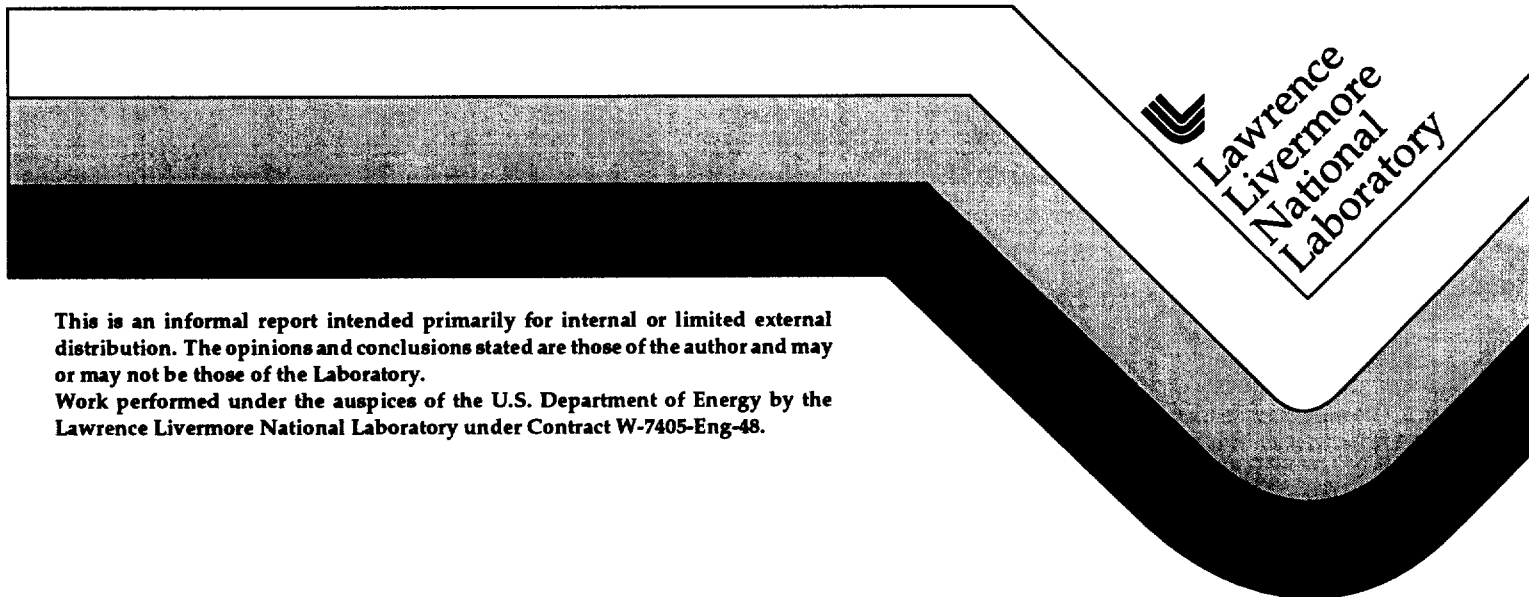


**Results of Fracture Mechanics Analyses of the  
Ederer Cranes in the Device Assembly Facility Using  
Actual, Rather than Conservative, Stress-Components**

**E. N. C. Dalder**

**December 26, 1996**



**Lawrence  
Livermore  
National  
Laboratory**

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December 26, 1996

TO: A. M. Davito

FROM: Edward N.C. Dalder

SUBJECT: *Results of Fracture Mechanics Analyses of the Ederer Cranes in the Device Assembly Facility Using Actual, Rather than Conservative, Stress-Components*

---

**Abstract:** Per your verbal request, the suspect analyses were conducted on three critical locations on the lower flange of the load-beam of the Ederer 5 ton and 4 ton cranes in the D.A.F. Facility. Based on these results, it appears that:

1. Use of actual, rather than Von Mises stresses, where appropriate in conducting fatigue-life analyses on the subject components resulted in small increases (0-9.5%) in calculated fatigue lives;
2. Propagation of a 1/4" long flaw, with an aspect-ratio of 0.25, previously undetected by non-destructive examination to lengths sufficient to cause structural failure of either flange, should not occur in at least 180 times the postulated operating scenarios for either crane; and
3. Should each crane undergo annual inspection, any surface flaw with an exposed length greater than 1.05" should be removed and repaired by qualified and approved repair procedures.

**Introduction:** Per A. Davito's verbal request, fracture mechanic analyses were performed for the highly-loaded lower flange on the Ederer 5 ton crane (Ederer Dwg. No. A14855 ) and Ederer 4 ton or "Polar" crane (Ederer Dwg. No. A14937), using loads and stress information contained in Refs. 1-2. This work was done to determine (1) appropriate flaw-sizes for detection by non-destructive examination (NDE) methods during periodic inspection of these cranes, and (2) appropriate inspection-intervals.

**Procedure:** First, Refs. 1-2 were reviewed, stress-information for the two cranes were obtained, and are summarized in Table 1. The values of stress-components selected as the stress-value to be used in fracture-mechanics calculations were those provided in Refs. 1-2. Since the basis of these calculations was based on the growth of a pre-existing flaw under the action of cyclic stresses, it is appropriate to describe how such analyses are performed.

Crack growth analysis is based on the similitude provided by the stress intensity factor  $K$ , which provides a full description of the crack tip stress field, provided there is little plasticity.  $K$  can be expressed as

$$(1) \quad K = \sigma \sqrt{\pi a} \beta$$

where  $a$  is the crack size (or half the crack size when the crack has two tips);  $\sigma$  is the nominal (remote) stress, and  $\beta$  a factor accounting for geometry. It should be emphasized that  $\sigma$  is the nominal stress in a remote section not affected by the crack, as effects of the reduced area in the cracked section are accounted for in  $\beta$ , a non-dimensional function of crack size and other geometrical parameters. Such  $\beta$  values can be obtained from stress intensity handbooks such as Refs. 4-6.

The stress intensity provides a full description of the elastic crack tip stress field. If two cracks in the same material, but of different length and in different structural configurations, are subject to equal  $K$ , then the stress fields at both crack tips are identical. Hence, both cracks behave in the same manner, i.e., show the same rate of growth. This leads to:

$$(2) \quad \frac{da}{dN} = f(\Delta K, R)$$

where  $da/dN$  is the rate of propagation,  $N$  the number of cycles,  $K_{\max} - K_{\min}$  the range of stress intensity in a load cycle, and  $R = K_{\min} / K_{\max} = \sigma_{\min} / \sigma_{\max}$  is the so-called "stress ratio".

According to the equation, every time a certain combination of  $K$  and  $R$  appears, the amount of crack extension is the same. The function  $f(K, R)$  is obtained from crack growth tests on specimens in the laboratory. Data for many materials can be found in the literature, especially in Refs. 7-8.

The objective of crack growth analysis is to obtain a crack propagation curve for a crack in a structure. This requires integration of

$$(3) \quad N = \int \frac{da}{(da/dN)} = \int \frac{da}{f(\Delta k, R)}$$

Since  $f(K, R)$  is a complicated function,  $\beta$  for the structural crack a complicated function of  $a$ , and the stress range is different in every load cycle, the integration has to be performed numerically, using a computer program such as "Fatcrak" (Ref. 9)

When different load cycles have different stress-ranges, similitude may no longer be provided by  $K$ . In such cases,  $f(K, R)$  no longer provides the correct  $da/dN$ . This is called "load interaction". In most cases, the net load interaction effect is slower crack growth, which is called "crack retardation". Although load interaction may be explained

qualitatively, there is no wholly satisfactory way to qualitatively account for the effect . The net load interaction effect is almost always a retardation.

The user has to specify the function  $f(K,R)$ . Several empirical equations are available for this function, none of which has a theoretical basis. The simplest curve fitting equation is known as the Paris equation (Ref. 10) which assumes a log-log-linear relation between  $K$  and  $da/dN$ :

$$(4) \frac{da}{dN} = C_p (\Delta K)^{M_p}$$

where  $C_p$  and  $m_p$  are constants for a material. This equation ignores the effect of  $R$ , which is acceptable for our situation since  $R=0$  (minimum load = 0). See Appendix A for additional information on determination of  $C_p$  and  $M_p$ , the "Paris Law" constants for A36 steel at room temperature.

Hence, the input-information for operation of FATKRAK consists of:

1. The choice of flaw-configuration (Fig. 1), in our case, a semi-elliptical flaw with aspect-ratio of 0.25, oriented on the bottom surface of the lower flange of the crane-beam for locations (or "points") 0 and 1 (Fig. 2b), or oriented on the top surface of the lower flange of the crane-beam for location 2 (Fig. 2a) (choosing such a flaw-configuration determines the stress-intensity expression (Ref. 8)

$$(5) K_I = \sigma \sqrt{\pi a} \left\{ 1.12 \left[ \frac{1.05 + 10 \left(0.6 - \frac{a}{2c}\right)}{\sqrt{1 + 8 \left(\frac{a}{2c}\right)^2}} \right] \left(\frac{a}{w}\right)^3 \right\}$$

2. Initial flaw-size, ranging from flaw-depth values ("a") of 0.063" to 1.0"
3. Stress ( $\sigma$ ) values from Table 1;
4. Final defect-size, in terms of the critical value of flaw-depth, a, at which rapid, unstable failure occurs;
5. Paris-Law constants of  $C_p = 3.98 \times 10^{-12}$  in./cyc and  $M_p = 4.86$ , from Appendix A; and
6. Width (288") and thickness (1.0" for the 5 ton crane, or 0.75" for the 4 ton crane) of the flange from Fig. 1.

