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Bell Aerospace Company DIVISION OF textron

BUFFALO, NEW YORK 14240 716-297-1000

CONTRACT NAS 9-12996

FINAL REPORT, STUDY OF THE EFFECTS OF FUEL VORTEX FILM COOLING ON HIGH TEMPERATURE COATING DURABILITY

BELL MODEL 8701

REPORT NUMBER 8701-910045

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION

LYNDON B. JOHNSON SPACE CENTER

HOUSTON, TEXAS

REFERENCE: DATA ITEM T-889-2

JULY 1974

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RCS ENGINE PROGRAM

NASA TECHNICAL MONITOR: MR. NORMAN CHAFFEE

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FINAL REPORT, STUDY OF THE EFFECTS OF FUEL VORTEX FILM COOLING ON HIGH TEMPERATURE COATING DURABILITY

T-889-2

1.0 INTRODUCTION

This document comprises the final report of the study of the Effects of Fuel Vortex Film Cooling on High Temperature Coating Durability conducted by Bell Aerospace Company (BAC) under contract NAS 9-12996. It is submitted in compliance with Data Item T-889-2.

1.1 Program Objectives

The objective of this program was to evaluate candidate high temperature oxidation resistant RCS engine thrust chamber materials systems through analyses, design, fabrication and test. As a result of the evaluation the materials systems were rated such that RCS engine designs for current and future programs may be optimized from the materials standpoint. Engine firing data for the evaluation of one material system was generated. The program culminated in this comprehensive final report.

1.2 Program Scope

The program consisted of five phases as follows:

Phase I - Screening of Materials
Phase II - Thrust Chamber Fabrication
Phase III - Engine Testing
Phase IV - Analysis of Data
Phase V - Final Report

The baseline engine design for the program was as follows:

Thrust (F_{∞})	- 600 lbf
Area Ratio (ϵ)	- 40:1
Chamber Pressure (P_c)	- 200 psia
Propellants	- N_2O_4/MMH
Mixture Ratio (O/F)	- 1.6

The engine design is predicated upon the need for long life with minimum servicing. It specifically includes long life, compatible materials; injector/valve of the simplest type, free from contamination traps and having a high degree of visual inspectability; a chamber having wide thermal margins to provide an engine insensitive to feed system anomalies. Specific impulse is as high as possible commensurate with the reusability and servicing requirements and thermal margin.

The BAC flight type engine (see Figure 1-1) is a fuel vortex film cooled coated columbium thrust chamber and nozzle extension. The basic technology of this engine was demonstrated under NAS 9-12996, (reported by BAC Report Number 8701-910041). High performance (I_{sp_∞} = 295 sec @ ϵ = 40) with zero maintenance was achieved throughout multiple missions. The program reported herein further evaluated candidate RCS engine material systems.

1.3 Program Goals

The RCS engine technology requires a design capable of meeting long life, extended burn time, multi-mission life capability, multiple reuse, minimal maintenance and servicing with high reliability and maximum performance. The program goal is to demonstrate a high temperature materials system through approximately six equivalent missions* including endurance and worst case missions.

1.4 Program Schedule

The program schedule is presented in Figure 1-2.

*Thirty missions as defined by the Space Division of Rockwell International for Space Shuttle.

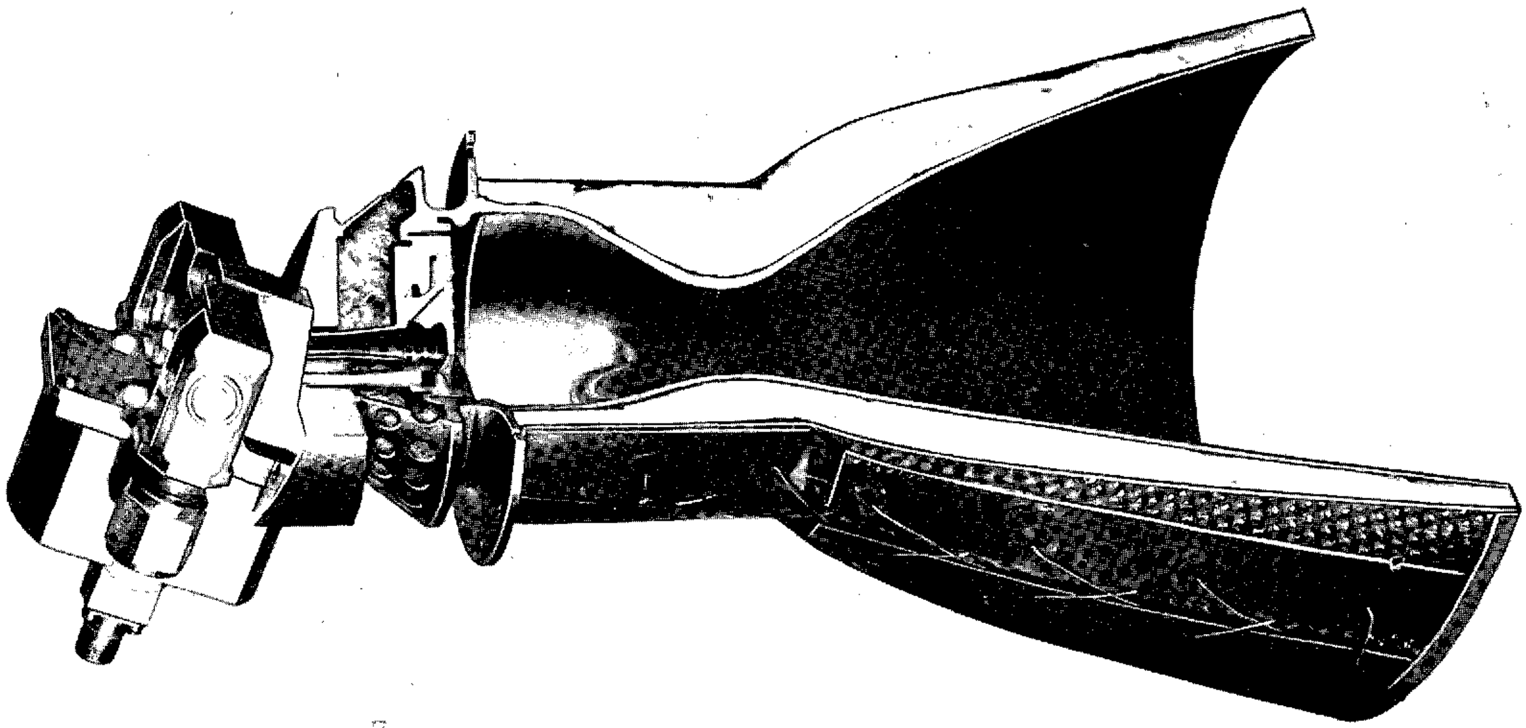
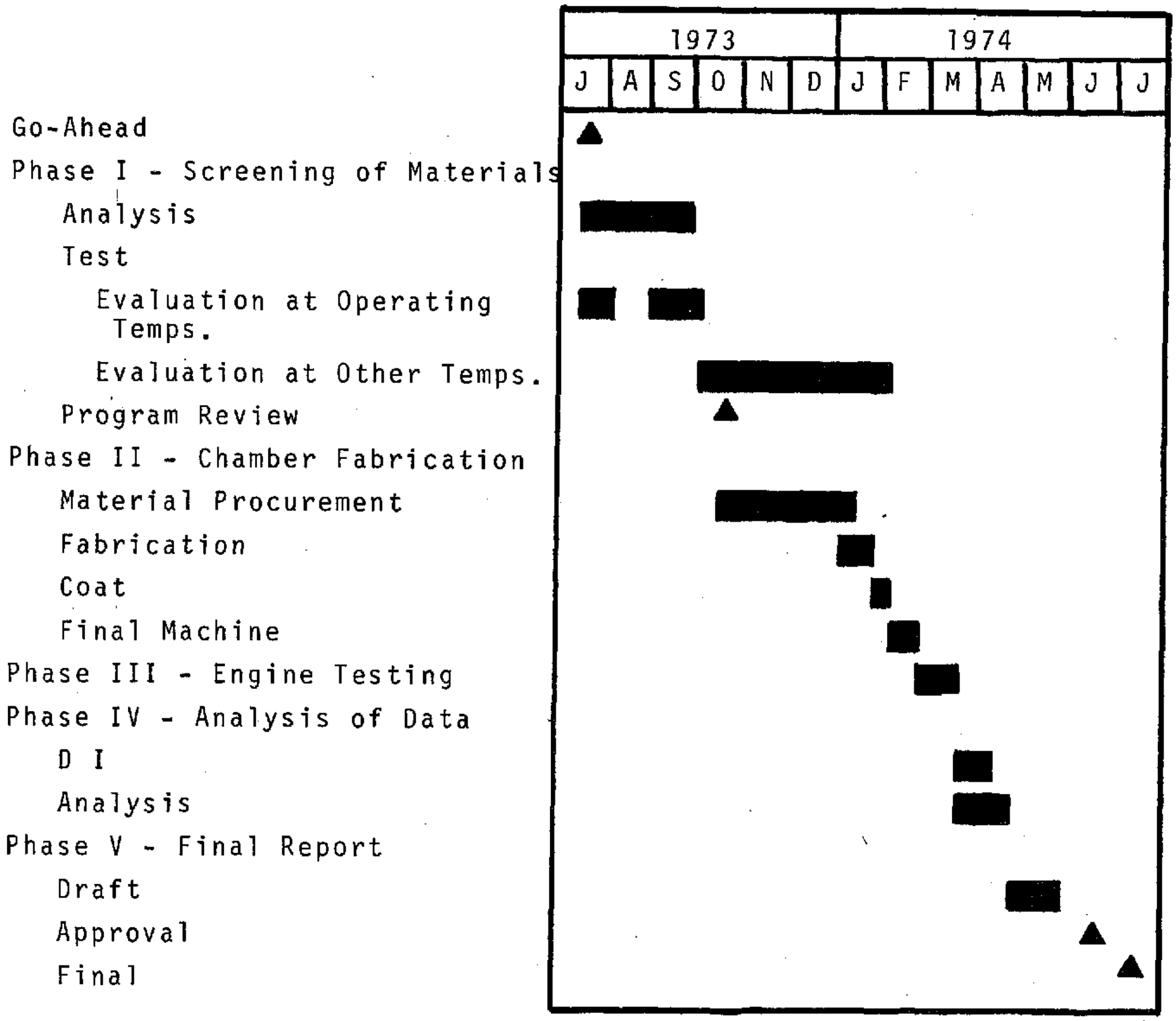


FIGURE 1-1. 600-LBF THRUST ENGINE

FIGURE 1-2

SPACE SHUTTLE RCS ENGINE

COATING DURABILITY PROGRAM



2.0 SUMMARY AND CONCLUSIONS

During this program, four columbium alloys coated with R512E silicide coating were evaluated for creep properties. The results demonstrated that the FS-85 alloy was the best from a creep standpoint (minimum creep/highest creep strength) over the 2000-2400°F temperature range evaluated. The FS-85 alloy was selected for hot fire evaluation based on its high creep strength although SCb-291 was determined equal in the overall evaluation but was previously evaluated successfully for 10,411 seconds firing time on the basic technology program.

A total of 5500 seconds was successfully accumulated on the FS-85 thrust chamber coated with R512E silicide coating. The test program subjected the engine to the worst case mission duty cycles over the range of conditions including maximum operating conditions (maximum chamber pressure, mixture ratio and propellant temperatures) as well as maximum endurance firing (600 seconds continuous).

The engine was subjected to a post test disassembly and inspection. Metallurgical evaluations indicated the coating was in excellent condition. However, the base metal showed a reduction in elongation. Because the all-welded SCb-291 configuration was successfully tested for 10,411 seconds on the basic technology program without a reduction in elongation or material properties, it is hypothesized the uncoated edges where the injector and nozzle extension are mechanically attached, allowed the interstitial pickup causing the elongation reduction. Tests on Bell Independent Research and Development Programs evaluated the susceptibility of R512E coated and uncoated SCb-291 and FS-85 to embrittlement from the products of combustion. The results indicated the coating is protective to the products of combustion which further substantiated the hypothesis.

The performance (including wall temperature) of the engine utilized for this program is similar to the two engines evaluated on the basic technology program. Helium saturated propellants do not affect steady state performance or wall temperatures.

Consequently, the vortex cooled columbium engine will meet the Space Shuttle objectives for RCS.

3.0 PROGRAM RESULTS

3.1 Phase I - Screening of Materials

Phase I consisted of three areas relating to screening of materials. These areas were generation of information on materials system properties based on a literature search, evaluation of creep testing of four columbium alloys and an informal review with NASA-JSC.

Four columbium alloys were evaluated with the R512E coating. The R512E coating was selected based on available data indicating it to be the best coating for columbium for the Space Shuttle RCS engine application where multiple mission duty cycle capability is necessary with minimal servicing. The four columbium alloys selected were FS-85, SCb-291, C129Y and C103. Their selection was based on the maturity, experience and high creep rupture (except C103) at 2200-2400°F.

3.1.1 Materials Information

Evaluation of available pertinent data for the four columbium alloys indicated that the FS-85/R512E alloy/coating system shows the greatest promise as the candidate material of construction for the subject application. This selection was based on the superior creep (rupture and strain), fatigue, mechanical property retention, coating durability and fabricability attributes demonstrated compared to the other three materials as shown in Table 3.1-1. However, it may well be noted that the design has large margins so that the material properties are not utilized in the most optimum manner. The FS-85 has the highest density but the weight difference between the lowest density material and highest density material is 0.28 lb. for the thrust chamber (to $\epsilon = 5$). The SCb-291 and FS-85 have high reduction of area indicating excellent ductility while the C129Y is the worst from this consideration. The SCb-291 has the lowest cost while C129Y has the greatest cost. The overall assessment is that SCb-291 is essentially equal to the FS-85 but FS-85 was evaluated since the SCb-291 was successfully evaluated on the basic RCS technology program (NAS 9-12996). The results of the literature search are shown in Appendix I.

3.1.1.1 Processing History Effects

Inadequate hot work reduction from the ingot stage to the final form results in a non-equiaxed coarse structure in which evidence of the original cast structure is apparent. Insufficiently worked materials are characterized by significantly reduced elongation values in the transverse

TABLE 3.1-1. COLUMBIUM ALLOY EVALUATION PROPERTIES

MATERIAL	FS-85	SCb-291	C129Y	C103
Density, lb/in^3	0.383	0.347	0.343	0.320
Modulus of Elasticity, R.T.	20.0	18.0	16.3	13.1
Modulus of Elasticity, 2200°F	16.0	9.6	12.0	8.3
Properties, R.T.				
Ultimate, KSI	85	75	87	61
Yield, KSI	65	60	70	42
Elongation (%)	25	25	25	25
Properties, 2000°F				
Ultimate, KSI	37	32	40	27
Yield, KSI	28	24	30	20
Elongation (%)	30	24	40	45
Properties, 2200°F				
Ultimate, KSI	31	27	31	20
Yield, KSI	22	20	24	16
Elongation (%)	35	22	50	-
Properties, 2400°F				
Ultimate, KSI	22	21	22.5	14
Yield, KSI	16	15	21	11
Elongation (%)	50	25	50	70
Tensile Ultimate Stress/Density				
R.T.	222,000	213,000	252,000	185,000
2200°F	80,000	78,000	95,000	66,000
2400°F	63,000	60,000	80,000	50,000
Fatigue Life (Cycles)				
2200°F	2.5×10^6	2×10^6	2×10^6	10^7
2400°F	1.4×10^6	1.5×10^6	1.7×10^6	8×10^6
Creep Rupture (KSI at 2400°F for 30 Hours)	11.3	7	6	4.4
Creep Strain (1%)-KSI at 2400°F for 30 Hours	8	5.5	1.9	2.2
Reduction of Area (%)	91.6	98.4	20	70.7

RATING FACTORS EVALUATION*

MATERIAL	FS-85	SCb-291	C129Y	C103
Weight	3	2	2	1
Fatigue Life	2	2	2	1
Creep Rupture	1	2	3	4
Creep Strain	1	2	3	3
Modulus Elasticity	1	2	2	3
Weldability	1	1	2	1
Reduction of Area	2	1	4	3
Cost	2	1	3	2
TOTALS	13	13	21	18
RATING	1	1	3	2

*NOTE: Lowest number is best for evaluation.

direction and coarse grain (ASTM 1 or larger) which raises the ductile-brittle transition temperatures of the weldments and degrades ductility. In addition, inadequately worked, coarse grained (ASTM 0 and larger) columbium alloy has indicated sensitivity to thermal shock; however, incorporating ample hot-work reduction into the same material eliminated the sensitivity to thermal shock and increased the ductility of the material.

3.1.1.2 Mechanism for Coating Failure Mode

The mechanism for R512E coating failure mode depends on the service environment. The coating protects the columbium from the gas species at the wall (i.e., N_2 and H_2) and oxidation. The mode of failure for protection from the gas species is crack propagation through the coating to the substrate resulting in embrittlement of the substrate. The failure mode for oxidation is depletion of the reservoir resulting in porosity and/or thermal expansion cracking.** Test data* indicates the R512E coating is capable of 212 hours (steady state oxidation-erosion) life at 2200°F and 80 hours of life at 2400°F and greater than 10,000 cycles (thermal fatigue) at 2200°F and greater than 8800 cycles at 2400°F. The BAC technology program engine (SCb-291 chamber) demonstrated 10,411 seconds operation with 6377 firings and 567 thermal cycles with no degradation.

3.1.1.3 Coating Diffusion Rates

The limited data available with R512E coated FS-85 indicate that 0.0004 inch of substrate material is consumed for each 0.001 inch of coating formed. Consumption of the substrate by diffusion at 2400°F is 7×10^{-7} inch per minute. Consequently, the impact of coating diffusion rate is minimal based on the BAC design of operation at 2200°F.

3.1.2 Evaluation of Creep Testing

Creep rupture testing was conducted on the four columbium alloys coated with R512E over a temperature range of 2000-2400°F. A total of 30 specimens of data were obtained on the four columbium alloys which were tested at Battelle Columbus Laboratories in a vacuum of 5×10^{-5} torr. The specimens were placed individually in a test chamber, which was then evacuated, and then heated to test temperature in approximately

*AFML-TR-71-127, "Evaluation of Coated Columbium Alloys for Burner Application", Pratt and Whitney Aircraft, Div. United Aircraft Corp.

**See Appendix I, Page I-23

one hour. After test temperature stabilization (0.5-1 hour), the specimens were loaded until they ruptured or the test discontinued. Temperature was monitored, controlled and recorded by means of thermocouples (Pt-PtRh) with periodic checking using an optical pyrometer.

Figures 3.1-1 through 3.1-4 show the creep rupture data for each columbium alloy at 2000, 2200, and 2400°F. Figures 3.1-5 through 3.1-7 show the creep rupture comparison of the four alloys at a given temperature and indicate the FS-85 alloy has the highest creep rupture strength at any temperature with SCb-291 next at 2400°F and 30 hours rupture time (design point). At still higher temperatures and longer times, the strength of these two alloys approach each other. Figures 3.1-8 through 3.1-12 show the results of creep strain data for 1%, 2%, and 5% creep deformation. The Larson-Miller rupture curves are plotted in Figures 3.1-13 through 3.1-17.

3.2 Phase II - Thrust Chamber Fabrication

A thrust chamber (8701-470014-1) was fabricated for use in Phase II and tested in the Phase III engine test program. Figure 3.2-1 shows the dimensions of the hardware.

The chamber material, as selected in accordance with the results of the Phase I material evaluation screening, was FS-85.

The thrust chamber was machined from bar stock in the same manner as chambers previously made from SCb-291 with no manufacturing difficulties.

The flanges were electron beam welded to the chamber in the same manner employed with the SCb-291 columbium thrust chambers. Again no difficulties were experienced.

Final machining of the thrust chamber was completed after welding and the chamber assembly was delivered to HiTemCo for R512E silicide coating (both inside and outside).

Characteristics of the thrust chamber are:

$L^* = 14$

$\epsilon_c = 5.5/1$

$\epsilon = 5/1$ (to flange joint)

Radiation cooled

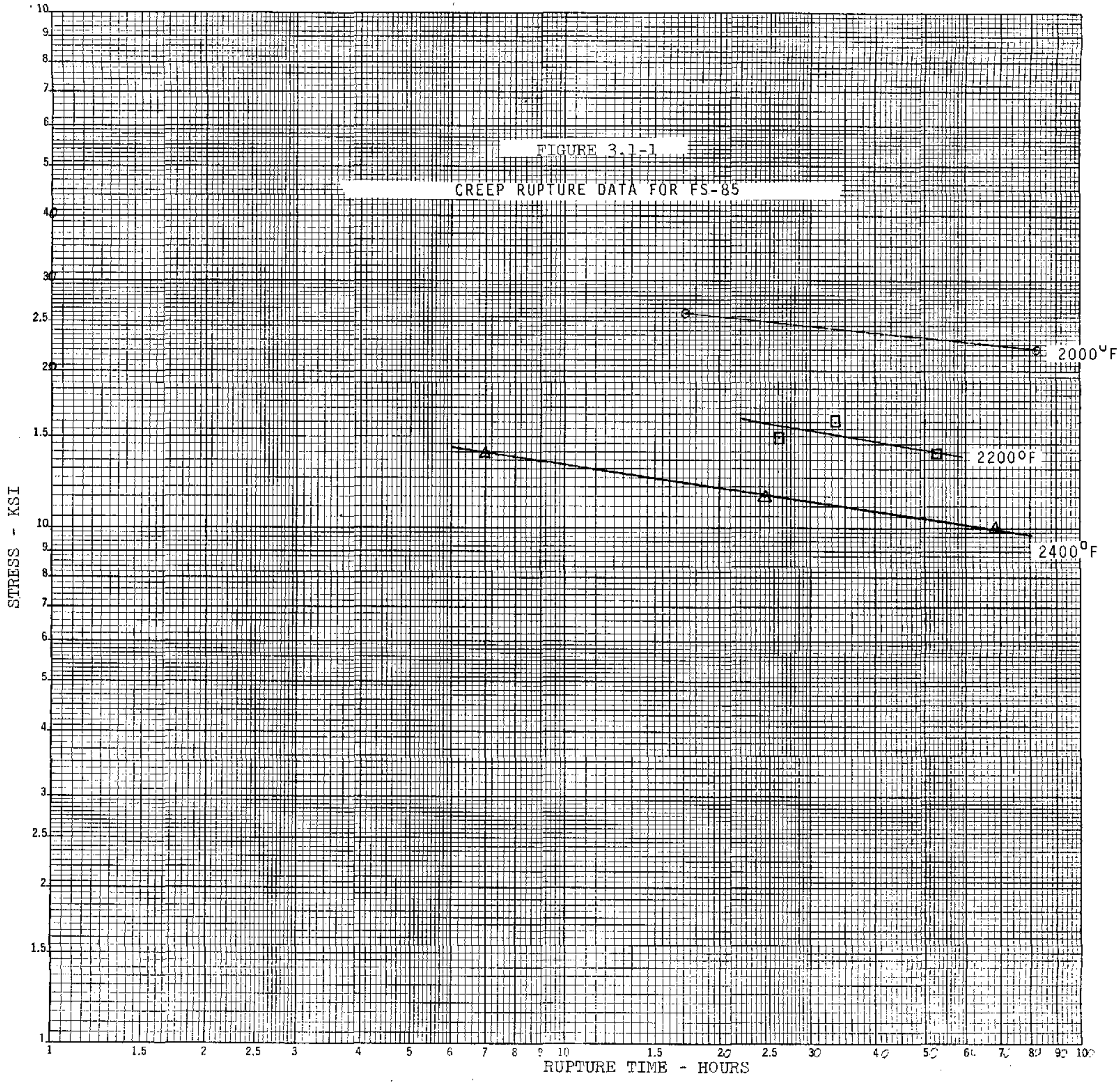


FIGURE 3.1-1
CREEP RUPTURE DATA FOR FS-85
STRESS - KSI
RUPTURE TIME - HOURS
2000°F
2200°F
2400°F

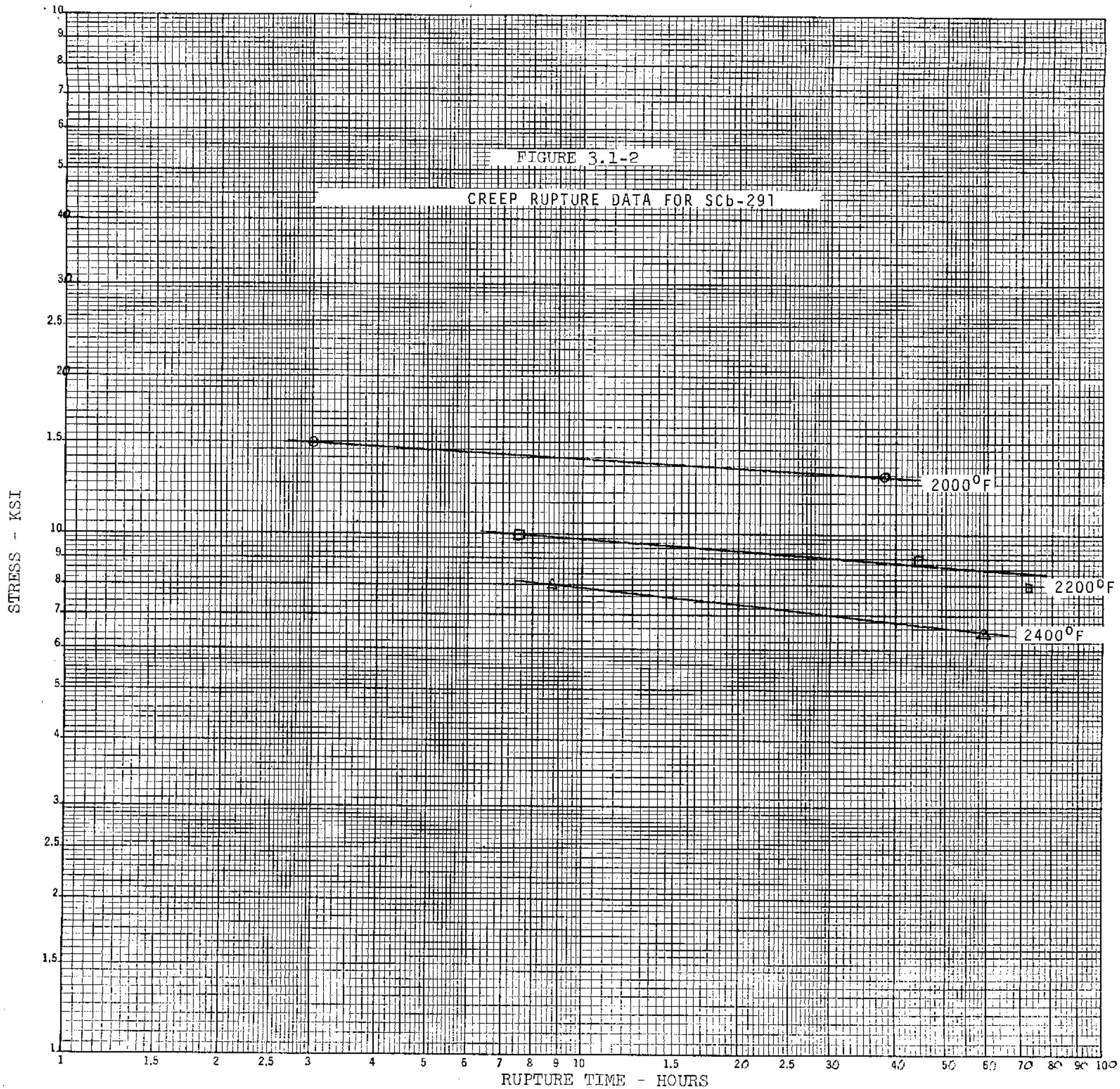


FIGURE 3.1-2
CREEP RUPTURE DATA FOR SCb-291
2000°F
2200°F
2400°F
STRESS - KSI
RUPTURE TIME - HOURS

11

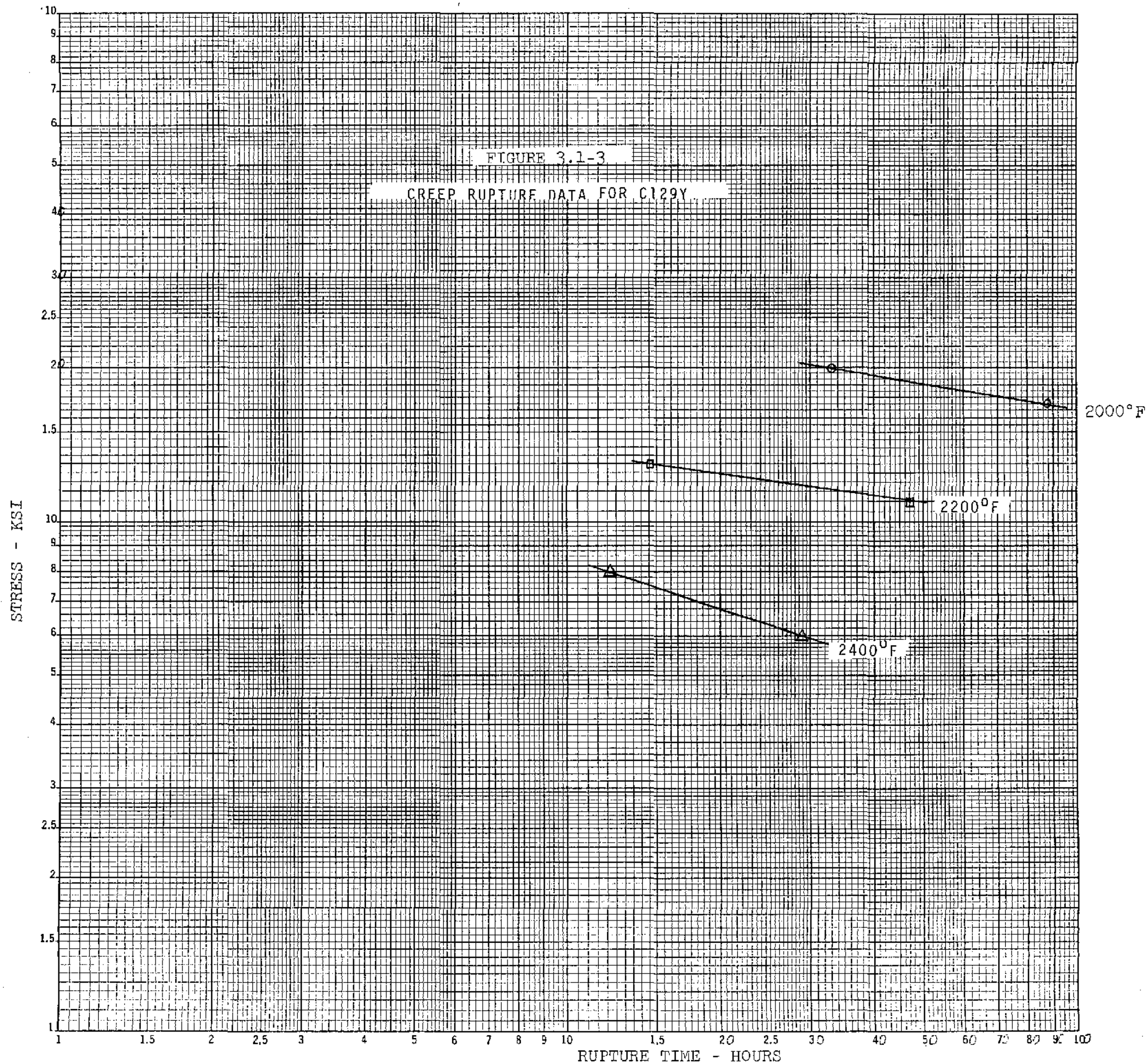


FIGURE 3.1-3
CREEP RUPTURE DATA FOR C129Y
STRESS - KSI
RUPTURE TIME - HOURS
2000°F
2200°F
2400°F
10
9
8
7
6
5
4
3
2.5
2
1.5
1
1.5
2
2.5
3
4
5
6
7
8
9
10
15
20
25
30
40
50
60
70
80
90
100

