UNITED STATES
NUCLEAR REGULATORY COMMISSION
WASHINGTON, D. C. 20555

MAY 9 1980

Generic Task No. A-11

MEMORANDUM FOR: Distribution

RROM: R. E. Johnson, TAP A-11 Manager
Generic Issues Branch, DST

SUBJECT: REPORT ON MEETING OF TECHNICAL TEAM, TAP A-11

The second techn:cal meeting of the TAP A-11 team was held at NRC Headquarters, Bethesda, Maryland, on April 9-10, 1980.

Enclosure 1 is a copy of the Meeting Notice. Enclosure 2 is a copy of the Agenda. Enclosure 3 is a list of attendees.

At the meeting, each attendee was given a copy of Task A-11, Revision 3, "Reactor Vessel Materials Toughness," April, 1980. Additional copies are available by request to the TAP Manager (Johnson).

During the meeting, the issue of problems on tasks which could occupy the attention of the team came up repeatedly. Several "shopping lists" had been prepared at different times by several people prior to the meeting. Copies were handed out. The lists have been recopied and are included here as Enclosure 4 (of 6 pages). By this letter, comments are solicited from all team members by the TAP Manager.

Prof. Paris reviewed his analytical results. Enclosure 5 is a scaled-down copy of his easel chart. Enclosure 6 (10 pages) is a set of his viewgraph charts.

Paris concluded that the final equations for the leak-before-burst analysis were independent of the assumptions made with regard to the plasticity model (i.e., it was the same for plasticity-modified LEFM, power law hardening, Ramberg-Osgood, etc.). The basic approach was to develop the ratio J/T for the structure being analyzed* (where J = applied J-integral; T = applied tearing modulus), in which case the stress correction cancels out and the shell correction function becomes analytic. For essentially zero crack growth, J/T is a straight line with slope

* Specifically: a cylindrical shell (the r.p.v. beltline) with a through-wall crack.

THIS DOCUMENT CONTAINS
POOR QUALITY PAGES

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(for a typical vessel) of about 500:1. Using available materials test data, curves of J (material) as a function of T (material) formed a family of curves (roughly: hyperbalae), ranked in proportion to the corresponding Charpy upper shelf energy (the lower the USE the closer the curve to the origin). Unstable growth would be predicted at the intersection of the applied and materials J-T curves. The approach led to the tentative conclusion that leak-before-burst would be likely for Charpy USE of 50 ft-lb and above.

Dr. Merkle presented a summary of his analyses. Copies of his view-graphs are attached as Enclosure 7 (10 pages).

Merkle's analysis essentially supported Paris'. He showed that the concept of using the J-T relationship to establish instability could be related to the Euler buckling analysis, which utilizes a σ - E_t (stress-tangent modulus) relationship with instability identified by the intersection of the beam and materials curves.

Dr. Riccardella took the tearing modulus analysis and applied it to an hypothetical vessel of typical dimensions and properties for the HSST Intermediate Test Vessels, starting with a surface crack and allowing growth to a through-wall crack with a length about equal to the starting part-through crack surface length. His result showed that the observed vessel behavior (i.e., burst, rather than leak-before-burst) would have been predicted. Therefore, the through-crack analysis showed no inconsistancy.

There was a discussion centered on the term "upper shelf" and the various means of establishing it. Prof. Irwin discussed facture test results in which the spring constant was varied. He said they showed that one must go 50F° (maybe as much as 100F°) above the onset of the CVN upper shelf to totally avoid cleavage instability after some initial tearing.

Dr. Loss presented experimental data and analyses; copies of his view-graphs are included as Enclosure 8 (14 pages).

Using single specimen unloading compliance methods, his J-R curves showed continously decreasing T with J, unless cleavage interceeded. Graphs of J = f(T) showed a family of hyperbolae, decreasing rather regularly with C_v U.S.E. Taking J at T = 20, the data correlated with C_v energy and ^{v} with absorbed energy per unit flow stress but with greater scatter. Taking J along the line of slope J/T = 50 lb./in. improved both correlations (a toss-up as to which was better). As Paris had pointed out and Riccardella confirmed, the ratio J/T for a vessel with a through-wall crack would be about 500 lb/in. so the significance of 50 lb./in. was that it picked off values of J_{matl} at a value of T roughly 1/10 of the T_{appl} associated with the leak-before-break criterion.

Discussion during the two-day meeting was too extensive to be documented in any detail. A few things which made an impression on me are listed as follows.

1. Paris noted the importance of making Δa corrections to the J-R curves before trying to use elastic-plastic fracture mechanics (e-p f.m.) in a search for correlations with Charpy data or as input to the vessel analyses.

2. Cooper suggested that for PWR accident analysis, the upper limit for pressure could be the "set pressure" (giving a stress of about 26 ksi) or the "accumulated pressure" (giving about 30 ksi).

3. Some questions the Team felt should be considered were:

   a. What is the likelihood of cleavage fracture intervening after some tearing?

   b. What is a sufficient amount of e-p f.m. data?

   c. can data from specimens under bending loading be applied to tensile instabilities in hardware?

   d. What is the role of crack arrest in the elastic-plastic pressure vessel problem?

4. I was asked to determine the availability of WCAP Reports on the pressure vessels at the Turkey Point and Point Beach plants. They are marked nonproprietary but not to be distributed outside of Westinghouse or its licensees without the customer's approval. Since the Team is enjoined by NRC restrictions, I believe they could review the reports as if they were NRC Staff members. Anyone who wants to pursue the matter can contact me.

5. Suggested topics which the materials engineers should consider were listed, as follows:

   a) Evaluate the tendency for $J = f(\Delta a)$ data to follow a power law (straight-line curve on logarithmic coordinates);

   b) Compare multiple (Δa by heat tinting) and single (unloading compliance) specimen J-R curves to see if the unloading influences the shape (curved or straight);

   c) Include Δa adjustments in J-R curves.

   d) Evaluate geometrical factors (e.g., size effect and side groove effect) on J-R curve power law;

e) Correlate J-R curves with tensile parameters, if possible;

f) Correlate J-R curves with Charpy data (e.g., C_v U.S.E), if possible. Include C_v lateral expansion data in this effort.

6. It was agreed that an action plan was needed for the analytical effort. Some considerations were:

   a) Apply the e-p f.m. analyses as now developed to the Ft. Calhoun RPV (Paris has data on vessel);

   b) Utilize RPV data available in computerized storage and retrieval program, MATSURV (Strosnider, NRC, is preparing a NUREG report on the program);

   c) NUTECH can bring some manpower into the calculation effort;

   d) The e-p f.m. analyses should be applied to the HSST ITV results.

7. Irwin promised to prepare a written contribution to the A-11 NUREG covering the background leading to the leak-before-burst concepts.

8. Cooper agreed to draft a section of the A-11 NUREG dealing with safety margins and code requirements.

There are two other things, outside of the specific subjects of the meeting, which I would like to call to the attention of the Review Team.

The first is a paper by Mike Aycock, NRC, presented at the ANS Conference in Knoxville in late April, titled: "Unresolved Safety Issues - Where Do We Go From Here?". With minor modifications by me, the definition given for an unresolved safety issue was:

An Unresolved Safety Issues is a matter:

(1) affecting a number of nuclear plants;

(2) that poses important questions concerning the adequacy of existing safety requirements;

(3) for which a final resolution has not yet been developed; and

(4) that involves conditions not likely to be acceptable over the lifetime of the plants it affects.

Since that is what the Review Team is working on, the definition should clarify and guide their activities. From the same source, the steps to resolve an issue were given as a table:

TABLE II. STEPS IN RESOLVING AN ISSUE

STEP		PRODUCTS
1.	Identify, Investigate & Evaluate Significance of Potential Issue	Decisions regarding: . Is/Is Not a USI . Priority . Need for Interim Measures
2.	Plan Technical Approach, Resources, Schedule	Task Action Plan Aqua Book
3.	Generate and Assemble Necessary Technical Information	Technical Reports
4.	Evaluate and Decide What Licensing Requirements are Needed for Public Safety	NUREG Report Containing Proposed Requirements and Safety Evaluations
5.	Peer, Public, ACRS and Industry Review	Comments
6.	Promulgate Requirements	Orders, Letters, Rules, Guides, Standard Review Plans
7.	Implementation	Changes in Design, Testing Operation, Maintenance, Training, etc.

Obviously, the Review Team is working on item 3. Steps 1, 2, 4 and 6 are performed by the NRC staff and management. Use the above to both guide and limit your efforts.

The second is a dialogue between Marston (EPRI) and Randall (NRC) dealing with some of the RPV problems. Two letters are enclosed (Enclosure 9) with the authors' permission. Please excuse a few editorial marks made by me. Hopefully, the letters will stimulate further discussion among Review Team members.

Richard E. Johnson

Richard E. Johnson
TAP A-11 Manager
Generic Issues Branch
Divsion of Safety Technology

Enclosures: As stated

DISTRIBUTION

MAY 9 1980

Central Files
Generic Issues Branch R/F
S. Hanauer
M. Aycock
R. Mattson
K. Kniel
F. Schroeder
D. Eisenhut
V. Noonan
L. Shao
J. Strosnider
R. E. Johnson
P. Kapo
R. Gamble
R. Klecker
W. Hazelton
J. Knight
P. Check
S. Pawlicki
W. Regan
P. Randall, OSD
C. Serpan, RES
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Mr. R. G. Berggren, ORNL
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Prof. H. T. Corten, U. of Ill.
Mr. J. R. Hawthorne, US Navel Research Lab.
Prof. G. R. Irwin, U. of Maryland
F. J. Loss, US Naval Research Lab.
J. G. Merkle, ORNL
Prof. P. C. Paris, Washington U.
Dr. P. C. Riccardella, NUTECH
Mr. G. M. Slaughter, ORNL
Dr. Theodore U. Marston, EPRI
Dr. M. F. Kanninen, BCL
Mr. John P. Gudas, DTNS R&D Center

ENCLOSURE 1

UNITED STATES
NUCLEAR REGULATORY COMMISSION
WASHINGTON, D. C. 20555

MAR 3 1 1980

Generic Task No. A-11

MEMORANDUM FOR: Vincent S. Noonan, Chief, Engineering Branch
Division of Operating Reactors

FROM: Richard E. Johnson, TAP A-11 Manager, Engineering Branch
Division of Operating Reactors

SUBJECT: MEETING NOTICE: REVIEW OF PROGRESS ON TAP A-11

DATES/TIMES: April 9, 1980 - 10:00 am
April 10, 1980 - 9:00 am

LOCATION: Room P-110 Phillips Building

PURPOSE: ORNL to present progress items and establish action plan for the immediate future. Specific presentations will include elastic-plastic r.p.v. analysis (Paris and Merkle) and e-p fracture toughness results/correlations (Loss, Berggren and Canonico).

PARTICIPANTS: NRC, ORNL, Washington U., NRL, ORNL Sub-Contractors and visitors.

Richard E. Johnson

Richard E. Johnson, TAP A-11 Manager
Engineering Branch
Division of Operating Reactors

cc: R. Gamble
R. Klecker
W. Hazelton
J. Strosnider
P. Randall
R. Johnson
S. Hanauer
M. Aycock
C. Serpan
M. Vagins
Mr. R. G. Berggren, Oak Ridge Nat. Lab.
Dr. D. A. Canonico, Oak Ridge Nat. Lab.
Dr. W. E. Cooper, Teledyne Engr. Services
Prof. H. T. Corten, Dept. of Theoretical and Applied Mechanics
Mr. J. R. Hawthorne, NRL
Prof. G. R. Irwin, Dept. of Mechanical Engr.
Dr. F. J. Loss, NRL
Dr. J. G. Merkle, Oak Ridge Nat. Lab.
Prof. P. C. Paris, Washington U.
Dr. P. C. Riccardella, NUTECH
Mr. G. M. Slaughter, Oak Ridge Nat. Lab.

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ENCLOSURE 2

(Meeting Notice is Being Distributed by NRC)

AGENDA

SECOND TECHNICAL PLANNING SESSION ON TAP A-11: REACTOR PRESSURE VESSEL TOUGHNESS

Wednesday and Thursday, April 9-10, 1980

April 9, 1980

10:00 AM	Introduction	G. M. Slaughter (ORNL)
	Review of Pertinent Points from February 27 Meeting	R. E. Johnson (NRC)
	Elastic-Plastic Analyses Applicable to Reactor Pressure Vessels	P. C. Paris (Wash. U.) J. G. Merkle (ORNL)
	Elastic-Plastic Fracture Toughness Results/Correlations	F. J. Loss (NRL) R. G. Berggren (ORNL) D. A. Canonico (ORNL)
	Other Considerations	All Participants
	(a) Comparison of Tearing Instability Method with other Methods	
	(b) Data Compilation	
	(c) Safety Margin	
	(d) Other	
	Planning and Assignments	All Participants
	Summary	R. E. Johnson G. M. Slaughter

April 10, 1980

2 [illegible] M	Adjournment	

ENCLOSURE 3

ATTENDEES - A-11 Meeting, April 9, 1980

Name	Organization	Phone
Richard E. Johnson	NRC/DOR/EB	301 492-7385
Jack Strosnider	NRC/DOR/EB	301 492-7356
Paul C. Paris	Washington U.	312 726-2942
Karl Kniel	NRC/DSS	301 492-7139
Peter C. Riccardella	NUTECH	408 629-9800
Herbert T. Corten	Univ. of Ill.	217 333-3175
William E. Cooper	Teledyne Engrs. Services	617 890-3350
Frank Loss	NRL	202 767-2562
Russell Hawthorne	NRL	202 767-2617
George R. Irwin	Univ. of Maryland	301 474-4755
Milton Vagins	NRC/RES/M&MRB	301 427-4262
Charles Z. Serpan, Jr.	NRC/RES	301 427-4262
Pryor N. Randall	NRC/OSD	301 443-5997
Dominic Canonico	ORNL/M&C	615 574-4465
Gerry Slaughter	ORNL/M&C	615 574-4267
John Merkle	ORNL/ETD	615 574-0661
Rey Berggren	ORNL/M&C	615 574-4468

ENCLOSURE 4

Shopping Lists

March 5, 1980

A-11 Tasks

1. shell effects for

   a. leak-before-break

   b. very large crack (e.g., through-wall, 2a long; a=R=10t)

2. sample calculation on an actual RPV (Ft. Calhoun chosen)

3. analyze data: see how well the Ramberg-Osgood model (being used in the PRV analysis) describes the experimental J-E curves for PRV steel; irradiated and nonirradiated.

4. need to develop more J vs. T diagrams, esp. to higher J-values. (experimenters should not stop J-R curve test at Δa = 1.5 mm; can't understand why ASTM set such an arbitrary limit, anyway.)

5. Correlate J-T curves with Charpy data.

6. Apply analysis to a variety of RPVs (all (?) HSST ITVs).

7. Identify holes in the data base - take steps to fill them in.

8. Codify the e-p leak-before-break analysis.

Solicit EPRI (Ted Marston) to participate, release relevant data.

Open questions to be considered (and answered) by the A-11 Group.

I. Clevage intercession: can it be predicted?

II. If the RPV crack runs (fast fracture) but arrests outside the beltline region (low fluence; high toughness), what are the dynamic effects (quantitatively)?

III. As diagrams and correlations are developed, do we have a statistically-significant data base?

P. C. Paris
R. E. Johnson

Enclosure 4
Shopping Lists

March 4, 1980

ADDITIONAL WORK TO BE DONE ON "LEAK-BEFORE-BREAK"

I. Analysis (Paris will work on these)

(a) For $\lambda = \frac{a}{\sqrt{Rt}} \rightarrow 1$ (or Greater)

A shell correction factor should be incorporated in leak-before-break (Paris to analyze).

(b) For (See CSNI - NUREG - Vazquez-Paris & Cheissoux) "Shell Effects". Also look into possible plastic (zone) instability failure condition (Paris) (See Ditto)

(c) Do analysis on typical example nuclear vessel for L-B-B. (Paris & Johnson to analyze).

II. Material Data (Need Troops to work on these)

(a) Need stress-strain curves for typical base & weld materials to various degrees of irradiation in order to redo hardening analysis (get σ_o, E, ν, $\bar{\alpha}$, n for each (& correlate on cross plots?).

(b) Need further R-curve data plotted on J vs T diagram. Should be run to higher J values (bigger Δa than 1.5 mm) (but valid: $\omega > 10$, $\Delta a > 10\% b$, $B \geq b$, etc.)

(c) Study correlation of J_{mat} vs T_{mat} diagrams with respect to Charpy upper shelf correlations.

(d) Redo hardening analysis for T_{appl} & J_{applb} for various $\bar{\bar{\alpha}}$ & n values found in II (a).

III Open Questions (Whole Group to answer?)

(a) Does cleavage intercede above transition temp? or well above transition temp? (how high?)

(b) For running crack in "belt line" which might arrest outside belt line are dynamic effects important? (better or worse?)

(c) Do we have a "statistically significant" data base in II (a-d)?

IV. Application to Typical Reactors - Many

(a) Simply take typical reactors of all kinds (sizes, material properties, beginning to end of life) and look at implications of L.B.B (NRC-ORNL Staff?)

V. Identify any areas of lack of data or understanding and ensure programs to take care of these items (NRC).

VI Formulate "Code" type rules for L.B.B. computations and requirements (Whole Group).