A typical table of output is presented in Table 2, wherein progressively-larger flaw-dimensions are tabulated for increasing numbers of loading cycles. The results of 5-8 such runs, using increasing values of the initial flaw-size, a as the input-parameter, are plotted in Fig. 3. (Additional plots for other load-cases and locations are contained in Appendix B). Information such as Fig. 3 may be used to set flaw-size units for safe operation, periodic inspection, and "Retirement for Cause"- based fracture safety as follows:

1. Determine the annual number of load-cycles (200-400 per Ref. 9) and total number of load-cycles (12,000) at the "end-of-life", Of 30 years (Ref. 10);
2. Enter Fig. 3 at the indicated number of cycles, say 400, and proceed vertically upward until the desired curve of "flaw dimension vs. cycles" is reached.
3. Proceed to the left until the "dimension of flaw" axis is reached, and read off the indicated flaw dimension for the chosen number of cycles of loading. For the "initial flaw length", a quantity measurable by NDE, the value is 2.8".

The significance of this "initial flaw length", (2c), of 2.80" is that after 400 applications of a tensile stress of 11.6 ksi, rapid failure will occur. Proceeding in a similar manner with the computed information summarized in Figs. B1-B3, the information in Tables 3-4 was generated. Considering Table 3 first, it is seen that initial surface flaw-lengths on the order of 1.88" to 3.40" will cause failure in 200-400 cycles, a typical year's worth of operation. For a 30 year usage period, hereafter referred to as "a lifetime", initial surface flaw-lengths to cause failure drop to the order of 1.27-2.75".

Consider Table 4, wherein is summarized the number of loading-cycles needed to grow a small flaw, one with initial surface-length of 0.25", to sizes great enough to cause structural-failure of the lower flange. The initial surface-length value of 0.25" was chosen on the basis of it being the largest length flaw that might not be detected by common NDE methods, such as magnetic-particle inspection or dye-penetrant methods, during periodic inspection of the cranes (Ref. 1). Note that, under such conditions, the predicted cyclic lives to failure are of the order  $10^6 - 10^8$  cycles of load, or 187 to 1593 lifetimes of predicated crane usage. Hence, growth of a "reasonably small" undetected flaw to cause structural failure of the lower flange of either crane's beam is unlikely.

Another, more quantitative, way of assessing the degree of conservatism introduced in the Ref. 1 Fracture-Mechanics Analysis is to consider the "Margin of Conservatism", or "M. C.", introduced by the use of the maximum stress-component (Ref. 3), rather than the Von Mises stress (Table 1):

$$(6) \text{ Margin of Conservatism} = 1 - \frac{\text{Indicated Flaw Dimension (Conservative Case)}}{\text{Indicated Flaw Dimension (Actual Case)}}$$

For the "characteristic flaw-dimension" was chosen the length of the crack, 2c, as shown in Figure 2C. Crack-length was chosen because it is a parameter that can readily be measured at the beginning of operation ("initial flaw-length"), or at any time in the operational lives of the cranes up to the onset of rapid fracture ("final flaw-length"). In Table 5 is summarized the initial flaw-length values obtained from analyses conducted using actual stress-components, hereafter described as the "actual case", and initial flaw length values obtained from analyses conducted using the Von Mises stresses, hereafter described as the "conservative case." Substituting these values of "initial flaw-length" into Eqn. 5 produced the array of "margins of conservatism" values presented in the far-right side of Table 5. Proceeding in a similar manner, the "margins of conservatism" array, based on "final flaw length" as the characteristic flaw-dimension was generated, and is presented in Table 6.



Considering the "margin of conservatism" values based on "initial flaw length", the following trends can be obtained from an examination of Table 5:

1. Margin of conservatism values, based on a year's operation (200-400 cycles) are small, and range from 0 to 0.052 or 0% to 5.2%. In general, the margin of conservatism values decreased with cyclic life (200 cycles to 400 cycles) for the 5 ton crane, but increased with increasing cyclic life for the 4 ton crane.
2. Margin of conservatism values, based on the full 30 years or 12,000 cycles design-life were small, ranging from 0 to 0.091, or 0 to 9.1%.

Considering the "margin of conservatism" values based on "final flaw length", or flaw-length at which rapid fracture would occur, the following trends can be obtained from an examination of Table 6:

1. Based on a year's operation (200-400 cycles), the margin of conservatism values ranged from 0 to 0.095, or 0% to 9.5%. In general, the margin of conservatism values increased with increasing cyclic life (200 cycles to 400 cycles) both for the 5 ton crane, and the 4 ton crane.
2. Based on the full 30 year design-life, or 12,000 cycles, margin of conservatism values ranged from 0 to 0.069, or 0 to 6.9%.

### **Discussion:**

#### **1. Setting an "Initial Flaw Length" for Possible Removal and Repair**

Since periodic inspections of other sub-systems of the cranes are likely to be performed on an annual basis (Ref. 13), i.e. every 400 cycles, detection of a flaw with a surface-length of 1.05" (half the surface-length of a "fatal flaw") for the most highly-stressed location could be cause for retirement of the crane-beam. The choice of a factor of two reduction in flaw-length is based on the A.S.M.E. Boiler and Pressure Vessel Code Section III (Nuclear) reduction factors on fatigue-performance (Ref. 14), i.e. the greater of a factor of 2 on strain-range (or stress-range) or a factor of 20 on cyclic life. In this treatment, the "strain-range; stress-range" parameter has been replaced by "initial flaw length". The choice of using half of the initial flaw-length of the most highly-stressed location; location 1 on the 4 ton crane, was done to introduce a single "go-no go" parameter rather than having 6 such values (3 per crane), that may cause confusion among inspectors. Should it be considered desirable by the D.A.F. operations management, detection of a flaw with a surface-length of 1.05" might be made the point at which such a defect would be removed and replaced by suitable methods controlled by approved repair procedures.

#### **2. Effect of Using Actual, Rather than Von Mises, Stresses in Performance of Fracture-Mechanics Analyses of the Lower Flanges of the Ederer Cranes**

Use of actual stresses in place of Von Mises stresses had small positive impacts on the calculated cyclic lives to failure, in that for the four cases when actual stresses were slightly less than the Von Mises stresses, calculated fatigue lives increased up to 9.6%. For the two cases where the Von Mises stresses were used throughout, there was no change in the calculated fatigue lives.

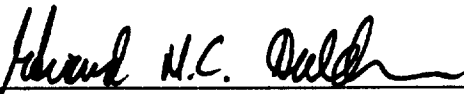
Conclusions:

1. Fracture-mechanics analyses on 3 critical locations of the Ederer 5 ton crane and 4 ton crane in the Device Assembly Facility, using actual stresses rather than Von Mises stresses, showed that:

- a. Up to a 9.6% increase in calculated fatigue lives would occur, relative to previous analyses (Ref. 3), which used Von Mises stresses throughout; and
- b. The use of actual stress values in the afore-mentioned analyses introduced small increases in the results of the analyses, typically 0% to 9.1% based on changes in initial flaw length, or 0 to 6.9% based on changes in final flaw length at fracture.

2. Under the situations described herein for the analyses conducted using the actual stresses in place of the Von Mises stresses, propagation to failure of a semi-elliptical surface with an aspect-ratio of 0.25 and an initial length of 0.25", should not occur in at least 180 times the assumed "operational life" of the crane-beam lower flange of either Ederer crane.

For additional information, please contact the undersigned at ext. 2-7270.

  
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**Table 1: Stresses and Final Defect Sizes Used as Inputs to Fracture Mechanics Calculations**

Crane Type	Flaw Information		Location No.	Stress-Component Information (KSI)			Final Defect size (inches)	Basis
	Type	Orientation		$\Sigma\sigma_x$	$\Sigma\sigma_y$	$\sigma_{VM}$		
5 Ton	Surface Flaw $a/2c = 0.25$	Along the Flange	zero	-5.84	7.5	(11.6)	0.835	
			one	2.90	13.8	(12.6)	0.816	
			two	5.84	6.41	(6.14)	0.998	
4 Ton	Surface Flaw $a/2c = 0.25$	Along the Flange	zero	-4.05	12.1	(15.0)	0.605	
			one	2.3	17.0	(16.0)	0.595	
			two	4.63	11.2	(9.75)	0.634	

Notes:

1.  $\Sigma\sigma_x$  = Total stress in X direction (Fig. 1)
2.  $\Sigma\sigma_y$  = Total stress in Y direction (Fig. 1)
3.  $\sigma_{VM}$  = Von Mises Stress =  $\sqrt{\sigma_x^2 + \sigma_y^2 - \sigma_x\sigma_y}$
4. (x) = Circled values of stress used as inputs to fracture mechanics calculation;

Table Two

RUN 71, 4 TON CRANE, LOCATION ONE, FLAW IS A SINGLE SURFACE CRACK WITH AN ASPECT-RATIO OF 0.25 AND IS ORIENTED ALONG THE LONG DIRECTION OF THE FLANGE, INITIAL FLAW-DEPTH IS 0.500", FINAL FLAW-DEPTH IS 0.585", WIDTH OF MEMBER IS 288", DEPTH OF MEMBER IS 0.75", SMAX IS 17 KSI, SMIN IS 0, SY IS 36 KSI

CRACK LENGTH	CRACK DEPTH	CYCLES	CYCLES	BETA
	0.5000"	0	0	2.027
1.0000"		14	14	2.027
1.0010	0.5050	27	27	2.045
1.0019	0.5101	39	39	2.063
1.0029	0.5152	51	51	2.081
1.0040	0.5203	62	62	2.100
1.0051	0.5255	72	72	2.118
1.0062	0.5308	82	82	2.138
1.0073	0.5361	91	91	2.157
1.0085	0.5414	100	100	2.177
1.0097	0.5468	108	108	2.197
1.0110	0.5523	116	116	2.217
1.0123	0.5578	123	123	2.238
1.0137	0.5634	130	130	2.259
1.0150	0.5690	137	137	2.281
1.0165	0.5747	143	143	2.302
1.0179	0.5805	143	143	2.302
1.0179	0.5863			18142

FATKRAK2

-----  
 CRACK SIZE DEFINED AS THE CRACK DEPTH FROM SURFACE TO DEEPEST POINT  
 PRESS 'ENTER' TO CONTINUE?

