

The results of the independent analysis performed by the staff are presented in Figures 5 through 8. Figures 5 and 6 show the J-R curves for the lowest projected USE level of 48.5 ft-lbs and the  $J_{\text{applied}}$  curves computed using the material inputs as described in Section 3.1, compared against the criteria of the Code Case. The staff analysis shows that a USE of 48.5 ft-lbs exceeds the requirements of Code Case N-512.

Figures 7 and 8 show the J-R curves for "bounding" projected USE levels and the  $J_{\text{applied}}$  curves computed using the material inputs as described in Section 3.1, compared against the criteria of the Code Case. This analysis shows 42 ft-lbs to be controlling for criterion 1 (flaw growth) while 45 ft-lbs controls for criterion 2 (flaw stability). This compares to 35 ft-lbs and 38 ft-lbs, respectively as determined from the CEOG analysis.

Based on this analysis, the staff has concluded that a USE of approximately 45 ft-lbs would be limiting based on an axially oriented flaw for the limiting CEOG material and vessel geometry. As the limiting CEOG beltline plate was demonstrated to exhibit 48.5 ft-lbs at EOL, the staff has concluded that the subject report demonstrates equivalent margins of safety to the ASME Code, Appendix G for CEOG plate materials.

Since the minimum acceptable USE values from the equivalent margins analysis were based on fracture toughness data for plate material, these values will not apply to weldments. However, calculations performed for NUREG/CR-6023 [10] with the worst case Linde 80 weld model have shown a minimum acceptable USE of 41 ft-lbs for a PWR. Therefore the staff considers that, while weldments for the CEOG plants are not likely to be limiting for USE, the subject report does not demonstrate equivalent margins of safety to Appendix G of the ASME Code for welds. Individual licensees desiring to reference CEN-604, Revision 01 as the basis for addressing the USE requirements of 10 CFR 50, Appendix G must confirm its plant-specific applicability by either demonstrating that all beltline welds will have EOL USE above 50 ft-lb or that the bounding plate used in the report has a lower J-R curve than any other beltline material in the vessel. Further, individual licensees must request review and approval of CEN-604, Revision 1 in accordance with 10 CFR 50, Appendix G.

In the subject report, the CEOG cited EOL USE values as low as 13 ft-lbs from the equivalent margins analysis. As noted in the report, while numbers this low can result from the calculations, their significance is not clear at this time and they represent an extrapolation of the data used to develop the correlations in NUREG/CR-5729 [7]. There is not at present a technical consensus on the CVN USE lower limit for equivalent margins analyses. However, values below 30 ft-lb for reactor pressure vessel steels are highly suspect as such low energies are likely to be associated with ductile tearing in combination with other fracture modes (e.g., intergranular, incipient cleavage) not considered in the development of the low upper shelf criteria.

#### 4.0 CONCLUSIONS

The staff has evaluated the equivalent margins analysis presented in report CEN-604, Revision 01, submitted by the CEOG. The staff evaluation supports the following conclusions:

- (1) The methodology employed for the CEOG report is consistent with the guidelines in ASME Code Case N-512 and is therefore acceptable to the staff.

- (2) The subject report demonstrates margins of safety equivalent to those of the ASME Code for CEOG beltline plate materials.
- (3) An equivalent margins analysis based on weldment properties was not performed because the CEOG concluded that all of the CEOG beltlinewelds would be above 50 ft-lb at EOL.
- (4) Individual licensees desiring to reference CEN-604, Revision 01 as the basis for addressing the USE requirements of 10 CFR 50, Appendix G must confirm its plant-specific applicability by either demonstrating that all beltline welds will have EOL USE above 50 ft-lb or that the bounding plate used in the report has a lower J-R curve than any other beltline material in the vessel. Further, individual licensees must request approval in accordance with 10 CFR 50, Appendix G.
- (5) Calculated minimum acceptable USE values below 30 ft-lb for reactor pressure vessel materials are highly suspect as such low energies are likely to be associated with ductile tearing in combination with other fracture modes (e.g., intergranular, incipient cleavage) which were not considered in the development of the low upper shelf criteria.

