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FRACTURE CHARACTERISTICS
OF
6Al—4V TITANIUM ALLOY FORGINGS
CONTAINING
ALPHA STRINGER MICROSTRUCTURE

By

W. D. Bixler

Prepared For

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION

Contract NAS 9-8809

THE BOEI

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FINAL REPORT

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January 1969

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Technical Management

NASA Manned Spacecraft Center

Houston, Texas

G. M. Ecord

Aerospace Group

THE BOEING COMPANY

Seattle, Washington

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ABSTRACT

Mechanical properties, plane strain fracture toughnesses and plane strain sustained and cyclic load flaw growth characteristics were obtained for 6AL-4V titanium forgings with and without alpha stringers. Sustained load tests were conducted in environments of nitrogen tetroxide, Aerozine 50 and Freon TF at a nominal temperature of 80°F while all other tests were performed in air at room temperature. It was concluded based on these test results that the fracture characteristics are not degraded by the presence of alpha stringers. Only the ductility was significantly different in the forging containing alpha stringers.

KEY WORDS

Fracture characteristics
6AL-4V titanium
Mechanical properties
Plane strain fracture toughness
Sustained load flaw growth
Cyclic load flaw growth
Nitrogen tetroxide
Aerozine 50
Freon TF

FORWARD

The discovery of unusually low elongation properties and an associated microstructure containing alpha phase titanium in the form of stringers in Lunar Module propellant tank forgings prompted NASA/MSC Houston, Texas to initiate a study aimed at determining the effects of alpha stringers on the fracture characteristics of 6AL-4V titanium forgings. NASA requested the Space Division of The Boeing Company to conduct this investigation. This work was performed under NASA Contract NAS 9-8809 during the period from September 10, 1968 to January 24, 1969, and the results are reported herein. The work was administered under the direction of Mr. G. M. Ecord at NASA/MSC.

Boeing personnel who participated in this investigation include J. N. Masters, Program Supervisor and W. D. Bixler, Technical Leader. Structural testing of the specimens was conducted by A. A. Ottlyk, G. A. VanStaalduine, and G. E. Vermilion. Metallurgical support was provided by L. Albertin.

The information contained in this report is also released as Boeing Document D2-121005-1.

SUMMARY

The objective of this program was to determine the effects of the presence of alpha stringers on the linear elastic fracture properties of 6AL-4V S.T.A. titanium forgings. Tests were performed on two separate forgings; one containing alpha segregation in the form of stringers and the other one containing normally dispersed islands of alpha phase. These tests consisted of mechanical property tests, plane strain fracture toughness tests, sustained load tests and cyclic load tests. The sustained load tests were conducted in environments of nitrogen tetroxide (NO content 0.65 percent), Aerozine 50 and Freon TF at a nominal temperature of 80°F. All remaining tests were performed in an environment of air at room temperature.

Results of these tests indicated there were negligible differences in yield strengths, ultimate strengths, plane strain fracture toughnesses and the cyclic growth behaviors between the alpha and normal forgings. The alpha forging exhibited 25 percent less ductility and 5 percent higher stress intensity thresholds than the normal forging.

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1.0 INTRODUCTION

In general, unexpected failures in pressure vessels originate at flaws. Failures of pressure vessels have occurred during proof test and operational service. Proof test failures result where the size of a flaw is sufficiently large to become unstable before proof stress is attained or the flaw grows sufficiently large to become unstable at proof stress during a hold period. In the former case the critical stress intensity of the material is exceeded on loading. In the latter case the threshold stress intensity of the material/pressurizing fluid is exceeded resulting in subcritical flaw growth until the critical stress intensity of the material is reached. Operational failures have often occurred after a flaw grew sufficiently in size to become unstable at the operating stress. An estimate of the performance capability of pressure vesels requires knowledge of initial flaw sizes, critical flaw sizes, and subcritical flaw growth characteristics of the vessel material.

It is the purpose of this investigation to determine the effects of alpha stringers on the fracture characteristics of 6AL-4V titanium. This includes determination of the mechanical properties, fracture toughness, sustained growth behavior and cyclic growth behavior. The sustained load tests are performed in nitrogen tetroxide, Aerozine 50 and Freon TF, with the remaining tests conducted in air. In order to ascertain the effects of alpha stringers, two forgings were investigated; one containing alpha stringers and the other of normal microstructure.

2.0 MATERIALS

2.1 TITANIUM FORGINGS

Two separate 6AL-4V titanium forgings were supplied by NASA/MSC Houston, Texas. The material was taken from Lunar Module ascent propellant vessel dome forgings which were rejected because of low elongation properties and the presence of alpha segregation in the trim rings. The material was 0.60 inches thick with a diameter of approximately 50 inches. One forging, designated -105, reportedly contained alpha segregation in the form of stringers whereas the other forging, designated -76, reportedly exhibited well dispersed islands of alpha matrix. These two forgings, -105 and -76, will be referred to as the alpha forging and normal forging, respectively. Heat treatment and composition of both forgings are shown in Table I.

A metallurgical examination revealed a significant amount of alpha stringers in the alpha forging. These alpha stringers were oriented parallel to the circumferential and meridional directions in approximately equal quantities. The normal forging also contained alpha stringers but were shorter, narrower and fewer in quantity than the alpha forging. Typical alpha forging and normal forging microstructure is shown in Figure 1.

2.2 TEST FLUIDS

Nitrogen tetroxide, Aerozine 50 and Freon TF samples of the test fluids were analyzed per MSC-PPD-2B, MIL P-27402 and MSC-C28, respectively, with the results shown in Table II. The nitrogen tetroxide was "spiked" to a nitric oxide (NO) content of 0.65 percent. No attempt was made to determine the amount of soluble and insoluble residue in the Freon TF sample due to the lack of sufficient test fluid.

3.0 PROCEDURES

3.1 SELECTION OF SPECIMEN ORIENTATION AND FLAW LOCATION

A test was performed prior to machining specimens for the basic program to determine the most critical specimen orientation and flaw location. This involved the use of tensile specimens, fracture specimens, and metallurgical examination. Tensile specimens and fracture specimens were machined from various locations throughout the alpha and normal forging. These specimens were oriented in both the meridional and circumferential directions. All specimens conformed to the configuration and fabrication procedures as described in paragraph 3.2. The results from statically testing these tensile specimens and fracture specimens indicated no significant directionality with respect to mechanical properties and fracture toughness. The results of the specimens tested are reported in detail in Sections 4 and 5 of this report.

Metallurgical examination throughout the forgings did not indicate any preferred orientation of the alpha stringers. The degree or density of alpha stringers was also relatively uniform throughout the forgings. After viewing the microstructure, it was felt that it would be impossible to specifically locate the flaw tip at an alpha stringer. To demonstrate this, a typical alpha forging fracture specimen is shown in Figure 2.

Based on the results of these tests plus the metallurgical evaluation, an arbitrary decision was made to orient the program specimens in the meridional direction. Selection of specimen location was also arbitrary.

3.2 SPECIMEN FABRICATION

The location and orientation of the alpha and normal specimen blanks are shown in Figure 3. All tensile specimen blanks were stress relieved at 950°F for 8 hours prior to final machining. The fracture specimens were first machined flat to the desired thickness and then stress relieved at 950°F for 8 hours prior to final machining. The tensile and fracture specimen configurations are shown in Figure 4.

Fracture specimens containing precracked surface flaws were used for all static, sustained and cyclic load tests. Flaws were made by electric discharge machining (EDM), a starter notch and extending the notch by low stress/high cycle tension-tension fatigue. The fatigue extension was accomplished at a maximum gross stress of 30 ksi at 1800 cpm. From 8,000 to 16,000 cycles were required, depending upon the initial notch dimensions. All pre-cracking was done in air at room temperature.

3.3 STATIC AND FLAW GROWTH TEST SETUPS

The tensile and fracture specimens were tested in a 12,000 lb. Baldwin and a 20,000 lb. Riehle universal testing machines, respectively. All static tests were performed in an environmentally controlled laboratory at the Boeing Space Center.

The sustained load test specimens were loaded in 10,000 lb. dead-load creep machines. Those tests using nitrogen tetroxide and Aerozine 50 utilized a setup as shown in Figures 5, 6, and 7. Liquid was contained in two pressurized tanks connected with flex lines to each other and to a small cup clamped to the test specimen. Periodically, one of the tanks was raised or lowered so that the fluid would flow through the specimen cup thus supplying fresh fluid. Temperature was controlled by warm air supplied from Coates heaters. A schematic of the fluid and pressurization system is shown in Figure 8. These tests involving hazardous propellants were performed at Boeing's remote Tulalip Test Site.

The non-hazardous tests involving Freon TF were conducted in an environmentally controlled laboratory at the Boeing Space Center. Fluid containment was accomplished by encompassing the specimen with a polyethylene container as shown in Figure 9. After securing the wrapped specimen in the testing machine grips, Freon TF was injected into the plastic container with a hyperdermic needle.

Cyclic tests were performed in an environmentally controlled laboratory at the Boeing Space Center in a 20,000 lb. Riehle universal testing machine.

3.4 EXPERIMENTAL APPROACH FOR STATIC, SUSTAINED AND CYCLIC LOAD TESTS

Mechanical property specimens were tested at a strain rate of 0.004 inch/inch/min while the static fracture specimens were tested at a load rate of 10,000 lb/min. All cyclic flaw growth tests were conducted at 10 cycles per minute with a sinusoidal shaped zero-to-tension loading profile.

The approach used to define threshold stress intensity levels is shown schematically in Figure 10. The first surface flawed specimen (after determining the static K_{Ic} value) was loaded to a target stress intensity level less than critical (i.e., an initial stress intensity value, K_{Ii}). The specimen was held at constant load until failure or for approximately 48 hours. If failure did not occur, the specimen was low stress cycled in air to mark the flaw front, and then pulled to failure. Evidence of sustained load growth was then observed by a separation between the initial fatigue crack extension and that of the final marking. With either failure or evidence of growth in the first specimen, subsequent specimens were loaded at successively lower K_{Ii} values until neither failure nor growth took place.

3.5 STRESS INTENSITY SOLUTIONS

Initial and critical stress intensity values for all specimens tested were calculated using the expression:

$$K_I = 1.1\sigma \sqrt{\frac{\pi a}{Q}} M_K$$

where

K_I = stress intensity

σ = gross stress

a = flaw depth

Q = shape parameter

M_K = Kobayashi's deep flaw magnification factor

Values for Q and M_K are shown in Figures 11 and 12.

4.0 TEST RESULTS

4.1 MECHANICAL PROPERTIES

Mechanical property tests were conducted at room temperature for both the alpha forging and the normal forging. For the alpha forging, 10 specimens were oriented in the meridional direction and two in the circumferential direction. Five meridional and one circumferential tensile specimens from the normal forging were tested. The values obtained from each specimen is shown in Table III. A summary presenting the average values of the meridionally oriented specimens is given below:

MECHANICAL PROPERTIES	ALPHA FORGING	NORMAL FORGING
Yield Strength (ksi)	161.43	160.92
Ultimate Strength (ksi)	171.11	170.68
Elongation (%)	6.5	8.6
Area Reduction (%)	15.7	21.6

The circumferentially oriented specimens were tested to determine if any significant mechanical property difference existed due to specimen orientation.

4.2 PLANE STRAIN FRACTURE TOUGHNESS

Plane strain fracture toughness values were determined from alpha and normal forging specimens tested at room temperature. For the alpha forging, 11 specimens were oriented in the meridional direction and two in the circumferential direction. Six meridional and one circumferential fracture specimens from the normal forging were tested. The values obtained from each specimen are shown in Tables IV and V. The average fracture toughness values were 51.50 ksi $\sqrt{in}$ and 52.24 ksi $\sqrt{in}$ for the alpha and normal forgings, respectively, based on the meridionally oriented specimens.

The alpha forging exhibited a fracture toughness range of between 46.07 ksi $\sqrt{in}$ and 54.71 ksi $\sqrt{in}$ while the normal forging varied between 47.60 ksi $\sqrt{in}$ and 56.33 ksi $\sqrt{in}$. The circumferentially oriented specimens were tested to determine if any significant fracture toughness difference existed due to specimen orientation.

4.3 SUSTAINED LOAD FLAW GROWTH

The results of the sustained load tests using alpha and normal forging material are plotted in Figures 13 through 18. The tests were performed at a nominal temperature of 80°F in environments of nitrogen tetroxide, Aerozine 50 and Freon TF. The graphs present the data as a stress intensity ratio versus sustained time. The stress intensity ratio is the applied initial stress intensity divided by the respective average fracture toughness determined from static tests. A summary of the sustained load thresholds is tabulated below:

ENVIRONMENT	ALPHA FORGING	NORMAL FORGING
Nitrogen Tetroxide	0.80	0.76
Aerozine 50	0.74	0.71
Freon TF	0.81	0.74

The thresholds determined above are based on 10 alpha specimens and 5 normal specimens for the nitrogen tetroxide tests; 15 alpha specimens and 9 normal specimens for the Aerozine 50 tests; and 8 alpha specimens and 7 normal specimens for the Freon TF tests.

Tables VI through XI present the sustained load test results along with the maximum temperature recorded during the test run.

4.4 CYCLIC LOAD FLAW GROWTH

Cyclic load flaw growth tests were conducted at room temperature using both alpha and normal forging specimens oriented in a meridional direction. Eight alpha forging specimens and four normal forging specimens were cycled to failure at three different stress levels. The results are presented in Figure 19 and Table XII.

5.0 DATA ANALYSIS

5.1 STATIC LOAD BEHAVIOR

The yield and ultimate strengths of the alpha forging were found to average less than one percent more than that of the normal forging. A more significant effect of the alpha stringers was noticed in the ductility properties, such as elongation and area reduction. The ductility of the alpha stringer material was approximately 25 percent less than the normal material. A minimum elongation of 5 percent was exhibited by two alpha specimens, both oriented in the meridional direction.