**Table 3: Initial and Final Lengths of Semi-Elliptical Cracks (Aspect ratio = 0.25) that will Cause Failure of the Lower Flange of the Ederer Five Ton and Four Ton Cranes when Cranes are Cyclically - Loaded**

Crane Type	Location No.	Range of Stresses	(1) Initial Flaw-Length to Cause Failure in Indicated Number of Cycles			Final Flaw Length to Cause Failure in Indicated Number of Cycles		
			200	400	12,000	200	400	12,000
5 Ton	zero	0-11.6 KSI	2.8"	2.8"	2.0"	3.0"	3.0"	2.2"
	one	0-12.6	2.9	2.75	1.87	3.02	2.8	2.15
	two	0-6.14	3.4	3.3	2.75	3.85	3.75	3.00
4 Ton	zero	0-16	2.05	2.0	1.55	2.15	2.1	1.50
	one	0-9.75	1.98	1.88	1.27	2.15	2.10	1.52
	two	0-11.2	2.4	2.35	1.72	2.6	2.55	1.98

Notes:

(1) For a semi-elliptical surface-crack with an aspect-ratio of 0.25

**Table 4: Number of Cycles needed to Grow a Semi-Elliptical Flaw with Aspect-Ratio of 0.25 and Initial Surface Length of 0.25" to Structural Failure of the Lower Flange:**

Crane Type	Location No.	Range of Stresses	Number of Cycles to Grow a Flaw <sup>(1)</sup> with Initial Surface Length of 0.25" to Structural Failure of Flange	Number of Operational Lives (1 life = 12,000 cycles) to Grow Said Flaw to Failure of Flange
5 Ton	zero	0-11.6 KSI	$8.673 \times 10^6$ cycles	722
	one	0-12.6	$5.801 \times 10^6$	483
	two	0-6.14	$1.912 \times 10^7$	1593
4 Ton	zero	0-15	$2.292 \times 10^6$	191
	one	0-16	$2.25 \times 10^6$	187
	two	0-9.75	$1.874 \times 10^7$	1561

Notes:

(1) Initial flaw is a semi-elliptical surface crack with an aspect ratio of 0.25 and a surface-length of 0.25"

**Table 5 Margins of Conservatism Introduced in Fracture Mechanics Analyses Based on Initial Flaw-Lengths by use of the Maximum Stress Component, Rather than the Von Mises Stress, for A.S.T.M. A-36 Steel Flanges in the Ederer 5 Ton and 4 Ton Cranes in the Device Assembly Facility**

Crane Type	Location No.	Stress Range (KSI)		Conservative Case Initial Flaw Length to Cause Failure in Indicated Number of Cycles (inches)			Actual Case Initial Flaw Length to Cause Failure in Indicated Number of Cycles			Margin of Conservatism on Initial Flaw Length to Cause Failure in Indicated number of Cycles		
		Conservative	Actual	200	400	12,000	200	400	12,000	200	400	12,000
5 Ton	zero	0-11.6	0-11.6	2.9"	2.8"	2.0"	Same as	Conser.	Case	0	0	0
	one	0-13.8	0-12.6	2.75"	2.70"	1.70"	2.90"	2.75"	1.87"	0.052	0.018	0.091
	two	0-6.41	0-6.14	3.40"	3.30"	2.75"	3.40"	3.30"	2.75"	0	0	0
4 Ton	zero	0-15	0-15	2.05"	2.0"	1.30"	Same as	Conser.	Case	0	0	0
	one	0-17	0-16	1.9"	1.8"	1.17"	1.98"	1.88"	1.27"	0.040	0.043	0.079
	two	0-11.2	0-9.75	2.40"	2.20"	1.60"	2.40"	2.35"	1.72"	0	0.064	0.070

Notes:

(1) Margin of Conservatism =  $1 - \frac{\text{Initial flaw-length (conservative case)}}{\text{Initial flaw-length (actual case)}}$

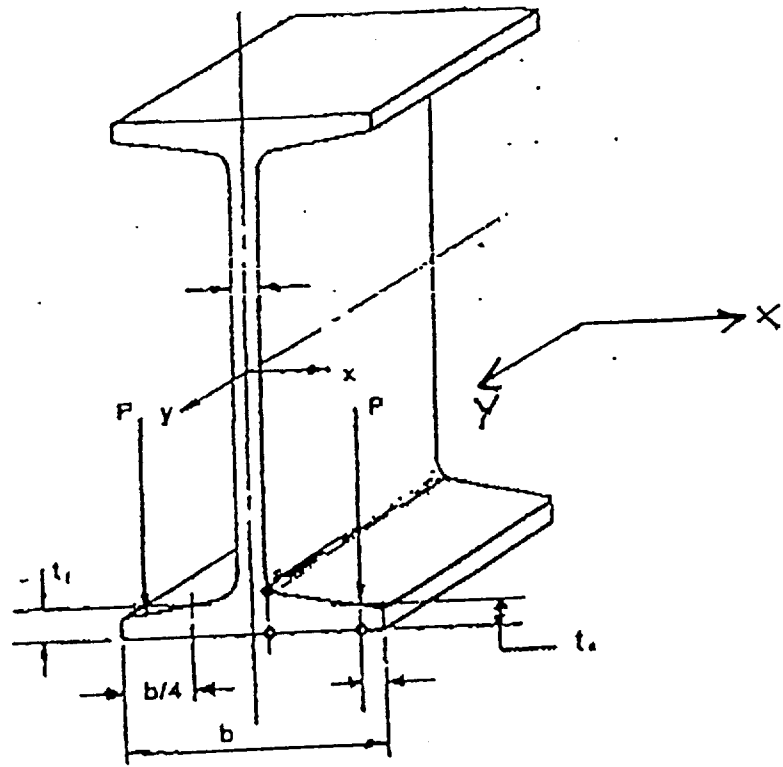


**Table 6 Margins of Conservatism Introduced in Fracture Mechanics Analyses Based on Final Flaw-Lengths by Use of the Maximum Stress Component, Rather than the Von Mises Stress, for A.S.T.M. A-36 Steel Flanges in the Ederer 5 Ton and 4 Ton Cranes in the Device Assembly Facility**

Crane Type	Location No.	Stress - Range (KSI)		Conservative Case Final Flaw Length to Cause Failure in Indicated Number of Cycles (inches)			Actual Case Final Flaw Length to Cause Failure in Indicated Number of Cycles			Margin of Conservatism on Final Flaw Length to Cause Failure in Indicated number of Cycles		
		Conserv.	Actual	200	400	12,000	200	400	12,000	200	400	12,000
5 Ton	zero	0-11.6	0-11.6	3.00"	3.00"	2.10"	Same as	Conser.	Case	0	0	0
	one	0-13.8	0-12.6	2.85"	2.80"	2.00"	3.02"	2.80"	2.15"	0.056	0	0.069
	two	0-6.41	0-6.14	3.85"	3.70"	2.90"	3.85"	3.75"	3.00"	0	0.013	0.033
										0	0	0
4 Ton	zero	0-15	0-15	2.15"	2.10"	1.50"	Same as	Conser.	Case	0	0	0
	one	0-17	0-16	2.10"	1.90"	1.48"	2.15"	2.10"	1.52"	0.023	0.095	0.026
	two	0-11.2	0-9.75	2.50"	2.40"	1.90"	2.60"	2.55"	1.98"	0.038	0.059	0.040

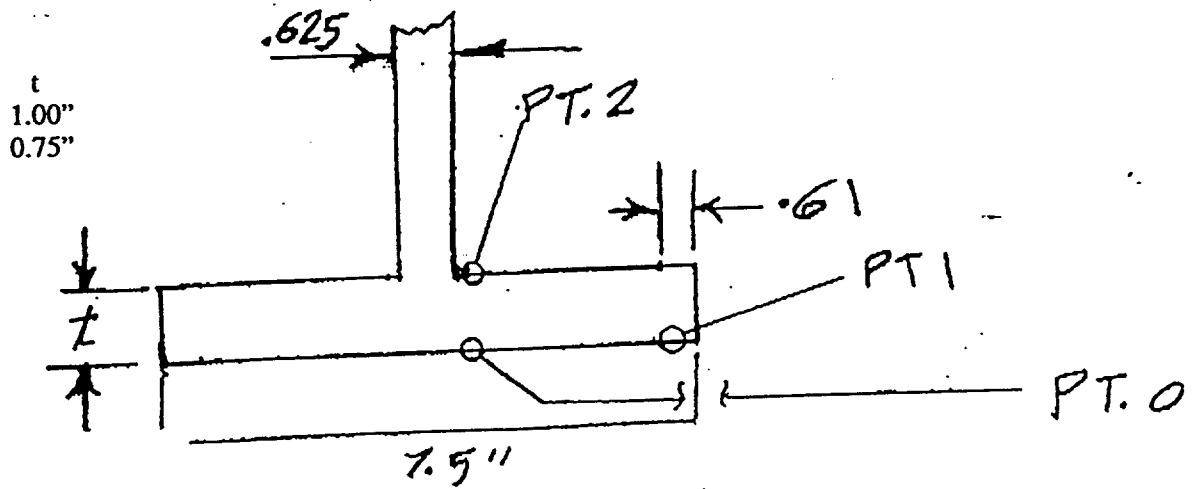
Notes:

(1) Margin of Conservatism =  $1 - \frac{\text{Final flaw-length (conservative case)}}{\text{Final flaw-length (actual case)}}$



(A) SCHEMATIC OF CROSSECTION OF BEAM

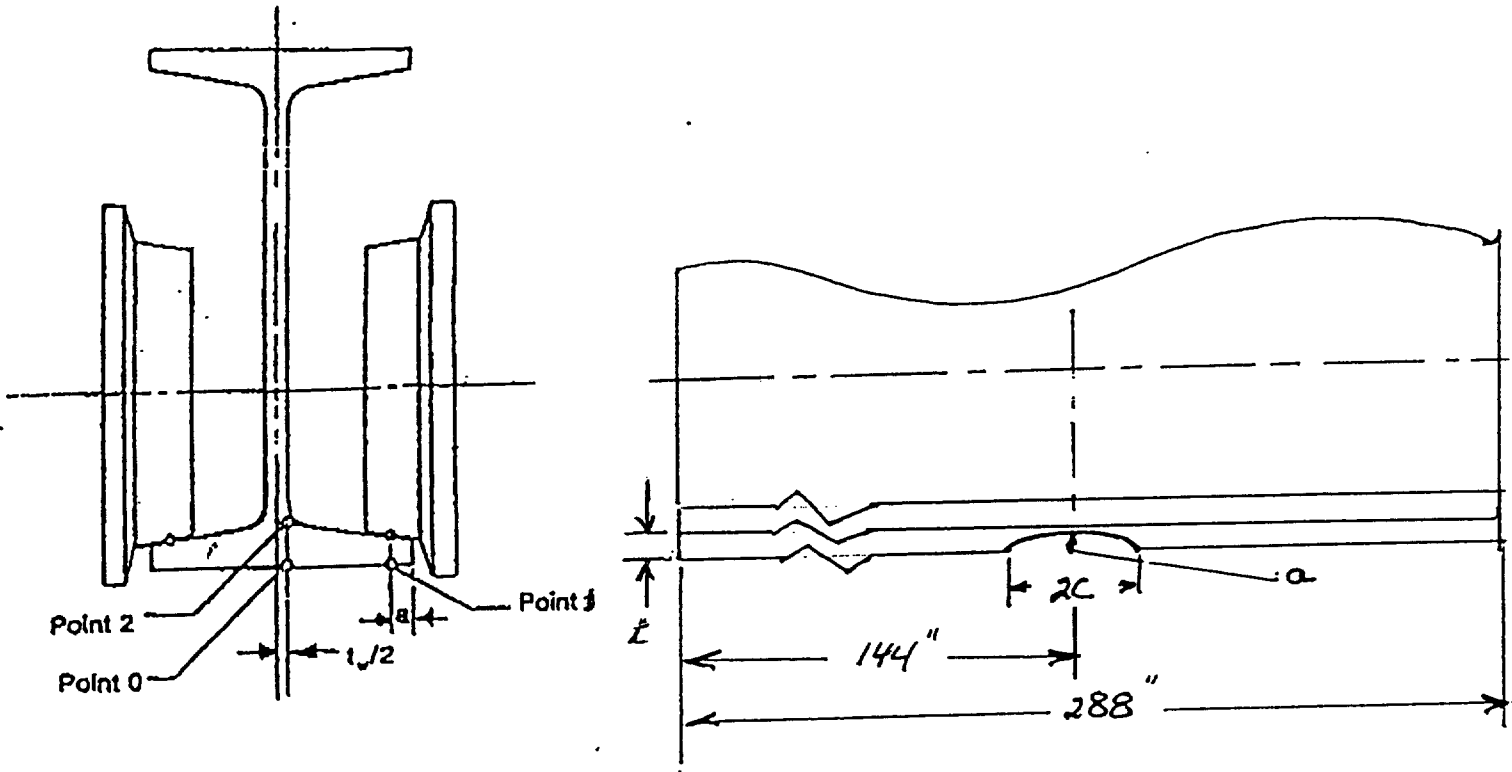
CRANE TYPE  
5 TON  
4 TON



(B) SCHEMATIC OF LOWER FLANGE OF BEAM

FIGURE 1

FIGURE 2

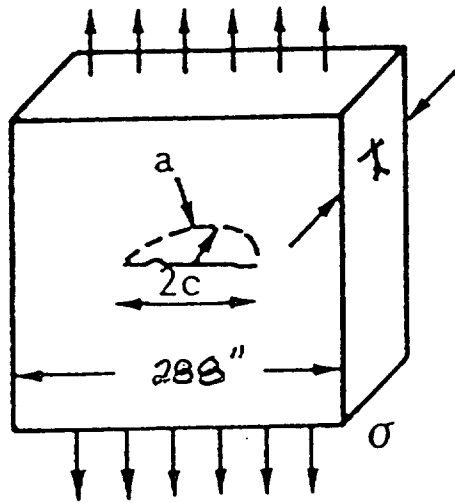


(A) CROSSSECTION OF BEAM, SHOWING LOCATIONS OF LOAD-APPLICATION

(B) LOCATION OF SEMI-ELLIPTICAL SURFACE CRACK IN FLANGE OF BEAM

CRANE TYPE  
5 TON  
4 TON

$t$   
1.00"  
0.75"



$a/2c = 0.25$

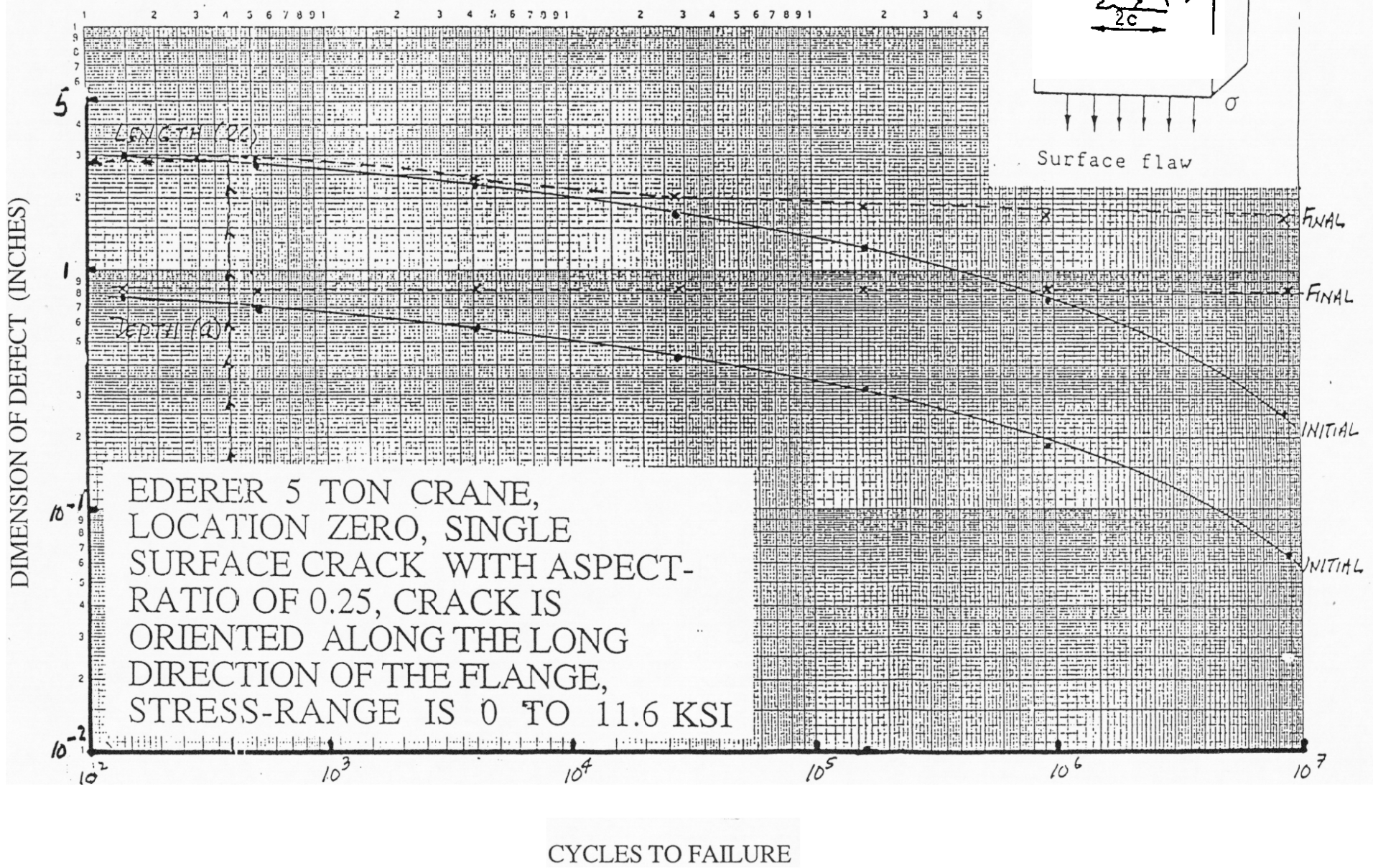
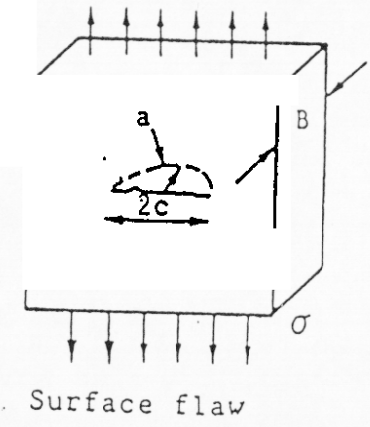
(C) SCHEMATIC OF A SEMI-ELLIPTICAL SURFACE CRACK