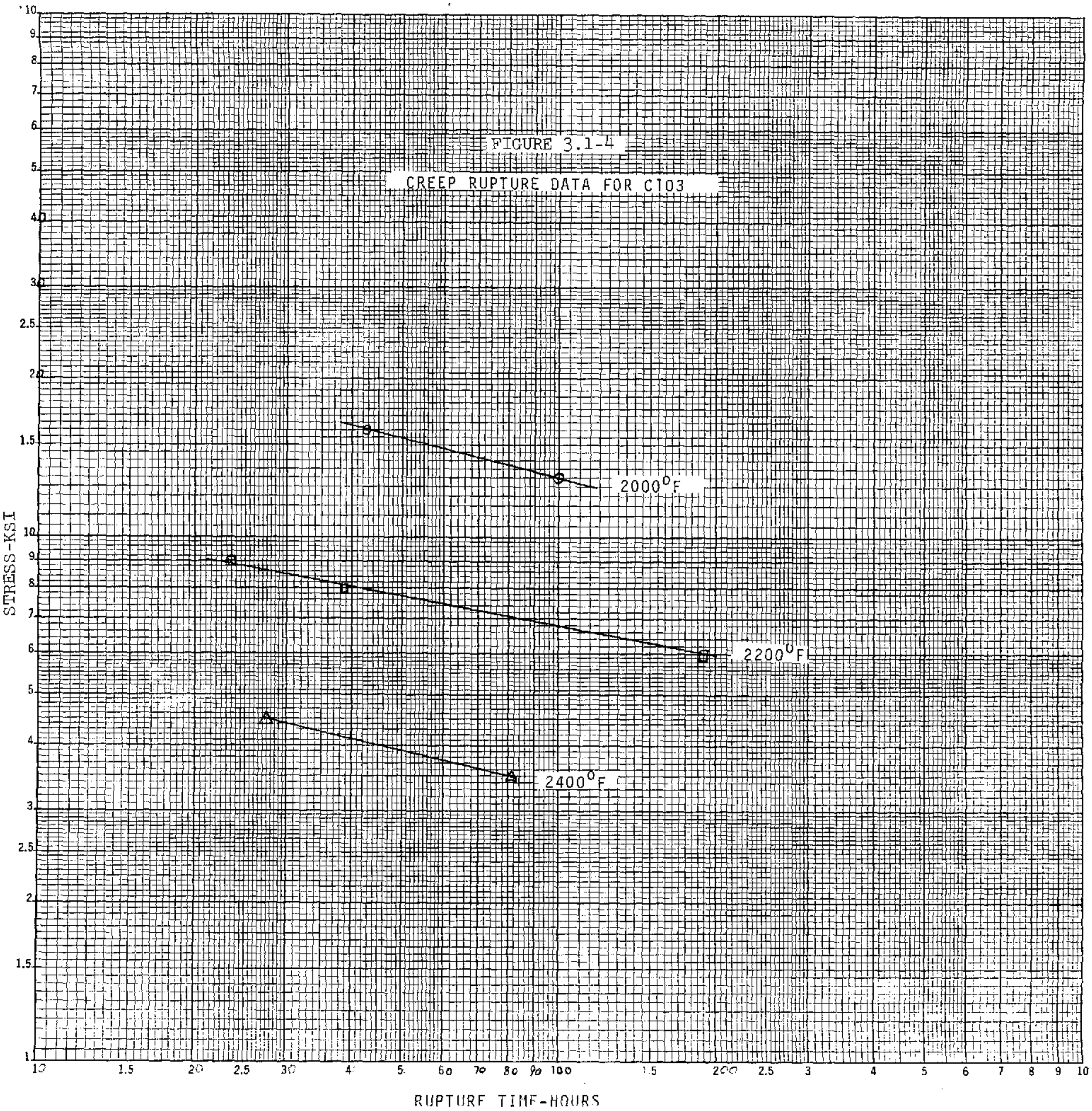


FIGURE 3.1-4
CREEP RUPTURE DATA FOR C103
STRESS-KSI
RUPTURE TIME-HOURS
2000°F
2200°F
2400°F

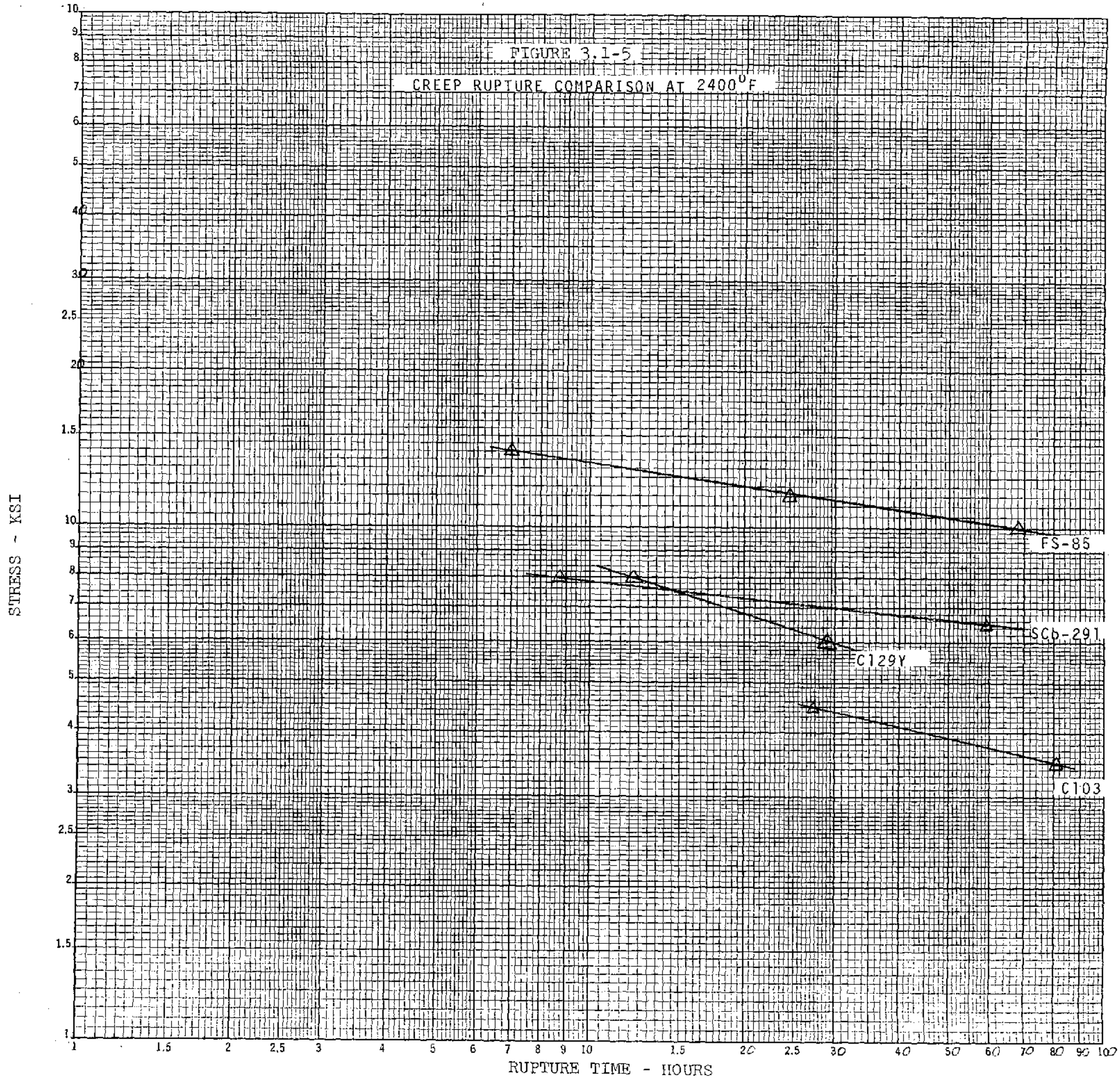


FIGURE 3.1-5

CREEP RUPTURE COMPARISON AT 2400°F

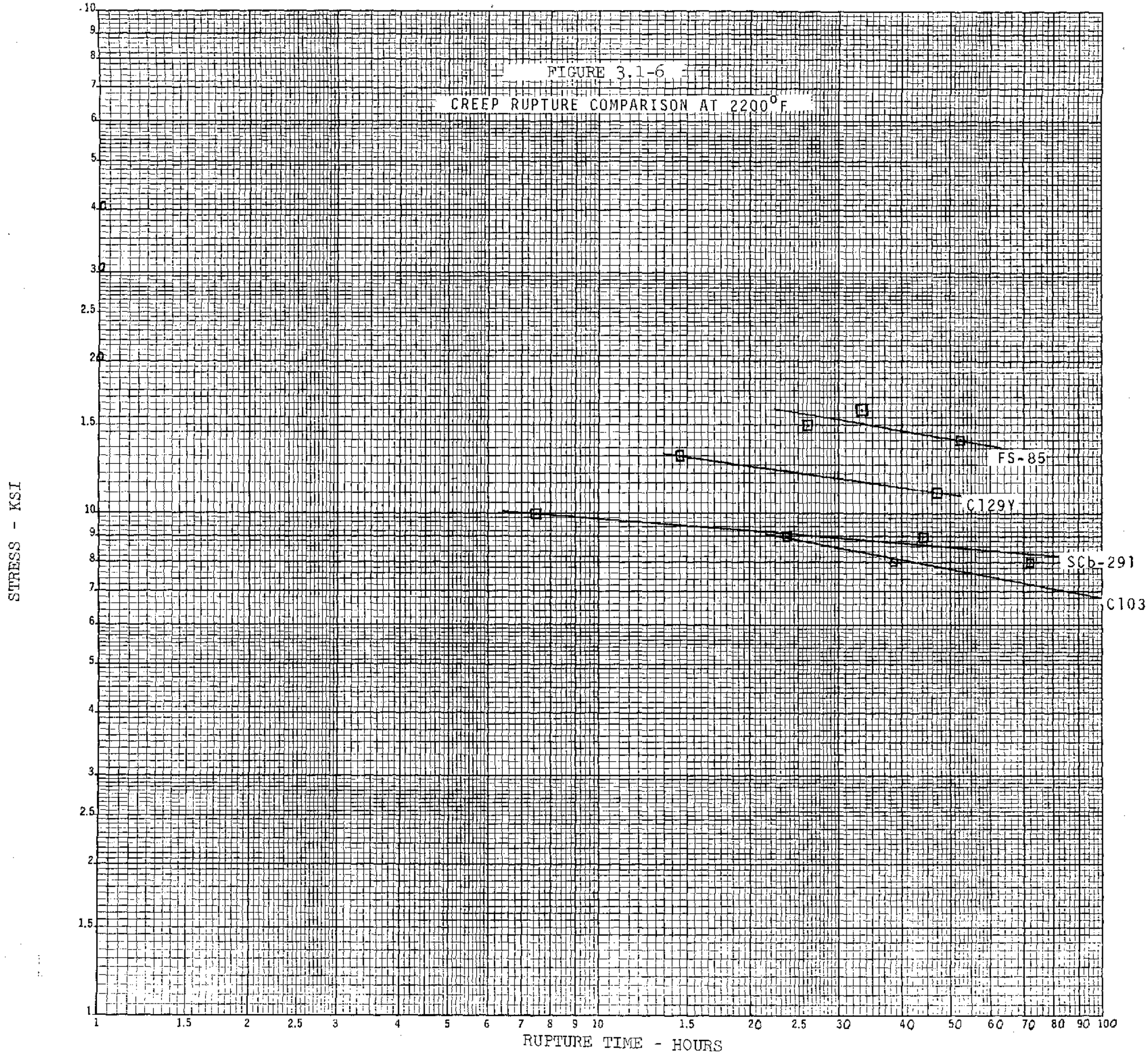


FIGURE 3.1-6

CREEP RUPTURE COMPARISON AT 2200°F

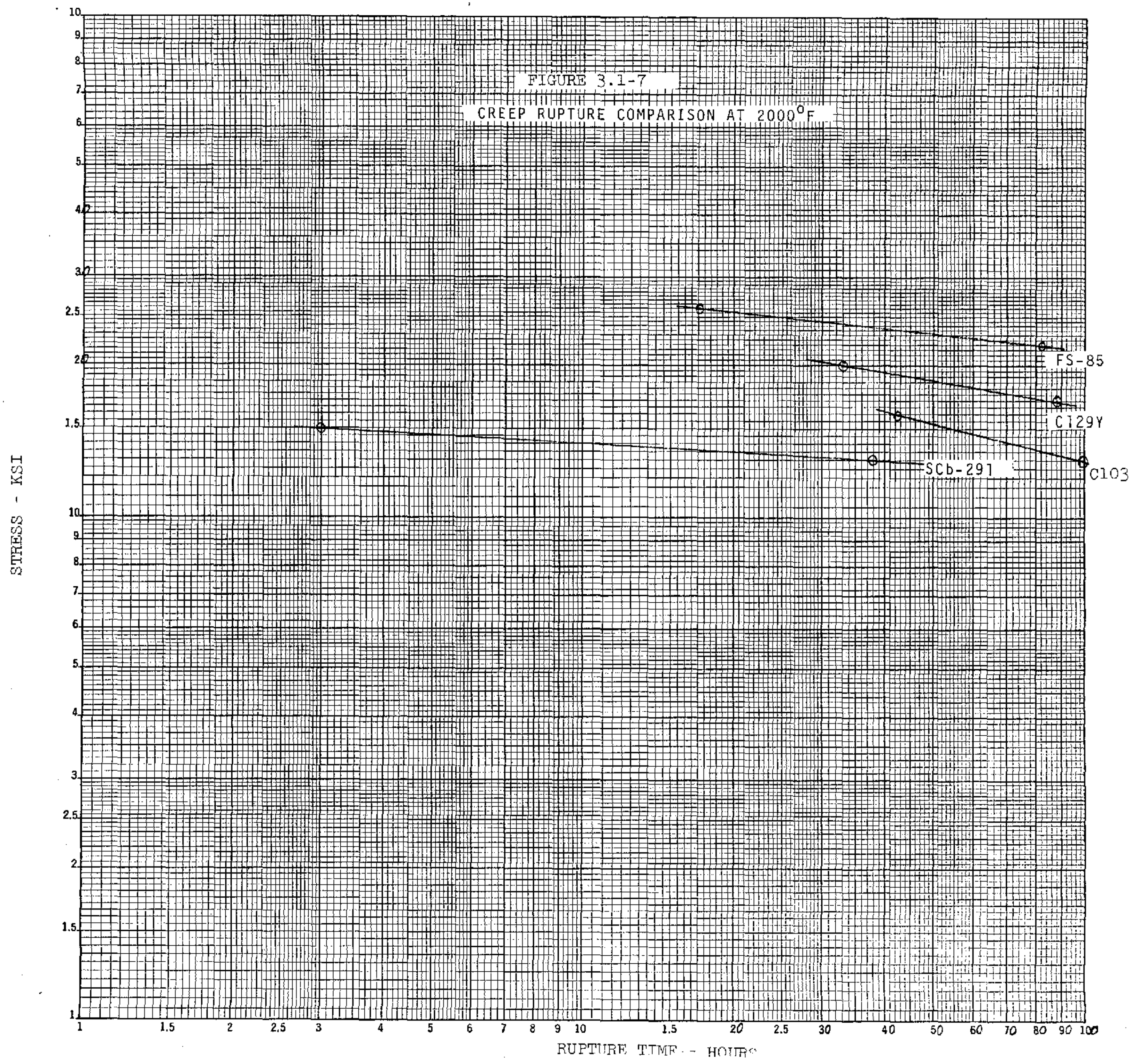


FIGURE 3.1-7

CREEP RUPTURE COMPARISON AT 2000°F

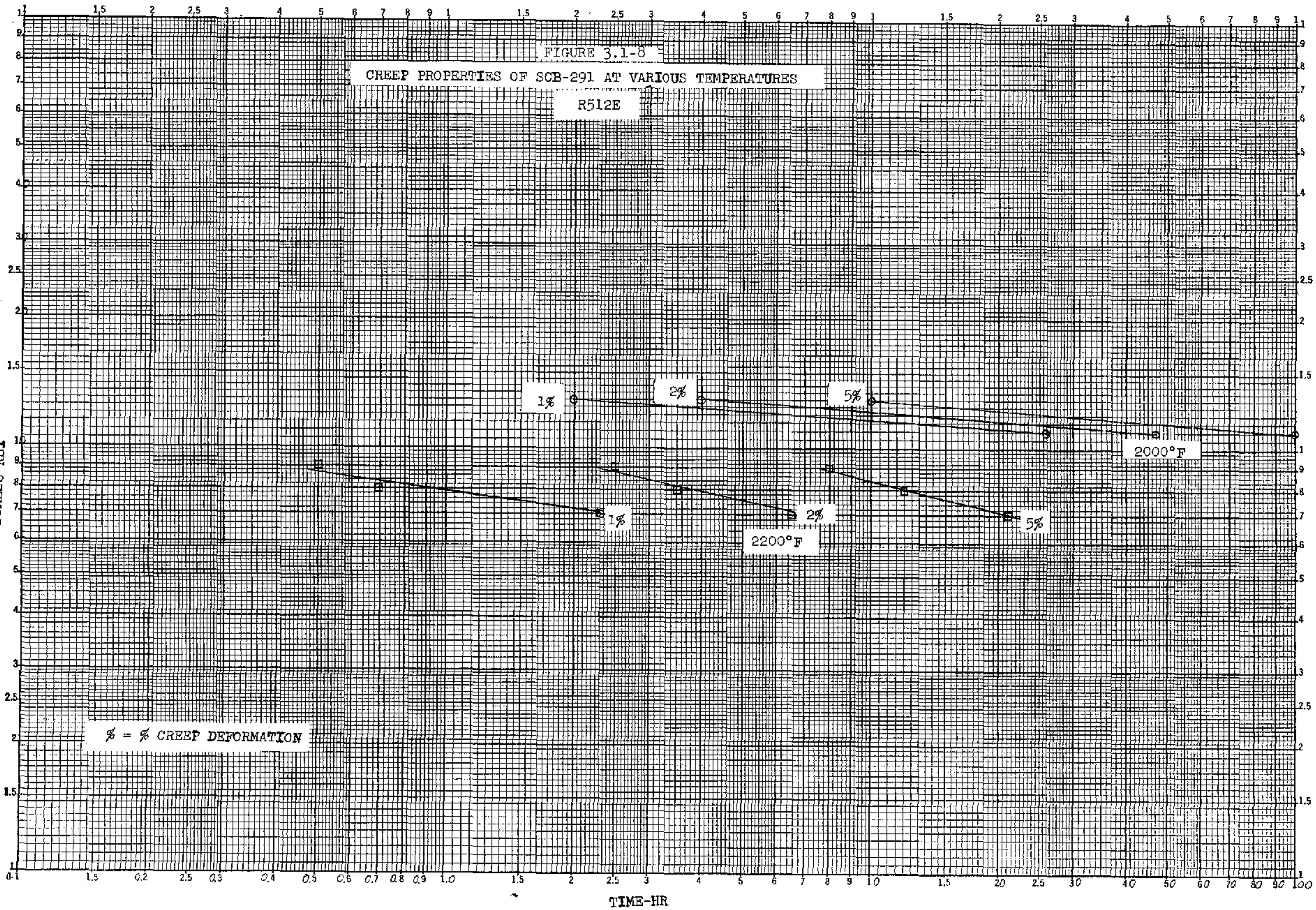


FIGURE 3.1-8
CREEP PROPERTIES OF SCB-291 AT VARIOUS TEMPERATURES
R512E

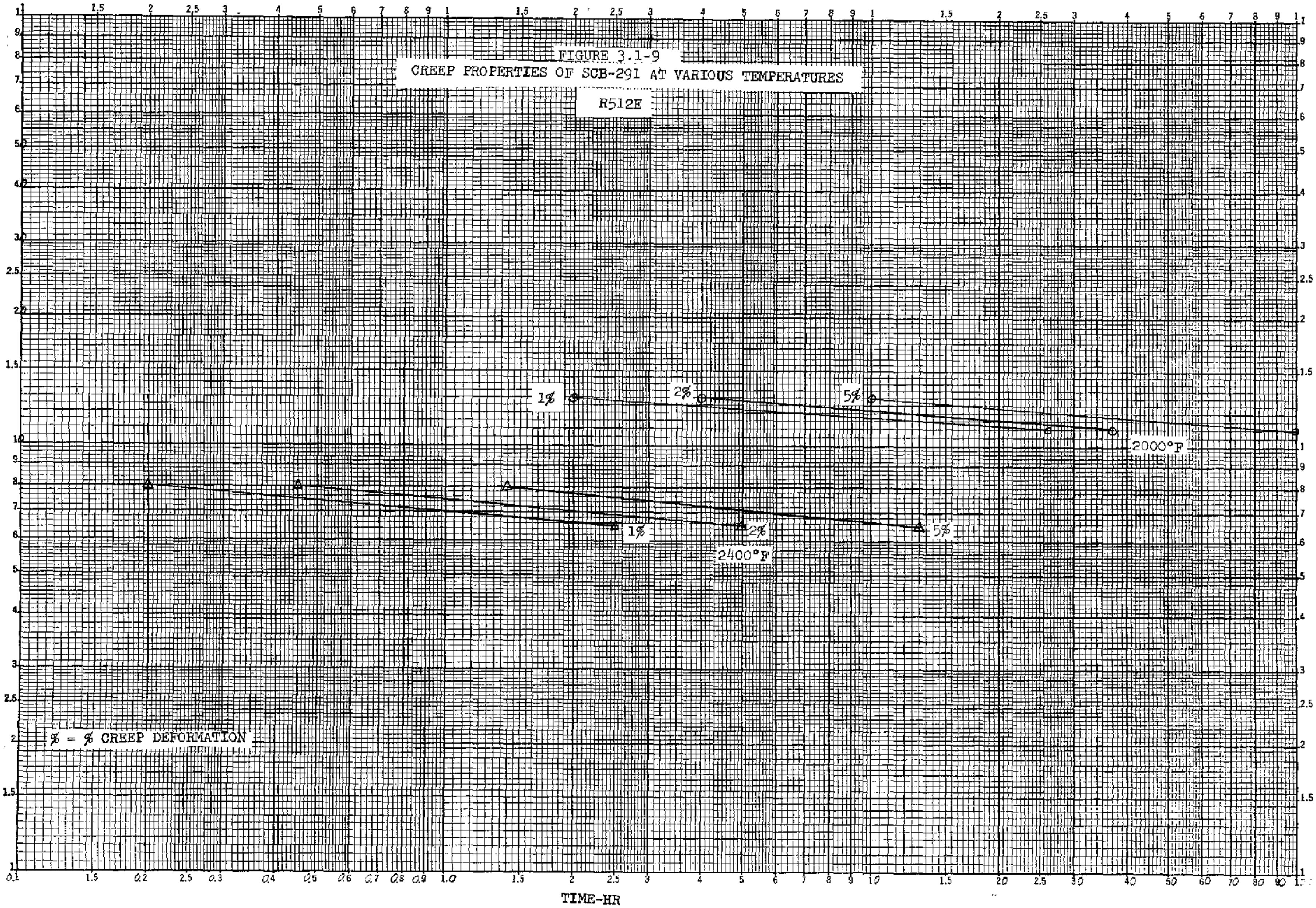


FIGURE 3.1-9
CREEP PROPERTIES OF SCB-291 AT VARIOUS TEMPERATURES

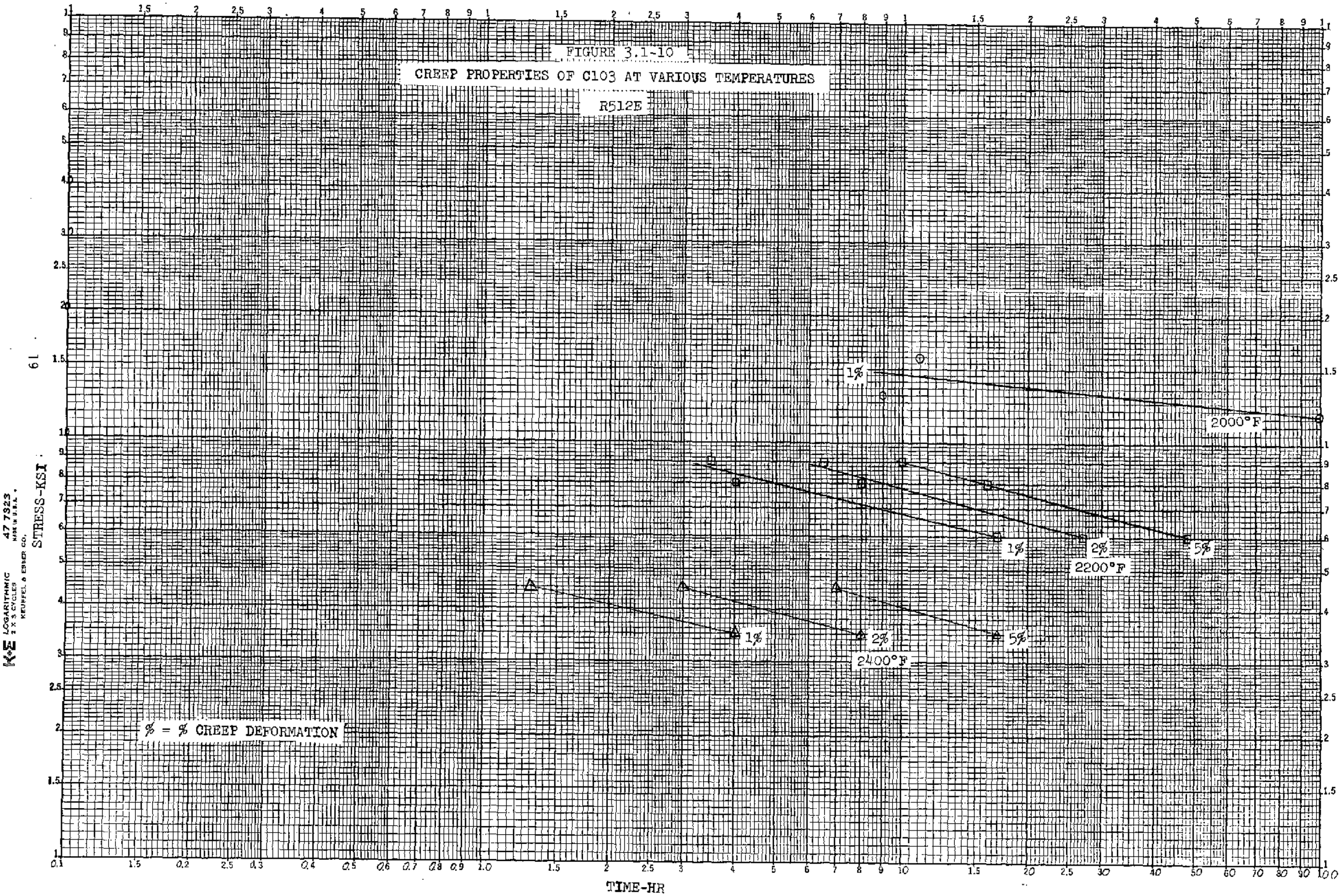


FIGURE 3.1-10
CREEP PROPERTIES OF C103 AT VARIOUS TEMPERATURES
R512E
STRESS-KSI
TIME-HR
1%
2000°F
1%
2%
5%
2200°F
1%
2%
5%
2400°F
% = % CREEP DEFORMATION
K+E LOGARITHMIC 2 X 3 CYCLES KEUFFEL & ESSER CO. 47 7923 MADE IN U.S.A.

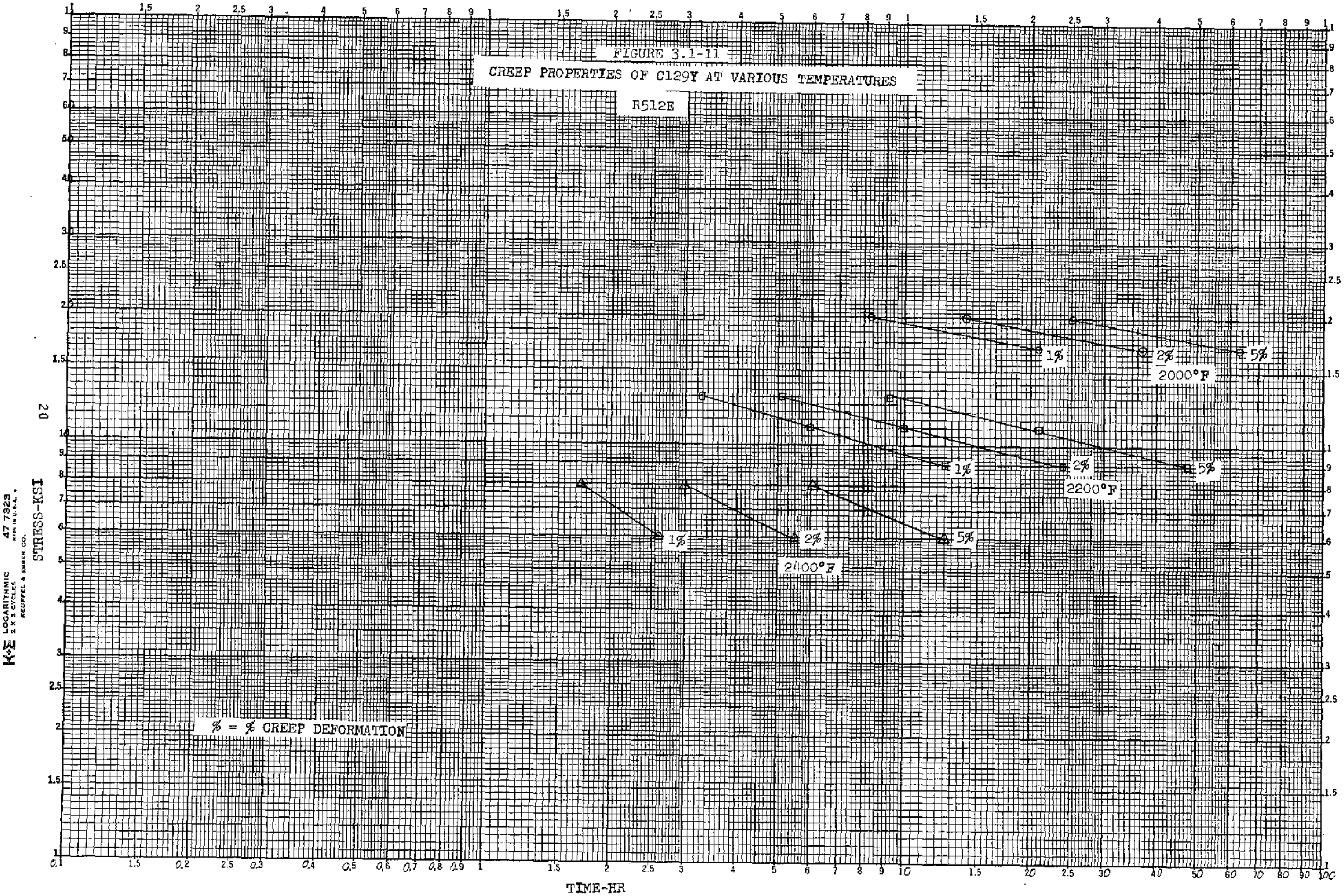


FIGURE 3.1-11
CREEP PROPERTIES OF C129Y AT VARIOUS TEMPERATURES
R512E
1%
2%
5%
2000°F
1%
2%
5%
2200°F
1%
2%
5%
2400°F
% = % CREEP DEFORMATION
STRESS-KSI
TIME-HR
K&E LOGARITHMIC 2 X 3 CYCLES KEUFFEL & ESSER CO. 47 7323

20

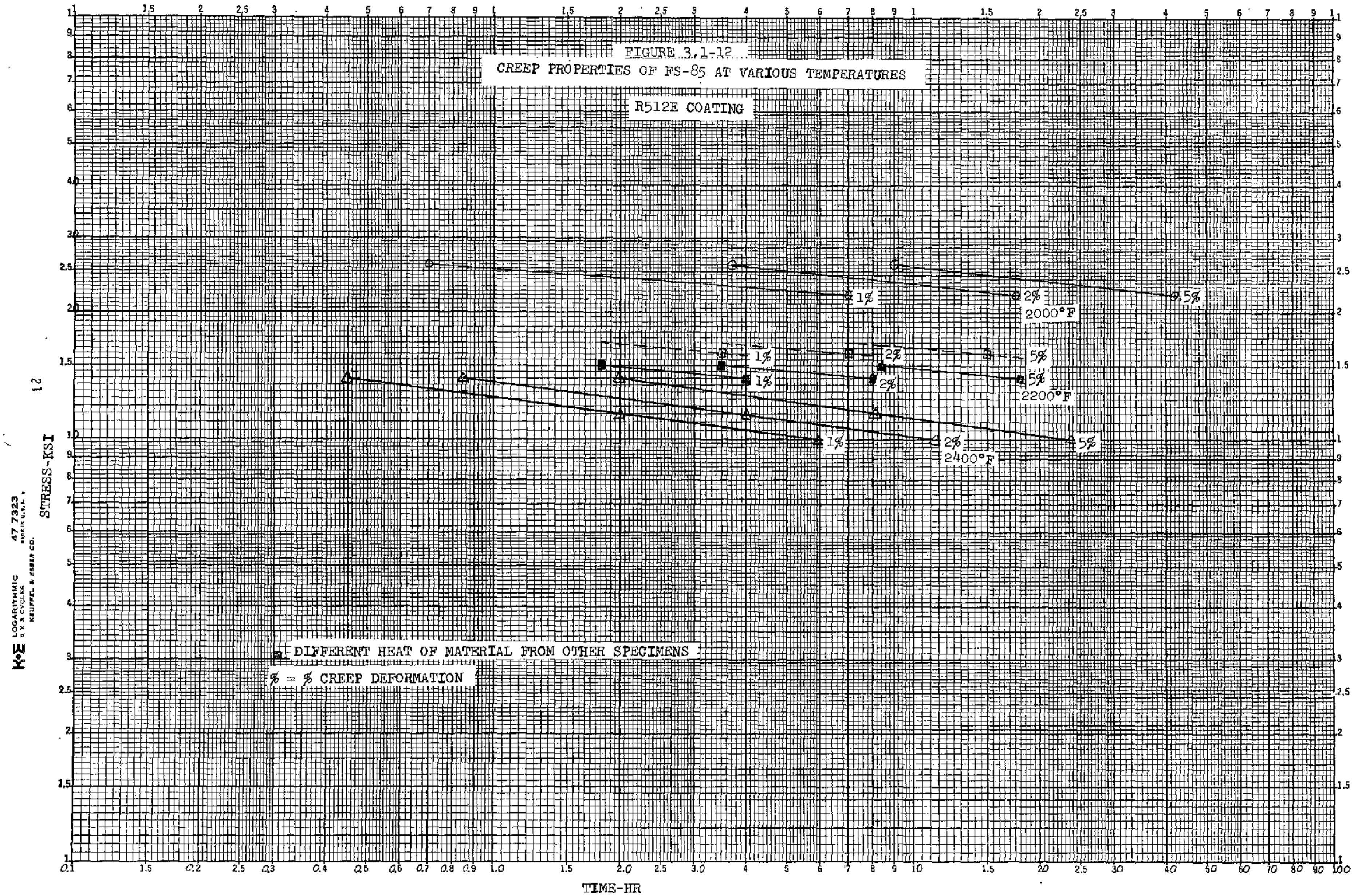


FIGURE 3.1-12
CREEP PROPERTIES OF FS-85 AT VARIOUS TEMPERATURES
R512E COATING
1%
2%
5%
2000°F
2200°F
2400°F
DIFFERENT HEAT OF MATERIAL FROM OTHER SPECIMENS
% = % CREEP DEFORMATION
STRESS-KSI
TIME-HR