P. Paris

Analysis to Define T_{app} vs J Relationships for

Problem 1 Upper Shelf Problem

Part through flaw
Nominal Stress = 50 KSI
Neglect Residual Stress
Neglect Thermal Stress
Material is on upper shelf

Problem 2 Transient Problems

Part through flaw
Real pressure stress
Real thermal stress (for range of transients)
Real residual stress
Material is not on upper shelf

R. Gamble

Shopping List per Paul Paris, et. al.,
At a Meeting at the NRL, March 25, 1980

1. P vs δ Record
2. σ vs ε Curve
3. R-Curve
4. J vs. T Curve

1. Spec. No.
2. Spec. Type and size
3. $\sigma_o = \frac{\sigma_y + \sigma_{ult}}{2}$
4. % side groove
5. C_v (USE)
6. Trans. Temp.
7. Test Temp.
8. Notes on Cleavage if present
9. J_{Ic} (by an Std. as possible)
10. J vs T vs ω vs $\Delta a/b$;
    for at least 5 points from J_{Ic} to as close to C_v correlation line as possible.

Correlation

a C_v vs $J_{(T=20)}$
b " " $J_{(T=10)}$
c " " $J/T = 50$

Normalize with σ_o?

Notes:

1. Is J corrected for

   a) crack extension

b) formula

c) side grooves

d) etc.

2. Is Δa corrected for

a) specimen rotation

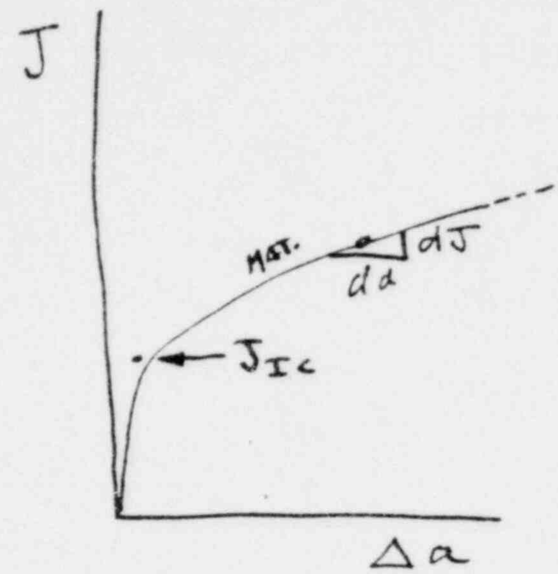
b) Heat tint or what?

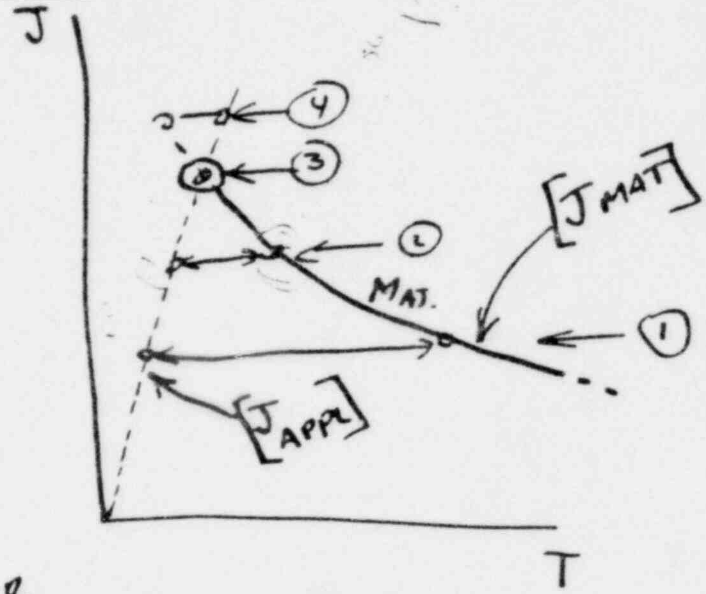
3. List

Estimate of accuracy on

a) J, dJ/da, Δa

ENCLOSURE 5





EQUIL $\quad J_{APP.} = J_{RES.\ OF\ MAT.}$

STABILITY $\quad \left.\frac{dJ}{da}\right|_{APPL} \geq \left.\frac{dJ}{da}\right|_{RES.\ OF\ MAT}$

OR

EQUIL $\quad J_{MAT} = J_{APPL.}$

(1) (2) } STABLE $\quad T_{MAT} > T_{APPL}$

(3) (4) } UNSTABLE $\quad T_{MAT} = T_{APPL}$, $\quad T_{MAT.} < T_{APPL.}$

$$J_{APPL} = \frac{\sigma_0^2 a}{E} \begin{Bmatrix} \text{STRESS} \\ \text{CORR.} \end{Bmatrix} \left[\text{SHELL CORRECTION, } Y^2 \right]$$

$$T_{APPL.} = \begin{Bmatrix} \text{SAME STRESS} \\ \text{CORRECTION} \end{Bmatrix} \left[\begin{matrix} \text{SHELL CORRECTION} \\ Y^2 + 2\lambda Y' Y \end{matrix} \right]$$

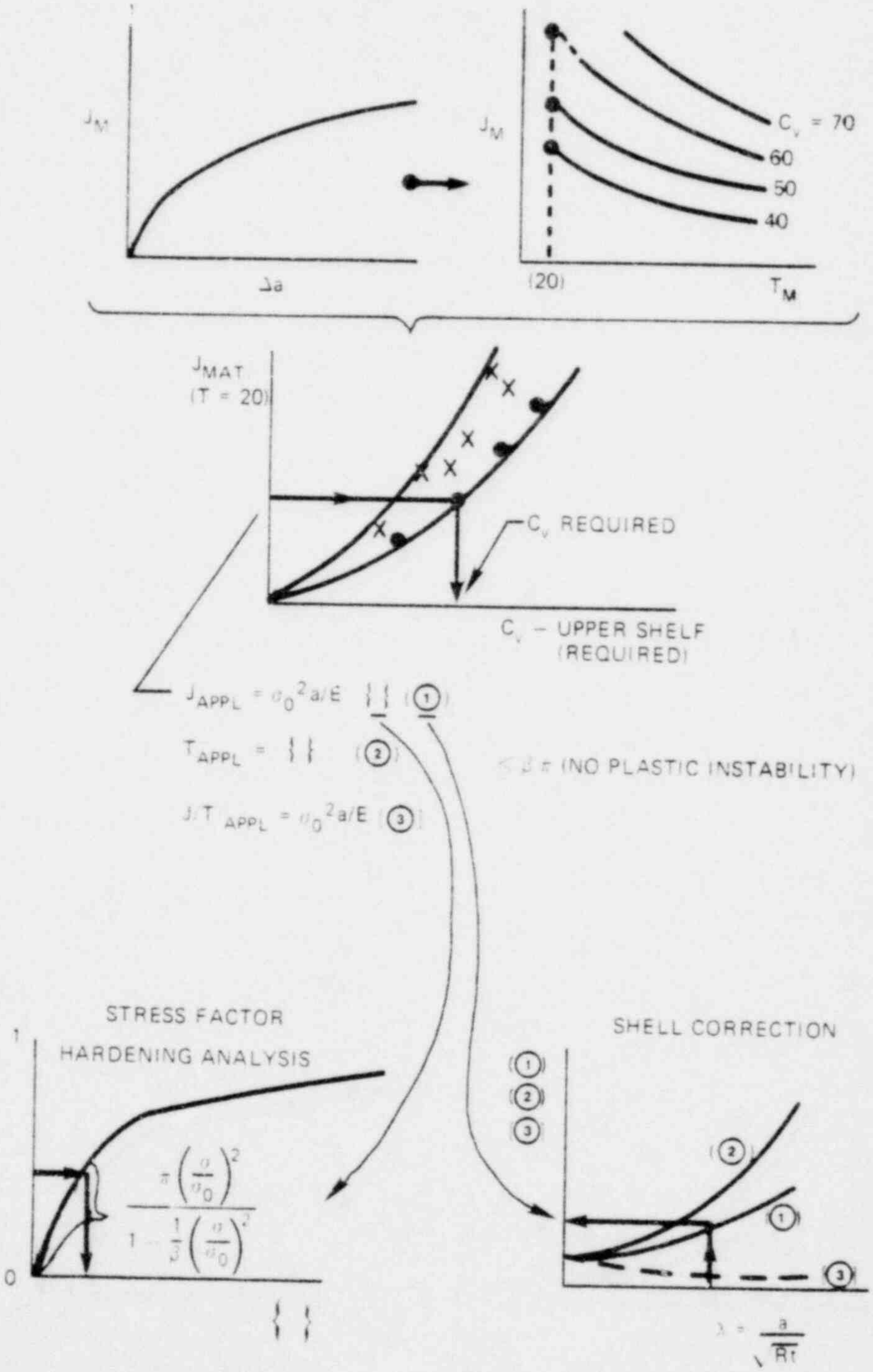
$$\left.\frac{J}{T}\right|_{APPL.} = \underbrace{\frac{\sigma_0^2 a}{E}}_{>1000} \underbrace{\left[\frac{1}{1 + 2\lambda Y'/Y} \right]}_{1 \text{ TO } 1/3}$$

($\sigma_0 > 60$ K.S.I., $a > 8"$)

ENCLOSURE 6

ORNL–DWG 80–4555 ETD

J-BASED "LEAK BEFORE BREAK" ANALYSIS



ORNL-WS-8424 ETD

ANALYSIS EQUATIONS

$$J_{APPL} = \sigma_0{}^2 a/E \ \{\,\} \ (Y^2) \qquad Y = Y\,(a/\sqrt{Rt})$$

FOR (1) L.E.F.M.

$$\{\,\} = \pi(\sigma/\sigma_0)^2$$

(2) P.Z.C. – L.E.F.M.

$$\{\,\} = \pi(\sigma/\sigma_0)^2 \ / \ 1 - 1/\beta\ (\sigma/\sigma_0)^2 \qquad (\sigma/\sigma_0 \leq 0.67)$$

$$\left(\beta = \begin{matrix} 2 \text{ PL STRESS} \\ 6 \text{ PL STRAIN} \end{matrix}\right)$$

(3) STRIP YIELD

$$\{\,\} = (8/\pi\,\gamma)\ln\sec(\pi/2\ \sigma/\sigma_0)$$

PL STRAIN $0.7 \leq \gamma \leq 1$ PL STRESS

(4) POWER HARDENING

$$\epsilon/\epsilon_0 = \bar{\alpha}\,(\sigma/\sigma_0)^n$$

$$\{\,\} = \bar{\alpha}\, f^*\,(\sigma/\sigma_0)^{n+1}$$

(f^* = π (n = 1), 2.22 (n = 3), 1.25 (n = 5),
0.88 (n = 7), ETC.)

(5) RAMBERG-OSGOOD (PL STRESS)

$$\epsilon/\epsilon_0 = \sigma/\sigma_0 + \bar{\bar{\alpha}}\,(\sigma/\sigma_0)^n$$

$$\{\,\} = \Psi^*\,(\sigma/\sigma_0)^2 + G^*\,\bar{\bar{\alpha}}\,(\sigma/\sigma_0)^{n+1}$$

(Ψ^* AND G^* FROM ZAHOOR)

FOR (Y) – SHELL CORRECTION FOR LONGITUDINAL CRACK IN CYLINDER

$$Y = (1 + 1.25\,\lambda^2)^{1/2} \qquad \lambda \leqslant 1$$
$$(0.6 + 0.9\,\lambda) \qquad 1 \leqslant \lambda \leqslant 5$$
$$(\lambda = a/\sqrt{Rt})$$

FOR THIS AND OTHER CONFIGURATIONS SEE ROOKE AND CARTWRIGHT HANDBOOK AND OTHER SOURCES.

FOR T – WITH σ = CONSTANT, DIFFERENTIATE J

$$T_{APPL} = E/\sigma_0^{\,2}\; dJ/da = \{\,\}\quad (Y^2 + 2\,\lambda\, Y \cdot Y')$$

FOR ALL CASES ABOVE

THEN FOR J/T

$$J/T|_{APPL} = \sigma_0^{\,2} a/E\;[1/1 + 2\,\lambda\,(Y'/Y)]$$

NOTE: $1 \geqslant [\;\;] \geqslant 1/3$

PLASTIC ZONE INSTABILITY

$$r_y = JE/\beta\,\pi\,\sigma_0^{\,2} \text{ OR}$$

$$\frac{dJ_{MAT}}{da} = \frac{\partial J}{\partial r_y} = \beta\,\pi\,\frac{\sigma_0^{\,2}}{E} \leqslant \frac{dJ_{APPL}}{da} = T_{APPL}\,\frac{\sigma_0^{\,2}}{E}$$

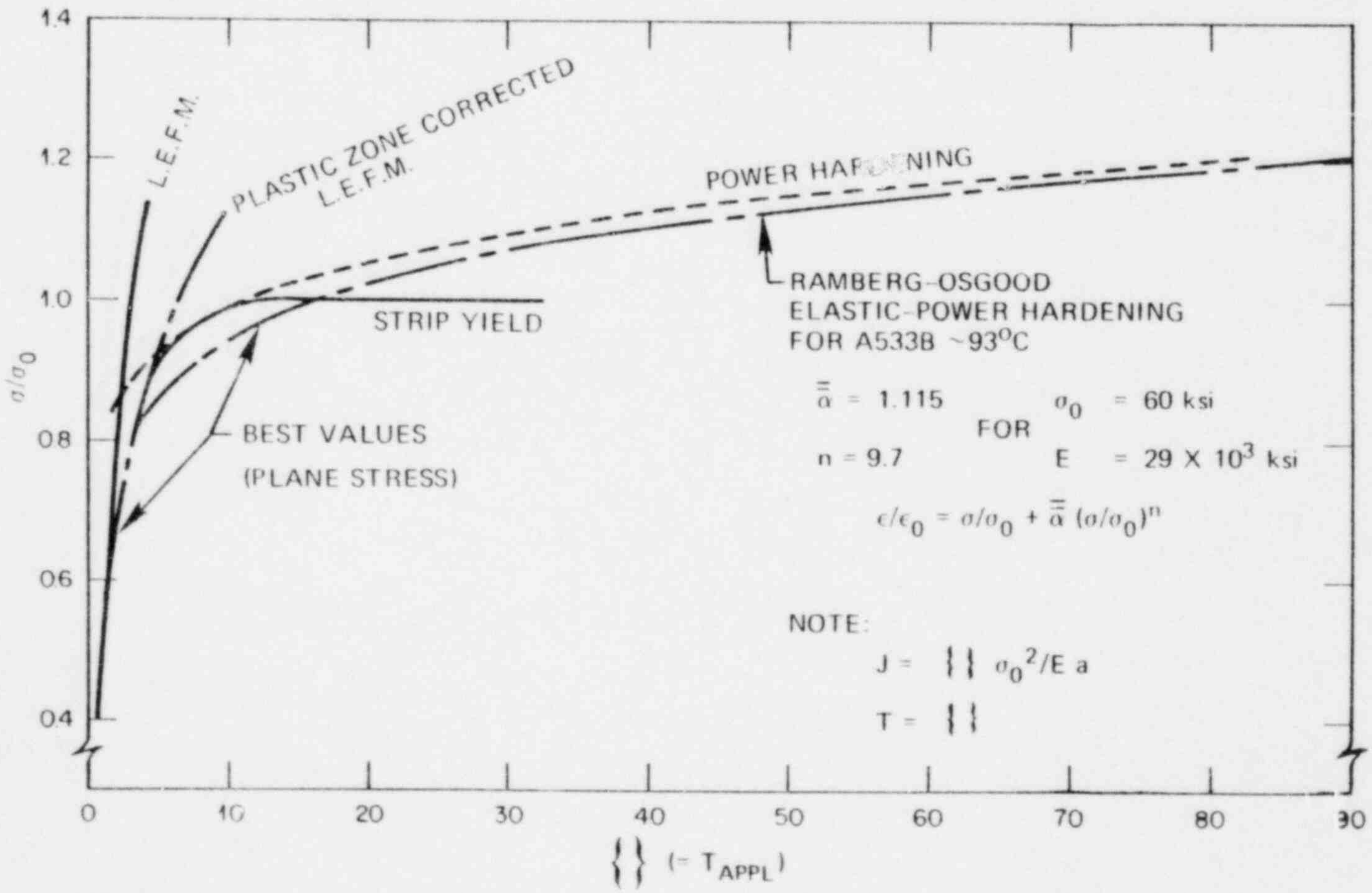
IF $(\sigma/\sigma_0 < 0.67)$ THEN: $T_{APPL} \geqslant \beta\,\pi$ (UNSTABLE)