DETAILS OF MODEL FLAW AND ITS LOCATION IN LOWER FLANGE OF CRANE-BEAM

E.D.  
8/26

FIGURE 3

LOG ARITHMIC  
 12 1/2 CYCLES  
 NEUFEL & BEKER CO.  
 46 7520



CYCLES TO FAILURE

## **Appendix A - Construction of Materials Design-Allowables for ASTM A-36 Steel Used in Construction of the Ederer Cranes in the Device Assembly Facility (D.A.F.)**

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### **Introduction:**

Steel supplied to recent version of ASTM specification A-36 (A-36-89, Ref. A-1) falls in the category of a "plain carbon", or carbon-steel, and is supplied as rolled structural shapes (angles, channels, and tees, for example), plates, and bars of structural quality for use in riveted, bolted, or welded construction. It is seldom supplied with any type of fracture-toughness requirements. In plate up to 4" thick supplied to earlier versions of ASTM A-36 (Ref. A-2), material could be supplied without having had excess dissolved oxygen removed by liquid-state deoxidation with Si, Al, (or both) to form insoluble particles of oxides called "inclusions". Such steels are called "Rimmed Steels". Partial liquid-state deoxidation is also allowable in plates up to 3/4" thick, and steel so treated is referred to as "semi-killed steel". Plates above 3/4" thick supplied to Ref. 2, and plates above 2" thick supplied to earlier versions of ASTM A-36, are supplied in the fully-deoxidized or "fully-killed" condition. The reasons for the concern about the deoxidation-state of A-36 steel are: (1) The higher the dissolved (soluble) oxygen-content in A-36 steel, the higher is the toughness-transition temperature and the lower will be the upper shelf energy, a measure of ductile fracture-toughness (Ref. A-3); and (2) The higher the inclusion-content (caused by less than complete liquid state deoxidation), the greater will be the directional-dependence of fracture-toughness in the finished product, since large numbers of the oxide inclusions will be elongated in the primary rolling-direction and will serve as semi-continuous paths of easy crack growth in this direction during mechanical loading (Ref. A-3).

How the steel used in manufacture of the cranes D.A.F. were made and whether these heats of steel were evaluated for fracture-toughness is of importance for two reasons:

1. Both LLNL Mechanical Engineering Design Safety Standards (Ref. A-4) and the NTED Design Guide (Ref. A-5) mandate the use of a "lower bound plane-strain fracture-toughness" ( $K_{Ic}$ ) of 25 ksi $\sqrt{in}$ . for uncharacterized steels; and
2. The arbitrary use of such a low  $K_{Ic}$  value for fracture-mechanics-based analyses of the fracture safety of critical components in D.A.F. could result in imposition of expensive and unreasonable restrictions on operation and periodic inspection of the D.A.F. cranes.

Review of documentation (Ref. A-6) submitted with the stress-analyses of the D.A.F. cranes indicated that the A-36 steel used in the manufacture of the D.A.F. cranes was fully deoxidized, and both charpy v-notch impact and (in a few cases), dynamic tear tested. Hence, use of plane-strain fracture-toughness values greater than the aforementioned "lower-bound value" is appropriate. The results of a literature search on the variation of  $K_{Ic}$  with temperature for A-

36 (and similar) steels (Refs. A-7 to A-12) is presented in Figure A-1, where the "lower bound"  $K_{Ic}$  values for this material at and slightly below room temperature is 45-47 KSI  $\sqrt{in}$ . Accordingly, a  $K_{Ic}$  value of 45 KSI  $\sqrt{in}$  was adapted for use in the subject analyses.

A similar search for fatigue-crack-growth-rate (F.C.G.R.) information yielded the information (Refs. A-13 to A-19) in the form that is plotted in Eqn (A-1) and is presented in Figures A-2 through A-4.

$$(A-1) \text{ F.C.G.R.} = \frac{da}{dn} = C (\Delta K)^m$$

where  $da$  = incremental increase in crack-length  
 $dn$  = incremental increase in number of load-cycles  
 $C, m$  = material-constants that are fixed for constant material, temperature, and ratio of minimum to maximum load ("R")

$K$  = Range of stress intensity =  $K_{max} - K_{min}$ , where  
 $\sigma_{max} - \sigma_{min}$

$\sigma$  = applied stress

$a$  = characteristic dimension of crack (or flaw), it may be depth, surface length or half of the surface length.

$\beta$  = A parameter that depends on the geometric constraints of the problem; in particular any angular relationships between the load (or loads) and direction of crack-extension, as well as the geometry of the structure.

Examination of Figs. A-2 through A-4 indicates that the highest F.C.G.R. data-set is that for hot-rolled A-36 steel tested under conditions of  $R=0$ ; i.e.

$$(A-2) \quad \frac{da}{dn} = 3.98 \times 10^{-12} (\Delta K)^{4.86}$$

which is the F.C.G.R. expressed selected for use in the fatigue crack growth analyses.

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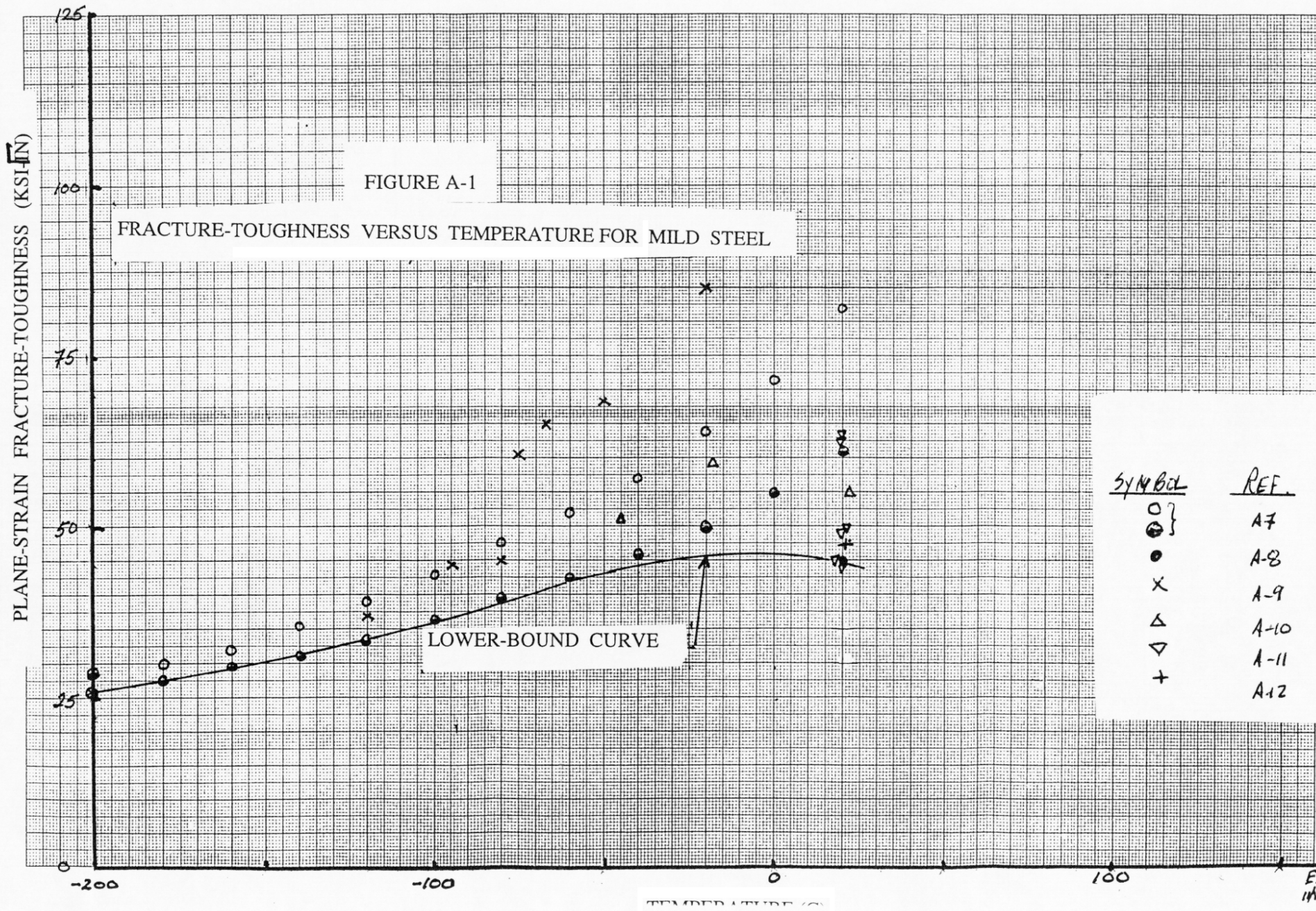
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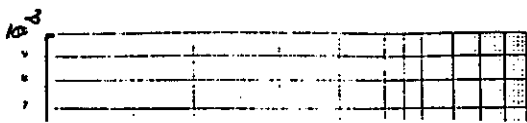
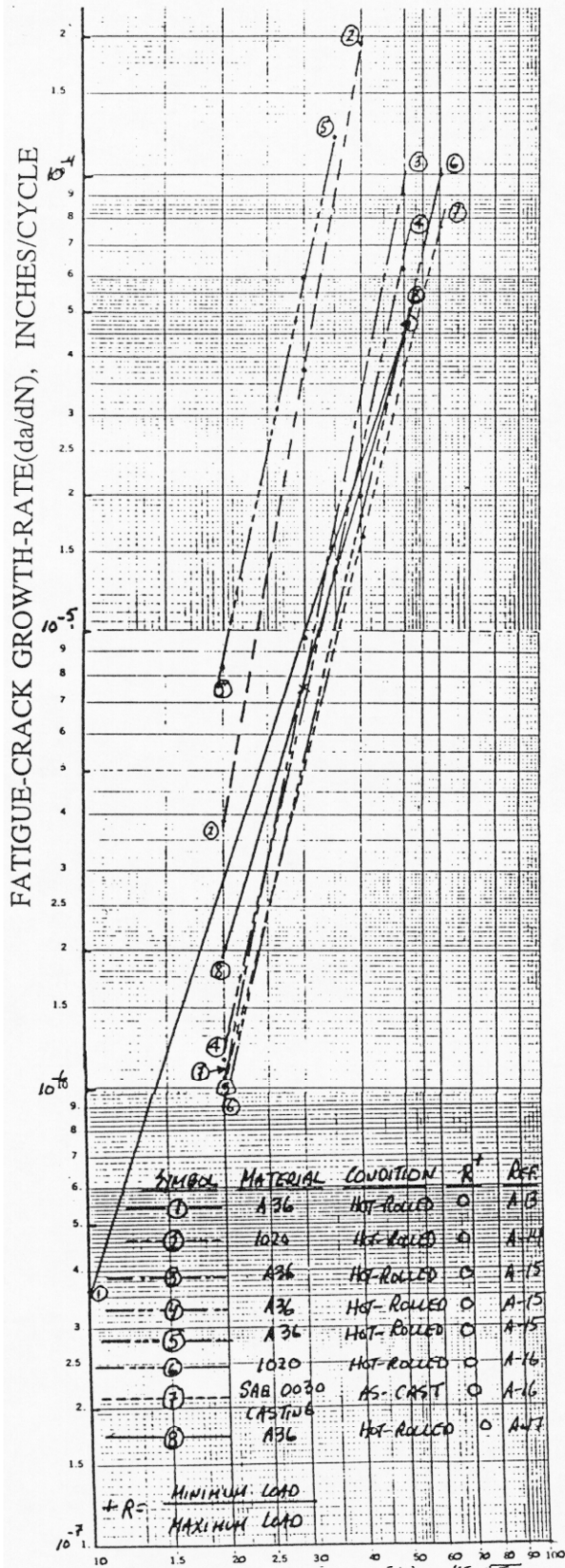