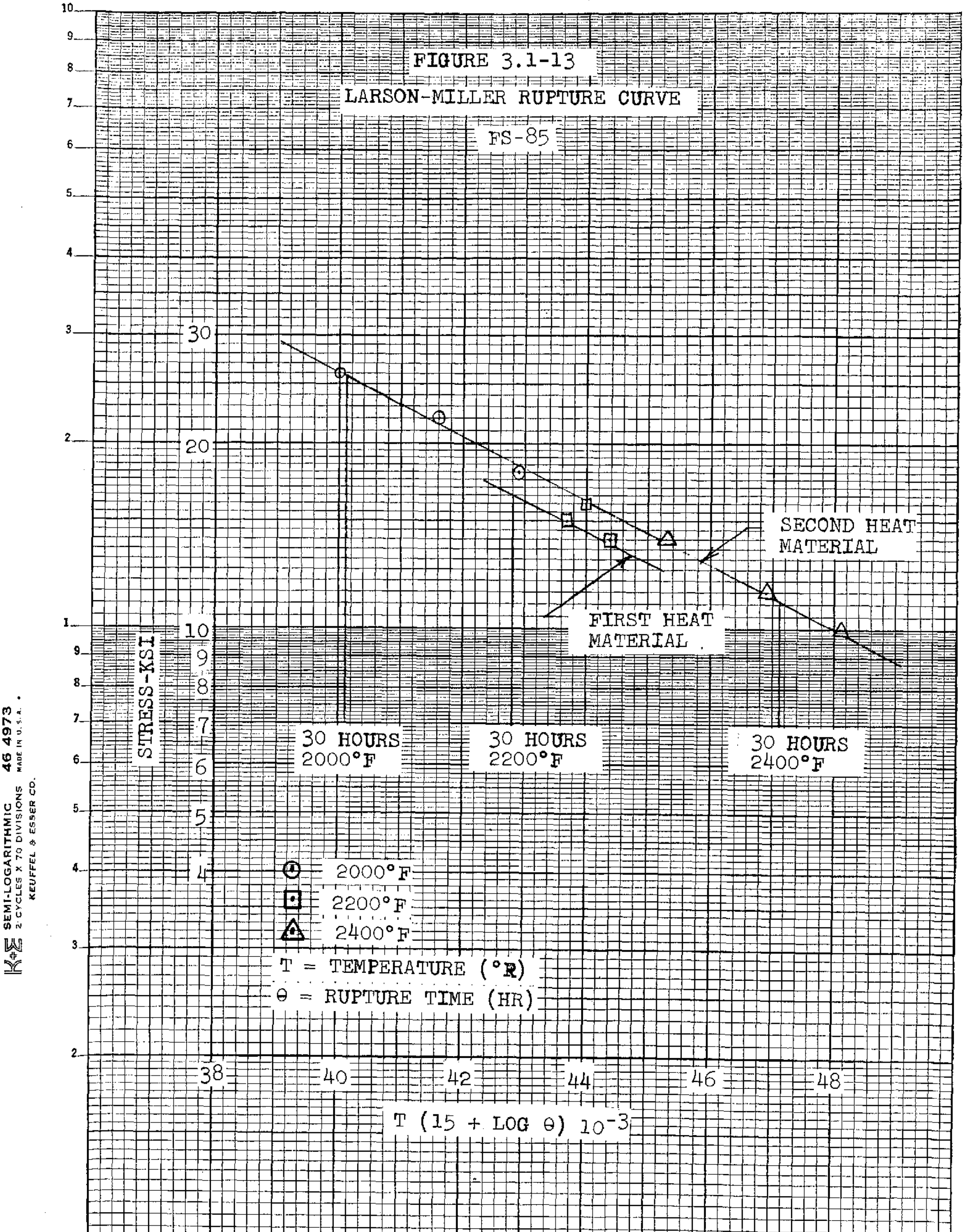


FIGURE 3.1-13
LARSON-MILLER RUPTURE CURVE
FS-85
SECOND HEAT MATERIAL
FIRST HEAT MATERIAL
STRESS-KSI
30
20
10
9
8
7
6
5
4
30 HOURS 2000°F
30 HOURS 2200°F
30 HOURS 2400°F
2000°F
2200°F
2400°F
T = TEMPERATURE (°R)
Θ = RUPTURE TIME (HR)
38
40
42
44
46
48
T (15 + LOG Θ) 10^-3
SEMI-LOGARITHMIC 46 4973
2 CYCLES X 70 DIVISIONS MADE IN U.S.A.
KEUFFEL & ESSER CO.

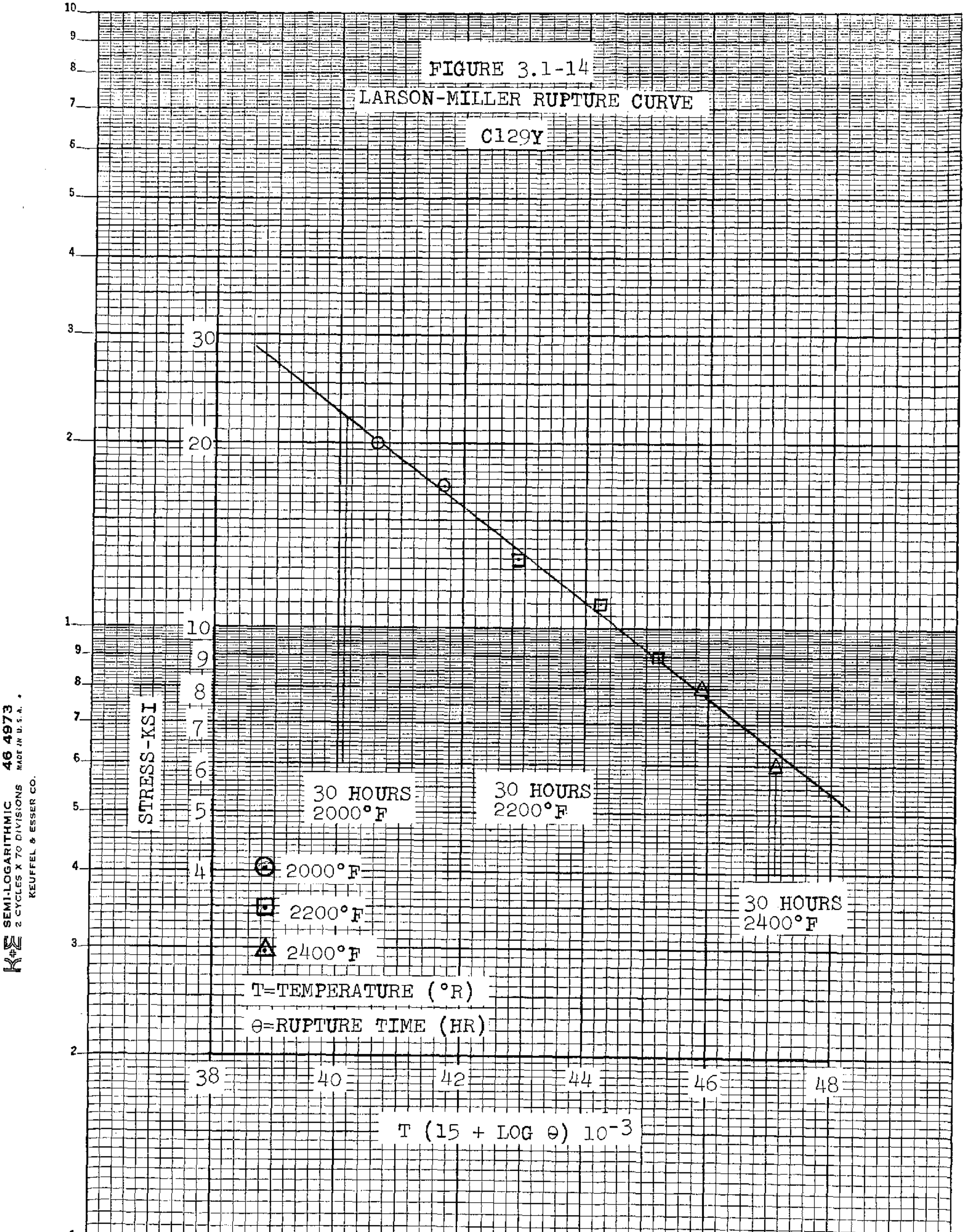


FIGURE 3.1-14
LARSON-MILLER RUPTURE CURVE
C129Y
STRESS-KSI
30
20
10
9
8
7
6
5
4
30 HOURS
2000°F
30 HOURS
2200°F
30 HOURS
2400°F
2000°F
2200°F
2400°F
T=TEMPERATURE (°R)
θ=RUPTURE TIME (HR)
38
40
42
44
46
48
T (15 + LOG θ) 10-3
K+E SEMI-LOGARITHMIC 46 4973
2 CYCLES X 70 DIVISIONS MADE IN U.S.A.
KEUFFEL & ESSER CO.

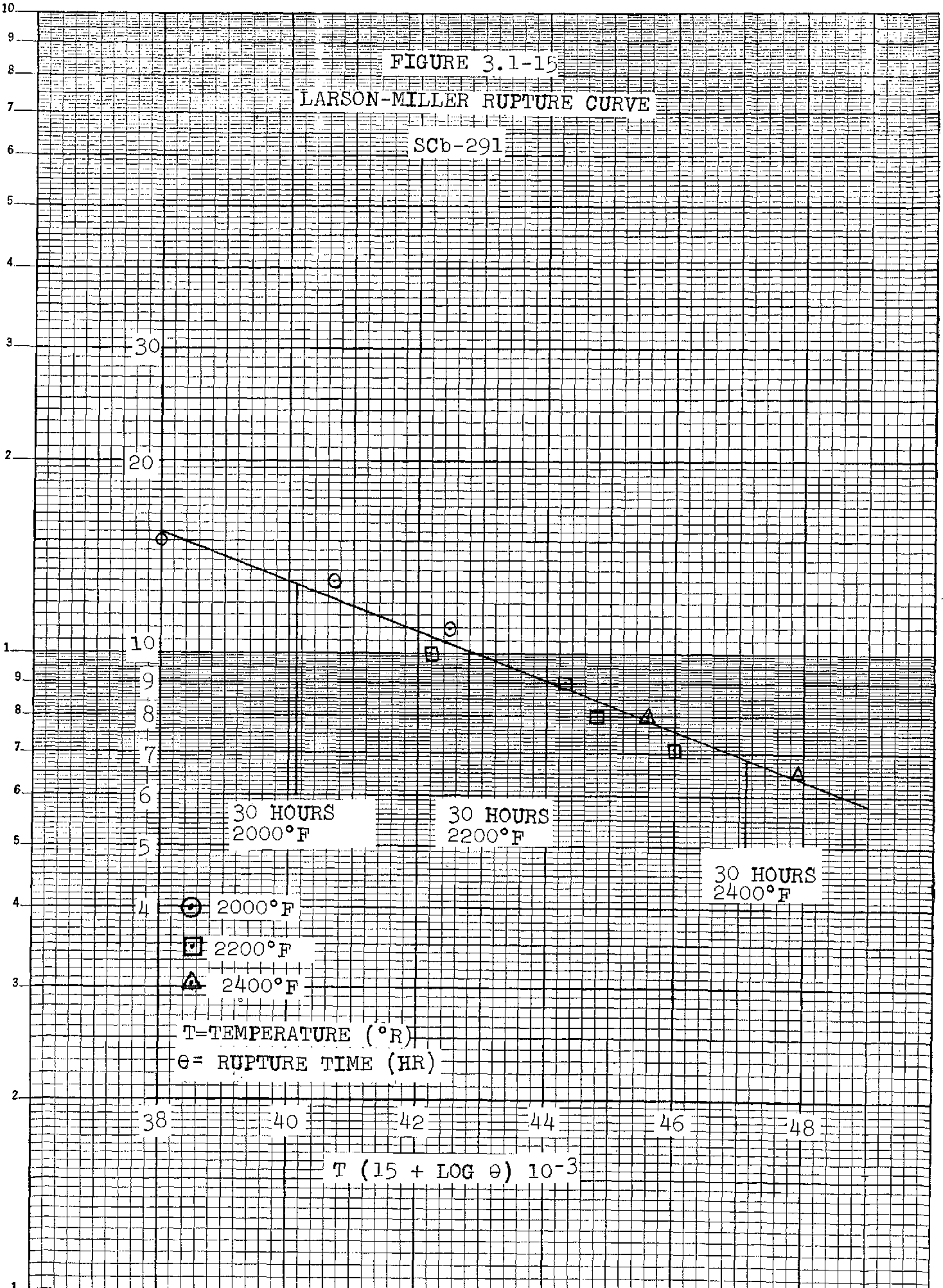


FIGURE 3.1-15
LARSON-MILLER RUPTURE CURVE
SCb-291

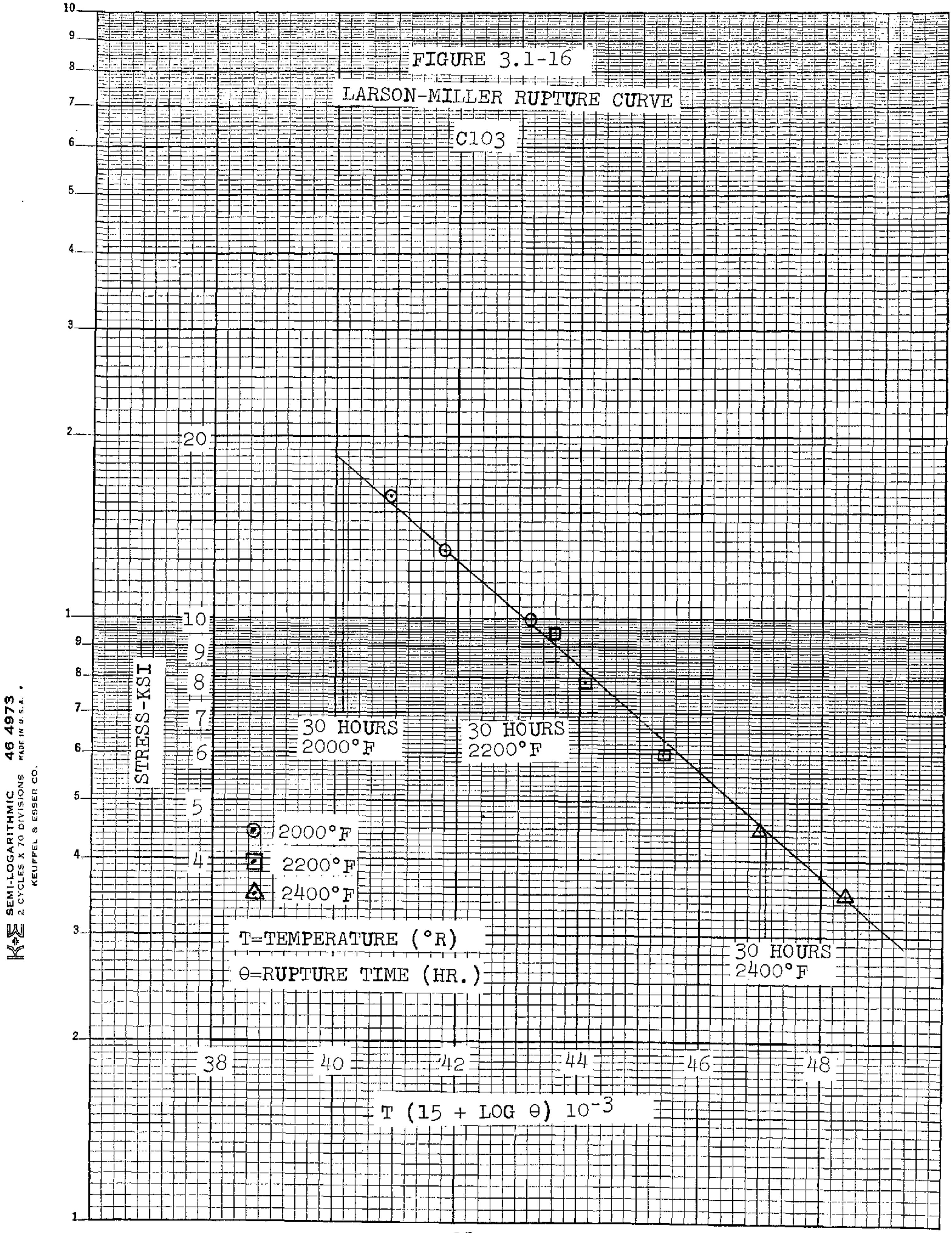


FIGURE 3.1-16
LARSON-MILLER RUPTURE CURVE
C103
STRESS-KSI
20
10
9
8
7
6
5
4
30 HOURS
2000°F
30 HOURS
2200°F
30 HOURS
2400°F
2000°F
2200°F
2400°F
T=TEMPERATURE (°R)
Θ=RUPTURE TIME (HR.)
38
40
42
44
46
48
T (15 + LOG Θ) 10-3
K&E SEMI-LOGARITHMIC 46 4973
2 CYCLES X 70 DIVISIONS MADE IN U.S.A.
KEUFFEL & ESSER CO.

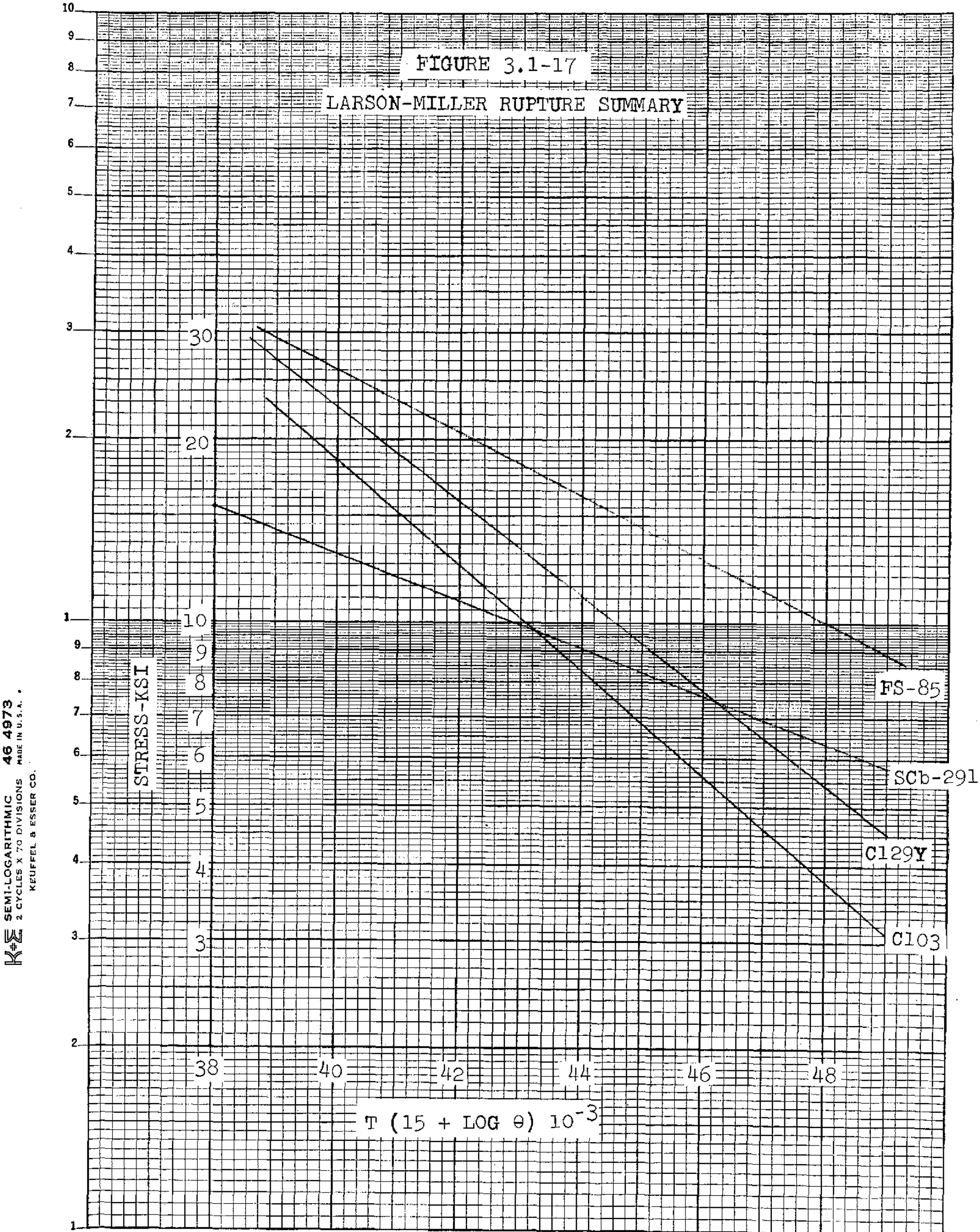


FIGURE 3.1-17
LARSON-MILLER RUPTURE SUMMARY
STRESS-KSI
30
20
10
9
8
7
6
5
4
3
38
40
42
44
46
48
T (15 + LOG θ) 10-3
FS-85
SCb-291
C129Y
C103
SEMI-LOGARITHMIC 46 4973
2 CYCLES X 70 DIVISIONS MADE IN U.S.A.
KEUFFEL & ESSER CO.

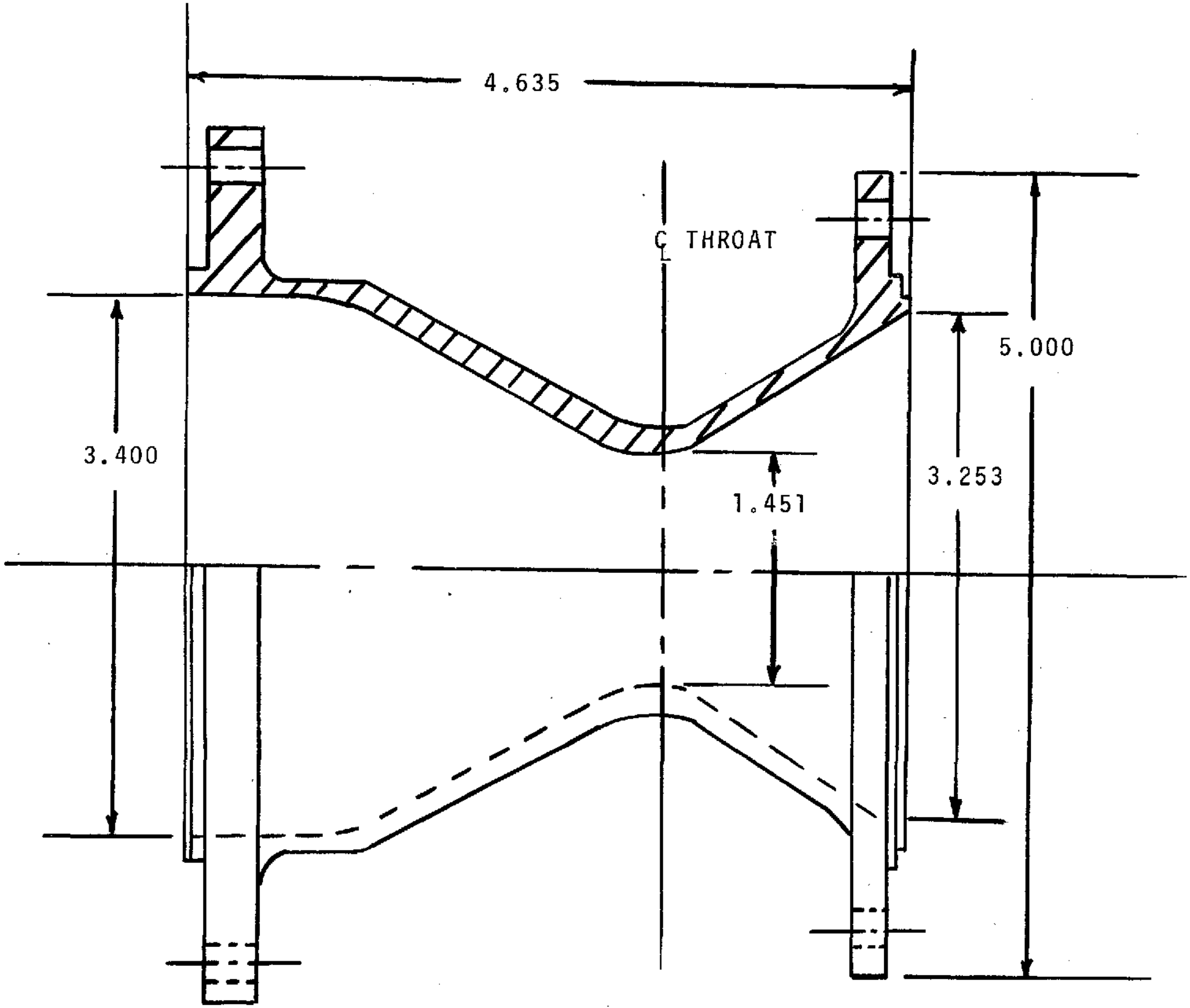


FIGURE 3.2-1.   THRUST CHAMBER S/N FS-85-P-1

The thrust chamber was provided with flanges which permitted bolting the injector to the upstream end and the nozzle extension to the downstream end.

An existing nozzle extension (8689-470009-1) made from columbium (C103) alloy and coated with R512E silicide coating was bolted to the nozzle end of the thrust chamber. This bolt-on nozzle extension permits an area ratio of 31/1.

An existing bolt-on injector assy (8701-473001-1), S/N FT-1C, was used. It is of all welded construction, containing 36 combustion doublets and six vortex fuel barrier cooling orifices as shown in Figure 3.2-2. This injector provides a fuel barrier flow of 13.8% (% of total flow). The face dam between the outer row fuel and oxidizer orifices was removed during an early design modification. The injector incorporates acoustic cavities to permit operation in a dynamically stable condition over a wide operating regime. A chamber pressure pickup opens into one acoustic cavity. A valve mounting face is machined onto the injector to permit bolting of the valve to the injector assembly.

A test bipropellant valve was used during this program. This valve (see Figure 3.2-3) a normally open poppet type valve, consisting of an actuating piston chamber with a spring loaded piston, an oxidizer propellant chamber and a fuel propellant chamber. All three chambers are enclosed in a single body with the actuating piston chamber being in between the two propellant chambers. The activating piston shaft, the oxidizer poppet shaft, and the fuel poppet shaft are all interconnected externally by a single yoke.

Figure 3.2-4 is a photograph showing all of the hardware details as utilized in this test program.

Figure 3.2-5 is a photograph of the test hardware as assembled just prior to test cell installation.

