HEDL-7257

FRACTURE MECHANICS MATERIALS DATA BASE FOR USE IN CRBR PIPING INTEGRITY ANALYSES

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NRC MEETING

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FRACTURE MECHANICS
MATERIALS DATA BASE FOR USE IN CRBR PIPING
INTEGRITY ANALYSES

- PURPOSE
  - TO ILLUSTRATE HOW FRACTURE MECHANICS DATA CONFIRM THE BEHAVIOR/FAILURE CHARACTERISTICS EXHIBITED IN CONVENTIONAL MATERIAL DESIGN DATA BASE.

- SCOPE
  - BASED UPON CRBRP PIPING INTEGRITY STUDIES.
  - INCLUDES EFFECTS SUCH AS WELDMENTS, AGING, ENVIRONMENTAL CONSIDERATIONS, METALLURGICAL VARIABLES.

- CONCLUSION
  - AVAILABLE DATA IS ADEQUATE FOR SAFE RELIABLE DESIGN OF CRBRP ELEVATED TEMPERATURE COMPONENTS FOR 30 YEAR PLANT LIFE.

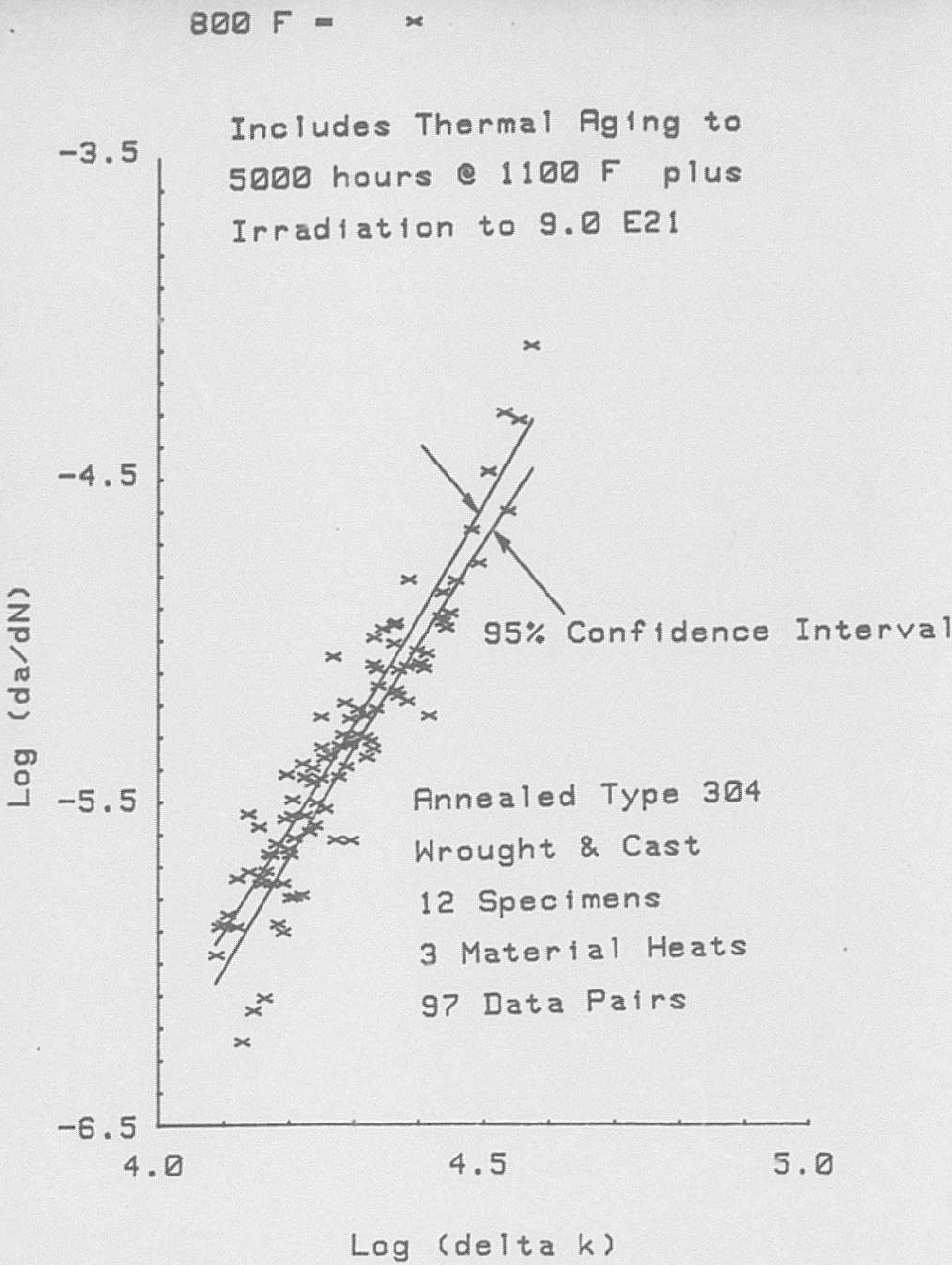
<u>FATIGUE-CRACK GROWTH IN</u>
<u>AUSTENITIC STAINLESS STEELS & WELDMENTS</u>

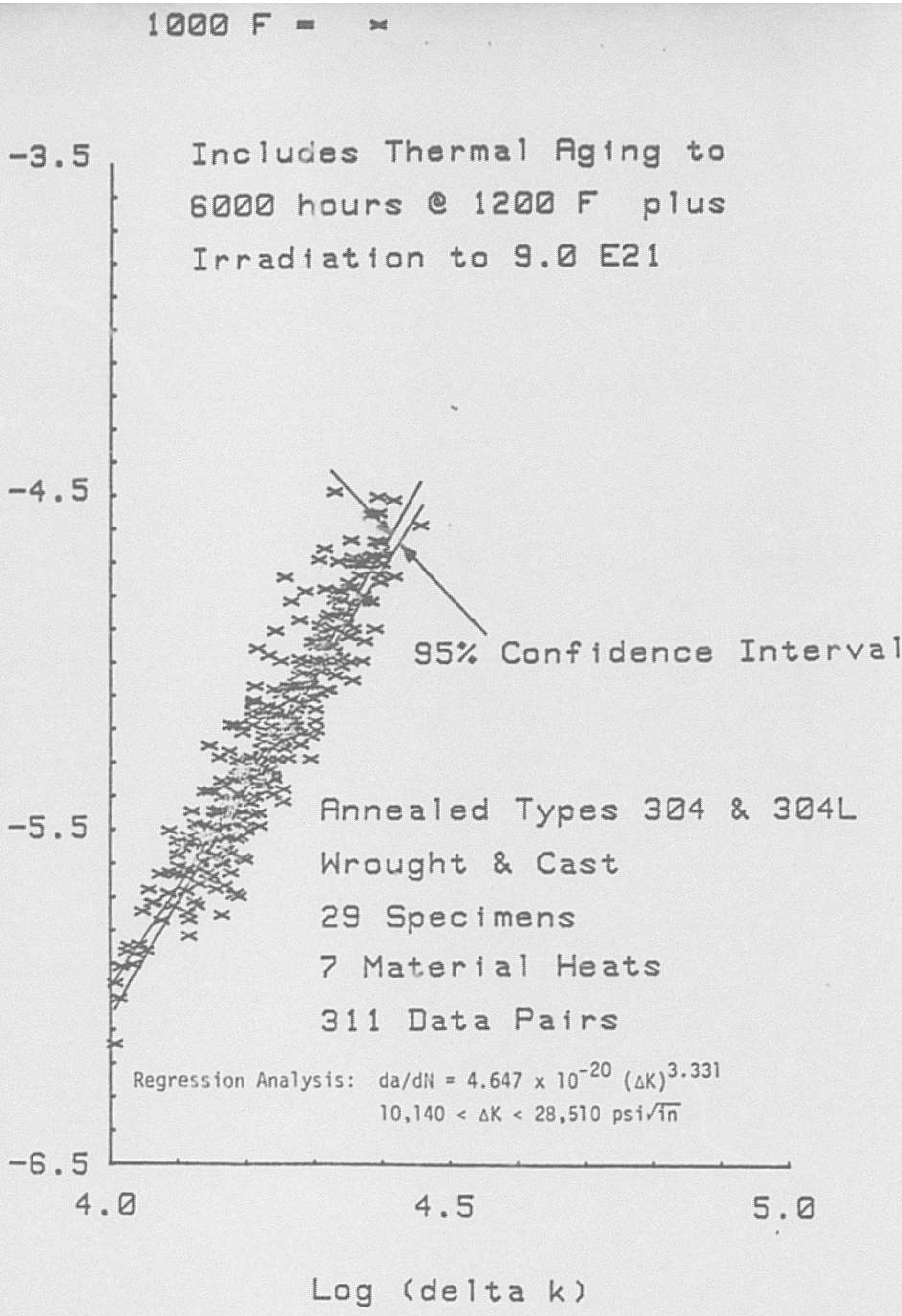
- LARGE WELL-CHARACTERIZED DATA BASE INCORPORATING SEVERAL MATERIAL HEATS AND PRODUCT FORMS AND WELD TYPES.

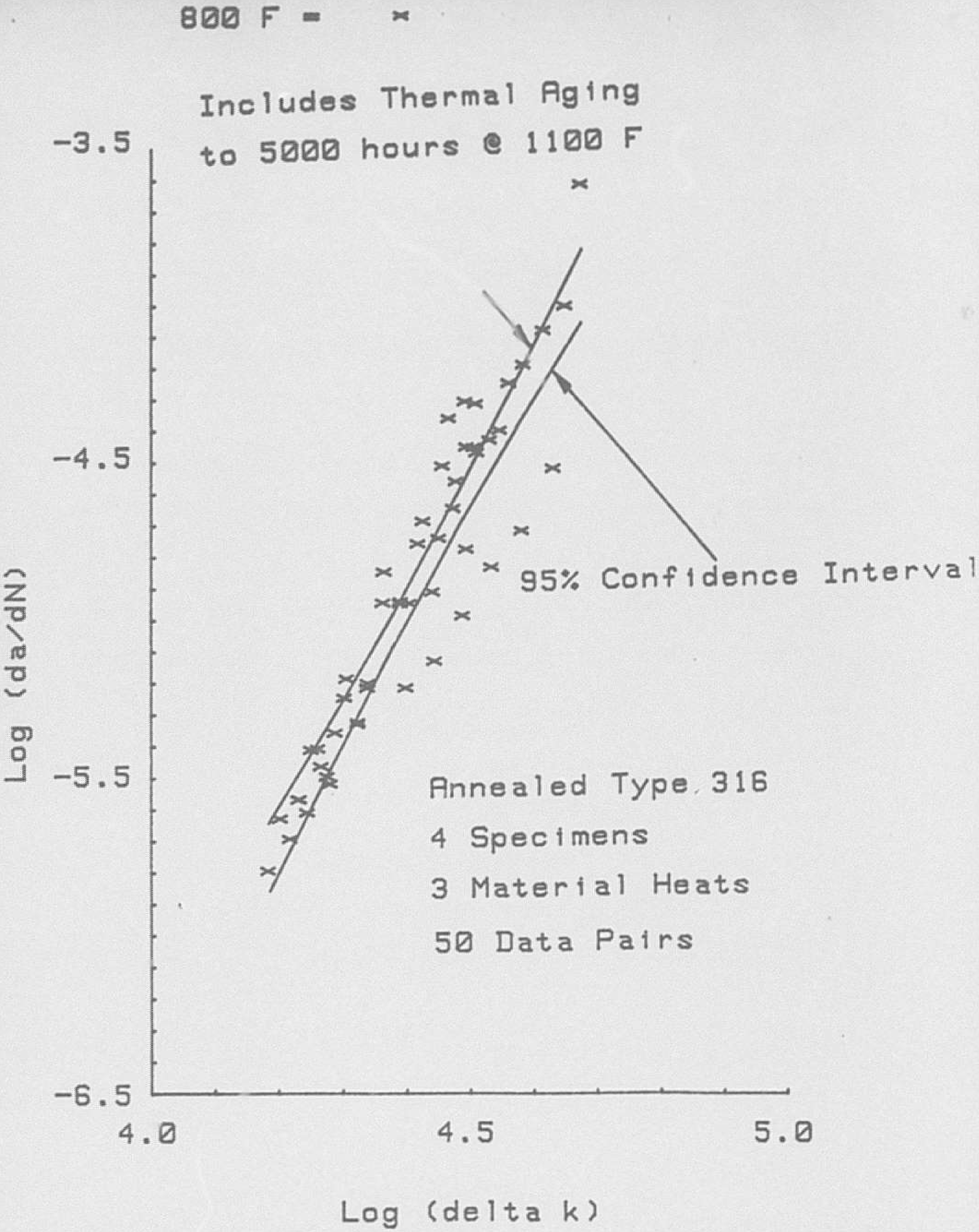
- ONLY "VALID DATA" EMPLOYED (VALID PER ASTM E647). CORRELATIONS DEVELOPED ARE IN PROCESS OF CONSIDERATION FOR NSMH REVISION.

- QUALITY AND QUANTITY OF DATA ARE SUFFICIENTLY HIGH THAT RELATIVELY NARROW CONFIDENCE INTERVALS ARE PRODUCED -- I.E., WE HAVE A HIGH LEVEL OF CONFIDENCE THAT THE CRACK GROWTH EQUATIONS EMPLOYED ARE CORRECT.

- METHODS ARE AVAILABLE TO ACCOUNT FOR FREQUENCY EFFECTS AND STRESS RATIO EFFECTS.

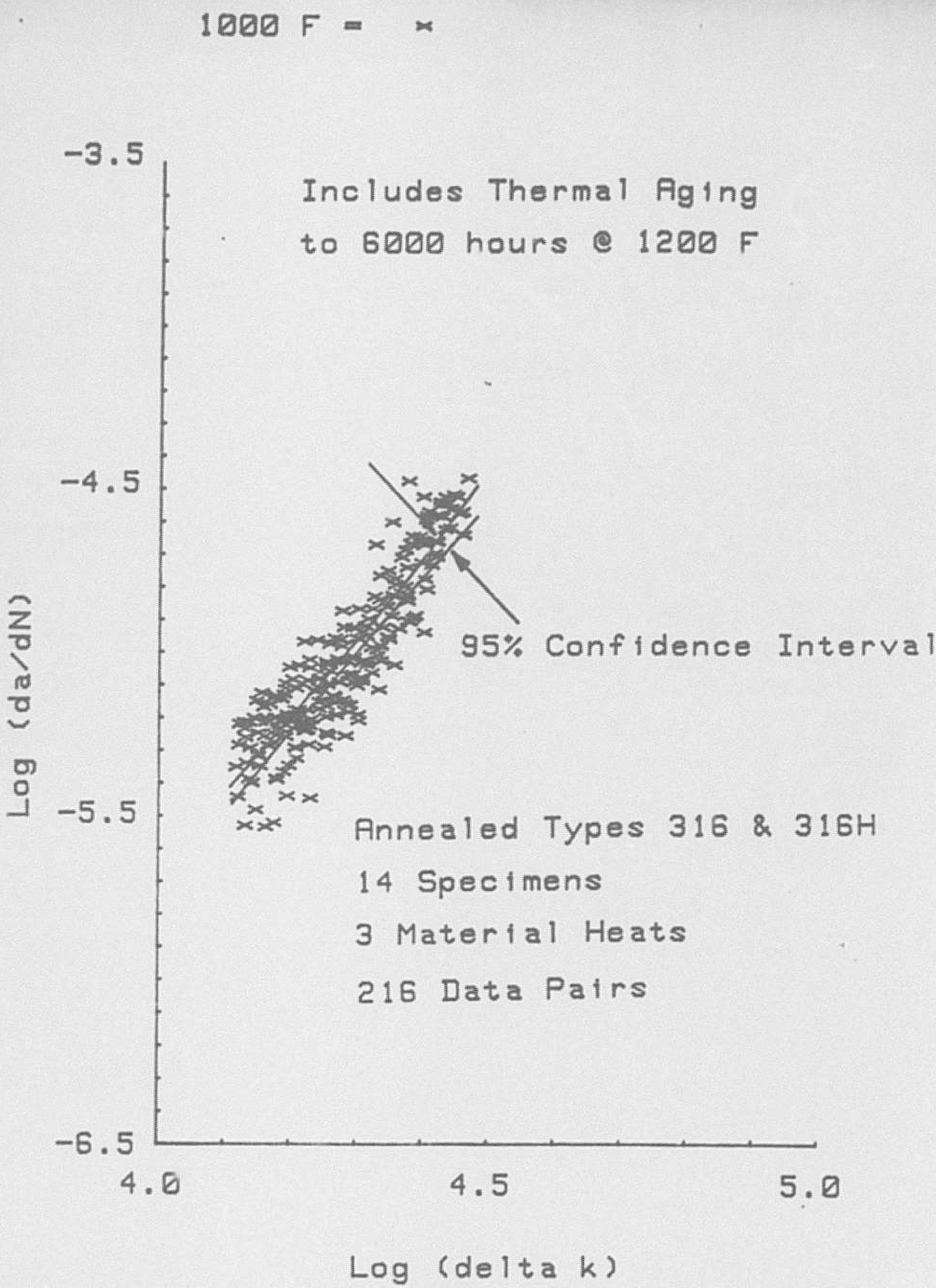

800 F = ×
Includes Thermal Aging to
5000 hours @ 1100 F plus
Irradiation to 9.0 E21
-3.5
-4.5
-5.5
-6.5
Log (da/dN)
95% Confidence Interval
Annealed Type 304
Wrought & Cast
12 Specimens
3 Material Heats
97 Data Pairs
4.0
4.5
5.0
Log (delta k)