FIGURE A-2

ROOM-TEMPERATURE FATIGUE-CRACK GROWTH BEHAVIOR OF A.S.T.M. A-36 STEEL AND EQUIVALENT MATERIALS



STRESS-INTENSITY RANGE(Δ K), KSI√IN

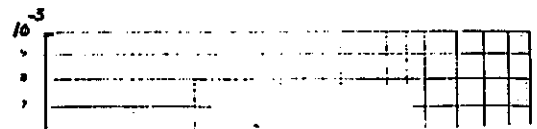
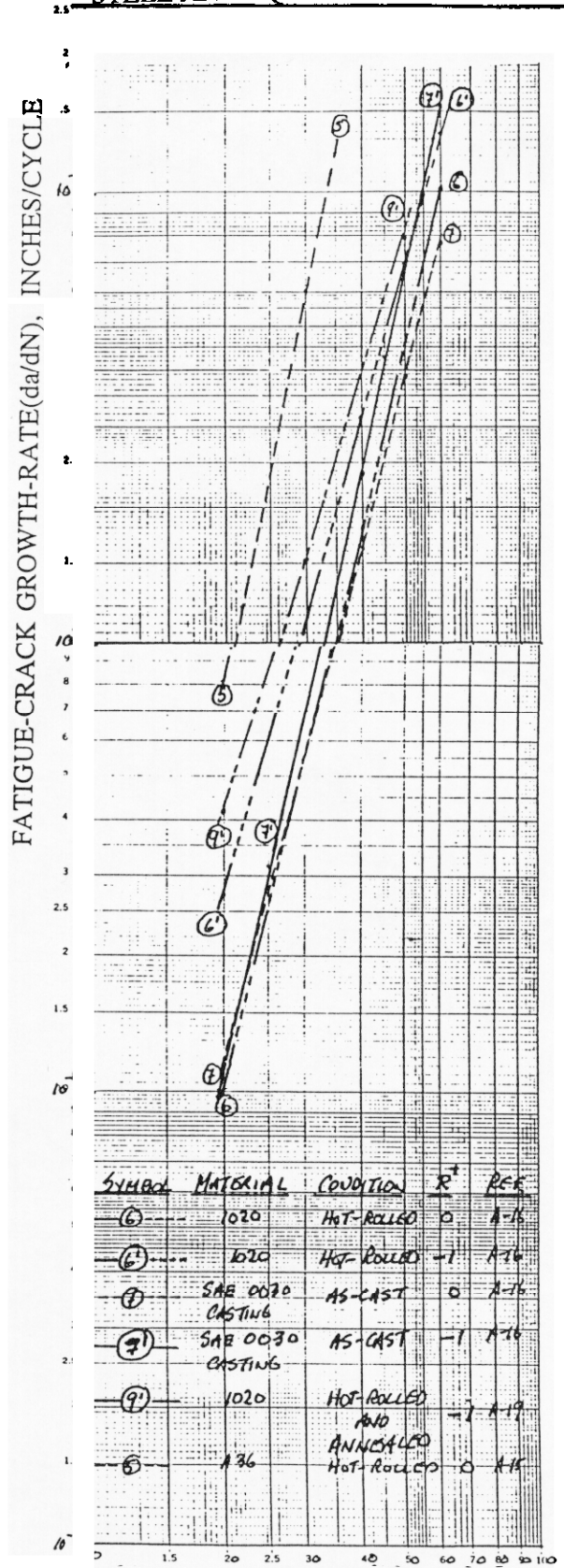


FIGURE A-3

EFFECT OF LOAD-RATIO ON ROOM-TEMPERATURE FATIGUE-CRACK GROWTH BEHAVIOR OF A.S.T.M. A-36 STEEL AND EQUIVALENT MATERIALS



STRESS-INTENSITY RANGE(Δ K), KSI√IN

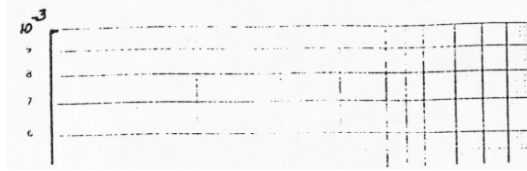
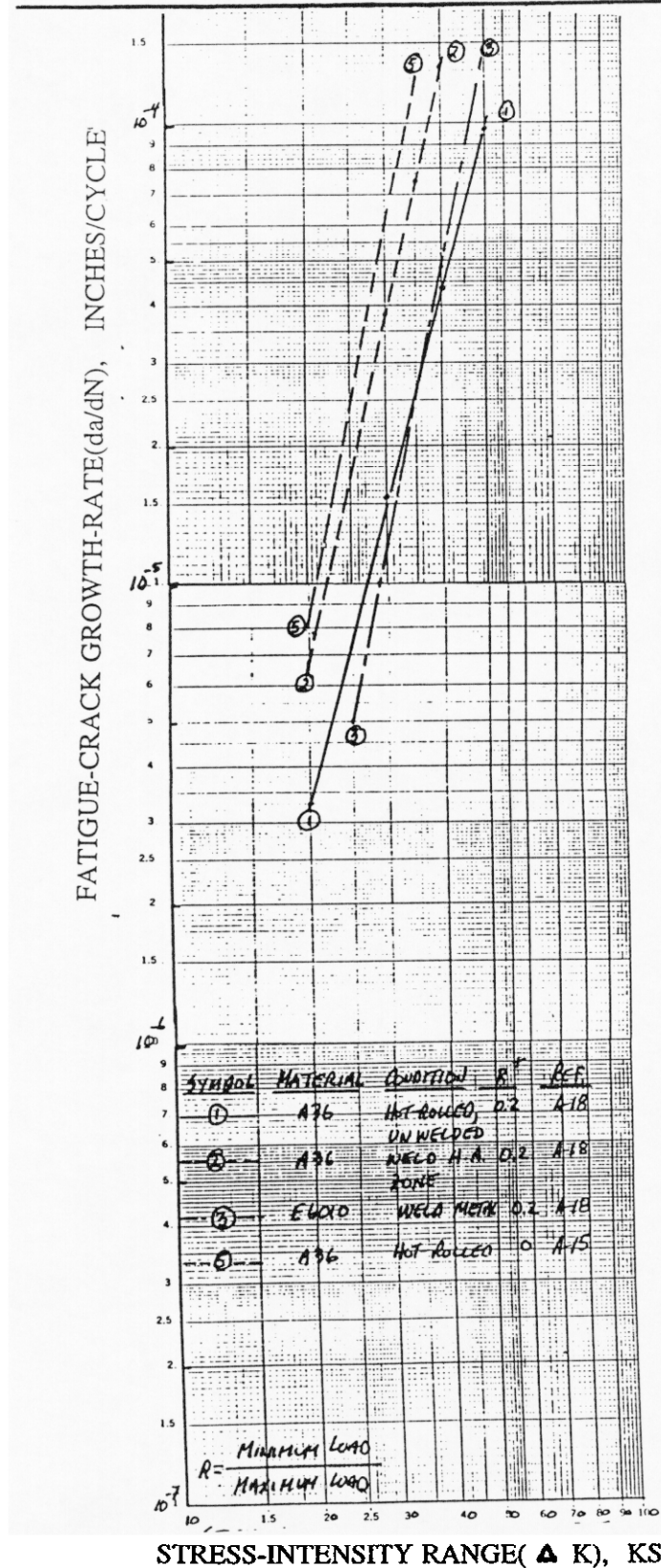