#### 5.0 REFERENCES

1. Submittal from the Combustion Engineering Owners Group to the USNRC, CEN-604 Revision 01, "Evaluation of Low Upper Shelf Energy for Combustion Engineering Nuclear Steam Supply Systems Reactor Pressure Vessels, Final Report," September 1993.
2. Letter from Raymond Burski, CEOG, to James Wiggins, USNRC, "Response to NRC Questions on CEN-604 Revision 01, "Final Evaluation of Low Upper Shelf Energy for Combustion Engineering Nuclear Steam Supply Systems Reactor Pressure Vessels," February 21, 1994.
3. ASME Code Case N-512, "Assessment of Reactor Vessels with Low Upper Shelf Charpy Impact Energy Levels," Section XI, Division 1, ASME Boiler and Pressure Vessel Code, February 12, 1993.
4. Appendix K, "Assessment of Reactor Vessels with Low Upper Shelf Charpy Impact Energy Levels," Section XI, Division 1, ASME Boiler and Pressure Vessel Code, 1993.
5. Draft Regulatory Guide DG-1023, "Evaluation of Reactor Pressure Vessels with Charpy Upper Shelf Energy Less than 50 ft-lb," U.S. Nuclear Regulatory Commission, August 1993.
6. Regulatory Guide 1.99 Revision 2, "Radiation Embrittlement of Reactor Vessel Materials," U.S. Nuclear Regulatory Commission, May 1988.
7. NUREG/CR-5729, "Multivariable Modeling of Pressure Vessel and Piping J-R Data," E.D. Eason, J.E. Wright, and E.E. Nelson, USNRC, Washington D.C., 1991.

8. Material and Chemical Engineering Branch Technical Position, MTEB 5-2, "Ratio of Transverse to Longitudinal Orientation Charpy Upper Shelf Energy," June 25, 1990.
9. Tables TM-1, Y-1, and U, ASME Boiler and Pressure Vessel Code, Section II, Part D.
10. NUREG/CR-6023, "Generic Analyses for Evaluation of Low Charpy Upper Shelf Energy Effects on Safety Margins Against Fracture of Reactor Pressure Vessel Materials," T.L. Dickson, USNRC, Washington, D.C., July 1993.
11. NUREG-0744 Revision 1, "Resolution of the Task A-11 Reactor Pressure Vessel Materials Toughness Safety Issue," USNRC, R. Johnson, October 1992.

Figure 1  
 J-INTEGRAL VS. CRACK DEPTH  
 100 F/HR CD, PRESSURE = 2750 psia  
 AXIAL FLAW ORIENTATION, LEVEL A, PLATE MATERIAL  
 VESSEL SIZE: NOMINAL ID = 182 in, BELTLINE THICKNESS = 9.06 in  
 FLAW GROWTH