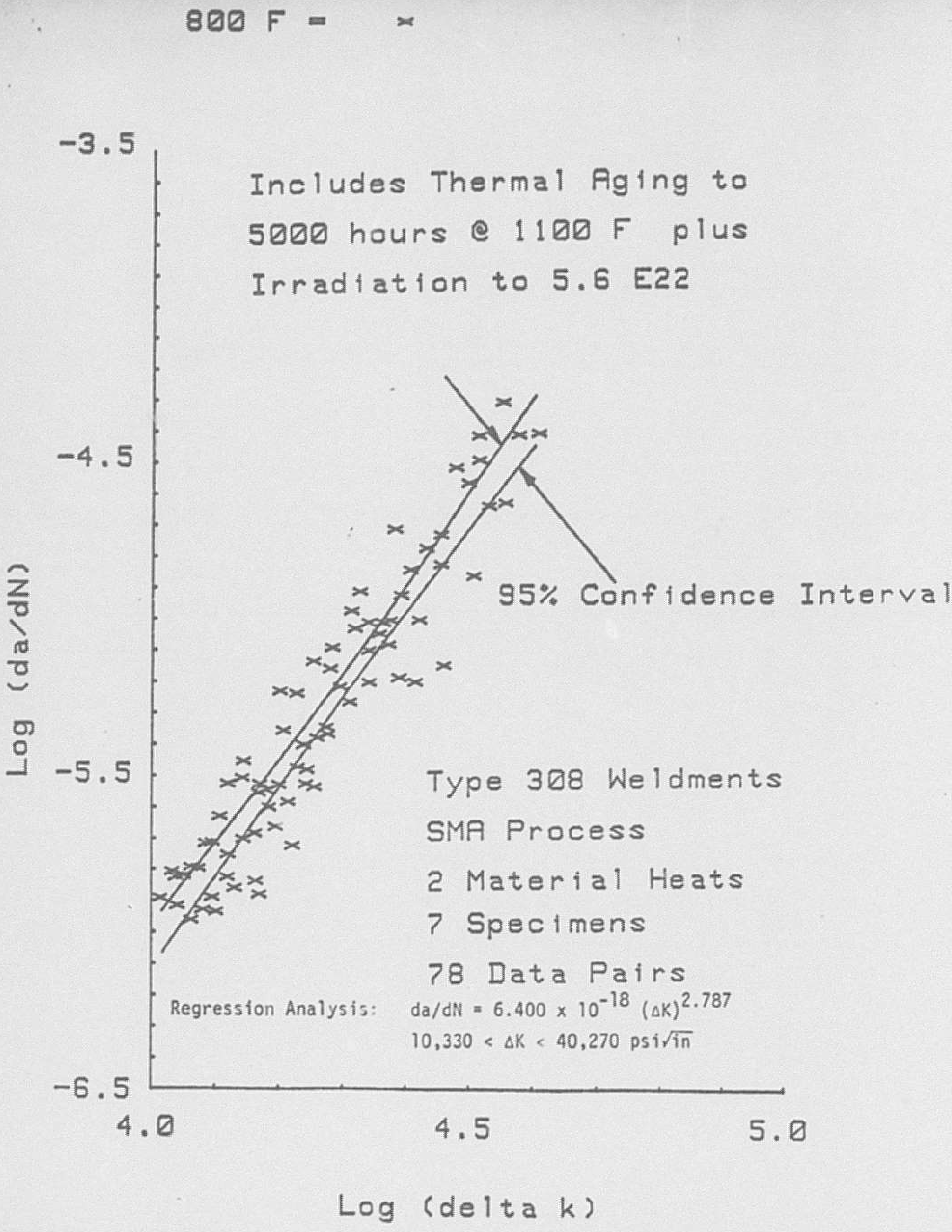

1000 F = ×
Includes Thermal Aging to
6000 hours @ 1200 F plus
Irradiation to 9.0 E21
95% Confidence Interval
Annealed Types 304 & 304L
Wrought & Cast
29 Specimens
7 Material Heats
311 Data Pairs
Regression Analysis: $da/dN = 4.647 \times 10^{-20} (\Delta K)^{3.331}$
$10{,}140 < \Delta K < 28{,}510\ psi\sqrt{in}$
-3.5
-4.5
-5.5
-6.5
Log (da/dN)
4.0
4.5
5.0
Log (delta k)



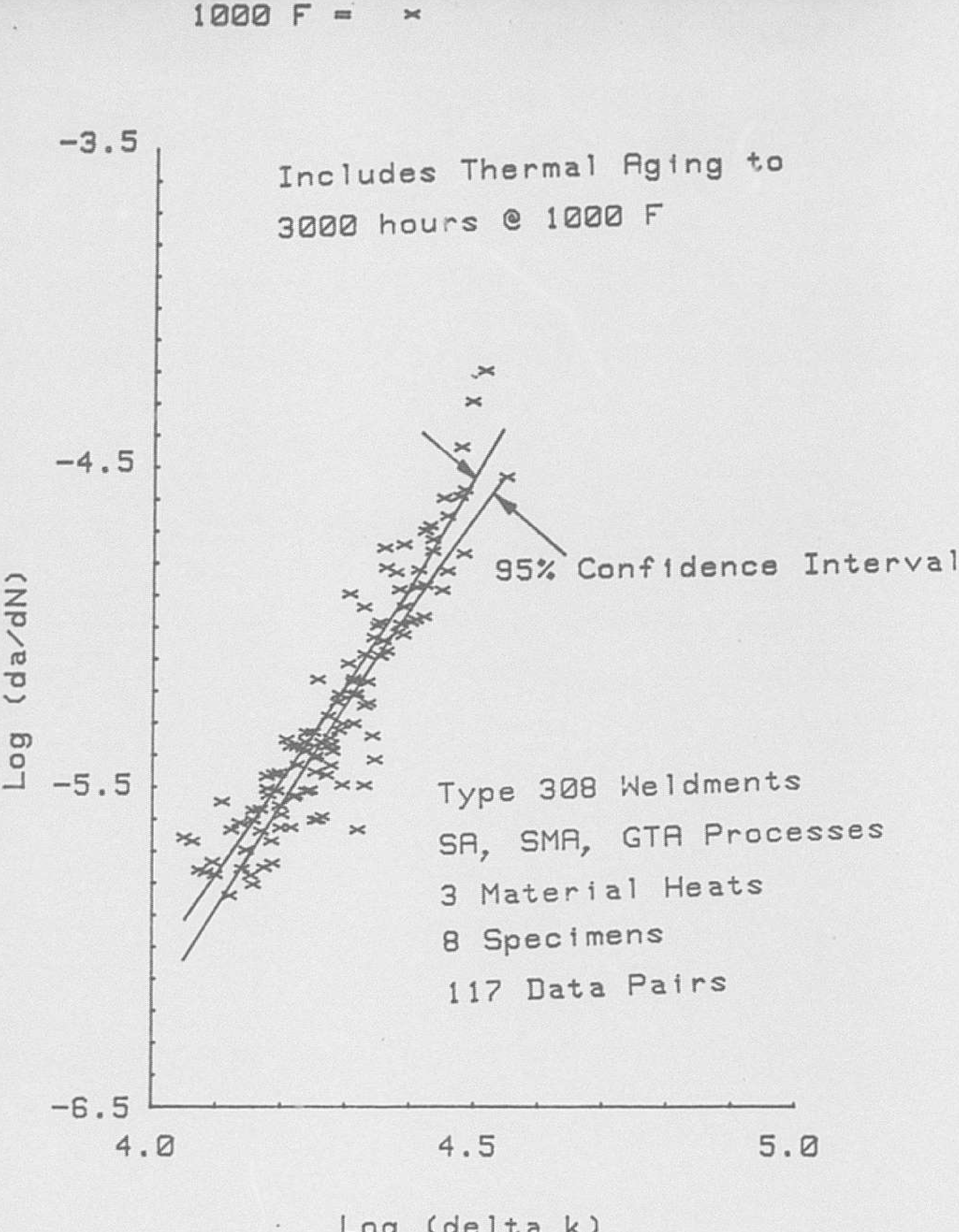
800 F = ×
Includes Thermal Aging
to 5000 hours @ 1100 F
-3.5
-4.5
-5.5
-6.5
Log (da/dN)
95% Confidence Interval
Annealed Type 316
4 Specimens
3 Material Heats
50 Data Pairs
4.0
4.5
5.0
Log (delta k)

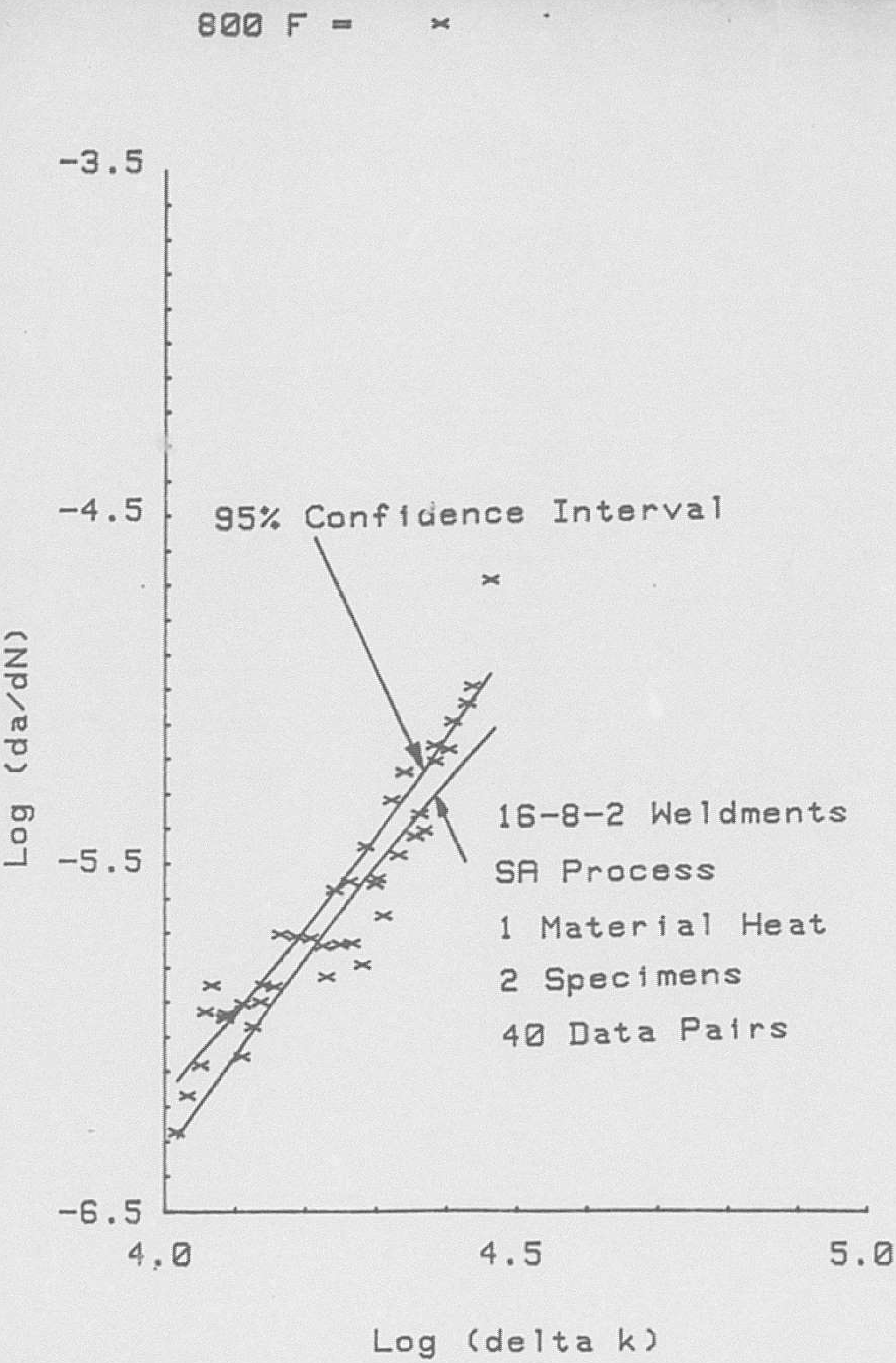
8 4 1 0 5 / 7 1 0 5 0

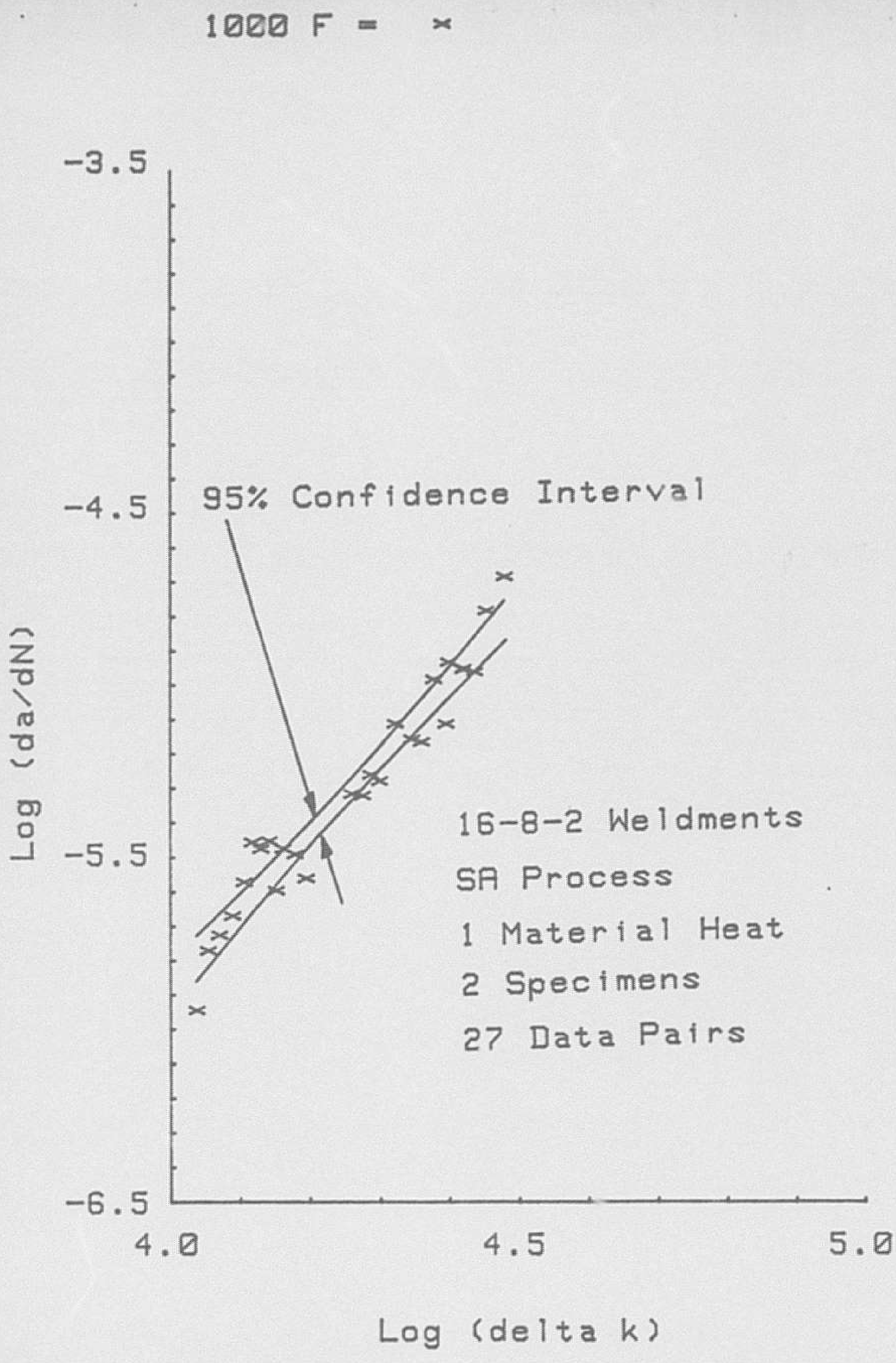

1000 F = ×
-3.5
-4.5
-5.5
-6.5
Log (da/dN)
Includes Thermal Aging
to 6000 hours @ 1200 F
95% Confidence Interval
Annealed Types 316 & 316H
14 Specimens
3 Material Heats
216 Data Pairs
4.0
4.5
5.0
Log (delta k)