FIGURE A-4

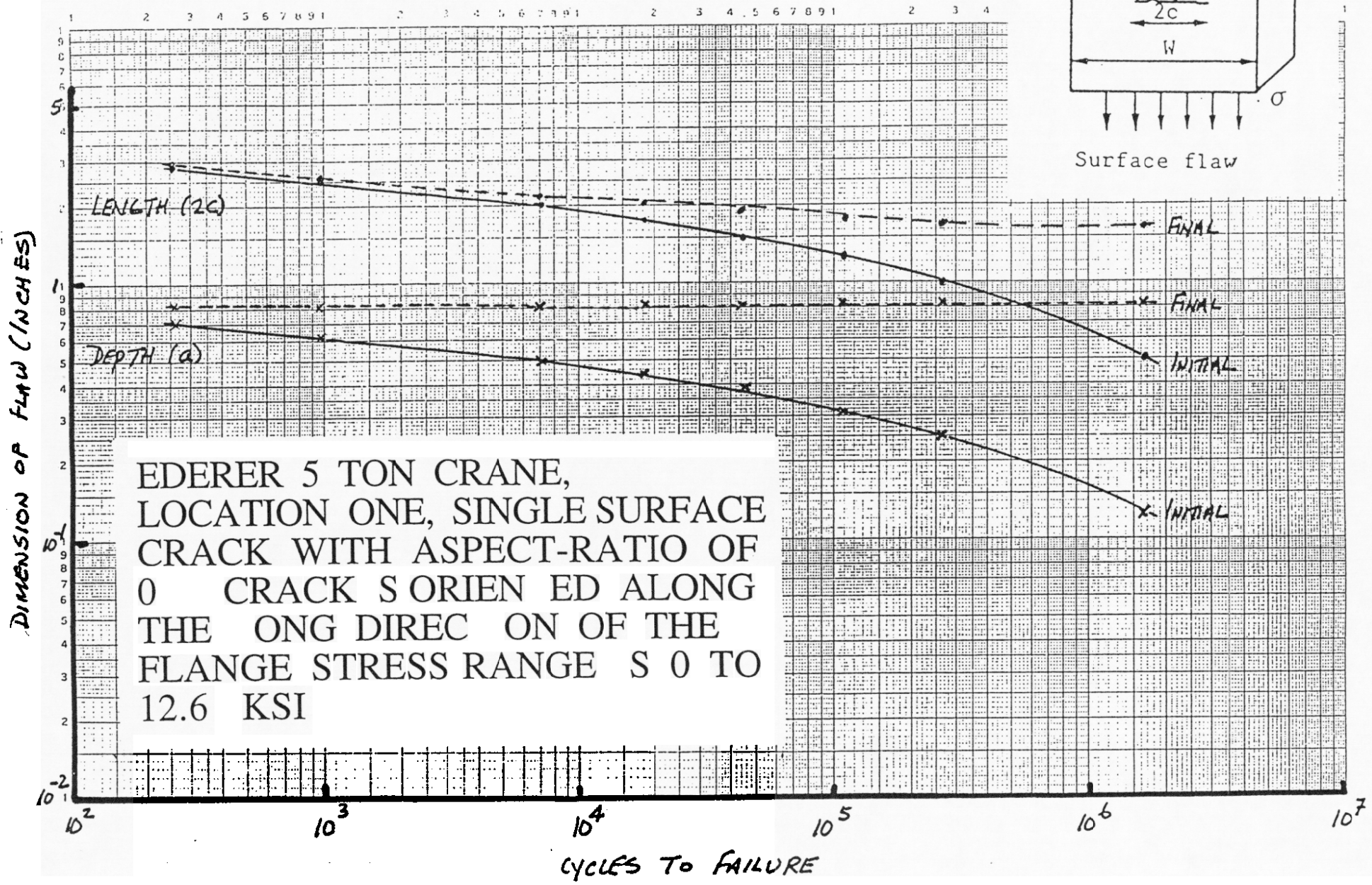
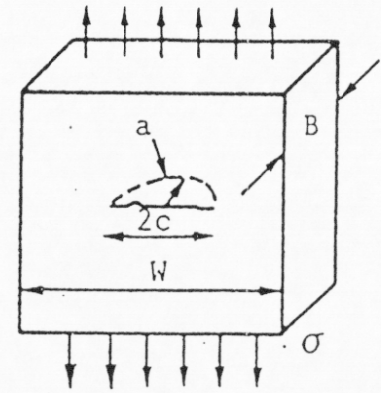
EFFECT OF FUSION-WELDING ON THE ROOM TEMPERATURE FATIGUE-CRACK GROWTH-RATE OF A.S.T.M. A-36 STEEL AT FIXED LOAD-RATIOS

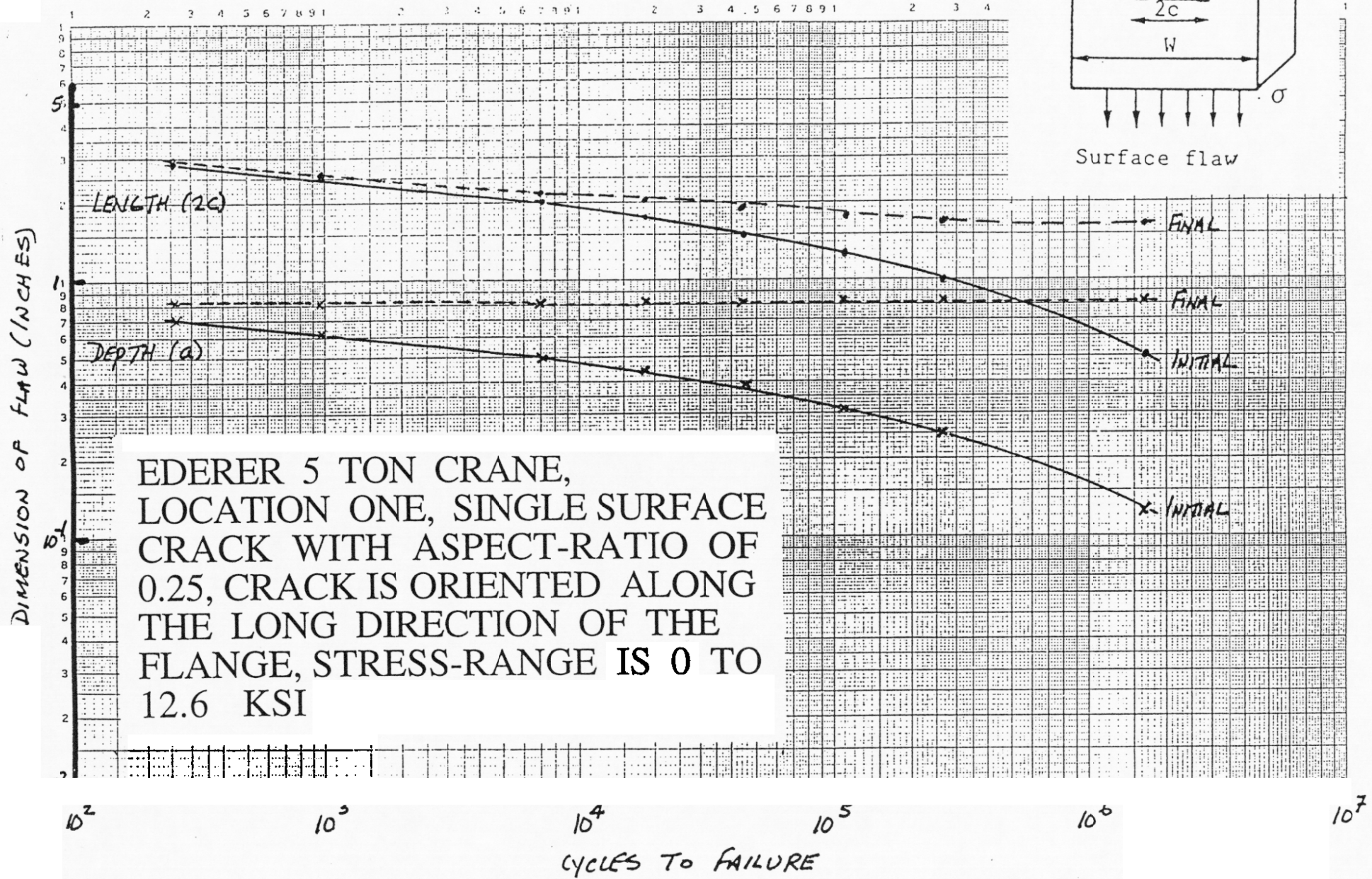
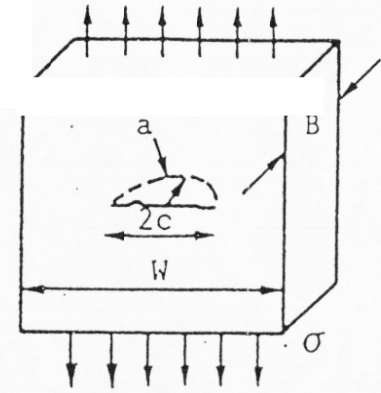