The average fracture toughness of the normal forging was determined to be approximately one percent more than that of the alpha forging. There was approximately a 17 percent spread in the fracture toughnesses of both the alpha and normal forgings. In general, both forgings exhibited a toughness higher than average than most 6AL-4V S.T.A. titanium forgings.

Mechanical properties and fracture toughness of the circumferentially oriented specimens were found to be within the range of the results of the meridionally oriented specimens.

5.2 SUSTAINED LOAD BEHAVIOR

The results of the sustained load tests indicate thresholds for the alpha forging which were approximately 5 percent higher than for the normal forging in the same environment. A possible explanation for this effect is that the alpha stringers act as crack arresters under sustained load. Fractographs showing typical sustained growth areas are presented in Figure 20 for both forgings in various environments.

5.3 CYCLIC FLAW GROWTH BEHAVIOR

In general, the cyclic flaw growth behavior of both forgings fall within the scatter band of data from Reference 1 as shown in Figure 19. The scatter band of Reference 1 data is from a variety of 6AL-4V S.T.A. titanium forgings which did not contain alpha stringers. Specimens 34 and 129, stressed to 121 ksi, fell outside the scatter band. This may be a result of using average fracture toughness in plotting the data rather than an actual specimen toughness. As pointed out in paragraph 5.1, there was a 17 percent spread in fracture toughness in both forgings and it is possible that these two specimens had lower than average toughness.

6.0 CONCLUSIONS

Test results of the alpha forging and normal forging indicate the following characteristics:

1. MECHANICAL PROPERTIES

There is negligible difference in the yield and ultimate strengths between the alpha and normal forgings but the alpha forging has 25 percent less ductility than the normal forging.

2. FRACTURE TOUGHNESS

There is negligible difference in the plane strain fracture toughnesses between the alpha and normal forgings.

3. SUSTAINED FLAW GROWTH

The alpha forging exhibits a 5 percent higher stress intensity threshold than the normal forging in environments of nitrogen tetroxide, Aerozine 50 and Freon TF.

4. CYCLIC FLAW GROWTH

There is negligible difference in the cyclic flaw growth behavior between the alpha and normal forgings.

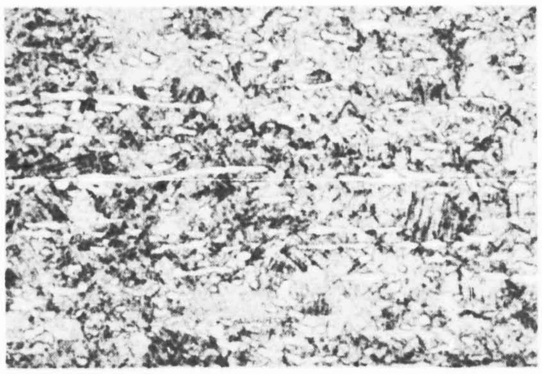
REFERENCES

1. Masters, J. N., "Cyclic and Sustained Load Flaw Growth Characteristics of 6AL-4V Titanium," NASA CR-92231, July 1968.

Circumferential

Meridional

ALPHA FORGING
(-105)

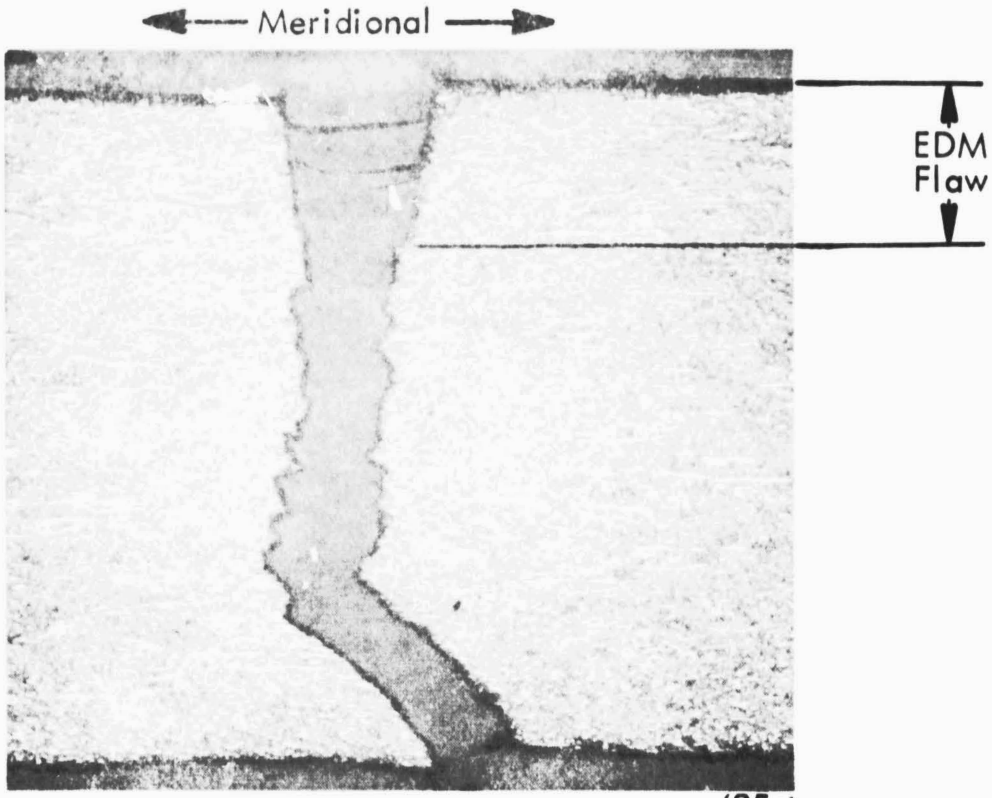


Circumferential

Meridional

NORMAL FORGING
(-76)

Figure 1 : TYPICAL ALPHA AND NORMAL FORGING MICROSTRUCTURE
(100 x)



FRACTURE EDGES
SPECIMEN C-1 (25x)

FRACTURE FACE
SPECIMEN 1 (25x)

Figure 2 : TYPICAL ALPHA FORGING FRACTURE SURFACES

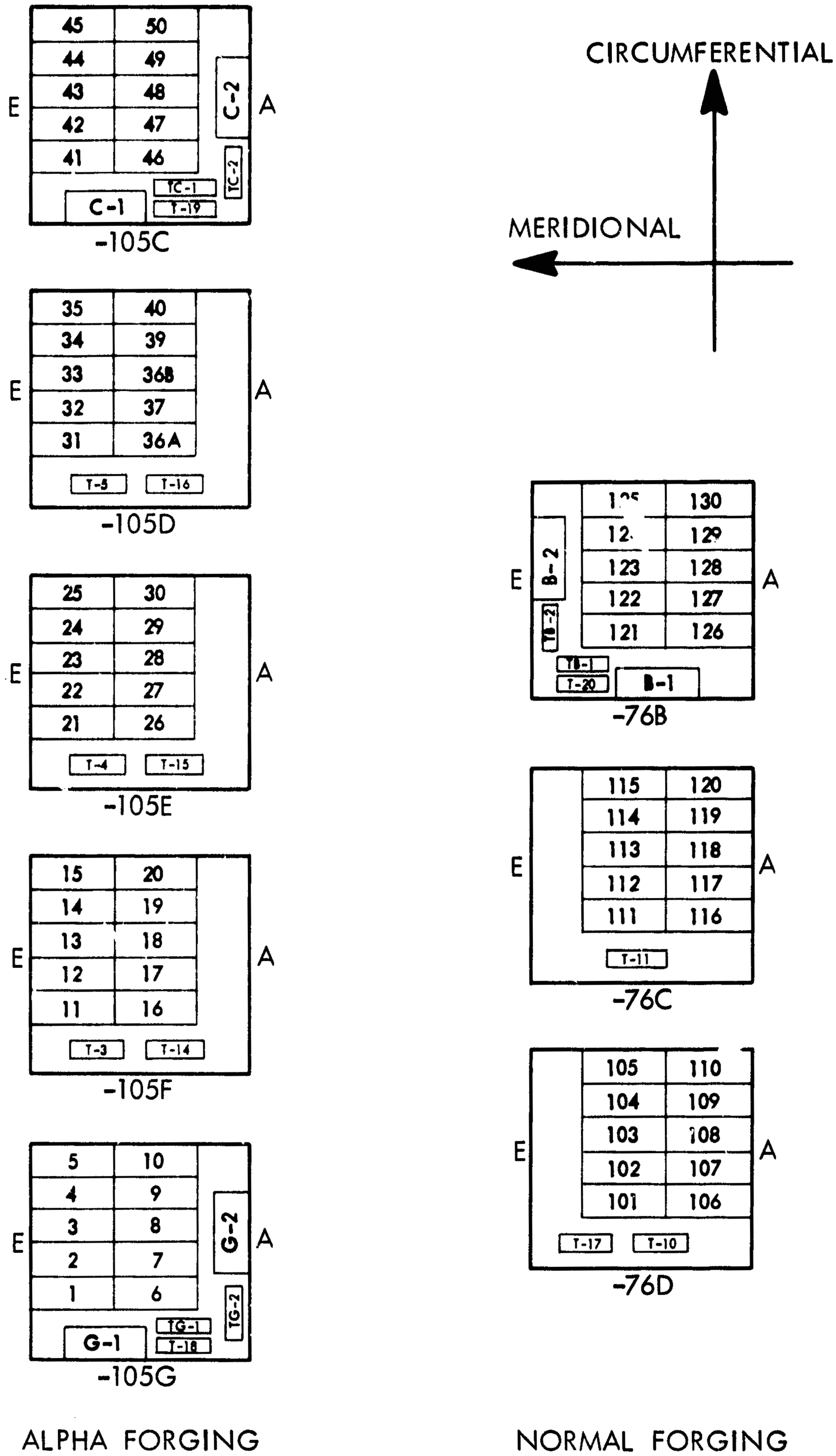
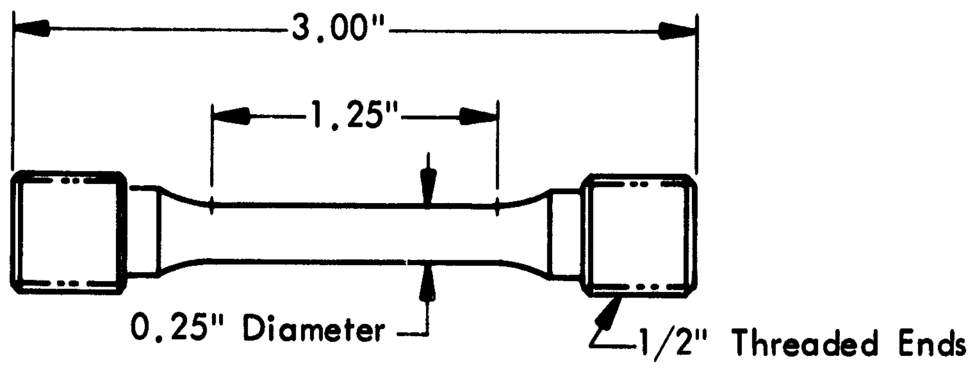
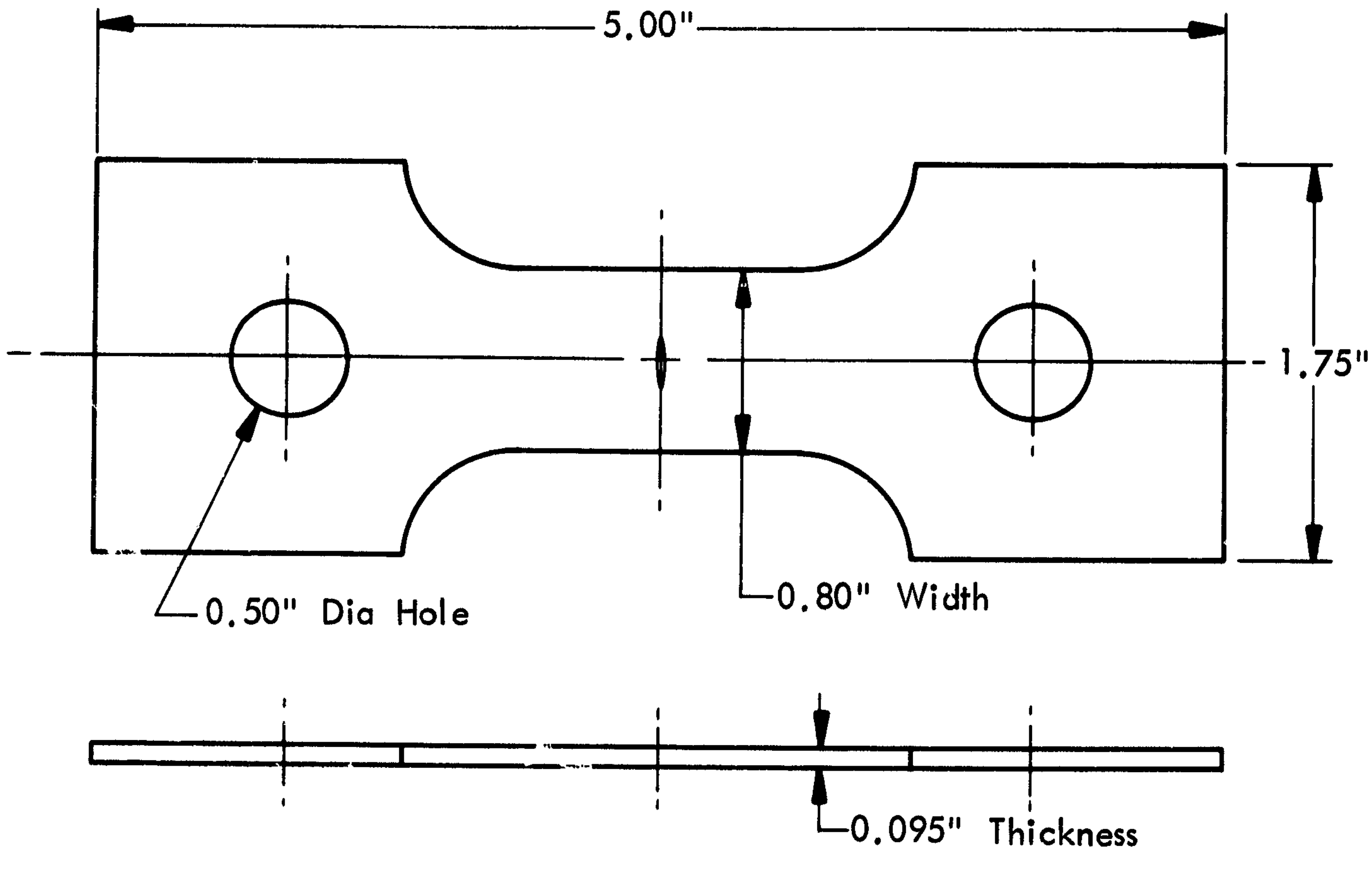