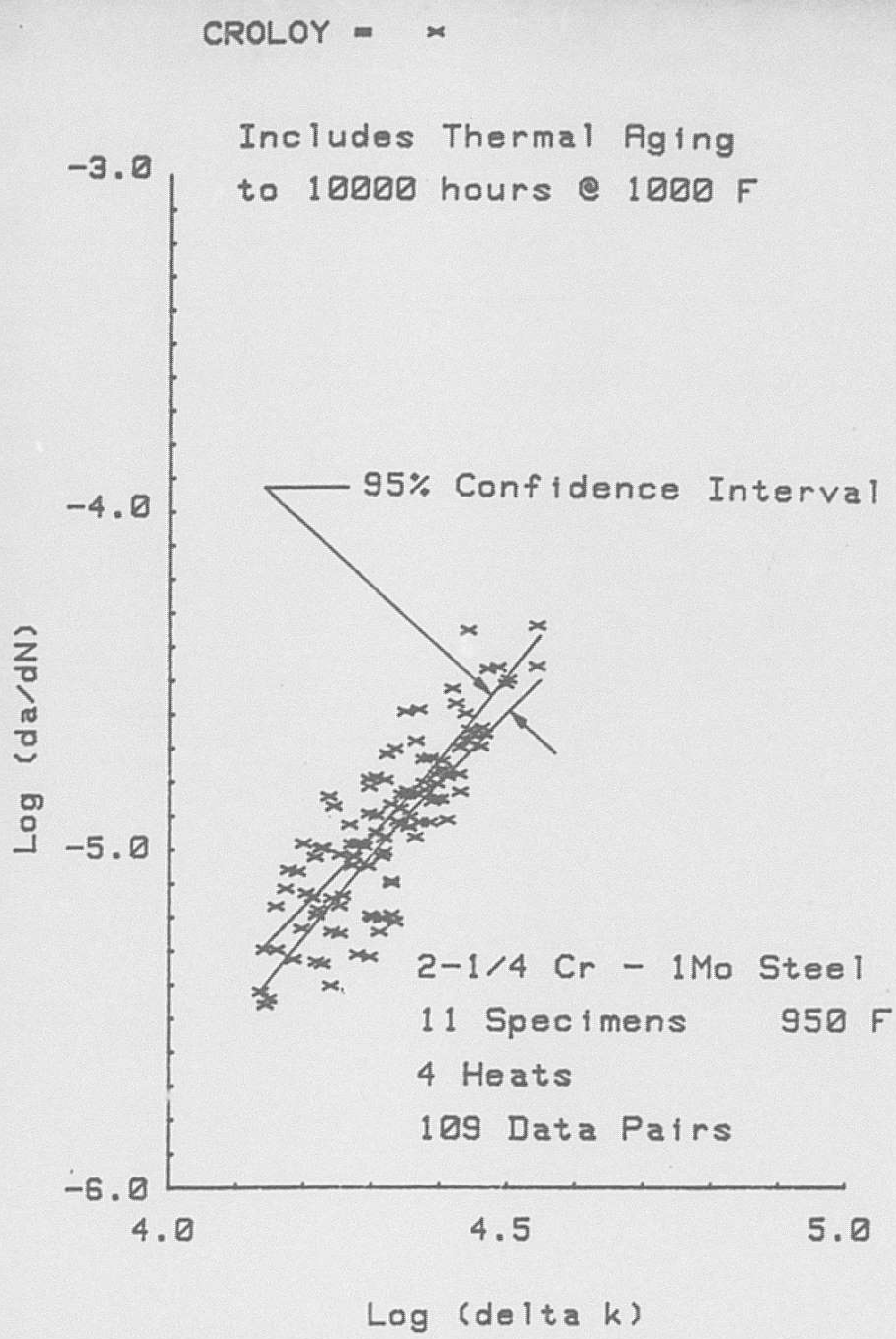

800 F = ×
Includes Thermal Aging to
5000 hours @ 1100 F plus
Irradiation to 5.6 E22
95% Confidence Interval
Type 308 Weldments
SMA Process
2 Material Heats
7 Specimens
78 Data Pairs
Regression Analysis: da/dN = 6.400 x 10^-18 (ΔK)^2.787
10,330 < ΔK < 40,270 psi√in
-3.5
-4.5
-5.5
-6.5
4.0
4.5
5.0
Log (da/dN)
Log (delta k)

3 4 1 0 5 / 7 1 6 5 2

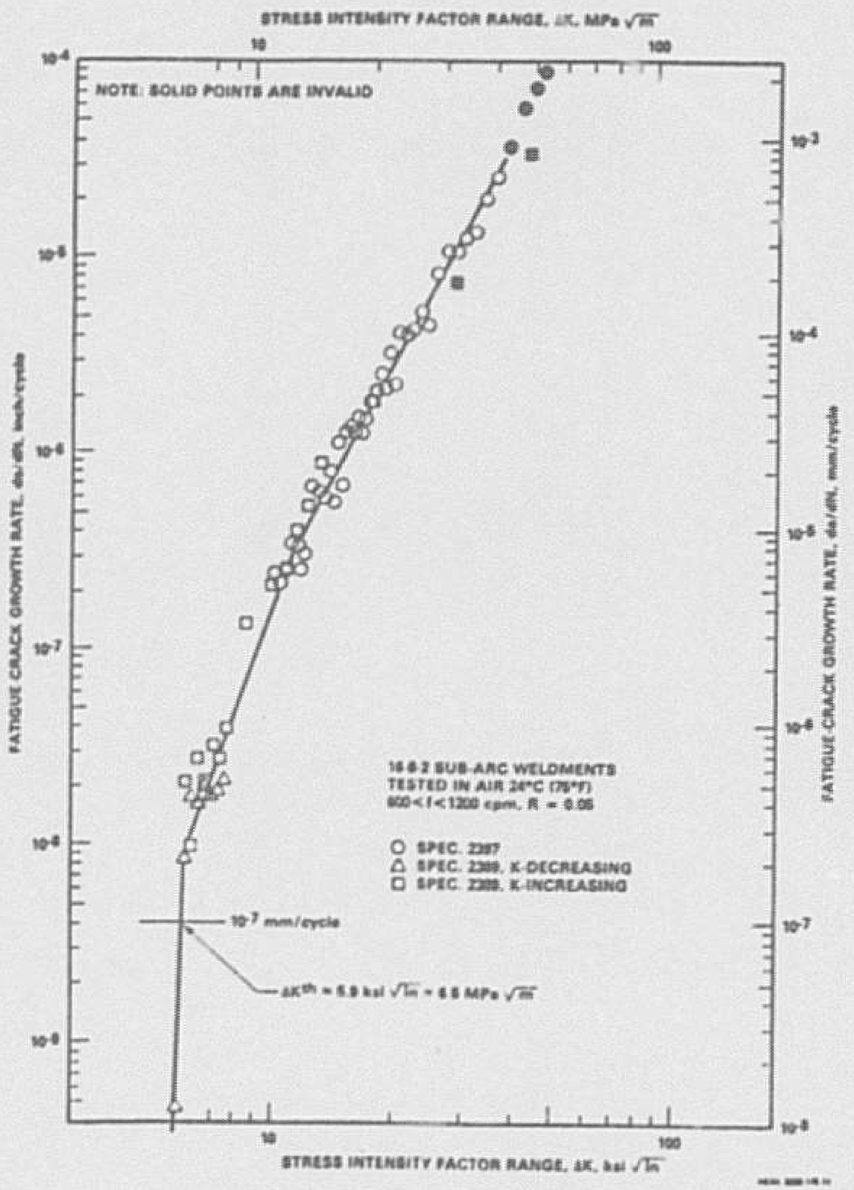

1000 F = ×
Includes Thermal Aging to
3000 hours @ 1000 F
95% Confidence Interval
Type 308 Weldments
SA, SMA, GTA Processes
3 Material Heats
8 Specimens
117 Data Pairs
Log (da/dN)
-3.5
-4.5
-5.5
-6.5
4.0
4.5
5.0
Log (delta k)

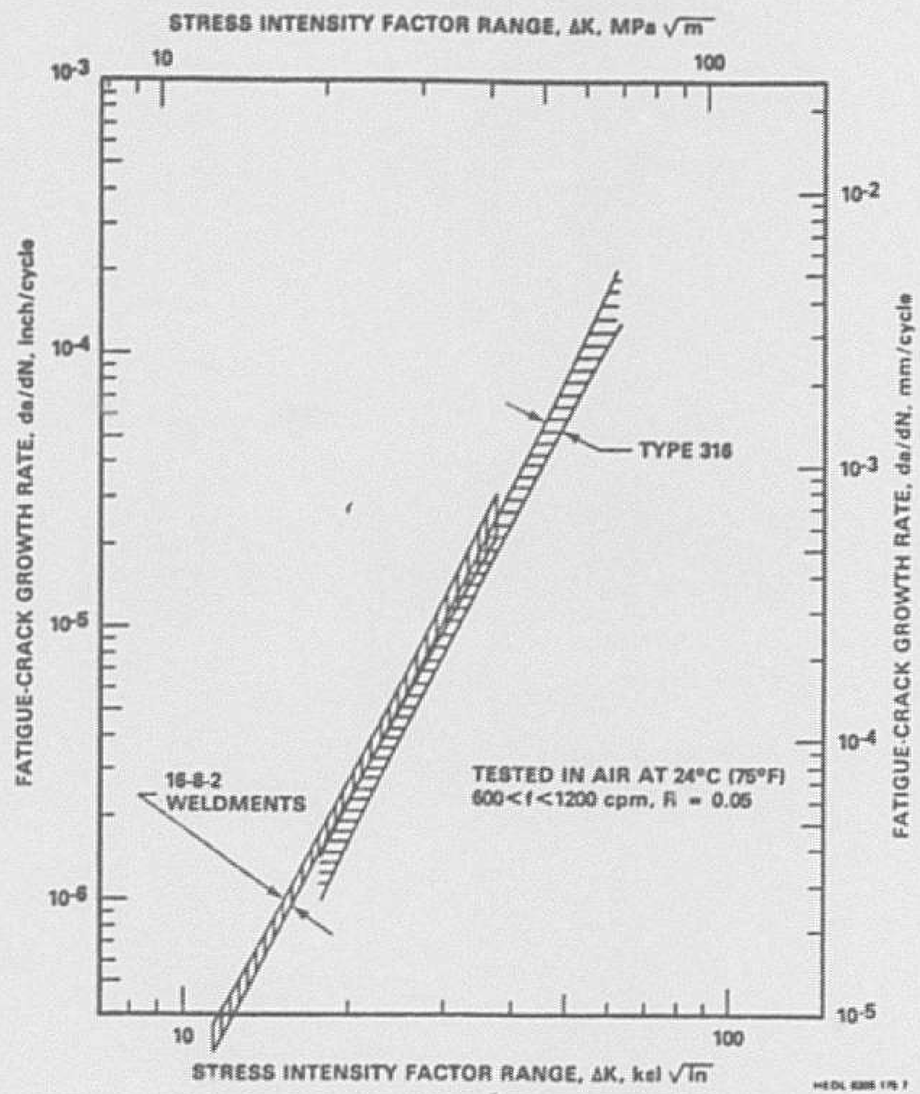

800 F = ×
-3.5
-4.5
-5.5
-6.5
4.0
4.5
5.0
Log (da/dN)
Log (delta k)
95% Confidence Interval
16-8-2 Weldments
SA Process
1 Material Heat
2 Specimens
40 Data Pairs


1000 F = ×
95% Confidence Interval
16-8-2 Weldments
SA Process
1 Material Heat
2 Specimens
27 Data Pairs
-3.5
-4.5
-5.5
-6.5
4.0
4.5
5.0
Log (da/dN)
Log (delta k)


CROLOY = ×
Includes Thermal Aging
to 10000 hours @ 1000 F
95% Confidence Interval
2-1/4 Cr - 1Mo Steel
11 Specimens 950 F
4 Heats
109 Data Pairs
-3.0
-4.0
-5.0
-6.0
4.0
4.5
5.0
Log (da/dN)
Log (delta k)

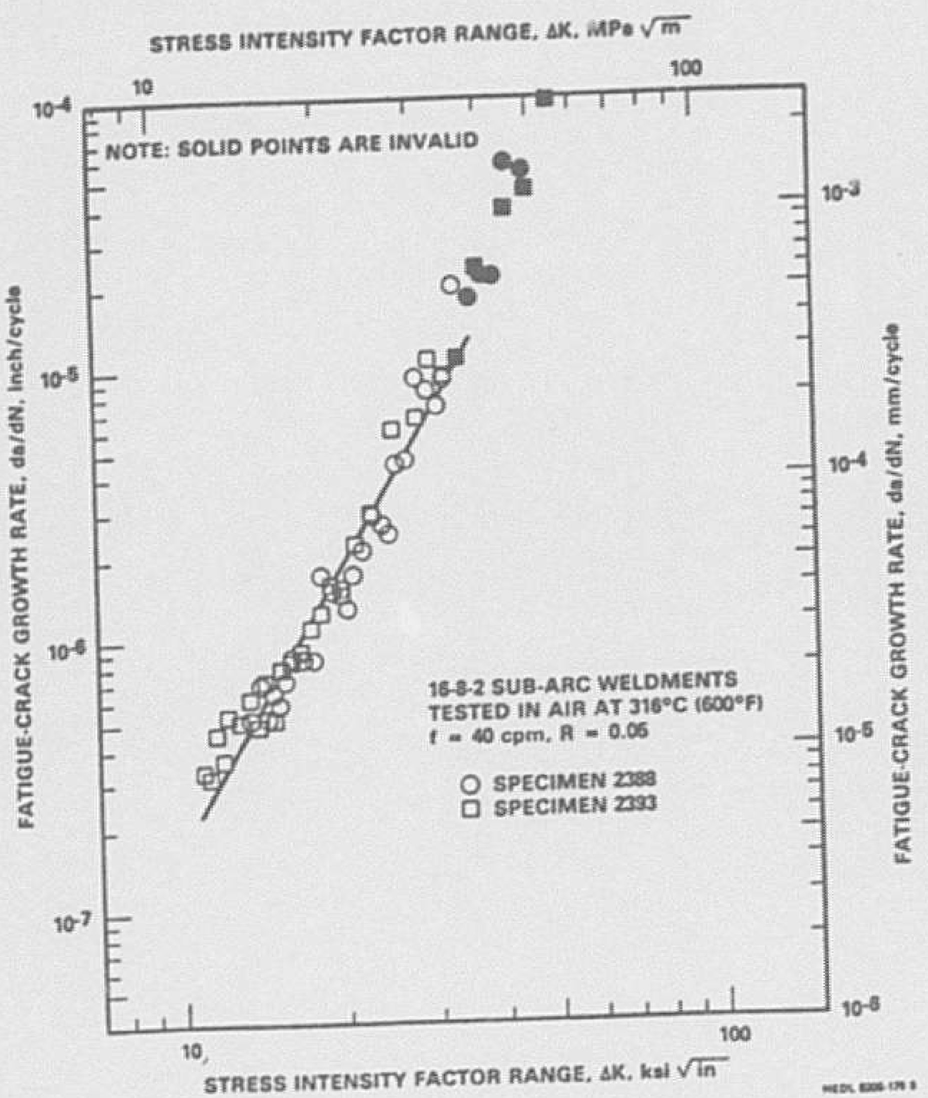
CRACK GROWTH IN 16-8-2 WELDMENTS AT 75 F
(REF. HEDL-TME 82-14)

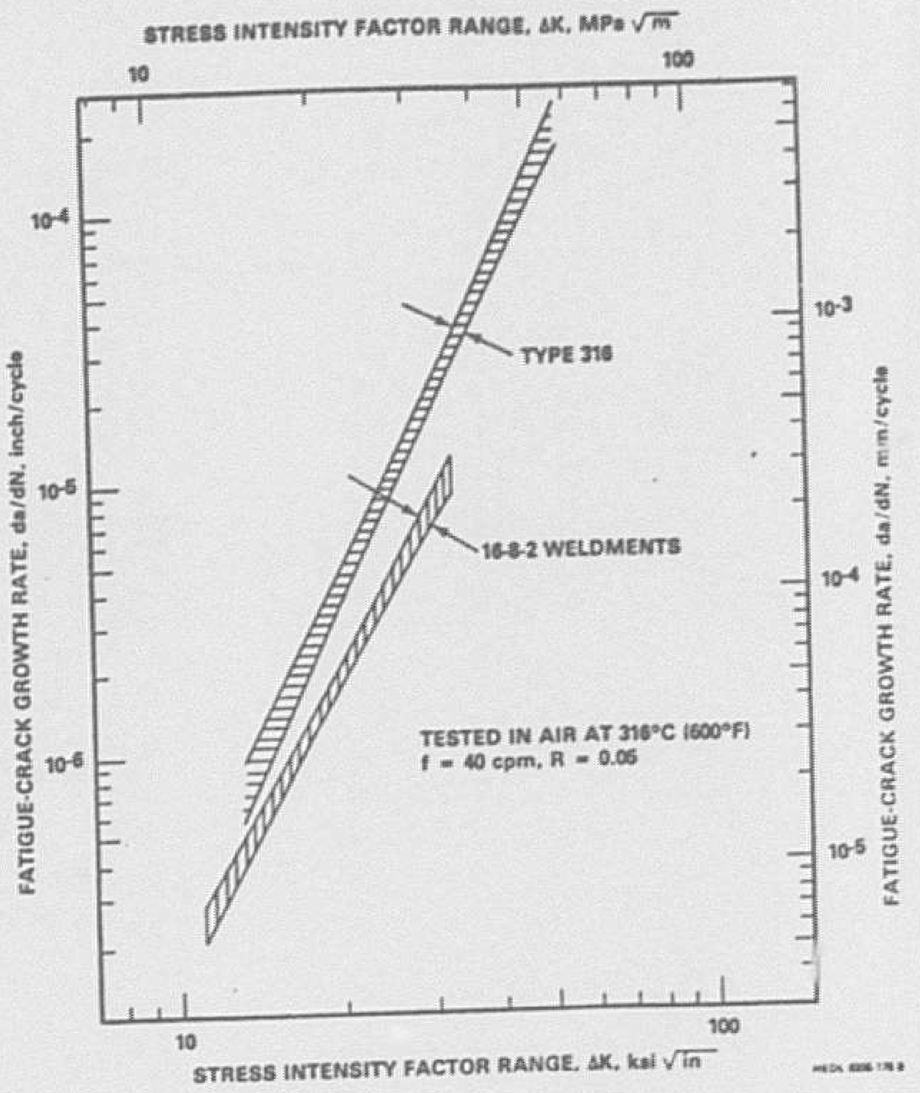




95% CONFIDENCE INTERVALS

CRACK GROWTH IN 16-8-2 WELDMENTS AT 600 F
(REF. HEDL-TME 82-14)