Enclosure 6

-4-

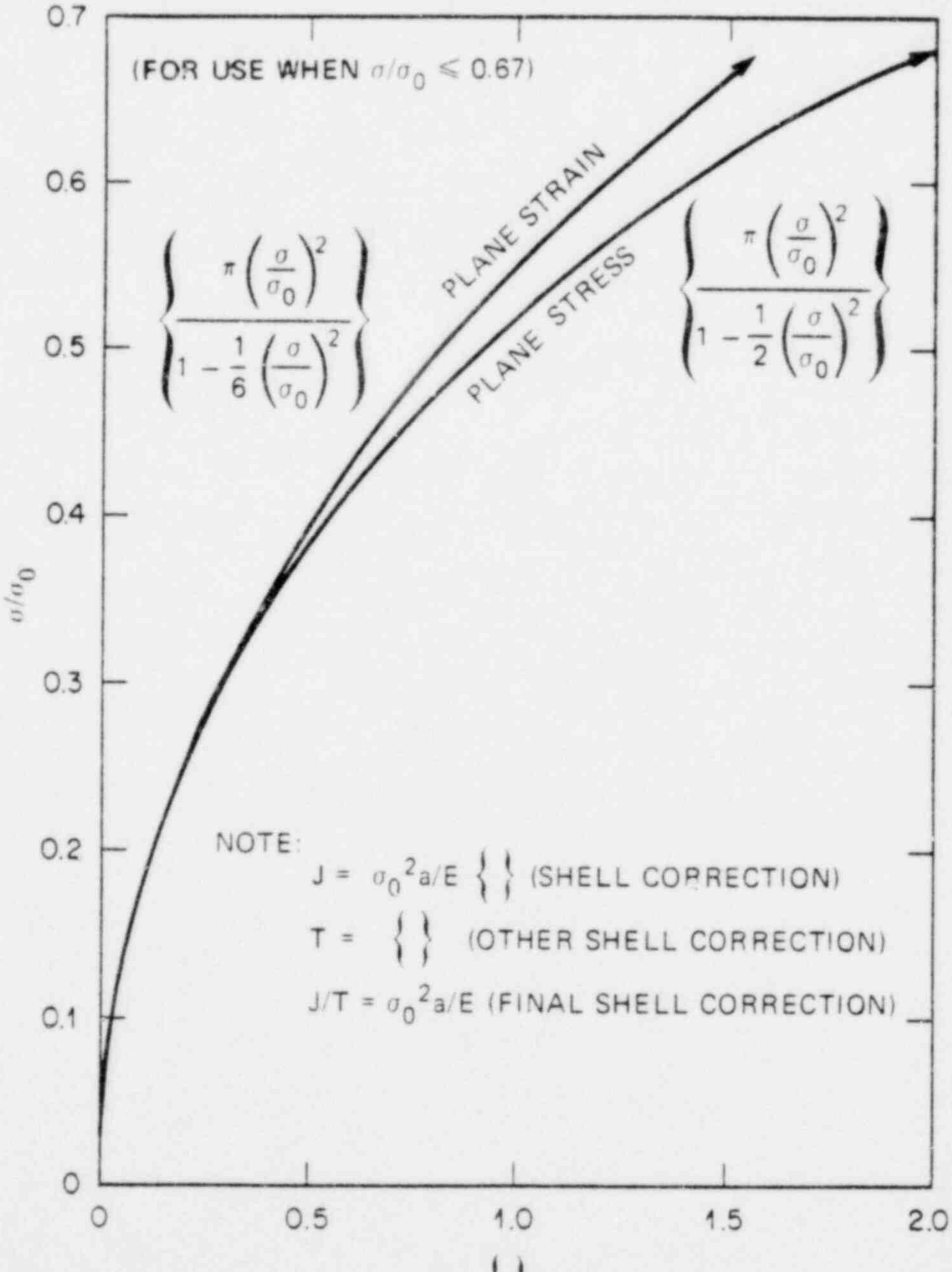
ORNL-DWG 80-4561 ETD

ESTIMATES OF { } OR T_{APPL} FOR LEAK-BEFORE-BREAK OF A533B



ORNL-DWG 80-4560 ETD

STRESS FACTOR FOR J AND T

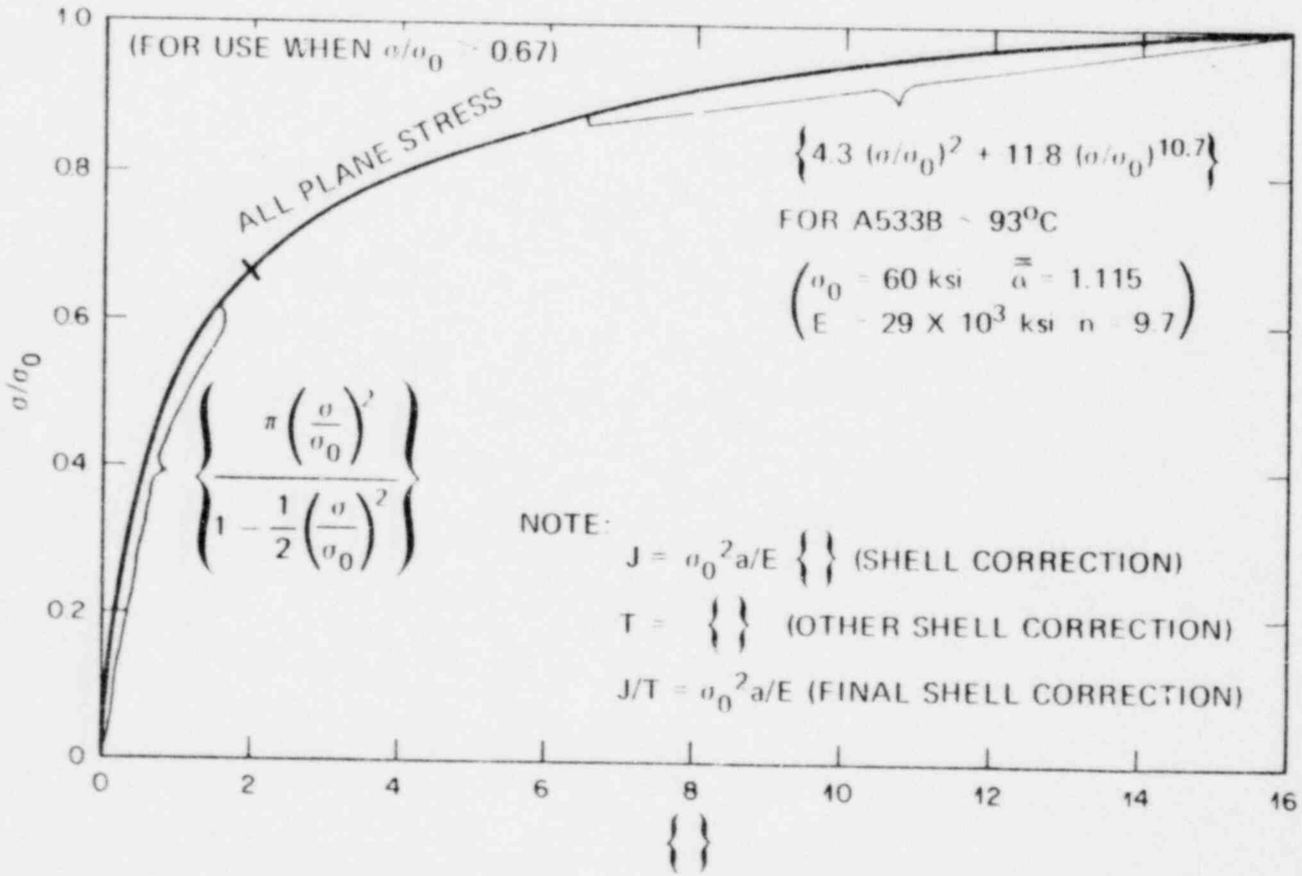


$$\left\{\frac{\pi\left(\frac{\sigma}{\sigma_0}\right)^2}{1-\frac{1}{6}\left(\frac{\sigma}{\sigma_0}\right)^2}\right\}$$

$$\left\{\frac{\pi\left(\frac{\sigma}{\sigma_0}\right)^2}{1-\frac{1}{2}\left(\frac{\sigma}{\sigma_0}\right)^2}\right\}$$

