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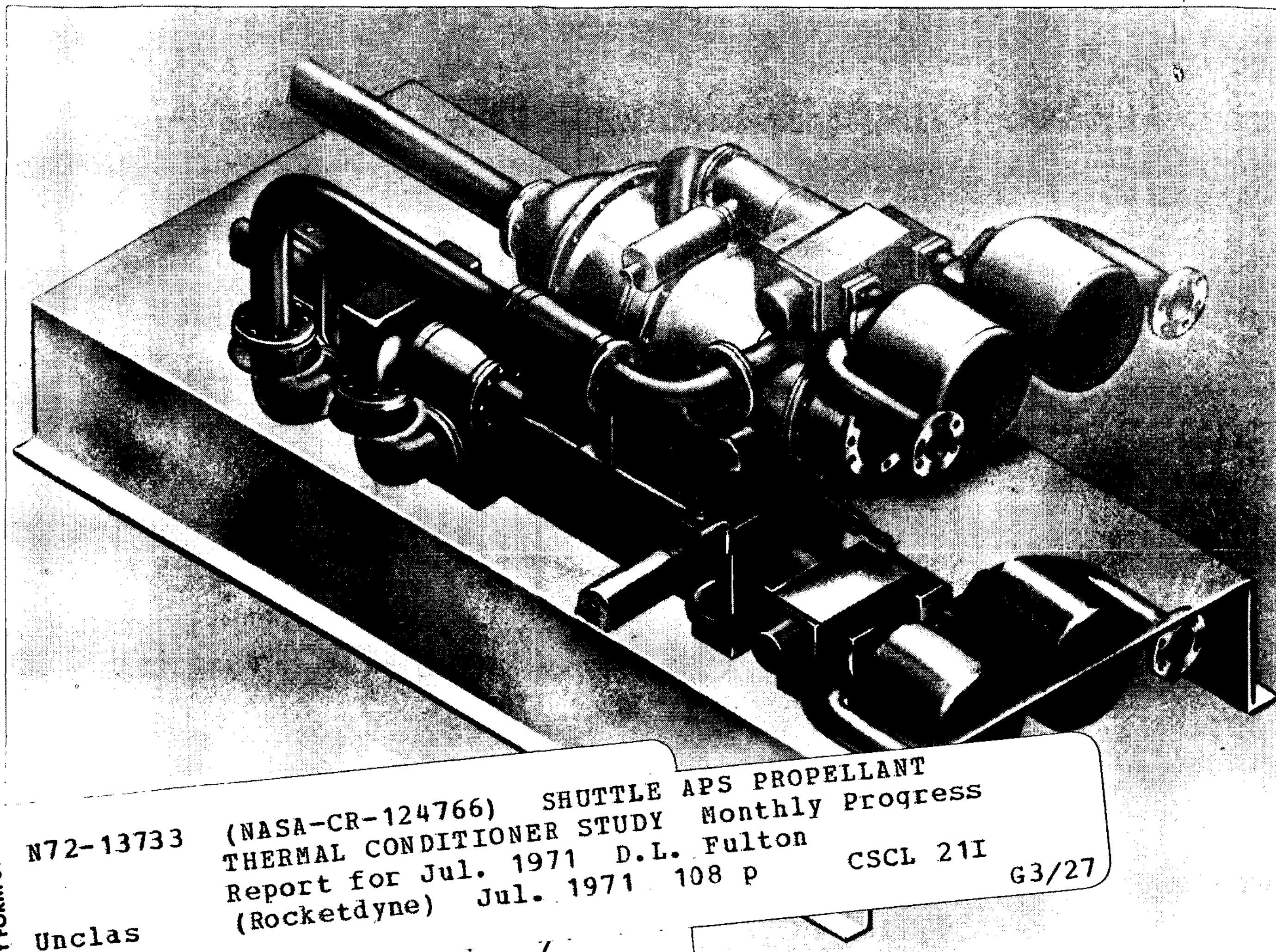

FACILITY FORM 602

N72-13733 (NASA-CR-124766) SHUTTLE APS PROPELLANT THERMAL CONDITIONER STUDY Monthly Progress Report for Jul. 1971 D.L. Fulton (Rocketdyne) Jul. 1971 108 p CSCL 21I G3/27

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SHUTTLE APS PROPELLANT THERMAL CONDITIONER STUDY

NAS9-12046

MONTHLY PROGRESS REPORT NO. 1

JULY 1971

Rocketdyne
North American Rockwell

space shuttle engine

AUXILIARY PROPULSION SYSTEM

ASR71-236

SHUTTLE APS PROPELLANT THERMAL CONDITIONER STUDY

NAS9-12046

Monthly Progress Report No. 1

July 1971

Prepared for

NASA Manned Spacecraft Center

Houston, Texas 77058

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CONTENTS

INTRODUCTION

The objective of this program is to study, design, fabricate, test and deliver hardware to thermally condition the propellants for the Space Shuttle auxiliary propulsion system and to document the activity. The thermal conditioners used on the Space Shuttle vehicle will be long-life reusable components providing proper balance of performance and safety. The end product of the effort is to be a final report containing all pertinent information, and working hardware capable of demonstrating predicted performance capabilities. The program, which started 29 June 1971, is of 12 months duration, including delivery of hardware, and encompasses analytical, design, fabrication, and test effort.

An initial study will analytically evaluate the baffle-type conditioner design concept and generate sufficient information to select the final design configuration. Detail designs will be prepared, design review conducted with NASA and, following NASA approval, fabricated with detail documentation of the as-built configuration. The conditioner hardware then will be tested to verify compliance with the design requirement. Test instrumentation will be selected to allow correlation of predicted and measured values to verify the design analysis and the approach (e.g., temperature, strain, etc.). Finally, a schedule/cost analysis will be accomplished for carrying the concept through development, qualification, and production of flight hardware. A parallel technology development effort supplemented by the results of an on-going company-sponsored thermal conditioner program will provide the technology basis for the selected design concept.

SUMMARY

The conditioner design concept selected for evaluation on this program consists of the integral reactor and baffle-type heat exchanger shown schematically in Fig. 1. Heat exchange is accomplished by flowing reactor hot gases past a series of slotted and formed plates, through which the conditioned propellant flows.

Heat transfer analysis completed to date has resulted in the selection of a reactor hot gas nominal mixture ratio of 1.0, resulting in a combustion temperature of 1560° F with a hydrogen inlet temperature of 275° R. Worst case conditions (MR = 1.1, T_{H_2} = 600° R) results in a combustion gas temperature of 2060° F, satisfying the condition of no damage to the conditioner in case of failure to flow cold fluid.

In addition, evaluation of hot gas flow requirements and conditioner weight has resulted in the selection of a reactor hot gas exhaust temperature of 750° R.

Preliminary design values that have been established for the hydrogen conditioner are:

H_2 Side:			Hot Gas Side:		
$\dot{w}$	=	4.5 lb/sec	MR	=	1.0
P_{in}	=	1600 psia	P_c	=	240 psia
T_{in}	=	55° R	$\dot{w}_c$	=	1.2 lb/sec
T_{out}	=	225° R	T_{out}	=	750° R
ΔQ	=	2800 Btu/sec	$q/A_{(max)}$	=	4 Btu/in^2-sec

APS PROPELLANT CONDITIONER

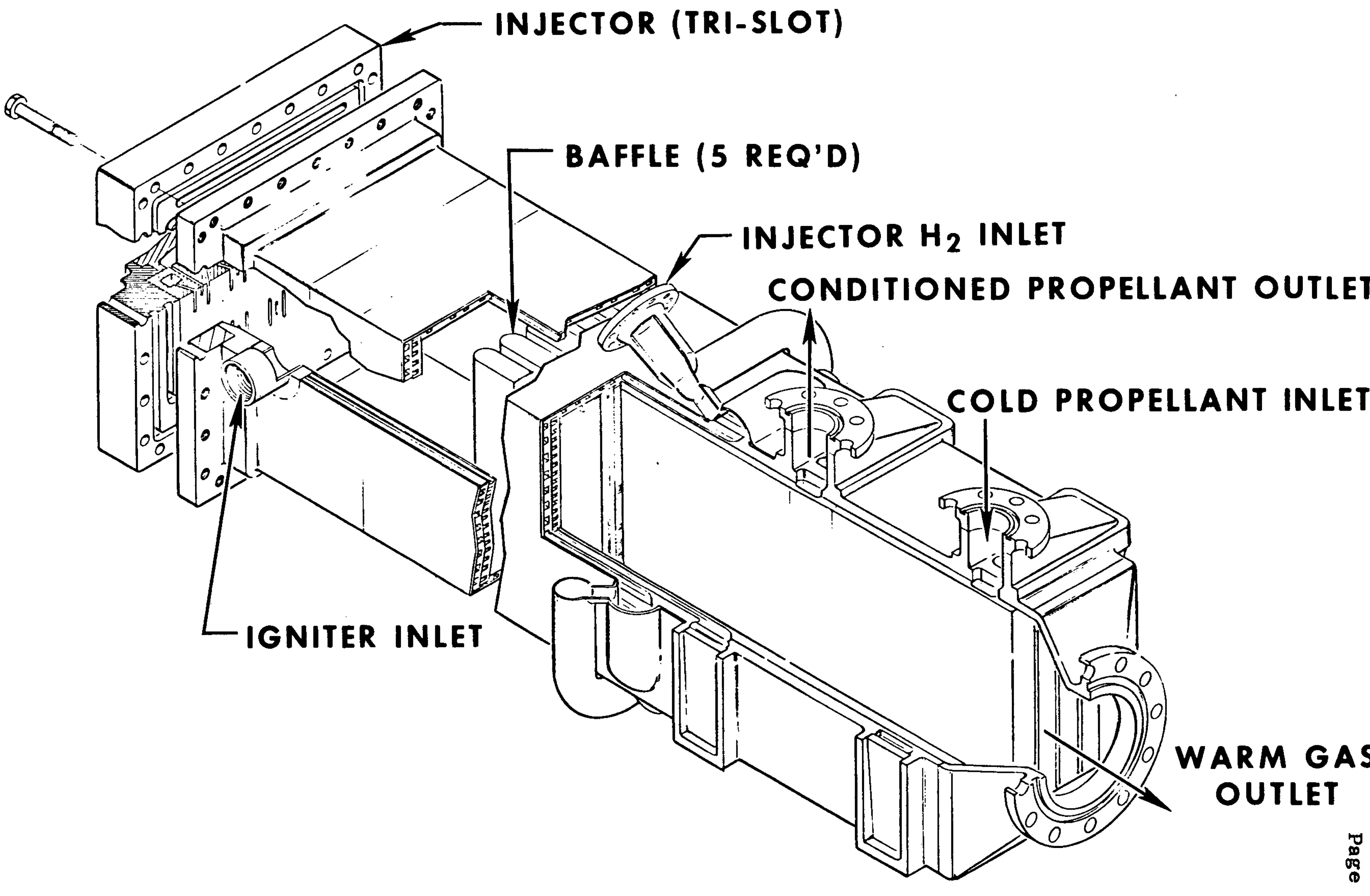


Figure 1

Materials of construction are Haynes 188 for the hot gas surfaces and 304L or 347 stainless steel for closures.

Structural/cyclic life analysis effort to date has concentrated on the evaluation of candidate material combinations for the heat exchanger baffles and in establishing parametric temperature differentials for the baffle consistent with the established cycle life goal. Results to date indicate that use of Haynes 188 as the hot gas wall and stainless steel as the closure material offer a good combination.

Design and fabrication effort have concentrated on evaluating the fabrication, procedure and sequence to be followed and in fabricating appropriate samples. Results to date indicate that the use of Electrical Discharge Machining (EDM) for producing the slots followed by furnace brazing, forming to contour and assembly is a quite promising fabrication approach.

Activity related to hot fire testing has involved preliminary test planning and evaluation of test instrumentation requirements.

Effort on the technology task has involved preliminary design and analysis effort relative to the injector, igniter assembly and solid wall (uncooled) chamber.

PROGRAM DESCRIPTION

The program, which started 29 June 1971, is of 12 months duration and encompasses the analysis, design, fabrication, test, and delivery of thermal conditioners for the Shuttle APS. The end product will be a final report documenting all activity, conclusions, recommendations, etc., and the delivery of sufficient hardware to support a systems level test.

REQUIREMENTS

Requirements and operational parameters for the thermal conditioners as set forth in the Work Statement are presented in Tables I through IV.

SELECTED DESIGN CONCEPT

The baseline thermal conditioner selected to meet these requirements consists of an integral heat exchanger and reactor as shown in Fig. 1. The heat exchanger is of channel-wall construction and consists of a series of baffles or plates through which the propellant to be conditioned flows. The reactor consists of a tri-slot injector (2 fuel passages impinging on a central oxidizer passage), a cooled reactor shell (cooled with injector hydrogen), and a side-mounted spark igniter.

Standard materials and fabrication processes are used throughout and are based on Rocketdyne's extensive experience in the analysis, design, fabrication, and test of non-tubular bell thrust chambers and annular chamber (aerospike) segments.

Table I

Thermal Conditioner Operating Requirements

- Simultaneous or Individual Operation
- Unlimited Duty Cycle
- 1/2 to 1-1/2 sec precondition time (receive same signal as pump section)
- Provide Conditioned Fluid Within 1/2 Second After Flow Started
- Cease to Produce Conditional Fluid Within 1/2 Second After Flow Terminated
- Hot Gas Flow Only - No Damage or Life Degradation
- Cold Propellant Flow Only - No Damage a Life Degradation
- Outer Surface Temperature 600°F Maximum (even with double failure)

Table II

Design Requirements & Goals

Minimum Weight - Hardware Plus Reactant

Long Life - 100 missions over 10 years

Standard Materials and Manufacturing Processes Where Possible

Realistic Design Specifications

FMEA on Hardware Designs

Hazard and/or Safety Features Outlined

Special Operating Procedures and/or Support Hardware Defined

Table III

Operating Parameters - Cold Gas Section

PARAMETER	OXYGEN	HYDROGEN
Temperature, R		
Inlet	160 to 200	40 to 70
Outlet	375 to 425	200 to 250
Pressure, psia		
Inlet		
Nominal	1600 (@ 15.6 lb/sec)	1600 (@ 4.5 lb/sec)
Minimum	1100 (@ 21.0 lb/sec)	1100 (@ 5.95 lb/sec)
Maximum	2100 (@ 11.5 lb/sec)	2100 (@ 3.0 lb/sec)
Outlet		
Nominal	1500 (@ 15.6 lb/sec)	1500 (@ 4.5 lb/sec)
Flowrate, lb/sec		
Nominal	15.6	4.5

Table IV

Operating Parameters - Hot Gas Section

Propellants	O_2/H_2
Mixture Ratio	As required
Inlet Pressure, Psia	
Steady State	375 ± 10%
Start Up (Ignition)	375 ± 20%
Inlet Temperature, R	
Oxygen	375-600
Hydrogen	275-600
Nominal Values (Test Conditions)	
Inlet Pressure, psia	375
Inlet Temperature, R	530

Further, the baffle-type conditioner with integral reactor and heat exchanger has been demonstrated on a company-funded program. On this program, a single baffle conditioner was designed, fabricated and hot-fire tested to demonstrate heat exchange capability and feasibility of the design concept.

PROGRAM PROGRESS

A narrative description of program progress on the Shuttle APS Propellant Thermal Conditioner Study (NAS 9-12046) is presented in the following pages.

WORK BREAKDOWN STRUCTURE

In compliance with the Work Statement, all effort is being accomplished under the following work breakdown structure (WBS):

01XXX	Design Configuration Analysis
02XXX	Design Conditioning Units
03XXX	Manufacturing
04XXX	Test
05XXX	Reporting
06XXX	Technology Development
07XXX	Program Management

A further subdivision of the WBS to delineate specific tasks within each major subdivision of work is shown in Fig. 2 . The schedule as well as the description of progress and planned effort narratives presented in subsequent pages is keyed to the WBS for easy reference.