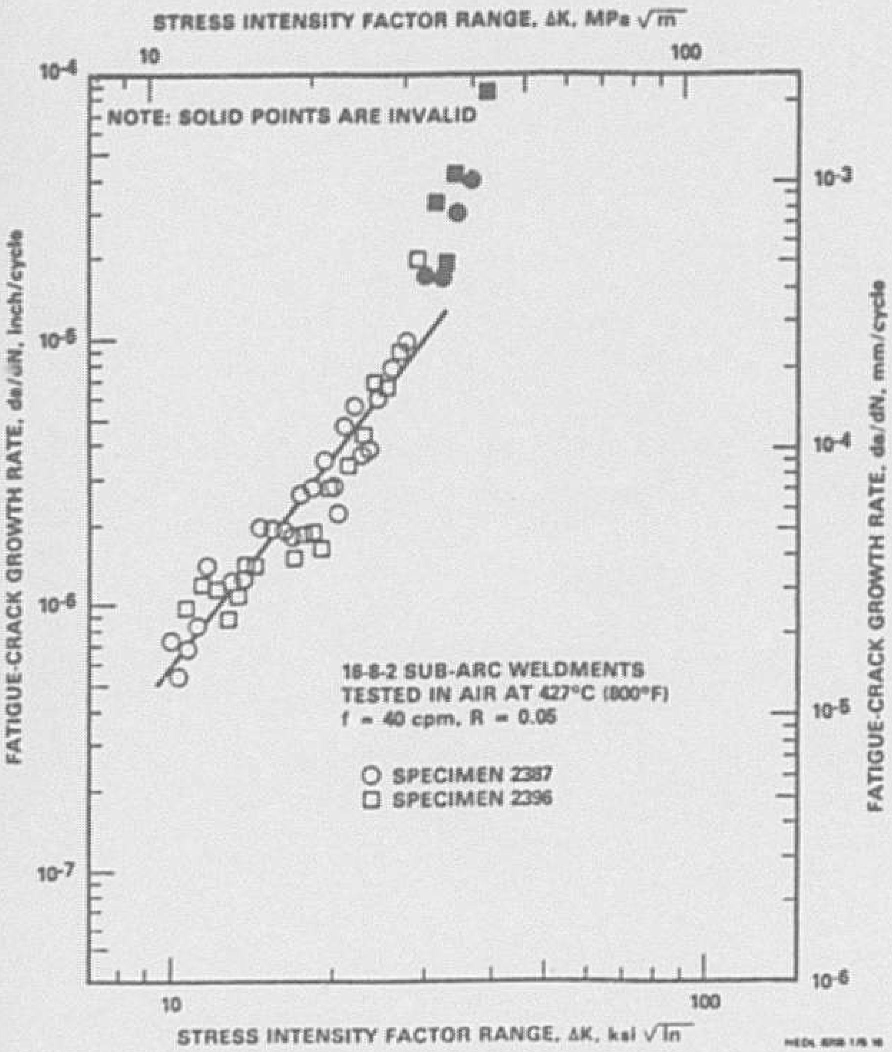


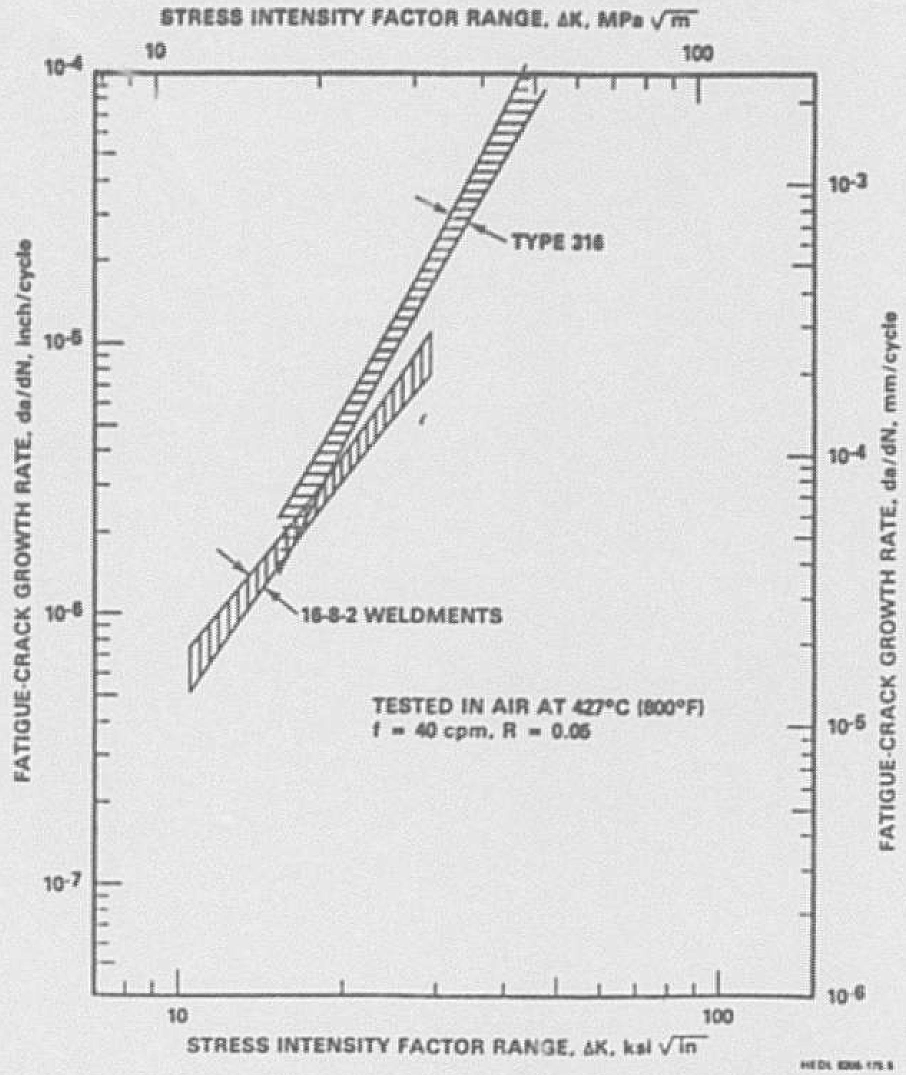


95% CONFIDENCE INTERVALS

3 4 1 0 5 / 7 1 8 5 3

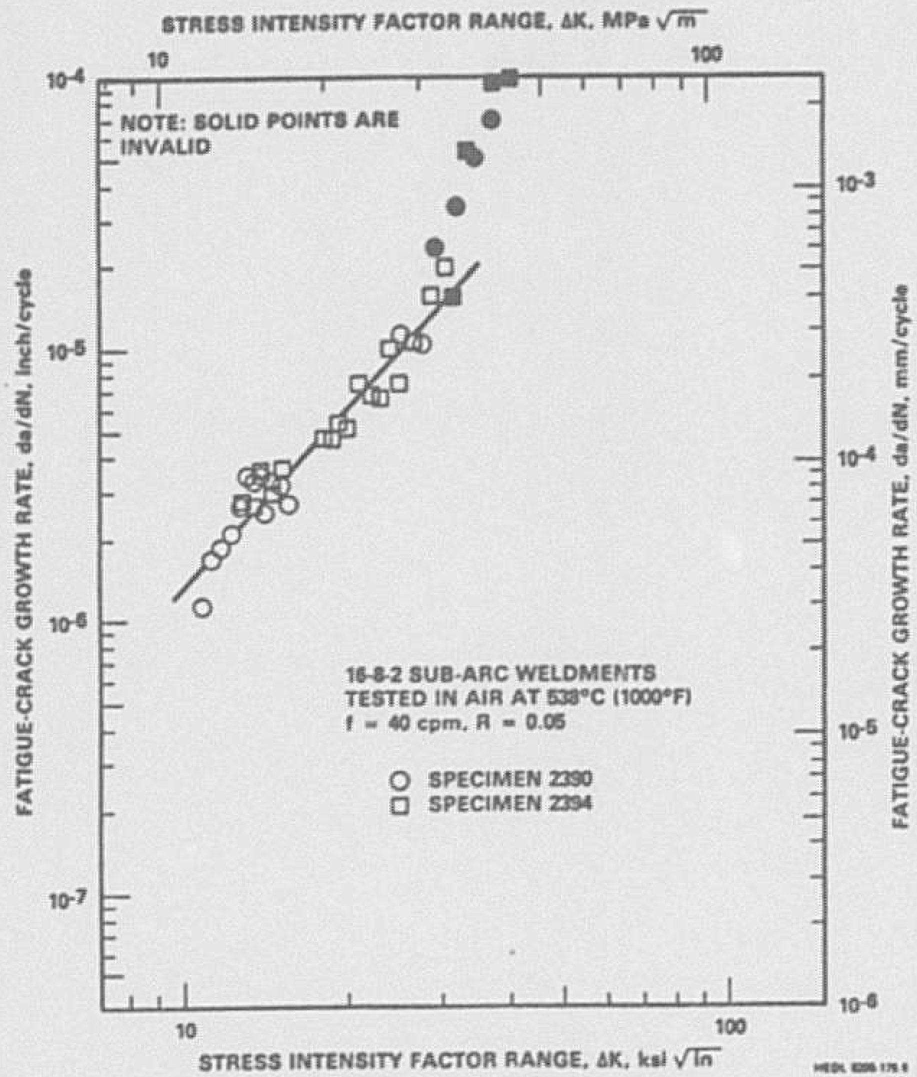
CRACK GROWTH IN 16-8-2 WELDMENTS AT 800 F
(REF. HEDL-TME 82-14)

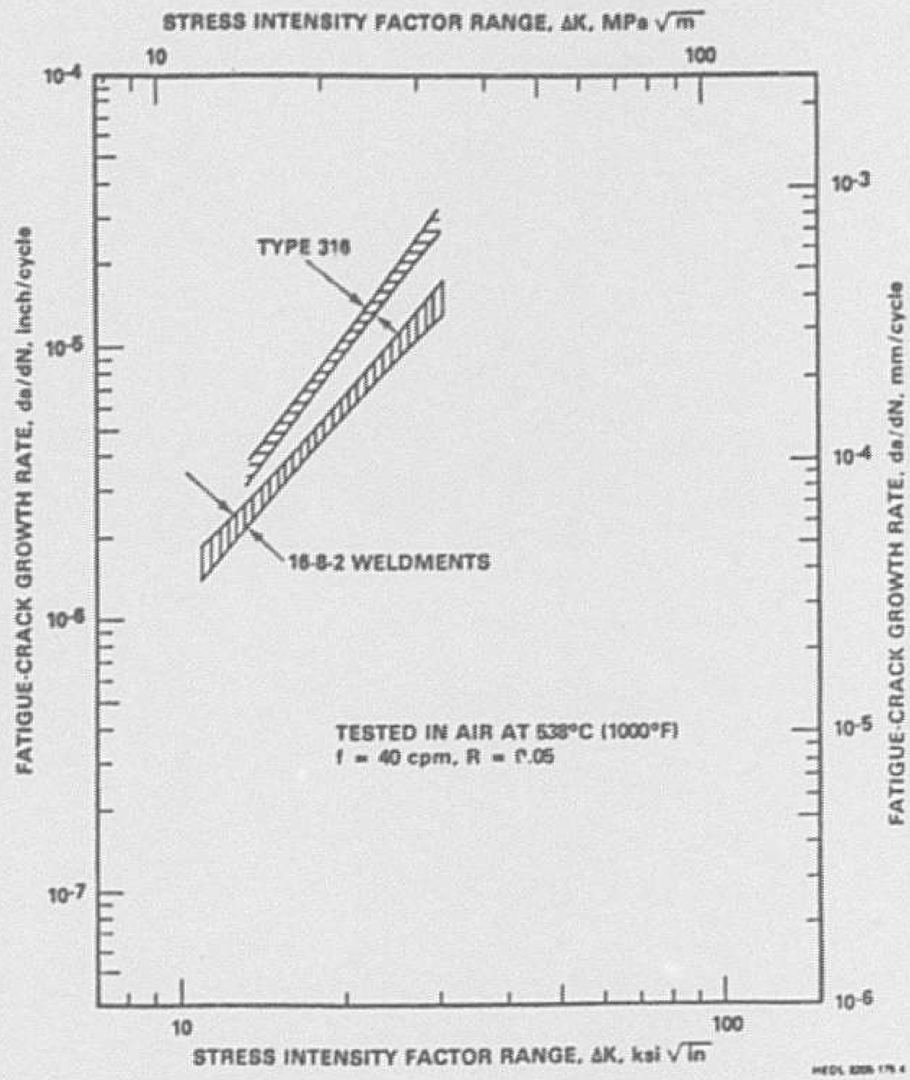




95% CONFIDENCE INTERVALS

CRACK GROWTH IN 16-8-2 WELDMENTS AT 1000 F
(REF. HEDL-TME 82-14)

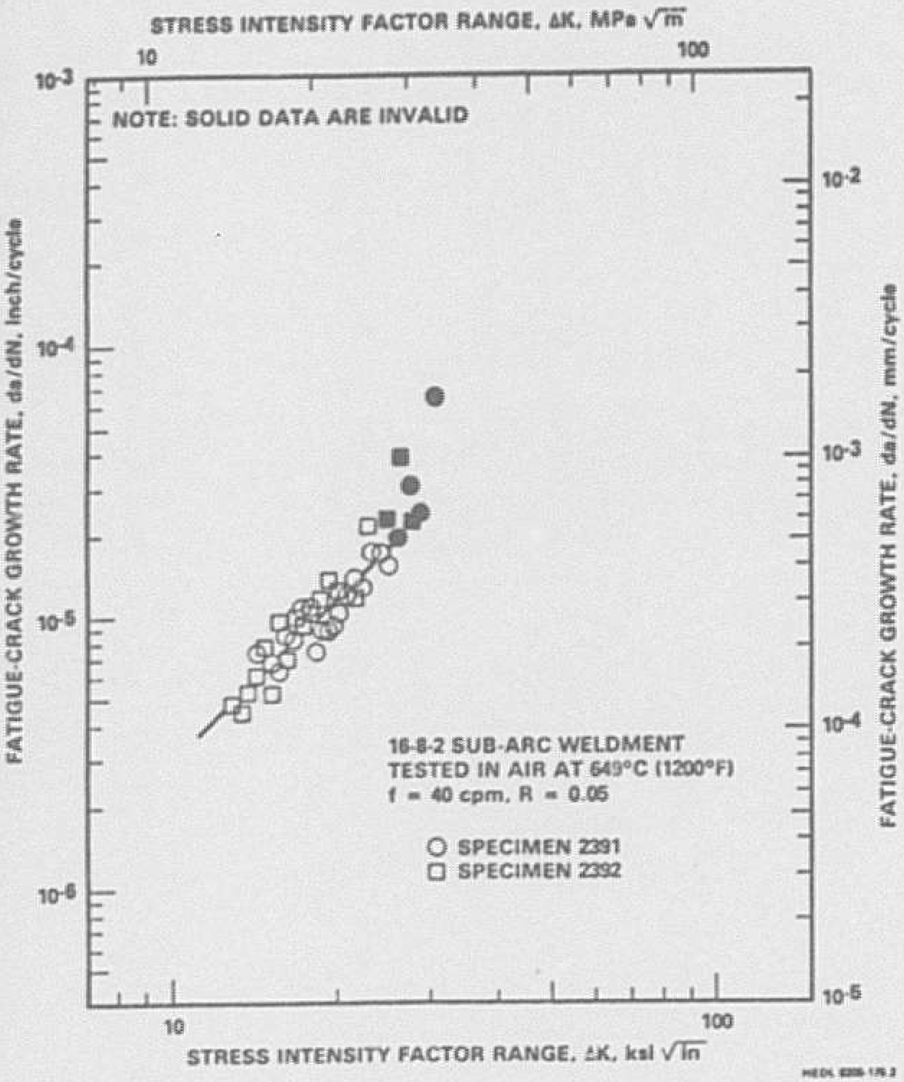


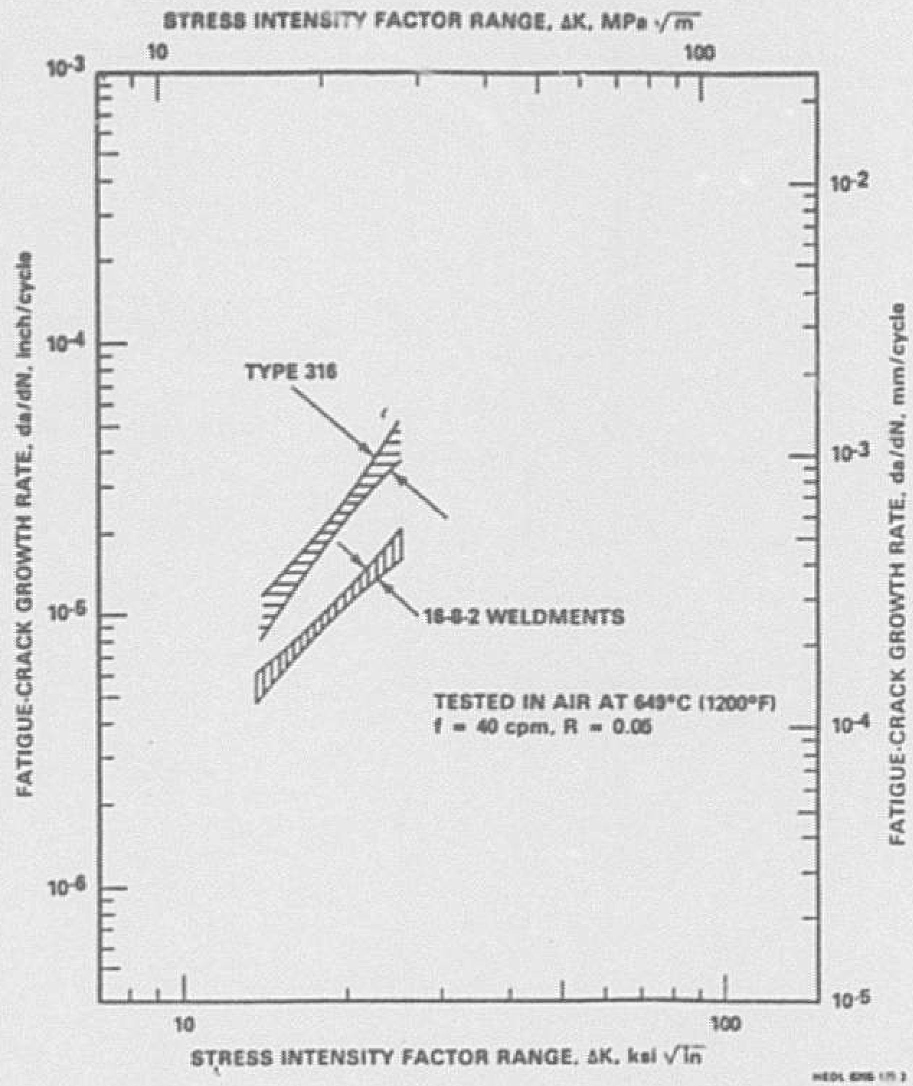


95% CONFIDENCE INTERVALS

3 4 1 0 5 7 7 1 0 6 0

CRACK GROWTH IN 16-8-2 WELDMENTS AT 1200 F
(REF. HEDL-TME 82-14)