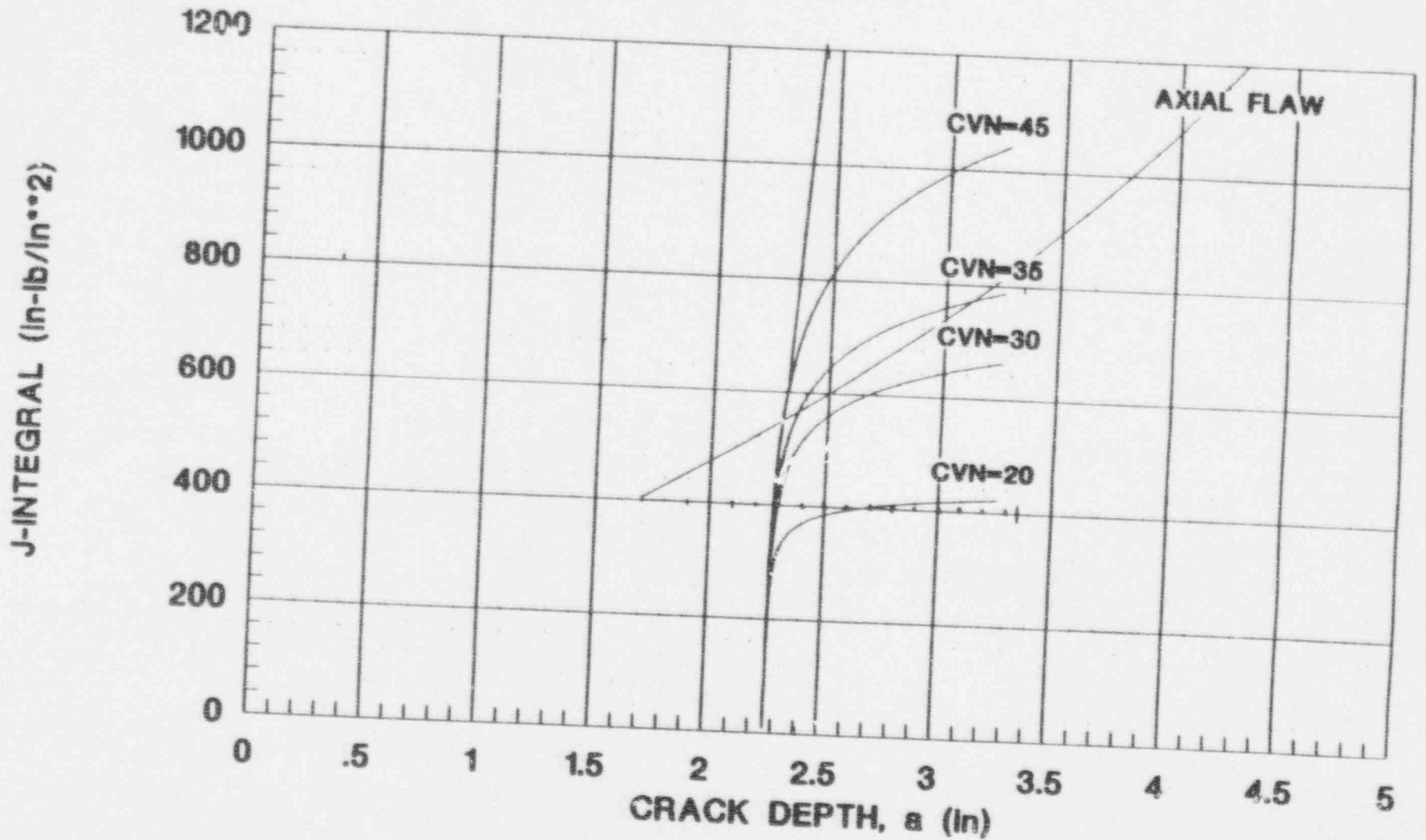


Figure 2  
J-INTEGRAL VS. CRACK DEPTH  
100 F/HR CD, PRESSURE = 2750 psia  
AXIAL FLAW ORIENTATION, LEVEL A, PLATE MATERIAL  
VESSEL SIZE: NOMINAL ID = 182 in, BELTLINE THICKNESS = 9.06 in  
FLAW STABILITY