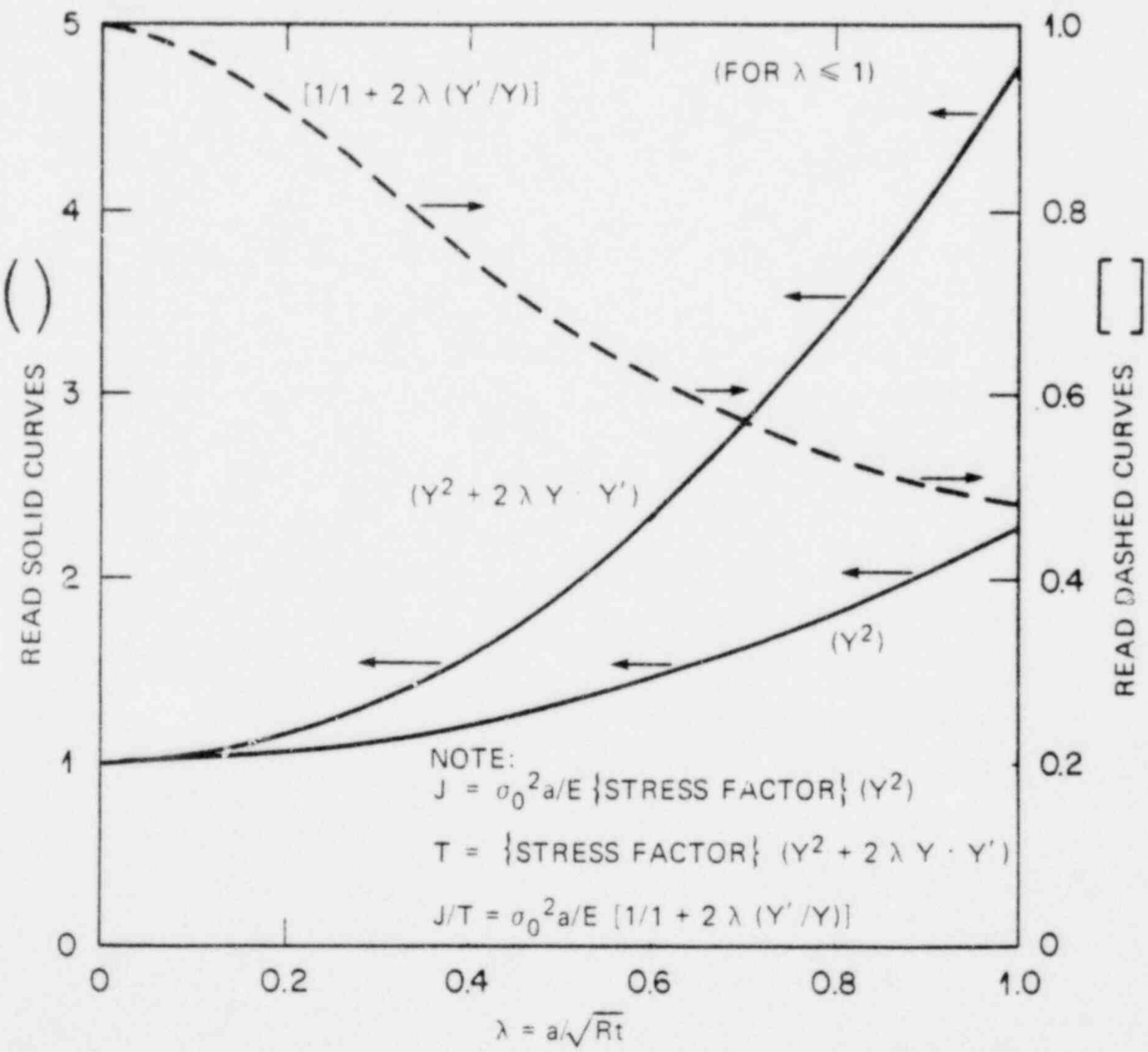
ORNL-DWG 80-4554 ETD

RAMBERG-OSGOOD HARDENING – STRESS FACTOR FOR J AND T



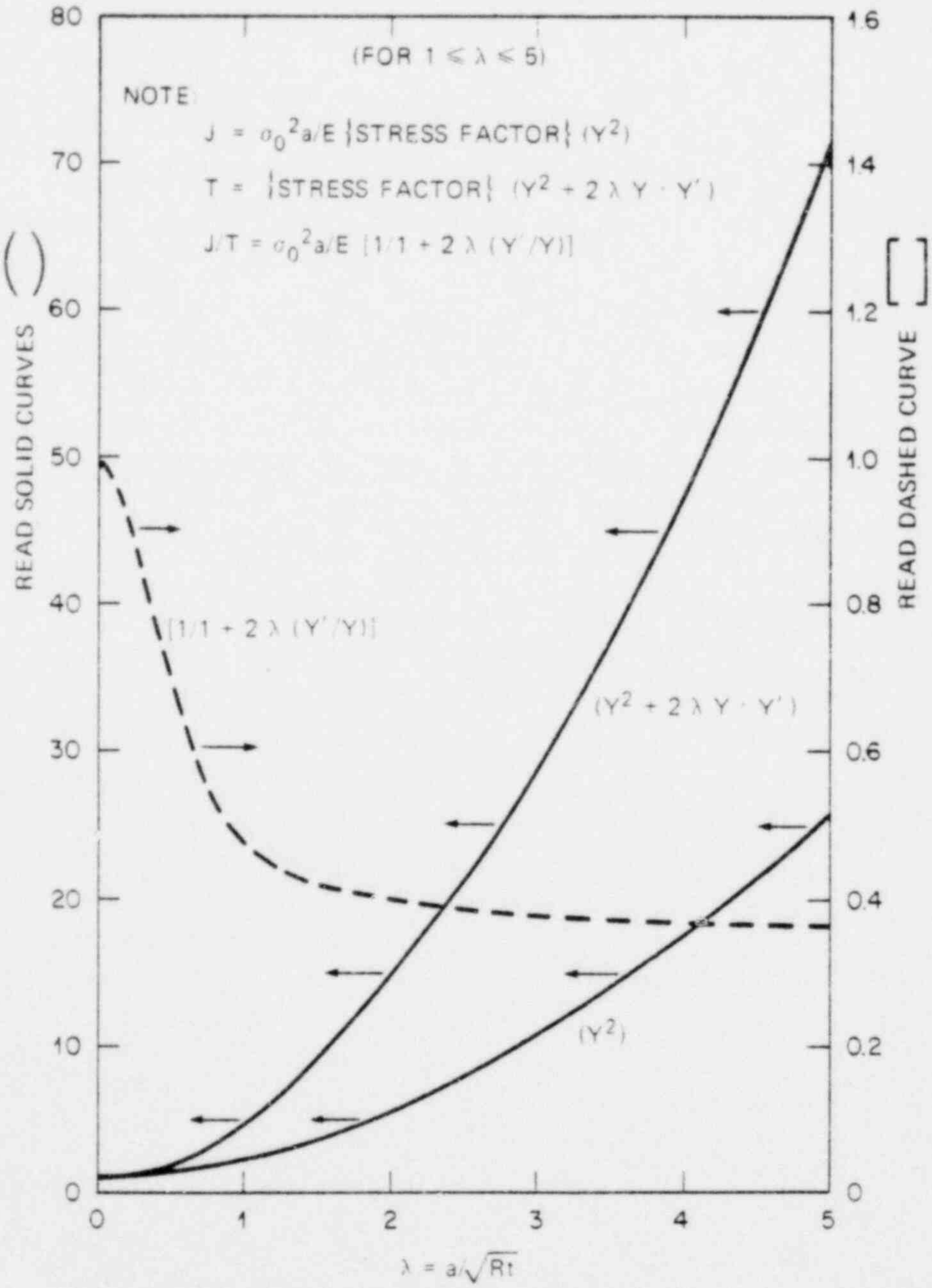
ORNL-DWG 80-4558 ETD

SHELL CORRECTIONS FOR LONGITUDINAL CRACKS IN CYLINDERS



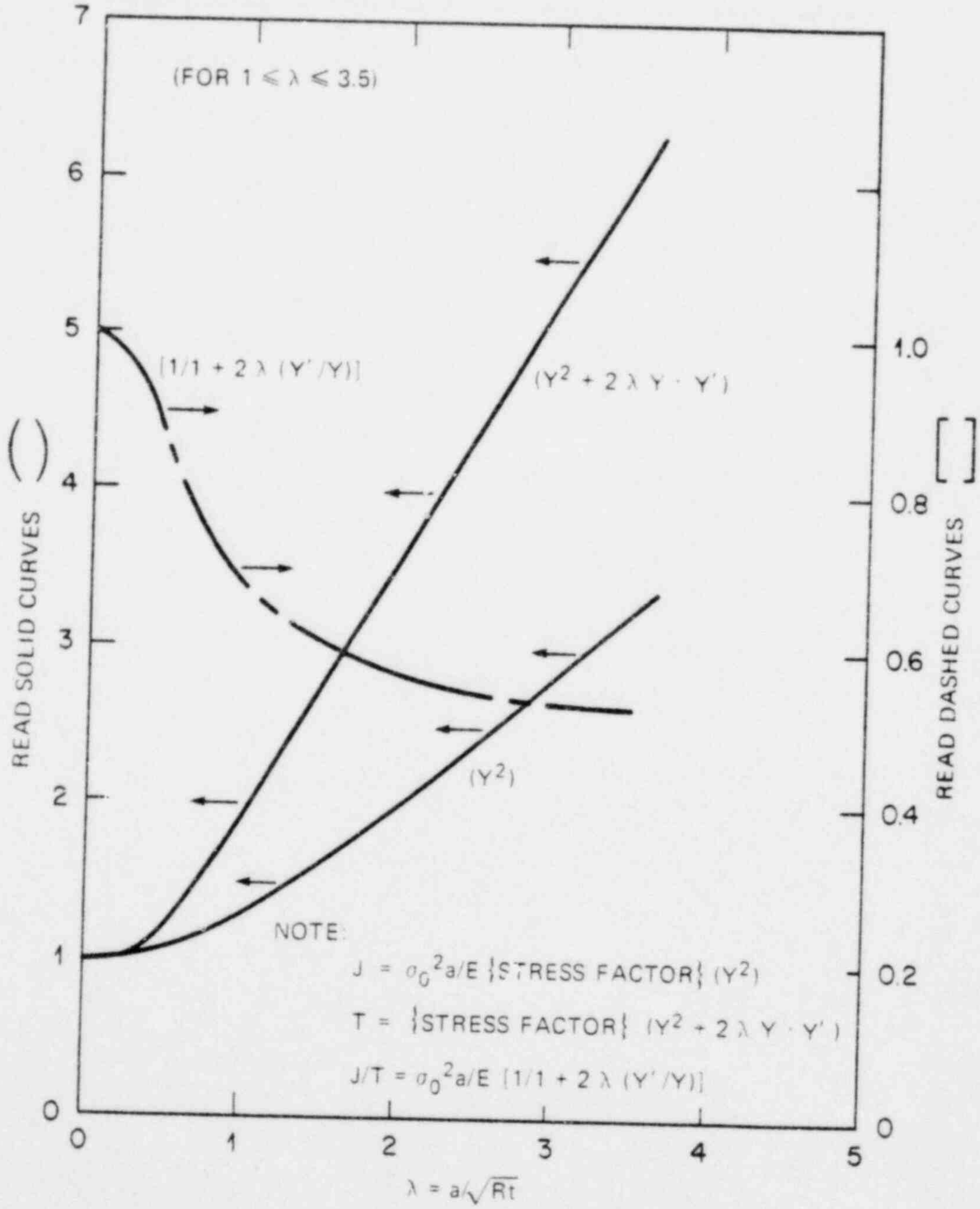
ORNL-DWG 80-4559 ETD

SHELL CORRECTIONS FOR LONGITUDINAL CRACKS IN CYLINDERS



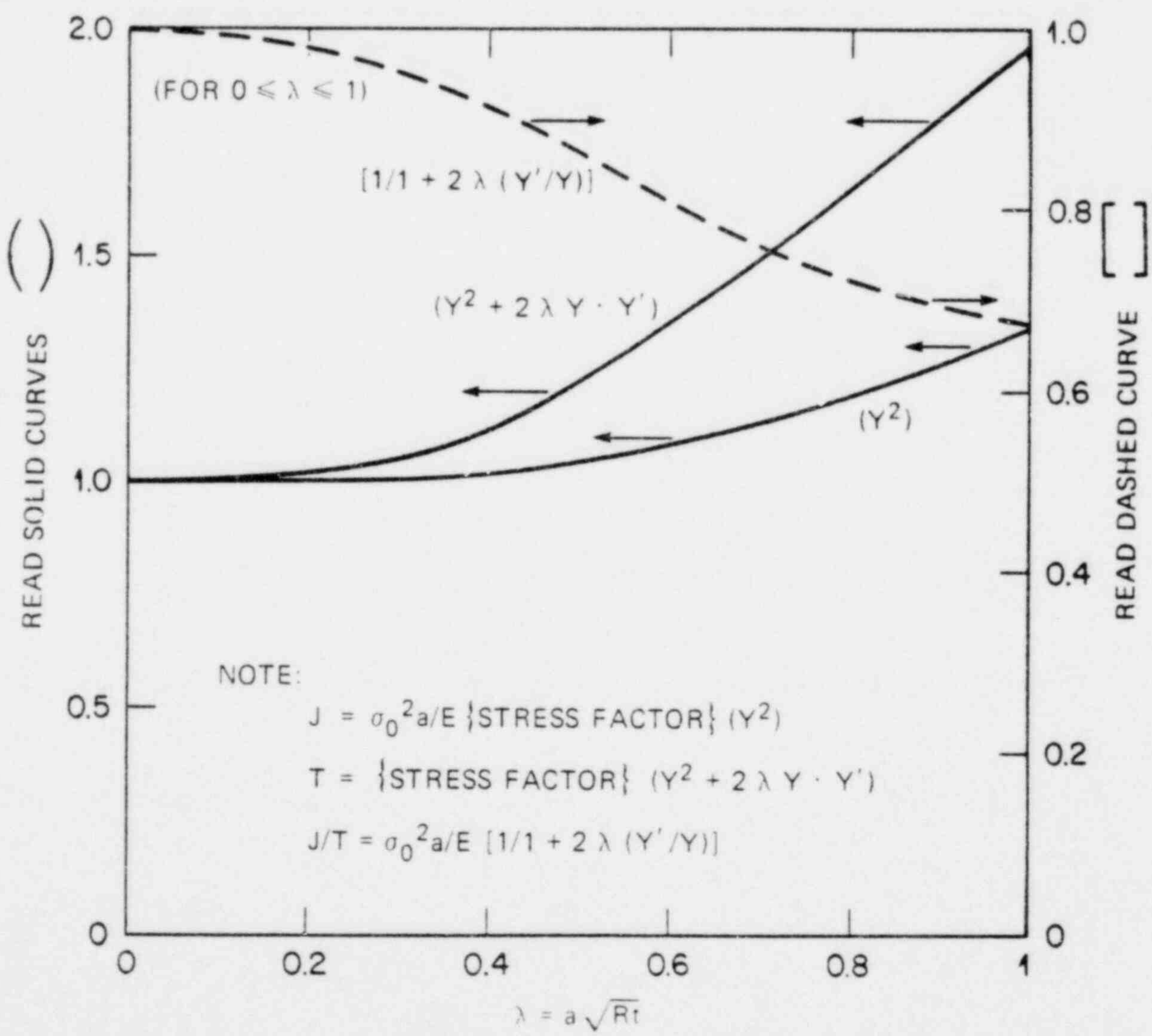
ORNL–DWG 80–4567 ETD

SHELL CORRECTIONS FOR CIRCUMFERENTIAL CRACKS IN CYCLINDERS



ORNL–DWG 80–4556 ETD

SHELL CORRECTIONS FOR CIRCUMFERENTIAL CR/ CKS IN CYCLINDERS



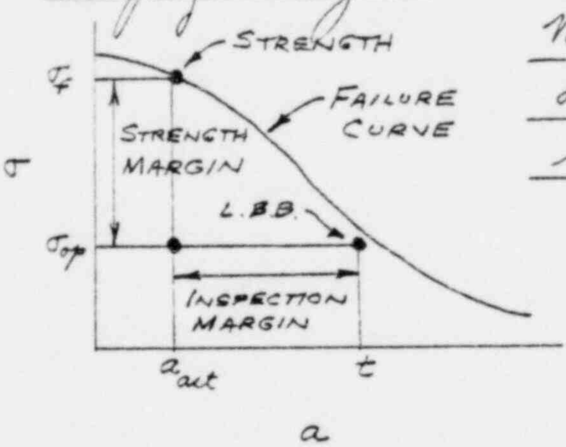
ENCLOSURE 7

Notes for T.A.P. Item A-11 Meeting, Bethesda, MD, April 9-10, 1980

J. G. Merkle

Comment: These notes primarily review and amplify a method for performing leak-before-break analyses for upper shelf conditions suggested by P.C. Paris in his notes of 2/12/80 to 3/8/80.

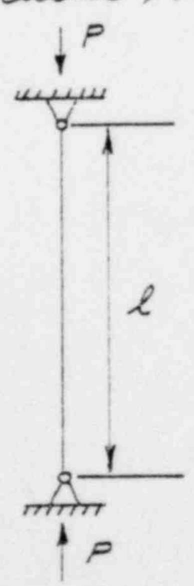
A. Safety margins

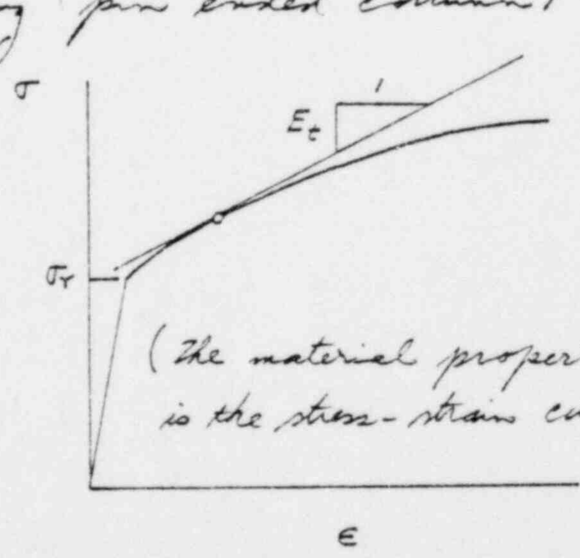


Neither margin guarantees the other. Both margins must be verified.

B. Instability analysis diagrams

1. Inelastic buckling (pin ended column)



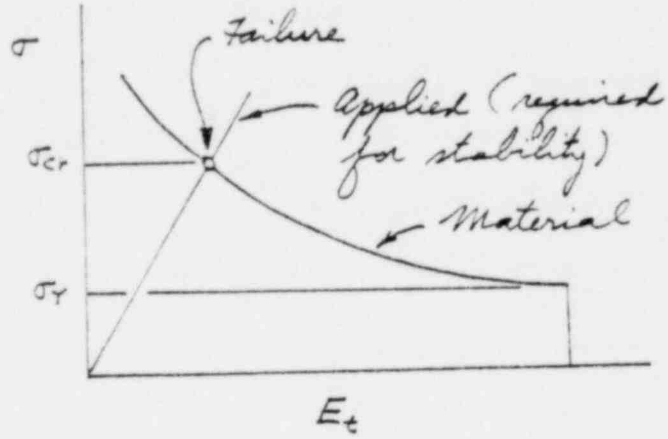


(The material property is the stress-strain curve.)

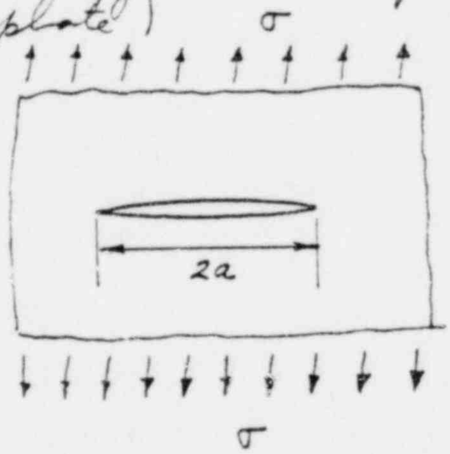
$$\sigma_{cr} = \frac{\pi^2 E_t}{\left(\frac{l}{r}\right)^2}$$

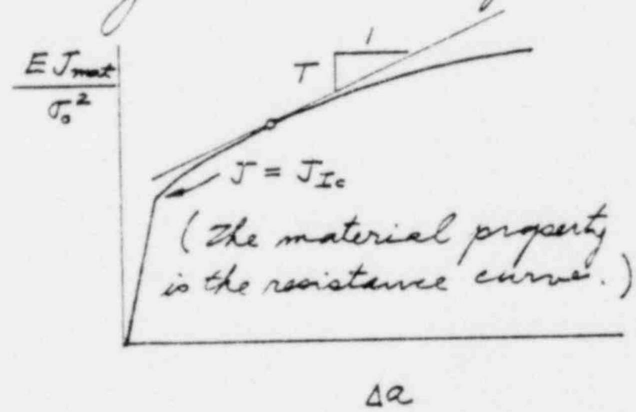
$$r^2 = \frac{I}{A}$$

$$E_{t,req} = \left(\frac{l}{\pi r}\right)^2 \sigma$$



2. Tearing instability (through crack in a flat plate)





$$K = \sigma\sqrt{\pi(a + r_Y)}$$

$$r_Y = \frac{1}{\beta\pi}\left(\frac{K}{\sigma_o}\right)^2$$

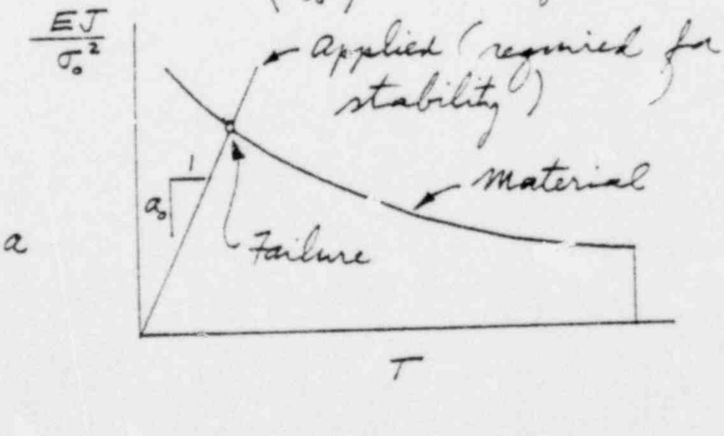
$$\left(\frac{K}{\sigma_o}\right)^2 = \frac{EJ}{\sigma_o^2}$$

$$\therefore \quad \frac{EJ}{\sigma_o^2} = \left\{ \frac{\pi\left(\frac{\sigma}{\sigma_o}\right)^2}{1 - \frac{1}{\beta}\left(\frac{\sigma}{\sigma_o}\right)^2} \right\} a$$

$$T_{req} = \frac{\partial\left(\frac{EJ}{\sigma_o^2}\right)}{\partial a} = \frac{\left(\frac{EJ}{\sigma_o^2}\right)}{a}$$

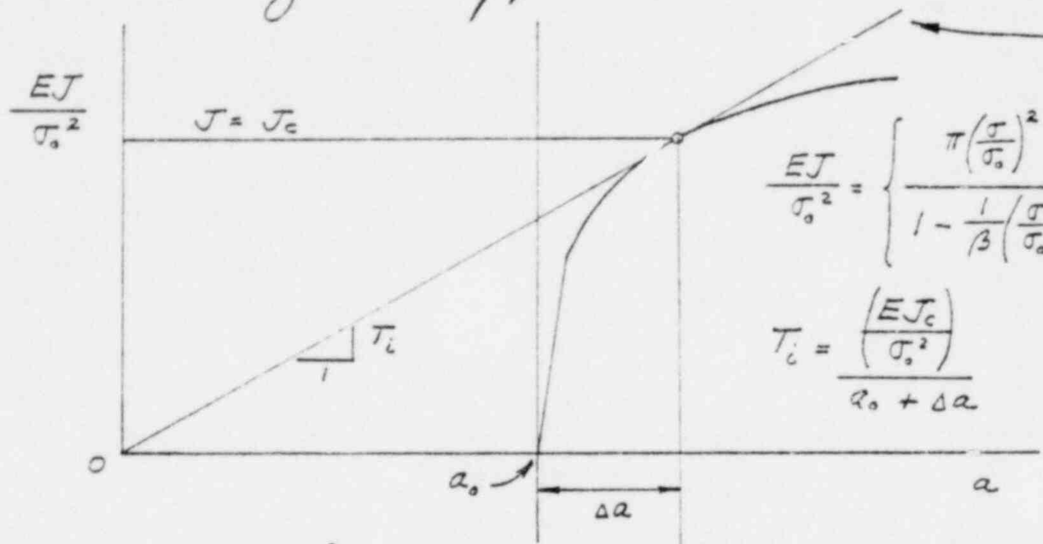
assuming $\frac{\Delta a}{a_o} \sim 0$

$$\left(\frac{EJ}{\sigma_o^2}\right) = a_o T_{req}$$



3. R curve diagram

a) Original approach



$$\frac{EJ}{\sigma_o^2} = \left\{ \frac{\pi\left(\frac{\sigma}{\sigma_o}\right)^2}{1 - \frac{1}{\beta}\left(\frac{\sigma}{\sigma_o}\right)^2} \right\} a$$

$$T_i = \frac{\left(\frac{EJ_c}{\sigma_o^2}\right)}{a_o + \Delta a}$$

$$T_i = \frac{\pi\left(\frac{\sigma}{\sigma_o}\right)^2}{1 - \frac{1}{\beta}\left(\frac{\sigma}{\sigma_o}\right)^2}$$

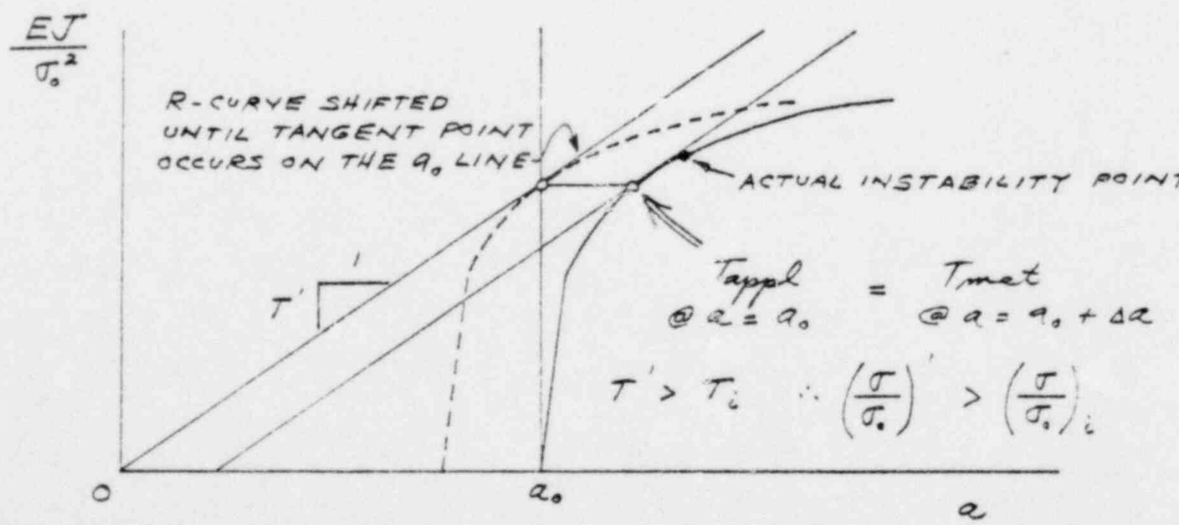
$$T_i - \frac{T_i}{\beta}\left(\frac{\sigma}{\sigma_o}\right)^2 = \pi\left(\frac{\sigma}{\sigma_o}\right)^2$$

$$\Rightarrow$$

$$\left(\frac{\sigma}{\sigma_o}\right)^2\left[\pi + \frac{T_i}{\beta}\right] = T_i$$

$$\frac{\sigma}{\sigma_o} = \sqrt{\frac{T_i}{\pi + \frac{T_i}{\beta}}}$$

b) Diagram corresponding to the J-T diagram



$$T_{appl} \text{ @ } a = a_o \quad = \quad T_{mat} \text{ @ } a = a_o + \Delta a$$

$$T' > T_i \quad \therefore \left(\frac{\sigma}{\sigma_o}\right)' > \left(\frac{\sigma}{\sigma_o}\right)_i$$

4 Discussion

For $\left(\frac{\sigma}{\sigma_o}\right) = 1$ and $\beta = 2$

$$T_i = \frac{\pi}{1 - \frac{1}{2}} = 2\pi$$

For plastic zone instability

Let $$T_{mat} = \frac{\partial\left(\frac{EJ}{\sigma_o^2}\right)}{\partial r_Y}$$

$$r_Y = \frac{1}{\beta\pi}\left(\frac{EJ}{\sigma_o^2}\right)$$

$$\frac{EJ}{\sigma_o^2} = \beta\pi r_Y$$

$$\therefore \quad T_{mat} = \beta\pi = 2\pi$$

For a through crack in a flat plate, the tearing moduli corresponding to failure at general yield and plastic zone instability are the same.