95% CONFIDENCE INTERVALS

TIME-DEPENDENT EFFECTS ON CRACK PROPAGATION IN AUSTENITIC STAINLESS STEELS

SEVERAL STUDIES HAVE ADDRESSED TIME-DEPENDENT EFFECTS ON THE FATIGUE-CRACK PROPAGATION BEHAVIOR OF AUSTENITIC STAINLESS STEELS. THE FINDINGS MAY BE SUMMARIZED AS FOLLOWS:

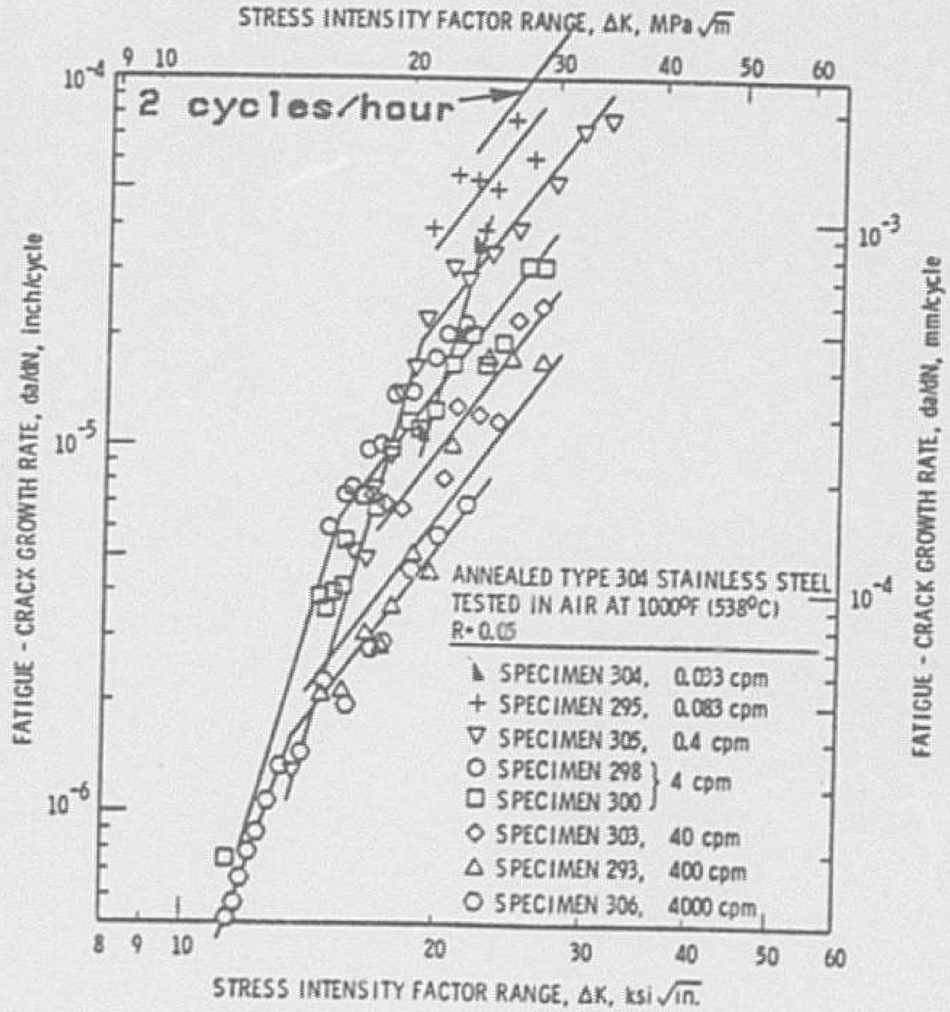
- IN ELEVATED TEMPERATURE AIR ENVIRONMENTS, CRACK GROWTH RATES GENERALLY INCREASE WITH DECREASING CYCLIC FREQUENCIES

- TIME-DEPENDENT EFFECTS ARE GREATLY REDUCED (OR ELIMINATED ALTOGETHER) IN INERT ENVIRONMENTS (E.G. LIQUID SODIUM, VACUUM, ARGON)

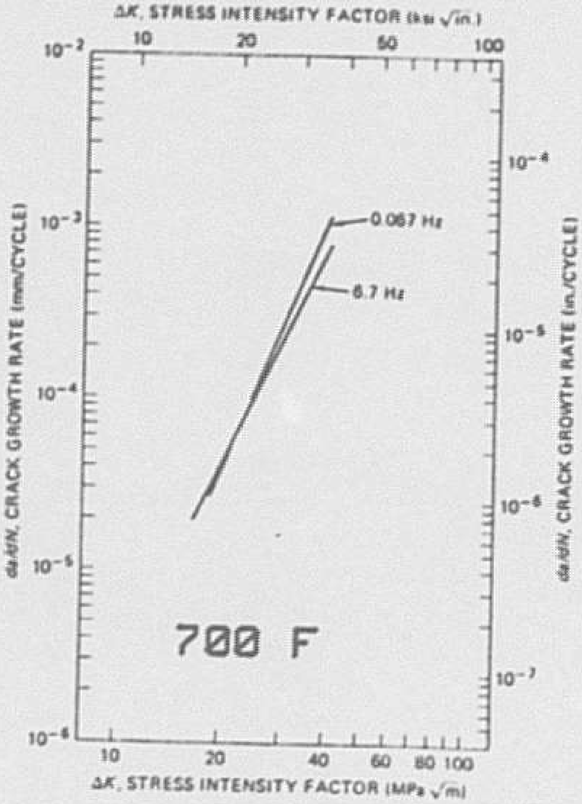
- LOADING WAVEFORM (E.G. HOLD-TIME) PLAYS NO SIGNIFICANT ROLE IN INFLUENCING CRACK GROWTH BEHAVIOR BEYOND THAT PRODUCED BY THE CYCLIC FREQUENCY EFFECT

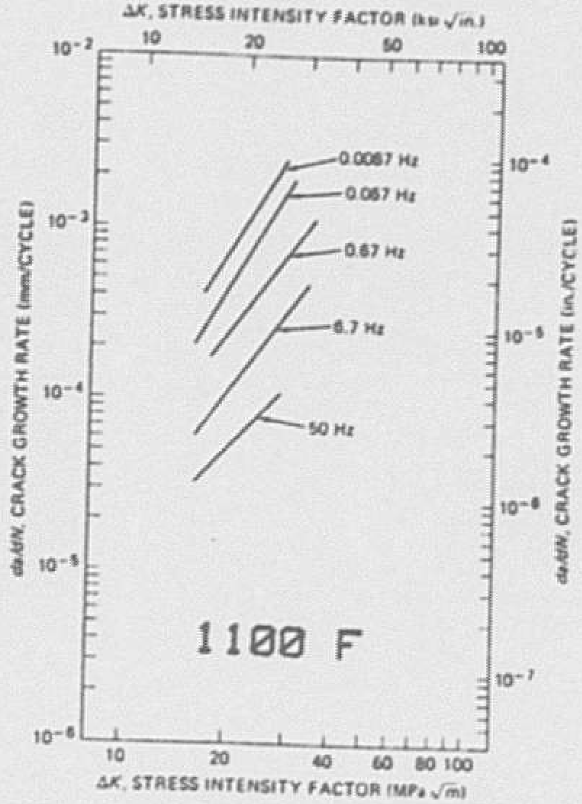
- A FREQUENCY CORRECTION FACTOR (IN POLYNOMINAL FORM) CAN BE USED TO ESTIMATE TIME-DEPENDENT EFFECTS AT ELEVATED TEMPERATURES. POLYNOMINAL IS BASED ON EXPERIMENTAL DATA OVER A FACTOR OF 120,000 ON FREQUENCY AT 1000°F

TIME-DEPENDENT EFFECTS ON THE FATIGUE-CRACK GROWTH BEHAVIOR OF TYPE 304 S.S. IN AIR AT 1000 F



TIME-DEPENDENT FATIGUE-CRACK GROWTH BEHAVIOR OF 2 1/4Cr - 1Mo STEEL IN AIR

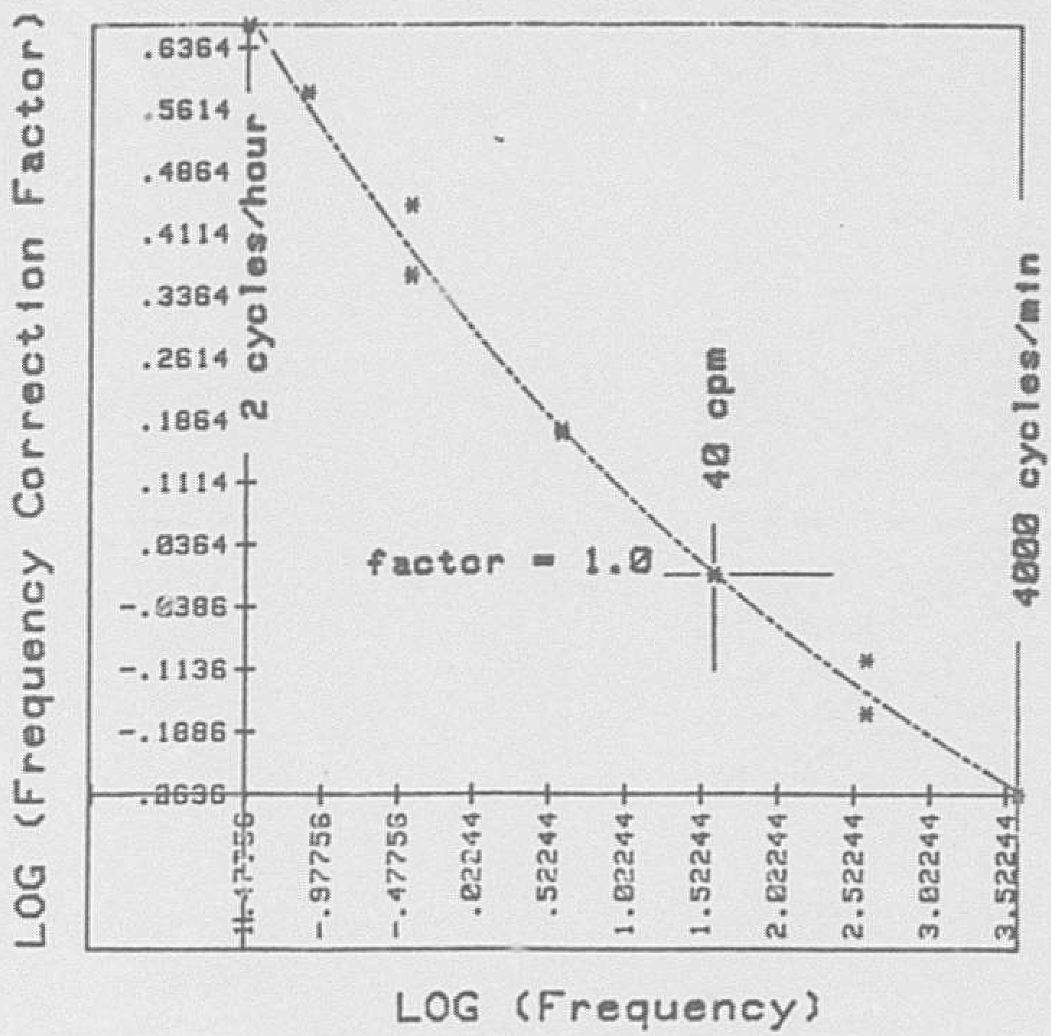




$$DA/DN = A_0 \left[K_{MAX} (1-R)^{0.5} \right]^{3.5}$$

$$A_0 = -10.106 + 1.359 \times 10^{-5} (T)^2$$
$$-1.432 \times 10^{-8} (T)^3 - 1.7 \times 10^{-9} (T)^3 (\text{LOG } F)$$

TIME-DEPENDENT EFFECTS ON THE FATIGUE-CRACK GROWTH BEHAVIOR OF TYPE 304 S.S. IN AIR AT 1000 F



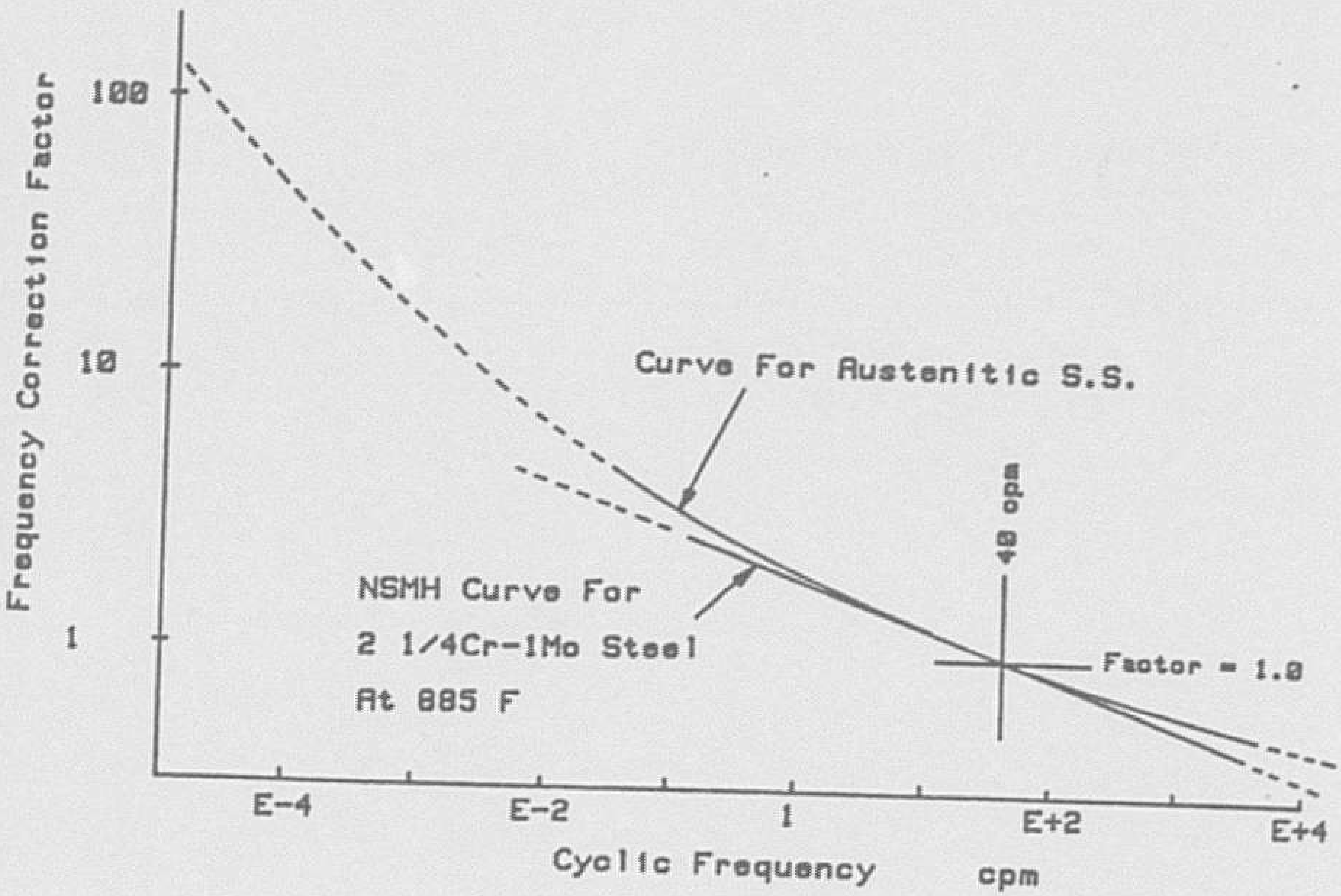
Y = 0.299077 - 0.21897(X)