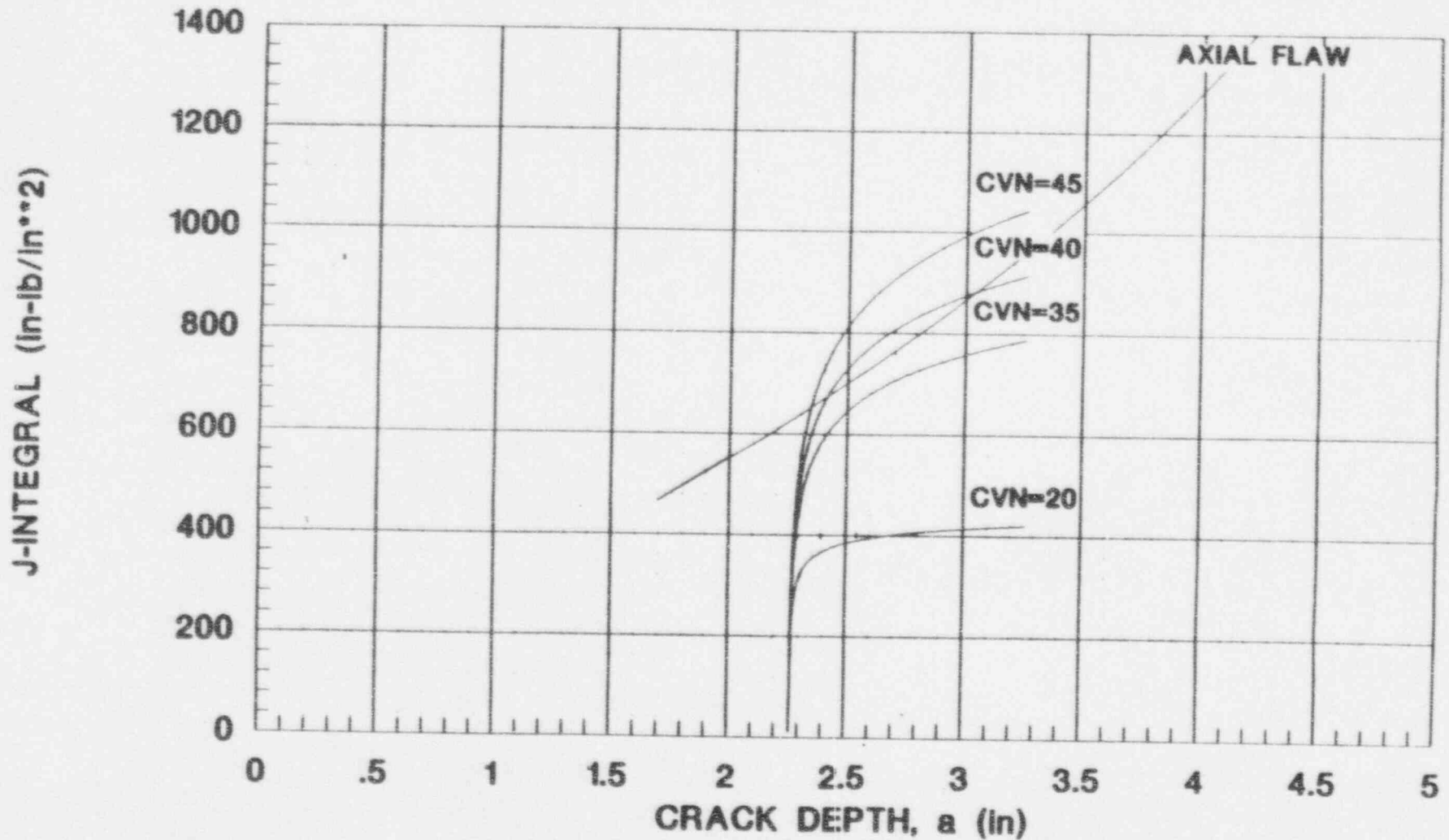


Figure 3  
J-INTEGRAL VS. CRACK DEPTH  
STEAM LINE BREAK  
AXIAL FLAW ORIENTATION, LEVEL C, PLATE MATERIAL

VESSEL SIZE: NOMINAL ID = 172 in, BELTLINE THICKNESS = 8.625 in  