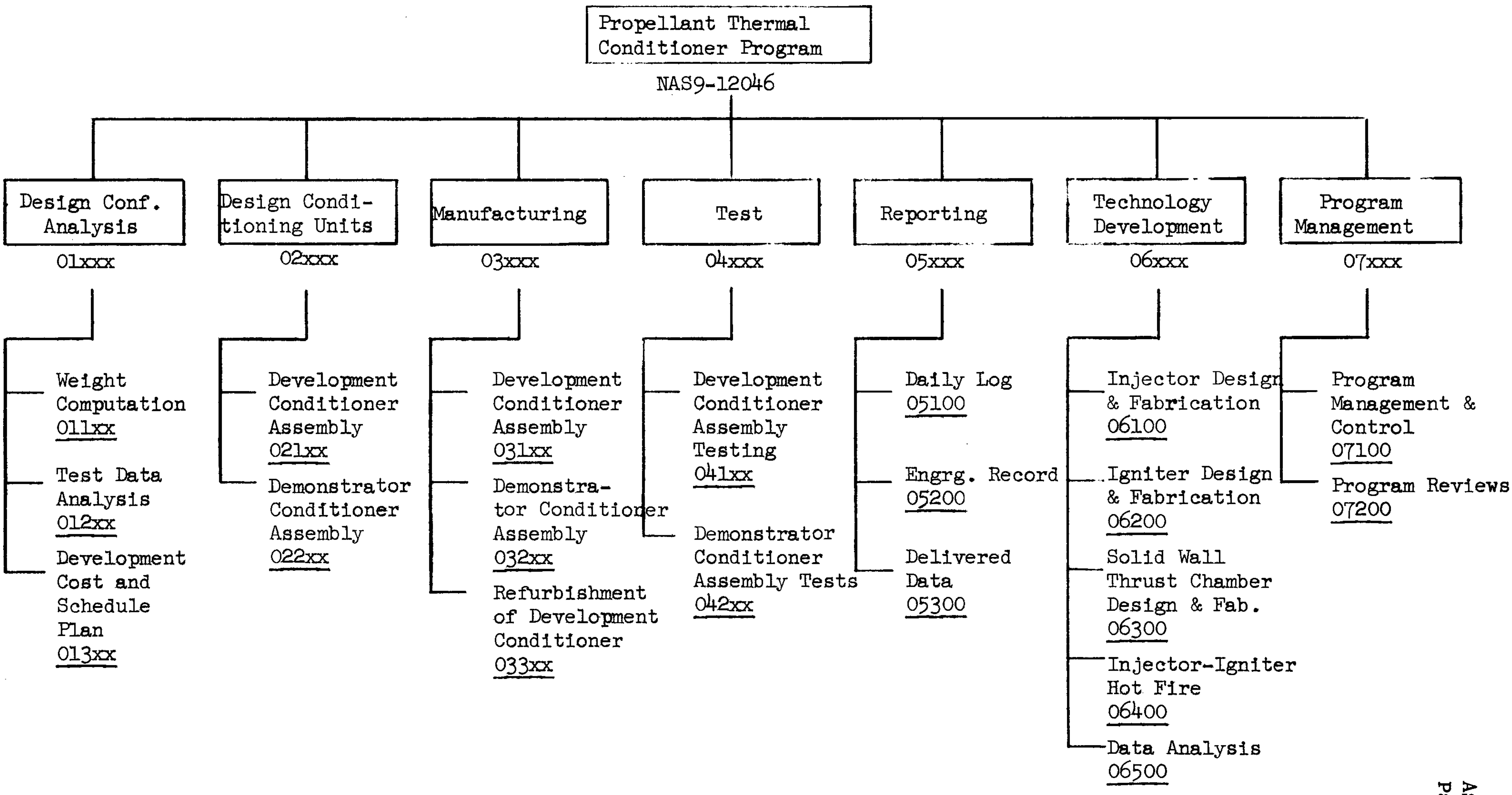


Figure 2. Work Breakdown Structure

SCHEDULE

The program schedule which has been established consistent with the program goals and the WBS presented earlier is given in Fig. 3. Major milestones, as well as the required time phasing of the specific tasks of this program are also reflected on this figure.

DESIGN CONFIGURATION ANALYSIS (01XXX)

The objective of this task is to study the conditioner design concept selected to meet the requirements set forth previously in Tables I through IV. The analysis is to be done on a system which delivers 5000 pounds of H_2 and O_2 at o/f = 3.5. Results are to include a graph of total weight (hardware plus reactant) vs reactant exhaust (or dump) temperature. This effort is to include thermal, structural and cyclic life analyses in sufficient depth to be used in making the selection of a configuration for further detail design, manufacture and test.

The analysis completed during the past month is included in the following paragraphs.

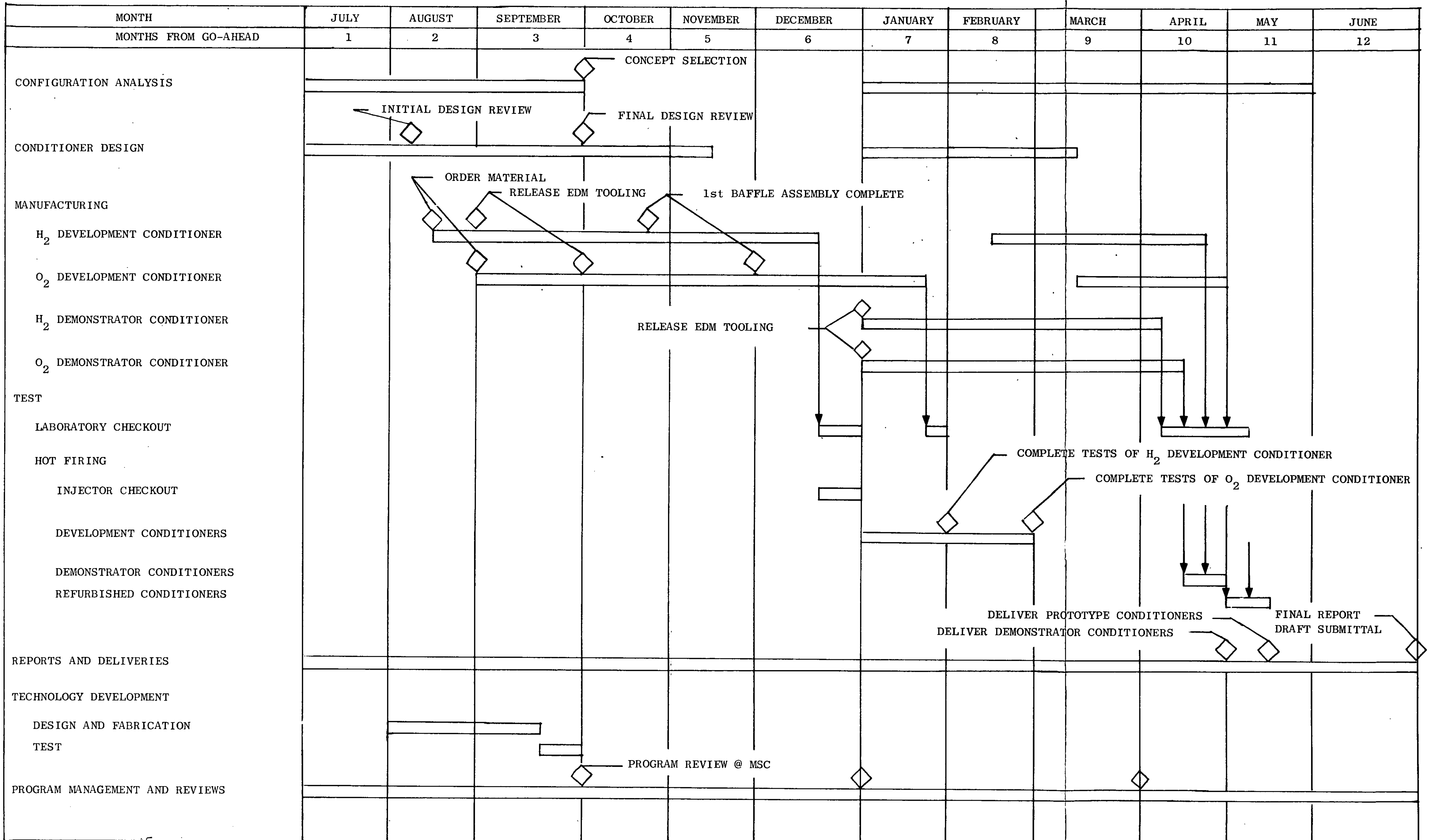
<u>Heat Transfer Analysis</u>

Presented in this section is a summary of the past month's activity relative to the thermal analysis of the baffle-type conditioners. A discussion of the computer program used for this analysis is presented in Appendix B.

FIGURE 3
PROGRAM SCHEDULE

SHUTTLE APS PROPELLANT THERMAL CONDITIONER STUDY

NAS9-12046



FOLDOUT FRAME 1

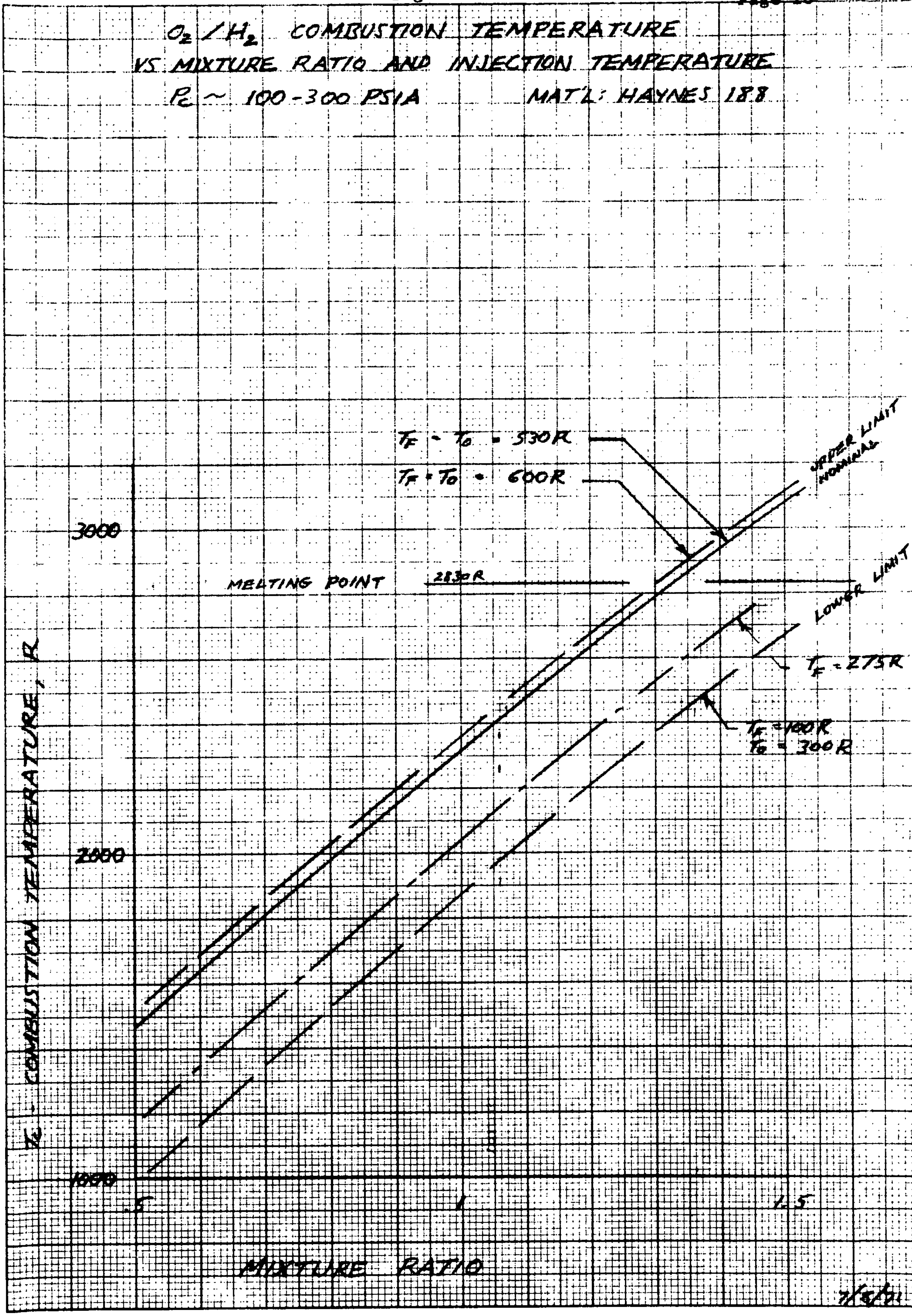
FOLDOUT FRAME 2

Mixture Ratio Selection. Selection of the hot gas mixture ratio is based on the requirement that no damage or life degradation result if either hot gas or cold flow is not initiated.[1] Superimposed on this is the requirement that the conditioner be capable of accommodating a situation where full hot gas flow is experienced with a long delay in achieving cold flow, i.e., the heat exchanger baffles are heated to a temperature equal to the combustion temperature and then cold flow at full pressure is realized. This dictates that the gas steady-state combustion temperature cannot exceed the maximum allowable uncooled steady-state wall temperature of the heat exchanger baffles. This maximum temperature for Haynes 188 (the selected heat exchanger material) is about 2100 F. A discussion of the rationale used to select Haynes 188 for the heat exchanger baffles is presented in a subsequent section. Combustion temperature as a function of mixture ratio and hydrogen injection temperature is shown in Fig. 4. At the low mixture ratios under investigation, the oxygen injection temperature has negligible effect on the combustion temperature. Another restraint initially placed on the mixture ratio selection is that the maximum combustion temperature should not be exceeded with a ± 10 percent control tolerance on mixture ratio. Subsequent analysis will explore the system benefits of a tighter control on mixture ratio. For the analysis, a nominal mixture ratio of 1.0 has been selected, giving the combustion temperature range shown below:

Mixture Ratio	0.9	1.0	1.1
H_2 injection T = 275 R (nom.)	1430 F	1580 F	1740 F
T = 600 R (max.)	1740 F	1900 F	2060 F

(1) It is noted that with the unique flow ladder sequence used in the design concept, this can only occur after a double failure (i.e., oxidizer flow control valve must fail open and pump system must fail to deliver cold propellant.

Figure 4


O2 / H2 COMBUSTION TEMPERATURE
VS MIXTURE RATIO AND INJECTION TEMPERATURE
Pc ~ 100-300 PSIA
MAT'L: HAYNES 188
TF = TO = 530R
TF = TO = 600R
UPPER LIMIT
NOMINAL
MELTING POINT
2830 R
LOWER LIMIT
TF = 275R
TF = 160R
TO = 300R
3000
2000
1000
.5
1
1.5
Tc - COMBUSTION TEMPERATURE, R
MIXTURE RATIO
7/8/71

Selection of a nominal mixture ratio of 1.0 results in a nominal combustion temperature of 1560 F and a maximum combustion temperature with maximum hydrogen inlet temperature of 2060 F--about 300 F under the melting point of Haynes 188. This is considered an acceptable design point.

As noted previously, the development conditioners are to be tested with ambient temperature propellants. As is shown in Fig. 4 , testing with hydrogen at 530 R results in a combustion temperature approximately 250 degrees higher than that experienced with 275 R hydrogen when operating at the same mixture ratio and chamber pressure.

Therefore, two possibilities exist for selecting the mixture ratio for the development conditioners--the same mixture ratio or the same nominal combustion temperature can be maintained. If the same nominal temperature is maintained, the resulting mixture ratio and combustion temperatures are:

Mixture Ratio	0.75	0.83	0.91
H_2 injection temperature = 250 R	1150 F	1290 F	1420 F
= 530 R	1440 F	1560 F	1700 F
= 600 R	1490 F	1620 F	1750 F

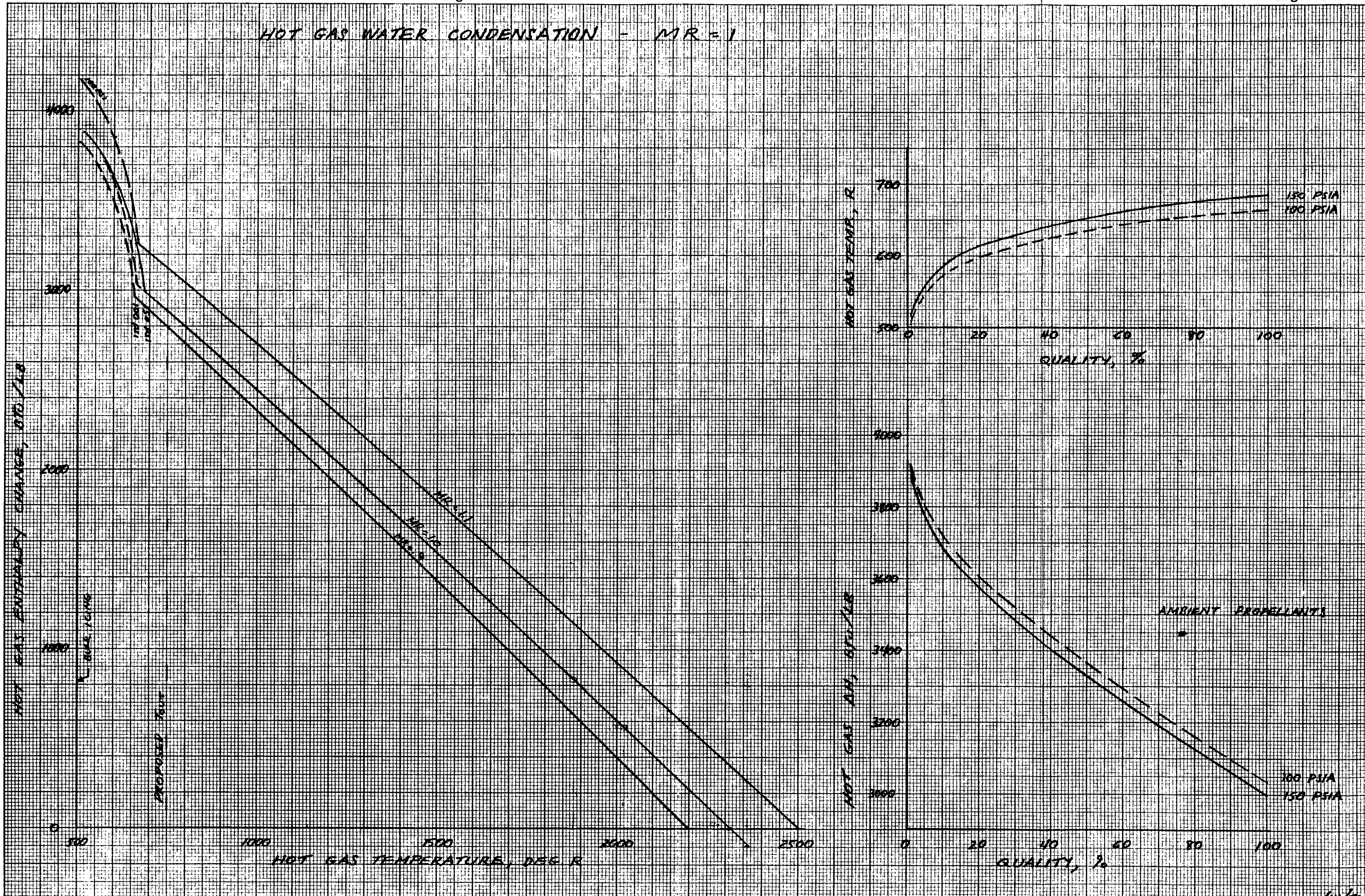
Evaluation in this area is continuing and a selection of test conditions will be made in the near future.