Figure 3 : SPECIMEN LOCATION AND ORIENTATION IN THE ALPHA AND NORMAL FORGINGS



TENSILE SPECIMEN



FRACTURE SPECIMEN

Figure 4 : SPECIMEN CONFIGURATIONS

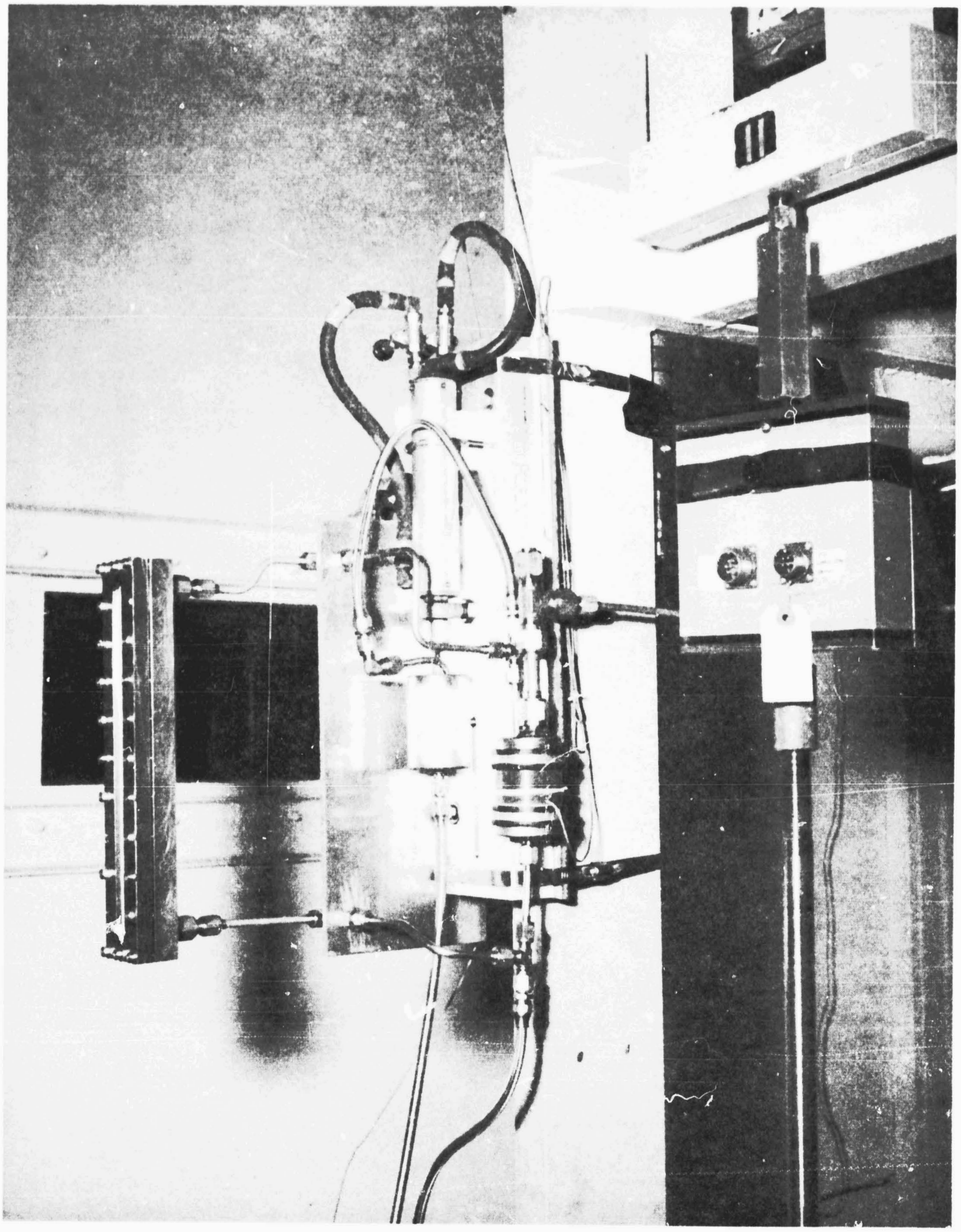


Figure 5: SUSTAINED LOAD TEST SETUP SHOWING SUPPLY SYSTEM

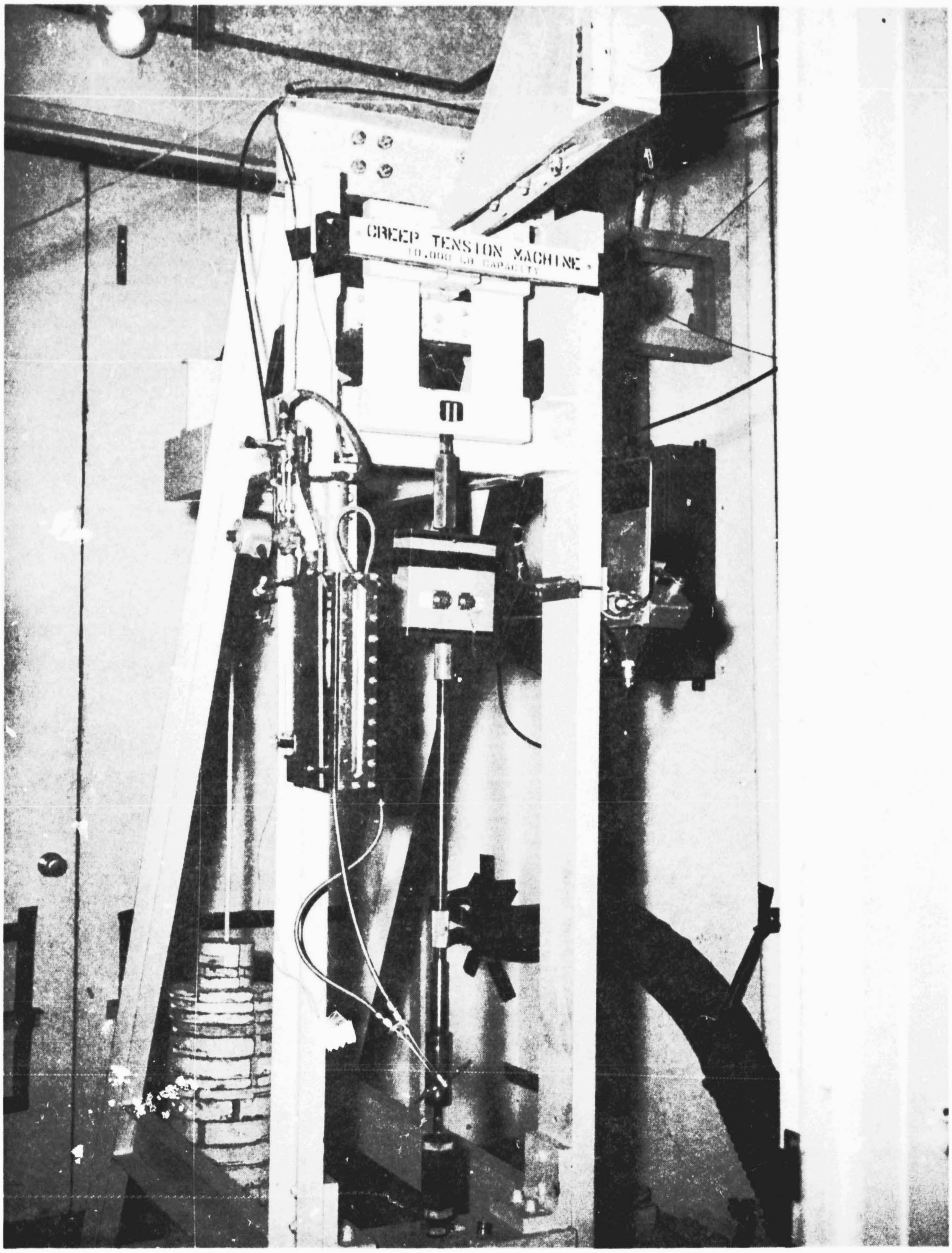


Figure 6: SUSTAINED LOAD TEST SETUP - OVERALL VIEW

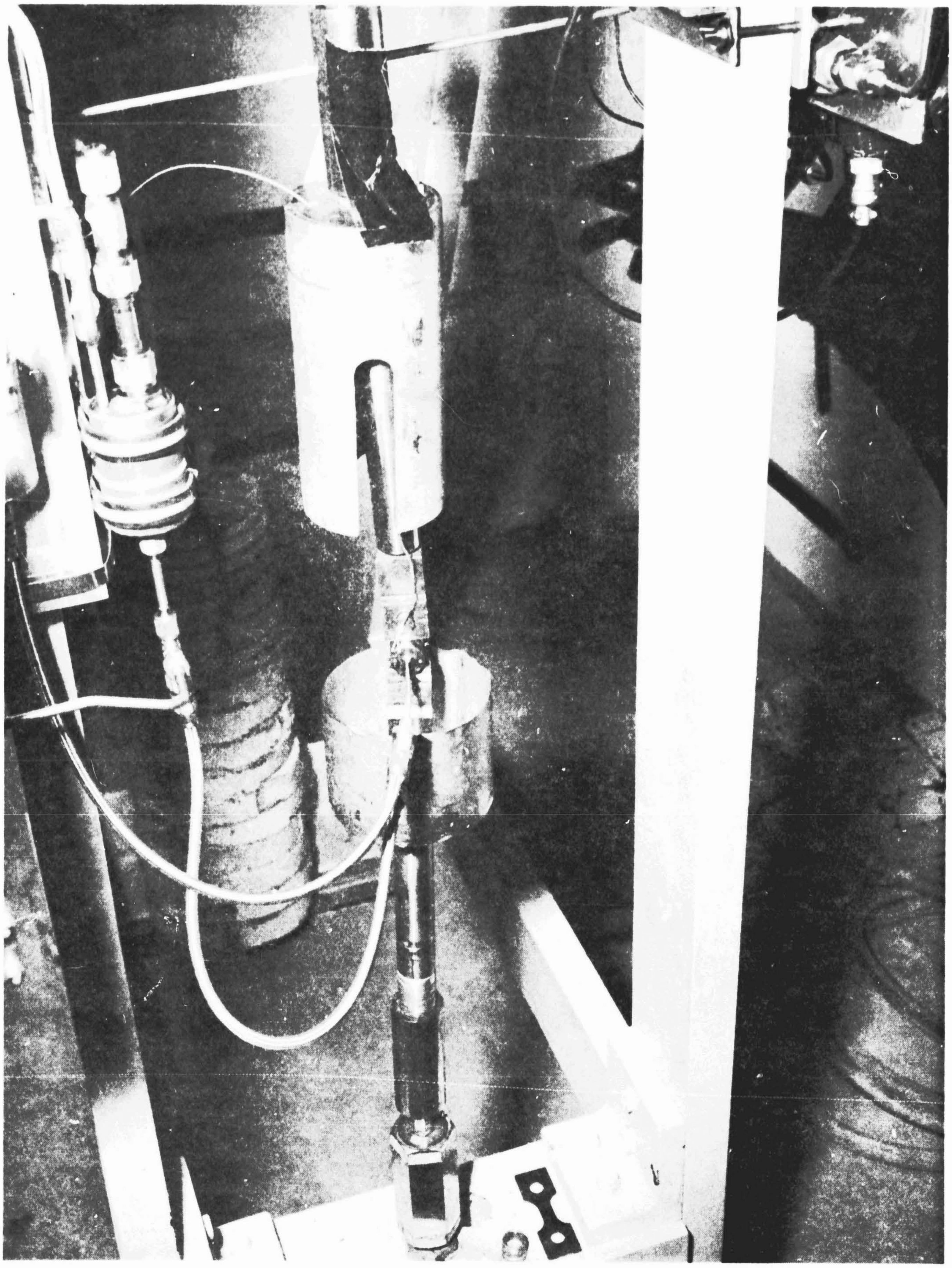
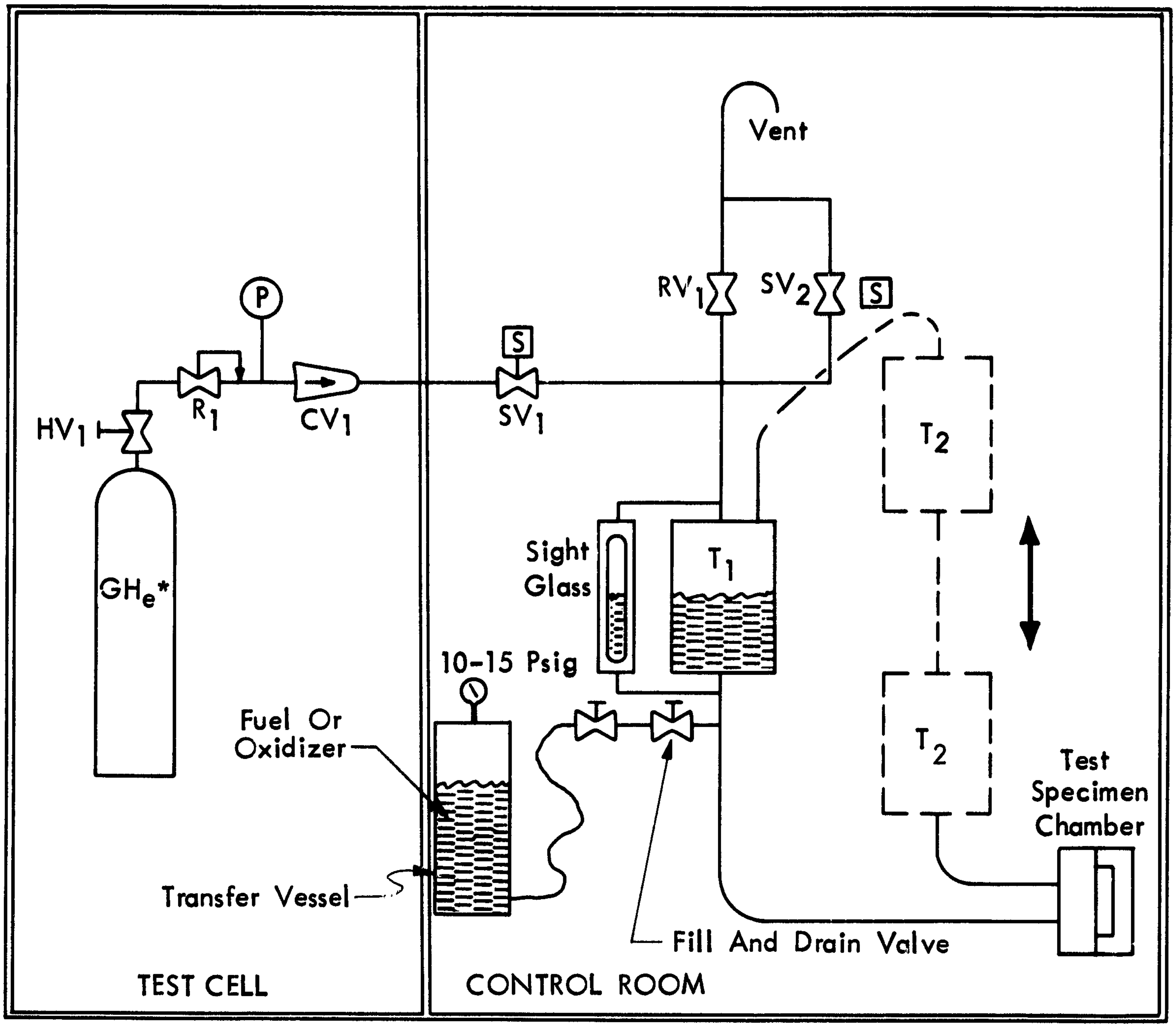