+ 0.0227776(X)^2 - 0.00139477(X)^3

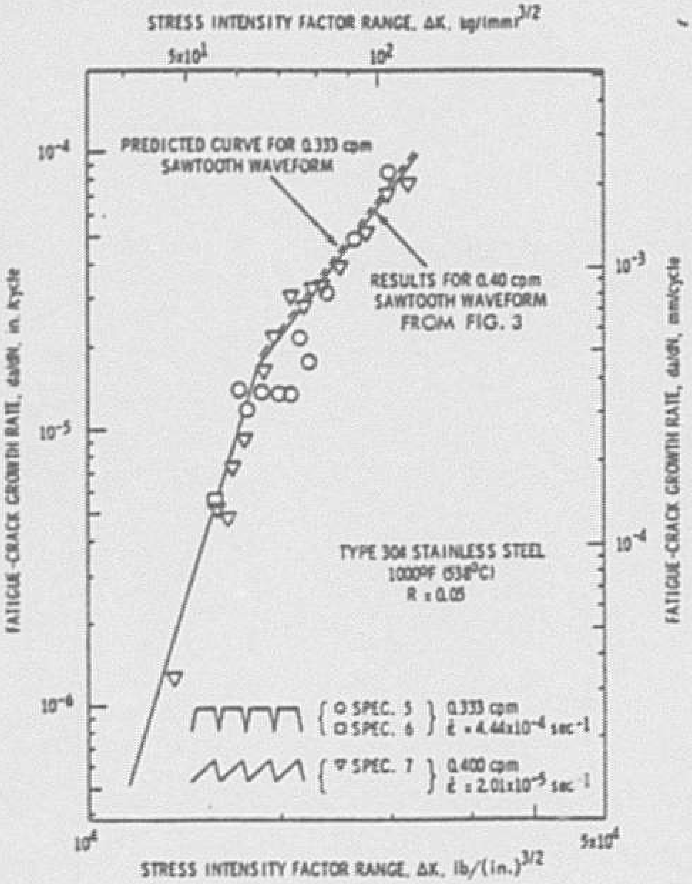
WHERE X = Log(Frequency) in cpm

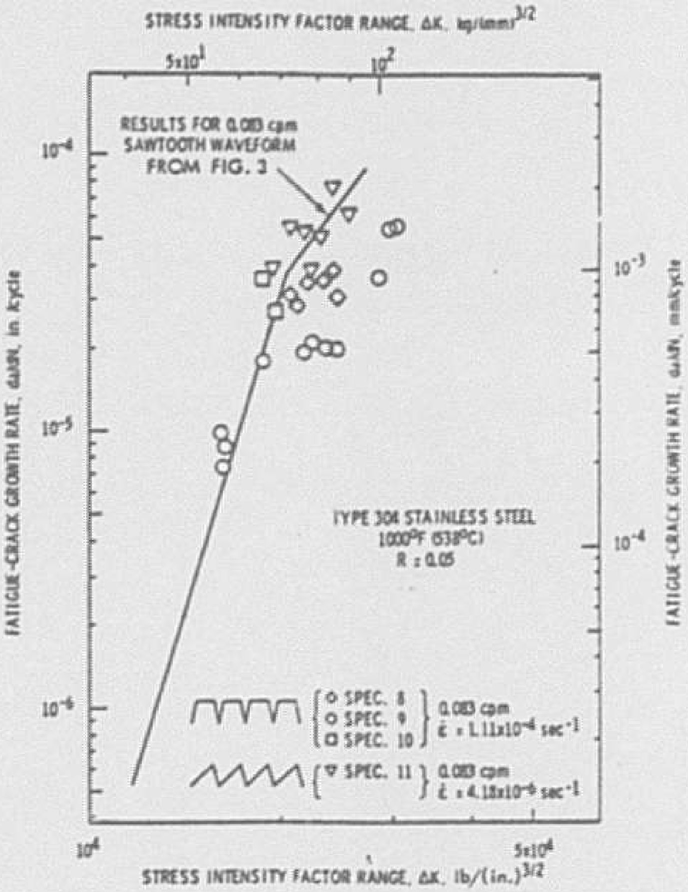
Y = Log(Frequency Correction Factor)

FREQUENCY CORRECTION FACTORS FOR AUSTENITIC & FERRITIC STEELS



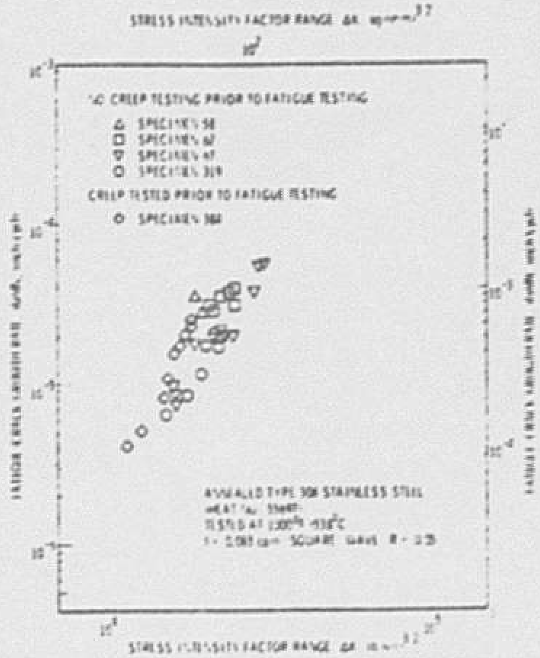
TIME-DEPENDENT EFFECTS ON THE FATIGUE-CRACK GROWTH BEHAVIOR OF TYPE 304 S.S. IN AIR AT 1000 F



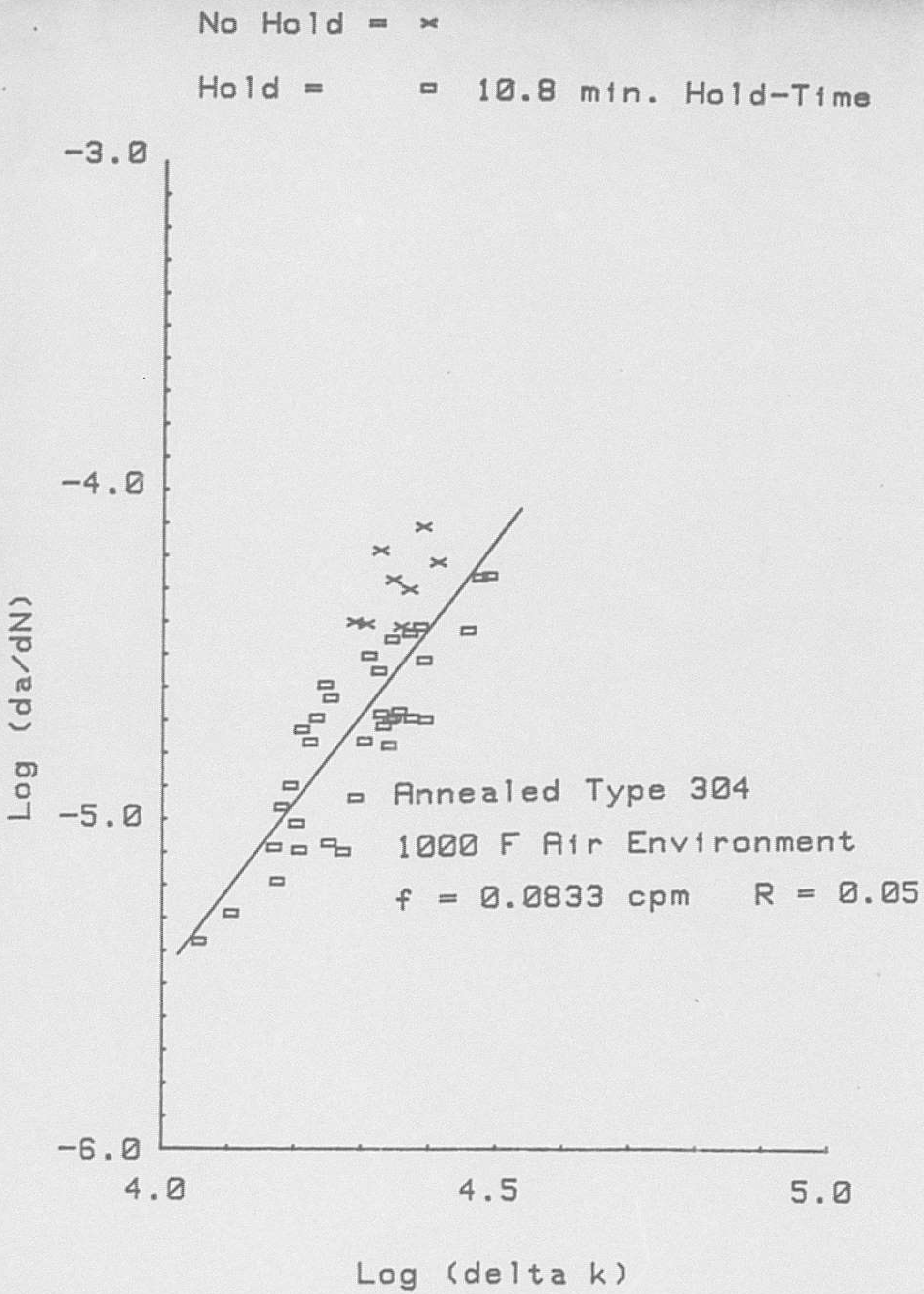


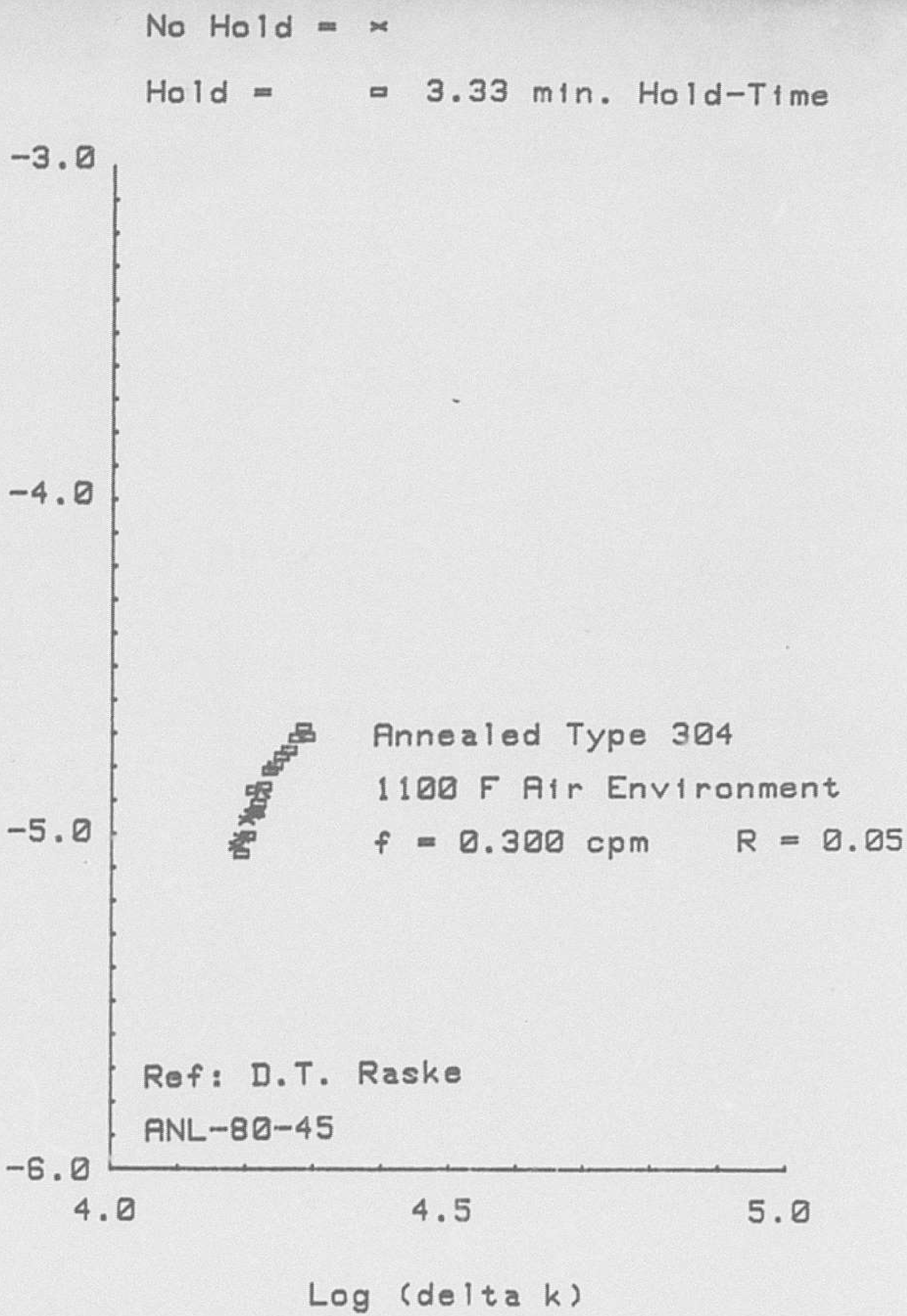
No deleterious effect of tensile hold-time upon the fatigue-crack growth behavior at 1000 F in air.

TIME-DEPENDENT EFFECTS ON THE FATIGUE-CRACK GROWTH BEHAVIOIR OF TYPE 304 S.S. IN AIR AT 1000 F



Significant creep damage introduced prior to fatigue testing resulted in no effect upon crack growth behavior under tensile hold-time conditions.

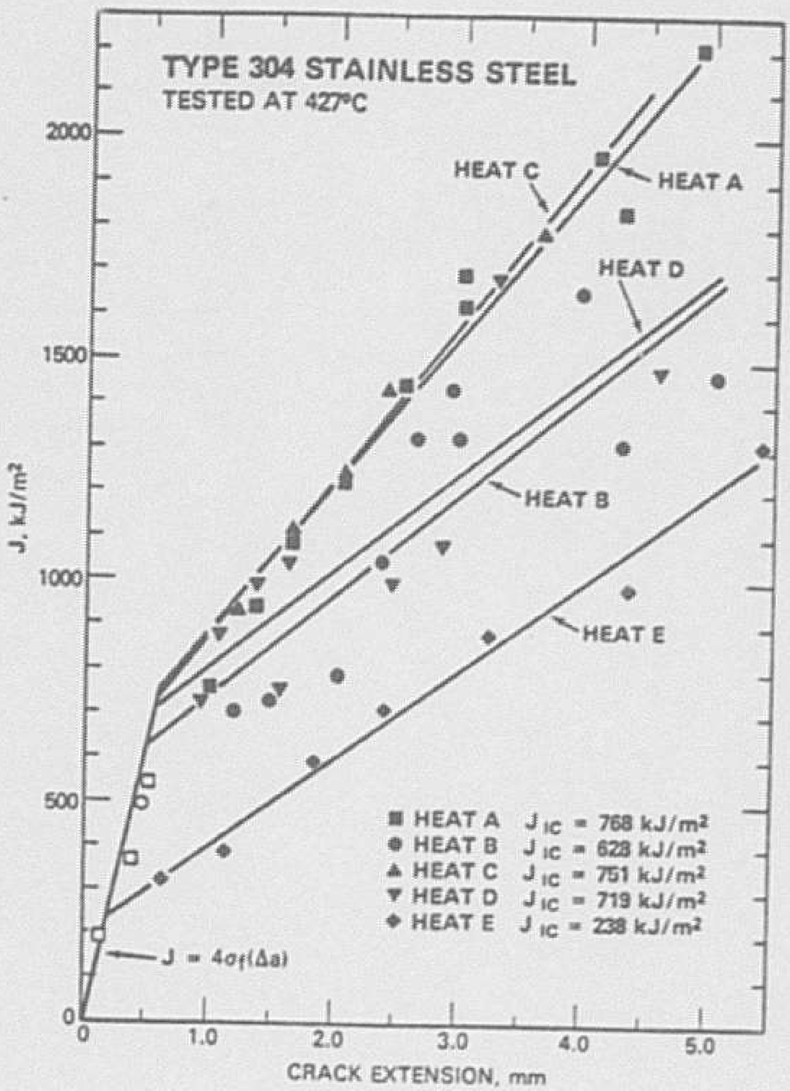

No Hold = ×
Hold = ▭ 10.8 min. Hold-Time
-3.0
-4.0
-5.0
-6.0
Log (da/dN)
4.0
4.5
5.0
Log (delta k)
Annealed Type 304
1000 F Air Environment
f = 0.0833 cpm R = 0.05


No Hold = ×
Hold = ▫ 3.33 min. Hold-Time
-3.0
-4.0
-5.0
-6.0
4.0
4.5
5.0
Log (da/dN)
Log (delta k)
Annealed Type 304
1100 F Air Environment
f = 0.300 cpm R = 0.05
Ref: D.T. Raske
ANL-80-45

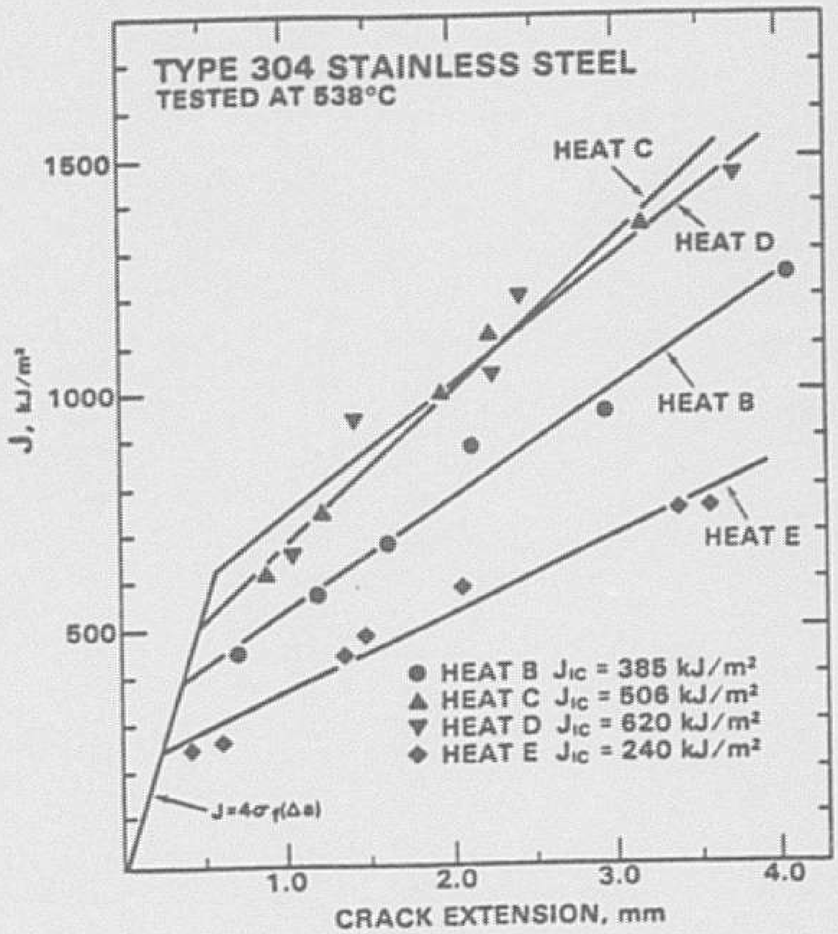
FRACTURE TOUGHNESS OF AUSTENITIC STAINLESS STEELS AND WELDS

- LARGE WELL-CHARACTERIZED DATA BASE INCORPORATING SEVERAL MATERIAL HEATS AND WELD TYPES.
- ONLY "VALID DATA" EMPLOYED. TOUGHNESS VALUES AND TEARING MODULI DEVELOPED ARE IN PROCESS OF CONSIDERATION FOR NSMH SECTION.
- HEAT-TO-HEAT VARIATIONS IN TOUGHNESS OBSERVED IN AUSTENITIC STEELS. THESE VARIATIONS CAN BE RELATED TO MICROSTRUCTURE. VARIATIONS ARE ALSO NOTED IN AUSTENITIC STAINLESS STEEL WELDMENTS AND CAN BE RELATED TO WELDING PROCESSES.
- FRACTURE TOUGHNESS OF AUSTENITIC STEELS AND WELDMENTS ARE GENERALLY SO HIGH THAT SEMI-EMPIRICAL FAILURE CRITERIA (E.G., PARIS PLASTIC-INSTABILITY MODEL, HAHN MODEL, ETC.) ARE USED INSTEAD OF FRACTURE MECHANICS-BASED CRITERIA.
- THERMAL AGING CAN DECREASE INITIATION TOUGHNESS SOMEWHAT, BUT TEARING MODULI IN AGED MATERIALS REMAIN RELATIVELY UNCHANGED. TOUGHNESS IN AGED AUSTENITIC STEELS REMAINS SUFFICIENTLY HIGH THAT SEMI-EMPIRICAL FAILURE CRITERIA ARE THE MOST APPROPRIATE.