3.3 Phase III - Engine Test

The Phase III test program was designed to demonstrate a high temperature materials system through approximately six equivalent missions including worst case mission duty cycles and endurance. The testing (see Table 3.3-1) consisted of the following:

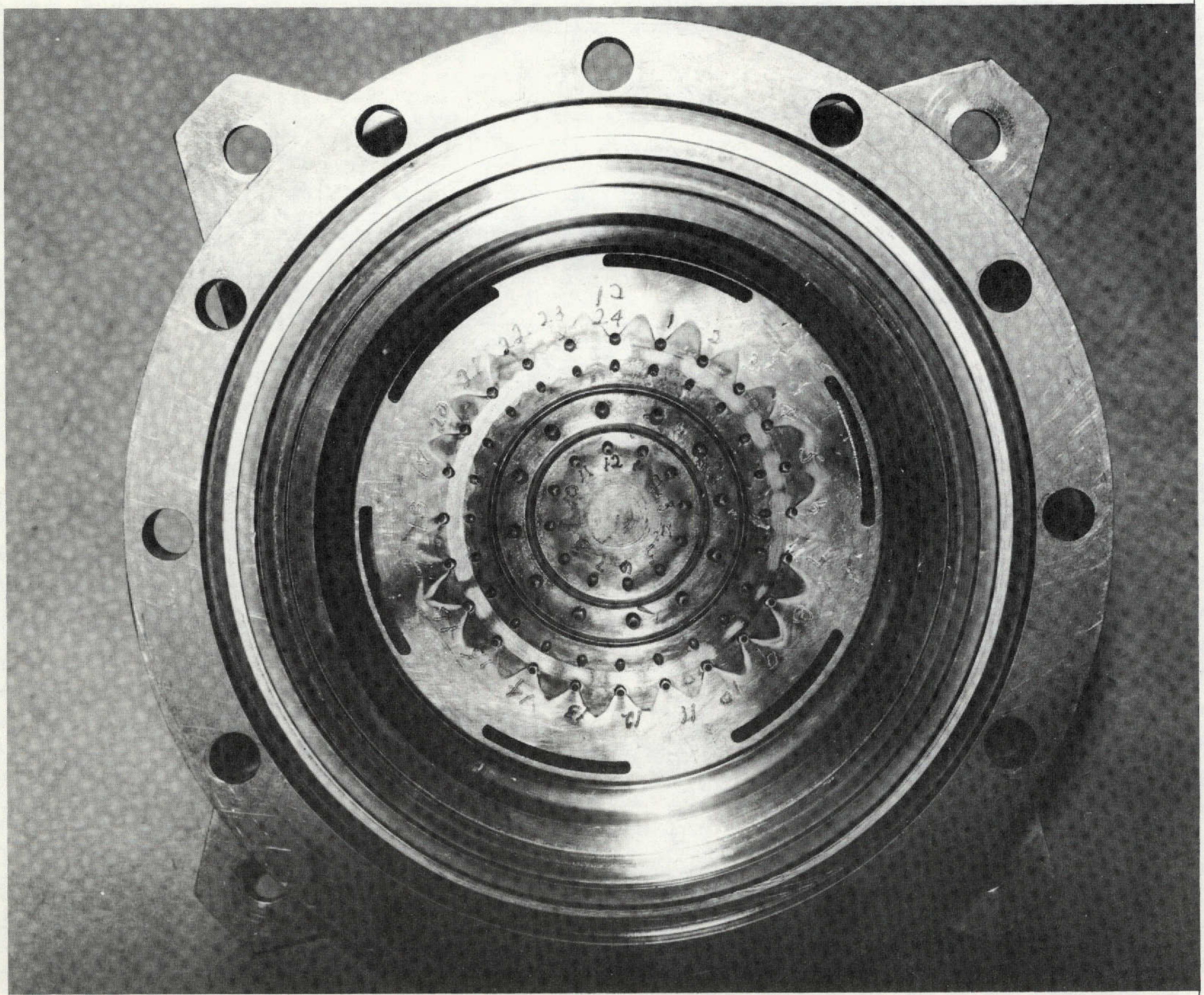


FIGURE 3.2-2. INJECTOR S/N FT-1C

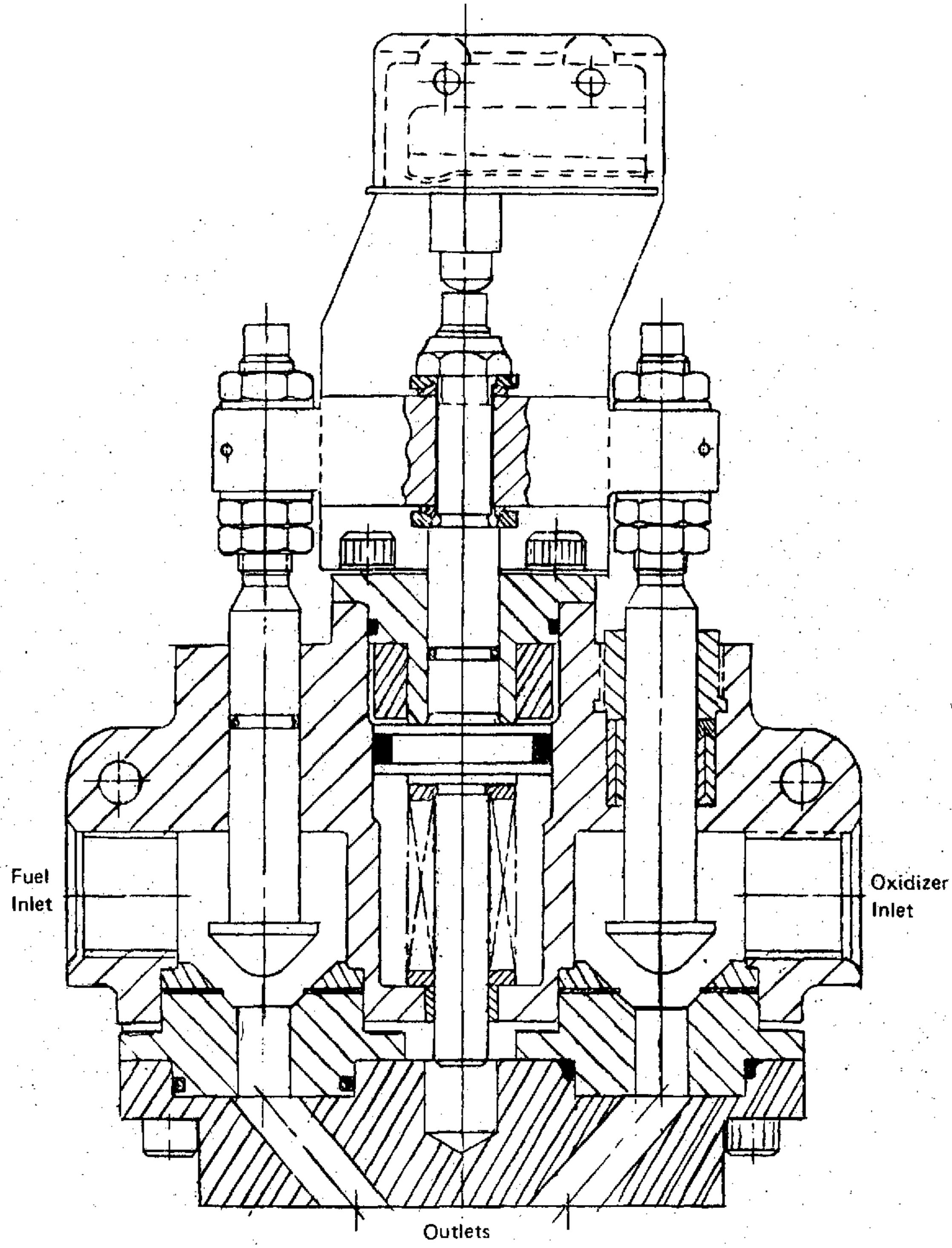


FIGURE 3.2-3. TEST VALVE

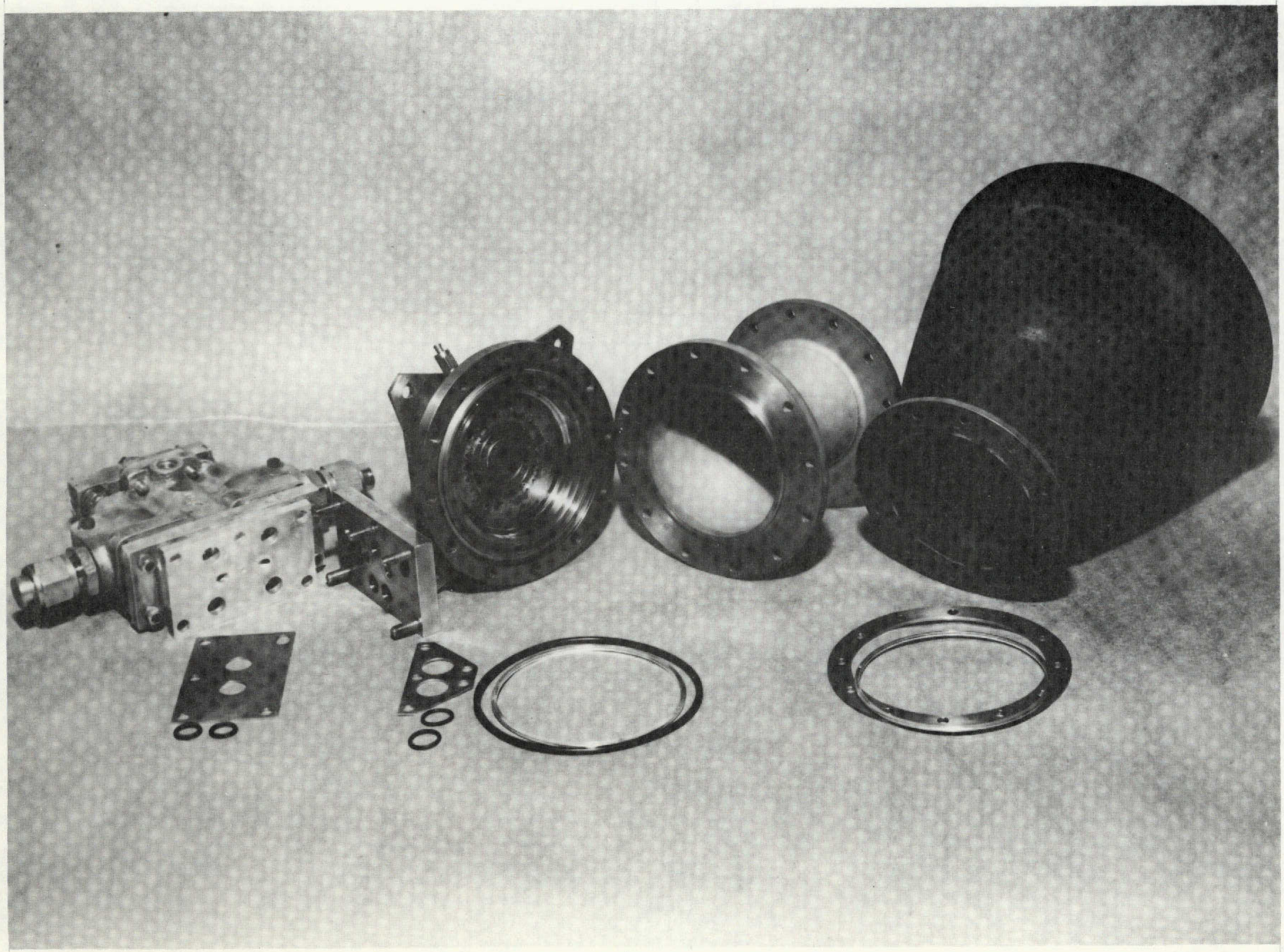


FIGURE 3.2-4. ENGINE COMPONENTS

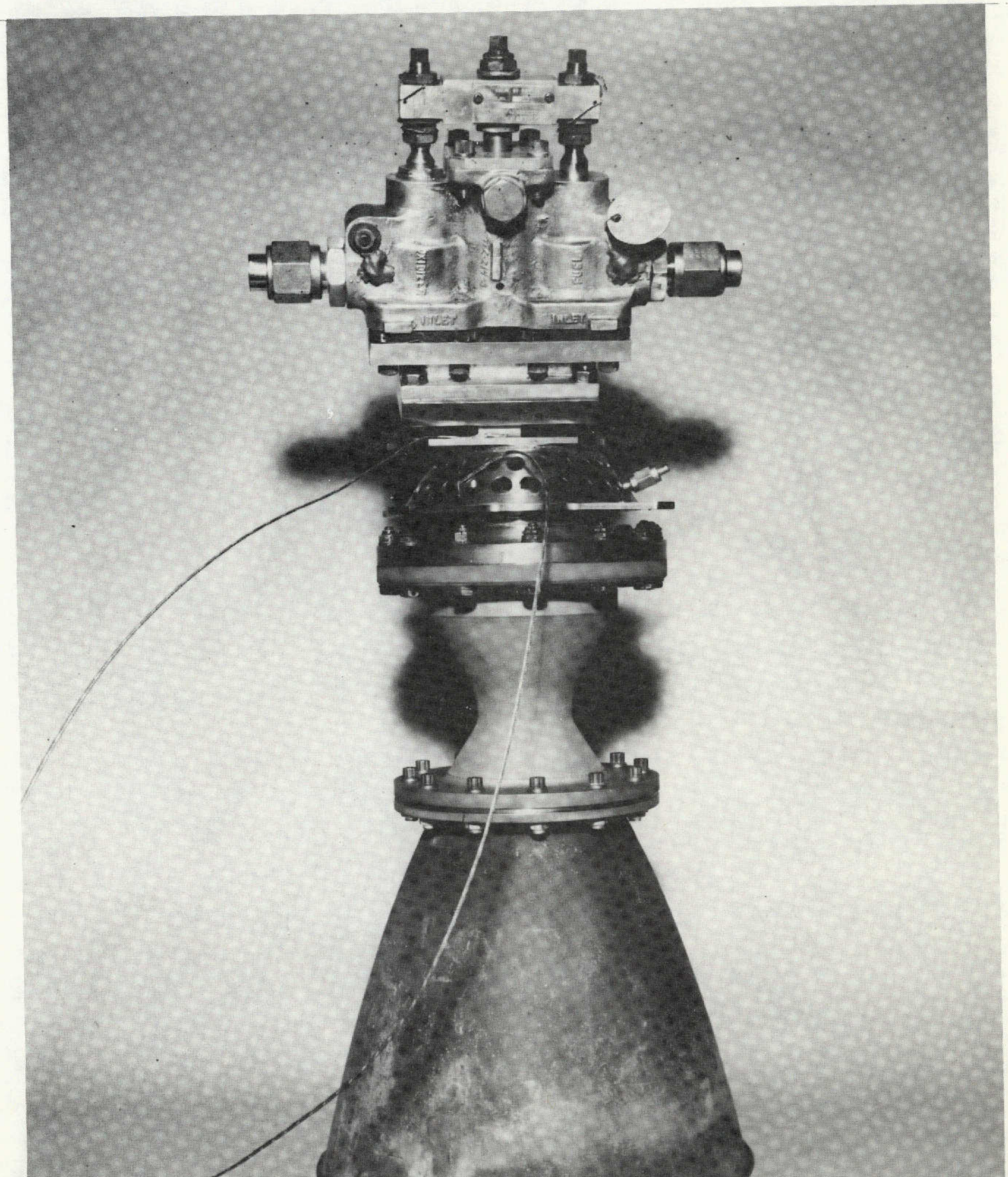
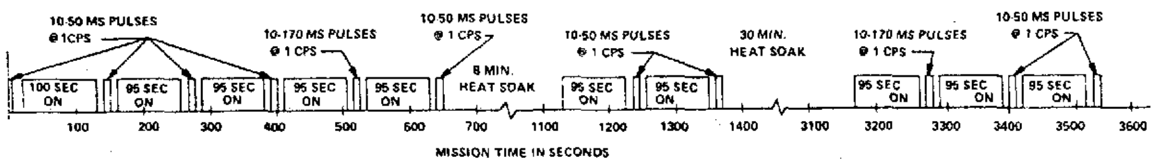


FIGURE 3.2-5. TEST ENGINE

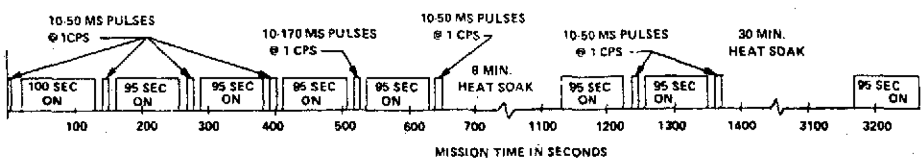
TABLE 3.3-1

PHASE III TEST PROGRAM

Worst Case MDC No.	P_c (psia)	O/F	T_p (^oF)	He Sat	Duration (Sec)
1.	200	1.6	75	No	* MDC-120 firings-965 Sec.
2.	200	1.5	75	No	*MDC-120 firings-965 Sec.
3.	200	1.7	75	No	*MDC-120 firings-965 Sec.
4.	200	1.6	75	No	600-Sec. continuous
5.	210	1.65	110	No	⊛ MDC-88 firings -760 Sec.
6.	210	1.65	110	Yes	⊛ MDC-88 firings -760 Sec.
7.	200	1.6	75	No	60-Sec. Continuous
8.	200	1.5	75	No	" " "
9.	200	1.7	75	No	" " "
10.	185	1.6	75	No	" " "
11.	185	1.5	75	No	" " "
12.	185	1.7	75	No	" " "
13.	215	1.6	75	No	" " "
14.	215	1.5	75	No	" " "
15.	215	1.7	75	No	" " "



*WORST CASE DUTY CYCLE



⊛ MODIFIED WORST CASE DUTY CYCLE

Injector cold flow

Engine level missions (MDC's)

MDC 1, 2, 3 at varying mixture ratios

Endurance test

MDC 5, 6 at maximum operating conditions

MDC 7 through 15 at varying mixture ratios and chamber pressures.

A summary of the test data is presented in Appendix II.

3.3.1 Test Facilities

The altitude test facility (B-1) was utilized for the engine test program which is located at the Wheatfield Rocket Test Site. Testing is conducted nozzle down in a 10 ft. diameter by 16 ft. high altitude chamber at 100,000 feet simulated altitude. Thrust measurement is utilized for performance evaluation and pyroscanners* are utilized for wall temperature measurement of the engine. Thermal conditioning of the propellants is accomplished by means of a heat transfer fluid which is circulated through the propellant line jacket and also used to adjust the bulk temperature of the propellants.

3.3.2 Data Acquisition and Handling

The majority of test parameters was recorded on a high speed Beckman analog to digital conversion system. The data was then processed by an IBM 360/44 general purpose digital computer using programs developed by BAC.

3.3.3 Testing

The injector was cold flowed prior to initiation of hot fire testing. The results indicated acceptable injector pattern with a fuel barrier flow rate of 13.8% (% total flow). A baseline test was conducted and then the worst case missions (as defined on the basic Technology Program) conducted. A minor anomaly occurred during the test program. After the seventh 95-sec. test of MDC #2 the test valve would not close due to a faulty actuation valve and the test was terminated at this point by closing the test stand valve. Replacement of the actuation valve corrected the situation. MDC's 5 and 6 were modifications of the worst case mission and were conducted at maximum operating conditions (max P_c, O/F, T_p). MDC's 7 - 15 were 60-seconds continuous firings each. Post test evaluation indicated the hardware to be in excellent condition.

*Direct measurement of thrust chamber wall temperatures obtaining a thermal profile of engine continuously during test.

A total of 5480* seconds and 547 firings was accumulated on this engine during the above test program. Figure 3.3-1 and 3.3-2 show the thrust chamber and Figure 3.3-3 shows the injector after the complete test program.

3.4 Phase IV - Analysis of Data

The analyses of the test results were devoted to assessments of hot fire test data and metallurgical aspects of the thrust chamber. The hot fire test data was analyzed with respect to performance and maximum wall temperatures. The metallurgical analyses were conducted to assess the coating condition after 5500 seconds accumulated firing time.

3.4.1 Analysis of Hot Fire Test Data

Statistical analyses were conducted on the steady state performance and maximum wall temperature data to determine trends due to operating parameters. Time history plots for three of the worst case mission duty cycles were also evaluated to assess the variations during test. The pulse mode data from the MDC's were not studied in depth due to the high fluid inertia of the mission feed system which masks the pulsing characteristics of the injector. However, a review of the pulse mode data indicates the pulse mode operation normal without anomalies and consistent to previous tests with this feed system.

3.4.1.1 Regression Studies

The effects of operating conditions on performance were assessed by multiple regression. The operating conditions evaluated were feed pressures and feed temperatures with its direct affect on mixture ratio and chamber pressure. The performance parameters studied were vacuum specific impulse and characteristic velocity (C*). In addition to the data obtained during the Coating Durability Program, the data obtained during baseline testing of this injector in June 1973 was utilized for assessment of the overall characteristics of the injector. The helium saturated MDC 6 (B-1-1195) was omitted from the assessment to allow the helium saturation impact (if any) to be independently evaluated. The feed temperatures are based upon the mean of the oxidizer and fuel feed temperatures as a single parameter since the individual measurements indicated minimum differences.

*A total of 5.5 missions defined by the Technology Program but 27 missions as defined for Space Shuttle by Space Division of Rockwell International.

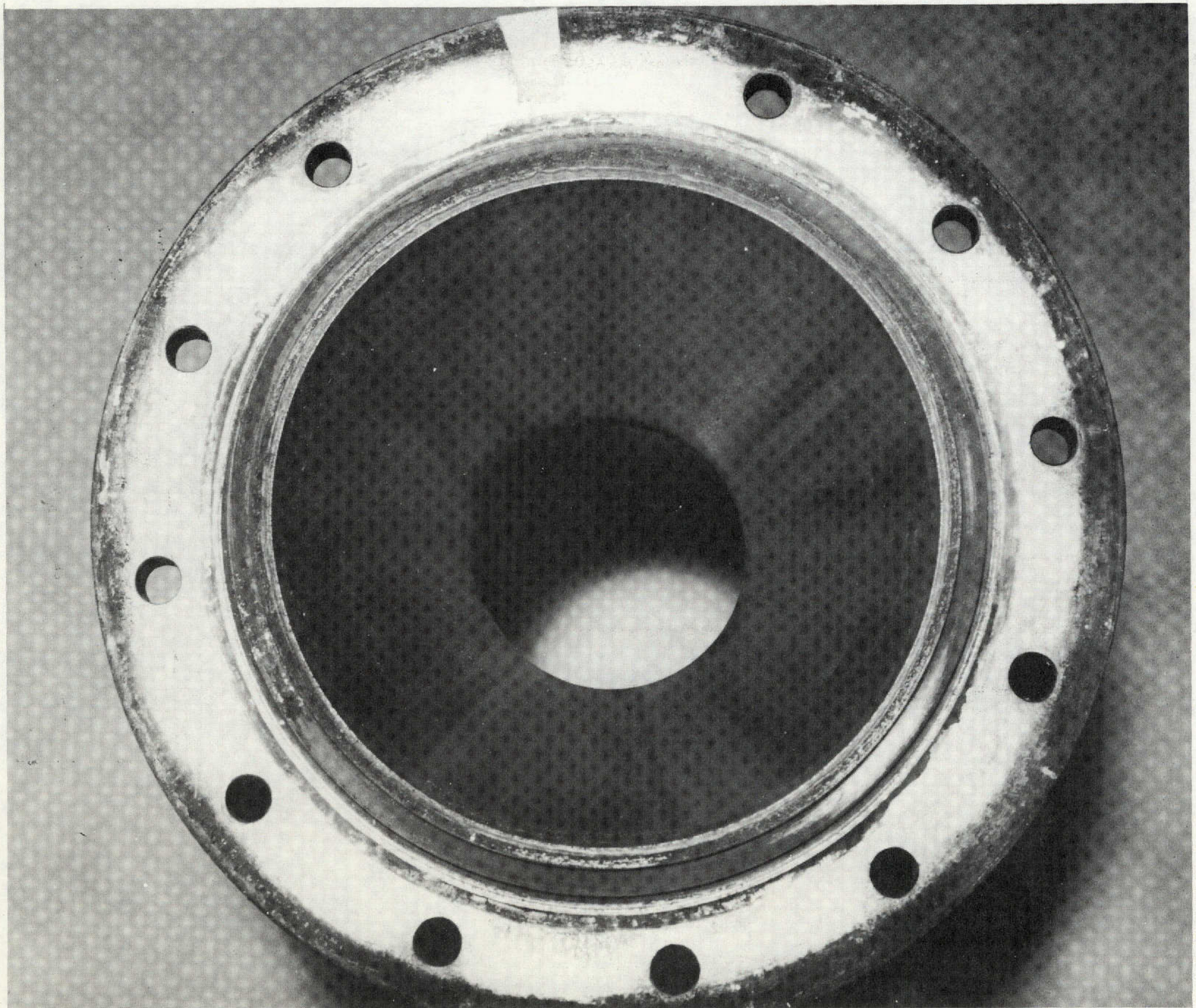


FIGURE 3.3-1. POST TEST B-1-1204. INJ. S/N FT-1C T.C. S/N FS 85-P1
(VIEW FROM NOZZLE END)

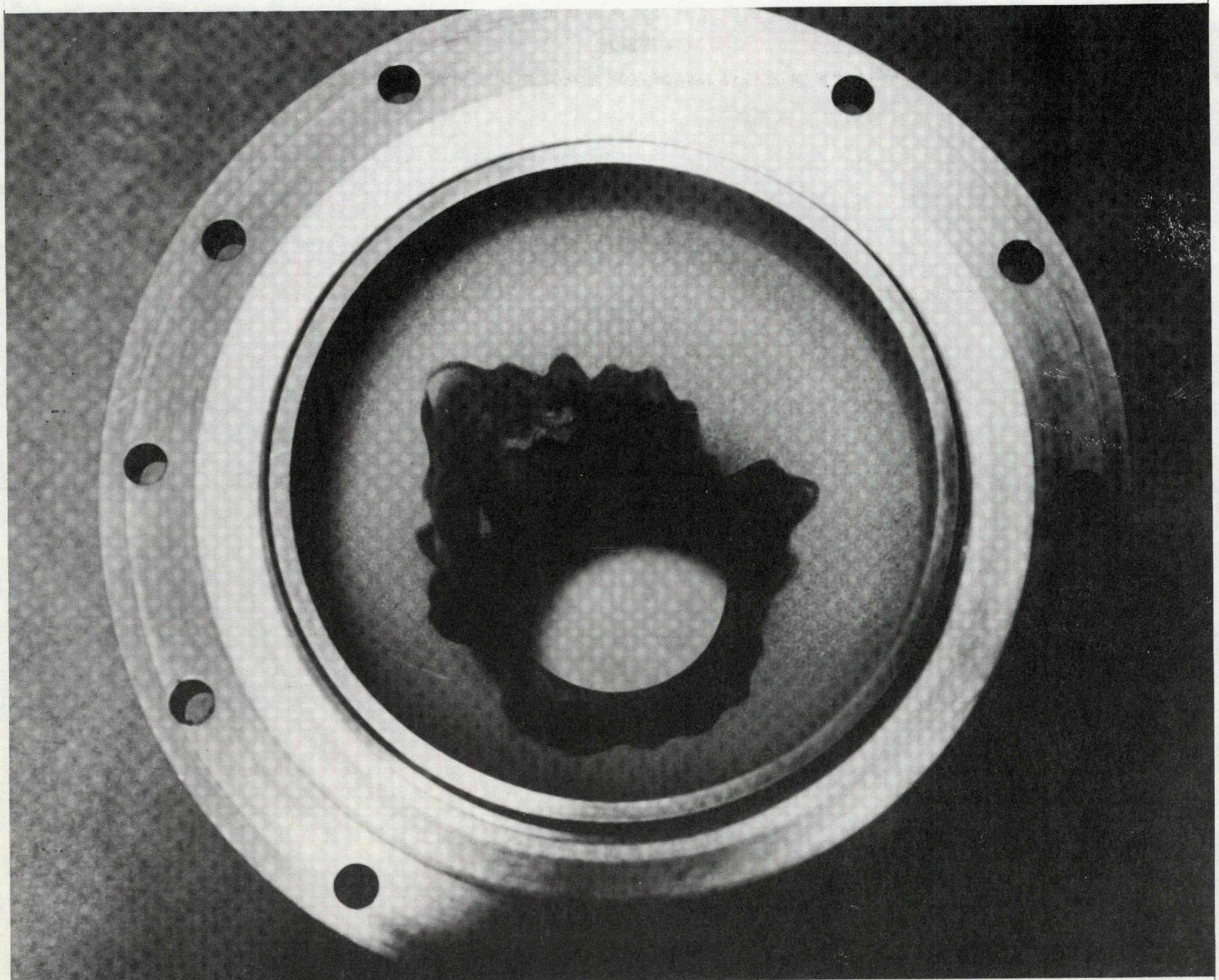


FIGURE 3.3-2. THRUST CHAMBER (VIEW FROM CHAMBER END)

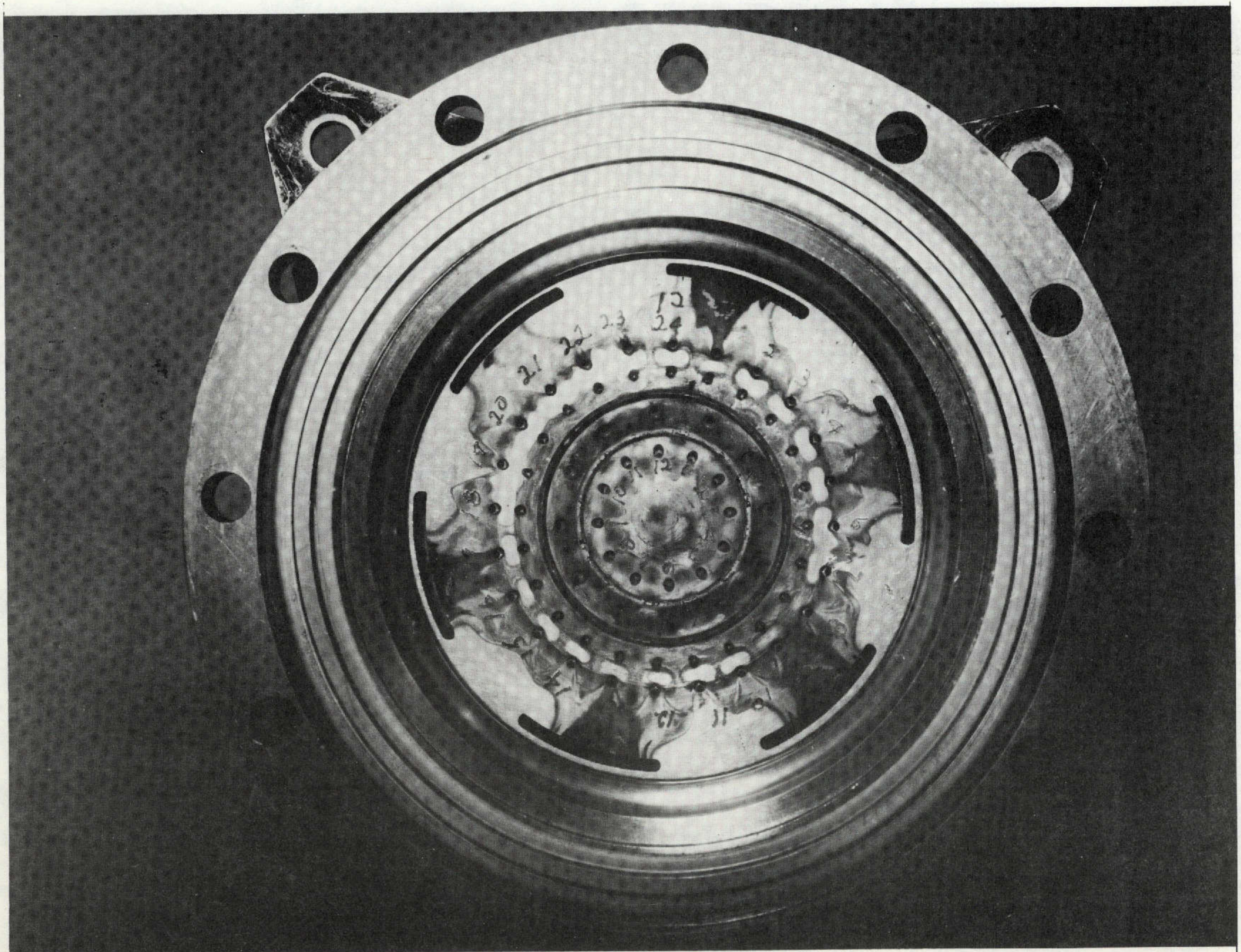


FIGURE 3.3-3. INJECTOR AFTER THE COMPLETE TEST PROGRAM

3.4.1.2 Performance

Performance assessments were made on the vacuum specific impulse and characteristic velocity measurements. The specific impulse data was corrected from the 31:1 expansion ratio of the test engine to the ϵ = 40 design point.

As in the past, it was found that the variation of C* and $I_{sp\infty}$ due to operating condition is similar to the accuracy of the parameters measured. Consequently, the correlations obtained were not as significant as desired. However, the results are consistent with earlier findings and are indicative of the existing trends. The effect of feed temperature ($\overline{FT}$) was not significant.

The results of the performance correlations are shown in Figure 3.4-1. Note that $I_{sp\infty}$ is practically invariant over the range tested.

The test data is plotted against O/F in Figure 3.4-2. It is seen that the helium saturated data points fall in the upper edges of the "data band" indicating that the presence of helium causes an insignificant increase in performance.

3.4.1.3 Maximum Wall Temperature

The engine maximum wall temperatures were correlated with operating conditions from the same time points ($\geqslant$30 seconds into the firing).

Again the variation in operating condition was similar to the measurement error. The effects of P_c and $\overline{FT}$ are more significant than those of O/F over the range tested and is shown in Figure 3.4-3.

The value at nominal operating conditions is 2009^{o}F maximum (radiation cooled).

The test data was normalized to P_c = 200 psia and $\overline{FT}$ = 75^{o}F using the regression coefficients and is shown in Figure 3.4-4. There is no impact of helium saturation.

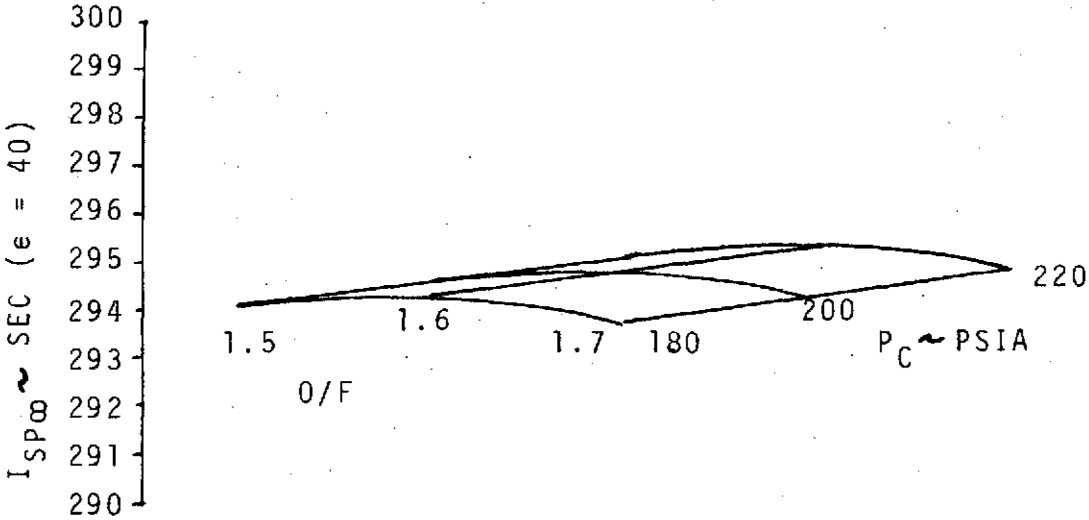
3.4.1.4 Time History Effects

The feed pressures, operating condition parameters, thrust and $I_{sp\infty}$ data from three of the tests are shown against mission time in Figures 3.4-5, -6, and -7. Shown are the 600-second Endurance test, the high operating condition unsaturated MDC and the similar helium saturated MDC.