<u>Hot Gas Flow Requirements.</u> The hot gas flow requirements are determined by the conditioned propellant flowrate and enthalpy rise as well as by the hot gas injection temperature, mixture ratio, and outlet temperature. The hot gas

enthalpy change as a function of temperature and mixture ratio is shown in Fig. 5 over the range of interest. Below 700 R, water condensation occurs, resulting in a steeper slope to the enthalpy curve. The effect of the hydrogen injection temperature on the hot gas flow requirements is shown in Fig. 6. For example, a hydrogen injection temperature of 100 R requires about 50 percent more flow than with 600 R hydrogen, whereas 275 R hydrogen only requires about 30 percent more hot gas flow. For a 750 R outlet temperature and a 275 R hydrogen injection temperature, the required hot gas flow is about 21 percent of the hydrogen flow.

The effect of the hydrogen enthalpy band specified (40 R - 70 R inlet, 200 R - 250 R outlet) is shown in Fig. 7 . The effect of hydrogen pressure is small; however, the difference between the minimum and maximum hydrogen temperature rise is about an additional 50 percent in hot gas flowrate. Due to the large differences involved, it was decided to base the heat input requirements on the nominal hydrogen flowrate of 4.5 lb/sec and the average enthalpy change of the hydrogen; the result is a required heat input of 2800 Btu/sec. A total nominal duration of 250 seconds was determined based on the average hydrogen flowrate and the total hydrogen to be conditioned of 1110 pounds. The resulting required total reactor propellant requirements are shown in Fig. 8 as a function of reactor discharge temperature, mixture ratio, and hydrogen injection temperature. The biggest gain in reactor propellant savings occurs by dropping the hot gas outlet temperature to 800 R; another gain occurs around 700 R when condensation occurs. Around 700 R discharge temperature, an increase in mixture ratio of 0.1 results in a propellant savings of 30 pounds with 275 R hydrogen and 15 pounds with 600 R hydrogen. This is equivalent to dropping the discharge temperature from 800 R to 700 R. These weight savings are offset by the increase in conditioner weight as the discharge temperature decreases.

Figure 5



FOLDOUT FRAME 1

FOLDOUT FRAME 2

Figure 6

HOT GAS FLOW REQUIREMENTS - H_2 CONDITIONER

$MR = 1$, $70R < T_{H_2} < 200R$, $P_{H_2} = 1600$ PSIA

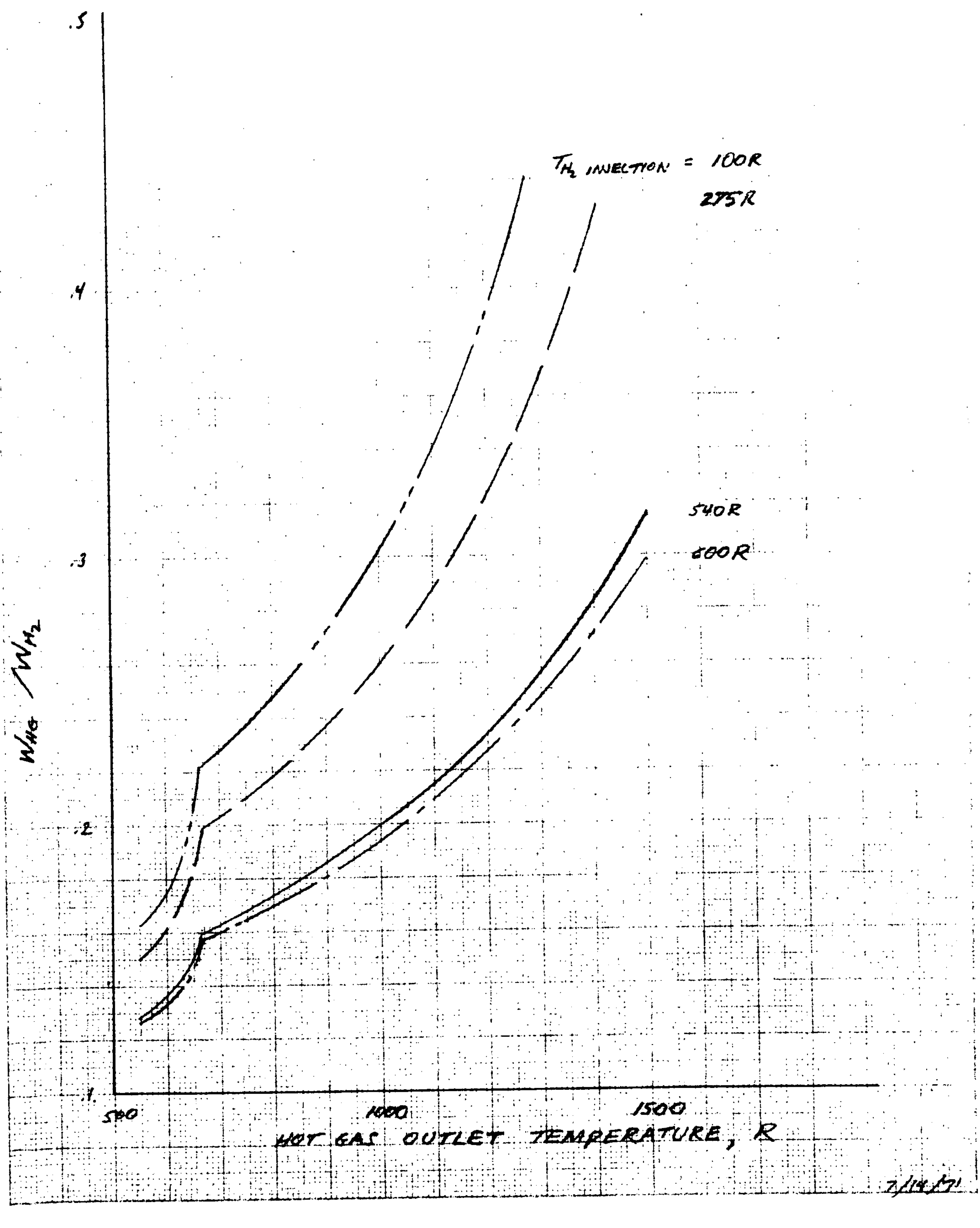


Figure 7

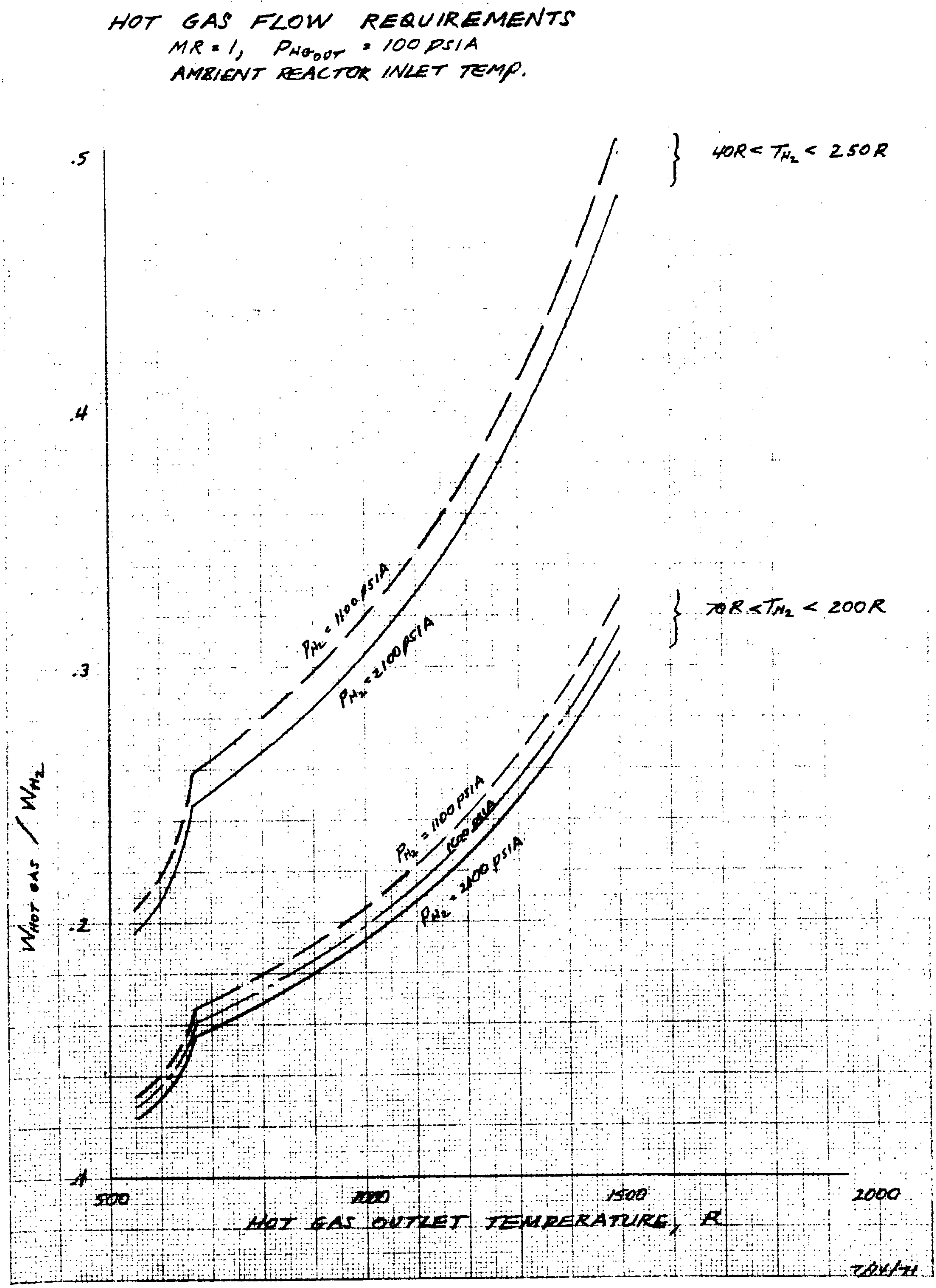
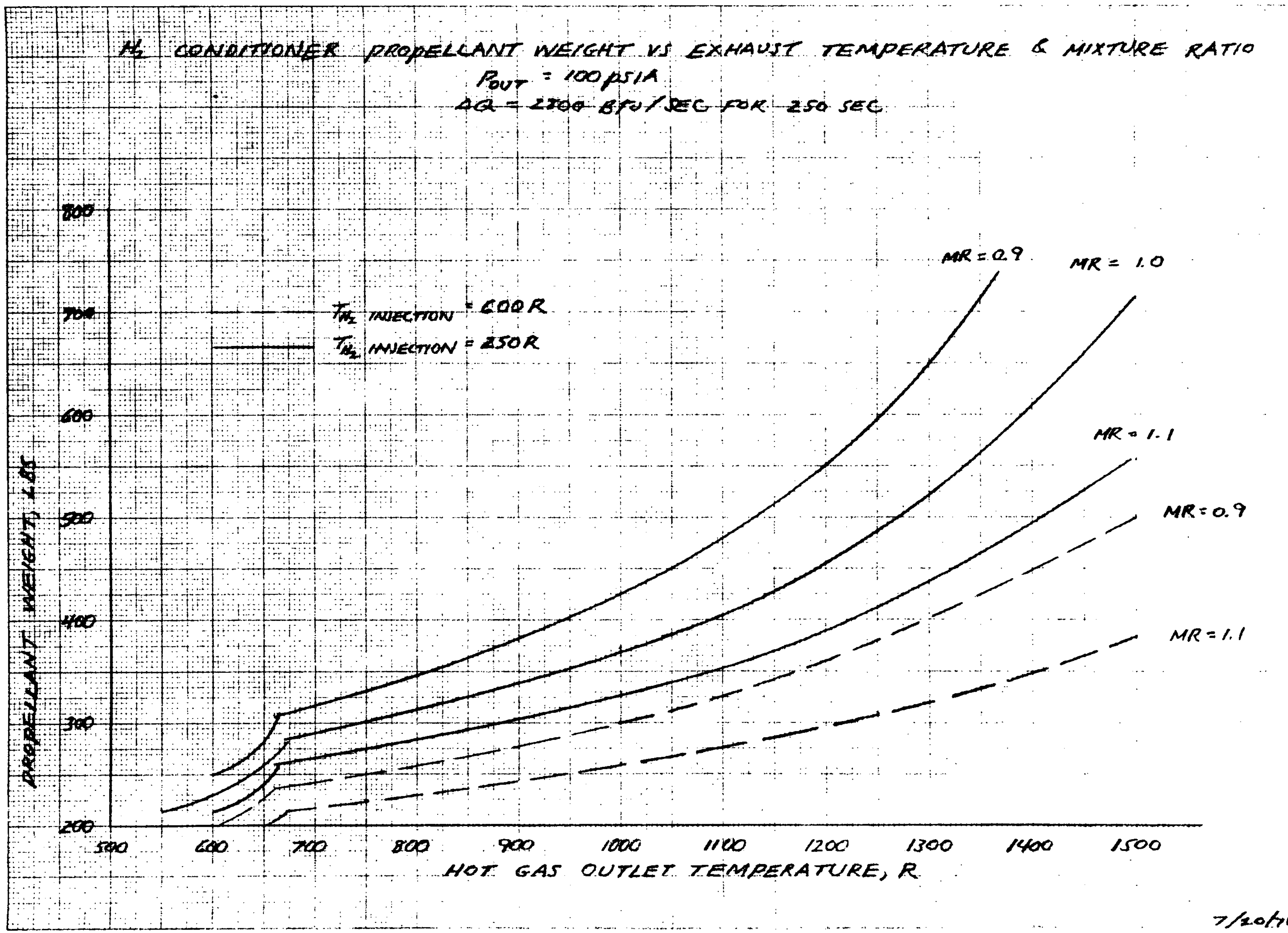

HOT GAS FLOW REQUIREMENTS
MR = 1, $P_{HG_{OUT}}$ = 100 PSIA
AMBIENT REACTOR INLET TEMP.
40R < T_{H_2} < 250R
70R < T_{H_2} < 200R
P_{H_2} = 1100 PSIA
P_{H_2} = 2100 PSIA
P_{H_2} = 1100 PSIA
P_{H_2} = 2100 PSIA
.5
.4
.3
.2
.1
500
1000
1500
2000
$W_{HOT\ GAS}$ / W_{H_2}
HOT GAS OUTLET TEMPERATURE, R

Figure 8



H2 CONDITIONER PROPELLANT WEIGHT VS EXHAUST TEMPERATURE & MIXTURE RATIO
POUT = 100 psIA
ΔQ = 2300 BTU/SEC FOR 250 SEC
TH2 INJECTION = 600R
TH2 INJECTION = 250R
MR = 0.9
MR = 1.0
MR = 1.1
MR = 0.9
MR = 1.1
PROPELLANT WEIGHT, LBS
800
700
600
500
400
300
200
500
600
700
800
900
1000
1100
1200
1300
1400
1500
HOT GAS OUTLET TEMPERATURE, R
7/20/71

It is noted that for the oxygen conditioner the propellant weight is only about 62 percent of that for the hydrogen conditioner.

Surface Area Determination. The weight of the conditioner is a function of the conditioner surface area. For an initial surface area determination, a maximum heat flux of 4.4 Btu/in^2-sec was used to meet life requirements. A maximum hot gas mass velocity of 0.88 lb/in^2-sec was assumed, based on a chamber pressure of 240 psia, a 750 R discharge temperature, and a mixture ratio of 1. In addition, a minimum wall gas side surface temperature of 525 R was assumed. The resultant surface area is based on the nominal heat input of 2800 Btu/sec. A typical curve of surface area vs hot gas exhaust temperature is shown in Fig. 9. This curve is essentially applicable for mixture ratios of 0.9 to 1.1. For hot gas exhaust temperatures in excess of 1500 R, the surface area is essentially independent of exhaust temperature since the heat flux can be maintained at a constant value by tapering the hot gas passage appropriately. For exhaust temperatures below 700 R, the hot gas temperature is approaching the minimum wall temperature (525 R assumed) with the result that the conditioner size is increasing very rapidly. For example, if the exhaust temperature is dropped from 700 R to 650 R, the size of the conditioner must be increased about 30 percent. This increase in size shows up principally as an increase in length of the conditioner.