Figure 7: SUSTAINED LOAD TEST SETUP SHOWING SPECIMEN MOUNTING DETA .



T_1 = Circulating Tank - Stationary

T_2 = Circulating Tank - Cycling

SV_1 = Normally Closed Solinoid Valve, 115 Vac

SV_2 = Normally Open Solinoid Valve, 115 Vac (Vent Valve)

RV_1 = Relief Valve, 280 Psig

CV_1 = Check Valve, 300 Psi

* H_e System Also Used For Purging System

Figure 8 : FLUID AND PRESSURIZATION SYSTEM SCHEMATIC

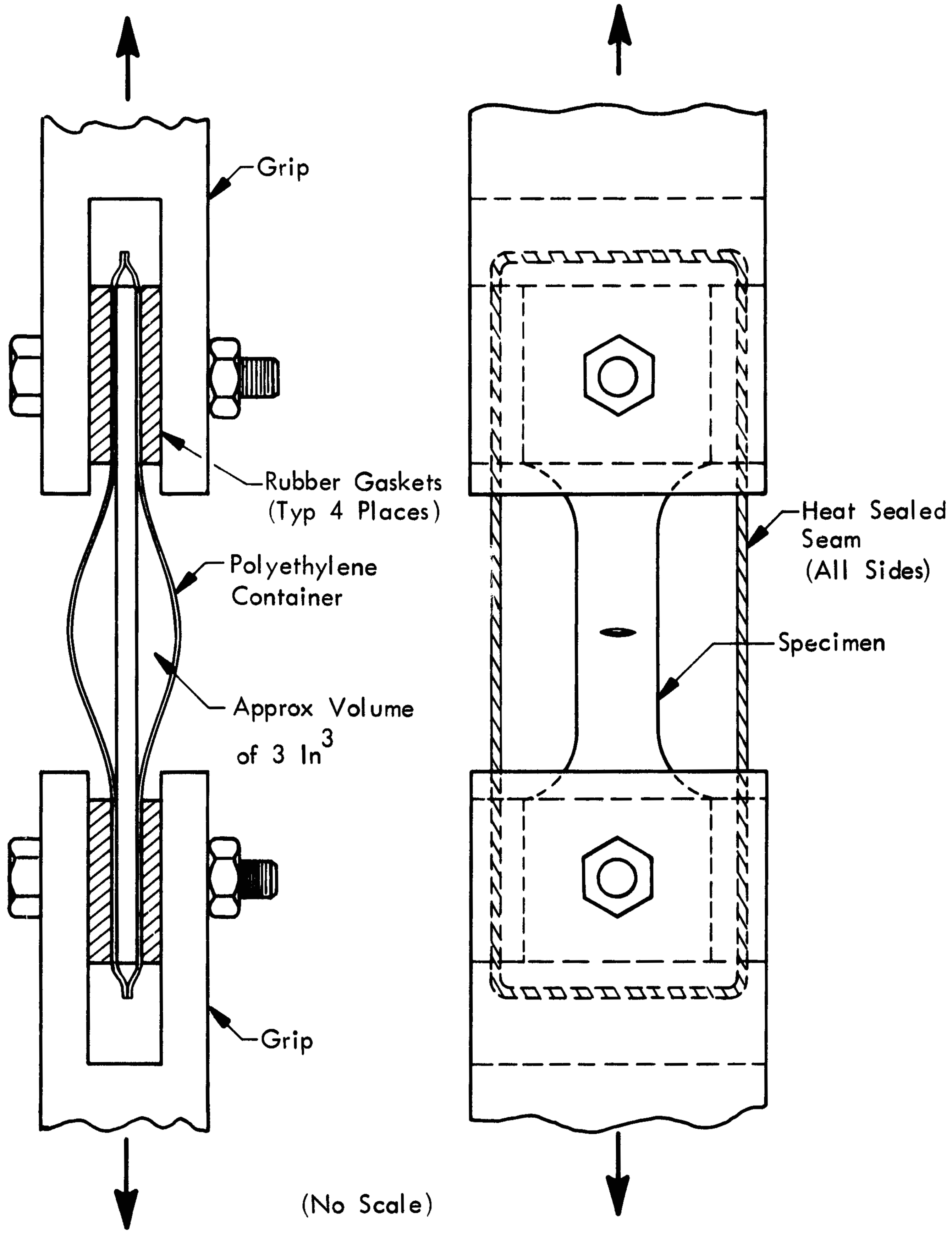


Figure 9 : FREON TF FLUID CONTAINMENT FOR SUSTAINED LOAD TESTS

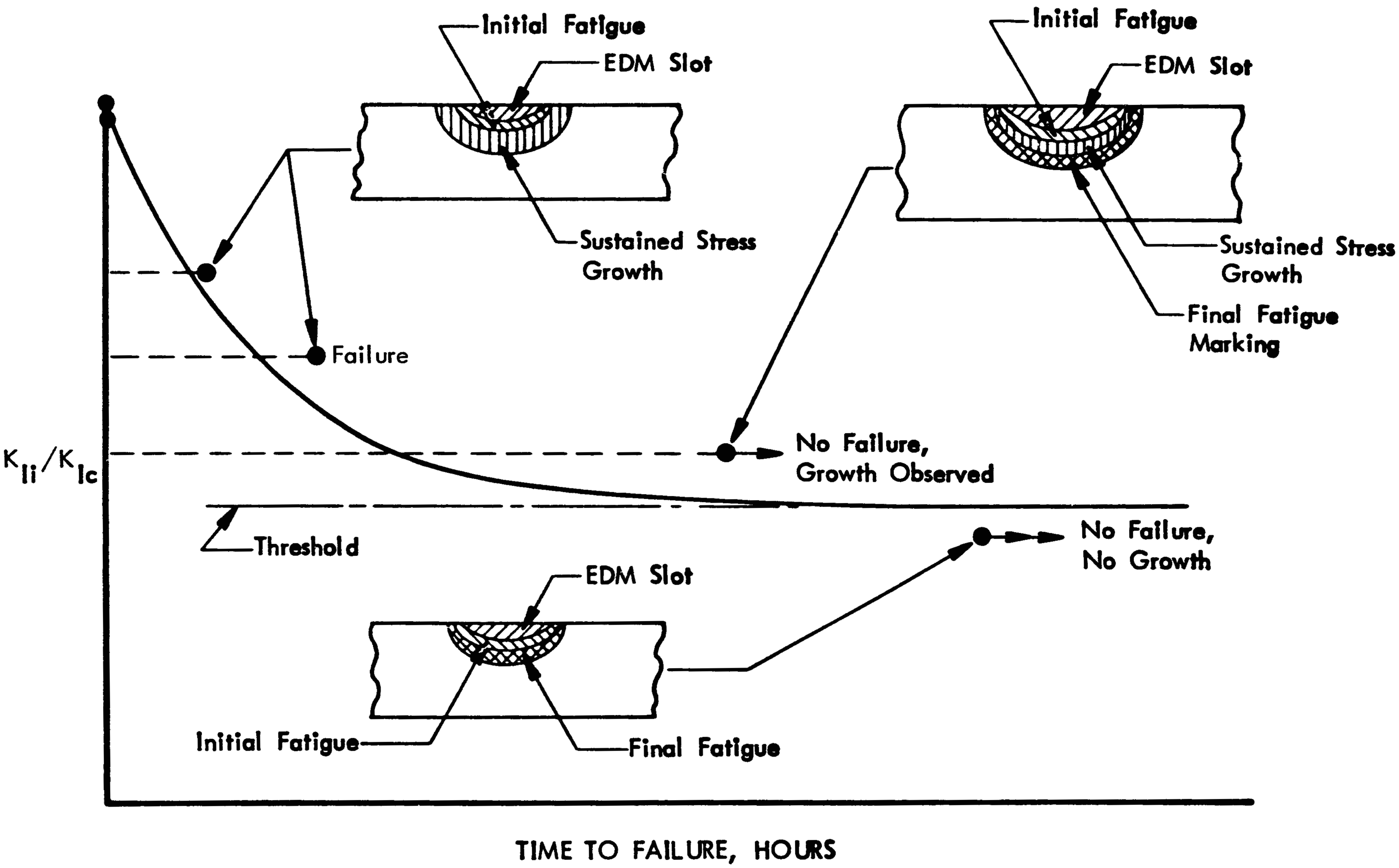