FIGURE 3.4-1

VARIATION OF PERFORMANCE WITH OPERATING CONDITION

INJECTOR S/N FT-1C, $\overline{FT}$ = 75°F



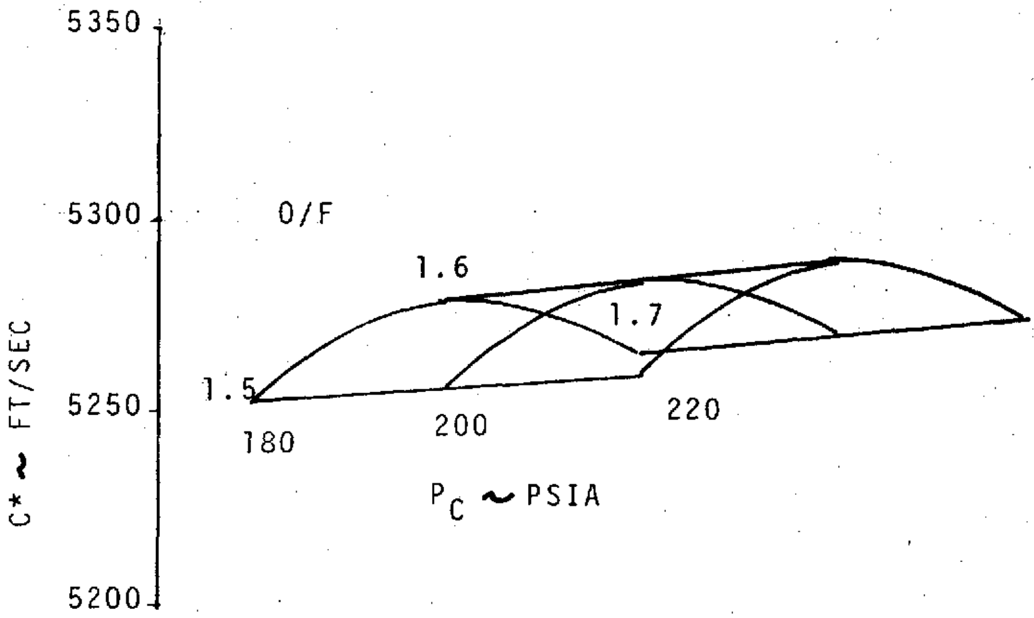


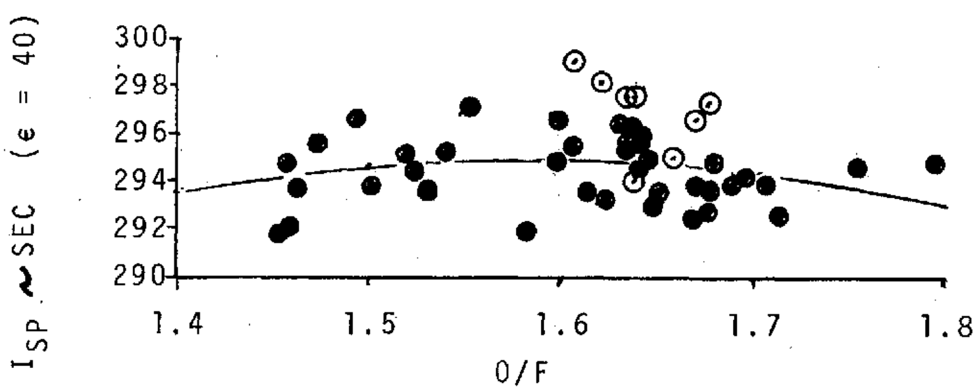
FIGURE 3.4-2

TEST PERFORMANCE DATA VS. MIXTURE RATIO

INJECTOR S/N FT-1C

(4.5 Sec. data, $\overline{FT}$ 49-104^{0}F, P_c 185-223 psia)

⊙ HELIUM SATURATED TEST (WCDC #6)-NOT IN REGRESSIONS



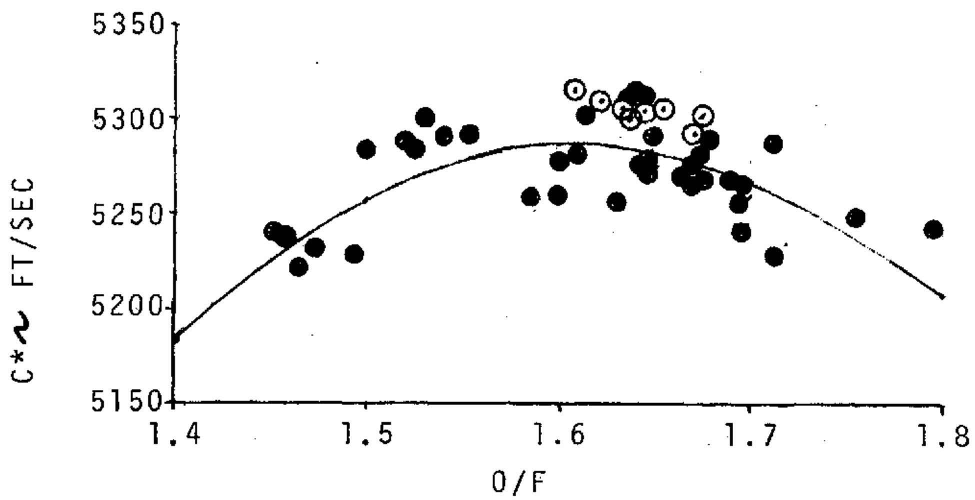


FIGURE 3.4-3

EFFECT OF OPERATING CONDITION ON MAXIMUM THROAT TEMPERATURE

(RADIATION COOLED)

INJECTOR SN FT-1C

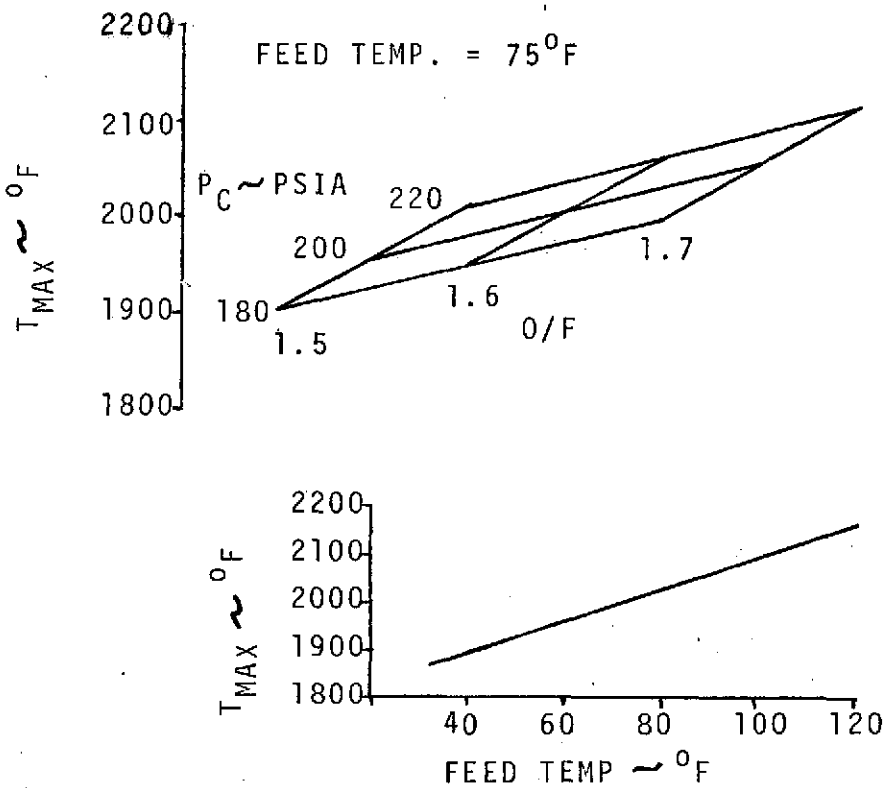


FIGURE 3.4-4

THROAT TEMPERATURE DATA VERSUS MIXTURE RATIO

(RADIATION COOLED)

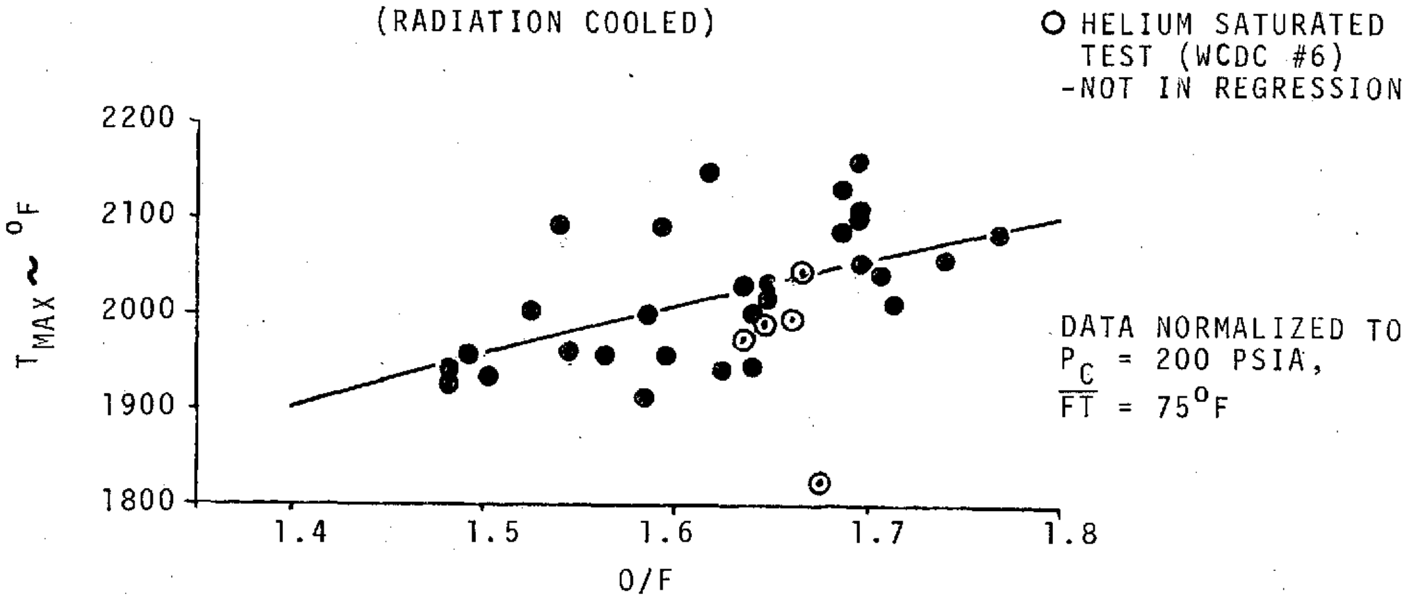
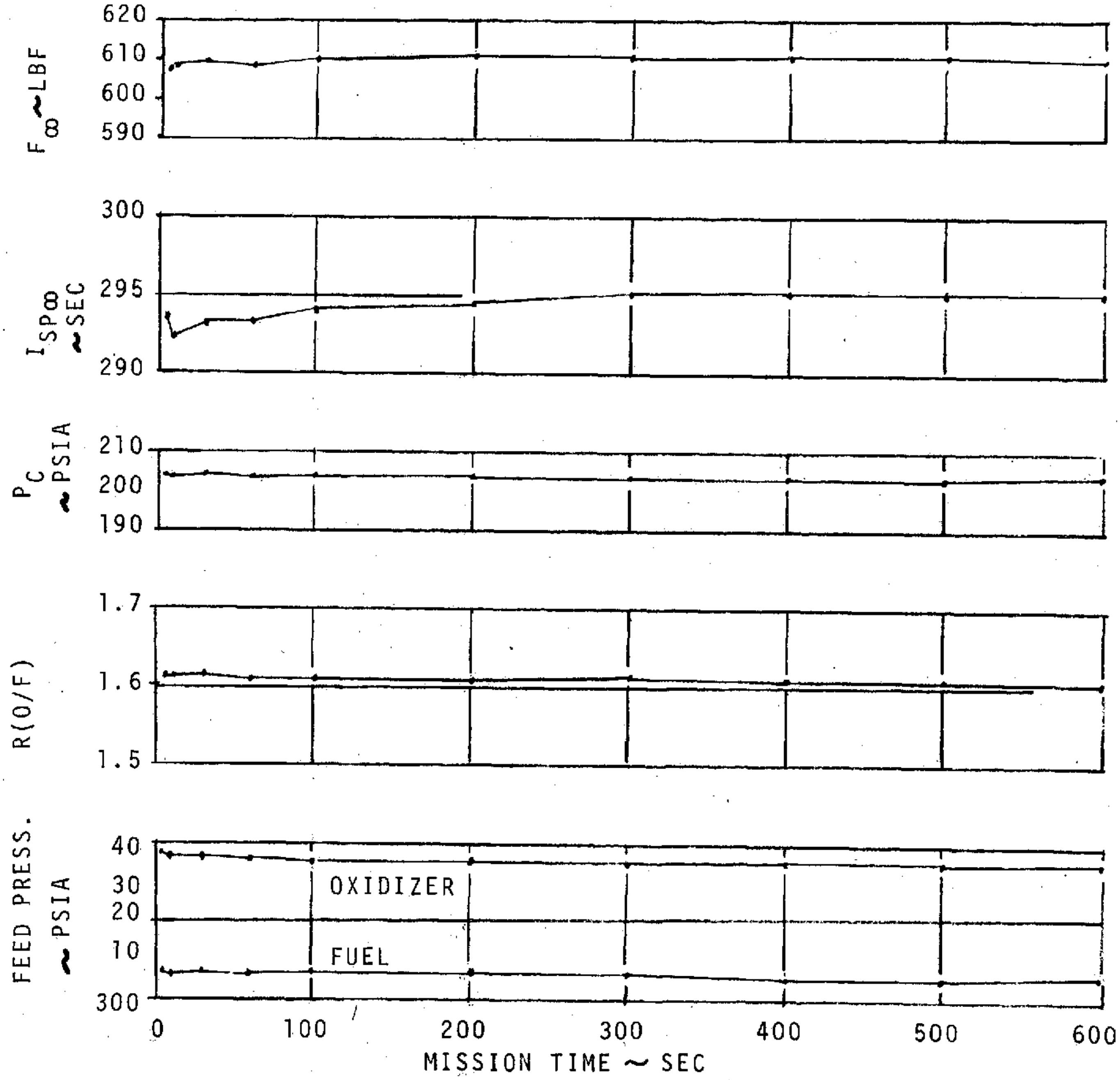


FIGURE 3.4-5

TIME HISTORY 600 SEC. ENDURANCE TEST (WCDC #4)

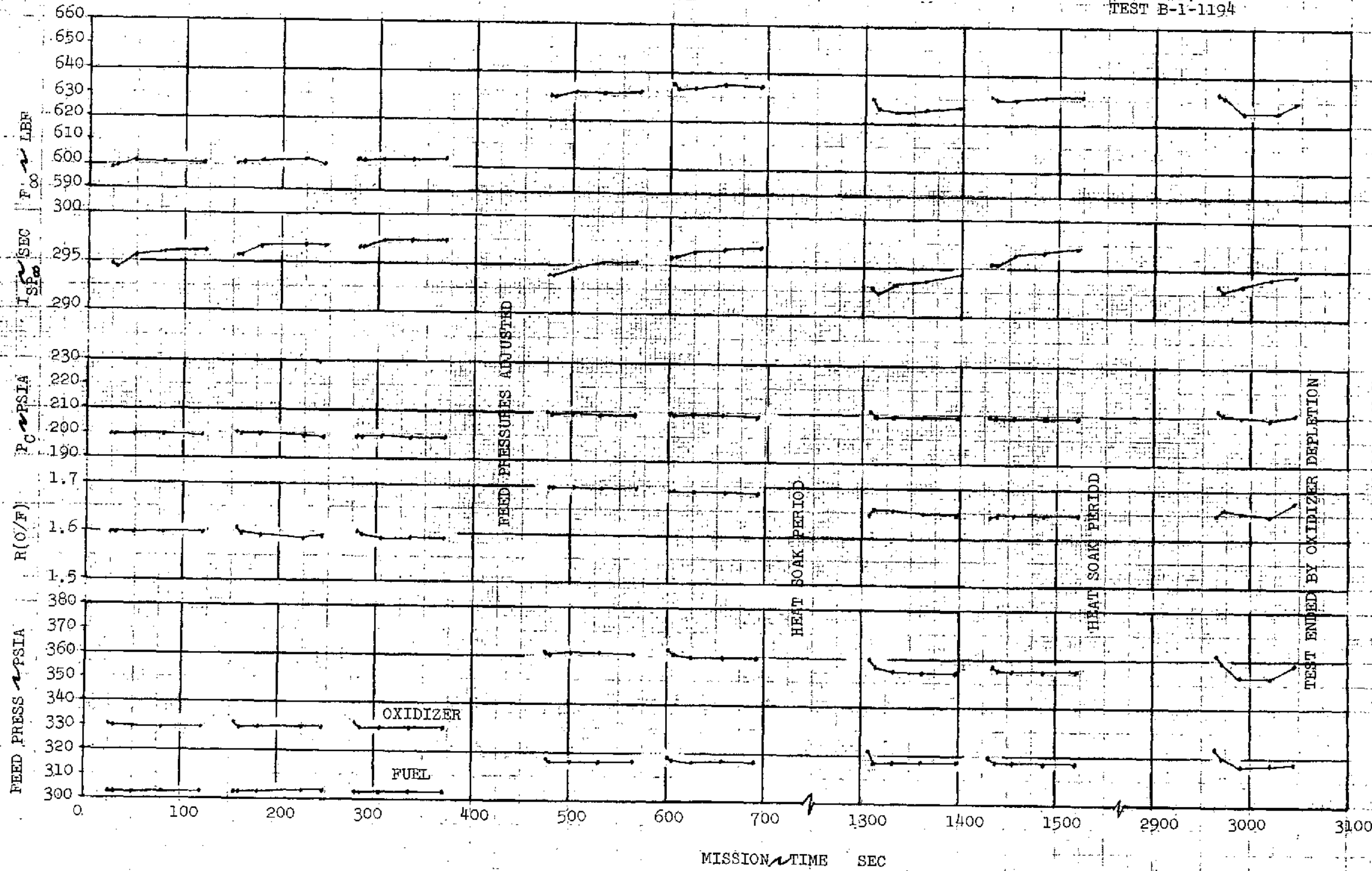
TEST B-1-1193

(THRUST & I_{SP} CORRECTED TO ϵ = 40,
FEED TEMPERATURES 69-80^{o}F,
NO HELIUM)



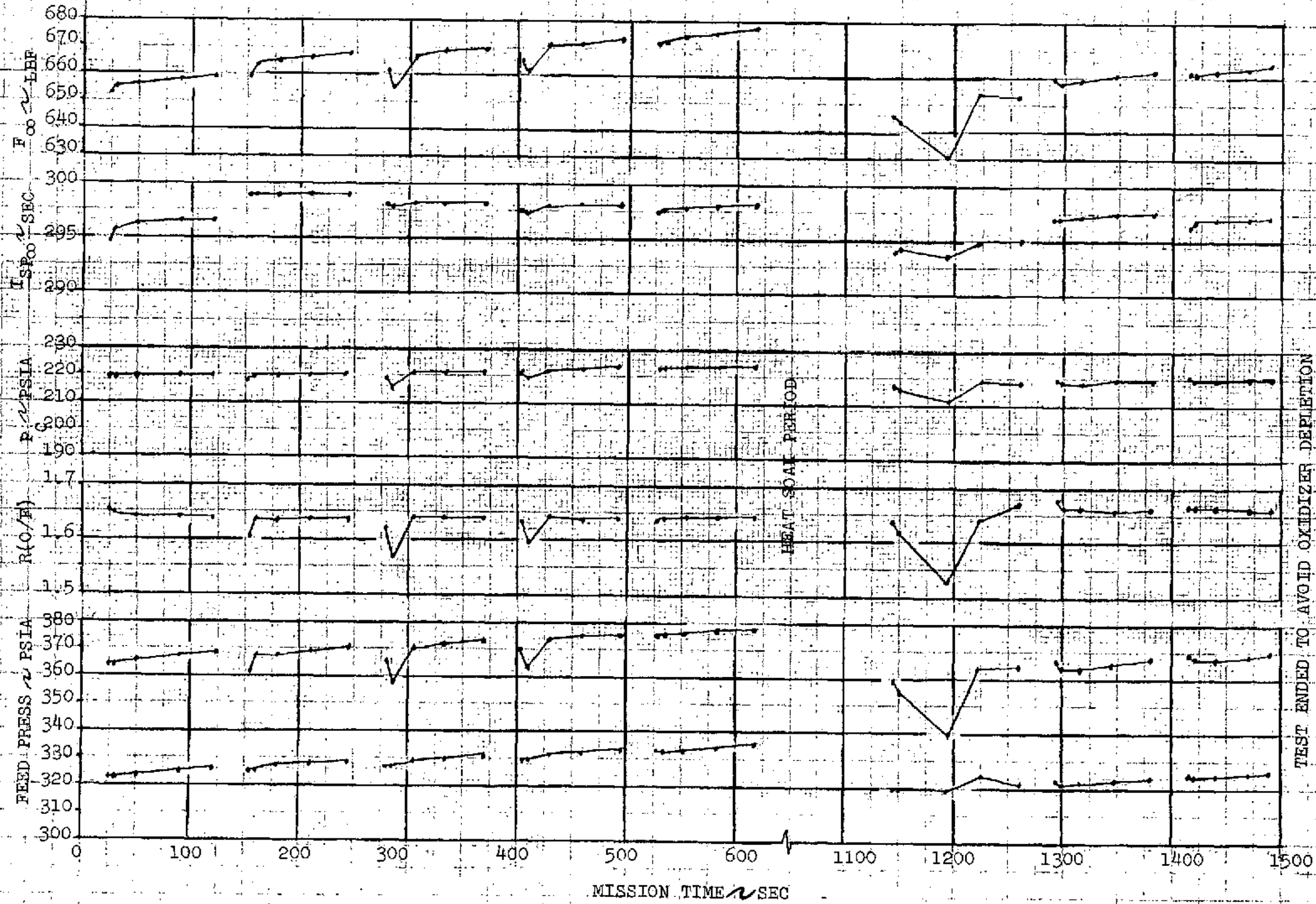
-Thrust and Isp corrected to ϵ=40
-Feed temperatures 96-105°F
-No helium

FIGURE 3.4-6
TIME HISTORY - HIGH AND HOT WCDC
(WCDC #5)
TEST B-1-1194



-THRUST AND I_{SP} CORRECTED TO ϵ=40,
-FEED TEMPERATURES 86-96°F
-HELIUM SATURATED

FIGURE 3.4-7
TIME HISTORY - HIGH, HOT, SAT WCDC
(WCDC #6)
TEST B-1-1195



It is clear that the minor performance variations that occurred are attributable to variations in feed pressures. It is concluded that there is no duty cycle effect on steady state performance.

3.4.1.5 Conclusions

The performance of injector S/N FT-IC is very similar to that of the two units tested during Phase III of the basic Technology Program.

Steady state performance is not impacted by either helium saturated propellants or duty cycle.

The presence of helium in the propellants does not affect maximum throat temperatures.

3.4.2 Metallurgical Evaluation

The R512E coated FS-85 thrust chamber (5500 seconds firing time) was metallurgically evaluated by analysis of metallographic samples at four locations:

Chamber end near injector
Convergent nozzle
Throat
Divergent nozzle

Figure 3.4-8 shows photomicrographs of the coated FS-85 thrust chamber at the four locations indicating the coating to be in excellent condition. As expected, there was no significant difference in coating thickness or constituents in the four locations. The outer silicide layer has remained intact on all samples including the throat region. The mid thickness complex silicide remained intact and continuous. No instances of complete separation or pull-out of the coating occurred. The microcracks (characteristic in sectioned samples) in the coating were tight extending down to or into the inner silicide diffusion zone. These were not oxidized or altered and many are generated during sectioning/polishing of the samples. There was no visible evidence of oxidation, nitriding or other degrading effect from the firing.

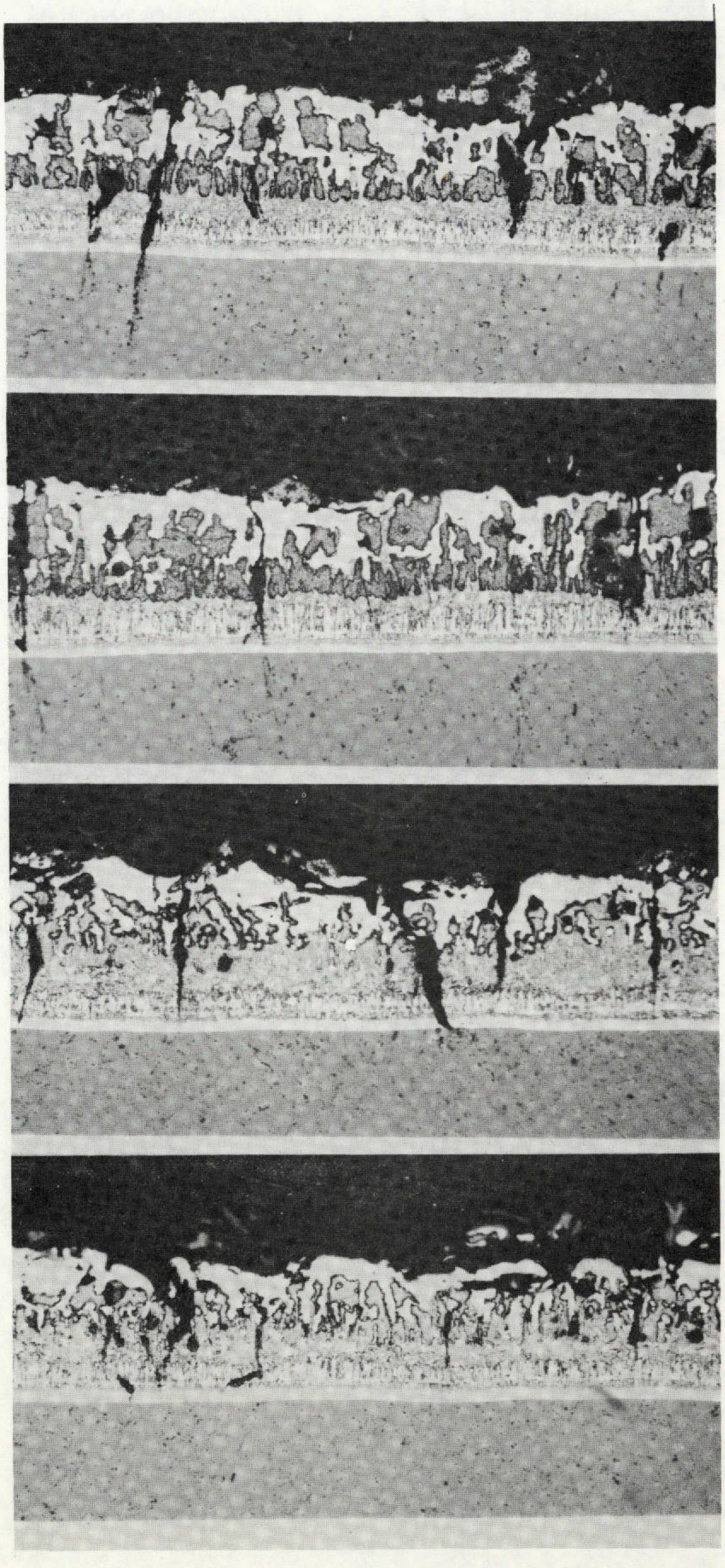
X-ray diffraction analysis was performed on a typical sample from the nozzle end and chamber end of the FS-85 thrust chamber to assess the coating constituents. In addition to the complex silicides, there were indications of oxides in the outer layer of the coating as expected with the nozzle end more pronounced than the chamber end. No indications of oxides were detected in the lower layer of coating or in the base metal surface. No positive indications of hydrides or nitrides were detected in the inner and outer layers of the coating.

Tensile specimens were machined from the FS-85 thrust chamber nozzle and chamber ends. These specimens were cut in a transverse direction to the thrust chamber axis and required considerable straightening to prepare the specimens. The results indicated significant reduction in elongation with the fracture appearance showing a flat cleavage with no necking around the fracture. The strength properties indicate little change. Table 3.4-1 summarizes the properties obtained and compares the results with unfired material. The decreased elongation and flat cleavage fractures with no necking down around the fracture indicate brittleness of the thrust chamber wall. However, contamination should result in higher mechanical properties. The microstructure and grain size reported by the vendor certification is identical to that observed in the final thrust chamber wall. A study of the microhardness properties of the thrust chamber wall does not indicate hardening of the material. Tests on Bell Independent Research and Development Programs evaluated the susceptibility of R512E coated and uncoated SCb-291 and FS-85 to embrittlement from the products of combustion (nitrogen, hydrogen, ammonia and methane). The results indicated the coating is protective to the products of combustion while the uncoated alloy shows microstructural changes. It is hypothesized that the uncoated edges (sealing surfaces) where the injector and nozzle extension are attached, allowed interstitial pickup causing the reduction in elongation. The results are completely unlike the SCb-291 engine (S/N RDV-2B) that completed 10,411 seconds of firing; however, S/N RDV-2B was an all-welded engine with no thrust chamber uncoated surfaces exposed to products of combustion. Consequently, further work is warranted to understand the mechanism and assess its impact on a design.

TABLE 3.4-1

PROPERTIES OF FS-85

SAMPLE IDENTIFICATION	YIELD STRENGTH KSI	ULTIMATE STRENGTH KSI	ELONGATION %
Thrust Chamber-Cool Portion Near Injector	62.8	86.9	10
Thrust Chamber-Cool Portion Near Injector	67.2	77.6	7
Thrust Chamber-Exit End	?	83.5	6
As-Coated Unfired Specimen	67.4	84.3	27
Vendor Certification (Raw Material)	64.8 64.4 62.3	83.1 82.8 80.9	35 34 35
BAC Check of Raw Material	65.3 65.3	83.5 83.8	33 32



a) Sample #1
Close to
injector.

Coating thickness:
0.0045"

b) Sample #2
Convergent
nozzle.

Coating thickness:
0.0044"

c) Sample #3
In throat.

Coating thickness:
0.0044"

d) Sample #4
Divergent
nozzle.

Coating thickness:
0.0041"

ALL VIEWS: MAG: 200X

UNETCHED/ANODIZED

FIGURE 3.4-8. PHOTOMICROGRAPHS SHOWING R512E COATING CONDITION IN VARIOUS LOCATIONS OF CHAMBER FS-85-P1

APPENDIX I

LITERATURE SEARCH

PHYSICAL CONSTANTS

Alloy	Density Lbs/Cu. In.	Melt. Temp. °F	Recryst Temp. °F	Thermal Conductivity Btu/Ft²/Ft/HR/°F 2000	2200	2400	Coeff. Of Thermal Expan In/In/°F-R.T. to Temp. Shown 2000	2200	2400	Specific Heat Btu/Lb-32°F To 2000	2200	2400
C103	.320	4260 ±90	2200	23.5	-	25.8	4.4	4.5	4.5	.073	-	.078
Cb291	.347	4610	2400	28.8 ③	29.0 ③	29.2 ③				.061	.062	.062
FS85	.383	4695	2400	24.1 ④	24.15 ⑤		4.8	4.9	5.1			
Cb129Y	.343	4350 ±90	2400	41.0	42.0	44.0	4.4	4.5		.064	.066	.069

Alloy	Modulus Of Elasticity Psi, x 10⁶ at °F RT	2000	2200	2400	Enthalpy Btu/Lb-Ref. 32°F 2000	2400	Total Reflectance RT-	Emissivity Total Emittance at °F 2000	2200	2400
C103	13.1	12.3	8.3	7.0	145	184	UNCOATED .750	.23-.37 ①	.24-.43 ①	.24-.41 ①
			2600°F 3.7	2800°F 1.8			COATED (Refractory Silicide) .180	(Modified Aluminide) .93 ②	.93 ②	.92 ②
Cb291	18.0	12.0	9.6	-	121	147	COATED -	(R508) .65	.65	.65
FS85	20.0	17.5	16.0	15.0			-	(R512E) .8	.8	.8 .63 ⑥
Cb129Y	16.3	14.2	12.0	9.6	127.5	163.5 148 (2200°F)	UNCOATED .810	.23	.45	.46
			2000°F 8.5	2800°F 6.3			COATED (VAC-HYDE VH 109)			.93

NOTES:
1. ① 180 minute total cycle from 1500°F to temperature listed and return to 1500°F. Apparent conflict in values for same temp.-values shown encapsulate total range.
2. ② 180 minute total cycle from 1000°F to temperature listed and return to 1000°F
3. ③ BAC data extrapolated from published CB 752 values.
4. ④ At 400°F
5. ⑤ At 600°F
6. ⑥ After 10 cycles plasma arc test simulating re-entry exposure Space Shuttle Orbiter T.P.S. - Temp. 2350°F.

COMPATIBILITY WITH ENVIRONMENTS

Compatibility Rating - Uncoated Material

Alloy	Chemical Composition	N_2O_4 Oxidizer	50/50 Fuel Blend	Nitric Acid (70%)	Salt Spray	Humidity	Oxygen	Hydrogen	Nitrogen	Ammonia Gas	MMH Fuel
C103	10Hf 1Ti Cb	A	A	A	A	A	D	D	D	D	A
Cb291	10W 10Ta Cb	A	A	A	A	A	D	D	D	D	A
FS85	28Ta 10W .9 Zr Cb	A	A	A	A	A	D	D	D	D	A
Cb129Y	10Hf 10 W1Y Cb	A	A	A	A	A	D	D	D	D	A
COMPATIBILITY RATING - R508C COATED MATERIAL-4 YEAR BAC STORAGE (PSRE)											
Cb291		A	-	-	-	A	-	-	-	-	A

LEGEND

A = Excellent

D = Bare material unsatisfactory in environment at elevated temperatures. Protective coating required.

FABRICABILITY CHARACTERISTICS

ALLOY	CONDITION	FORMABILITY Spinning-R. Temp.	MACHINABILITY Mechanical	MACHINABILITY EDM	WELDABILITY TIG	WELDABILITY EB	BRAZABILITY
C103	Rx 2400°F	A	B	-	A	A	-
Cb291	Rx 2375°F	B-	B	1	A	A	-
FS85	Rx 2375°F	B	B	-	A	A	A
Cb129Y	Rx 2400°F	B-	B	-	A	A	-

<u>LEGEND</u>

FORMABILITY - Ratings A through B are relative ratings in decreasing order of merit. "A" rating has spinability factor of .75, equal to that of 17-7 PH stainless steel.