FLAW GROWTH

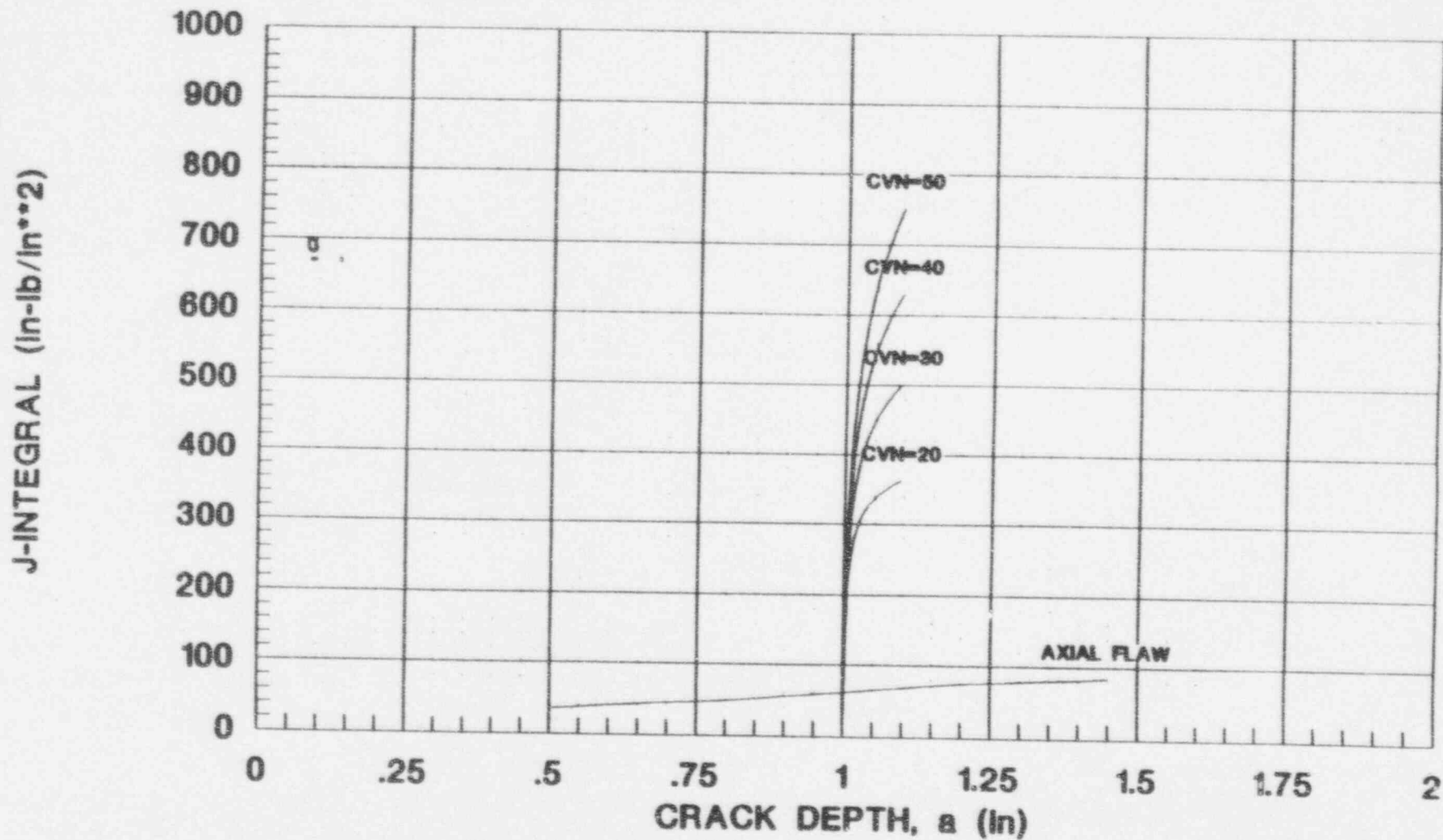


Figure 4  
J-INTEGRAL VS. CRACK DEPTH  
STEAM LINE BREAK  
AXIAL FLAW ORIENTATION, LEVEL D, PLATE MATERIAL