Figure 10: SUSTAINED STRESS FLAW GROWTH TEST APPROACH

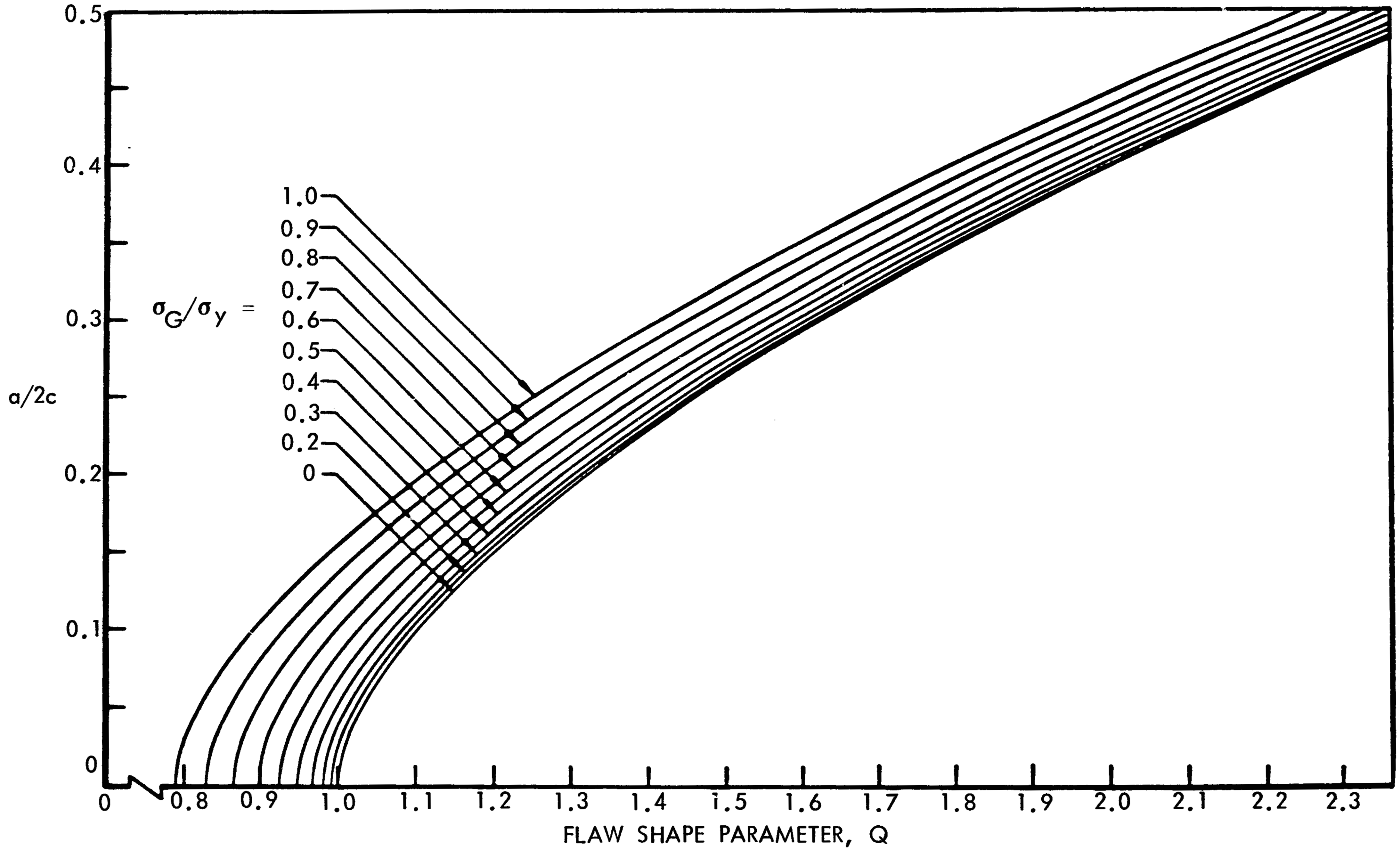


Figure 11 : SHAPE PARAMETER CURVES FOR SURFACE AND INTERNAL FLAWS

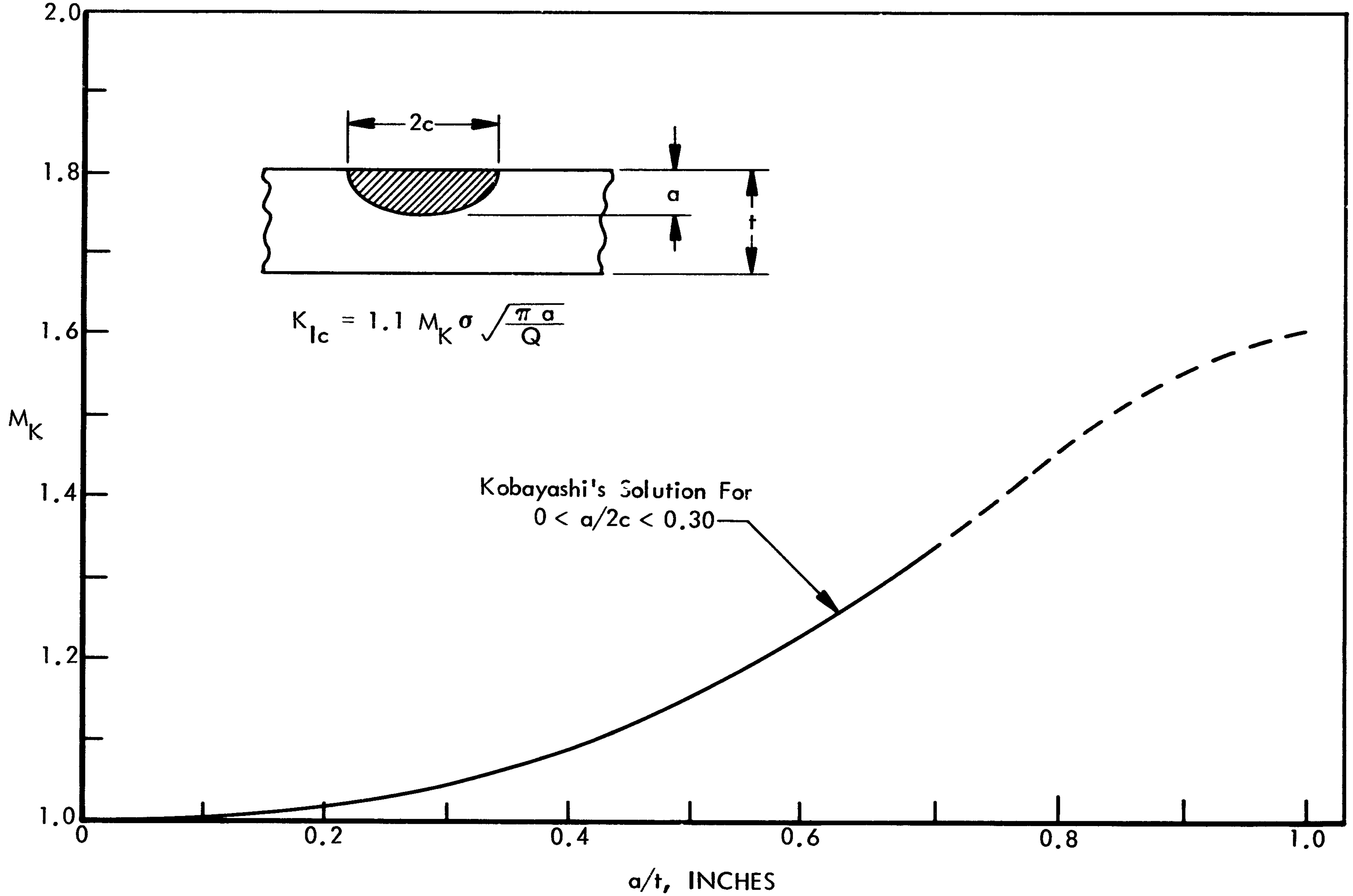


Figure 12: STRESS INTENSITY MAGNIFICATION FACTORS FOR DEEP SURFACE FLAWS

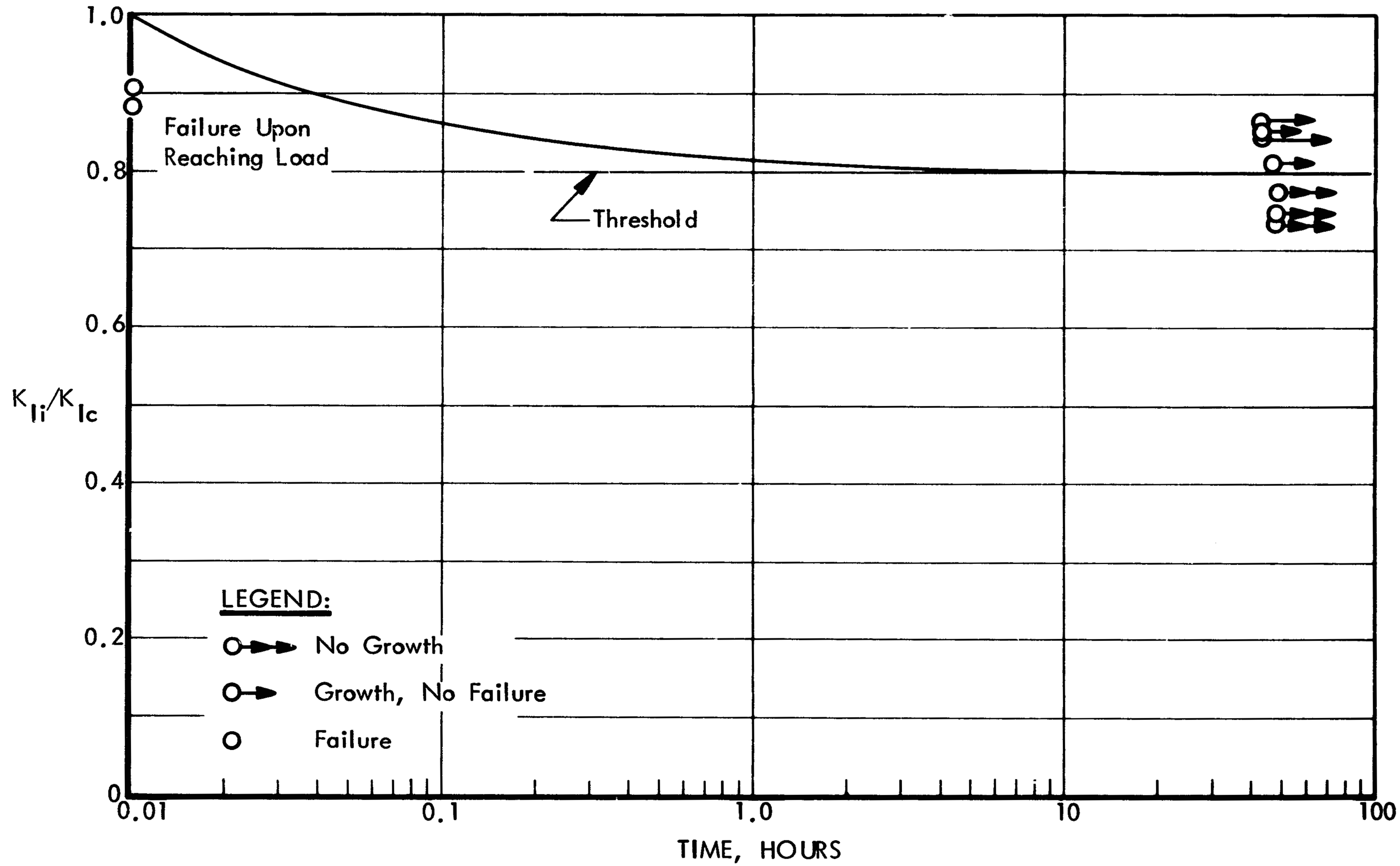


Figure 13 : ALPHA FORGING SUSTAINED LOAD FLAW GROWTH IN NITROGEN TETROXIDE
(Nominal 80°F)

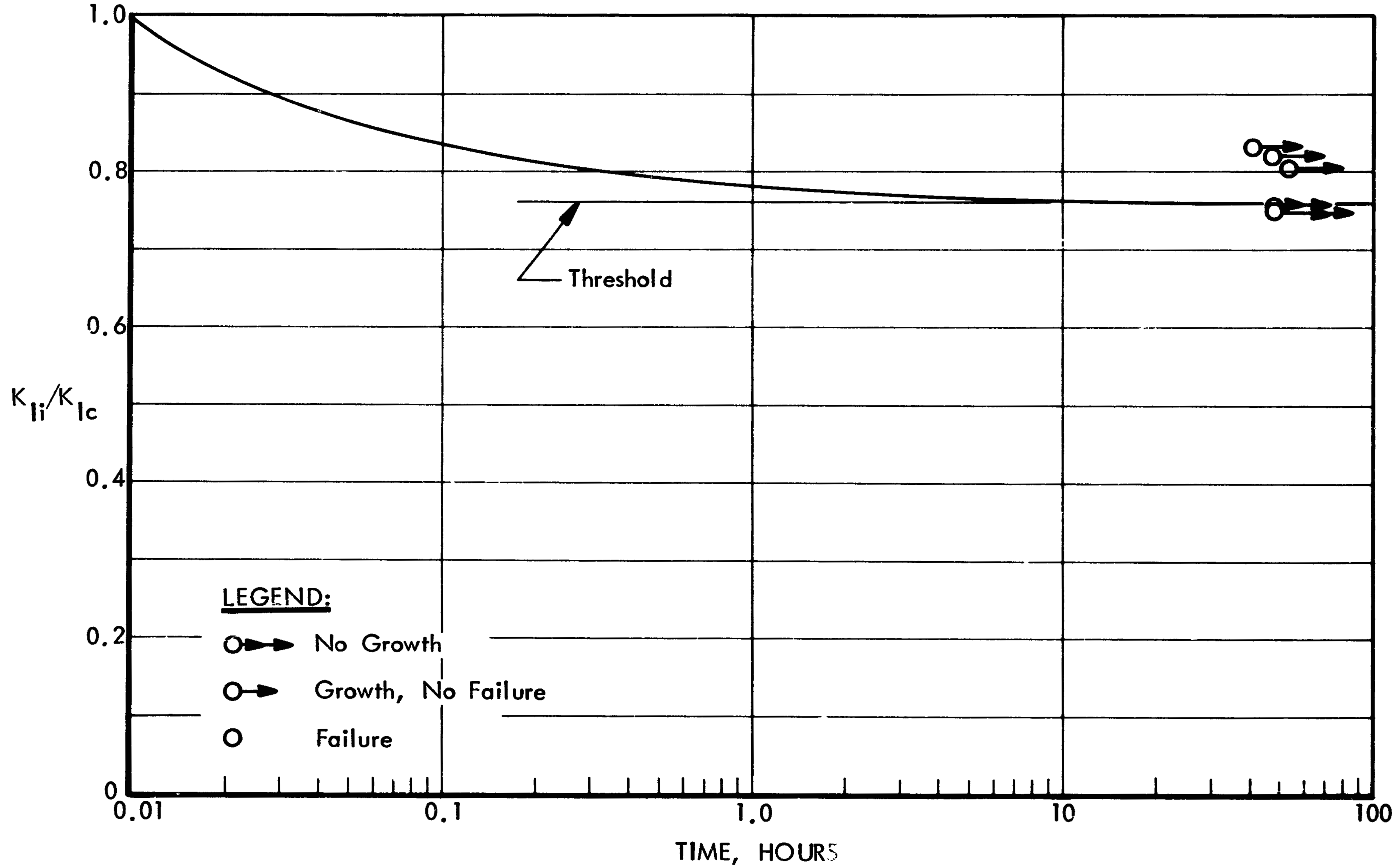


Figure 14: NORMAL FORGING SUSTAINED LOAD FLAW GROWTH IN NITROGEN TETROXIDE (Nominal 80°F)