Hot Gas Outlet Temperature Determination. As required, determination of the hot gas (reactor) outlet temperature is to be based on conditioner weight (sum of hardware and propellant weights). Results of this investigation are shown in Figs. 10 to 12 for mixture ratios of 0.9, 1.0 and 1.1, respectively. The data indicate that the minimum weight with one conditioner and 275 R hydrogen

Figure 9

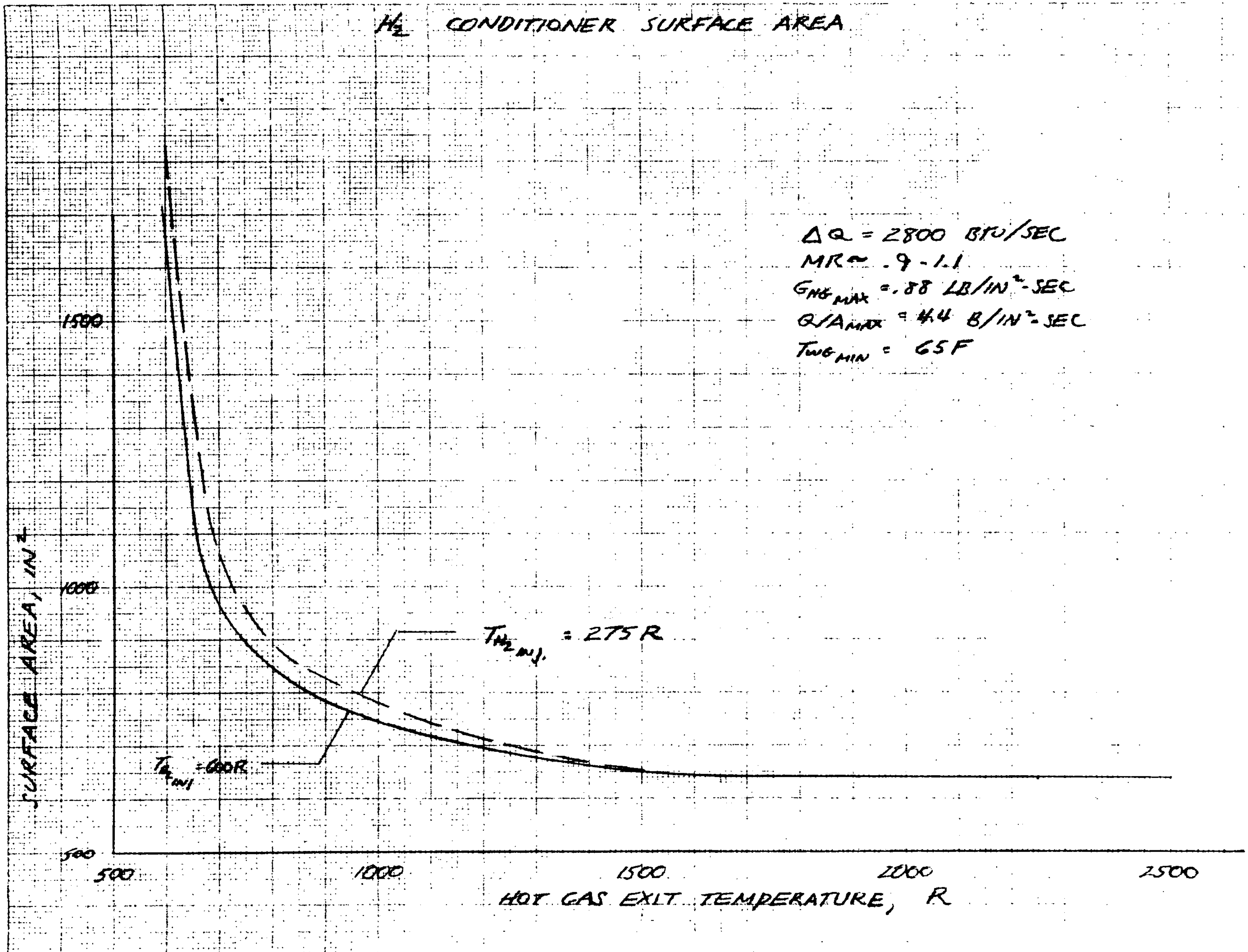


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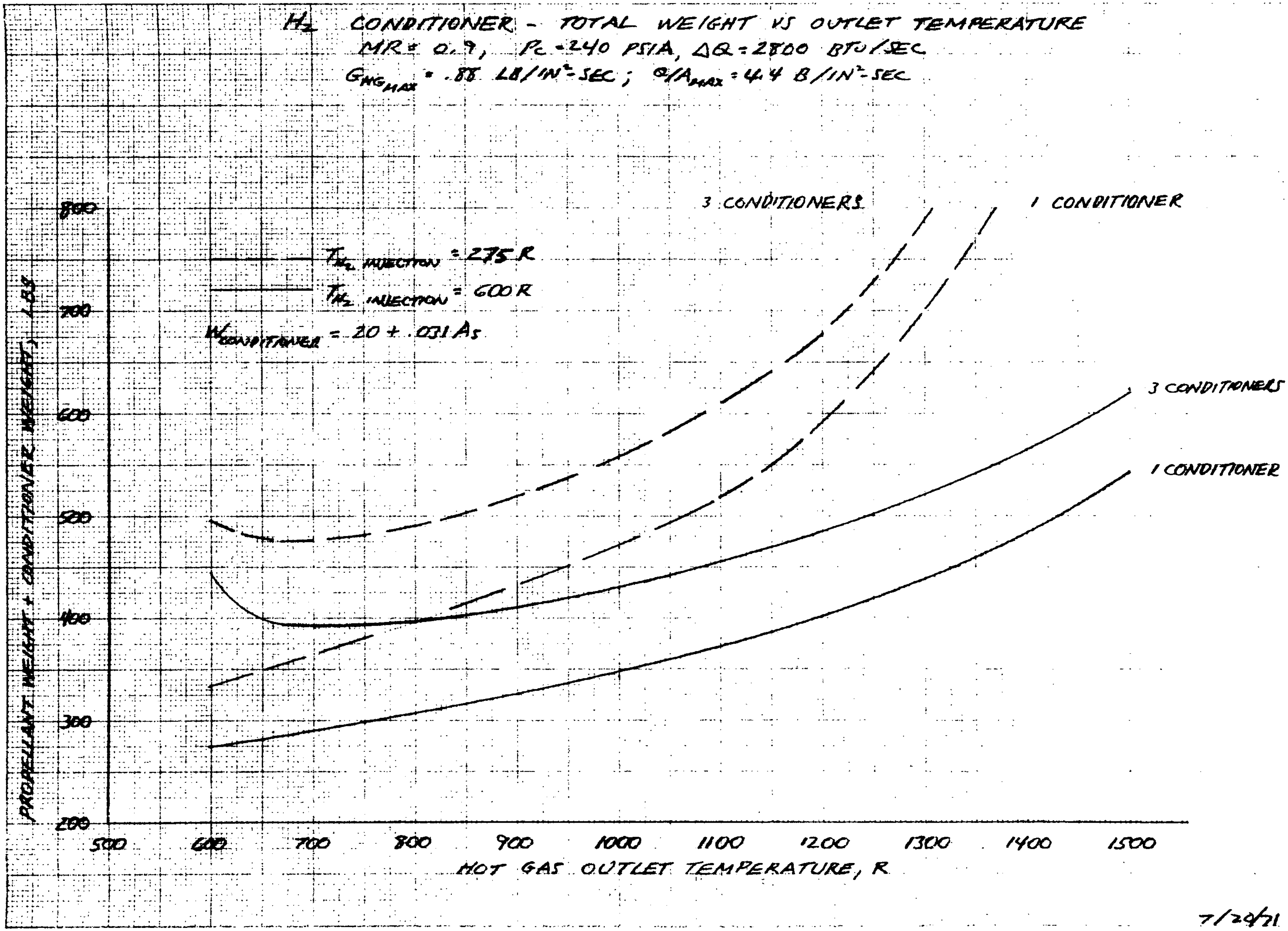
Figure 10



H2 CONDITIONER - TOTAL WEIGHT VS OUTLET TEMPERATURE
MR = 0.9, Pc = 240 PSIA, ΔQ = 2800 BTU/SEC
$G_{HG_{MAX}}$ = .88 LB/IN²-SEC; Q/A_{MAX} = 4.4 B/IN²-SEC
T_{H_2} INJECTION = 275 R
T_{H_2} INJECTION = 600 R
$W_{CONDITIONER}$ = 20 + .031 A_S
3 CONDITIONERS
1 CONDITIONER
3 CONDITIONERS
1 CONDITIONER
PROPELLANT WEIGHT + CONDITIONER WEIGHT, LBS
800
700
600
500
400
300
200
500
600
700
800
900
1000
1100
1200
1300
1400
1500
HOT GAS OUTLET TEMPERATURE, R
7/20/71

Figure 11

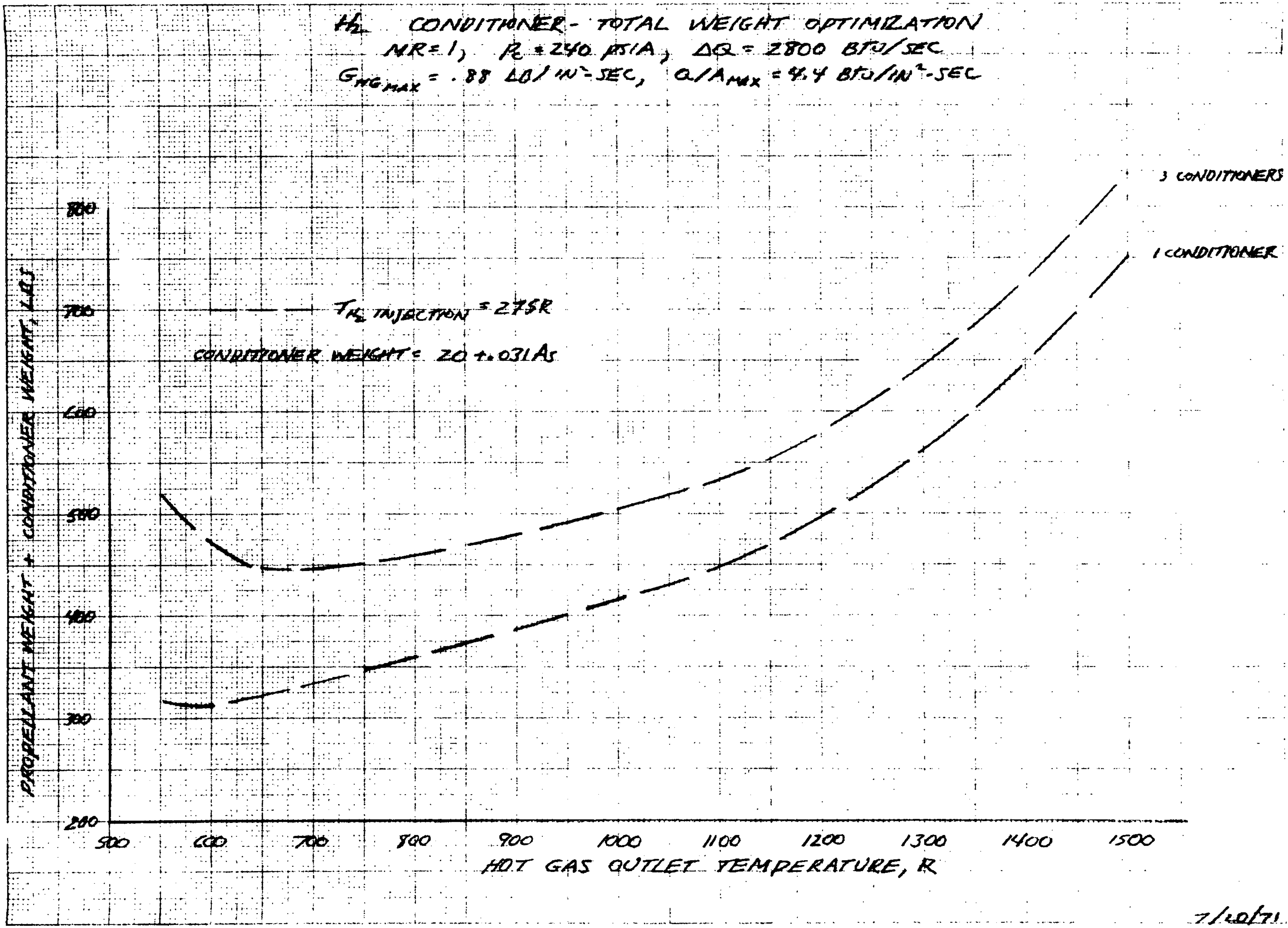


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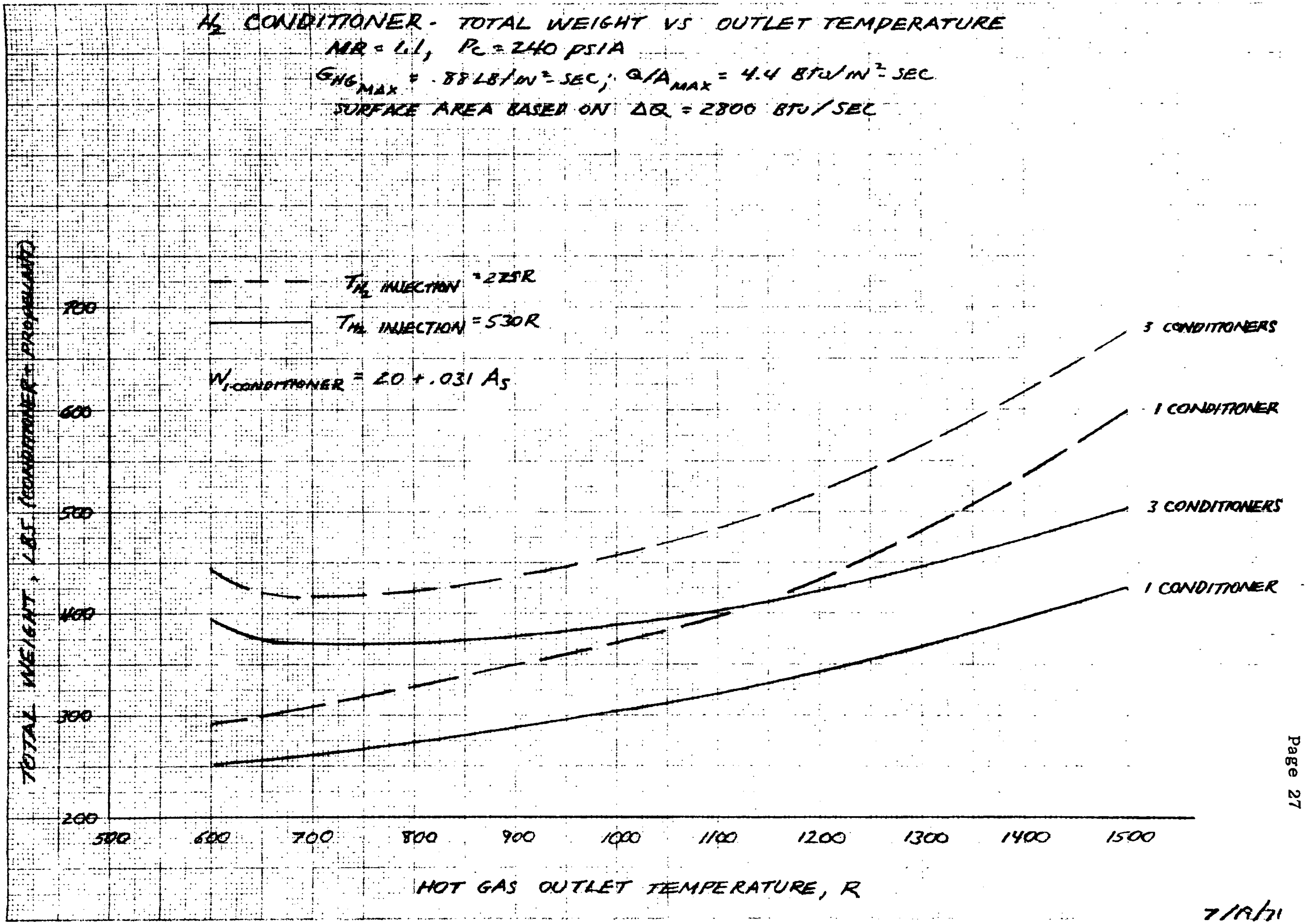
Figure 12



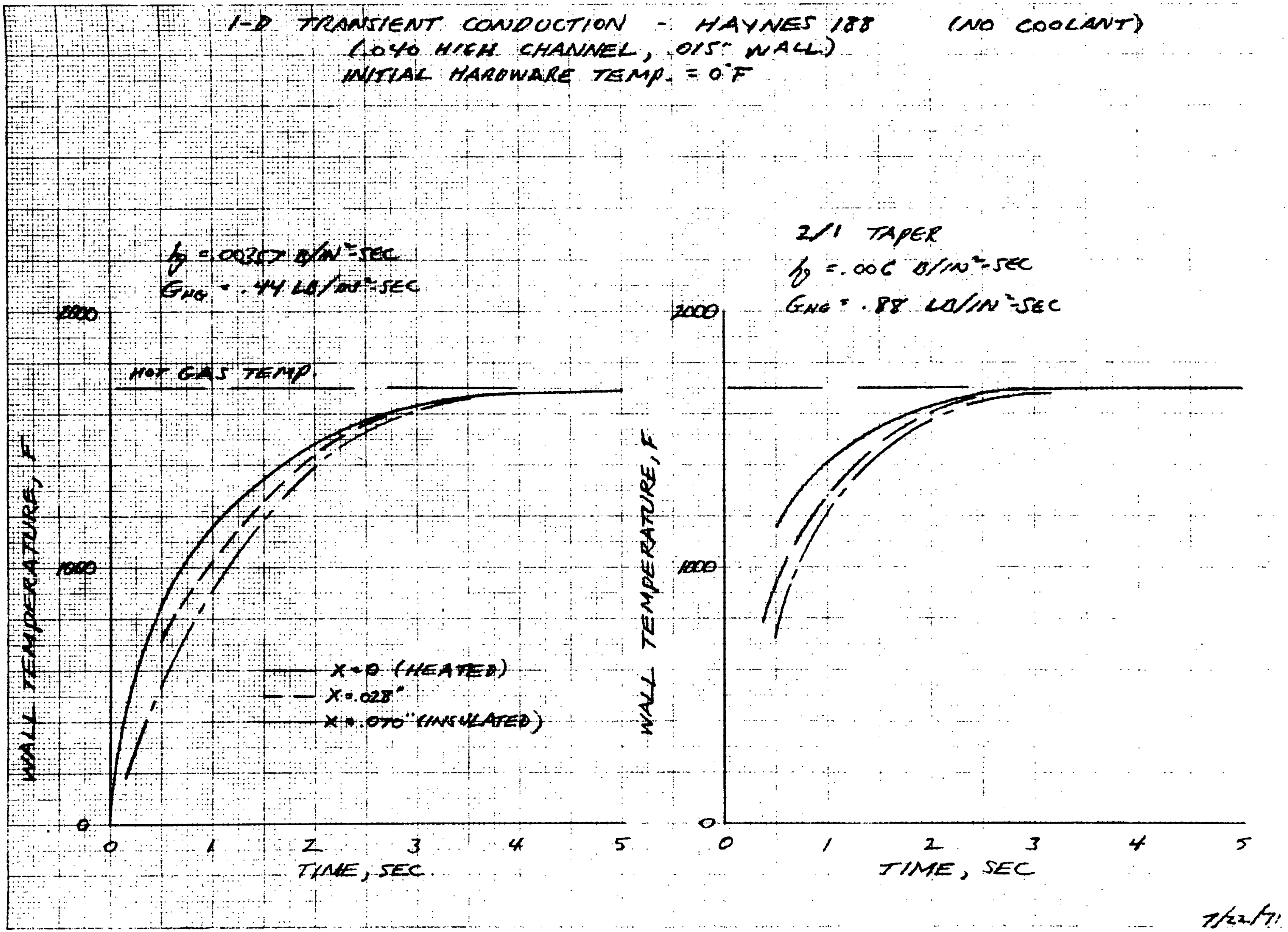
H_2 CONDITIONER - TOTAL WEIGHT VS OUTLET TEMPERATURE
MR = 6.1, Pc = 240 PSIA
$G_{HG_{MAX}}$ = .88 LB/IN² - SEC; Q/A_{MAX} = 4.4 BTU/IN² - SEC
SURFACE AREA BASED ON ΔQ = 2800 BTU/SEC
T_{H_2} INJECTION = 225R
T_{H_2} INJECTION = 530R
$W_{1\text{-CONDITIONER}}$ = 20 + .031 A_S
3 CONDITIONERS
1 CONDITIONER
3 CONDITIONERS
1 CONDITIONER
TOTAL WEIGHT, LBS (CONDITIONER + PROPELLANT)
200
300
400
500
600
700
500
600
700
800
900
1000
1100
1200
1300
1400
1500
HOT GAS OUTLET TEMPERATURE, R
7/12/71

injection temperature occurs at a hot gas exhaust temperature of about 600 R. However, if the weight is optimized based on three conditioners, the minimum weight occurs at hot gas exhaust temperatures of 650 R to 750 R. In order to keep the conditioner size as small as possible, the upper end of this band, namely 750 R, was selected for the nominal hot gas exhaust temperature. This also has the added benefit of minimizing potential freezing problems and, in addition, should result in faster response times.