MACHINABILITY - "B" rating indicates characteristics similar to those of austenitic stainless steel with respect to need for proper tooling and techniques to preclude galling and tearing.

WELDABILITY - "A" rating indicates that material is weldable by commercial processes.

<u>NOTE</u>: To obtain optimum ductility of weldments, it is recommended that all alloys be subjected to a post-weld recrystallization treatment at 2400°F for 1 hour.

BRAZEABILITY - "A" rating indicates that material is brazeable with no significant degradation of properties.

1 BAC experience 2 injectors. L/D ratio critical for EDM, where small diameter holes involved.

MECHANICAL PROPERTIES AS A FUNCTION OF TEMPERATURE

ALLOY	CONDITION	UNCOATED MATERIAL - TYPICAL PROPERTIES AT TEMPERATURES SHOWN															
		Room Temp.			2000°F-Vacuum			2200°F-Vacuum			2400°F-Vacuum			2600°F-Vacc.		2800°F-Vacuum	
		UTS KSI	YS-.2% KSI	Elong. % in 1"	UTS KSI	YS-.2% KSI	Elong. % in 1"	UTS KSI	YS-.2% KSI	Elong. % in 1"	UTS KSI	YS-.2% KSI	Elong. % in 1"	UTS KSI	YS-.2% KSI	UTS KSI	YS-.2% KSI
C103	Rx 2400°F-1 Hr.	61	42	25-30	27	20	45	20	16	--	14	11	70	10.3	10.1	5.8	5.5
Cb291	Annealed-Cycle Lacking	75	60	25(2")	32	24	24(2")	27	20	22(2")	21	15	25(2")	16	11	12	8.5
FS85	Rx 2375°F-1 Hr.	85	65	25	37	28	30	31	22	35	22	16	50	19	17		
Cb129Y	Rx 2400°F-1 Hr.	87	70	25	40	30	40	31	24	50	22.5	21	50	16.9	15.8	11.6	11.3
		BRAZED MATERIAL - TYPICAL PROPERTIES AT TEMPERATURES SHOWN															
FS85	Vac Brazed ① 2600°F-5 Mins.	79	--	23													
	Vac Brazed ① 2800°F-5 Mins.	78.5	--	24													
	Vac Brazed ① 3000°F-5 Mins.	79	--	21													
		TIG PROCESS BUTT WELDS - TYPICAL PROPERTIES AT TEMPERATURES SHOWN															
C103	As Welded, Bare	61	45	14													
	Coated-Aluminide	60	40	--													
Cb129Y	As Welded, Bare	87	65	14													
	Coated-Aluminide	87	65	18													
C103	PW Anneal 2200°F, Bare	60	41	18													
Cb129Y	PW Anneal 2200°F,	86.5	65	18	39	30	8	32	26	9	22	20	12				

① Joint cooled 3000°F/minute to 1200°F after brazing. Joints as brazed condition.

MECHANICAL PROPERTIES AS A FUNCTION OF TEMPERATURE

COATED MATERIAL - TYPICAL PROPERTIES

ALLOY	COATING	PRE-TEST TREATMENT	MECHANICAL PROPERTIES**																	
			Room Temp.			1400°F			2400°F			2600°F			2000°F			2200°F		
			UTS KSI	YS-.2% KSI	El. 1", %	UTS KSI	YS-.2% KSI	El.1", %	UTS KSI	YS-.2% KSI	El. 1", %	UTS KSI	YS-.2% KSI	El 1", %	UTS KSI	YS-.2% KSI	El 1" %	UTS KSI	YS KSI	El 1 %
FS85	VH109	As Coated	71	57	16	58	35	10	23	21	27	20	19.6	31	45	40	14	32	29	25
	R512E	As Coated	74	57	--	56	32	--	27.5	25	--	17.5	15	--	36.5	27	--	33.5	26	--
Cb129Y	VH109	As Coated	76	59	15	65	37	10	31	28.5	4	24	23.6	18	--					
	R512E	As Coated	70	54	15													30	24.5	7.7
FS85	VH109	32 Cycles static air 2400°F 100 Hr.	68.5	54	15	46	28	10	22.7	20.6	26	17	15	32						
FS85	R512E	100 Re-entry simulation exposures*	70	54	16	44	26	8	22	21	18.5	16	13.5	47	29	24	10	26	22	14
Cb129Y	VH109	32 cycles static air 2400°F 100 Hr.	70	52	12	54	37	7	27	24.7	10	21.5	20	10	--	--	--		--	
Cb129Y	R512E	100 Re-entry simulation exposures*	72	--	11	--	--	--		--	--	--	--	--	--	--	--		--	
		UNCOATED MATERIAL - NOTCH SENSITIVITY EDGE-NOTCHED TENSILE SPECIMENS, 0.040" TH. SHEET.																		
FS85	Rx 2375°F 1 Hr.		Notch Radius - .0013" Rapid Crack Length - 0 Net Fracture Strength - 54.3 KSI																	
		UNCOATED MATERIAL - IMPACT STRENGTH, CHARPY V-NOTCH																		
C103	As Rolled	Test Temp. °F Impact Strength R.T. 148-159 ft. lbs. -100°F 70-79 ft. lbs.																		

*Above 2000°F, as-coated specimens display somewhat higher strength levels than uncoated specimens because the coating makes a positive contribution to the strength of the composite. After re-entry exposure, however, this contribution appears to diminish.
Furnace re-entry simulation exposures - See Sheet 21 for definition of cycle.

MECHANICAL PROPERTIES AS A FUNCTION OF TEMPERATURE

ALLOY	CONDITION	TENSILE ULTIMATE STRENGTH/DENSITY RATIO UNCOATED MATERIAL RT	2000°F	2200°F	2400°F
C103	Rx 2400°F - 1 Hr.	185,000	85,000	66,000	50,000
Cb291	Annealed-Cycle Lacking	213,000	92,000	78,000	60,500
FS85	Rx 2375°F- 1 Hr.	222,000	103,000	80,000	63,000
Cb129Y	Rx 2375°F - 1 Hr.	252,000	120,000	95,000	80,000

ALLOY	CONDITION	TENSILE YIELD STRENGTH/DENSITY RATIO UNCOATED MATERIAL RT	2000°F	2200°F	2400°F
C103	Rx 2400°F - 1 Hr.	131,000	62,000	50,000	34,000
Cb291	Rx 2375°F - 1 Hr.	118,000	31,000	24,000	23,600
FS85	Rx 2375°F - 1 Hr.	170,000	73,000	58,000	42,000
Cb129Y	Rx 2375°F - 1 Hr.	204,000	87,000	70,000	61,000

ALLOY	COATING	PRE-TEST TREATMENT	COATED MATERIAL RT	Ftu/Density Ratio 1400°F	2400°F	2600°F
FS85	VH109	As Coated	184,000	150,000	50,600	51,090
Cb129Y	VH109	As Coated	238,000	189,000	90,600	75,000
				Ftu/Density Ratio		
FS85	VH109	As Coated	149,000	90,700	55,300	50,800
Cb129Y	VH109	As Coated	195,000	109,000	83,000	68,800
				Ftu/Density Ratio		
FS85	VH109	32 cycles static air 2400°F 100 hrs.	177,000	119,000	59,000	44,900
Cb129Y	VH109	"	218,000	157,000	79,400	62,700
				Ftu/Density Ratio		
FS85	VH109	"	140,000	72,000	53,500	39,700
Cb129Y	VH109	"	180,000	108,000	72,000	56,200

MECHANICAL PROPERTIES AS A FUNCTION OF PROCESSING HISTORY

MECHANICAL PROPERTIES AS A FUNCTION OF COLD WORK
UNCOATED MATERIAL

ALLOY	CONDITION	RT UTS	RT YS-.2%	RT El. % In.	2000°F UTS	2000°F YS-.2%	2000°F El. in 1"	2200°F UTS	2200°F YS-.2%	2200°F El. in 1"	2400°F UTS	2400°F US-.2%	2400°F El. in 1"	2500°F UTS	2500°F YS-.2%	2500°F El. in 1"
C103	Cold Rolled 50% Red-as Rolled				31	26	35							13	11	80
FS85	Cold Rolled 50% Red +Rx 2400°F	79	66	33(2")												
	CR50% + Rx 2300°F	86	70	22(1")												
	Cold Rolled 50% Red+Str Rel 1850°F 1 Hr.	105	95	14(2")												
	Cold Rolled 50% Red+As Rolled	129	119	5(1")												

MECHANICAL PROPERTIES AS A FUNCTION OF TEMPERATURE

Fatigue Strength At Room Temperature

ALLOY	COATING	Stress, KSI	Life-Cycles*	
FS85	R512E	58	10^4	
		51	10^5	
		42	10^6	
		29	10^7	

*To Fracture

IMPACT OF STRAIN RATE ON MECHANICAL PROPERTIES

SLOW STRAIN RATE DATA

- Tensile Test - 0.005 in/in/min. to Yield Strength, 0.05/in/in/min. To Rupture
- Bend Test - 1 in/min.

UNCOATED MATERIAL

ALLOY	CONDITION	TEST TEMP °F	MECHANICAL PROPERTIES UTS KSI	YS-.2% KSI	El. 1" %	BEND DUCTILITY Bend Angle	Bend Radius	MODULUS OF ELASTICITY x 10^6 Psi
C103	Stress Relieved 2150°F-1Hr	R.T.	59	45	26			12.6
		-100	78	58	25	180°	4T ①	13.0
		2500	16-23	11-16	11-15			9-11
Cb129Y	Stress Relieved 2150°F-1 HR	R.T.	86.4	68.9	18			18
		-100	105	86.4	25	180°	4T ②	18
		2500	19-29	18-21	3.5			11

COATED MATERIAL

ALLOY	COATING	PRE-TEST TREATMENT	TEST TEMP °F	MECHANICAL PROPERTIES UTS KSI	YS-.2% KSI	El.1" %	BEND DUCTILITY Bend Angle	Bend Radius	MODULUS OF ELASTICITY x 10^6 Psi
C103	Durak KA	2500°F-2 1/2Hr-Air	R.T.	62	46	27-32			15-15
			-100	79	63	18	180 ③	4T	18
			2500	14.5	10	18			11
C103	W + R508C	None	R.T.	68	52-54	17-20			19-20
			-100	84-90	69-72	17-19	180 ④	4T	22-23
			2500	17.5	12.4	3.0			12
Cb129Y	Durak KA	None	R.T.	84-87	64-67	18-24			16-17
			-100	94-108	78-94	9-29	180 ⑤	4T	15-17
			2500	23	16-18	13-15			10-13

NOTES:
① Small surface cracks edges and bend.
② Heavy surface cracks edges and bend.
③ Coating flaked edges and face.
④ Coating flaked and spalled
⑤ Cracked.
⑥ Cracked.

IMPACT OF HIGH STRAIN RATE ON MECHANICAL PROPERTIES

HIGH STRAIN RATE DATA

Tensile Test - 100 to 250 in/in/sec To Yield Strength, 500 in/in/sec To Rupture

UNCOATED MATERIAL

ALLOY	CONDITION	TEST TEMP °F	TEST ENVIRONMENT	MECHANICAL PROPERTIES UTS KSI	EL. 1", %
C103	Stress Relieved 2150°F 1 HR	R.T.	Air	70-105	28-31
		-100	Liquid N_2	131-144	19-28
Cb129Y	Stress Relieved 2150°F 1 HR	R.T.	Air	119-128	20-28
		-100	Liquid N_2	119-153	3-8

COATED MATERIAL

ALLOY	COATING	PRE-TEST TREATMENT	TEST TEMP °F	TEST ENVIRONMENT	MECHANICAL PROPERTIES UTS KSI	El. 1", %	BEND DUCTILITY BEND ANGLE	BEND RADIUS
C103	Durak KA	2500°F-2 1/2 HR - Air	R.T.	Air	137-148	26-33		
			-100	Liquid N_2	110-126	22-26	180°	4T
			-100	Vacuum	114-127	19-27		
			-100	15% H_2	117	22		
			-100	30% H_2	114	22		
C103	W + 508C	None	R.T.	Air	121-136	20-30		
			-100	Liquid N_2	117-165	14-16	180°	4T
			-100	Vacuum	127-169	17-18		
			-100	15% H_2	165-171	14-21		
			-100	30% H_2	134-172	16-22		
Cb129Y	Durak KA	None	R.T.	Air	142-171	22-28		
			-100	Liquid N_2	142-169	15-16	20-50°	4T
			-100	Vacuum	165-185	17-20		
			-100	15% H_2	167-176	15-17		
			-100	30% H_2	173-192	13-17		

IMPACT OF STRAIN RATE ON MECHANICAL PROPERTIES

SLOW STRAIN RATE DATA - .01"/SEC. ③

UNCOATED MATERIAL

ALLOY	CONDITION	TEST TEMP. °F	MECHANICAL PROPERTIES Longitudinal UTS KSI	YS-.2% KSI	El.1", %	Transverse UTS KSI	YS-.2% KSI	El.1" %
Cb291	① Condition I	R.T.	70.3	60.6	20	60.5	49.1	17
	① Condition I + Rx 3000°F 1 Hr.	R.T.	60.6	45	24	58	43.8	23
Cb291	② Condition II	R.T.	67.1	49.8	--	71.1	52.2	22

HIGH STRAIN RATE DATA - 2"/SEC. ③

COATED MATERIAL-R508 COATING

ALLOY	CONDITION	TEST TEMP. °F	MECHANICAL PROPERTIES Longitudinal UTS KSI	YS-.2% KSI	Extension	El.1"	Transverse UTS	YS-.2%	Extension	El.1"
Cb291	① Condition I	2400	26.7	-	.225-.260	35.5	23.5	-	.180-.285	31
		3000	22.9	-	.225-.240	32.7	20.5	-	.100-.155	19
Cb291	② Condition II	2400	21.7	18.9	.240-.295	37.7	21.5	18.6	.220-.270	36
		3000	13.3	-	.210-.245	31.7	14.2	-	.230-.255	34.7

NOTES: ① Condition I - Impact forged 6" diameter ingot to billet, imparting 47% reduction, then stress relieved.

② Condition II - Condition I material upset 2:1, reworked to original billet diameter, then recrystallized at 3000°F for 1 hour.

③ Data from BAC Report 912:67:0623-1:JF - Gleeble Program.

CREEP STRENGTH AS A FUNCTION OF TEMPERATURE

ALLOY	CONDITION	2000°F Stress to Rupture - KSI	2000°F Hours to Failure	2200°F Stress To Rupture - KSI	2200°F Hours to Failure	2400°F Stress To Rupture - KSI	2400°F Hours to Failure
		UNCOATED MATERIAL - CREEP RUPTURE PROPERTIES					
Cb291	Rx 2375°F-1 Hr.			12**	30**	14	.06
						12	.2
						10.6	3.8
						6	50.0*
FS85	Rx 2375°F-1 Hr.	30	1			16	1
		23	10			14	10
		20	20			12	12
						9***	50***
Cb129Y	Rx 2400°F-1 Hr.			14**	30**	7***	50***
C103	Rx 2400°F-1 Hr.	--	--	--	--	4***	50***
FS85	Cold Rolled 50% Red.	23	10			13	10
		17	158			12	10
Cb129Y	Cold Rolled 50% Red.	30	1	19.5	1		
		26	5	12.5	10		
		20	10	8	100		
		14	100	5	1000		
		9	1000				
		COATED MATERIAL - CREEP RUPTURE PROPERTIES					
C103	Mod Silicide Type TF1, Pfaudler					9	3
FS85	R512E			15**	30**		
	R512E			13	100		
	R512A			14	58.7		
Cb129Y	R512E			10	38.5		
				8	100		

* - Test terminated - No failure

** - Calculated from Larson - Miller Plot, using constant of 20.

*** - BAC extrapolated data

CREEP STRENGTH AS A FUNCTION OF TEMPERATURE

COATED MATERIAL - CREEP RUPTURE PROPERTIES

ALLOY	COATING	2850°F Stress To Rupture KSI	2850°F Time-Minutes	3000°F Stress To Rupture KSI	3000°F Time-Minutes	3125°F Stress To Rupture KSI	3125°F Time-Minutes	3200°F Stress To Rupture KSI	3200°F Time-Minutes
C103	VH109	3.5	94	2.45	105			2	47
		5.5	9						
Cb129Y	VH109			3.68	168			3	64
								5.5	4.5
	CoTiSi					2.45	27	2.0	3.8
	CrTiSi							2.5	4

CREEP STRENGTH AS A FUNCTION OF TEMPERATURE

ALLOY	CONDITION	UNCOATED MATERIAL - CREEP STRAIN PROPERTIES 2000°F % Strain	2000°F Stress KSI	2000°F Time-Minutes	2200°F % Strain	2200°F Stress KSI	2200°F Time-Minutes	2400°F % Strain	2400°F Stress KSI	2400°F Time-Minutes
FS85	Rx 2375°F-1 Hr.	.5	19	600	.5	12.5	600	.5	4.2	600
		1.0	20	600	1.0	14.0	600	1.0	6.5	600
		2.0	22	600	2.0	15.0	600	2.0	7.0	600
		1.0	17	6000	1.0	10.8	6000			
		2.0	18	6000	2.0	12.2	6000			
		5.0	18.5	6000	5.0	13.0	6000			
Cb129Y	Rx 2400°F-1 Hr.							.2*	1*	3000*
								.5*	1*	3000*
Cb291	Rx 2375°F-1 Hr.							.2*	1.1*	3000*
								.5*	1.5*	3000*
FS85	Rx 2375°F-1 Hr.							.2*	1.5*	3000*
								.5*	2.5*	3000*
C103	Rx 2400°F-1 Hr.							.2*	1*	3000*
								.5	1*	3000*

*BAC Extrapolated Data.

CREEP STRENGTH AS A FUNCTION OF TEMPERATURE

ALLOY	CONDITION	UNCOATED MATERIAL - CREEP STRAIN PROPERTIES														
		2000°F			2200°F			2400°F			2500°F			3000°F		
		% Strain	Stress KSI	Time-Minutes	% Strain	Stress KSI	Time-Minutes	% Strain	Stress KSI	Time-Minutes	% Strain	Stress KSI	Time Minutes	% Strain	Stress KSI	Time-Minutes
C103	Rx	.2	25 20 15	<1 <1 >60							.2	7 5	3 5			
Cb129Y	Rx	.2	25 20	5 32	.2	15 10	8 25				.2	7 5	4 7			
C103	Rx	.5	25 20 15	<1 <1 -							.5	7 5	6 11			
Cb129Y	Rx	.5	25 20	12 60	.5	15 10	30 60				.5	7 5	10 18			
C103	Rx	1.0	25	<1							1.0	7 5	10 18			
Cb129Y	Rx	1.0	25	30	1.0	15	40				1.0	7 5	25 40			
C103	Rx	2.0	25 20	3 60							2.0	7 5	17 31			
Cb129Y	Rx	2.0	25	45	2.0	15	80				2.0	7 5	40 65	1% 2%	3.4 3.4	5.33 14.24
C129Y	Rx	5.0	25	110	5.0	15	130				5.0	7	110			
C129Y	Cold Worked 50% as Rolled	1.0	26 14 8.5	6 180 1200	1.0	20 10 5	6 150 960									
		2.0	26 14 8.5	30 480 4800	2.0	20 10 5	21 300 2400									
		5.0	26 14 8.5	300 6000 27,000	5.0	20 10 5	31 60 600									

CREEP STRENGTH AS A FUNCTION OF TEMPERATURE

COATED MATERIAL - SHORT TIME CREEP STRAIN PROPERTIES

ALLOY	COATING	2% CREEP STRAIN			5% CREEP STRAIN			10% CREEP STRAIN			0.5% CREEP STRAIN			1% CREEP STRAIN			2% CREEP STRAIN		
		Temp. °F	Stress KSI	Time-Minutes	Temp. °F	Stress KSI	Time-Minutes	Temp. °F	Stress KSI	Time-Minutes	Temp. °F	Stress KSI	Time-Minutes	Temp. °F	Stress KSI	Time-Minutes	Temp. °F	Stress	Time-Min.
Cb129Y	VH109	3000	3.68	10	3000	3.68	25	3000	3.68	58									
		3125	2.45	18															
		3200	3.0	8	3200	3.0	23	3200	3.0	49									
		3200	5.5	1	3200	5.5	2	3200	5.5	3.5									
Cb129Y	20Cr-5Ti-75Si (LMSC)	3000	3.4	12.0															
		3125	2.45	10.5															
		3200	2.5	2.3															
Cb129Y	Co-24Ti-56Si (LMSC)	3000	3.4	10															
		3125	2.45	6	3125	2.45	24												
		3200	2.0	3.5															
FS85	R512A										2200	14	2.8	2200	14	5.2	2200	14	8.4
FS85	R512E ①										2200	10	42.3	2200	10	56.7	2200	10	76.7
											2200	9	40.0	2200	9	65.0	2200	9	108.0
Cb129Y	R512E ②										2200	10	2.0	2200	10	3.4	2200	10	6.0

NOTES: ① No interstitial contamination or intergranular cracking within gage length of specimens after testing.

② Extensive intergranular cracking in gage section adjacent to fracture edge. This condition can lead to eventual rupture at relatively low total strain.

CREEP STRENGTH AS A FUNCTION OF TEMPERATURE

COATED MATERIAL - SHORT TIME CREEP STRAIN PROPERTIES

ALLOY	COATING	2% CREEP STRAIN Temp. °F	2% CREEP STRAIN Stress KSI	2% CREEP STRAIN Time-Minutes	5% CREEP STRAIN Temp. °F	5% CREEP STRAIN Stress KSI	5% CREEP STRAIN Time-Minutes	10% CREEP STRAIN Temp. °F	10% CREEP STRAIN Stress KSI	10% CREEP STRAIN Time-Minutes
C103	R512E	2600	5.5	9						
		2850	2.7	9						
		3000	2.4	3						
		3000	1.8	10						
C103	VH109	2850	3.5	10.3	2850	3.5	23	2850	3.5	43
			5.5	2		5.5	3.7		5.5	6
		3000	2.45	10	3000	2.45	24	3000	2.45	46
		3200	2	7	3200	2	20	3200	2	43
Cb291	VH109	2940	3.75	11.6						
		3125	2.75	12						
FS85	VH109	2940	4.4	10						
FS85	20Cr-5Ti-75Si (LMSC)	2850	5.8	10.5						
		2940	4.4	10						
		3000	4.5	9						
FS85	Co-24Ti-56Si (LMSC)	2850	5.4	9						
		3000	4.5	11.4						
Cb129Y	R512E	2600	11.0	13						
		2850	5.4	10						
		3000	3.8	10						
		3125	2.6	11						
		3200	1	Coating Failed at 1.3 Minutes						
Cb129Y	R512A	3000	3.6	10						
		3125	3.5	10						

DUCTILITY CHARACTERISTICS

DUCTILITY-BRITTLE TRANSITION TEMPERATURES (DBTT)

ALLOY	CONDITION	UNCOATED MATERIAL BEND RADIUS	UNCOATED MATERIAL BEND ANGLE°	UNCOATED MATERIAL TRANSITION TEMP.-°F	COATED MATERIAL BEND RADIUS	COATED MATERIAL BEND ANGLE°	COATED MATERIAL TRANSITION TEMP.-°F	COATING
C103	Rx 2400°F-1 Hr.	2T	90	-320	-	-	-	-
Cb291	Ann. 2100°F-1 Hr.	1T	120	-275	-	-	-310	R512E
FS85	Rx 2375°F-1 Hr.	1T**	> 120	-275	-	-	-280	R512E
	Rx 2375°F-1 Hr.	3.2T*	> 120	-280				
Cb129Y	Rx 2400°F-1 Hr.	1T	105	-320	2T	105	-320	Mod. Aluminide

*Westinghouse Co. Data
**Fansteel Data

ALLOY	CONDITION	UNCOATED TIG WELDS BEND RADIUS	UNCOATED TIG WELDS BEND ANGLE°	UNCOATED TIG WELDS TRANSITION TEMP.-°F LONG.	UNCOATED TIG WELDS TRANSITION TEMP.-°F TRANS.	UNCOATED EB WELDS BEND RADIUS	UNCOATED EB WELDS BEND ANGLE°	UNCOATED EB WELDS TRANSITION TEMP.-°F LONG.	UNCOATED EB WELDS TRANSITION TEMP.-°F TRANS.
C103	Stress Relieved	2T	90	-320	-320	-	-	-	-
Cb291	Stress Relieved	1T	90	-275	-275	1T	90°	-320	-250
FS85	Stress Relieved	2T	90	-175	-175	2T	90°	-200	-200
Cb129Y	Stress Relieved	1T	90	-200	-200	1T	90°	-225	-175

NOTES:
(1) All Cb alloys generally require post-weld annealing to improve ductility.
(2) Weld conditions optimum.
(3) Oxygen contamination embrittles welds all Cb alloys.
(4) Coarse grain in HAZ raises DBTT of weldment.

DUCTILITY CHARACTERISTICS

COATED MATERIAL

ALLOY	COATING	PRE-BEND TREATMENT	BEND TEST RESULTS BEND ANGLE	BEND RADIUS	TEMP.	REMARKS
FS85	VH109	Cycle Static Air 2400°F 100 Hrs. Plus 2600°F 4 hrs.	105°	2T	R.T.	Coating intact after cyclic oxidation exposure.
Cb129Y	VH109	Cycle Static Air 2400°F 100 Hrs. Plus 2600°F 4 hrs.	105°	2T	R.T.	Edge failures coating after cyclic oxidation exposure-surfaces coating O.K.
FS85	VH109	41 cycles static air 2400°F 224 hrs.	160°	1T	R.T.	Coating intact after cyclic oxidation exposure.
		"	105°	2T	-110°F	"
		"	105°	2T	<-320°F	Bend specimens fractured at -320°F. Coating intact after cyclic oxidation exposure.
Cb129Y	VH109	"	160°	1T	R.T.	Coating intact after cyclic oxidation exposure.
		"	105°	2T	-110°F	"
		"	105°	2T	-320°F	"

COATING DURABILITY

ALLOY	COATING	CRITICAL TEMP. ③ Coating Defect Rapid Growth in Static Thermal Exposure ①	CRITICAL TEMP. ③ Coating Defect Rapid Growth in Dynamic Thermal Exposure ②	SENSITIVITY TO COATING DEFECT CONTAMINATION EMBRITTLEMENT AFTER DYNAMIC THERMAL EXPOSURE ② No. Thermal Cycles	SENSITIVITY TO COATING DEFECT CONTAMINATION EMBRITTLEMENT AFTER DYNAMIC THERMAL EXPOSURE ② Room Temp. Pop-In Strength, KSI, After Cycling	POST-TEST APPEARANCE OF COATED SPECIMENS AFTER STATIC THERMAL EXPOSURE ① 5 Cycles	POST-TEST APPEARANCE OF COATED SPECIMENS AFTER DYNAMIC THERMAL EXPOSURE - 10 Cycles ②
FS85	R512E	2610°F	2560°F	1	60	Both alloy combinations- Dark, brownish-colored oxides	Both alloy combinations- Creamy, dense, white adherent Oxide developed between 3 and 5 cycles. Continued cycling to 10. Cycles produced no additional change.
				5	60		
				10	60		
Cb129Y	VH109	2610°F	2485°F	1	73		
				5	55		
				10	15		

NOTES:

① Static thermal exposure - specimens under partial vacuum (10 to 15 Torr) in a controlled leak rate furnace.

② Dynamic thermal exposure - in plasma arc using wedge model to simulate free-stream enthalpies and velocities, aerodynamic shear and surface pressures (approximately 10 to 15 Torr of reconstituted air).

③ Temperature above which intentional coating defects grow rapidly.

McDonnell-Douglas Test Program found that with fused silicide coatings, no embrittling reactions occurred with substrate material on all Cb alloys evaluated (C103, Cb291, FS85, Cb129Y). The temperature cycle used to apply coatings is such that solution heat treatment occurs on all (4) alloys considered.

ALLOY	COATING	Cyclic Oxidation Life In Hrs. at 2400°F	Failure Mode
FS85	VH109	164	No Failure
Cb129Y	VH109	127	Coating Spalled

NOTES: ① Heating medium-flame-JP5 fuel burned in air.
② Heating medium-flame-JP5 fuel burned in air. Cycle-3 min. at 1600°F, followed by 2 mins. at 2200°F, followed by 2 min. cooling in air.
③ Heating medium-flame-natural gas injected with O_2. Cycle-30 seconds flame exposure followed by 30 second cooling in ambient temp air stream.
④ Heating medium-flame-oxy-acetylene. Cycle-30 seconds flame exposure followed by 30 second cooling in ambient temp air stream.
⑤ Failure is onset of oxidation in highest stress region of specimen (key hole region).

COATING DURABILITY

ALLOY	COATING	STEADY STATE OXIDATION/EROSION ① COATING/ALLOY LIFE - HOURS				CYCLIC OXIDATION/EROSION ② COATING/ALLOY LIFE AT 2200°F			THERMAL FATIGUE ⑤		
		2200°F	SPECIMEN FAILURE MODE	2400°F	SPECIMEN FAILURE MODE	NO. OF CYCLES	TOTAL CYCLE/ TEST-TIME-HOURS	SPECIMEN FAILURE MODE	NO. CYCLES TO FAILURE 2200°F ③	NO. CYCLES TO FAILURE 2400°F ④	SPECIMEN FAILURE MODE
FS85	R512A	205	Substrate oxidation at trailing edge plus interstitial contamination of substrate ahead of oxidized zone.	90	After 60 hrs-substrate local trailing edge oxidation. After 120 hrs general coating breakdown along trailing edge plus interstitial contamination at grain boundaries. Hardness DPH Adjacent to Oxidation Front: 544 10 Mils Ahead Of Oxidation Front: 331	1180	137	Trailing edge oxidation-No Substrate cracks	10,000-No Failure	8750	Coating cracks substrate oxidation. No substrate cracks.
FS85	R512E	212	As Above	80	After 60 hrs-substrate local trailing edge oxidation. After 100 hrs-numerous oxide filled coating cracks adjacent to oxidation sites. interstit. contam. ahead of oxide front and beaneath coating cracks. Hardness DPH Adjacent to Oxidation Front: 552 10 Mils Ahead Of Oxidation Front: 215	1890	220	As Above	10,000-No Failure	8812	As Above
Cb129Y	R512E	250	As Above	77-5	After 55 hrs-substrate local trailing edge oxidation. After 100 hrs-trailing edge oxidation-not extensive, numerous oxide-filled coating cracks, extensive interstit. contam. ahead of oxide front and beneath coating cracks. Hardness DPH Adjacent to Oxidation Front: 720 10 Mils Ahead Of Oxidation Front: -	1545	180	As Above	10,000-No Failure	3300	As Above

COATING DURABILITY
CYCLIC OXIDATION

ALLOY	COATING	PRE-TEST CONDITIONS	***LIFE TO FIRST COATING BREAKDOWN-CYCLES	LIFE TO SPECIMEN STRUCTURAL FAILURE CYCLES	COATING CHARACTERISTICS APPEARANCE	DEGRADATION	TOTAL SUBSTRATE DIFF. (Beyond as coat. diff. lay.)
FS85 Test Panels	R512E	*Applied external pressure furnace re-entry exposures simulating Space Shuttle Orbiter Re-entry thermal protection system requirements.	110	>200	Thick oxide formed on external surfaces and filled the widened natural coating cracks	Net reduction in coating thickness-12%. (Only a fraction of potential coating life consumed.)	**0.0004"
C129Y Test Panels	R512E	" "	100	-	--	--	--
FS85 Test Panels	R512E	Applied stagnation mode plasma arc exposures with a 30-minute square wave temperature profile. Each cycle included exposure at 2550°F for 30 minutes at 4.6 Torr press.	30 - >50	-	Oxide formed on external surfaces but relatively no oxide at natural coating cracks.	More coating consumed and more interdiffusion with substrate than furnace cycled specimens.	--
C129Y Test Panels	R512E	" "	12-18	-	--	--	--

*One cycle includes temperature exposure for 30 minutes above 1600°F, of which 6 minutes at 2400°F, along with 7425 psi external pressure periodically applied.

**Calculated diffusion rate at 2400°F - .0000007"/minute. (Beyond as-coated diffusion layer).

***Breakdown occurred at edges.

COATING DURABILITY

ALLOY	PART DESCRIPTION	COATING	PRE-EVAL. CONDITIONS	COATING CHARACTERISTICS					MATERIAL CHARACTERISTICS
				APPEARANCE		COATING THICKNESS - MILS			BASE METAL AFTER FIRING
				O.D. SURFACE	I.D. SURFACE	Outer Layer	Reserve Layer	Diffused Layer	
Cb291	Liner	R508C	Mission Duty Cycle Performed (Fire Test)	Very minor roughening of coating.	Some balling, flaking and roughening present in coating. Local erosion of coating in two bands, but diffused layer intact in these areas.	3.8-4.9	2.6-3.6	1.2-1.8	Unaffected-No cracks, Blisters, delaminations or spalling. Drain size-3.5 (2 or finer required).
Cb291	Liner	R508C	3-year system storage, plus mission duty cycle performed (fire test)	"	"	"	"	"	* "

*Liner displayed coarse grain (ASTM 1) in 1 of 2 specimens evaluated. The coarse-grained specimen, only, failed 90°, 2T bend (broke at 45°). This material procured prior to imposition of grain size controls and does not represent material used for production hardware.