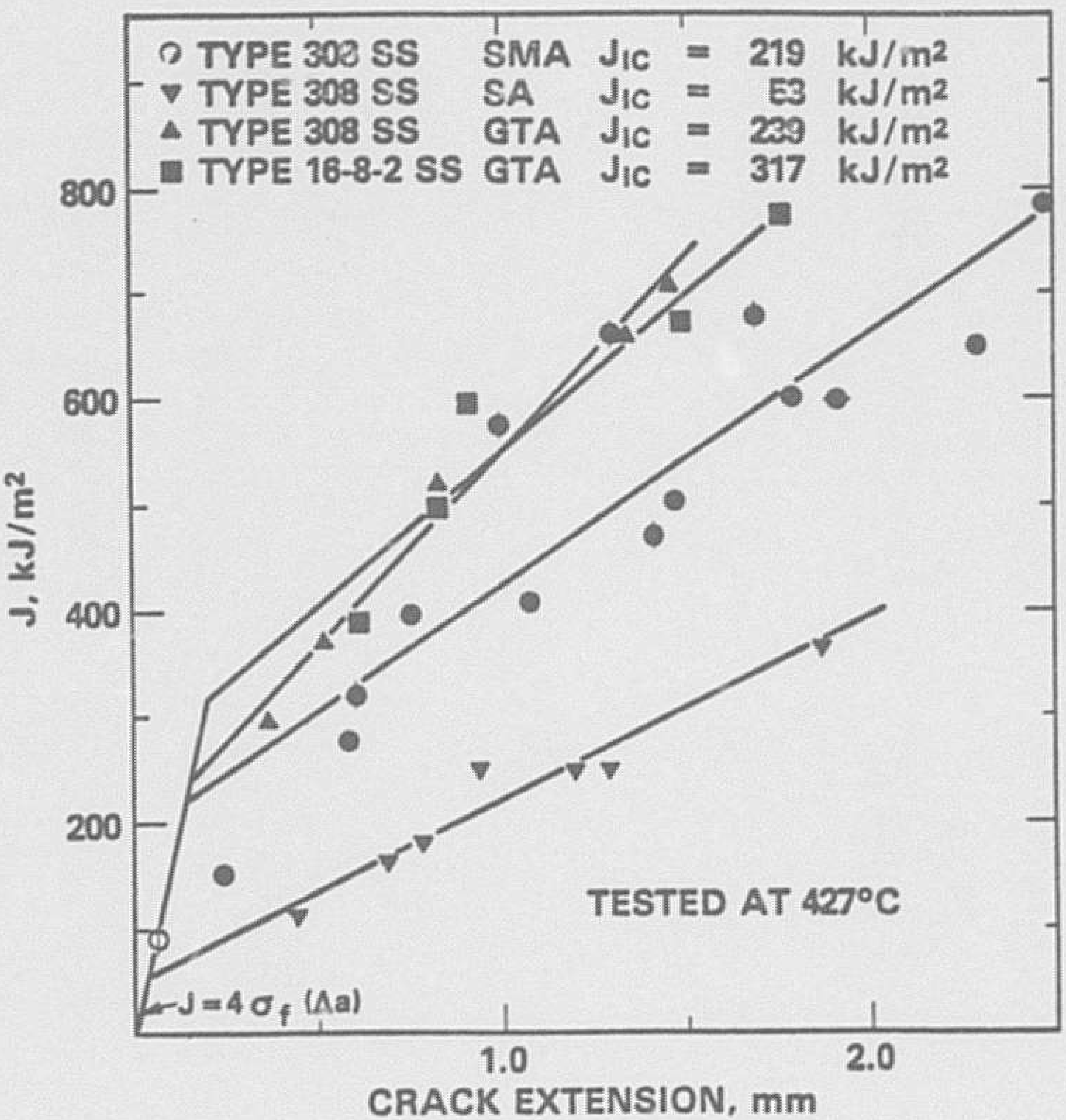
J-INTEGRAL TOUGHNESS OF SEVERAL HEATS OF TYPE 304 S.S. AT 800 F



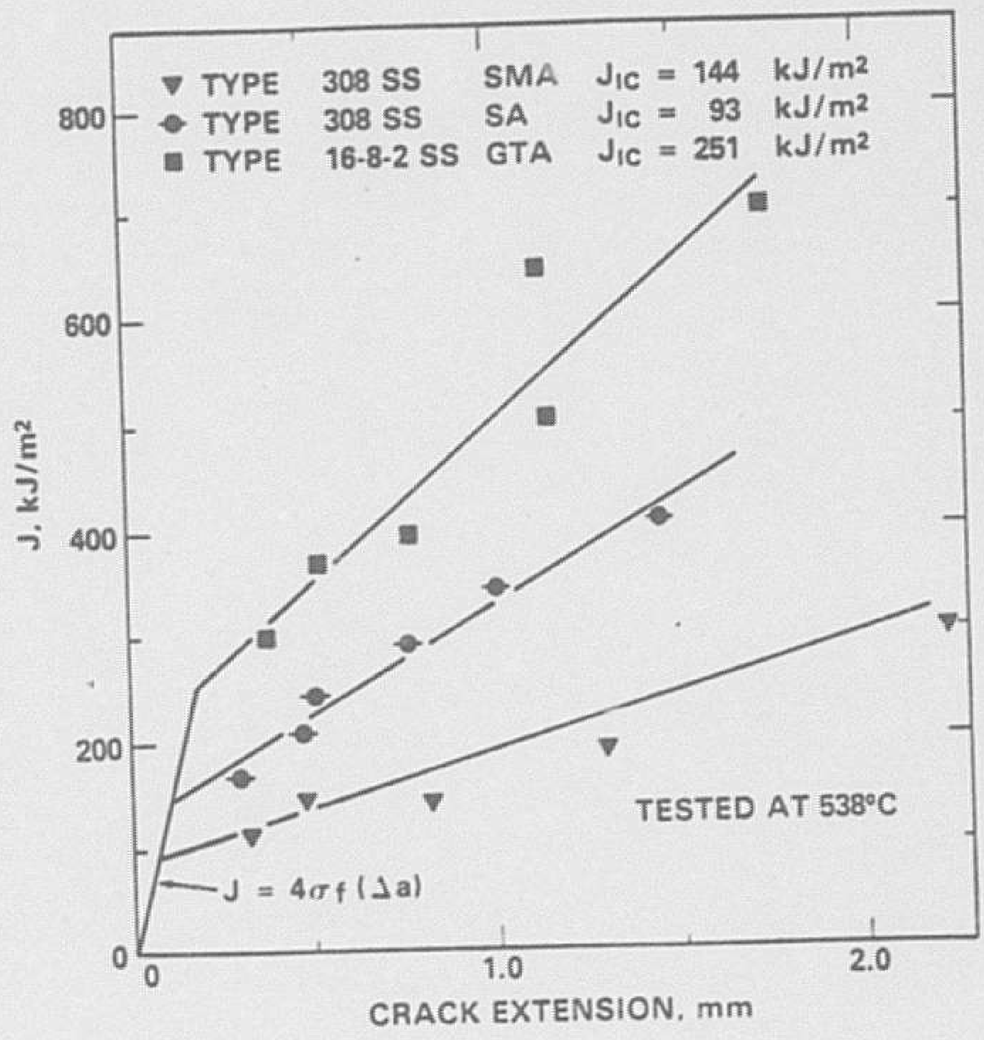
J-INTEGRAL TOUGHNESS OF SEVERAL HEATS OF TYPE 304 S.S. AT 1000 F



J-INTEGRAL TOUGHNESS OF AUSTENITIC S.S. WELDMENTS AT 800 F



J-INTEGRAL TOUGHNESS OF AUSTENITIC S.S. WELDMENTS AT 1000 F



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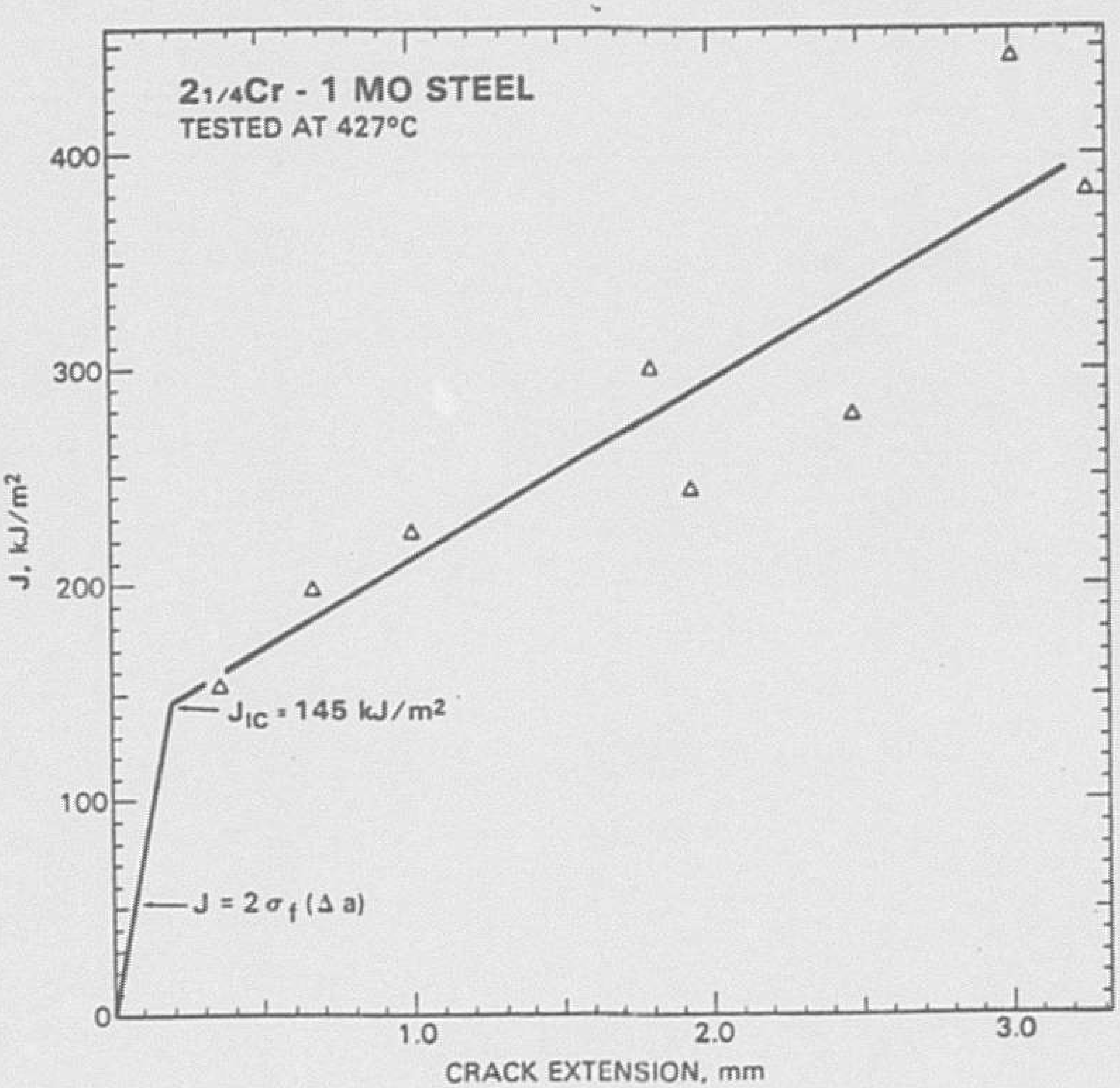
J-INTEGRAL FRACTURE TOUGHNESS OF 2 1/4Cr-1Mo PLATE AT 800 F



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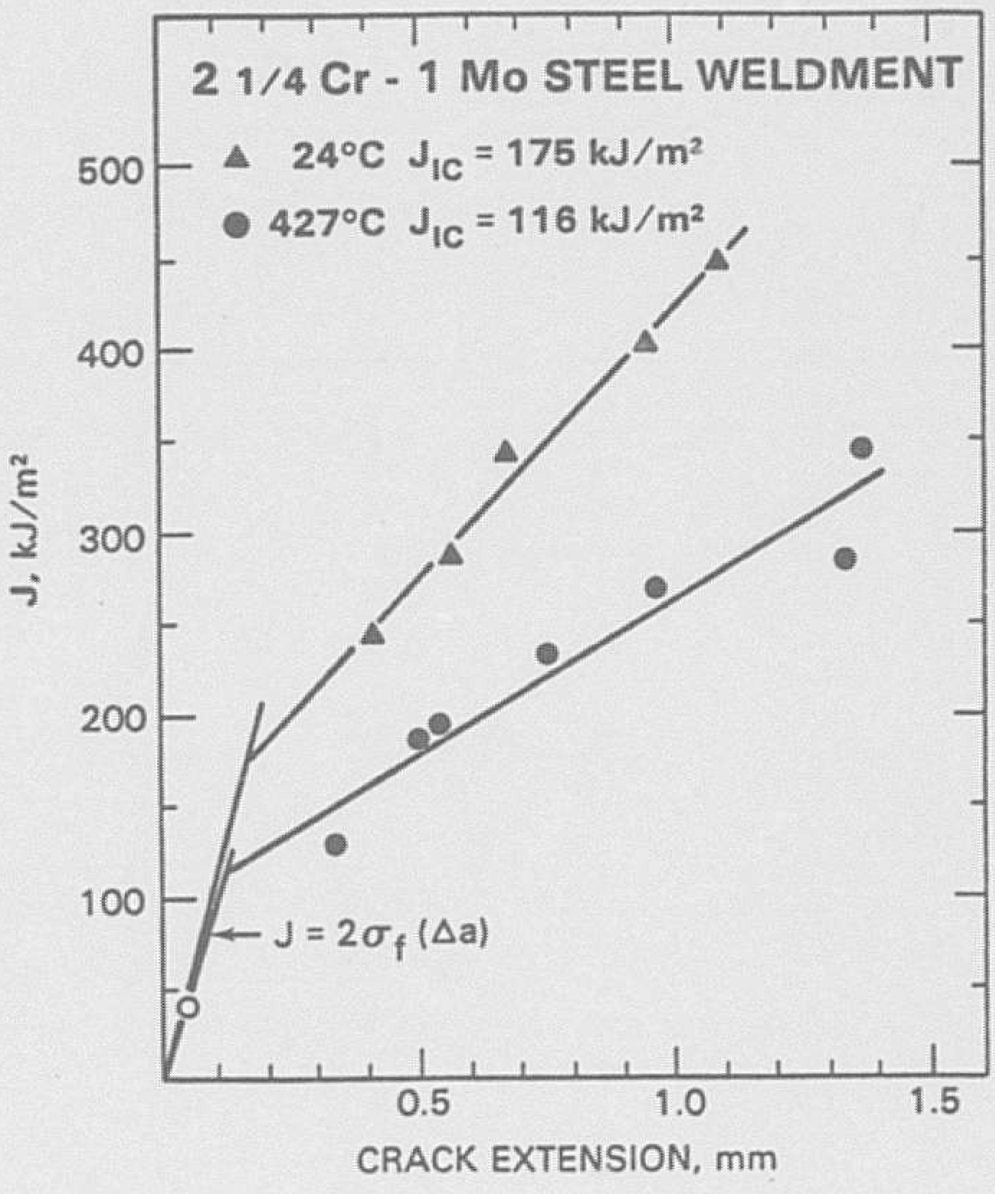
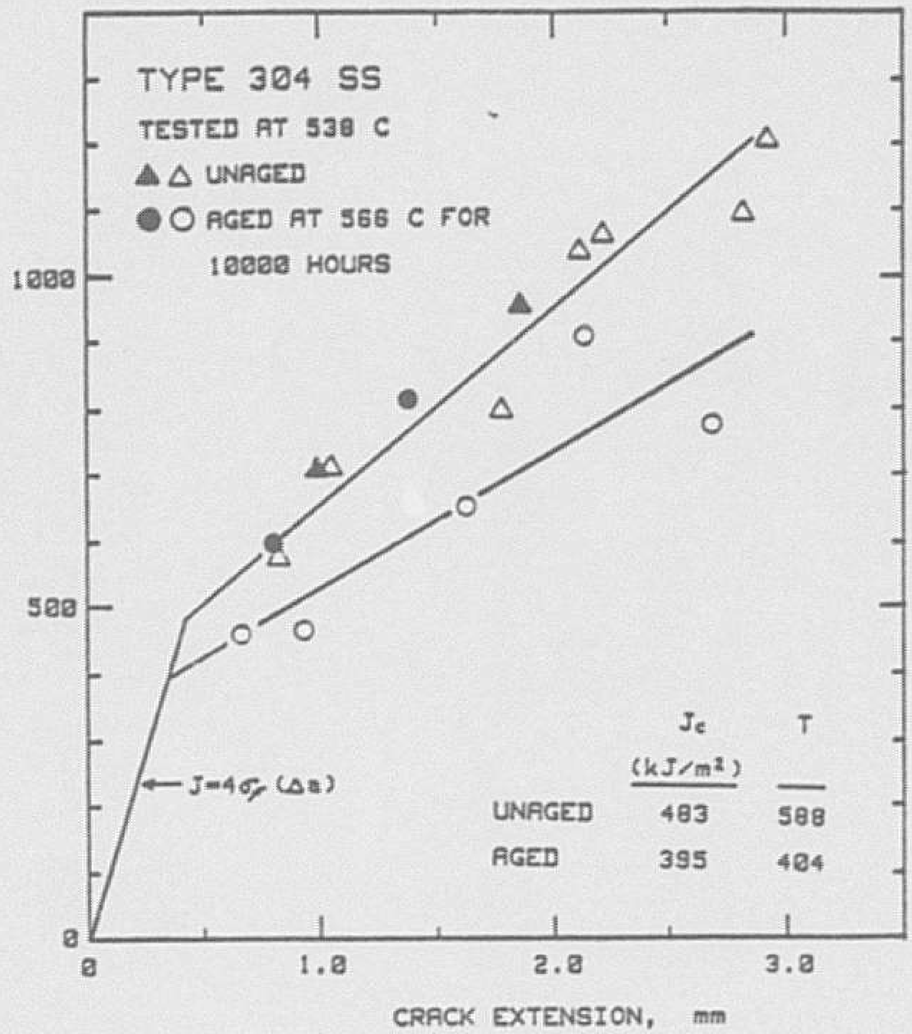
J-INTEGRAL FRACTURE TOUGHNESS OF 2 1/4Cr-1Mo WELDMENTS AT 75 F AND 800 F.