VESSEL SIZE: NOMINAL ID = 172 in, BELTLINE THICKNESS = 8.625 in  
FLAW GROWTH

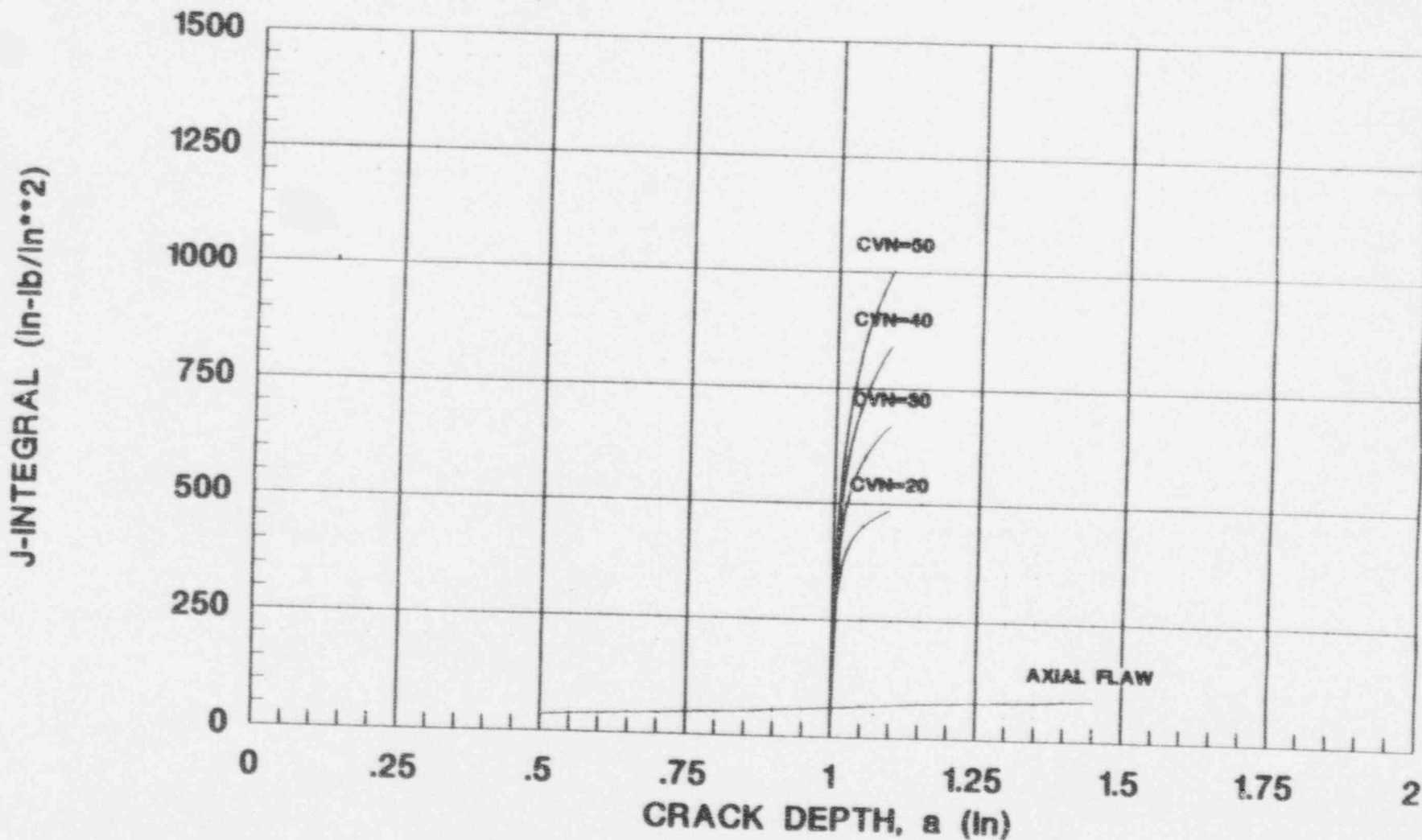


Figure 5

J vs. Crack Extension, Flaw Growth  
CEOG - Levels A&B, Axial Flaw