Degradation of R512E Coating:

(1) Effect upon coating composition of exposure to oxidizing environment

As Coated	After 50, 1 Hr. Slow Cycles to 2500F in Air (Normally, 63-71 cycles to fail)	After 10 Hr. at 2800F in Air (Normally, 9-15 hr. to fail)
$CbSi_2$	Consummed	4Cr, 9Fe, 42Cb (M_5Si_3)
19Cr, 13Fe, 20Cb (M_5Si_3)	15Cr, 12Fe, 26Cb (M_5Si_3)	7Cr, 9Fe, 41Cb (M_5Si_3)
10Cr, 18Fe, 27Cb (M_5Si_3)	9Cr, 19Fe, 26Cb (M_5Si_3)	6Cr, 8Fe, 42Cb (M_5Si_3)
Too Narrow (M_5Si_3)	7Cr, 9Fe, 40Cb (M_5Si_3)	4Cr, 8Fe, 45Cb (M_5Si_3)
4Cr, 8Fe, 45Cb (M_5Si_3)	0Cr, 8Fe, 47Cb (M_5Si_3)	3Cr, 6Fe, 47Cb (M_5Si_3)
Cb_5Si_3	Cb_5Si_3	Cb_5Si_3
Base Metal	Base Metal	Base Metal
	• Outer layer consumed • No significant changes in sublayers	• Depletion of Cr and Fe resulting in porosity in M_5Si_3

(2) Protective scale formation

(a) 50 slow cycles to 2500F - $CrCbO_4$ (primary) + SiO_2 (secondary)

(b) 10 hr. @ 2800F - SiO_2 (primary) + $CrCbO_4$ (secondary)

RCS - CRITICAL FATIGUE LIFE CURVES

For the determination of the critical fatigue life curves of the selected columbium alloys the Manson Equation, which relates cyclic life to total tensile strain range, was used.
This Equation is:

$$\epsilon_t = \frac{G}{E} N_f^{\gamma} + M N_f^{Z}$$

where

ϵ_t ~ Total Tensile Strain Range (in/in)

N_f ~ Critical Fatigue Life (Cycles)

E ~ Elastic Modulus (PSI)

$$G = \frac{9}{4} \sigma_u (\sigma_f / \sigma_u)^{0.9}$$

$$\gamma = -0.083-0.166 \log (\sigma_f / \sigma_u)$$

$$M = 0.827 D \left[1 - 82 \sigma_u/_E (\sigma_f / \sigma_u)^{0.179}\right]^{-\frac{1}{3}}$$

$$Z = -0.52 - 1/4 \log D + 1/3 \log \left[1-82 \sigma_u/_E (\sigma_f / \sigma_u)^{0.179}\right]$$

$$D = - \ln(1 - R.A.)$$

σ_u ~ Ultimate Tensile Strength (PSI)

σ_f ~ Actual tensile strength at failure, which includes the reduction in area, i.e.:

$$\sigma_f/\sigma_u = 1 / (1-R.A.)$$

R.A. ~ Reduction of Area

Where applicable the reduction of area was determined from creep rupture tests that were conducted on the columbium materials.

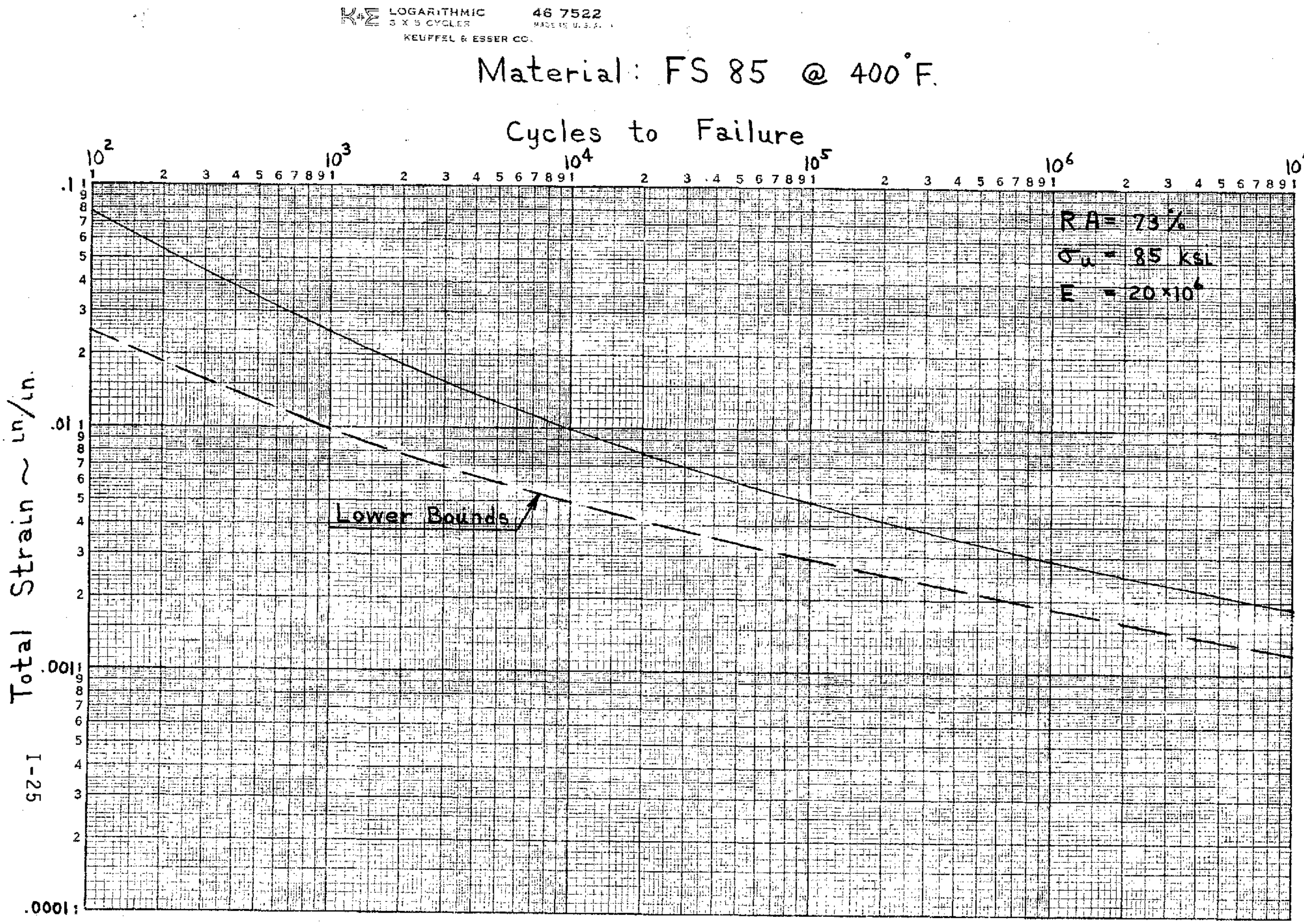
The above fatigue equation is denoted as the average life curve for the material, to arrive at a lower bound curve a factor of ten (10) was incorporated into this equation, i.e.:

$$\epsilon_t = {}^G/_E (10 N_f)^{\gamma} + M (10 N_f)^{Z}$$

The resultant cyclic life curves were then determined for temperatures of:

400, 2000, 2200 and 2400°F.

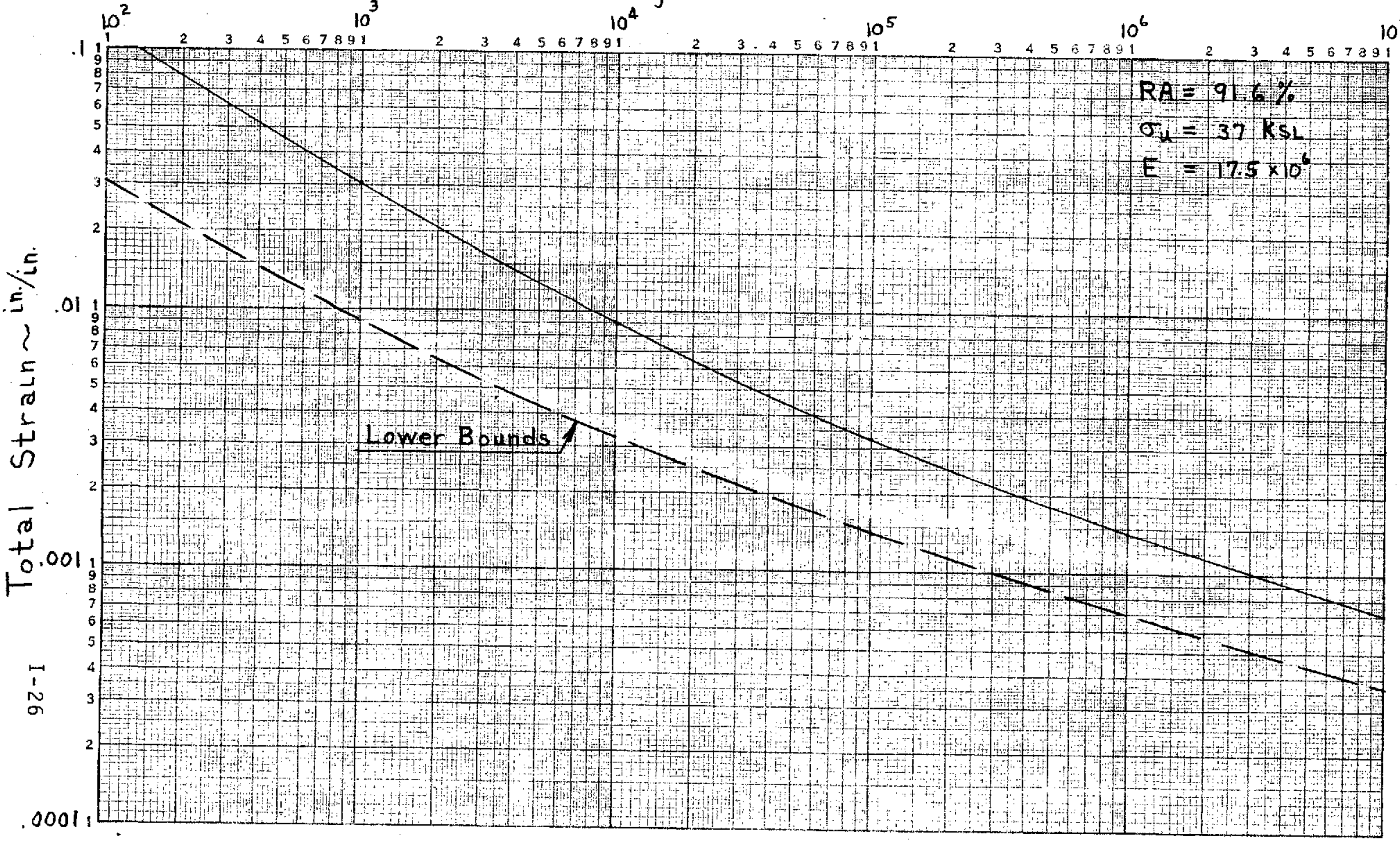
Material: FS 85 @ 400°F



I-25

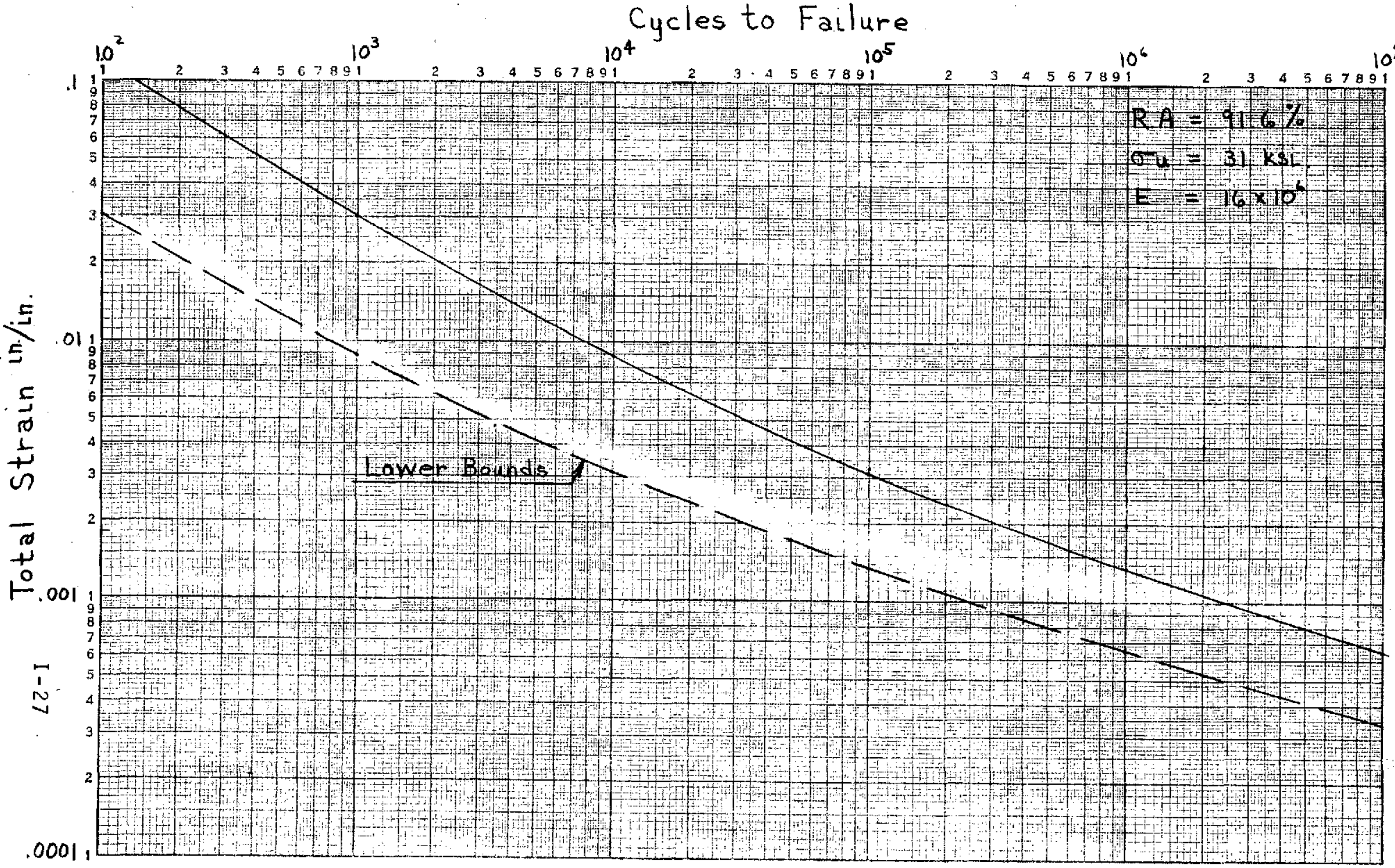
Material : FS 85 @ 2000°F

Cycles to Failure

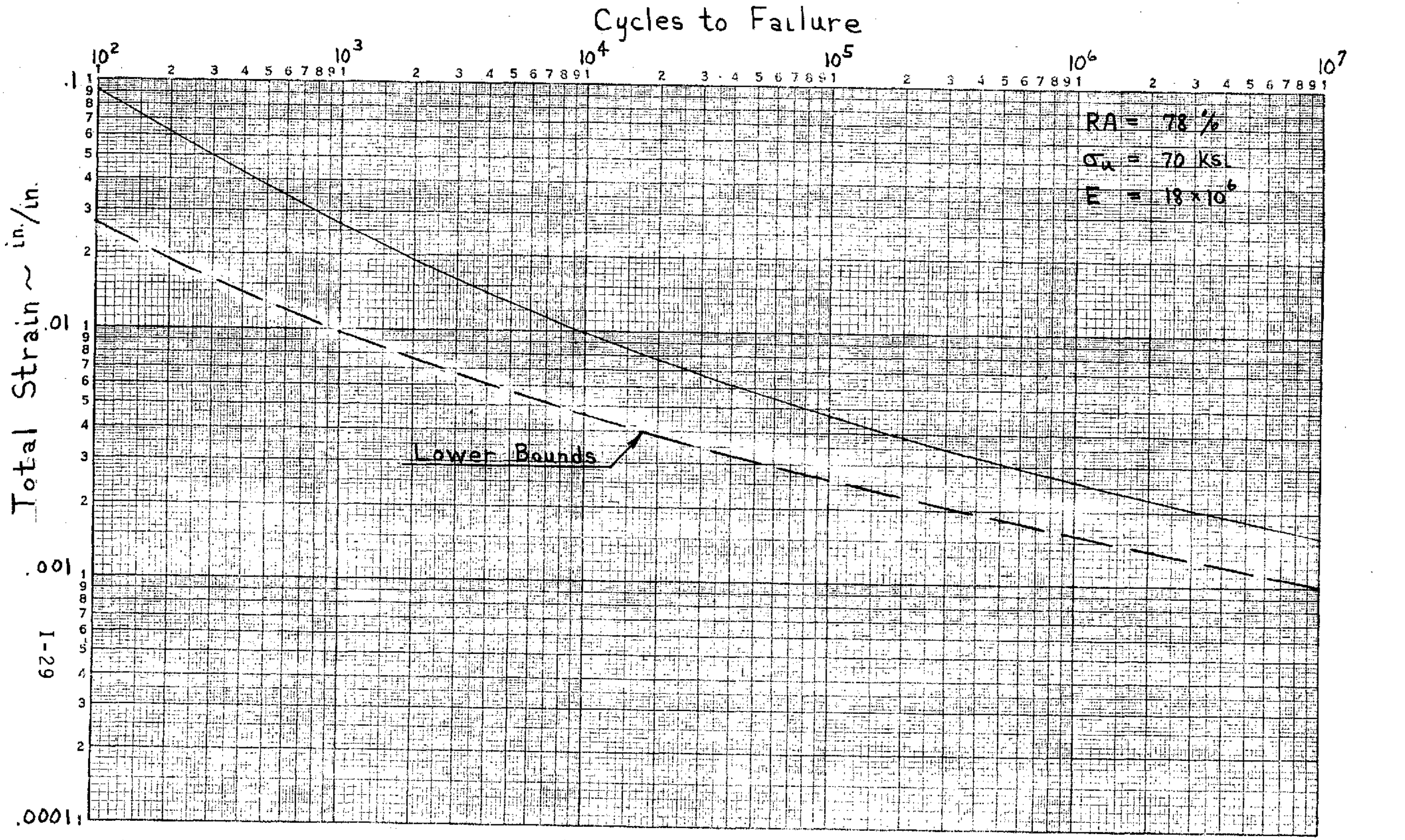


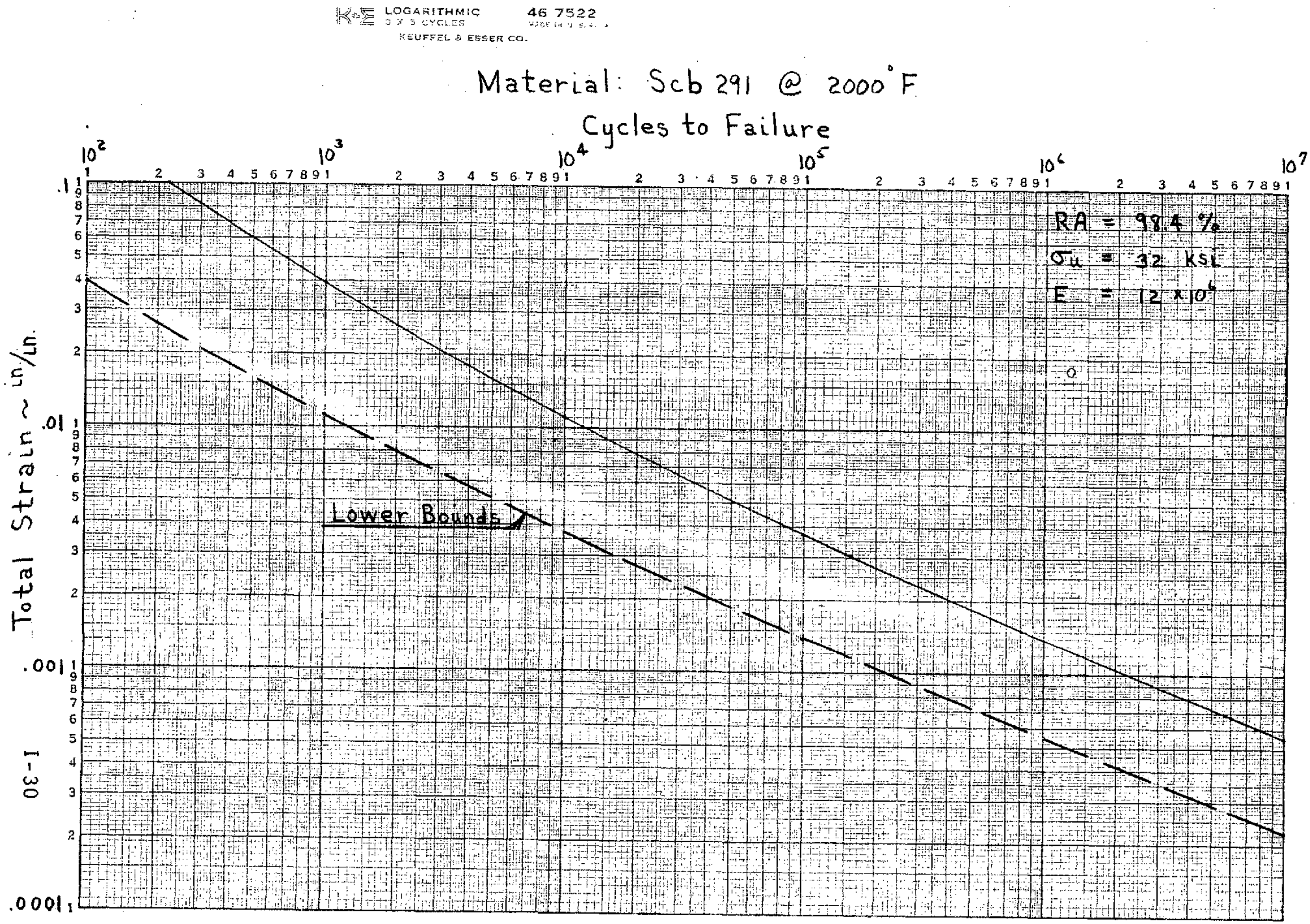
K+E LOGARITHMIC 3 X 5 CYCLES 46 7522 MADE IN U.S.A. KEUFFEL & ESSER CO.

Material: FS 85 @ 2200° F

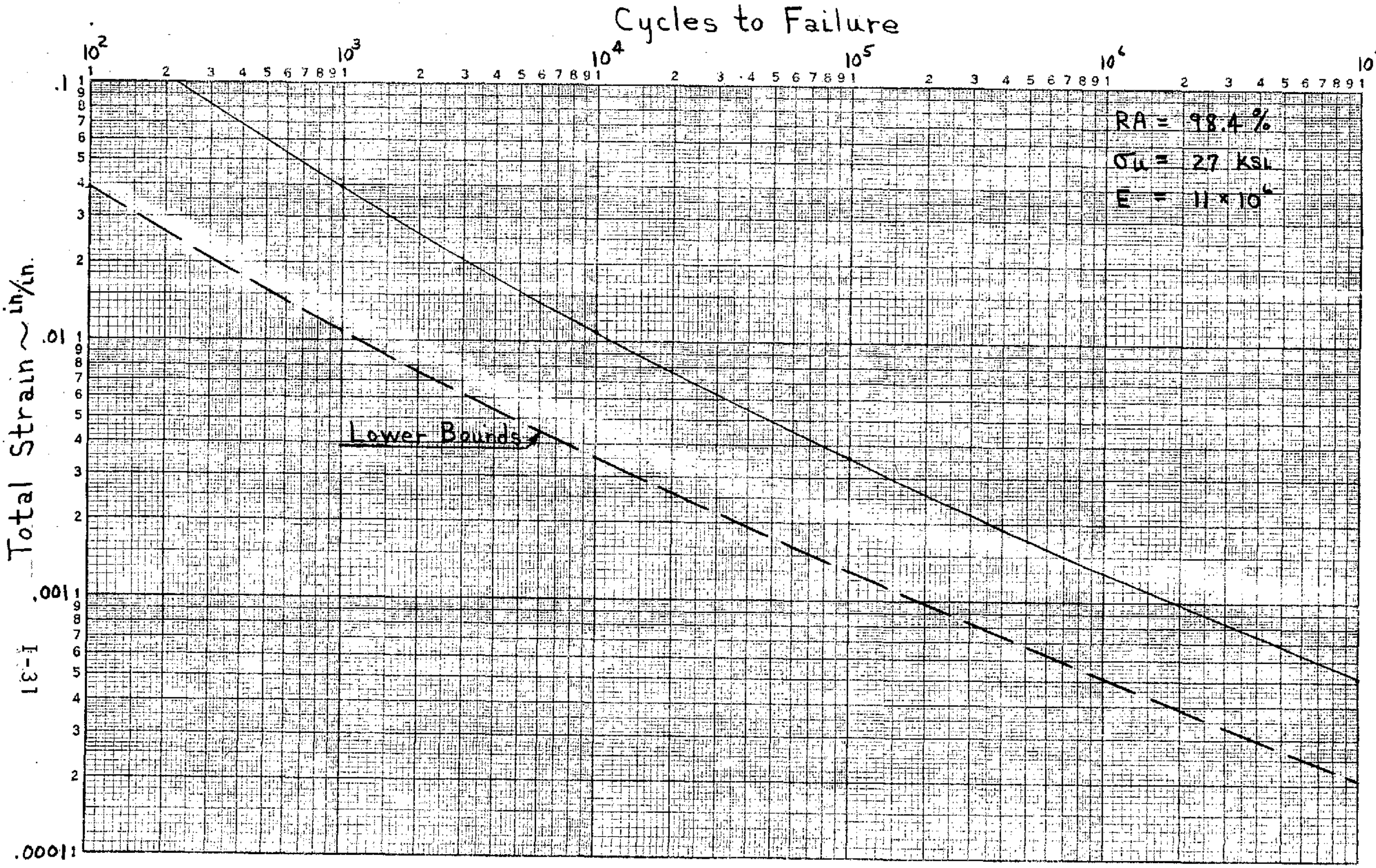


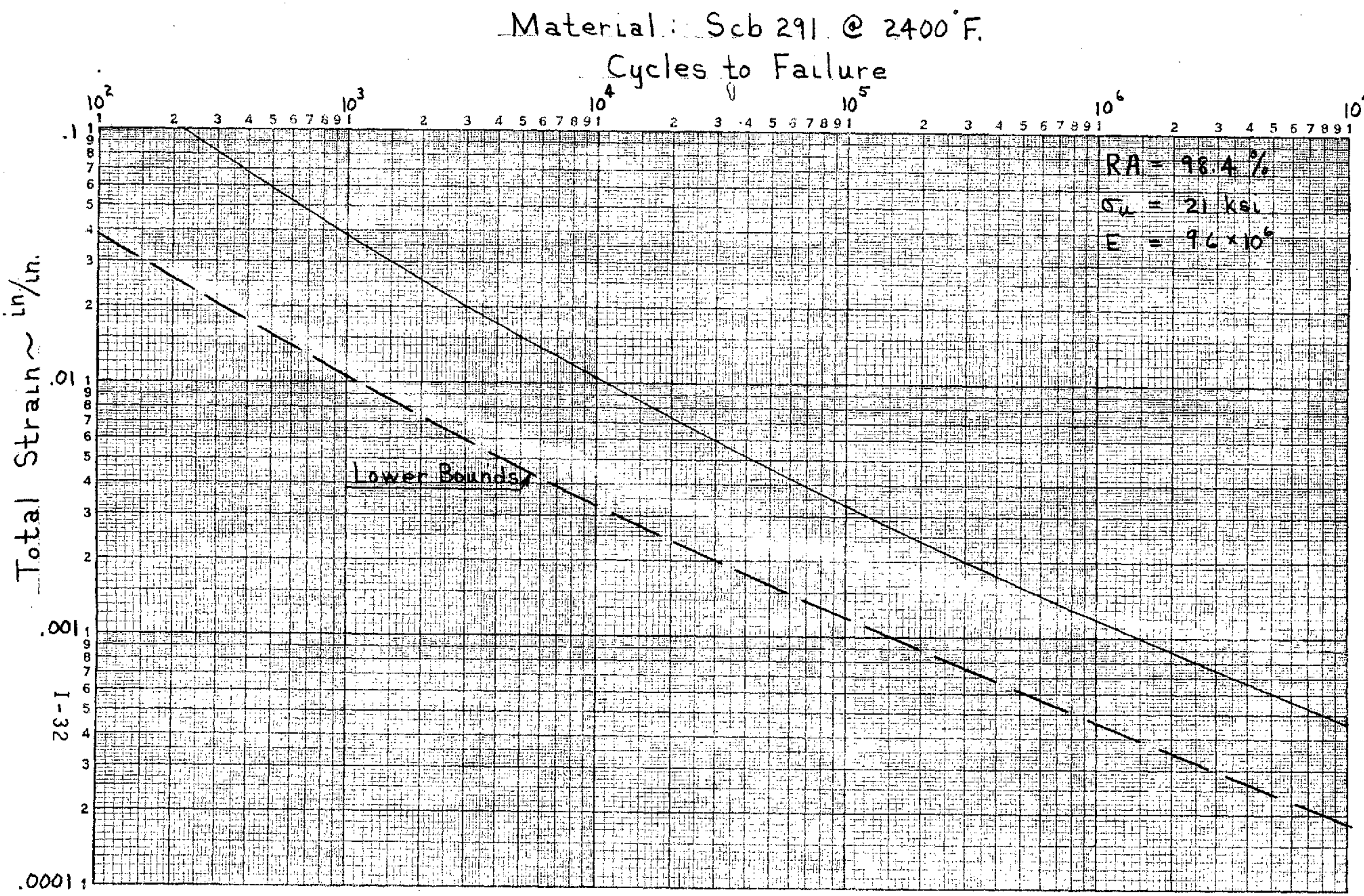
Material: Scb 291 @ 400°F




K+E LOGARITHMIC 3 X 5 CYCLES 46 7522
KEUFFEL & ESSER CO.
Material: Scb 291 @ 2000°F
Cycles to Failure
Total Strain ~ in/in
RA = 98.4 %
σu = 32 KSI
E = 12 x 10^6
Lower Bounds
I-30