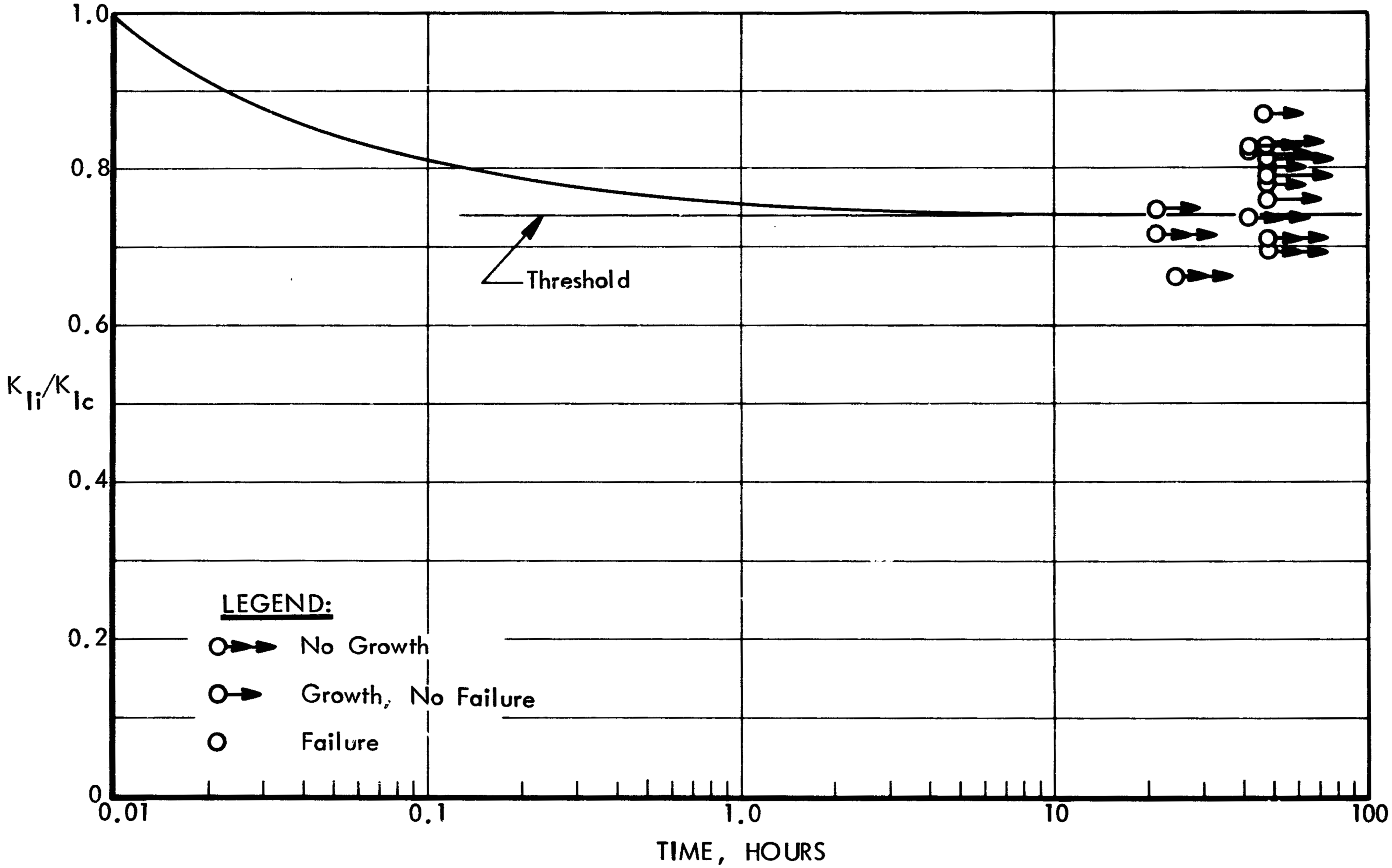


Figure 15: ALPHA FORGING SUSTAINED LOAD FLAW GROWTH IN AEROZINE 50
(Nominal 80°F)

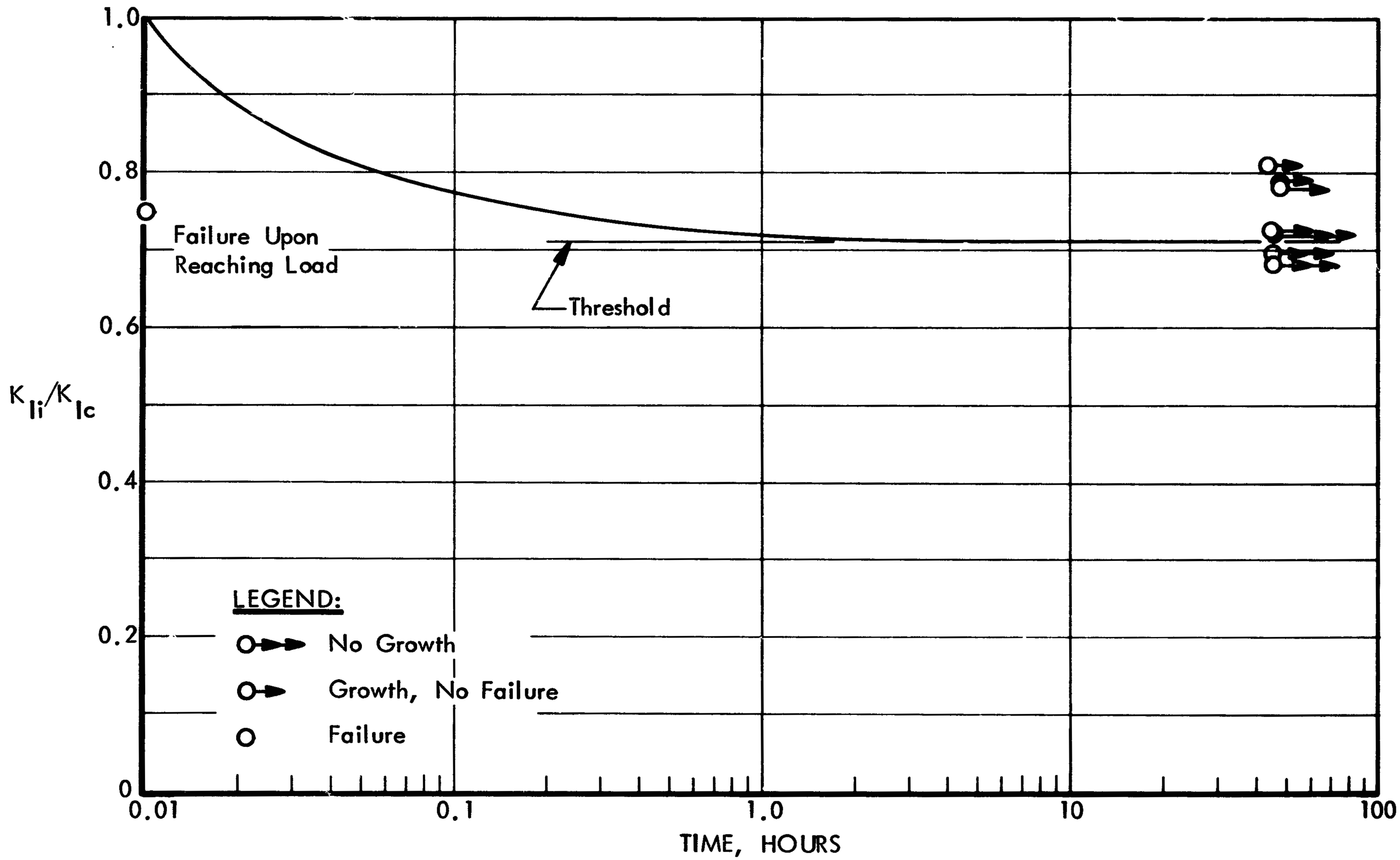


Figure 16 : NORMAL FORGING SUSTAINED LOAD FLAW GROWTH IN AEROZINE 50
(Nominal 80°F)

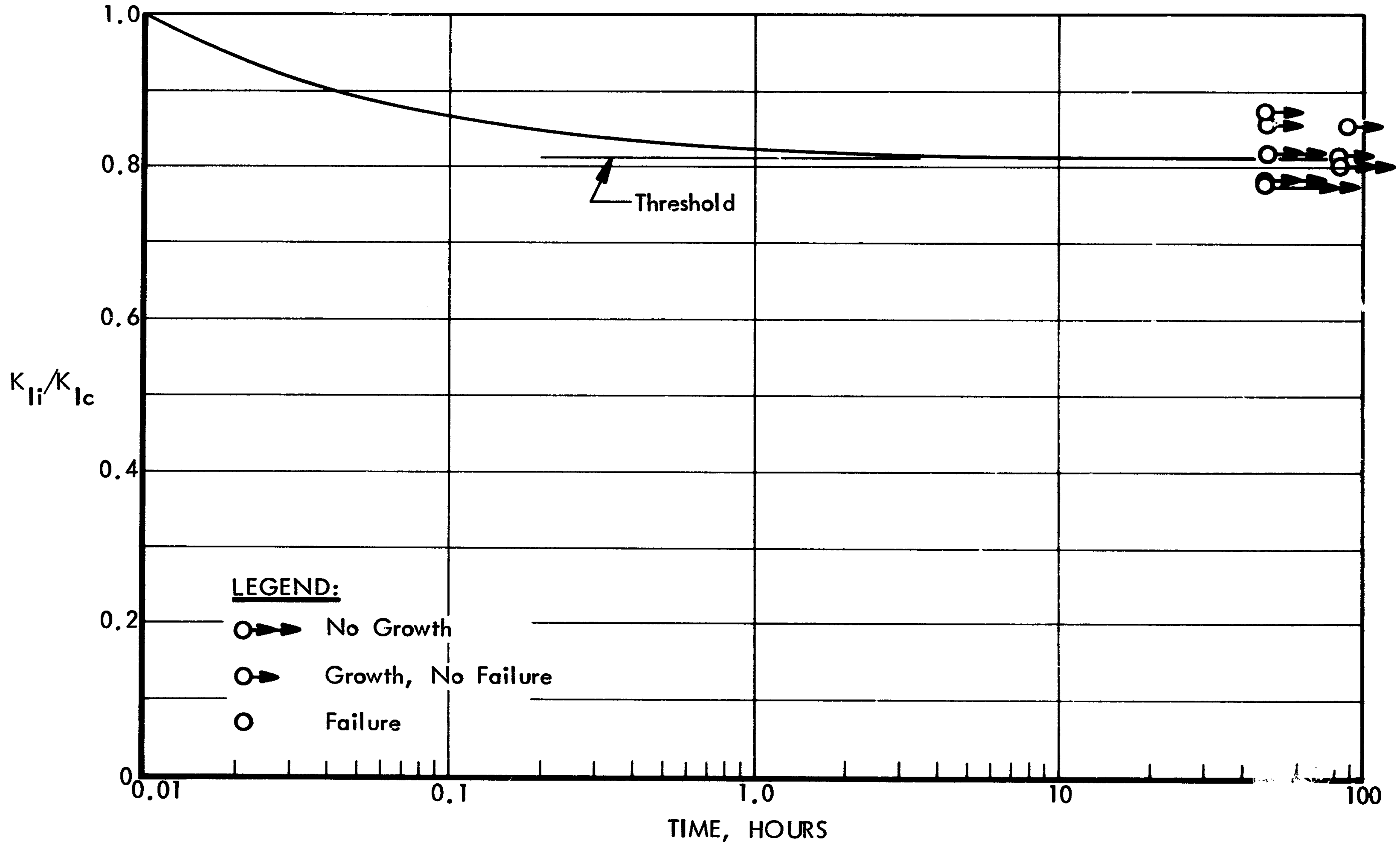


Figure 17: ALPHA FORGING SUSTAINED LOAD FLAW GROWTH IN FREON TF
(Room Temperature)

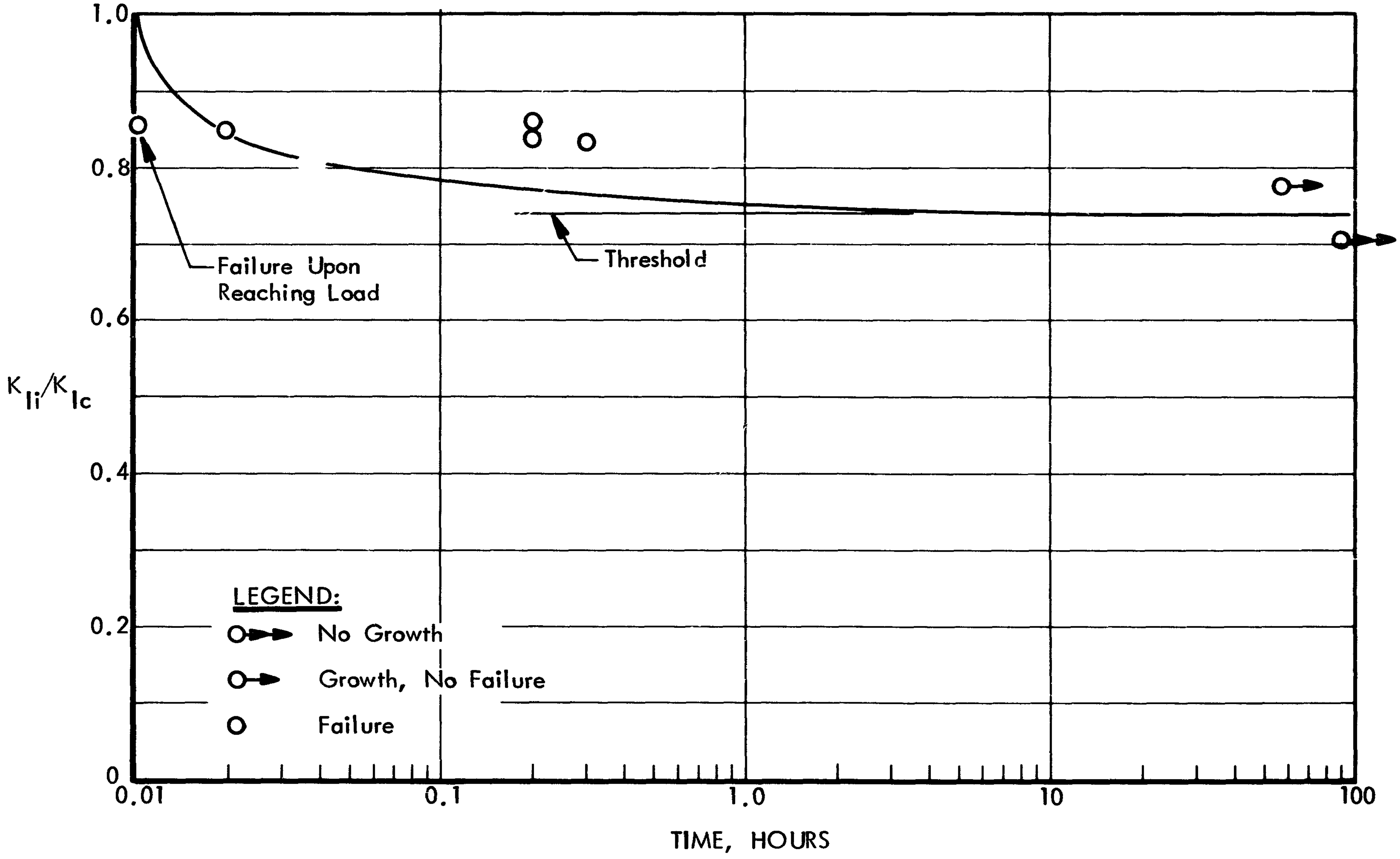


Figure 18 : NORMAL FORGING SUSTAINED LOAD FLAW GROWTH IN FREON TF
(Room Temperature)