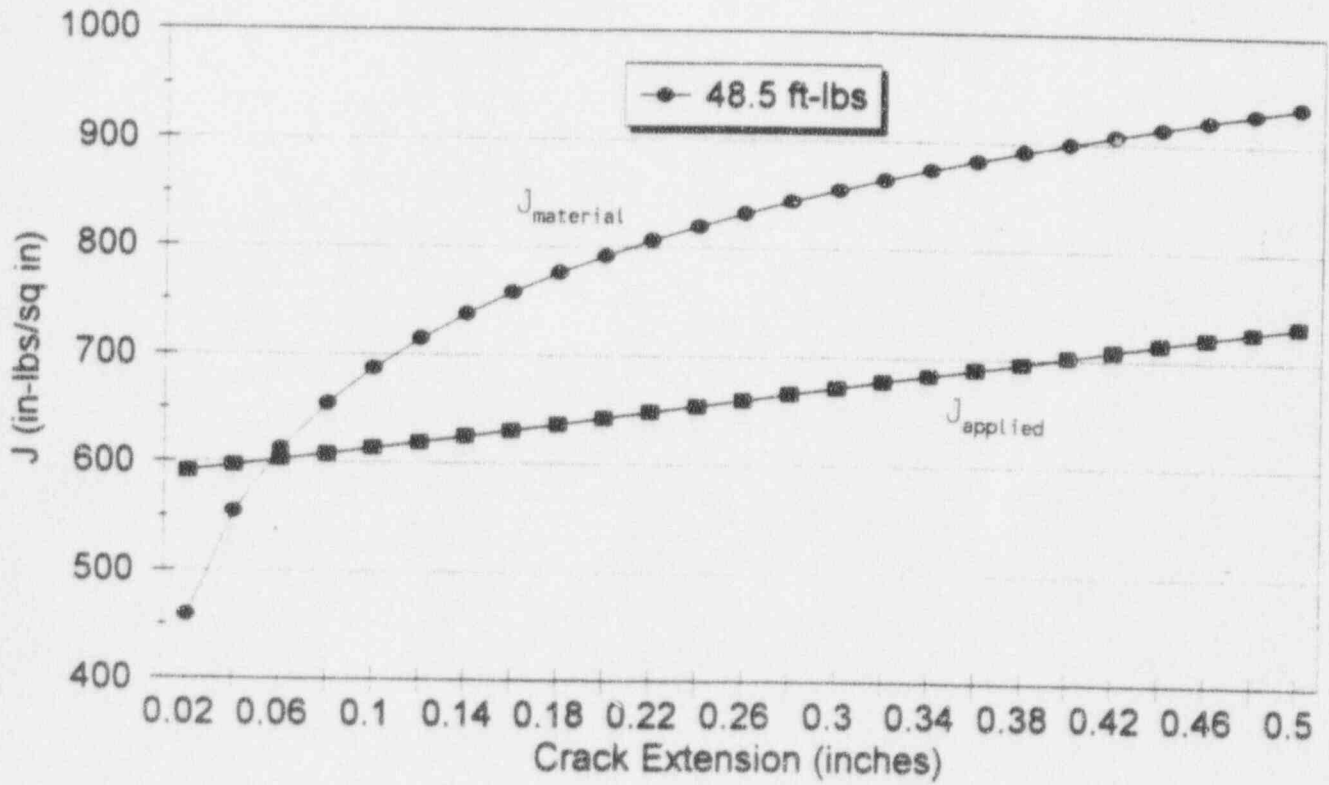


Figure 6

J vs. Crack Extension, Flaw Stability  
CEOG - Levels A&B, Axial Flaw

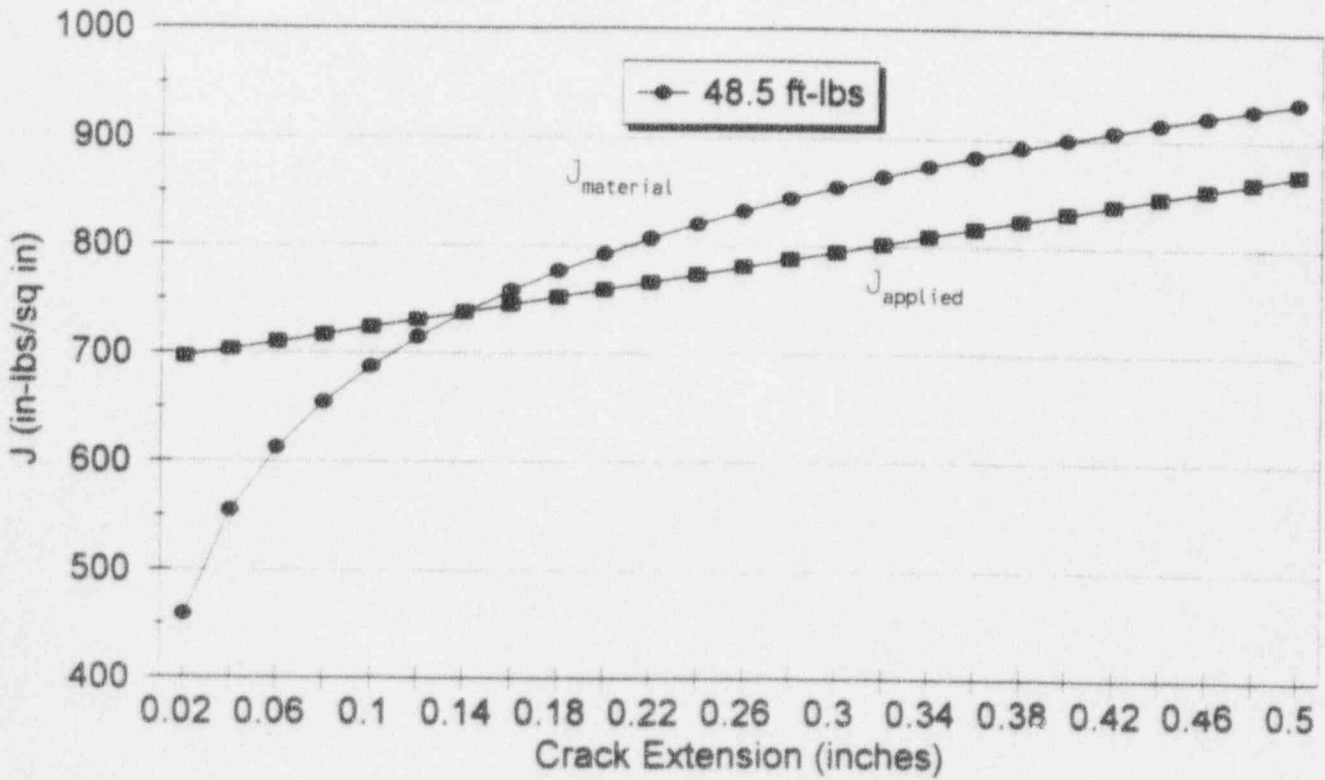


Figure 7