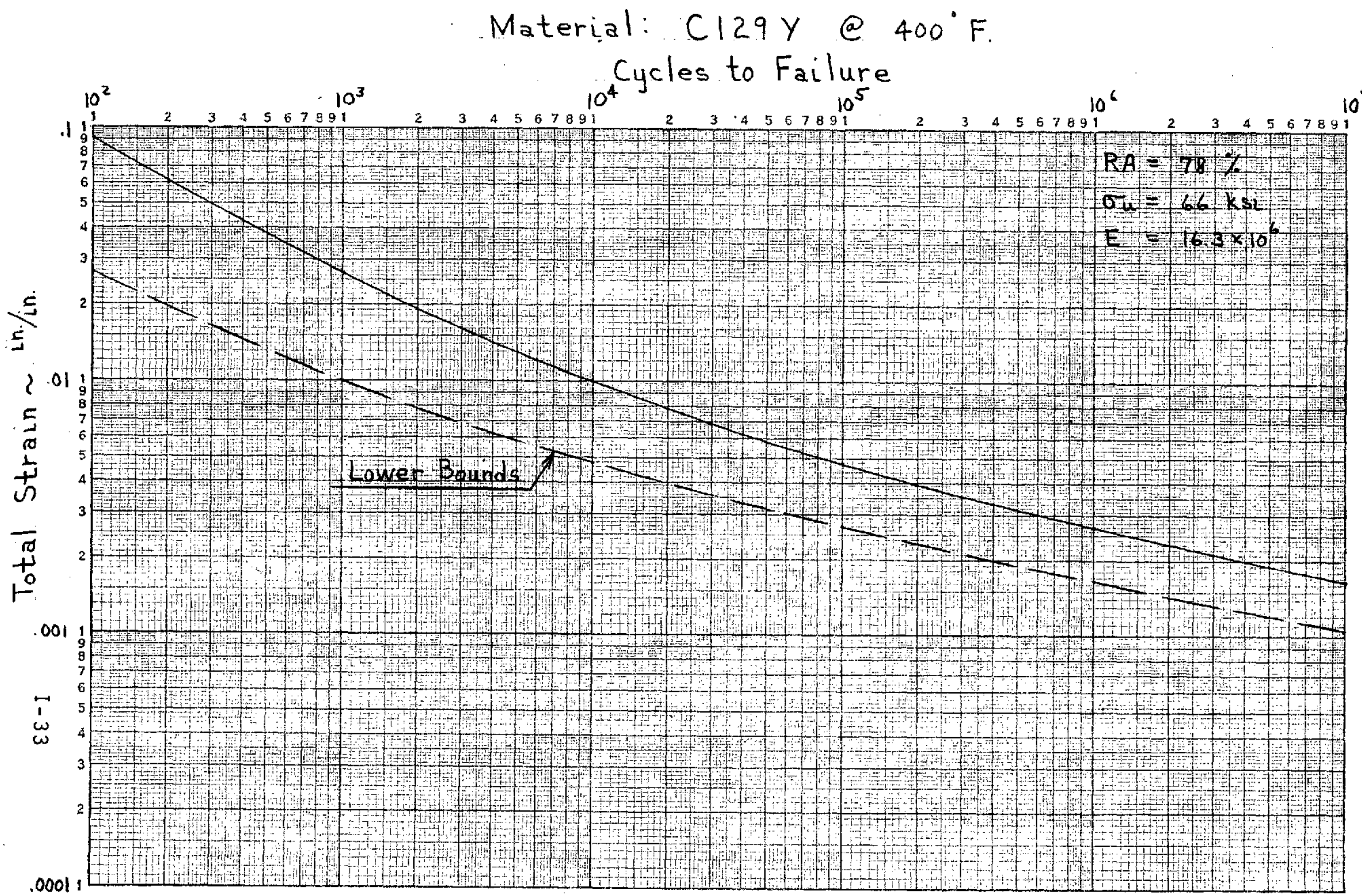
Material: Scb 291 @ 2200°F





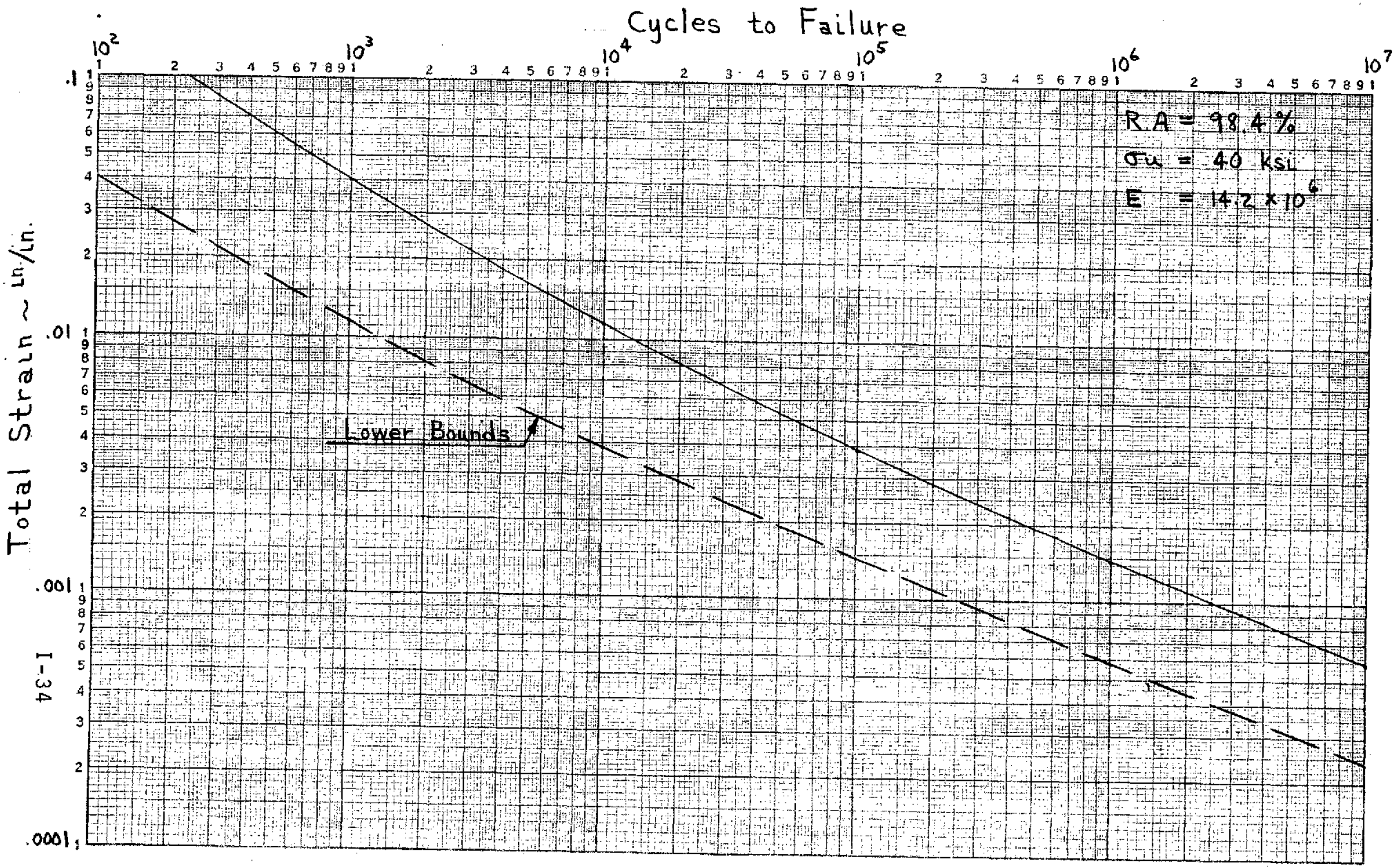
Material: Scb 291 @ 2400°F.
Cycles to Failure
10^2
10^3
10^4
10^5
10^6
10^7
Total Strain ~ in/in.
.1
.01
.001
.0001
RA = 98.4 %
σ_u = 21 ksi
E = 9.6 × 10^6
Lower Bounds

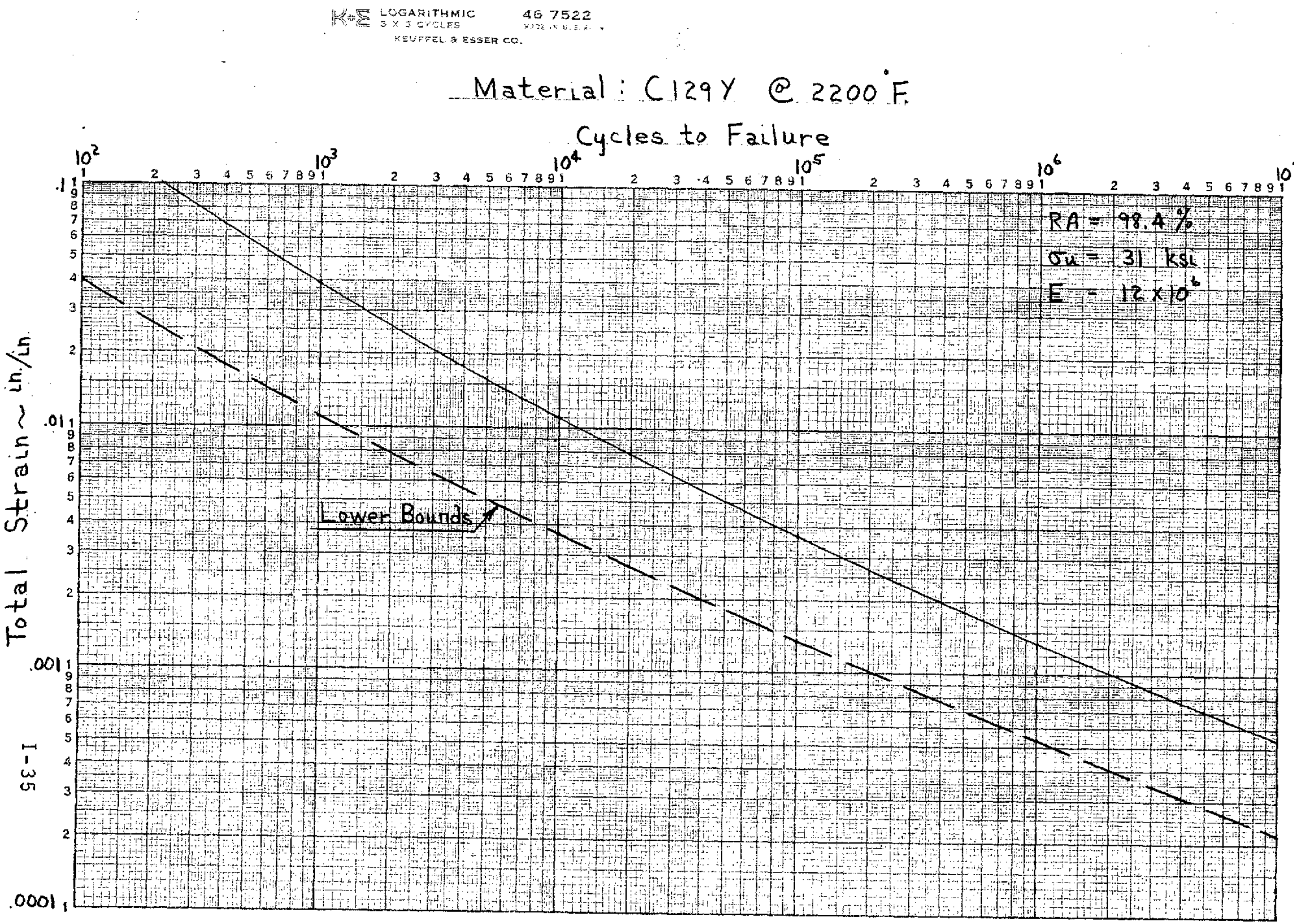
K+E LOGARITHMIC 3 X 5 CYCLES 46 7522 KEUFFEL & ESSER CO.

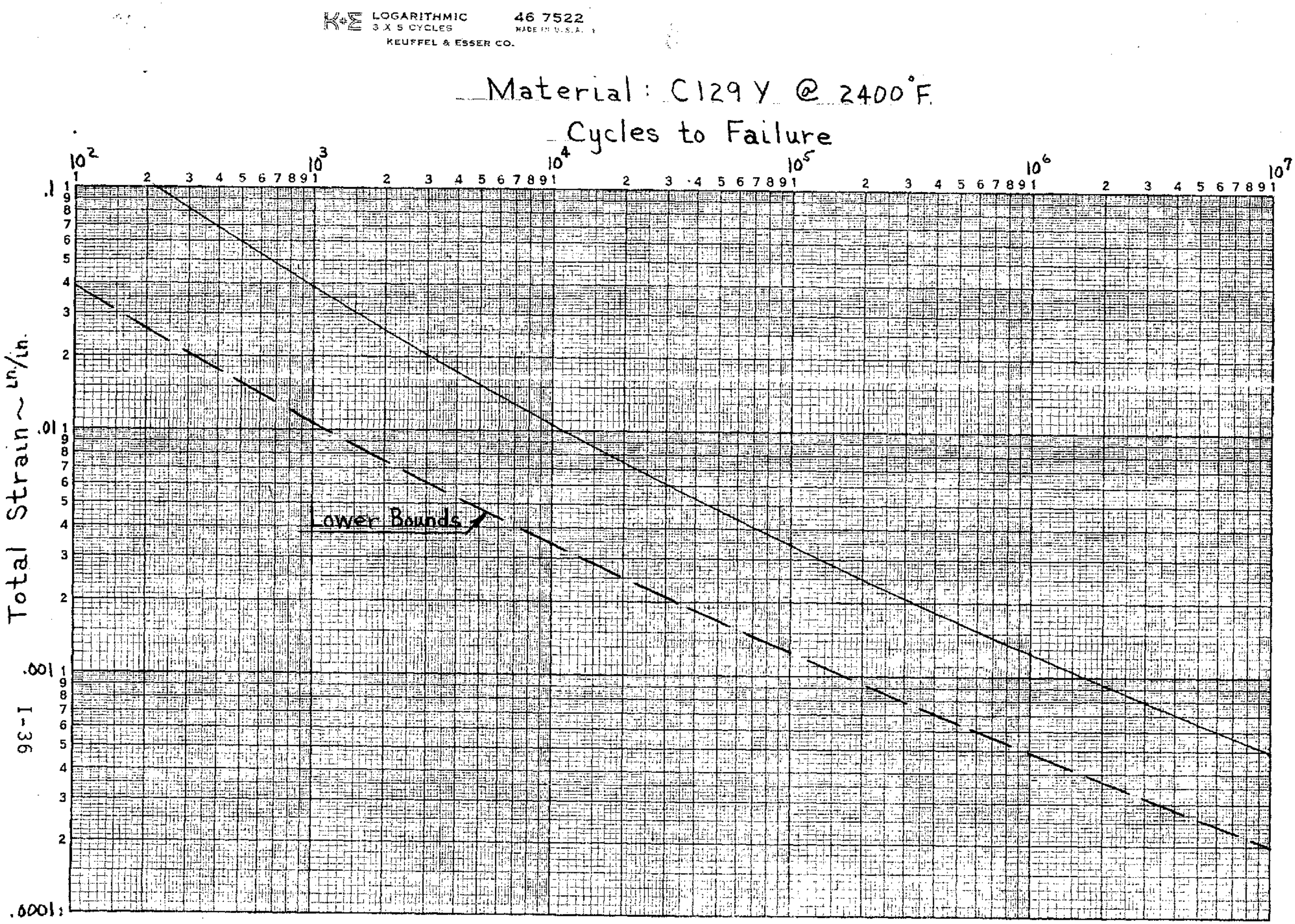


I-33

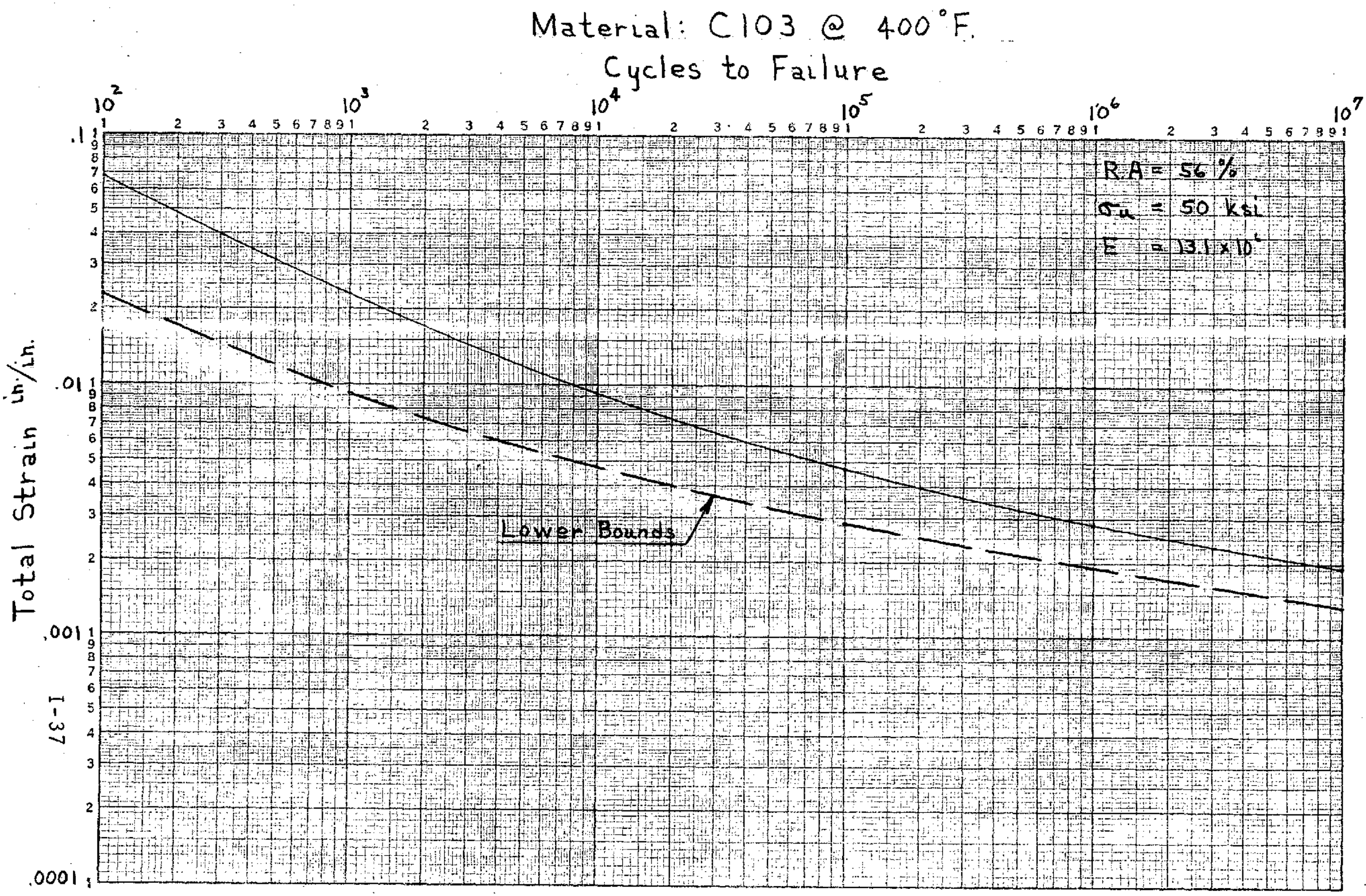
Material: C129Y @ 2000°F.




K+E LOGARITHMIC 3 X 3 CYCLES 46 7522
KEUFFEL & ESSER CO.
Material: C129Y @ 2200°F
Cycles to Failure
Total Strain ~ in./in.
RA = 98.4%
σu = 31 ksi
E = 12 x 10^6
Lower Bounds

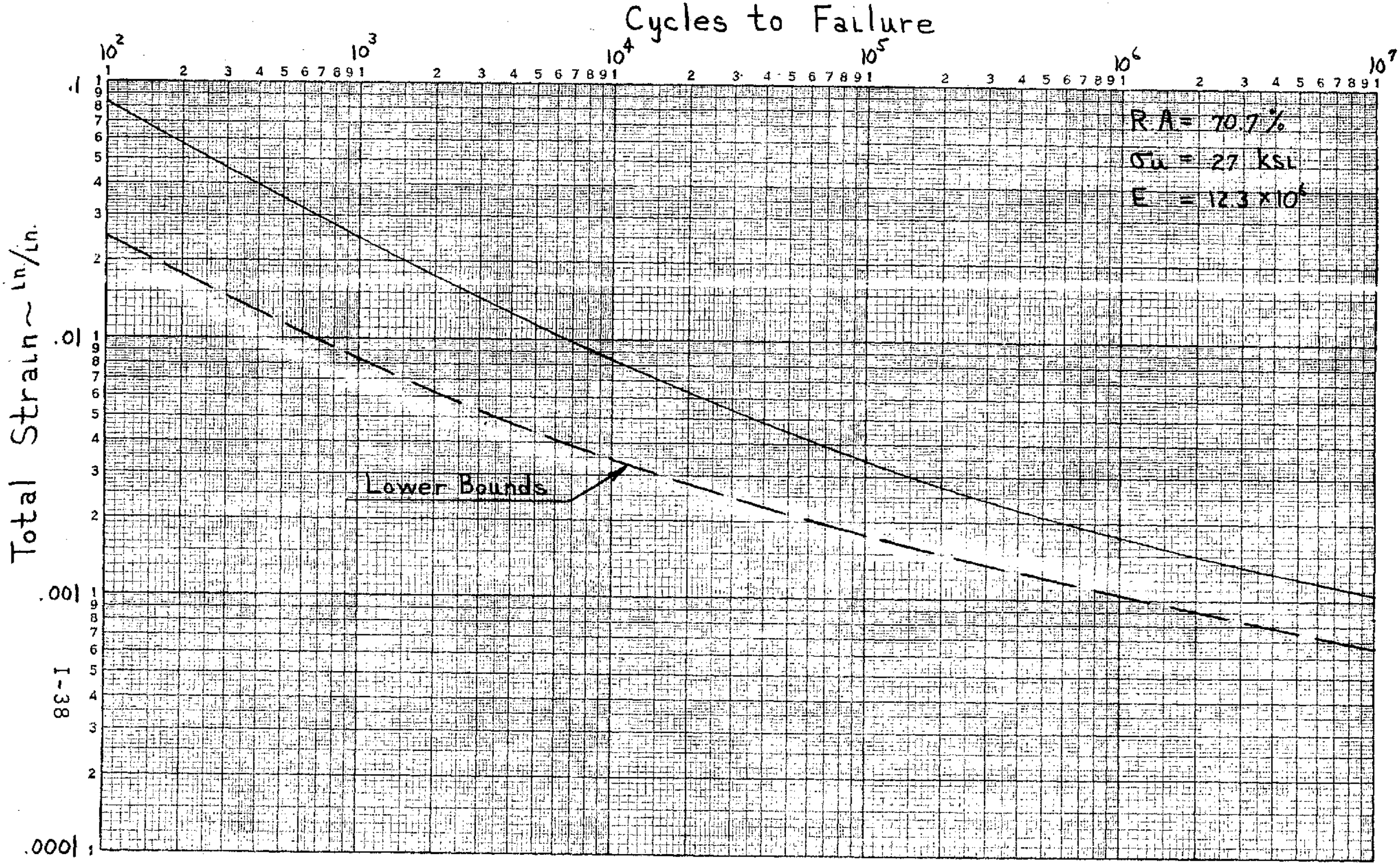


K+E LOGARITHMIC 3 X 5 CYCLES
KEUFFEL & ESSER CO.
46 7522
Material: C129Y @ 2400°F
Cycles to Failure
10^2
10^3
10^4
10^5
10^6
10^7
Total Strain ~ in/in.
.1
.01
.001
.0001
Lower Bounds

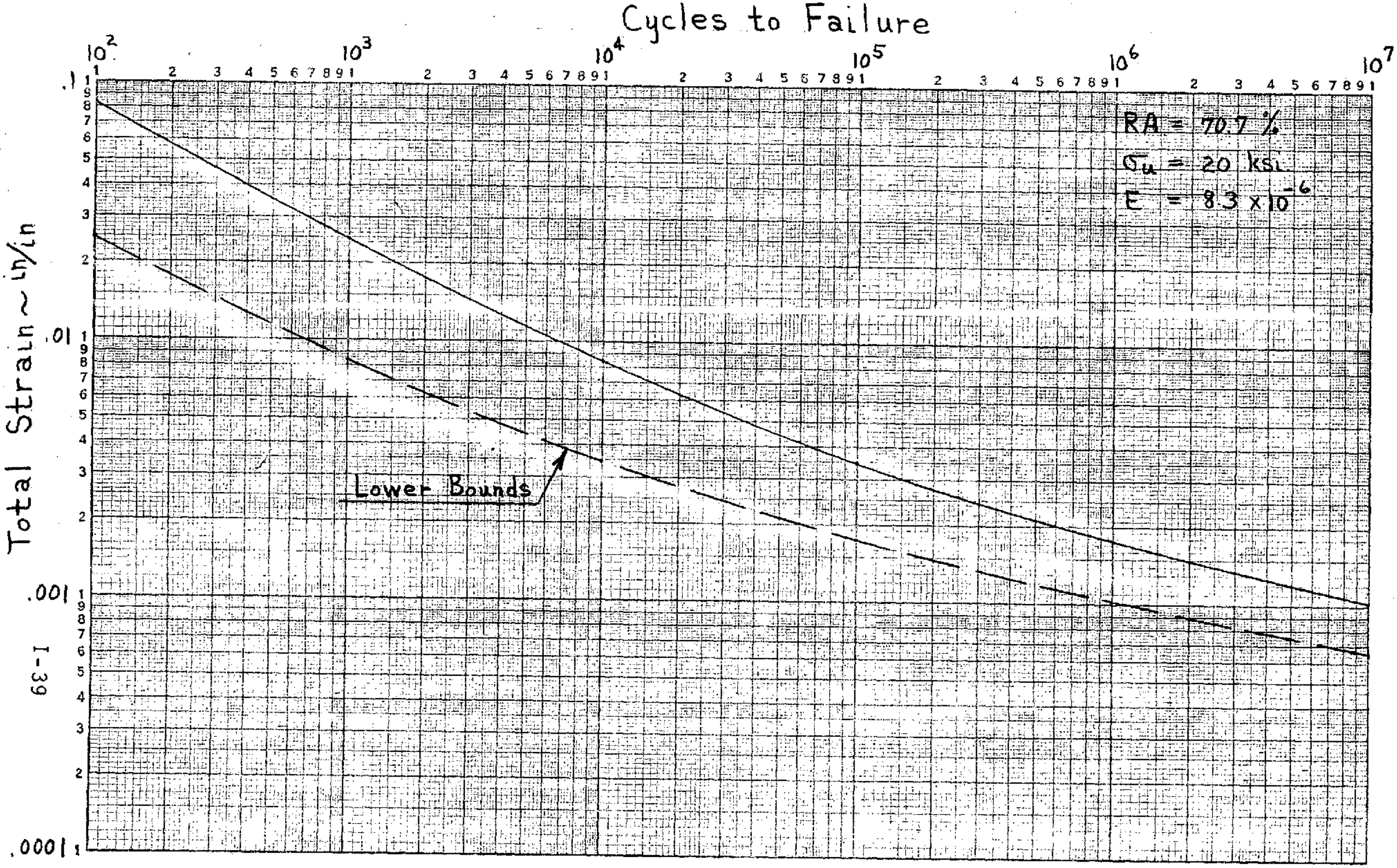


Material: C103 @ 400°F.
Cycles to Failure
Total Strain in./in.
R.A = 56 %
σu = 50 ksi
E = 13.1 x 10⁶
Lower Bounds

Material: C103 @ 2000°F



Material: C103 @ 2200°F.



BIBLIOGRAPHY

1. "Aerospace Materials Handbook"- Volume II, 1973.

2. Gibeault, W.A. and Bartlett, E.S., "Properties of Coated Refractory Materials", DMIC 195, January 10, 1964.

3. Van Echo, J. and Bartlett, E.S., "Creep of Columbium Alloys", DMIC Report - Battelle.

4. Donnelly, R.G. and Slaughter, G.M., "Weldability Evaluation of Advanced Refractory Alloys", Welding Research Supplement, June, 1966.

5. Allen, B.C. and Bartlett, E.S., "High Temperature Oxidation Resistant Coatings", DMIC Review, February 16, 1973.

6. Lessmann, G.G., "Comparative Weldability of Refractory Metal Alloys", Welding Journal, December, 1966.

7. Miyagishima, T., "Investigation of High Strain Rate Behaviour of Refractory Alloys and Coatings", PR-3009-F, Contract NAS 9-4905, February, 1966.

8. Holloway, J.F., Jr., "Evaluation of Coated Columbium Alloys for Burner Applications", AFML-TR-71-127, August, 1971.

9. Gerardi, S.J., "Coating and Processing of Columbium Panels for Space Shuttle Applications", NASA 8-27280, April, 1972.

10. Westinghouse Astronuclear, "Tensile and Creep Testing of 90 Ta-10W and Cb 103", WANL-M-FR-73-004, May, 1973.

11. Fansteel Corp., "Short Time Elevated Temperature Creep and Tensile Properties of Fansteel 291 Metal", Development Project No. 991603, 1966.

12. Fansteel Corp., "FS 85 Metal", Bulletin TD-85-1, Bulletin TD-823-C1.

13. Bell Aerospace Company, "Evaluation of High Temperature Properties of Cb 291 - Gleeble Program", IOM 912:67:0623-1JF, June 23, 1967.

14. Teledyne Wah Chang Co., "Columbium, Tantalum and Tungsten Alloys", Technical Information, Volume III, January, 1968.

APPENDIX II

SUMMARY OF TEST DATA

SUMMARY OF MDC TEST DATA (STEADY STATE)

DATE	TEST NO. (B-1-)	DUR. (SEC)	O/F	P_C (PSIA)	C* (FPS)	$I_{SP\infty}$ $\mathcal{E}=31$ (SEC)	$I_{SP\infty}$ $\mathcal{E}=40$ (SEC)	T_{MAX} (^oF)
3-19-74	1188	5.1	1.54	193.5	5318	289.6	293.4	-
3-19-74	1189-1	10.1	1.62	197.8	5325	289.9	293.7	2235
	1189-2	95.0	1.62	197.9	5314	289.3	293.1	2218
	1189-3	95.3	1.60	197.5	5329	292.2	296.0	
	1189-4	95.7	1.60	198.0	5335	288.7	292.5	
	1189-5	96.1	1.59	198.0	5331	287.9	291.6	2238
	1189-6	95.4	1.61	198.1	5295	286.4	290.1	2206
	1189-7	86.7	1.59	198.2	5313	289.7	293.5	
	1189-8	95.4	1.60	200.2	5345	287.5	291.2	2218
	1189-9	95.6	1.58	198.7	5359	290.9	294.7	
	1189-10	95.3	1.58	199.0	5368	290.0	293.8	2221
3-21-74	1190-1	100.3	1.50	194.5	5282	289.4	293.2	1983
	1190-2	95.4	1.49	192.2	5228	292.0	295.8	2010
	1190-3	95.3	1.47	192.5	5231	291.2	295.0	
	1190-4	95.1	1.46	192.7	5224	289.2	293.0	
	1190-5	95.0	1.46	191.0	5179	287.6	291.3	2035
	1190-6	95.2	1.45	193.4	5240	287.5	291.2	2014
3-21-74	1190-7	105.7	1.46	193.2	5239	290.4	294.2	
3-25-74	1192-8	94.8	1.53	202.4	5300	289.3	293.1	2100
	1192-9	94.7	1.52	202.0	5286	290.7	294.5	
	1192-10	94.9	1.52	201.7	5285	290.0	293.8	2065
3-22-74	1191-1	100.0	1.71	195.9	5287	289.5	293.3	2088
	1191-2	95.0	1.70	195.8	5268	290.0	293.8	2148
	1191-3	94.8	1.69	195.8	5267	289.5	293.3	
	1191-4	95.1	1.68	196.0	5266	289.0	292.8	
	1191-5	94.4	1.67	196.0	5264	289.4	293.2	2070
	1191-6	94.9	1.67	197.4	5276	287.0	290.7	2123
	1191-7	94.9	1.67	195.9	5269	289.4	293.2	
	1191-8	95.3	1.68	197.8	5290	290.4	294.2	2041
	1191-9	95.1	1.67	195.8	5277	288.4	292.2	
	1191-10	94.7	1.67	197.0	5276	288.3	292.1	2081

NOTE: Injector S/N FT-1C used for above tests with FS-85 thrust chamber and $\mathcal{E}=31$ nozzle extension. Burns 1, 2, 5, 6, 8 and 10 of MDC's were reduced for wall temperature to minimize cost. $I_{sp\infty}$ is based on measured thrust.

DATE	TEST NO. (B-1-)	DUR. (SEC)	O/F	P_C (PSIA)	C* (FPS)	$I_{SP\infty}$ $\epsilon = 31$ (SEC)	$I_{SP\infty}$ $\epsilon = 40$ (SEC)	T_{MAX} (^oF)
3-25-74	1193	600.5	1.61	204.2	5302	289.3	293.1	2186
			1.61	203.7	5287	290.3	294.1	
			1.61	203.6	5290	290.7	294.5	
			1.61	203.3	5286	290.7	294.5	
			1.62	203.1	5284	290.7	294.5	
			1.61	203.1	5283	290.6	294.4	
3-27-74	1194-1	100.2	1.60	199.6	5276	290.4	294.2	2214
	1194-2	95.4	1.61	200.3	5291	291.3	295.1	2152
	1194-3	95.3	1.60	199.2	5257	292.1	295.9	
	1194-4	95.1	1.69	209.7	5255	289.6	293.4	
	1194-5	95.4	1.69	209.5	5238	291.3	295.4	2272
	1194-6	95.2	1.65	210.9	5271	288.4	292.2	2234
	1194-7	95.1	1.64	209.9	5275	291.0	294.8	
	1194-8	89.5	1.65	212.6	5287	288.9	292.7	1917
3-29-74	1195-1	100.1	1.65	218.8	5303	290.4	294.2	2179
	1195-2	95.1	1.61	218.0	5315	294.4	298.2	2171
	1195-3	95.1	1.62	219.3	5309	293.7	297.5	
	1195-4	95.5	1.63	220.9	5304	293.1	296.9	
	1195-5	95.4	1.64	222.9	5301	293.0	296.8	2220
	1195-6	95.1	1.64	216.7	5302	289.6	293.8	2214
	1195-7	95.0	1.68	219.3	5299	292.4	294.1	
	1195-8	80.0	1.67	220.2	5293	291.9	295.7	2219
3-29-74	1196	60.2	1.59	206.7	5280	291.3	295.1	2033
3-29-74	1197	60.0	1.55	208.1	5289	292.9	296.7	1966
3-29-74	1198	60.2	1.75	206.5	5242	290.0	293.8	2054
3-29-74	1199	60.0	1.63	186.7	5256	289.1	292.9	1928
3-29-74	1200	60.3	1.58	185.3	5258	289.0	292.8	1909
3-29-74	1201	60.2	1.71	186.7	5229	288.3	292.1	1968
3-29-74	1202	59.9	1.65	218.4	5279	290.6	294.4	2089
3-29-74	1203	60.3	1.54	219.1	5289	291.0	294.8	2013
3-29-74	1204	60.3	1.75	218.8	5247	290.2	294.0	2127