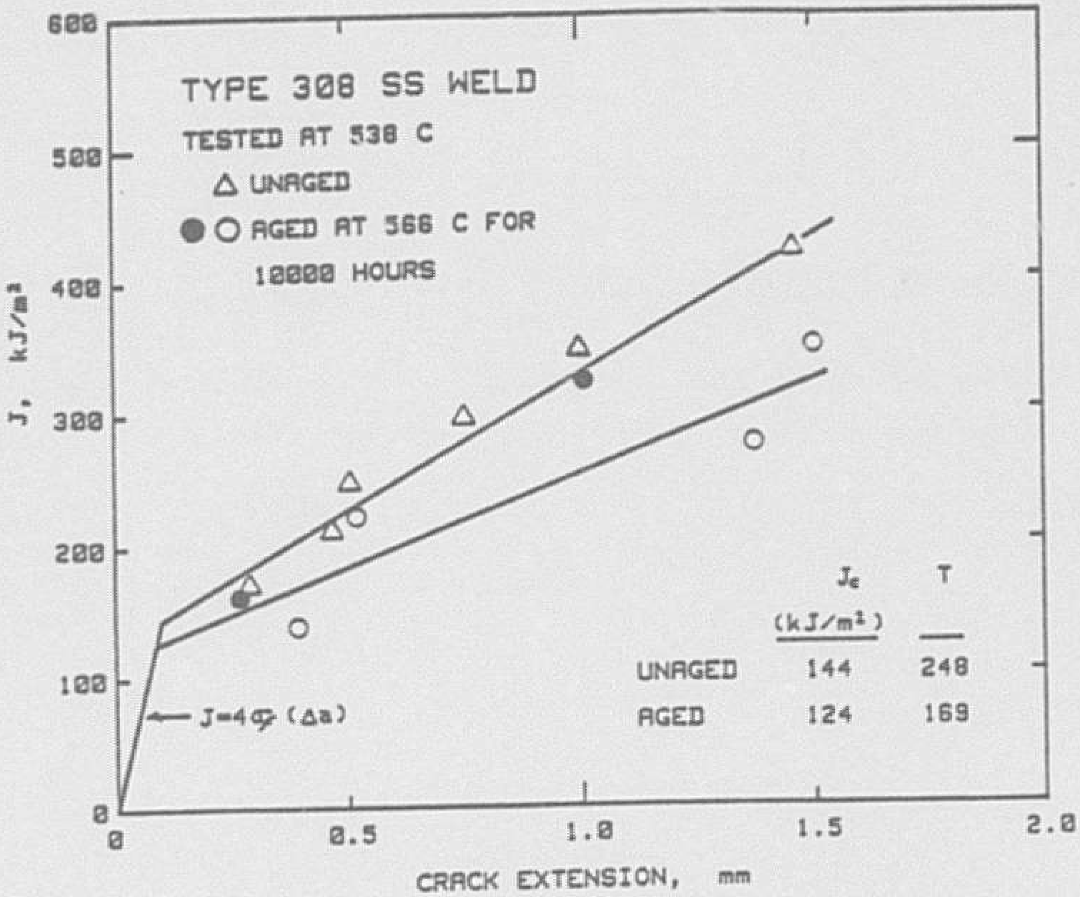
EFFECT OF THERMAL AGING ON J-INTEGRAL TOUGHNESS @ 1000 F TYPE 304 STAINLESS STEEL



OPEN SYMBOLS - QUASI-STATIC

CLOSED SYMBOLS - SEMI-DYNAMIC
(1-sec loading time)

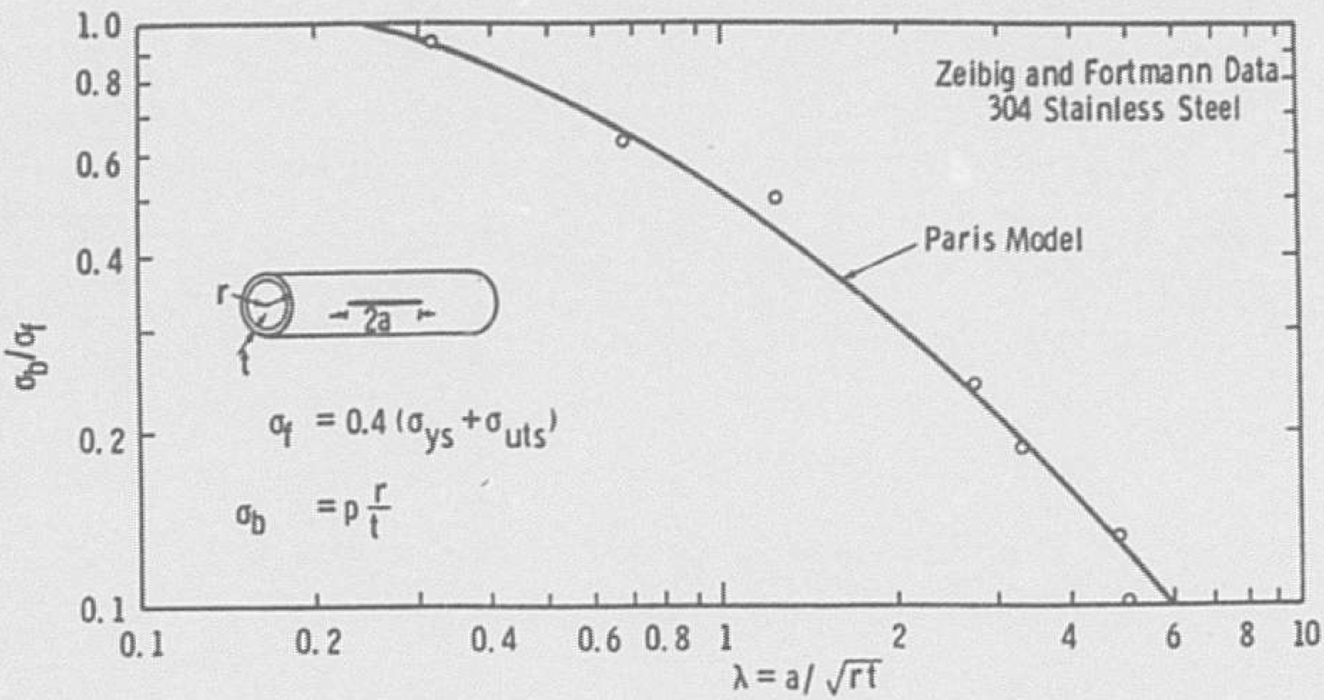
EFFECT OF THERMAL AGING ON J-INTEGRAL TOUGHNESS @ 1000 F TYPE 308 SMA WELDMENTS



OPEN SYMBOLS - QUASI-STATIC

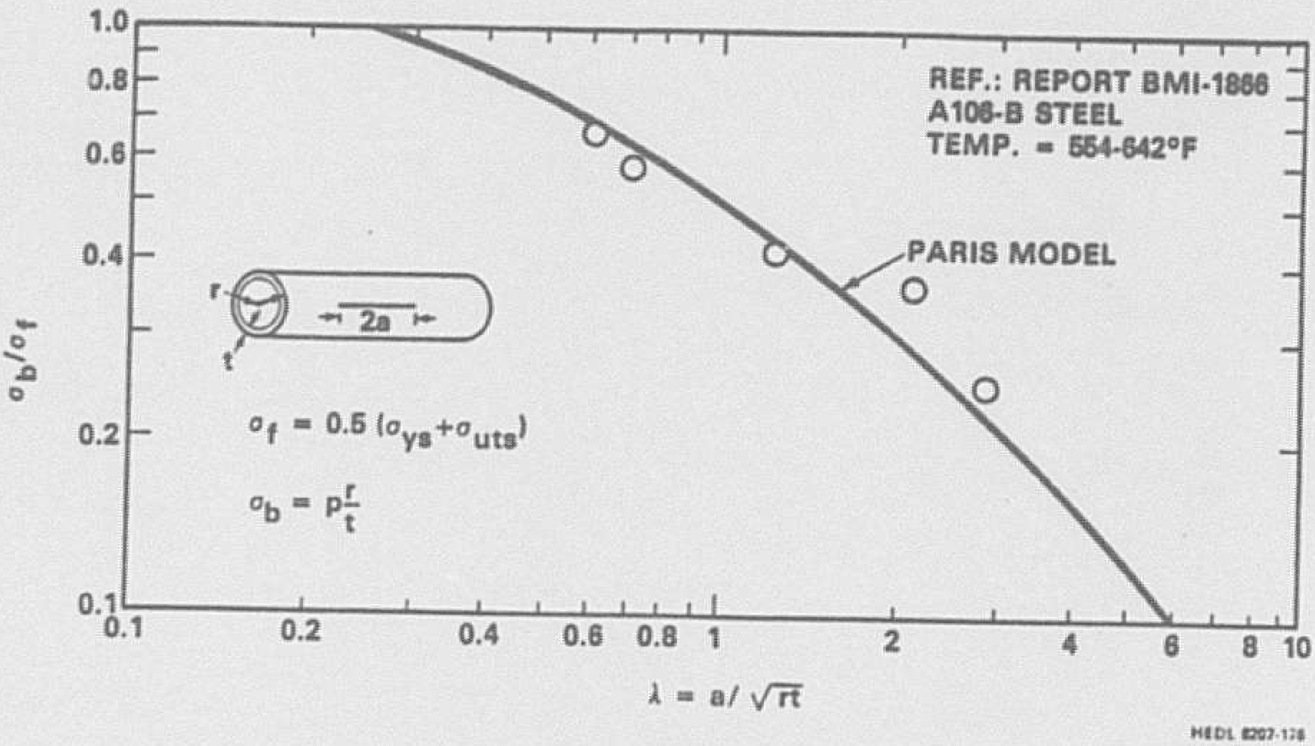
CLOSED SYMBOLS - SEMI-DYNAMIC (1-sec loading time)

USE OF THE PARIS MODEL TO PREDICT CRITICAL CRACK LENGTHS IN AUSTENITIC S.S. PIPES



ANALYSES FOR AUSTENITIC S.S. PIPES IN THE CRBR PHTS & IHTS PREDICT CRITICAL CRACK LENGTHS ON THE ORDER OF THE PIPE DIAMETER

USE OF THE PARIS MODEL TO PREDICT CRITICAL CRACK LENGTHS IN FERRITIC STEEL PIPES



ANALYSES FOR FERRITIC STEEL PIPES IN THE CRBR IHTS PREDICT CRITICAL CRACK LENGTHS ON THE ORDER OF THE PIPE DIAMETER.

REVIEW OF FRACTURE MECHANICS MATERIALS PROPERTIES IN SUPPORT OF CRBR PIPING INTEGRITY ANALYSES

SUMMARY

- LARGE WELL-CHARACTERIZED DATA BASE AVAILABLE TO SUPPORT BOTH FATIGUE-CRACK GROWTH AND FRACTURE TOUGHNESS ANALYSES

- THE QUALITY AND QUANTITY OF THE DATA PROVIDE CONSIDERABLE CONFIDENCE WHEN INPUT INTO THE INTEGRITY ANALYSES

- FRACTURE MECHANICS PROPERTIES COMPLEMENT THE MORE CONVENTIONAL MECHANICAL PROPERTIES AND CONFIRM THAT THE MATERIALS UTILIZED IN THE CRBR PIPING SYSTEMS ARE WELL-BEHAVED

- THE CONCLUSION IS THAT THE AVAILABLE DATA IS ADEQUATE FOR A SAFE RELIABLE DESIGN OF THE ELEVATED TEMPERATURE PIPING COMPONENTS FOR THE 30 YEAR PLANT LIFE

REFERENCE FATIGUE CRACK

OBJECTIVE:

- DEVELOP THE BASIS FOR SPECIFYING A CONSERVATIVELY LARGE REFERENCE FATIGUE CRACK THAT CAN BE USED IN THE SELECTION OF DESIGN BASIS LEAKS FOR VARIOUS PLANT ITEMS.

REFERENCE FATIGUE CRACK

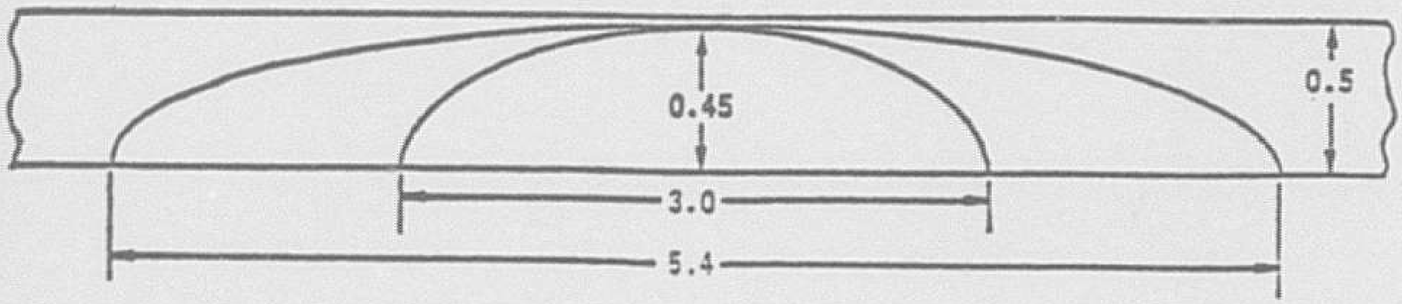
APPROACH:

- POSTULATE A MUCH DEEPER AND LONGER INITIAL CRACK THAN THAT USED IN THE CRACK GROWTH ANALYSES.
- ANTICIPATED PLANT LOADINGS WOULD CAUSE A CRACK TO PENETRATE (AND HENCE LEAK) BEFORE IT GOT VERY LONG. IN THE REFERENCE FATIGUE CRACK CALCULATIONS WE ARBITRARILY HOLD THE CRACK DEPTH CONSTANT AND ONLY ALLOW GROWTH TO TAKE PLACE IN THE LENGTH DIRECTION. THIS CONSERVATIVELY MAXIMIZES THE CRACK LENGTH.
- ONCE THE ENTIRE PLANT DUTY CYCLE OF LOADINGS HAS BEEN APPLIED, AN EQUIVALENT THROUGH-WALL CRACK IS CALCULATED BY ASSUMING THAT PENETRATION OVER THAT PORTION OF THE LIGAMENT WHERE THE NOMINAL NET SECTION STRESS EXCEEDS THE YIELD STRENGTH.
- THE RESULTING EQUIVALENT THROUGH-WALL CRACK IS CALLED THE "REFERENCE FATIGUE CRACK," AND IS USED IN THE SELECTION OF DESIGN BASIS LEAKS FOR VARIOUS PLANT ITEMS.

REFERENCE FATIGUE CRACK

DETAILS OF THE CALCULATION FOR THE PHTS:

- INITIAL CRACK WAS POSTULATED TO BE 0.45 INCH DEEP (90% OF WALL) AND 3.0 INCH LONG



- PLANT DUTY CYCLES EXTEND THE CRACK TO A SURFACE LENGTH OF 5.4 INCH. CRACK DEPTH WAS ABRITRARILY FIXED AT 0.45 INCH.
- EQUIVALENT THROUGH-WALL CRACK CALCULATED BY ASSUMING THAT WALL PENETRATION OCCURS OVER THAT PORTION OF THE UNCRACKED LIGAMENT WHERE THE NOMINAL NET SECTION STRESS EXCEEDS THE YIELD STRENGTH.
- THE CALCULATED LENGTH OF THE EQUIVALENT THROUGH-WALL CRACK IS 3.6 INCH AND THIS, WHEN ROUNDED OFF TO 4 INCHES, BECOMES THE "REFERENCE FATIGUE CRACK".

REFERENCE FATIGUE CRACK

CONSERVATISMS EMPLOYED:

- VERY LARGE POSTULATED INITIAL CRACK SIZE
- WALL PENETRATION (AND HENCE LEAKAGE) ARBITRARILY PREVENTED
- THROUGH-WALL FAILURE DEFINED AS REACHING THE MATERIAL YIELD STRENGTH
- LENGTH "ROUNDED OFF" TO 4 INCHES FROM A CALCULATED 3.6 INCHES
- LOCATION CHOSEN HAD HIGHEST STRESSES. HENCE, RESULTS ARE CONSERVATIVE FOR ALL OTHER PHTS LOCATIONS.