A similar conclusion would be expected from the oxidizer conditioner at the same mixture ratios since both the conditioner size and the reactor propellant requirements are proportional to the amount of heat transferred.

Transient Response of Uncooled Baffles. A brief investigation of the transient response of the conditioner heat exchange baffles in a double failure mode (full hot gas flow - no cold flow) was also completed. Two locations on the baffle [leading edge and at the end of the hot gas passage taper region (about one-third of the distance aft of the leading edge)] were analyzed. A conservative approach was taken by assuming no reduction in hot gas flow and no reduction in hot gas temperature at any location as a function of time. Resultant temperature response of the gas side wall surface, the back side (insulated) wall surface, and a point about 40 percent behind the gas surface are shown in Fig. 13 for a typical cross section. This analysis indicates that the wall will reach the combustion gas temperature in 2 to 3 seconds at the worst location and approximately 4 seconds on the leading edge.

Figure 13



1-D TRANSIENT CONDUCTION - HAYNES 188 (NO COOLANT)
(.040 HIGH CHANNEL, .015" WALL)
INITIAL HARDWARE TEMP. = 0°F
GHG = .44 LB/IN²-SEC
HOT GAS TEMP.
2000
1000
0
WALL TEMPERATURE, F
X = 0 (HEATED)
X = .025"
X = .070" (INSULATED)
0
1
2
3
4
5
TIME, SEC
2/1 TAPER
hg = .006 B/IN²-SEC
GHG = .88 LB/IN²-SEC
2000
1000
0
WALL TEMPERATURE, F
0
1
2
3
4
5
TIME, SEC
7/22/71

<u>Hydrogen Baffle--Preliminary Design</u>. The first step in determining the hot gas and coolant passage geometry, assuming that the hydrogen flowrate and heat input requirements have been determined, as well as the hot gas mixture ratio, inlet and outlet temperatures is to analyze two dimensional cross sections of the conditioner to determine conditions which will meet the life requirement and which will avoid ice formation on the wall while minimizing weight and pressure drop.

For this purpose, the nominal design point is summarized in Table V . Hot gas heat transfer coefficients are based on the Bartz simplified pipe flow equation:

$$N_{NU} = 0.025\, N_{RE}^{.8}\; N_{PR}^{.4}\, \sigma$$

where

$$\sigma = \left[.5\, \frac{T_{WG}}{T_{AW}} \left(1 + \frac{\gamma - 1}{2} M^2\right) + .5\right]^{-.68} \left[1 + \frac{\gamma - 1}{2} M^2\right]^{-.12}$$

The hydrogen heat transfer coefficients are based on a Rocketdyne-modified form of the Dipprey-Sabersky equation:

$$C_H = \frac{h(T_W/T_B)^{.55}}{G\, C_p} = \frac{C_{f/2}}{.92 + (C_{F/2})^{.5}\, [g\,(\epsilon *) - 8.48]}$$

where

$$g\,(\epsilon *) = 4.7\,(\epsilon *)^{.2} \qquad (\epsilon * > 7)$$

$$g\,(\epsilon *) = 4.5 + .57\,(\epsilon *)^{.75} \qquad (\epsilon * \leq 7)$$

$$\epsilon * = (\epsilon / D) N_{RE}\, (C_{f/2})^{.5}$$

TABLE V

NOMINAL DESIGN POINT - H_2 CONDITIONER

H_2 SIDE

$\dot{W}$	=	4.5 lb/sec
P_{in}	=	1600 psia
P_{out}	=	1500 psia
T_{in}	=	55° R
T_{out}	=	225° R
ΔQ	=	2800 Btu/sec

HOT GAS SIDE

Mixture Ratio	= 1.0
H_2 Injection Temperature	= 275° R
Chamber Pressure	= 240 psia
Combustion Temperature	= 2040° R
Exhaust Temperature	= 750° R
Combustion Efficiency	= 100 percent
Hot Gas Flowrate	= 1.2 lb/sec
Design Mixture Ratio Tolerance	= ±10 percent
Maximum Heat Flux	~ 4 Btu/in^2-sec
Min. Gas Side Wall Surface Temp.	~ 530° R
Min. Hot Gas Passage Width	= 0.050 in.

WALL MATERIAL

Haynes 188 - Hot Gas Wall and Lands
Stainless Steel - Closeout
  Min. Land Width 0.035 - 0.040 in.
  Constant Plate Thickness (gas wall + land)
  Constant Channel Width

Both of the above correlations gave good agreement with experimental data obtained from the single baffle hydrogen conditioner recently tested.

The analysis is based on a Haynes 188 baffle with a stainless steel closeout. The hot gas wall thickness of 0.015 inch was assumed reasonable to manufacture while permitting reasonable channel geometries. Based on the fail-safe requirements, the channel width (coolant channel) was limited to no greater than 5.3 times the gas wall thickness, taking into account the high temperature capability of Haynes 188. Since the thermal conductivity of Haynes 188 is a strong function of temperature, the temperature variation is included in the analysis.

Structural Analysis

Effort on this task during the past month has been concerned with:

(1) Establishing design criteria,

(2) Evaluating candidate materials, and

(3) Generating parametric cyclic life data for use in the thermal analysis.

Results to date are summarized below while a complete copy of all criteria, computations, etc., is given in Appendix A.

Design Criteria. The structural criteria set forth for each component includes a yield safety factor of 1.1 and an ultimate safety factor of 1.4, using minimum guaranteed material properties.

Rocketdyne's approach to evaluating the cyclic life capability of long life components is predicted on the fundamental theory that failure depends on the accumulation of creep damage and fatigue damage.

The life analysis is based on a definition of the stress-strain-time-temperature history during each operating cycle. Creep damage is evaluated from the stress-time-temperature cycle and fatigue damage from the strain-time-temperature cycle.

The increment of creep damage, $\Delta \phi_c$, is determined by the ratio of time spent at a particular stress level, t, to the time-to-rupture at that stress level, t_r

$$\Delta \phi_c = \Sigma \left(\frac{t}{t_r}\right) \sigma$$

$\Delta \phi_c$ = creep rupture damage

t = time at stress, σ

t_r = time to rupture at the stress, σ

The total creep damage, ϕ_c, is given by:

$$\phi_c = \Sigma \Delta \phi_c$$

Fatigue damage, ϕ_c, is determined by the ratio of the actual number of cycles (starts and stops) applied at a particular strain range to the number of cycles which would cause failure at that strain range.

$$\phi_f = \Sigma \frac{n}{N_f}$$

In the absence of experimental fatigue data on the material of interest, the Method of Universal Slopes is used to obtain isothermal fatigue design values for cycles to failure.

The method is given by:

$$\epsilon_t = 3.5\left(\frac{F_{tu}}{E}\right) N_f^{-.12} + D^{.6} N_f^{-.6}$$

where

ϵ_t = total calculated strain range

F_{tu} = material ultimate strength

E = Young's Modulus

D = Fracture Ductility, Ln $\left[\frac{100}{100-RA}\right]$

RA = percent reduction-in-area

The basic properties are used at the temperature of interest while the straining process with varying temperature is considered incrementally. Cyclic life for the strain range is based on values for F_{tu}/E and RA obtained over the temperature range of the strain cycle.

Ultimately this is replaced by isothermal fatigue data generated on the material(s) of construction over the predicted temperature and strain range. A plot of fatigue life vs temperature for the specific strain range of interest is the key element in the incremental technique. The number of allowable cycles, N_f, for the strain range, ϵ_t, is determined by graphically averaging the value of N_f over the operating temperature range.

A generalized life equation is used to consider the total damage caused by the interaction of low and high cycle fatigue and creep rupture.

The equation takes the following form:

$$4\ \phi_{fL} + 4\phi_c + 10\ \phi_{fH} = 1.0$$

where

ϕ_{fL} = low cycle fatigue damage

ϕ_c = creep rupture damage

ϕ_{fH} = high cycle fatigue damage

Safety Factor = 4 on low cycle fatigue and creep rupture
= 10 (on high cycle fatigue)

Evaluation of Candidate Materials. To maximize cyclic life capability of the conditioner heat exchanger baffles, it is desirable to evenly distribute the thermal strains in the hot gas wall and the closure. Since the hot gas wall will operate at a temperature level of several hundred degrees while the closure operates at a temperature nearly equivalent to the propellant bulk temperature, it is appropriate to use dissimilar materials on the two surfaces with the weaker material used as the closure. Analysis (see Appendix A) has shown that use of Haynes 188 or the Armco alloys 21-6-9 or 22-13-5 on the hot gas wall in conjunction with 304L or 347 stainless steel on the closure offers a good combination from a cyclic life standpoint (Table VI). The allowable strains are relatively close and can be made nearly equal by selective variation of the appropriate wall thickness as operating temperatures become finalized. Evaluation of these material combinations from a fabrication and processing standpoint (discussed in a later section) has led to the tentative selection of Haynes 188 for the hot gas wall and 304L or 347 stainless steel for the closure.

Table VI

Evaluation of Candidate Material Combinations

HOT GAS WALL MATERIAL	CLOSURE MATERIAL	TEMP F	ULTIMATE (1) STRENGTH KSI	YIELD (1) STRENGTH KSI	REDUCTION (1) OF AREA PERCENT	ALLOWABLE (2) STRAIN RANGE IN/IN
Haynes 188	-	400	123	53	57	.0054
	-	600	117	48	55	
Armco 21-6-9	-	400	90	42	65	.0048
	-	600	86	38	60	
Armco 22-13-5	-	400	101	49	64	.0053
		600	98	46	63	
-	304L SS	-300	180	45	53	.0069
		-200	154	44	56	
-	347 SS	-300	190	51	65	.0075
		-200	160	49	67	

(1) Typical material properties.

(2) Based on Universal Slopes equation, a required cyclic capability of 42,000 cycles, and a thickness of 0.015 inches

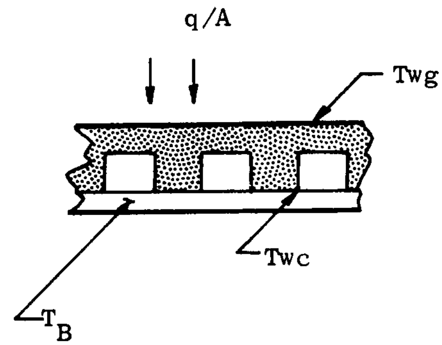
Parametric Cyclic Life Data. With the selection of the Haynes 188/stainless steel material combination, an analysis was completed to determine allowable temperatures for use in the thermal analysis. This data, shown in Fig. 14 for a life capability of 42,000 cycles, is predicted on the cyclic life ground rules and procedures summarized earlier and detailed in Appendix A.

DESIGN CONDITIONING UNITS (02XXX)

Presented in this section are the results to date related to the design of the baffle-type thermal conditioner.

Baffle Width Evaluation

Of initial interest relative to the design of the baffle-type heat exchanger to be used in the thermal conditioners is the establishment of reactor cross section (baffle width). Based on the heat transfer analysis completed to date which showed a required heat exchanger surface area of approximately 950 in.^{2}, a trade study was performed to determine the effect on conditioner cross section and weight of varying the total number of baffles used in the hydrogen conditioner. Results, shown in Table VII, combined with the sample fabrication effort discussed later, have led to the decision to use five baffles in the conditioner. The surface area of these five baffles combined with the reactor wall heat exchange area will meet the total surface area requirement listed above. Any variation in the surface area requirements that are realized due to a more detailed heat transfer analysis can be accommodated by proper adjustment of the baffle length. The same baffle width and height will be used for the oxygen conditioner with the length adjusted to accommodate differences in required surface area.



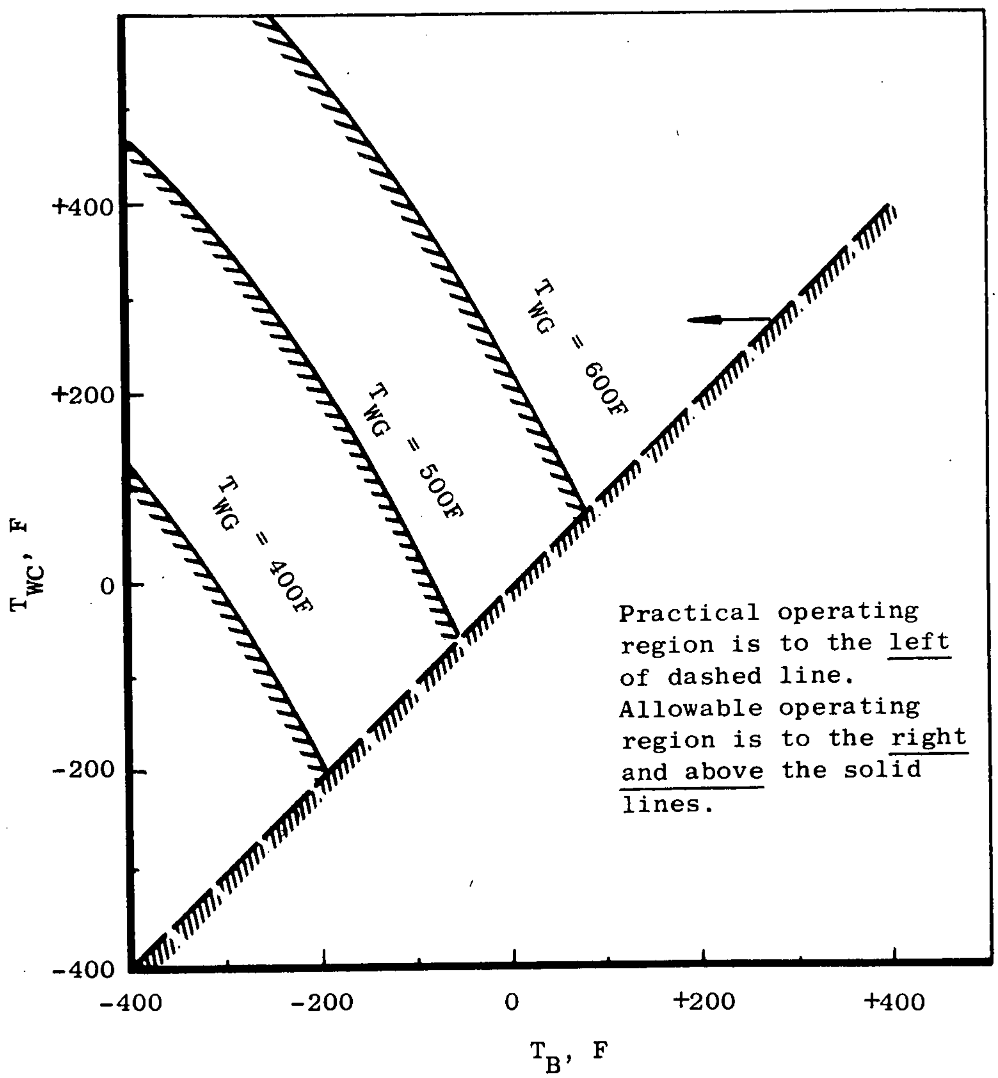


Figure 14 . Estimated Allowable Temperatures for Haynes 188 Baffles

TABLE VII

BAFFLE WIDTH EVALUATION

No. of Baffles	Baffle Length, in.	Conditioner[1] Width, in.	Baffle Width, in.	Baffle (Conditioner) Height, in.	Weight Change, lbs
3	17.3	4.25	1.30	6.60	+2
4	↓	↓	.95	5.34	+1
5	↓	↓	.74	4.47	0
6	↓	↓	.60	3.84	-1
7	↓	↓	.50	3.37	-2

(1) Included is a hot gas gap of 0.100 inch between each baffle & 0.0 75 inch between the wall and outer baffle.