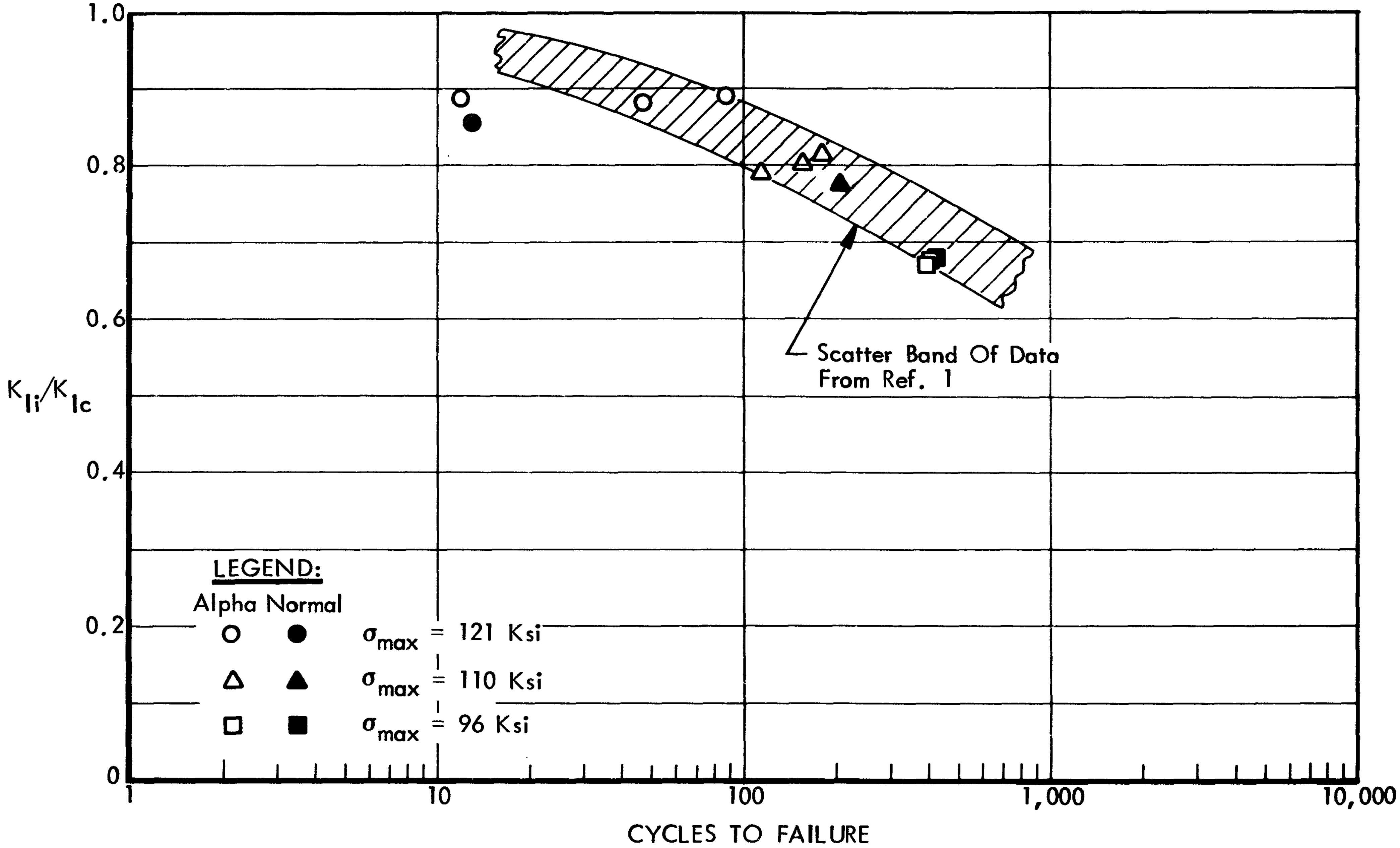


Figure 19 : CYCLIC LOAD FLAW GROWTH IN AIR (Room Temperature)

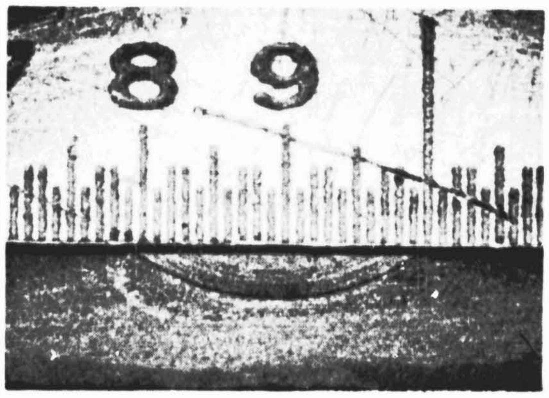
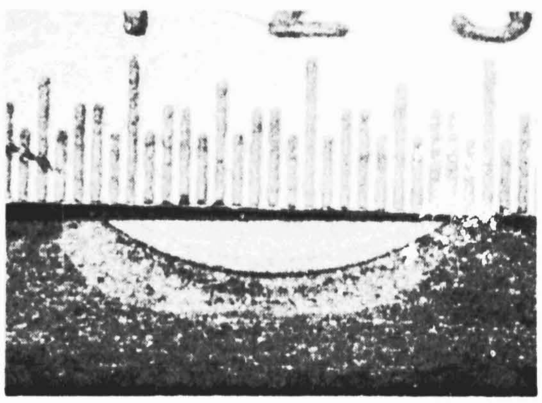
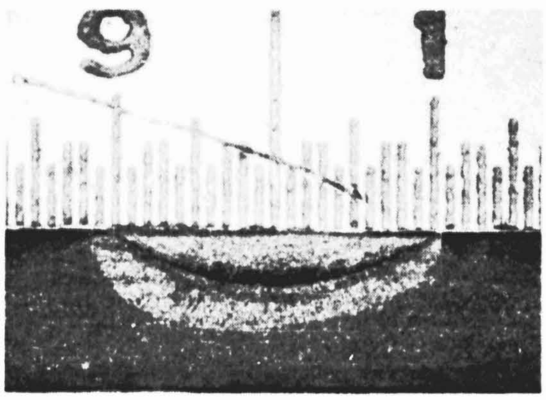
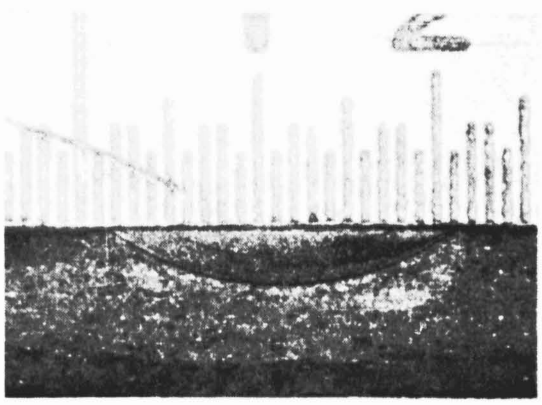
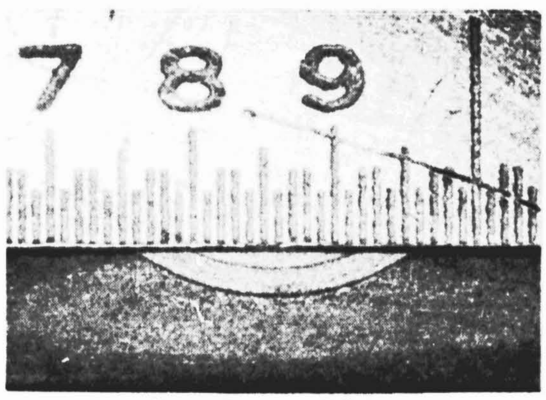
ALPHA FORGING	NORMAL FORGING	TEST MEDIA
 Specimen 15	 Specimen 123	Nitrogen Tetroxide
 Specimen 25	 Specimen 124	Aerozine 50
 Specimen 41	 Specimen 126	Freon TF

Figure 20 : FRACTOGRAPHS OF ALPHA AND NORMAL FORGING SUSTAINED LOAD SPECIMENS IN VARIOUS ENVIRONMENTS (Polarized Light)

Table I : HEAT TREATMENT AND PERCENT WEIGHT COMPOSITION OF ALPHA AND NORMAL FORGINGS

FORGING	HEAT TREATMENT	Al	V	Fe	O_2	C	N_2	H_2
Alpha (-105)	Solution Treated 1750 °F -- 1 1/2 Hours Water Quenched Aged 1050 °F -- 8 Hours Stress Relieved 950 °F -- 8 Hours	6.60	3.99	0.16	0.19	0.023	210 ppm	47 ppm
Normal (-76)	Solution Treated 1750 °F -- 1 1/2 Hours Water Quenched Aged 1100 °F -- 8 Hours Stress Relieved 950 °F -- 8 Hours	6.55	4.24	0.21	0.17	0.033	80 ppm	21 ppm

Table II: COMPOSITION OF TEST FLUIDS (% By Weight)

NITROGEN TETROXIDE (1)
(N_2O_4)

NITRIC OXIDE	0.65
WATER	0.024
CHLORIDE AS NITROSYLCHLORIDE	0.018
PARTICULATE MATTER	1 mg/ liter

AEROZINE 50 (2)

HYDRAZINE (N_2H_4)	50.5
UDMH	47.8
WATER	1.7
PARTICULATE MATTER	0

FREON TF (3)

PURITY	> 99.99
ACID	.003 mg NaOH/g
MOISTURE	12 ppm
CHLORIDE ION	0.07 ppm

(1) ASSAYED PER MSC-PPD-2B

(2) ASSAYED PER MIL P-27402

(3) ASSAYED PER MSC-C28

Table III : MECHANICAL PROPERTIES OF ALPHA AND NORMAL FORGINGS

FORGING	SPECIMEN NUMBER	SPECIMEN ORIENTATION	DIAMETER, D (IN.)	TEST ENVIRONMENT	TEST TEMPERATURE (°F)	0.2% OFFSET YIELD STRENGTH (KSI)	ULTIMATE TENSILE STRENGTH (KSI)	% ELONGATION IN 1.0 INCH	% REDUCTION IN AREA
ALPHA	T-3	Merid.	0.2493	Air	R.T.	163.5	172.9	6	12
	T-4	Merid.	0.2482			161.1	171.4	6	15
	T-5	Merid.	0.2484			162.4	172.7	5	10
	T-14	Merid.	0.2498			157.9	167.7	7	15
	T-15	Merid.	0.2482			158.6	169.0	6	10
	T-16	Merid.	0.2485			163.2	174.4	8	23
	T-18	Merid.	0.2495			158.4	169.7	7	11
	T-19	Merid.	0.2492			163.7	168.0	8	30
	TC-1	Merid.	0.2470			160.7	171.1	7	21
	TC-2	Circum.	0.2487			160.6	170.3	7	20
	TG-1	Merid.	0.2476			164.8	174.2	5	10
	TG-2	Circum.	0.2473			164.5	174.1	9	25
NORMAL	T-10	Merid.	0.2487			161.1	171.6	9	20
	T-11	Merid.	0.2488			161.5	172.0	11	35
	T-17	Merid.	0.2473			155.4	165.8	9	20
	T-20	Merid.	0.2487			166.4	172.8	6	15
	TB-1	Merid.	0.2480			160.2	171.2	8	18
	TB-2	Circum.	0.2485	Air	R.T.	157.9	168.6	7	19

Table IV: PLANE STRAIN FRACTURE TOUGHNESS FOR ALPHA FORGING

SPECIMEN NUMBER	SPECIMEN ORIENTATION	THICKNESS, t (IN.)	WIDTH, W (IN.)	FLAW DEPTH, a (IN.)	FLAW LENGTH, 2c (IN.)	GROSS STRESS, σ_G (KSI)	FLAW SIZE, a/Q (IN.)	TEST ENVIRONMENT	TEST TEMPERATURE (^oF)	FRACTURE TOUGHNESS, K_{Ic} (KSI $\sqrt{IN}$)
1	Merid.	0.0965	0.7980	0.0378	0.1998	135.0	0.0330	Air	R.T.	51.75
10	Merid.	0.0967	0.7987	0.0370	0.2000	139.3	0.0328			53.09
11	Merid.	0.0967	0.7890	0.0372	0.1994	130.0	0.0323			49.19
20	Merid.	0.0973	0.7900	0.0396	0.2007	138.9	0.0341			54.60
21	Merid.	0.0970	0.7950	0.0360	0.1997	142.9	0.0325			53.93
30	Merid.	0.0968	0.7970	0.0392	0.2007	129.6	0.0334			50.31
31	Merid.	0.0956	0.7997	0.0379	0.1982	121.5	0.0321			46.07
40	Merid.	0.0991	0.8012	0.0389	0.1910	136.8	0.0329			52.45
50	Merid.	0.0968	0.7870	0.0369	0.1980	140.5	0.0327			53.42
C-1	Merid.	0.1023	0.7994	0.0393	0.1995	140.9	0.0340			54.71
C-2	Circum.	0.0995	0.7987	0.0385	0.1970	125.8	0.0325			47.82
G-1	Merid.	0.1004	0.7997	0.0380	0.1960	124.8	0.0322			46.98
G-2	Circum.	0.1043	0.7990	0.0376	0.1983	141.4	0.0332	Air	R.T.	53.63