For stability (see the original R-curve diagram)

$$\boxed{T_{mat} \geq \frac{\left(\frac{EJ_{mat}}{\sigma_o^2}\right)}{a_o + \Delta a}}$$

(a) A factor of safety can be applied to the right hand side.

(b) Calculate EJ/σ_o^2 for L.B.B.; determine Δa & recalculate then check T_{mat} at the calculated value of J.

(c) Neglecting Δa in the denominator leads to the J-T diagram.

(d) Note that J_c will increase with increasing a.

C. Analysis for a through crack in a cylinder

1. Equations for $\frac{EJ}{\sigma_o^2}$ and T

$$K = \sigma\sqrt{\pi(a + r_Y)} \cdot Y \qquad (1)$$

$$r_Y = \frac{1}{\beta\pi}\left(\frac{K}{\sigma_o}\right)^2 \qquad (2)$$

$$\left(\frac{K}{\sigma_o}\right)^2 = \pi\left(\frac{\sigma}{\sigma_o}\right)^2\left[a + r_Y\right]Y^2 \qquad (3)$$

$$\left(\frac{K}{\sigma_o}\right)^2 = \pi\left(\frac{\sigma}{\sigma_o}\right)^2\left[a + \frac{1}{\beta\pi}\left(\frac{K}{\sigma_o}\right)^2\right]Y^2 \qquad (4)$$

$$\left(\frac{K}{\sigma_o}\right)^2\left[1 - \frac{Y^2}{\beta}\left(\frac{\sigma}{\sigma_o}\right)^2\right] = \pi\left(\frac{\sigma}{\sigma_o}\right)^2 Y^2 a \qquad (5)$$

$$\left(\frac{K}{\sigma_o}\right)^2 = \frac{EJ}{\sigma_o^2} \qquad (6)$$

$$\boxed{\frac{EJ}{\sigma_o^2 a} = \left\{\frac{\pi\left(\frac{\sigma}{\sigma_o}\right)^2}{1 - \frac{Y^2}{\beta}\left(\frac{\sigma}{\sigma_o}\right)^2}\right\}Y^2} \qquad (7)$$

$$T = \frac{\partial\left(\frac{EJ}{\sigma_o^2}\right)}{\partial a} = \frac{\partial\left(\frac{K}{\sigma_o}\right)^2}{\partial a} \qquad (8)$$

Therefore, using Eq (4),

$$T = \pi\left(\frac{\sigma}{\sigma_o}\right)^2\left\{\left[1 + \frac{T}{\beta\pi}\right]Y^2 + \left[a + r_Y\right]2Y \cdot Y'\frac{d\lambda}{da}\right\} \qquad (9)$$

$$Y = Y(\lambda) \quad ; \quad Y' = \frac{dY}{d\lambda} \tag{10}$$

$$\lambda = \frac{a}{\sqrt{Rt}} \tag{11}$$

$$\frac{d\lambda}{da} = \frac{1}{\sqrt{Rt}} = \frac{\lambda}{a} \tag{12}$$

$\therefore$

$$T = \pi\left(\frac{\sigma}{\sigma_0}\right)^2\left\{\left[1+\frac{T}{\beta\pi}\right]Y^2 + \left[1+\frac{r_Y}{a}\right]2\lambda Y\cdot Y'\right\}$$

$$T\left[1 - \frac{Y^2}{\beta}\left(\frac{\sigma}{\sigma_0}\right)^2\right] = \pi\left(\frac{\sigma}{\sigma_0}\right)^2\left[Y^2 + 2\lambda Y\cdot Y'\left(1+\frac{r_Y}{a}\right)\right] \tag{13}$$

$$T = \left\{\frac{\pi\left(\frac{\sigma}{\sigma_0}\right)^2}{1 - \frac{Y^2}{\beta}\left(\frac{\sigma}{\sigma_0}\right)^2}\right\}\left[Y^2 + 2\lambda Y\cdot Y'\left(1+\frac{r_Y}{a}\right)\right] \tag{14}$$

$$\boxed{T = \left\{\frac{\pi\left(\frac{\sigma}{\sigma_0}\right)^2}{1 - \frac{Y^2}{\beta}\left(\frac{\sigma}{\sigma_0}\right)^2}\right\}\left[Y^2 + 2\lambda Y\cdot Y'\left(1+\frac{1}{\beta\pi}\frac{EJ}{\sigma_0^2 a}\right)\right]} \tag{15}$$

Also, using Eq (7),

$$\boxed{T = \frac{EJ}{\sigma_0^2 a}\left[1 + 2\lambda\frac{Y'}{Y}\left(1+\frac{1}{\beta\pi}\frac{EJ}{\sigma_0^2 a}\right)\right]} \tag{16}$$

2. The bulging factor, Y

$$Y = (1 + 1.25\lambda^2)^{1/2} = \left(1 + \frac{5}{4}\lambda^2\right)^{1/2}, \qquad \lambda \le 1$$

$$Y = 0.6 + 0.9\lambda = \frac{6 + 9\lambda}{10}, \qquad 1 \le \lambda \le 5$$

$$Y' = \frac{1}{2}\left(1 + \frac{5}{4}\lambda^2\right)^{-1/2} \cdot \frac{5}{4}\lambda = \frac{\frac{5}{4}\lambda}{Y}, \qquad \lambda \le 1$$

$$2\lambda Y \cdot Y' = \frac{10}{4}\lambda^2 = 2.5\lambda^2, \qquad \lambda \le 1$$

$$Y' = \frac{9}{10}, \qquad 1 \le \lambda \le 5$$

$$\left.\begin{aligned} 2\lambda Y \cdot Y' &= 2\lambda\left(\frac{6 + 9\lambda}{10}\right) \cdot \frac{9}{10} \\ 2\lambda Y \cdot Y' &= (6\lambda + 9\lambda^2) \cdot \frac{9}{50} \end{aligned}\right\} \qquad 1 \le \lambda \le 5$$

For $\lambda = 1$

$$Y = \sqrt{\frac{9}{4}} = \frac{3}{2}$$

$$Y = \frac{15}{10} = \frac{3}{2}, \quad \text{OK}$$

$$2\lambda Y \cdot Y' = 2.5$$

$$2\lambda Y \cdot Y' = \frac{15 \cdot 9}{50} = \frac{27}{10} = 2.7$$

There is a discontinuity in Y' at $\lambda = 1$.

For $a = t$ and $\left(\frac{R}{t}\right) = 10$

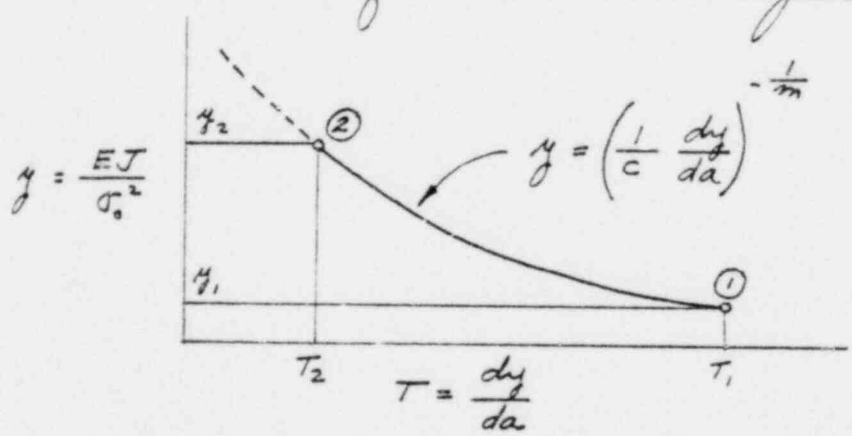
$$\lambda = \frac{t}{\sqrt{10t^2}} = \frac{1}{\sqrt{10}} < 1$$

$$Y = \sqrt{1 + \frac{5}{40}} = \sqrt{1\tfrac{1}{8}} = \sqrt{\frac{9}{8}} = \frac{3}{2\sqrt{2}} = \underline{\underline{1.06}}$$

$$Y^2 = 1\tfrac{1}{8} = \underline{\underline{1.125}}$$

$$2\lambda Y \cdot Y' = \frac{10}{40} = \frac{1}{4} = \underline{\underline{0.25}}$$

D. Estimates of stable crack growth



Let $\sigma_o = 90$ KSI
$E = 30 \times 10^6$ PSI
$\frac{\sigma_o^2}{E} = 270$ PSI

$$y = \left(\frac{1}{c}\frac{dy}{da}\right)^{-\frac{1}{m}} = \left(c\frac{da}{dy}\right)^{\frac{1}{m}}$$

$$y^m = c\frac{da}{dy} = \frac{c}{T}$$

$$\left(\frac{y_2}{y_1}\right)^m = \frac{T_1}{T_2}$$

$$m \ln\left(\frac{y_2}{y_1}\right) = \ln\left(\frac{T_1}{T_2}\right)$$

$$m = \frac{\ln\left(\frac{T_1}{T_2}\right)}{\ln\left(\frac{J_2}{J_1}\right)} = \frac{\ln\left(\frac{T_1}{T_2}\right)}{\ln\left(\frac{J_2}{J_1}\right)}$$

also,

$$C = T J^{m} \quad \text{and} \quad T = \frac{C}{J^{m}}$$

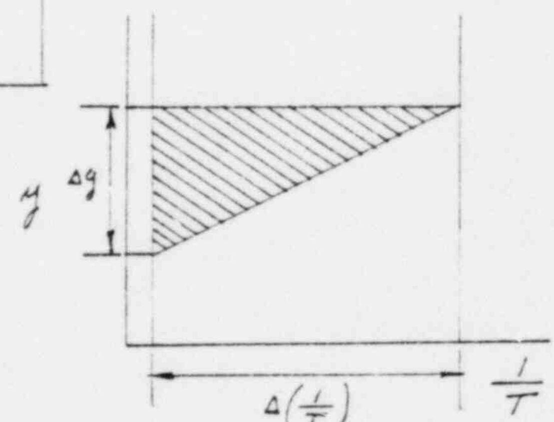
$$da = \frac{1}{C} J^{m} dJ$$

$$\Delta a = \frac{1}{C(1+m)} J^{1+m}$$

In addition

$$da = \frac{1}{T} dJ$$

$$\Delta a = \int \frac{1}{T} dJ$$



$$\Delta a_{approx} = \frac{1}{2}(\Delta J)\left(\Delta \frac{1}{T}\right)$$

(Paris' notes ; NRL data)

For V86-27 (Irradiated weld , CVN = 56 ft. lb.)

$J_1 = 450$ IN-LBS/IN^2 ; $T_1 = 89$

$J_2 = 900$ " " " $T_2 = 15$

$$\therefore \quad m = \frac{\ln\left(\frac{89}{15}\right)}{\ln\left(\frac{900}{450}\right)} = \underline{\underline{2.57}}$$

$$C = 15\left(\frac{900}{270}\right)^{2.57} = \underline{\underline{331}}$$

Check crack extension up to J_2

$$\Delta a = \frac{1}{(331)(3.57)}\left(\frac{900}{270}\right)^{3.57} = 0.062 \text{ IN} = \underline{1.57 \text{ mm}} \quad \text{OK}$$

E. Example problem

GIVEN: $t = 8$ IN. ; $R = 80$ IN. ; $a = t = 8$ IN.

$\sigma_o = 90$ KSI ; $\sigma = 30$ KSI ;

R CURVE AS PER SPECIMEN V86-27

REQ'D: J, T_{req}, T_{mat}, Δa

SOLUTION:

$$\lambda = \frac{1}{\sqrt{10}} \; ; \; Y^2 = 1.125 \; ; \; 2\lambda Y \cdot Y' = 0.25$$

$$\left\{\frac{\pi\left(\frac{\sigma}{\sigma_o}\right)^2}{1 - \frac{Y^2}{\beta}\left(\frac{\sigma}{\sigma_o}\right)^2}\right\} = \left\{\frac{\frac{\pi}{9}}{1 - \frac{1.125}{2}\left(\frac{1}{9}\right)}\right\} = \underline{0.372}$$

$$\frac{EJ}{\sigma_o^2 a} = (0.372)(1.125) = \underline{0.419}$$

$$J = (0.419)(270)(8) = \underline{905 \text{ IN-LBS/IN}^2}$$

$$K = \sqrt{30J} = \underline{165 \text{ KSI}\sqrt{\text{IN.}}}$$

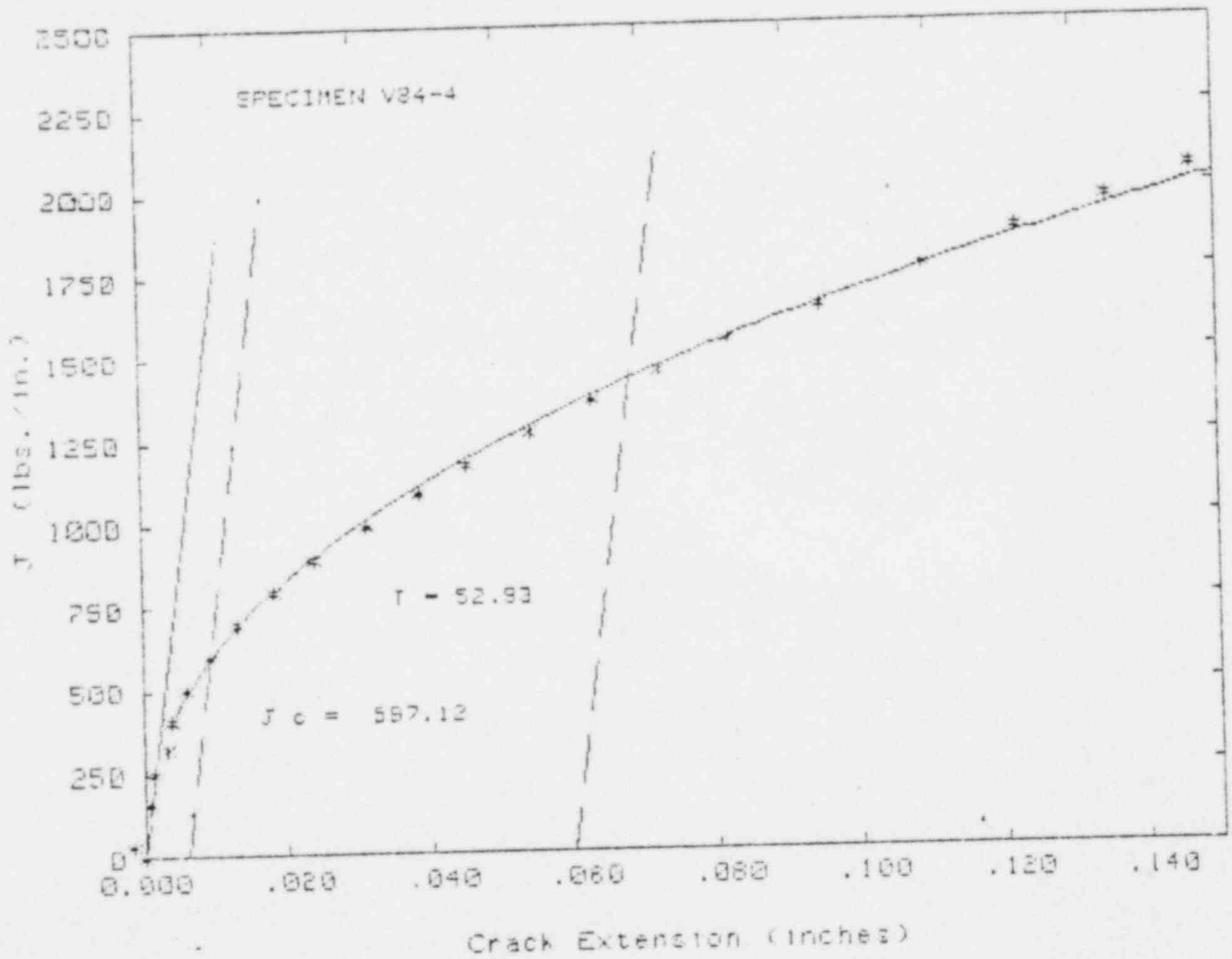
$$T_{req} = (0.372)\left[1.125 + (0.25)\left(1 + \frac{0.419}{2\pi}\right)\right] = \underline{0.518}$$