Baffle Material Selection

Consideration has been given to the choice of materials to be used in fabricating the hot gas wall of the heat exchanger baffles. Materials of interest were:

Haynes 188	Armco 22-13-5
Haynes 25	A-286
Hastelloy-X	304L Stainless Steel
Armco 21-6-9	347 Stainless Steel

Selection criteria were:

1) Use of standard materials and fabrication processes
2) Fabricability (machining, furnace brazing, welding)
3) High strength and ductility at elevated temperatures (to ~2000° F)
4) High resistance to oxidization and hydrogen embrittlement.

The A-286 material has very good resistance to hydrogen embrittlement; however, it has some very undesirable features which eliminated it from consideration for this application. These features are:

1) Plating is required in a brazed structure.
2) The alloy is difficult to weld without cracking.
3) Being a precipitation hardening alloy, optimum material properties cannot be obtained when processed through a braze cycle. Reheat treatment after brazing will present a problem of distortion control.
4) The alloy would not be stable in either the annealed or heat treated condition when exposed to a potential overtemperature condition (~1700° F).

Evaluation of the other alloys based on the above criteria has led to the selection of Haynes 188 for the hot gas wall of the baffles (a comparison of material properties is given in Appendix A).

Haynes 188 is a non-hardenable cobalt base alloy which exhibits a metallurgically stable structure over a wide temperature range and for prolonged exposure time at temperature. It is currently being used in advance gas turbine designs and has been selected as a structural material in both the Space Shuttle main engine and the Space Shuttle vehicle.

Rocketdyne has evaluated the material for propellant compatibility, welding and brazing characteristics, fabricability, and has established guaranteed tensile property design values. Haynes 188 is compatible with both hydrogen and oxygen within the temperature range anticipated in the thermal conditioner. The material exhibits a high degree of resistance to high-pressure hydrogen embrittlement in both notch bar testing and low cycle fatigue testing. Laboratory tests and limited hardware fabrication have proven that Haynes 188 is weldable (GTA or EB) and brazeable to itself and to other alloys. Machining and forming of sample baffles fabricated of Haynes 188 is currently underway. Material properties are presented in Appendix A.

Material Cleaning Procedures

An investigation is currently underway to establish cleaning procedures to be applied during fabrication of the conditioner. This evaluation is concerned with two levels of cleanliness. First, a cleanliness level must be established which will provide a good braze or weld joint and, secondly, a cleanliness level must be established for the completed unit which is compatible with the overall shuttle propulsion system. Results of this evaluation will be used to prepare a process specification for the conditioner units.

MANUFACTURING (03XXX)

As previously mentioned, the overall objective of this program is to design, manufacture, and test hydrogen and oxygen conditioners to meet the requirements of the Space Shuttle propulsion system. In addition to meeting the functional requirements of the Space Shuttle system, the conditioners should also meet the objectives of reliability, safe operation, low weight, small envelope, ease of manufacture, and low cost. Manufacturing effort planned around these goals and currently underway includes: (1) preparation of detail fabrication process flow charts and (2) fabrication of appropriate samples.

The fabrication process flow charts (Figs.15 thru 18) have been prepared and are undergoing detail evaluation with manufacturing personnel to define procedures, tooling requirements and critical fabrication and processing items. These results are currently being used to define suggested design modifications and necessary fabrication development samples. A typical example of this is the fabrication of sample heat exchanger baffles manufactured using the procedures planned for the full-size baffles (Fig. 19).

Here a flat plate of Haynes 188 was slotted by the EDM process to dimensions typical of the baffle for the hydrogen conditioner. Subsequently, a Haynes 188 closure was brazed in place and the flat panel successfully leak-checked and proof pressure tested. Subsequently, sections of this panel were formed into the "U" shape

FABRICATION SEQUENCE

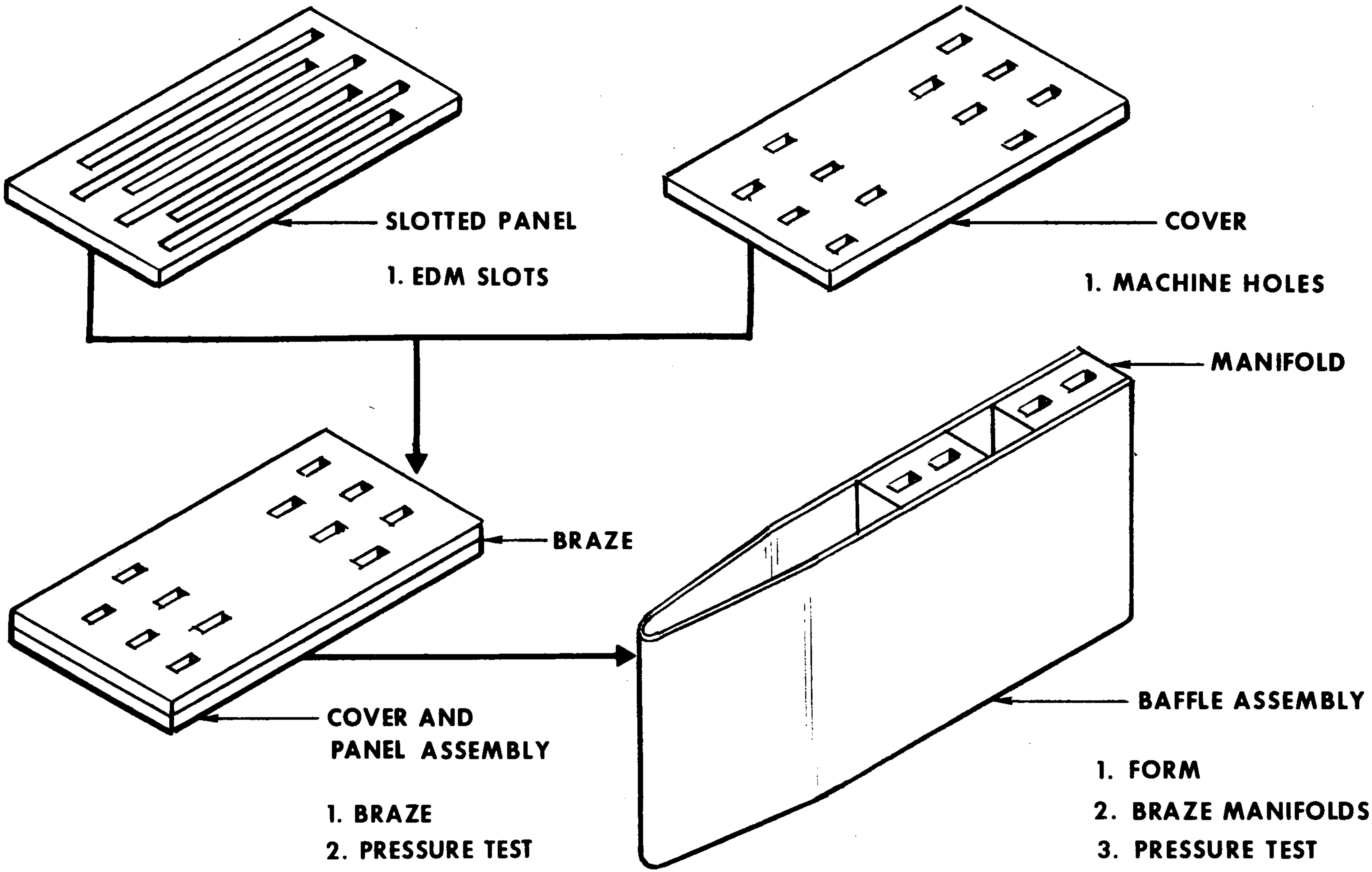


Figure 15

FABRICATION SEQUENCE CONTINUED

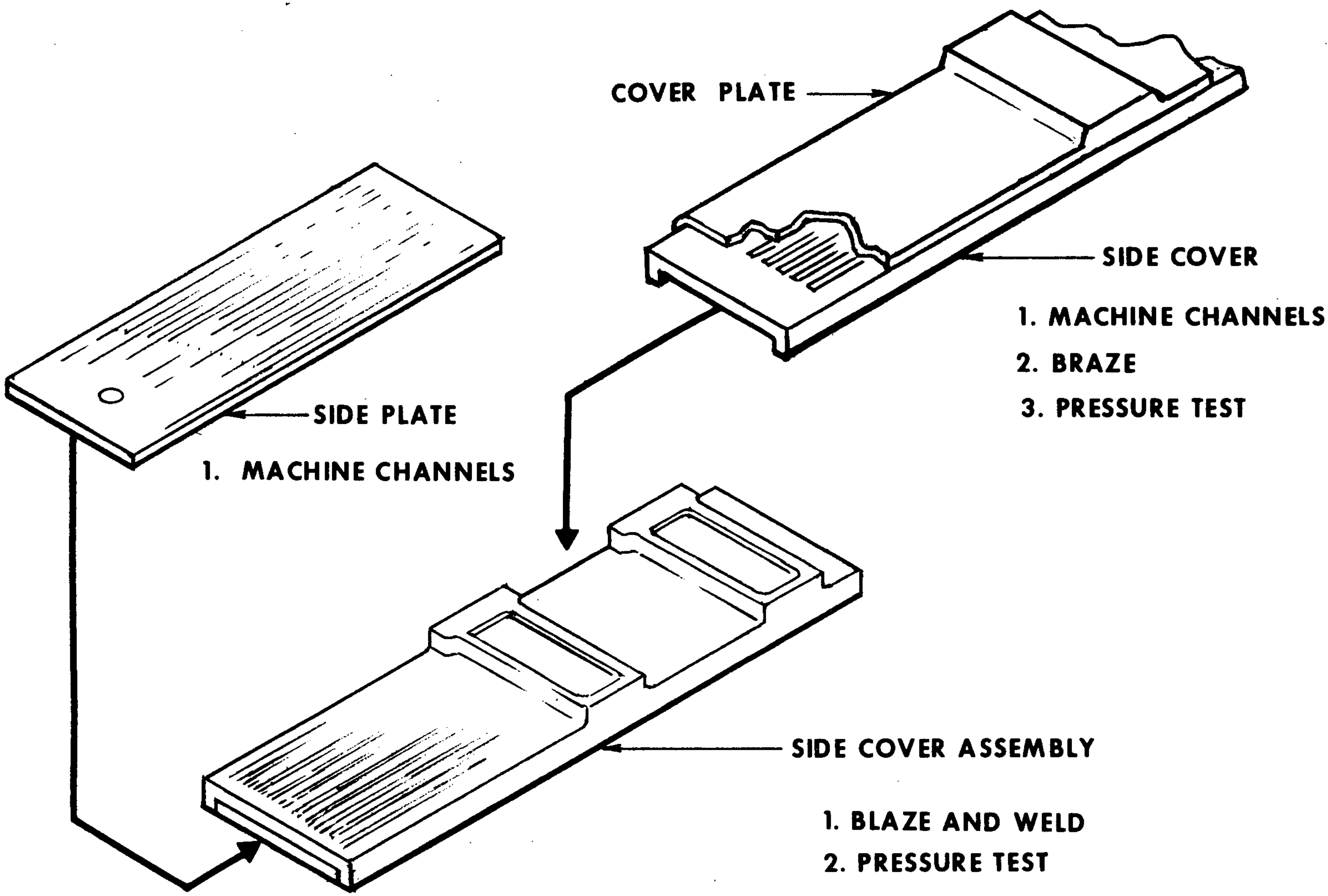


Figure 16

FABRICATION SEQUENCE CONTINUED

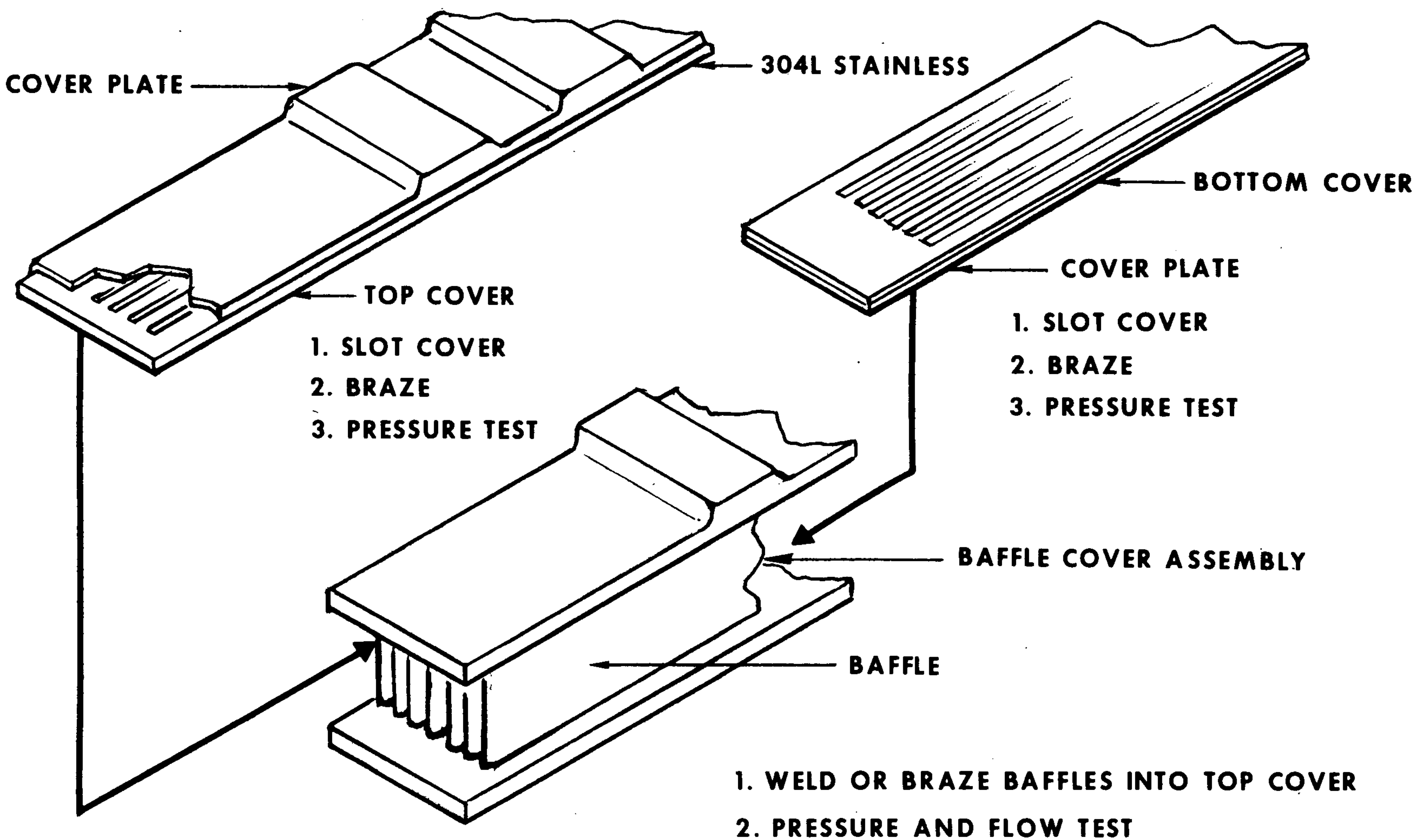
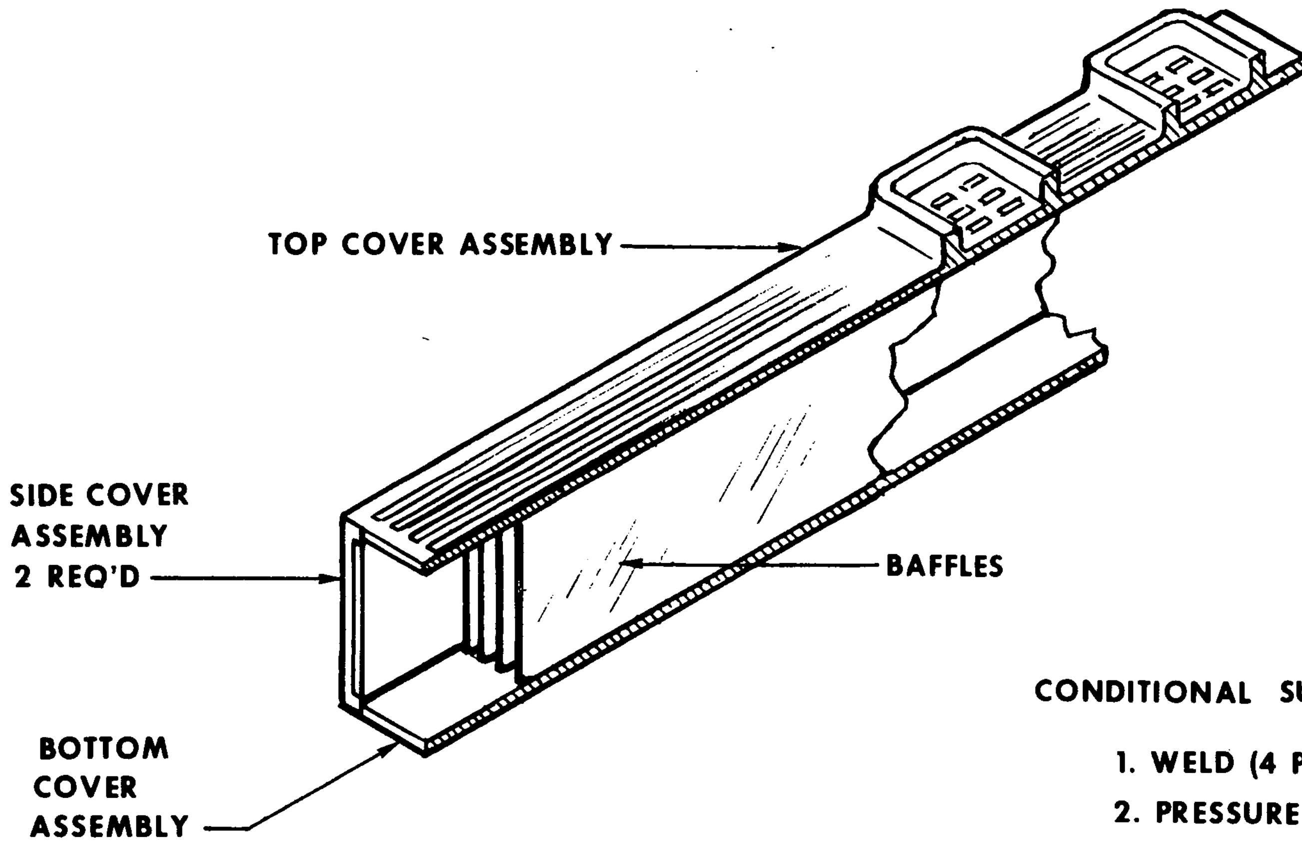