Table V : PLANE STRAIN FRACTURE TOUGHNESS FOR NORMAL FORGING

SPECIMEN NUMBER	SPECIMEN ORIENTATION	THICKNESS, t (IN.)	WIDTH, W (IN.)	FLAW DEPTH, a (IN.)	FLAW LENGTH, $2c$ (IN.)	GROSS STRESS, σ_G (KSI)	FLAW SIZE, a/Q (IN.)	TEST ENVIRONMENT	TEST TEMPERATURE (^oF)	FRACTURE TOUGHNESS, K_{Ic} (KSI $\sqrt{IN}$)
101	Merid.	0.0967	0.7850	0.0363	0.2015	139.6	0.0326	Air	R.T.	52.86
110	Merid.	0.1004	0.7982	0.0364	0.2013	127.8	0.0319			47.60
111	Merid.	0.0949	0.7995	0.0361	0.1965	135.2	0.0319			50.73
120	Merid.	0.0961	0.8014	0.0370	0.1973	141.0	0.0328			53.75
130	Merid.	0.0927	0.7973	0.0350	0.2000	139.4	0.0318			52.17
B-1	Merid.	0.1018	0.7986	0.0360	0.1986	149.4	0.0330			56.33
B-2	Circum.	0.1008	0.7995	0.0367	0.1989	141.9	0.0328	Air	R.T.	53.62

Table VI : ALPHA FORGING SUSTAINED LOAD FLAW GROWTH DATA IN NITROGEN TETROXIDE

SPECIMEN NUMBER	THICKNESS, t (IN.)	WIDTH, W (IN.)	INITIAL FLAW DEPTH, a (IN.)	INITIAL FLAW LENGTH, 2c (IN.)	SUSTAINED GROSS STRESS, σ_G (KSI)	FLAW SIZE a/Q (IN.)	TEST DURATION (HRS.)	TEST TEMPERATURE (AVERAGE/MAX) (^oF)	INITIAL STRESS INTENSITY, K_{Ii} (KSI $\sqrt{IN}$)	K_{Ii}/K_{Ic}	AMOUNT OF GROWTH
2	0.0965	0.7970	0.0356	0.2006	104.0	0.0302	47.9	80/86	37.80	0.734	None
3	0.0943	0.8030	0.0367	0.2000	104.0	0.0308	48.0	77/84	38.48	0.747	None
12	0.0933	0.7990	0.0384	0.1986	122.0	0.0324	0	80/80	46.82	0.909	Failure
13	0.0937	0.7985	0.0377	0.1973	120.0	0.0319	0	80/80	45.46	0.882	Failure
15	0.0965	0.7995	0.0373	0.2001	117.0	0.0317	42.9	81/85	43.88	0.852	Signif.
22	0.0938	0.7997	0.0382	0.1972	115.0	0.0318	43.3	81/88	43.66	0.847	Trace
23	0.0934	0.7983	0.0366	0.2000	119.0	0.0314	43.3	80/85	44.56	0.865	Trace
36A	0.0983	0.8026	—	—	113.0	—	47.1	81/85	—	—	[1]
46	0.0955	0.8005	0.0366	0.1968	108.0	0.0307	49.0	81/86	39.81	0.773	None
47	0.0954	0.8002	0.0385	0.2008	110.0	0.0320	47.0	79/82	41.78	0.811	Trace

[1] Fracture Face Destroyed During Marking

Table VII: NORMAL FORGING SUSTAINED LOAD FLAW GROWTH DATA IN NITROGEN TETROXIDE

SPECIMEN NUMBER	THICKNESS, t (IN.)	WIDTH, W (IN.)	INITIAL FLAW DEPTH, a (IN.)	INITIAL FLAW LENGTH, 2c (IN.)	SUSTAINED GROSS STRESS, σ_G (KSI)	FLAW SIZE a/Q (IN.)	TEST DURATION (HRS.)	TEST TEMPERATURE (AVERAGE/MAX) (°F)	INITIAL STRESS INTENSITY, K_{Ii} (KSI $\sqrt{IN}$)	K_{Ii}/K_{Ic}	AMOUNT OF GROWTH
102	0.1008	0.7992	0.0366	0.1983	107.0	0.0308	48.0	80/89	39.13	0.749	None
103	0.0974	0.8012	0.0365	0.1974	107.0	0.0307	48.0	82/96	39.26	0.751	None
114	0.0990	0.8002	0.0352	0.1957	118.0	0.0304	47.1	80/85	42.77	0.819	Trace
122	0.0955	0.8015	0.0379	0.1966	115.0	0.0317	41.0	81/86	43.32	0.829	Slight
123	0.0965	0.7998	0.0379	0.1998	111.5	0.0317	53.5	80/84	41.95	0.803	Signif.

Table VIII: ALPHA FORGING SUSTAINED LOAD FLAW GROWTH DATA IN AEROZINE 50

SPECIMEN NUMBER	THICKNESS, t (IN.)	WIDTH, W (IN.)	INITIAL FLAW DEPTH, a (IN.)	INITIAL FLAW LENGTH, 2c (IN.)	SUSTAINED GROSS STRESS, σ_G (KSI)	FLAW SIZE a/Q (IN.)	TEST DURATION (HRS.)	TEST TEMPERATURE (AVERAGE/MAX) (°F)	INITIAL STRESS INTENSITY, K_{Ii} (KSI $\sqrt{IN}$)	K_{Ii}/K_{Ic}	AMOUNT OF GROWTH
4	0.0963	0.8036	0.0363	0.1951	107.0	0.0304	47.9	82/86	39.13	0.760	Mod.
5	0.0972	0.7990	0.0382	0.2027	107.0	0.0318	47.9	81/85	40.33	0.783	Slight
8	0.0965	0.8042	0.0381	0.2016	96.0	0.0312	48.0	80/86	35.88	0.696	None
14	0.0946	0.7985	0.0374	0.2043	113.0	0.0318	41.4	81/89	42.64	0.828	Trace
18	0.0970	0.8018	0.0373	0.1957	93.0	0.0304	24.6	80/84	34.10	0.662	None
24	0.0942	0.7988	0.0371	0.2037	102.0	0.0311	41.9	82/104	38.03	0.738	None
25	0.0970	0.8018	0.0371	0.1959	115.0	0.0312	41.8	80/85	42.73	0.829	Signif.
28	0.0952	0.7983	0.0381	0.1982	98.0	0.0311	48.0	79/84	36.64	0.711	None
36B	0.0967	0.8021	0.0366	0.1958	105.0	0.0305	21.2	80/82	38.49	0.747	Trace
37	0.0983	0.8012	0.0377	0.1969	100.0	0.0309	21.2	84/88	36.98	0.718	None
39	0.0970	0.8020	0.0386	0.1963	118.0	0.0321	46.8	80/82	44.79	0.869	Irreg.
43	0.0933	0.7989	0.0398	0.2000	110.0	0.0326	47.1	80/88	42.65	0.828	Mod.
44	0.0935	0.7985	0.0383	0.2043	108.0	0.0320	47.1	80/87	41.17	0.799	Mod.
48	0.0938	0.7992	0.0383	0.2015	110.0	0.0319	48.0	81/85	41.85	0.812	Trace
49	0.0945	0.8002	0.0351	0.1966	111.0	0.0301	48.0	79/84	40.27	0.782	Mod.

Table IX: NORMAL FORGING SUSTAINED LOAD FLAW GROWTH DATA IN AEROZINE 50

SPECIMEN NUMBER	THICKNESS, t (IN.)	WIDTH, W (IN.)	INITIAL FLAW DEPTH, a (IN.)	INITIAL FLAW LENGTH, 2c (IN.)	SUSTAINED GROSS STRESS, σ_G (KSI)	FLAW SIZE a/Q (IN.)	TEST DURATION (HRS.)	TEST TEMPERATURE (AVERAGE/MAX) (°F)	INITIAL STRESS INTENSITY, K_{Ii} (KSI $\sqrt{IN}$)	K_{Ii}/K_{Ic}	AMOUNT OF GROWTH
104	0.0950	0.7989	0.0369	0.1985	110.0	0.0311	48.0	79/85	40.88	0.782	Mod
105	0.0976	0.8018	0.0371	0.1994	110.7	0.0313	48.0	81/87	41.11	0.787	Trace
113	0.0985	0.8012	0.0379	0.1964	102.0	0.0311	46.0	79/84	37.84	0.724	None
115	0.0969	0.7998	0.0348	0.1958	106.0	0.0296	44.6	81/87	37.99	0.727	Mod.
117	0.0983	0.8021	0.0[illegible]	0.1931	98.0	0.0301	45.4	82/86	35.61	0.682	None
118	0.0955	0.8001	--	--	95.0	--	45.3	80/82	--	--	1
119	0.0985	0.8003	0.0368	0.1939	100.0	0.0303	45.4	82/87	36.45	0.698	None
124	0.0978	0.7994	0.0360	0.2029	115.0	0.0311	43.6	81/87	42.39	0.811	Mod.
125	0.0945	0.8003	0.0365	0.1963	106.0	0.0305	0	80/80	39.02	0.747	Failure

1 Fracture Face Destroyed During Marking

Table X: ALPHA FORGING SUSTAINED LOAD FLAW GROWTH DATA IN FREON TF

SPECIMEN NUMBER	THICKNESS, t (IN.)	WIDTH, W (IN.)	INITIAL FLAW DEPTH, a (IN.)	INITIAL FLAW LENGTH, 2c (IN.)	SUSTAINED GROSS STRESS, σ_G (KSI)	FLAW SIZE a/Q (IN.)	TEST DURATION (HRS.)	TEST TEMPERATURE (°F)	INITIAL STRESS INTENSITY, K_{Ii} (KSI $\sqrt{IN}$)	K_{Ii}/K_{Ic}	AMOUNT OF GROWTH
6	0.0982	0.7997	0.0374	0.2012	108.0	0.0314	48.0	RT	40.20	0.780	None
7	0.0943	0.7998	0.0367	0.2000	108.0	0.0310	48.0	RT	40.08	0.778	None
16	0.0945	0.7988	0.0369	0.1988	111.0	0.0311	84.4	RT	41.33	0.802	None
17	0.0950	0.7984	0.0383	0.1992	111.0	0.0318	82.3	RT	42.05	0.816	Trace
26	0.0950	0.7988	0.0354	0.2008	115.0	0.0307	48.4	RT	42.15	0.818	None
27	0.0931	0.7991	0.0361	0.1962	119.0	0.0309	48.2	RT	44.12	0.856	Mod.
41	0.0951	0.7989	0.0364	0.1983	121.0	0.0313	46.8	RT	45.05	0.874	Signif.
42	0.0935	0.7982	0.0382	0.1965	116.0	0.0318	89.6	RT	44.07	0.855	Trace

Table XI: NORMAL FORGING SUSTAINED LOAD FLAW GROWTH DATA IN FREON TF

SPECIMEN NUMBER	THICKNESS, t (IN.)	WIDTH, W (IN.)	INITIAL FLAW DEPTH, a (IN.)	INITIAL FLAW LENGTH, 2c (IN.)	SUSTAINED GROSS STRESS, σ_G (KSI)	FLAW SIZE a/Q (IN.)	TEST DURATION (HRS.)	TEST TEMPERATURE (AVERAGE/MAX) (°F)	INITIAL STRESS INTENSITY, K_{Ii} (KSI $\sqrt{IN}$)	K_{Ii}/K_{Ic}	AMOUNT OF GROWTH
106	0.0952	0.7977	0.0374	0.2000	119.0	0.0319	0.2	RT	44.88	0.859	Failure
107	0.0988	0.8001	0.0375	0.1985	119.0	0.0318	0	RT	44.57	0.853	Failure
108	0.0918	0.7995	0.0370	0.2028	115.0	0.0316	0.3	RT	43.43	0.831	Failure
109	0.0939	0.8002	0.0391	0.1974	115.0	0.0323	0.02	RT	44.18	0.846	Failure
126	0.0969	0.8021	0.0368	0.1939	110.0	0.0307	56 9	RT	40.49	0.775	Trace
127	0.0966	0.7998	0.0359	0.1965	119.0	0.0309	0.2	RT	43.76	0.838	Failure
128	0.0978	0.8021	0.0356	0.1962	102.0	0.0299	90.3	RT	36.80	0.704	None

Table XII: ALPHA AND NORMAL FORGING CYCLIC LOAD FLAW GROWTH DATA

FORGING	SPECIMEN NUMBER	THICKNESS, t (IN.)	WIDTH, W (IN.)	INITIAL FLAW DEPTH, a (IN.)	INITIAL FLAW LENGTH, 2c (IN.)	MAXIMUM GROSS STRESS σ_G (KSI)	FLAW SIZE a/Q (IN.)	TEST ENVIRONMENT	TEST TEMPERATURE (^oF)	INITIAL STRESS INTENSITY, K_{Ii} (KSI $\sqrt{IN}$)	K_{Ii}/K_{Ic}	CYCLES TO FAILURE
ALPHA	9	0.0967	0.8037	0.0371	0.2000	121.0	0.0318	Air	R.T.	45.40	0.881	47
	19	0.0943	0.7990	0.0383	0.2023	110.0	0.0320	Air	R.T.	41.84	0.812	181
	29	0.0961	0.7987	0.0376	0.2023	121.0	0.0322	Air	R.T.	45.85	0.890	88
	32	0.0955	0.7988	0.0360	0.1971	96.0	0.0299	Air	R.T.	34.83	0.676	400
	33	0.0972	0.7999	0.0370	0.1971	110.0	0.0310	Air	R.T.	40.70	0.790	115
	34	0.0953	0.7987	0.0374	0.2014	121.0	0.0320	Air	R.T.	45.76	0.888	12
	35	0.0979	0.8008	0.0362	0.1951	96.0	0.0299	Air	R.T.	34.71	0.674	396
	45	0.0942	0.7993	0.0376	0.1978	110.0	0.0314	Air	R.T.	41.28	0.801	158
NORMAL	112	0.1005	0.8009	0.0363	0.1945	135.7	0.0319	Air	R.T.	50.49	--	[1]
	116	0.0951	0.8002	0.0372	0.1942	96.0	0.0303	Air	R.T.	35.30	0.676	426
	121	0.0962	0.7997	0.0366	0.1961	110.0	0.0308	Air	R.T.	40.53	0.776	206
	129	0.0953	0.7988	0.0359	0.1991	121.0	0.0312	Air	R.T.	44.79	0.857	13

[1] Accidently Pulled To Failure