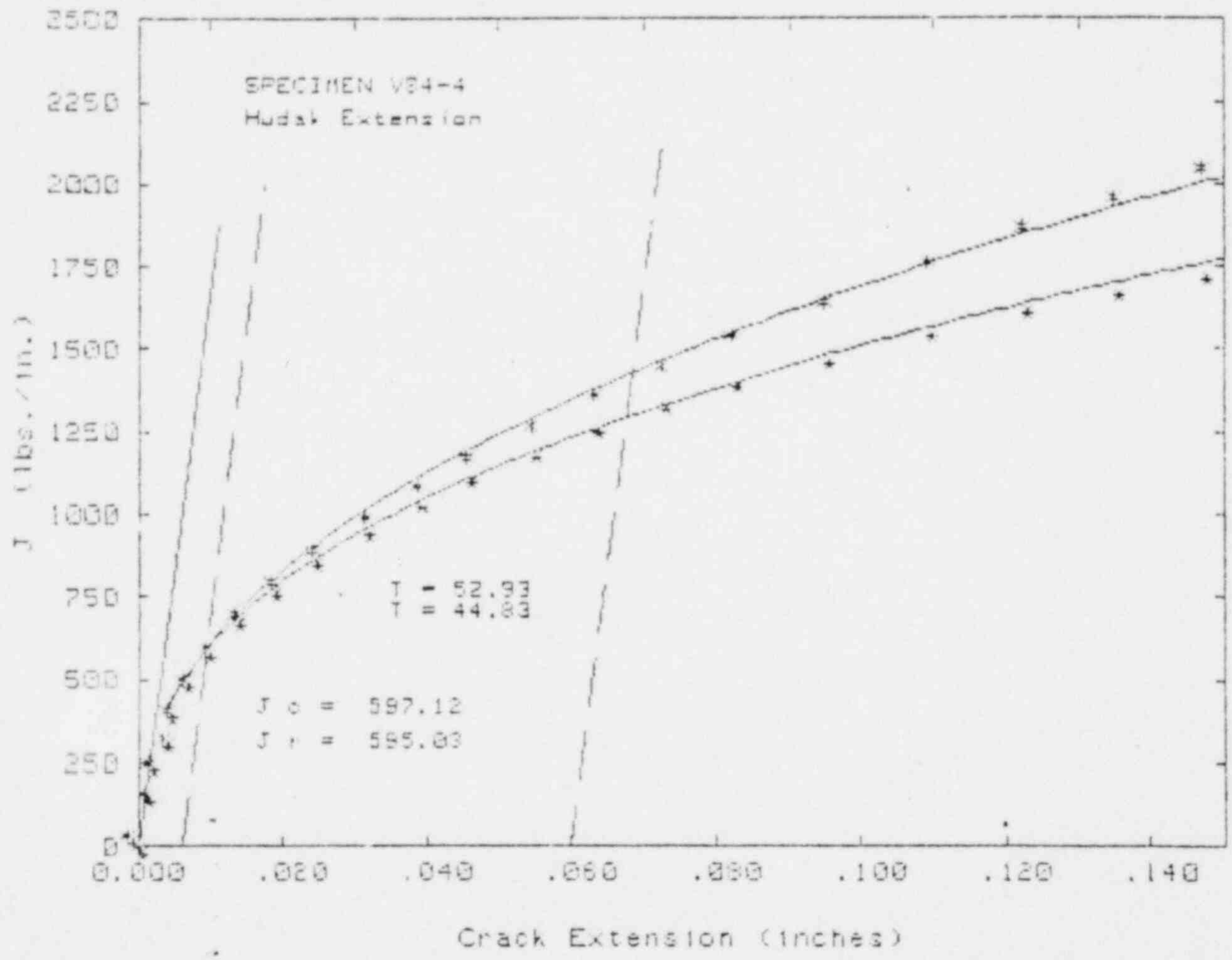
$$T_{mat} = \frac{331}{\left(\frac{905}{270}\right)^{2.57}} = \underline{14.8}$$

$$\Delta a = \frac{1}{(331)(3.57)}\left(\frac{905}{270}\right)^{3.57} = \underline{0.063 \text{ IN.} = 1.61 \text{ mm}}$$

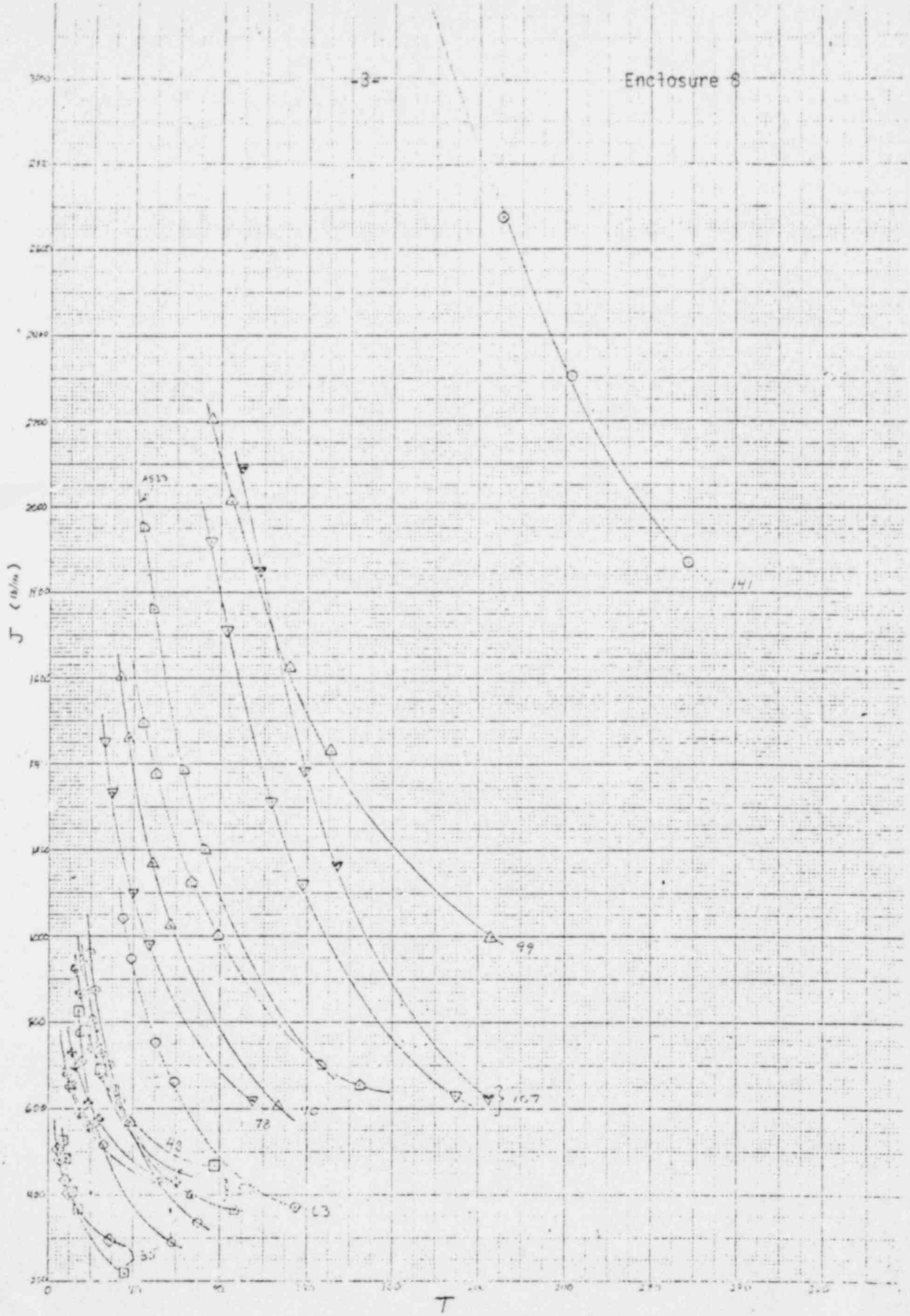
FJL
4/9/80

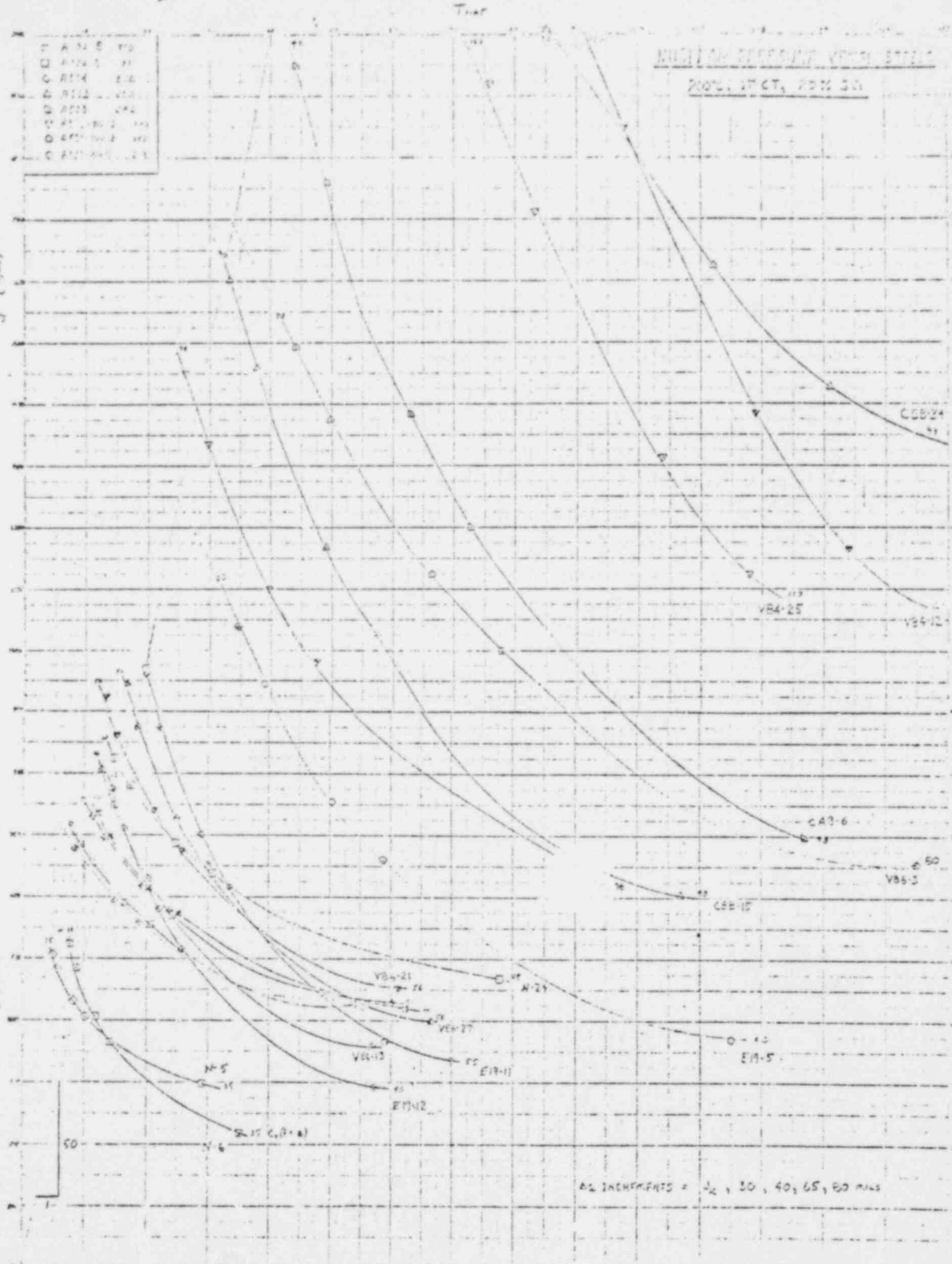
ENCLOSURE 8

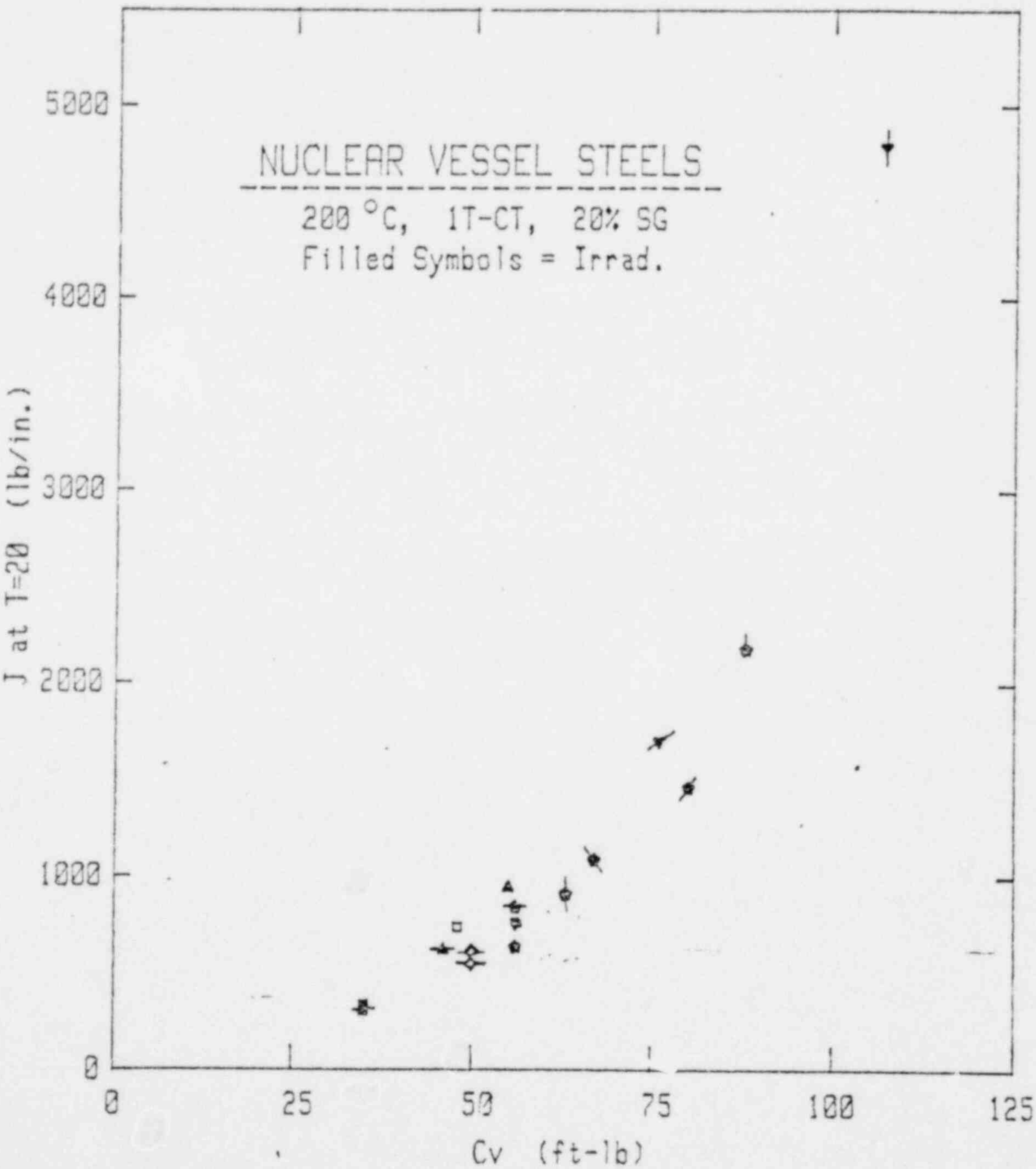


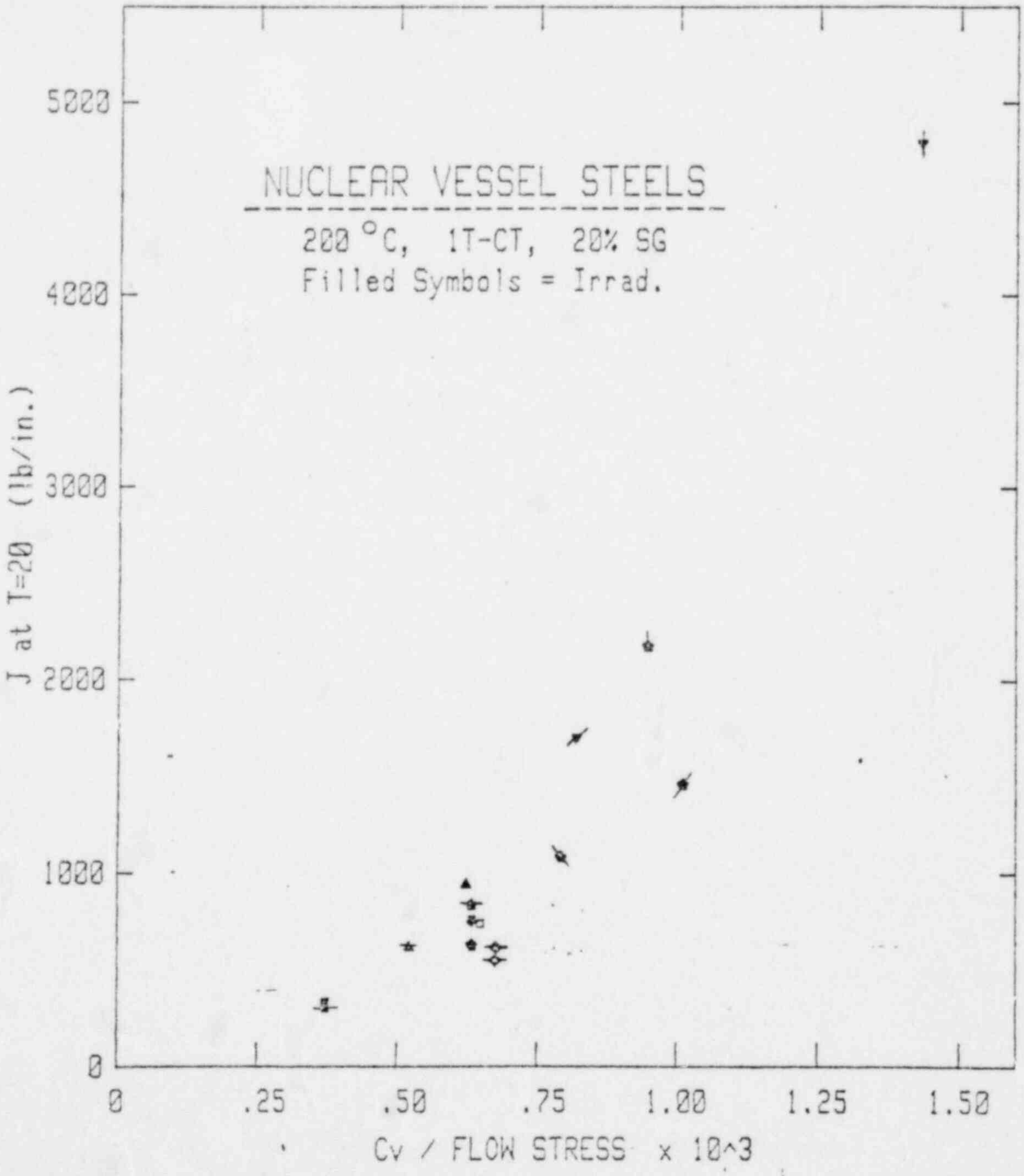

SPECIMEN V84-4
Hudak Extension
T = 52.93
T = 44.83
J c = 597.12
J r = 595.03
J (lbs./in.)
0
250
500
750
1000
1250
1500
1750
2000
2250
2500
0.000
.020
.040
.060
.080
.100
.120
.140
Crack Extension (inches)