Figure 17

FABRICATION SEQUENCE CONTINUED



CONDITIONAL SUB-ASSEMBLY

1. WELD (4 PLACES)
2. PRESSURE TEST

Figure 18

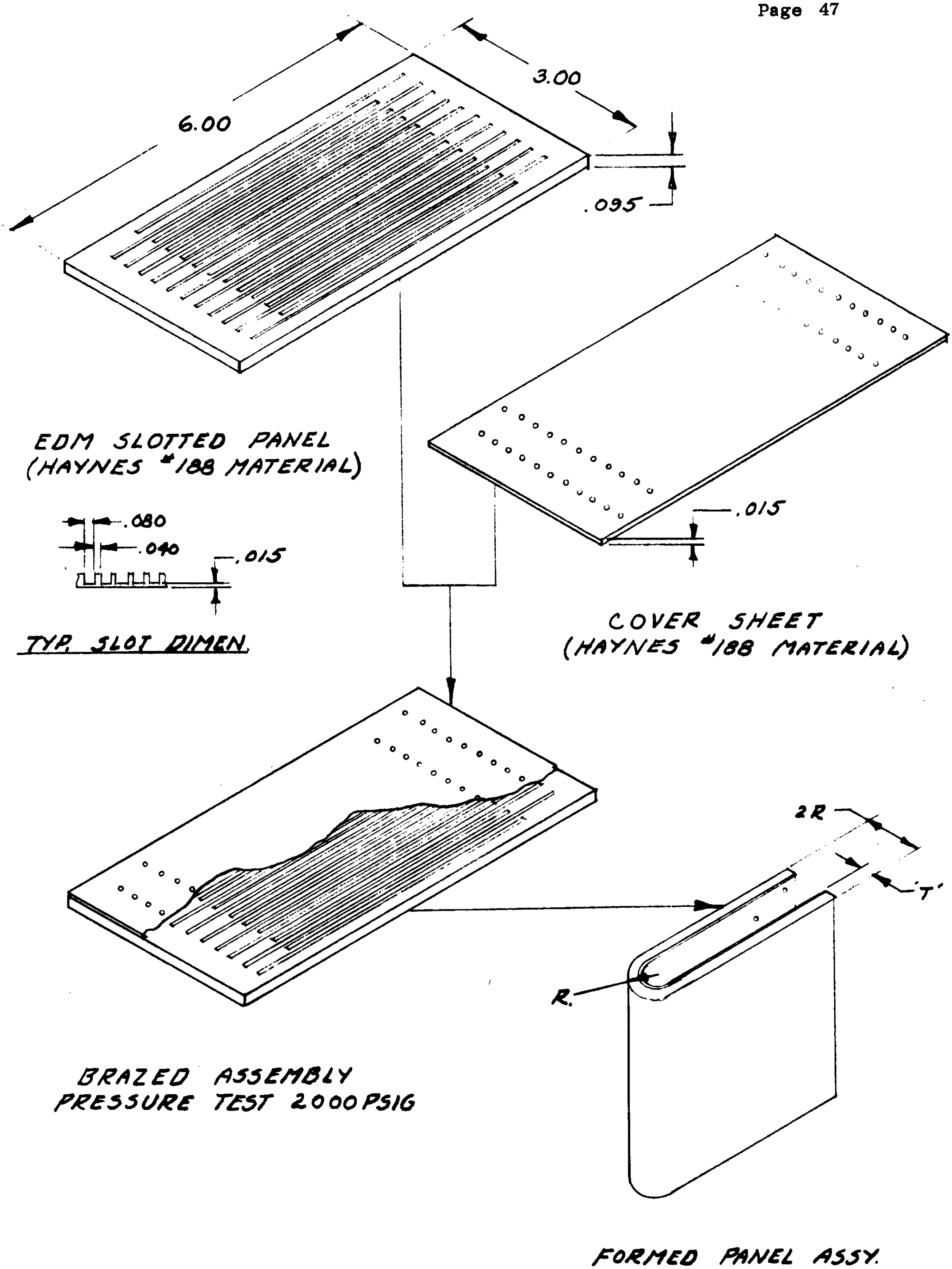


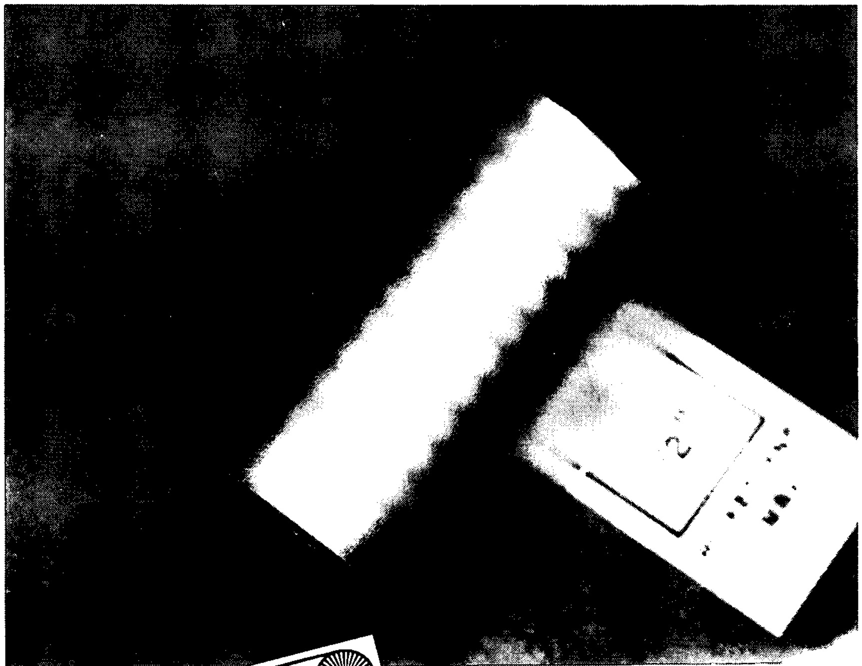
FIG. 19
PANEL ASSEMBLY ~ MANUFACTURING SEQUENCE

requirement of the heat exchanger baffles. Two forming radii, 0.25 and 0.375 inch (consistent with 7-baffle and 5-baffle conditioner assemblies, respectively), were evaluated. Results were highly encouraging with the 0.375-inch radius with no evidence of material cracking or braze joint damage in the formed region (Fig. 20). Conversely, the sample formed to the smaller 0.25-inch radius showed visible evidence of cracking on the outer surface (Fig. 21), indicating severe straining of the Haynes 188 alloy during the forming operation. As a result of this effort, it has been tentatively decided that the baffles used in both the hydrogen and the oxygen conditioners will be 0.75 inch wide, resulting in a 5-baffle assembly as discussed previously. Additional fabrication development samples will be evaluated to substantiate this selection prior to committing the conditioners to manufacturing.

TEST (04XXX)

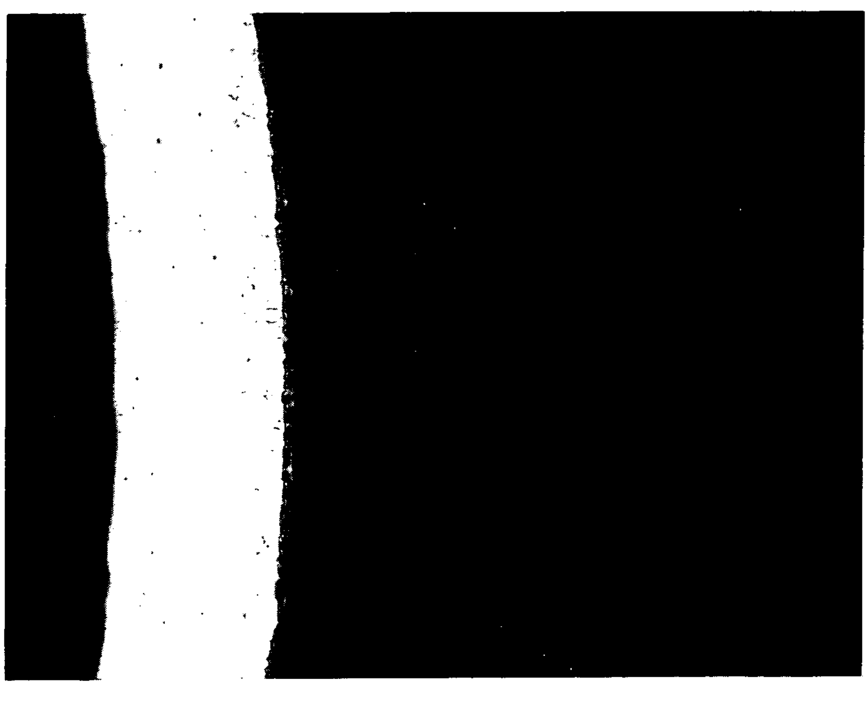
Conditioner test activity planned for this program consists of cold flow tests conducted at the Canoga Park Development Laboratory and hot firing tests conducted at the Santa Susana Component Test Laboratory Location IV (CTL-IV). Tests at the Development Laboratory will include containment, proof, flow and functional tests of the conditioners and their specific components before and after hot firing and prior to delivery. Specific activity during the past month has involved preparation of tentative test plans and instrumentation requirements for input to test facility personnel for planning purposes.

In addition, some investigation has been initiated into potential laboratory test techniques for cyclic testing baffle sample under conditions which simulate the temperatures, environment and strain ranges experienced by the baffle during hot fire testing.



(A)

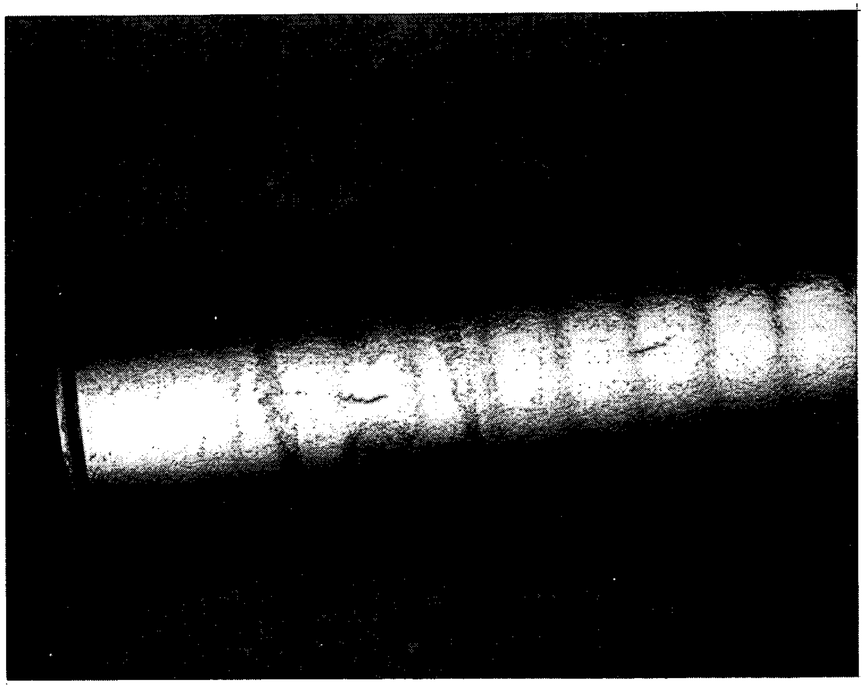
Leading Edge of Baffle Sample with 0.375 Forming Radius



(B)

Section Through Baffle Leading Edge

Figure 20. Baffle Sample Formed to 0.375 Radius



(A)

Leading Edge of Baffle Sample with 0.25 Forming Radius

(B)

Section Through Baffle Leading Edge Showing Forming Crack

Figure 21. Baffle Sample Formed to 0.25 Radius Showing Resulting Surface Cracks

TECHNOLOGY DEVELOPMENT (06XXX)

In parallel with the mainstream effort discussed previously, a task specifically planned to explore critical technology areas early in the program is underway. This effort is currently concentrated on experimentally verifying the compatibility of the reactor injector and side-mounted igniter. This verification will be accomplished through a series of hot firing tests in an uncooled solid wall chamber which simulates the conditioner assembly (Fig. 22).

The injector to be evaluated in this task is identical to the injector selected for use on the thermal conditioners. The injector incorporates a tri-slot injection element where two rectangular fuel streams impinge on a centrally located oxidizer stream. Element cold flow and hot firing test results have shown good mixing, maximum recirculation and uniform mixture ratio profile--elements essential to successful operation of the conditioners.

The igniter assembly selected for use on the conditioners is of the electrical type evaluated under several recent NASA contracts (Refs. 1, 2 and 3). In addition, results of on-going company-funded effort in this area will be used to suppelement the referenced data, providing the strongest possible technological base for the selection of the igniter type and operational requirements.

As mentioned previously, the injector and igniter will be hot-fire tested in a solid wall test chamber to evaluate ignition characteristics and to demonstrate that good mixing (no streaking) is being achieved.

TEST HARDWARE IGNITION AND TEMPERATURE

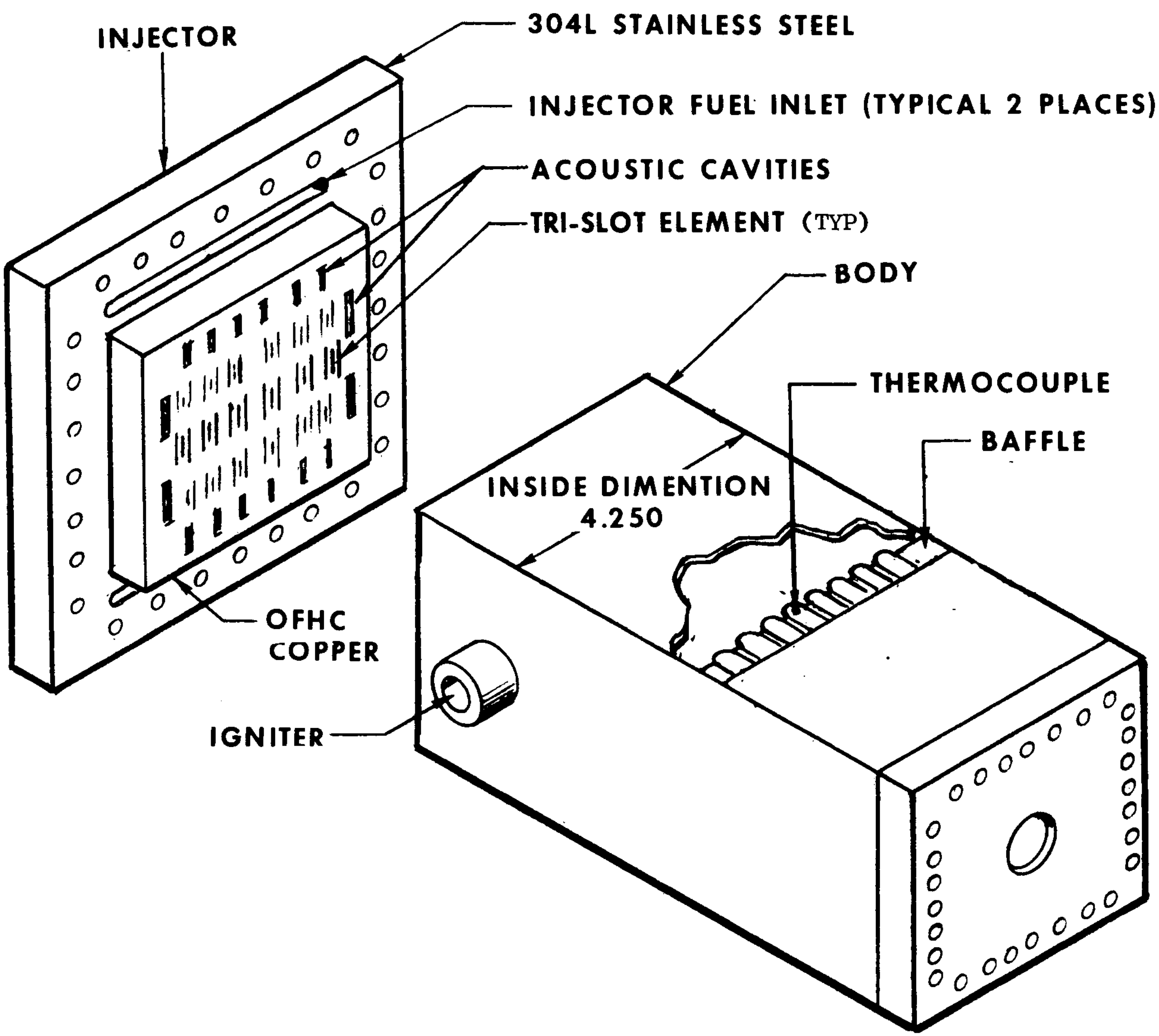


Figure 22

PLANNED EFFORT

DESIGN CONFIGURATION ANALYSIS (01XXX)

During the next month, the analysis will be directed at evaluating the advantages and disadvantages of using bypass on the conditioners, offering the potential for better control of conditioned fluid exit temperature. Also, a system balance will be completed reflecting reactor mixture ratio and combustion gas temperature ranges over the stated operating regime.