J vs. Crack Extension, Flaw Growth  
CEOG - Levels A&B, Axial Flaw

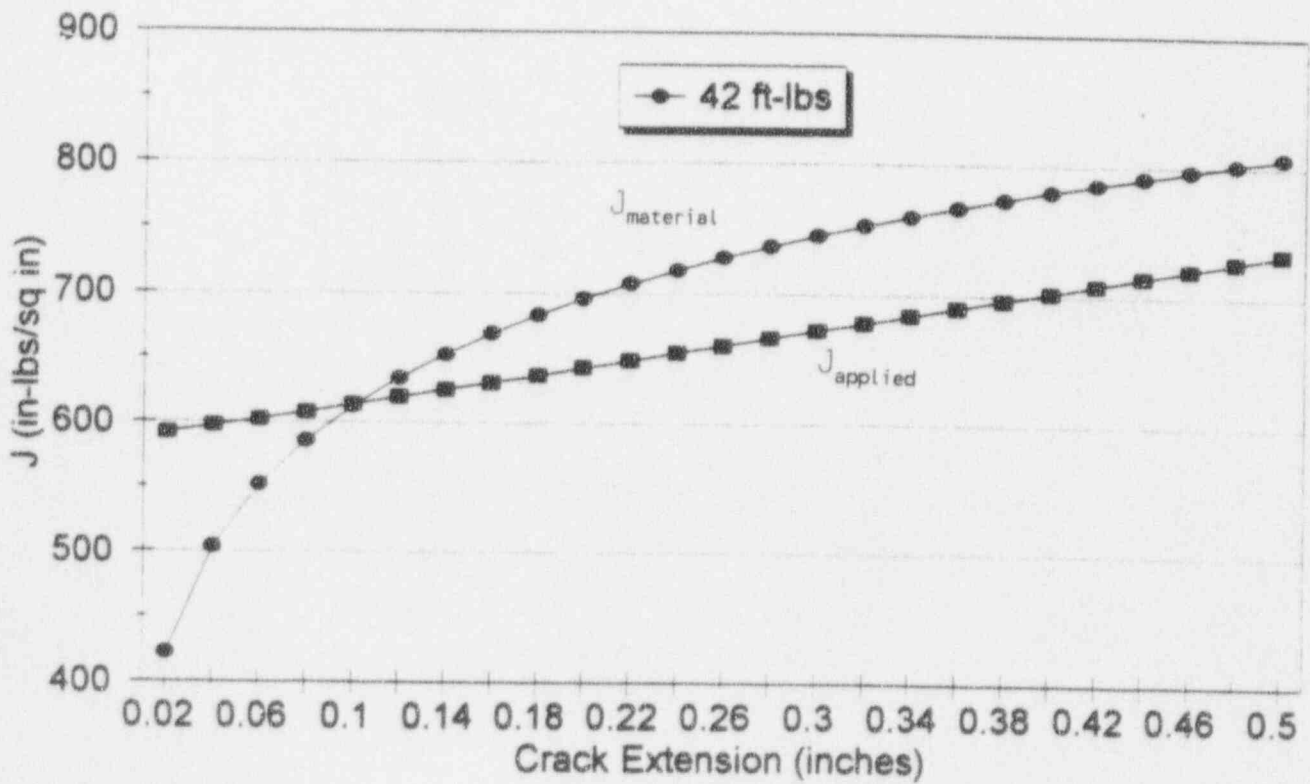


Figure 8

J vs. Crack Extension, Flaw Stability  
CEOG - Levels A&B, Axial Flaw