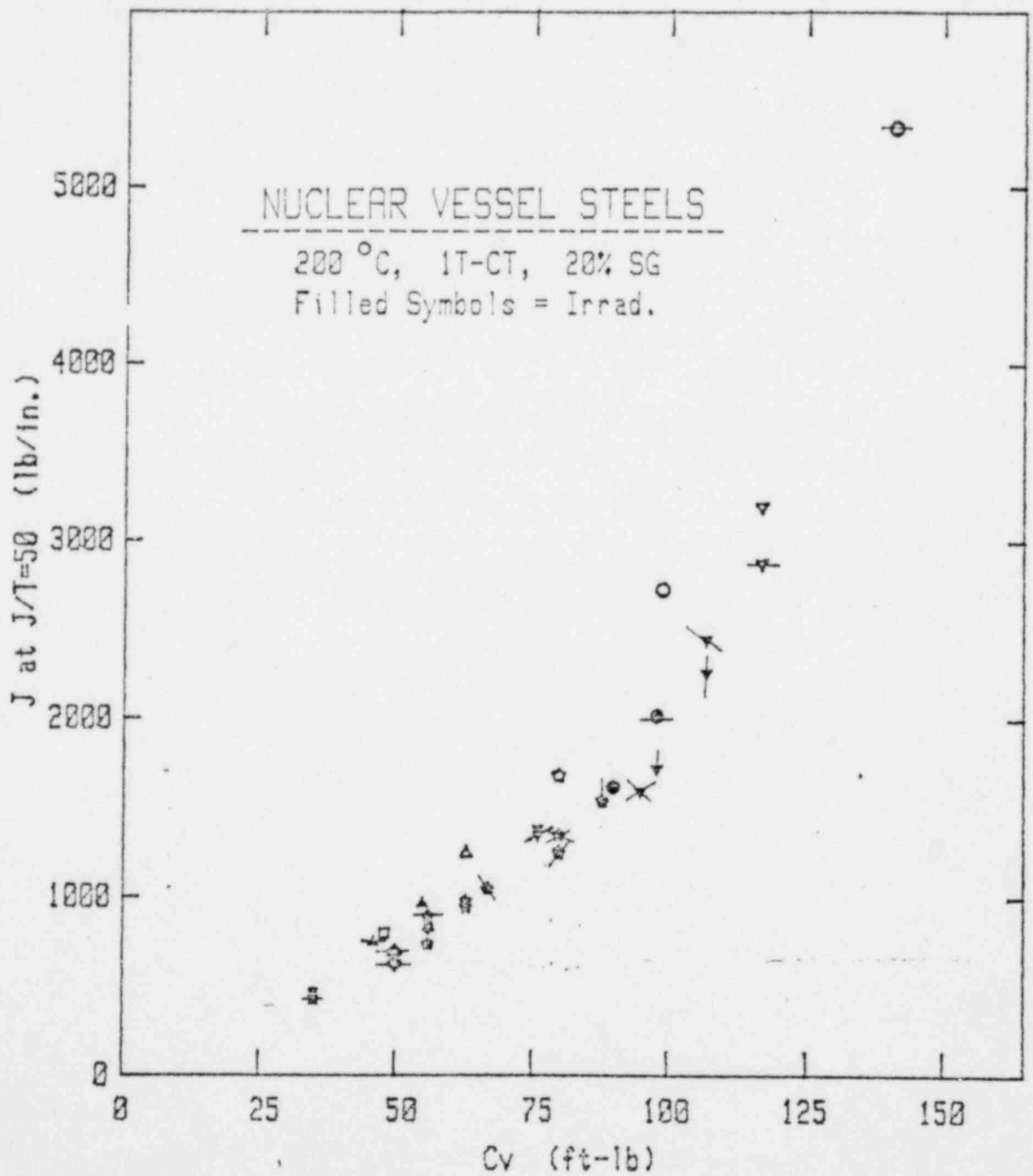
Enclosure 8

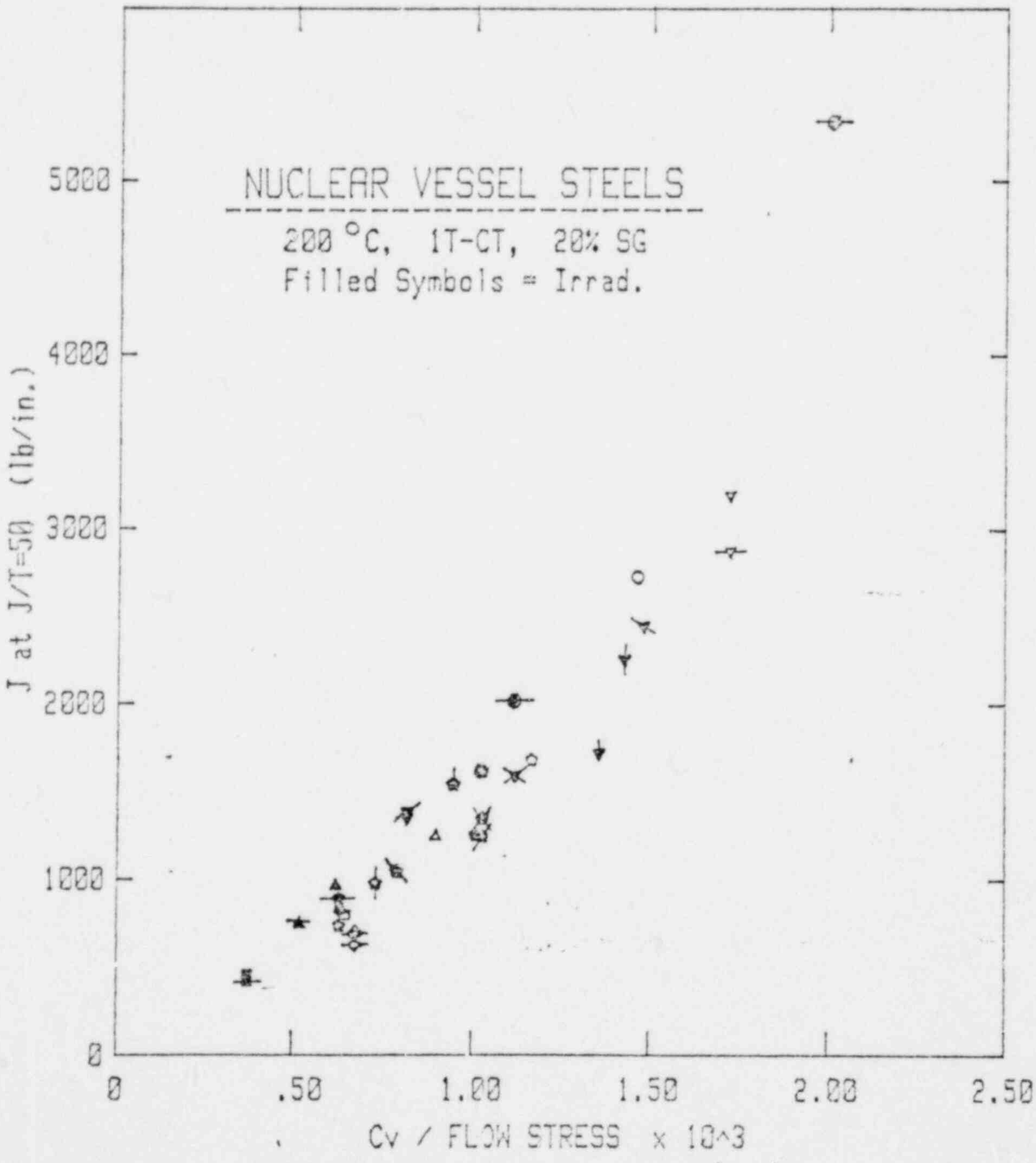


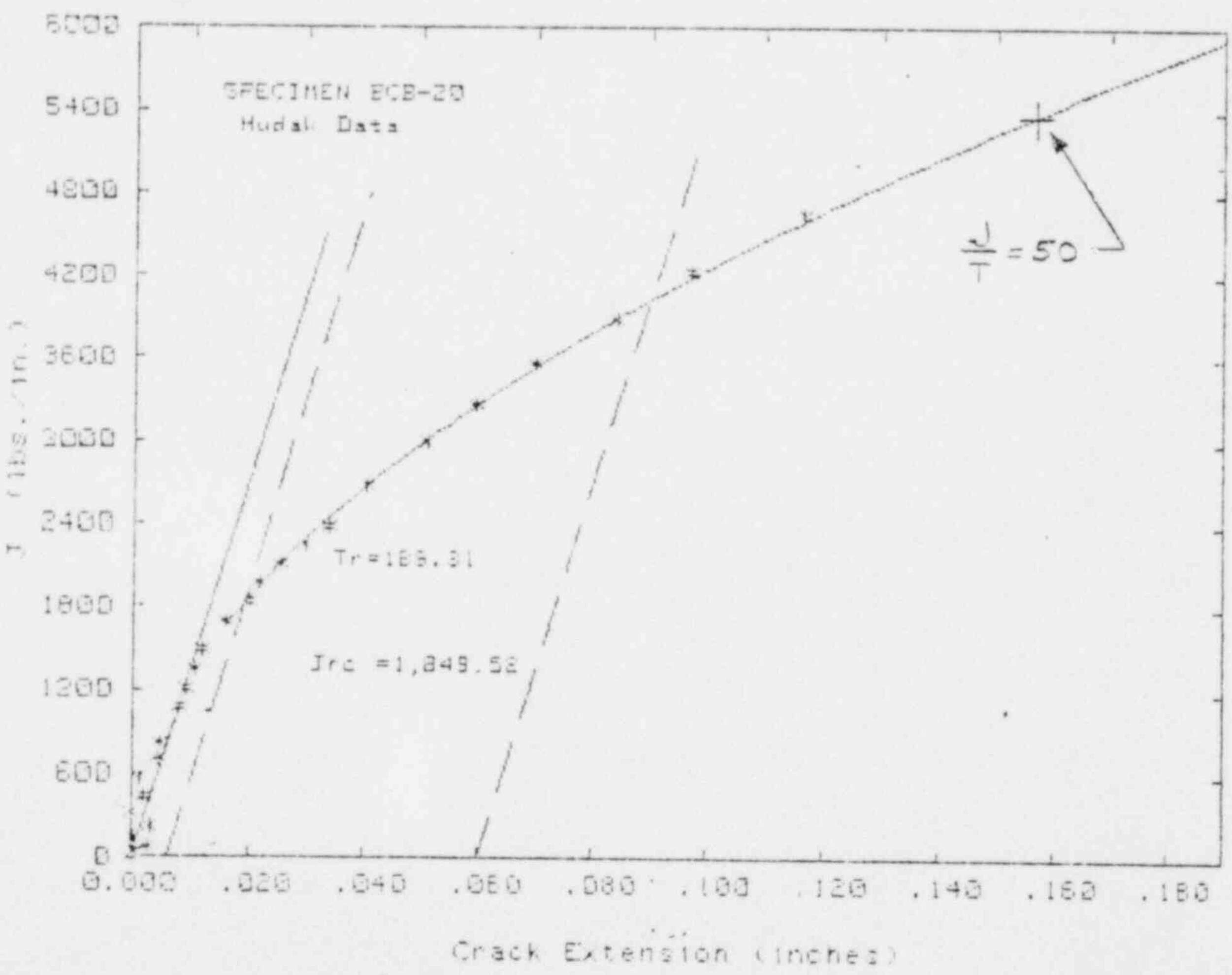

CSB-24
VB4-25
VB4-12
CA3-6
VB6-3
CSB-15
VB4-21
N-24
VB4-27
VB4-13
E19-11
E19-5
E19-12
N-5
N-6

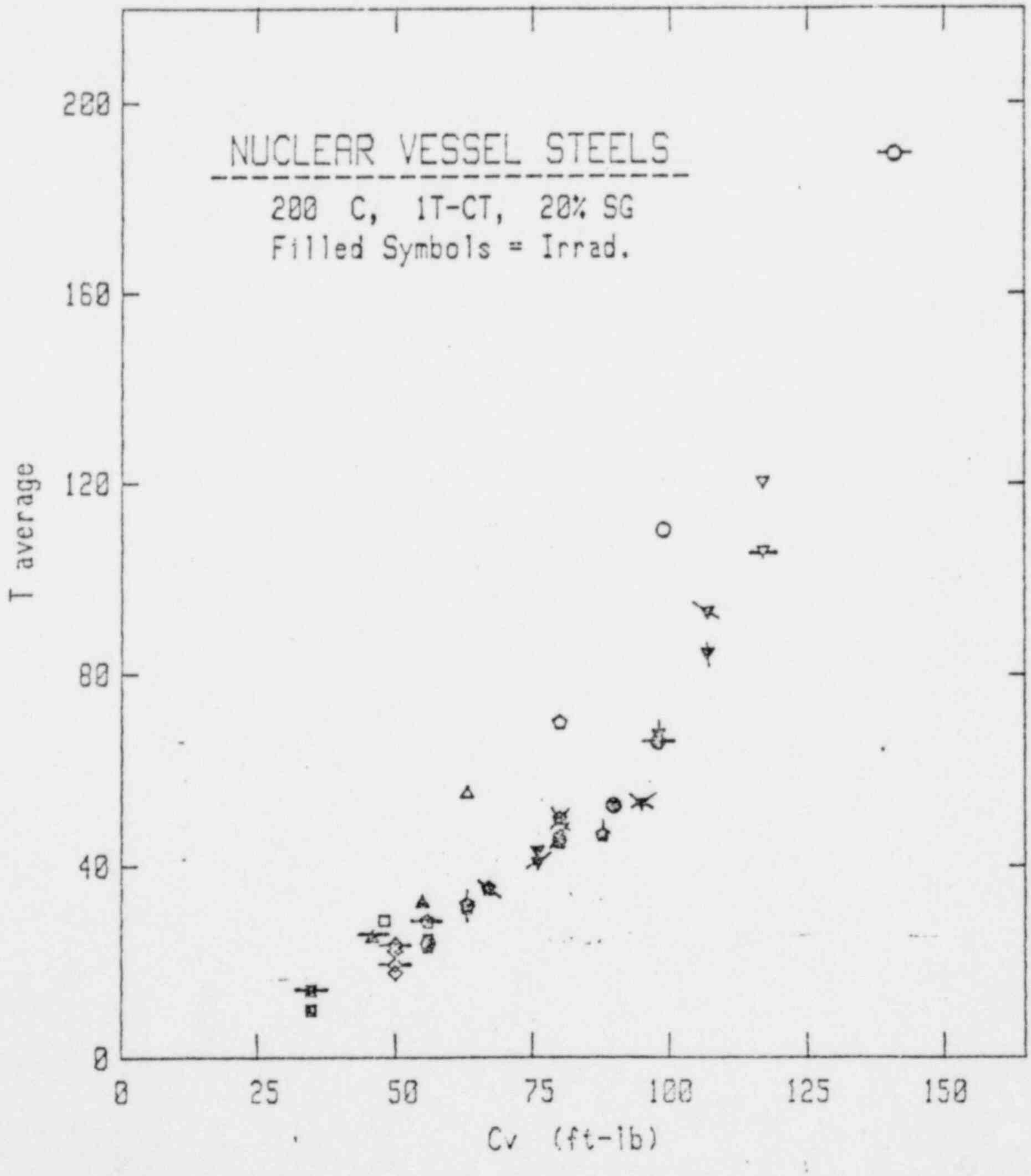

NUCLEAR VESSEL STEELS
200 °C, 1T-CT, 20% SG
Filled Symbols = Irrad.
J at T=20 (lb/in.)
0
1000
2000
3000
4000
5000
0
25
50
75
100
125
Cv (ft-lb)