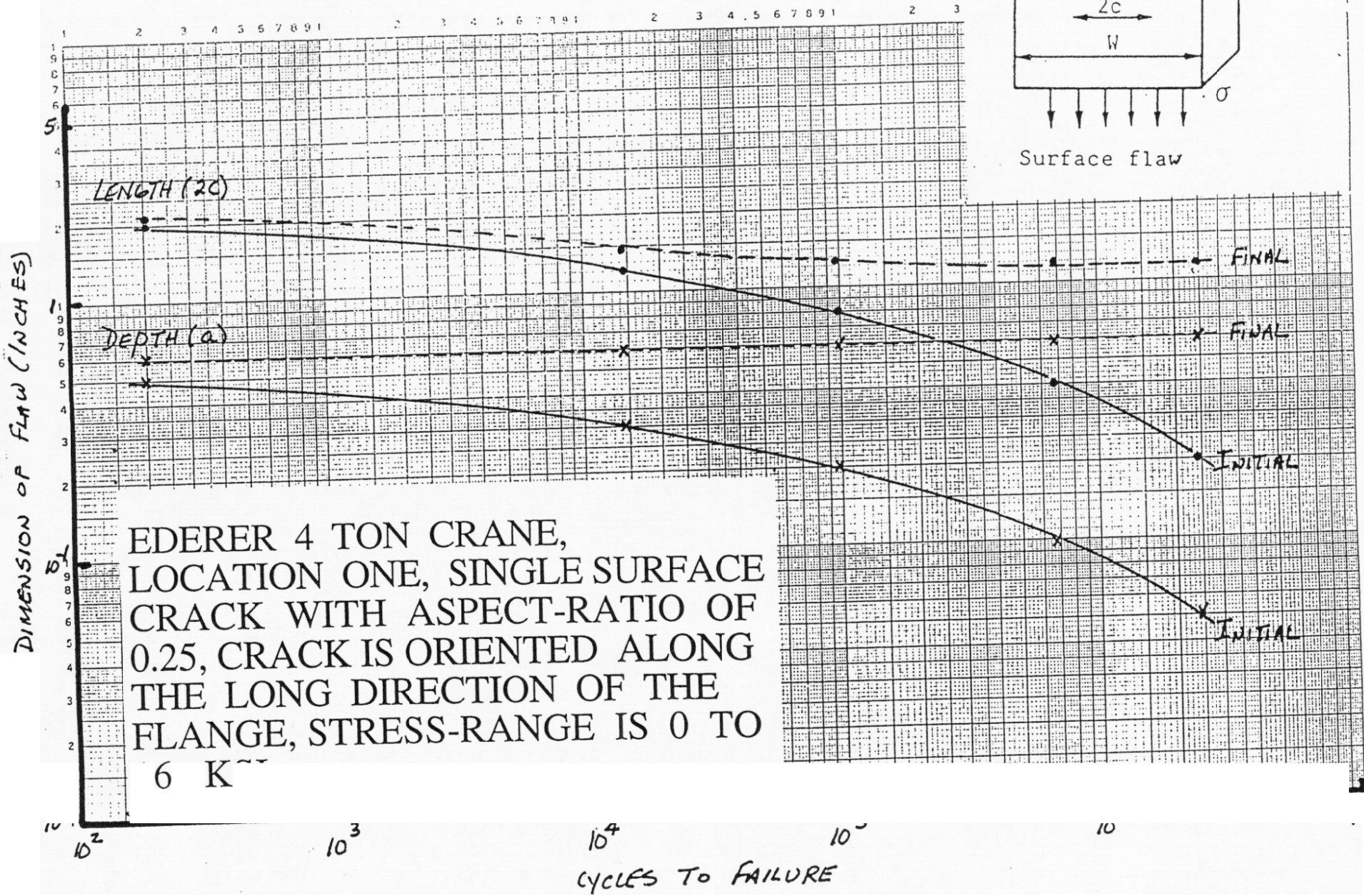
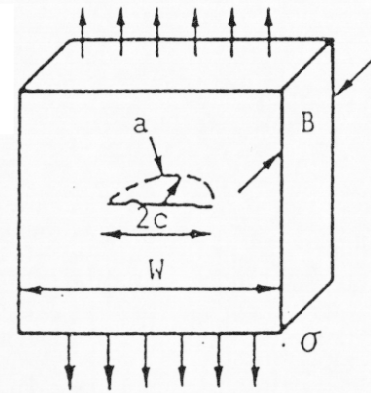
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8/76

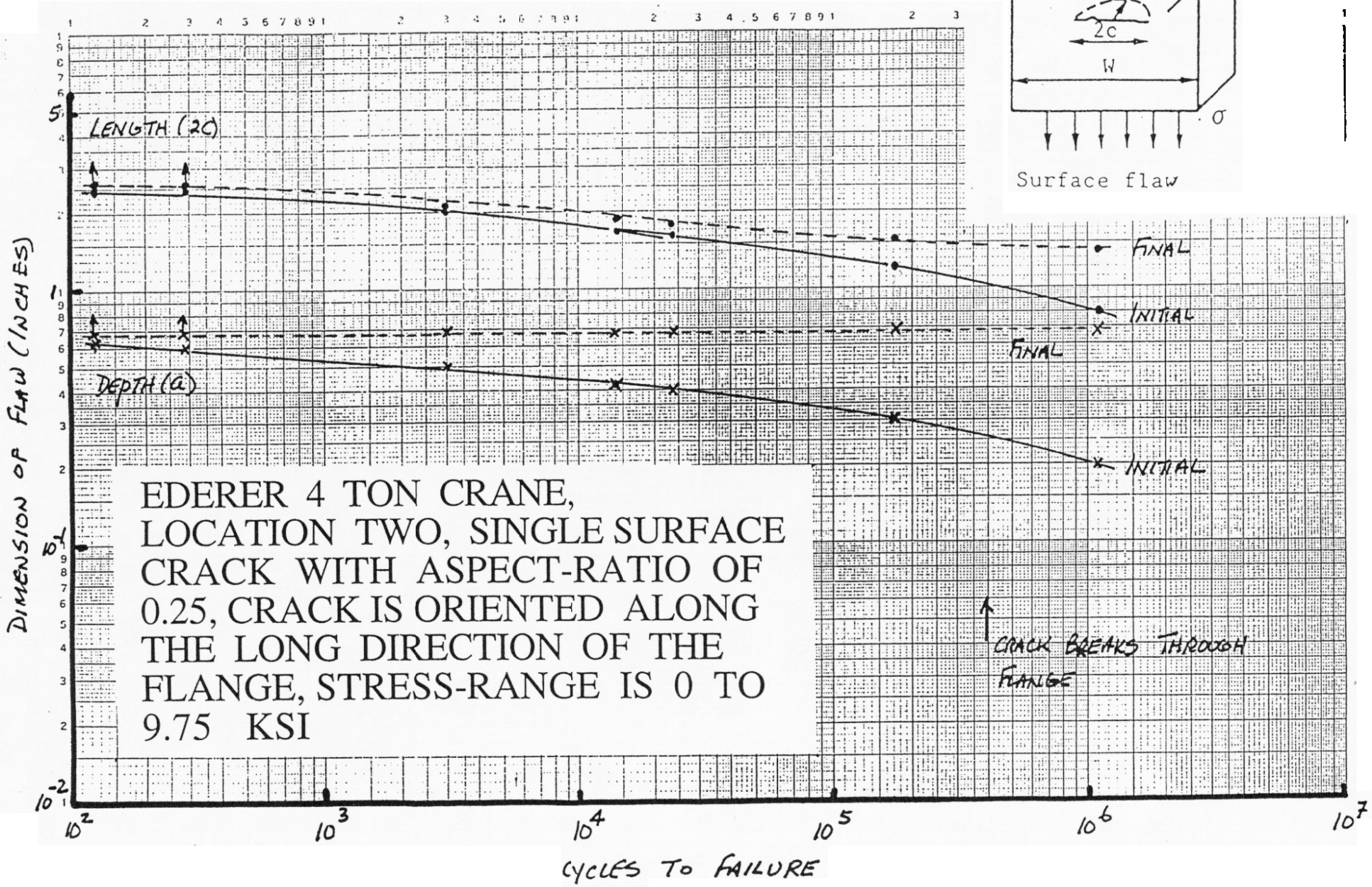
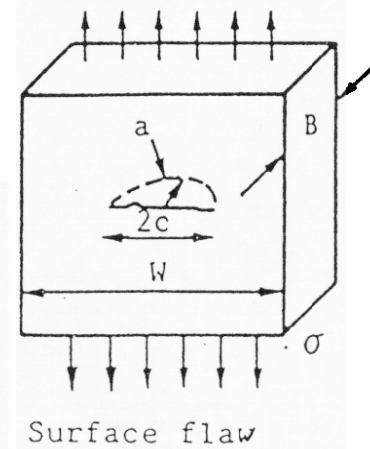
**Appendix B Plots of Flaw-Dimension Versus Cycles to Failure for  
Ederer Cranes**

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↑  
CRACK BREAKS THROUGH  
FLANGE



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