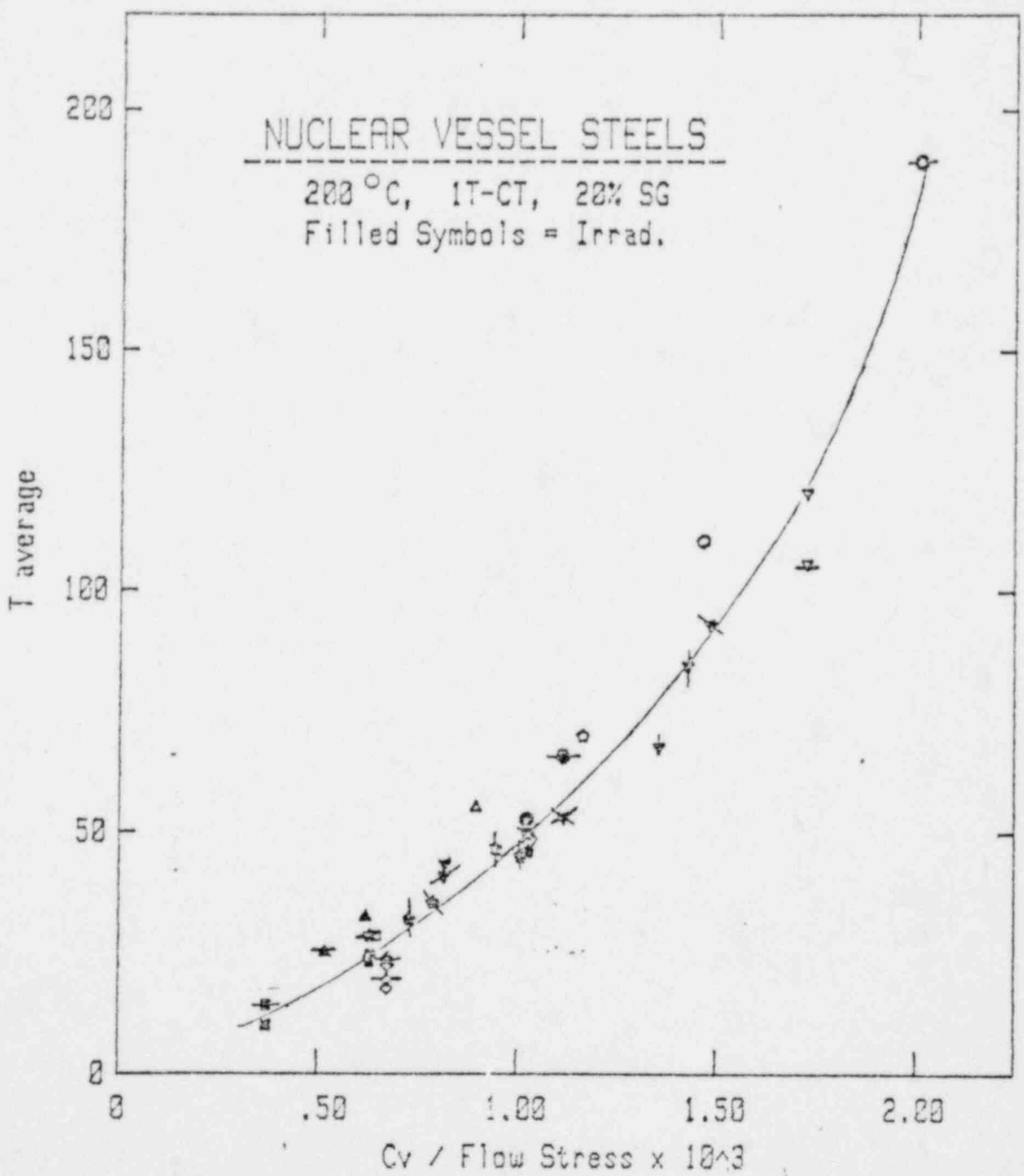

NUCLEAR VESSEL STEELS
200 °C, 1T-CT, 20% SG
Filled Symbols = Irrad.
J at T=20 (lb/in.)
0
1000
2000
3000
4000
5000
0
.25
.50
.75
1.00
1.25
1.50
Cv / FLOW STRESS x 10^3

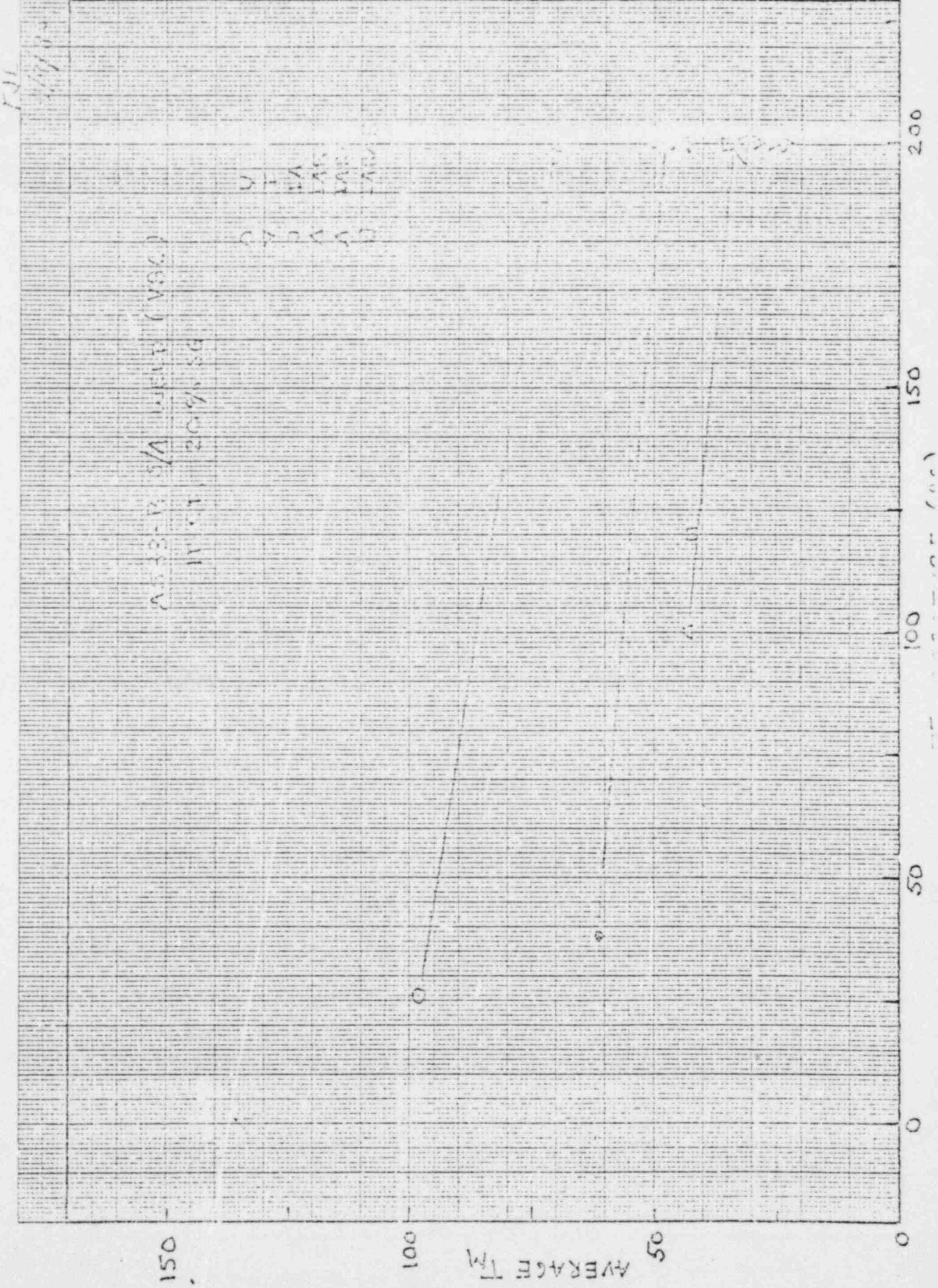

NUCLEAR VESSEL STEELS
200 °C, 1T-CT, 20% SG
Filled Symbols = Irrad.
J at J/T=50 (lb/in.)
0
1000
2000
3000
4000
5000
0
25
50
75
100
125
150
Cv (ft-lb)

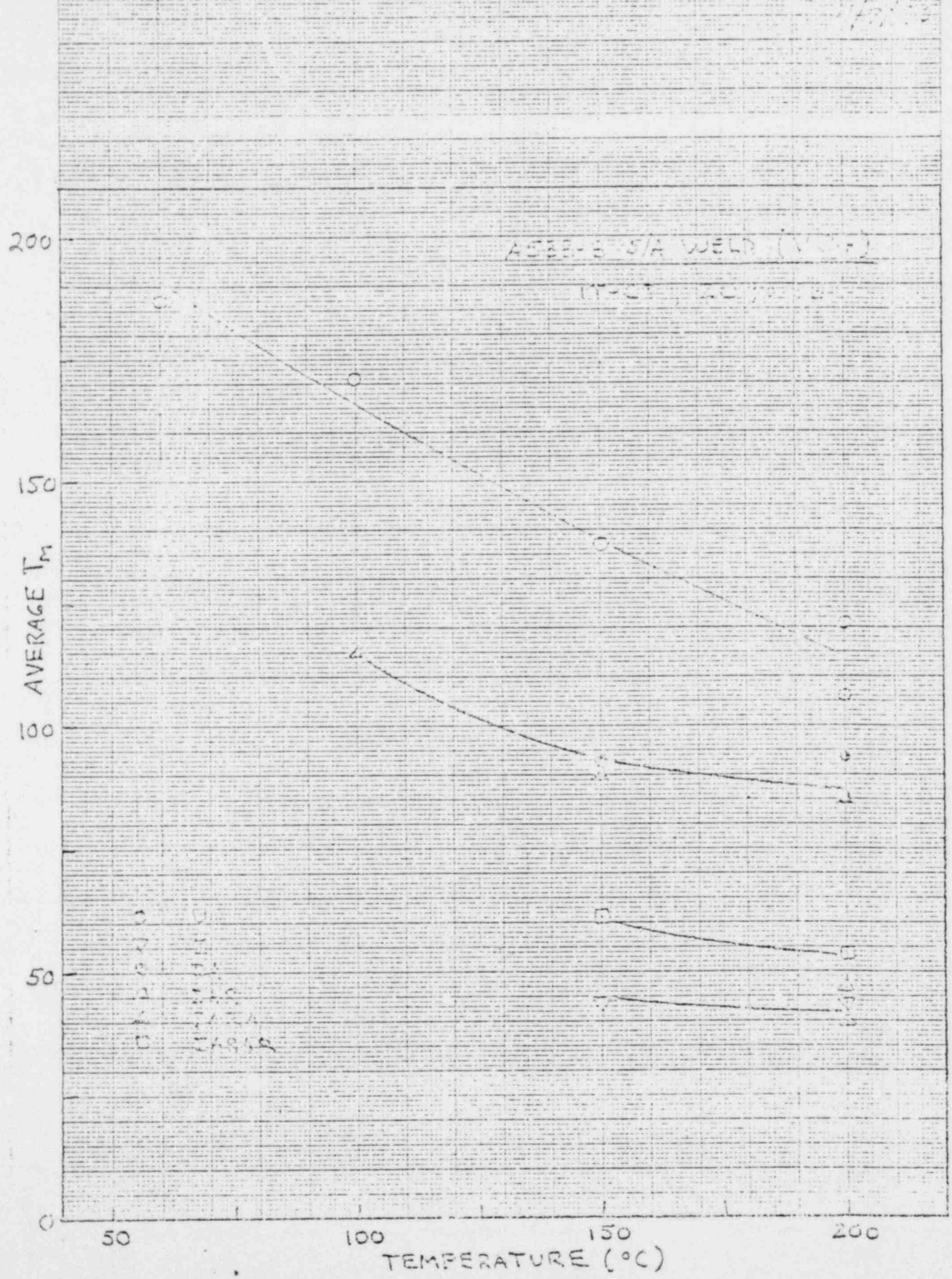

NUCLEAR VESSEL STEELS
200 °C, 1T-CT, 20% SG
Filled Symbols = Irrad.
J at J/T=50 (lb/in.)
0
1000
2000
3000
4000
5000
0
.50
1.00
1.50
2.00
2.50
Cv / FLOW STRESS x 10^3

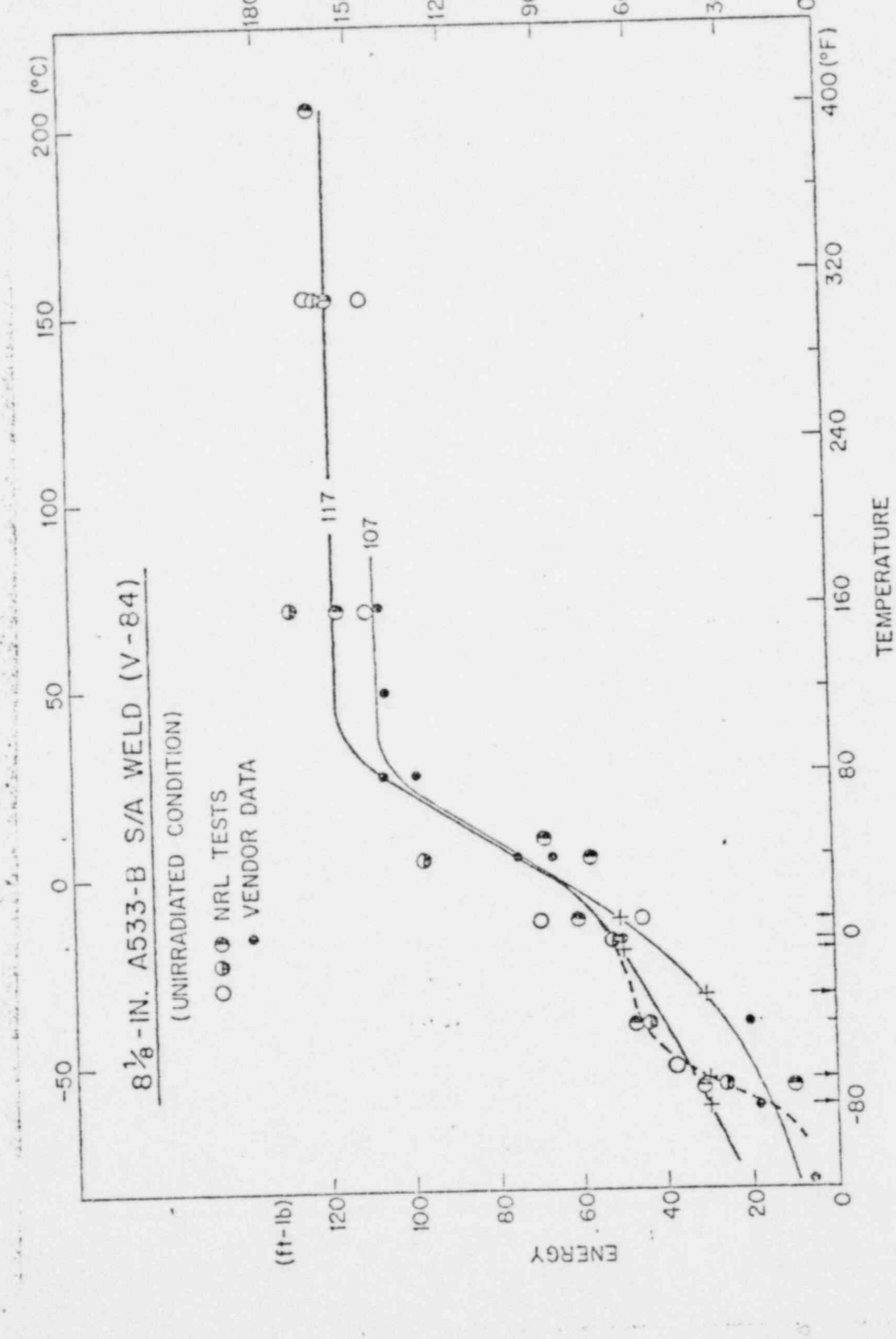

SPECIMEN ECB-20
Hudak Data
J (lbs./in.)
6000
5400
4800
4200
3600
3000
2400
1800
1200
600
0
0.000
.020
.040
.060
.080
.100
.120
.140
.160
.180
Crack Extension (inches)
Tr=188.31
Jrc =1,849.52
J/T = 50


NUCLEAR VESSEL STEELS
200 C, 1T-CT, 20% SG
Filled Symbols = Irrad.
T average
Cv (ft-lb)
0
40
80
120
160
200
0
25
50
75
100
125
150


NUCLEAR VESSEL STEELS
200 °C, 1T-CT, 20% SG
Filled Symbols = Irrad.
T average
200
150
100
50
0
0
.50
1.00
1.50
2.00
Cv / Flow Stress x 10^3


AVERAGE T_M
150
100
50
0
200
150
100
50
0


200
150
100
50
0
AVERAGE T_M
50
100
150
200
TEMPERATURE (°C)


8 1/8-IN. A533-B S/A WELD (V-84)
(UNIRRADIATED CONDITION)
NRL TESTS
VENDOR DATA
117
107
ENERGY
(ft-lb)
(J)
TEMPERATURE
(°C)
(°F)
-50
0
50
100
150
200
-80
0
80
160
240
320
400
0
20
40
60
80
100
120
30
60
90
120
150
180