DESIGN CONDITIONING UNITS (02XXX)

Hard line layouts of the hydrogen conditioner will be complete and design layout effort on the oxygen conditioner will be underway.

MANUFACTURING (03XXX)

Fabrication of appropriate samples will continue as well as evaluation of detail fabrication procedures for the conditioners.

TEST (04XXX)

Effort on this task will be limited to that required to support activity on the hot firing test facility and in establishing procedures for laboratory testing of the conditioners and their major components.

TECHNOLOGY DEVELOPMENT (06XXX)

The injector, igniter assembly and solid wall chamber for this task will be released to fabrication.

REFERENCES

1. Hydrogen Oxygen APS Engines, NAS3-14352.

2. Space Shuttle Auxiliary Propulsion (APS) Ignition System, NAS3-14351.

3. Ignition System for Space Shuttle Auxiliary Propulsion System, NAS3-14348.

APPENDIX A

Included in this appendix are the computations completed to date with respect to the structural analysis effort on the thermal conditioners. In addition, the criteria and logic employed on this analysis effort are included. In subsequent reports additional pages, coded to the index presented on the following pages, will be submitted.

SS-APS PROPELLANT CONDITIONERS

STRUCTURAL AND LIFE ANALYSIS

6.	Manifolds & Exit Nozzle
6.1	Inlet Manifold - Injector Hydrogen
6.2	Inlet Manifold - Conditioner Hydrogen (or oxygen)
6.3	Exit Manifold - Conditioner Hydrogen (or oxygen)
6.4	Exit Nozzle - Hot Gas
7.	Flanges
7.1	Flange - Injector End
7.2	Flange - Igniter
8.	Joints
8.1	Joint - Baffle to Top
8.2	Joint - Sides to Top and Bottom
8.3	Joint - Flange - Injector End
8.4	Joint - Exit Nozzle - Hot Gas
8.5	Joint - Inlet Manifold - Injector Hydrogen
8.6	Joint - Inlet Manifold - Conditioner Hydrogen (or oxygen)
8.7	Joint - Exit Manifold - Conditioner Hydrogen (or oxygen)
8.8	Joint - Flange - Igniter

Service Requirements

Life

Operating Life = 50 hours = t

Cycles of normal operation = 10,000 = n

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CHECKED BY:		REPORT NO. 1.2.1
DATE: 7/23/71	SS-APS - PROP. COND.	MODEL NO.

Operating Data

Hot Gas Section

Inlet Pressure - H_2 and O_2

Design Values

338 to 413 psia steady state

300 to 450 psia start

Nominal Value

375 psia steady state

Inlet Temperatures

Design Values

-360°F to 140°F for H_2

-160°F to 140°F for O_2

Nominal Value

70°F for H_2 and O_2

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CHECKED BY:		REPORT NO. 1.2.2
DATE: 7/23/71	SS-APS - PROP. COND.	MODEL NO.

Operating Data

Cold Gas Section - H_2

Inlet

Pressure

Design Values

1100 to 2100 psia

Nominal Value

1600 psia

Temperature

-420 to -390 °F

Outlet

Pressure

Nominal Value

1500 psia

Temperature

-260 to -210 °F

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CHECKED BY:		REPORT NO. 1.2.3
DATE: 7/23/71	SS-APS-PROP. COND.	MODEL NO.

Operating Data

Cold Gas Section – O_2

Inlet

Pressure

Design Values

1100 To 2100 psia

Nominal Value

1600 psia

Temperature

−300 to −260 °F

Outlet

Pressure

Nominal Value

1500 psia

Temperature

−85 to −35 °F

1.3 CRITERIA

Each component is designed in accordance with the following basic structural criteria:

Minimum Yield Factor of Safety ≥ 1.1

Minimum Ultimate Factor of Safety ≥ 1.4

These safety factors govern the combined stresses induced by all the operating loads. All other criteria, such as the pressure vessel and fatigue criteria, are special criteria and govern when they become more critical than the basic criteria.

The design loads represent the most critical expected 3-sigma operating conditions and are the combined effects of pressure, vibration, acceleration, thermal, and other load sources.

The minimum guaranteed material properties (yield strength, ultimate strength, rupture strength, and fatigue strength) are based on MIL-HDBK-5 ('A' Basic) or equivalent. They account for the operating environment effects and exposure to the maximum expected operating temperature for the duration of the specified service life.

The yield safety factor is computed by comparing the primary effective stress with the material minimum guaranteed yield strength at the maximum expected operating temperature. Yielding due to secondary stresses which are deflection limited is controlled by the ultimate and/or fatigue safety factor.

The ultimate safety factor maintains a factor of 1.4 on the stresses or strains that would cause failure whether the failure mode is tensile ultimate, creep rupture, buckling, or fatigue. The ultimate safety factor is computed by comparing:

(1) The effective primary stress with the material ultimate failure strength, and/or

(2) The effective peak strain with the material available elongation and low cycle fatigue properties.

All components are designed to have a minimum guaranteed start-steady-state-stop low-cycle fatigue life of at least four times the desired service life. A factor of 4 is also maintained on the time to rupture to account for creep effects.

Also, any component that experiences cyclic loading during operation is designed to have a minimum guaranteed high-cycle fatigue life of at least ten times the number of cycles it will experience during the desired service life.

For those components experiencing both high- and low-cycle fatigue as well as creep, a generalized life equation is used to take into consideration the accumulative damage interaction.

The fundamental theory used in the life prediction analyses is that failure depends on the accumulation of creep damage and fatigue damage. Data obtained from material fatigue specimens and test data of actual hardware are used in the life analyses. The analytical methods and types of material specimen data used in the analyses are discussed below.

The life analysis is based on a definition of the stress-strain-time-temperature history during each operating cycle. Creep damage is evaluated from the stress-time-temperature cycle and fatigue damage from the strain-time-temperature cycle.

The increment of creep damage, $\Delta\phi_c$, is determined by the ratio of time spent at a particular stress level, t, to the time-to-rupture at that stress level, t_r;

$$\Delta\phi_c = \Sigma\left(\frac{t}{t_r}\right)\sigma$$

$\Delta\phi_c$ = creep rupture damage

t = time at stress, σ

t_r = time to rupture at the stress, σ

The total creep damage, ϕ_c, is given by:

$$\phi_c = \Sigma\Delta\phi_c$$

Fatigue damage, ϕ_c, is determined by the ratio of the actual number of cycles (starts and stops), applied at a particular strain range, to the number of cycles which would cause failure at that strain range.

$$\phi_f = \Sigma\frac{n}{N_f}$$

The Method of Universal Slopes is used initially to obtain isothermal fatigue design values for cycles to failure.

The method is given by:

$$\epsilon_t = 3.5\left(\frac{F_{tu}}{E}\right) N_f^{-.12} + D^{.6} N_f^{-.6}$$

where

ϵ_t = total calculated strain range

F_{tu} = material ultimate strength

E = Young's Modulus

D = Fracture Ductility, $\ln\left[\frac{100}{100-RA}\right]$

RA = Percent Reduction-in-Area

The basic properties are used at the temperature of interest for isothermal problems. The straining process with varying temperature is considered incrementally. Cyclic life for the strain range is based on values for F_{tu}/E and RA obtained over the temperature range of the strain cycle.

Subsequently, experimental isothermal fatigue data will be obtained to replace the life capability as predicted by the Method of Universal Slopes. In this case, a plot of fatigue life vs temperature for the specific strain range of interest is the key element in the incremental technique. The number of allowable cycles, N_f, for the strain range, ϵ_t, is determined by graphically averaging the value of N_f over the operating temperature range.

A generalized life equation is used to consider the total damage caused by the interaction of low- and high-cycle fatigue and creep rupture.

The equation takes the following form:

$$4\,\phi_{fL} + 4\,\phi_{c} + 10\,\phi_{fH} = 1.0$$

where

ϕ_{fL} = Low-cycle fatigue damage

ϕ_{c} = Creep rupture damage

ϕ_{fH} = High-cycle fatigue damage

Safety Factor = 4 on low-cycle fatigue and creep rupture,
= 10 on high-cycle fatigue.

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Nomenclature

α = Coefficient of thermal expansion

T = Temperature & subscript for "Thermal"

t = Material Thickness & time at load

°F = Degrees Fahrenheit

E = Modulus of elasticity

K = Thermal strain distribution factor

w = subscript for "hot wall"

B = subscript for "back wall"

ϵ = Strain

e = subscript for "effective" or "equivelant"

p = subscript for "pressure"

a = subscript for "axial"

ℓ = subscript for "lateral"

c = subscript for coolant side

g = subscript for hot gas side

A = Subscript for ambient

σ = Stress

F_{TY} = yield strength

F_{TU} = Ultimate Strength

HAYNES® alloy No. 188

excellent high-temperature strength, oxidation resistance to 2000 deg. F. and good post-aging ductility

CABOT
STELLITE DIVISION

PAGE

Unique Combination of High-Temperature Properties – HAYNES alloy No. 188 is a cobalt-base alloy which possesses a unique combination of properties. It has excellent high temperature strength and oxidation resistance to 2000 deg. F. combined with outstanding post-aging ductility.

Alloy No. 188 has average room temperature tensile properties of 139,400 psi ultimate strength, 69,500 psi yield strength and 56 per cent elongation. At 1800 deg. F. the alloy has ultimate and yield strengths of 36,800 and 23,500 psi, respectively, with 72 per cent elongation. Cryogenic temperatures do not significantly affect the ductility of alloy No. 188 but strength levels are increased markedly.

The excellent oxidation resistance of HAYNES alloy No. 188 results from minute additions of lanthanum to the alloy system. The lanthanum modifies the protective oxide scale in such a manner that the oxide becomes extremely tenacious and impervious to diffusion when exposed to temperatures through 2000 deg. F.

HAYNES alloy No. 188 exhibits outstanding post-aged ductility after prolonged aging treatments of over 1000 hours at temperatures of 1400, 1500 and 1600 deg. F. No tensile elongation of less than 10 per cent has been noted for alloy No. 188 for aging times through 1000 hours in the temperature range of 1400 to 1600 deg. F.

Useful Properties for Gas Turbine and Aerospace Applications – Because of its excellent strength, ductility and oxidation resistance, HAYNES alloy No. 188 meets the critical high-temperature material requirements for gas turbine applications as well as many of those in the airframe, chemical and nuclear fields. Typical uses are as transition ducts, combustor cans, spray bars, flame-holders and liners in jet engines. Structural members on high-speed aircraft as well as in aerospace re-entry vehicles are also promising uses for this alloy.

Readily Fabricated – HAYNES alloy No. 188 can be forged and, because of its good ductility, can be cold worked. It can be welded by both manual and automatic welding methods including electron beam, gas-tungsten-arc (TIG), and resistance welding. Alloy No. 188 exhibits good restraint welding characteristics.

Available in a Variety of Forms – HAYNES alloy No. 188 is available in the forms of sheet, plate, strip, bar, wire and billet stock.

Simple Heat-Treatment – All wrought forms of HAYNES alloy No. 188 are furnished in the solution heat-treated condition unless otherwise specified. The standard heat-treatment is at 2150 deg. F. followed by either a rapid air-cool or water quench.

Properties Enhanced by Cold-Work and Aging – Because of its relatively high-strain hardening coefficient, HAYNES alloy No. 188 can be easily strengthened by cold deformation. Strengthening is further enhanced by aging the cold-worked structure near 1000 deg. F. for a period of 4 to 16 hours. This combination of treatments increases both the room and elevated tensile strength of alloy No. 188 sheet. Cold working prior to aging significantly increases the rate of the aging reaction.

Microstructure – HAYNES alloy No. 188 has a stabilized face-centered-cubic matrix containing 22 per cent chromium, 0.08 per cent lanthanum and 0.4 per cent silicon to promote oxidation resistance. Tungsten at 14 per cent is added for solid solution strengthening. Strengthening is further enhanced by the precipitation of M_6C and $M_{23}C_6$ carbides. Intermediate temperature ductility is achieved by deterring the formation of a A_2B Laves-type phase through selective alloying additions.

Properties Data – The properties listed in this booklet are typical or average values based on laboratory tests conducted by the manufacturer. They are indicative only of the results obtained in such tests and should not be considered as guaranteed maximums or minimums. Materials must be tested under actual service to determine their suitability for a particular purpose.

HAYNES alloy No. 188 is covered by U.S. Patent No. 3,418,111.

Condition	Structure
Solution Annealed	F.C.C. Matrix, Primary M_6C, La Rich Compound (La_xM_y) Associated with M_6C
Aged 1800° F.	F.C.C. Matrix, Primary M_6C, La_xM_y, Secondary M_6C
Aged 1600° F.	F.C.C. Matrix, Primary M_6C, La_xM_y, Secondary M_6C, $M_{23}C_6$
Aged 1400° F.	F.C.C. Matrix, Primary M_6C, La_xM_y, Secondary $M_{23}C_6$
Aged 1200° F. and Lower	Annealed Constituents

Samples Aged 200 and 500 Hours at Temperature

CHEMICAL COMPOSITION, PER CENT

Cobalt	Chromium	Nickel	Tungsten	Iron	Carbon	Silicon	Manganese	Lanthanum
Balance	20.00–24.00	20.00–24.00	13.00–16.00	3.00*	0.05–0.15	0.20–0.50	1.25*	0.03–0.15

* Maximum

PHYSICAL PROPERTIES

Physical Property	Temp., deg. C.	Metric Units	Temp., deg. F.	British Units
Density	22	9.13 g./cu.cm.	72	0.330 lb./cu.in.
Incipient Fusion Temperature	1302-1330		2375-2425	
Electrical Resistivity	21	92.2 microhm-cm	70	36.3 microhm-in. (605 ohms per cir. mil-ft.)
Thermal Diffusivity	300	0.036 cm.^{2}/sec.	572	0.006 in.^{2}/sec.
	400	0.040 cm.^{2}/sec.	752	0.006 in.^{2}/sec.
	500	0.045 cm.^{2}/sec.	932	0.007 in.^{2}/sec.
	600	0.048 cm.^{2}/sec.	1112	0.007 in.^{2}/sec.
	700	0.052 cm.^{2}/sec.	1292	0.008 in.^{2}/sec.
	765	0.053 cm.^{2}/sec.	1409	0.008 in.^{2}/sec.
	800	0.053 cm.^{2}/sec.	1472	0.008 in.^{2}/sec.
	900	0.051 cm.^{2}/sec.	1652	0.008 in.^{2}/sec.
	1000	0.055 cm.^{2}/sec.	1832	0.009 in.^{2}/sec.
	1100	0.058 cm.^{2}/sec.	2012	0.009 in.^{2}/sec.
	1200	0.059 cm.^{2}/sec.	2192	0.009 in.^{2}/sec.

PHYSICAL PROPERTIES

Physical Property	Temp., deg. C.	Metric Units	Temp., deg. F.	British Units
Mean Coefficient of Thermal Expansion	21 to −240	9.7 microns/m.-deg. C.	70 to −400	5.4 microinches/in.-deg. F.
	21 to −129	10.4 microns/m.-deg. C.	70 to −200	5.8 microinches/in.-deg. F.
	21 to −18	11.1 microns/m.-deg. C.	70 to 0	6.2 microinches/in.-deg. F.
	21 to 38	11.5 microns/m.-deg. C.	70 to 100	6.4 microinches/in.-deg. F.
	21 to 93	11.9 microns/m.-deg. C.	70 to 200	6.6 microinches/in.-deg. F.
	21 to 204	12.2 microns/m.-deg. C.	70 to 400	7.0 microinches/in.-deg. F.
	21 to 316	13.3 microns/m.-deg. C.	70 to 600	7.4 microinches/in.-deg. F.
	21 to 427	14.0 microns/m.-deg. C.	70 to 800	7.8 microinches/in.-deg. F.
	21 to 538	14.8 microns/m.-deg. C.	70 to 1000	8.2 microinches/in.-deg. F.
	21 to 649	15.5 microns/m.-deg. C.	70 to 1200	8.6 microinches/in.-deg. F.
	21 to 760	16.3 microns/m.-deg. C.	70 to 1400	9.0 microinches/in.-deg. F.
	21 to 871	17.0 microns/m.-deg. C.	70 to 1600	9.4 microinches/in.-deg. F.
	21 to 982	17.7 microns/m.-deg. C.	70 to 1800	9.9 microinches/in.-deg. F.
	21 to 1093	18.5 microns/m.-deg. C.	70 to 2000	10.3 microinches/in.-deg. F.
Thermal Conductivity	38	0.108 watt-cm./cm.^{2}-deg. C.	100	75 Btu-in./ft.^{2}-hr.-deg. F.
	93	0.134 watt-cm./cm.^{2}-deg. C.	200	84 Btu-in./ft.^{2}-hr.-deg. F.
	149	0.132 watt-cm./cm.^{2}-deg. C.	300	92 Btu-in./ft.^{2}-hr.-deg. F.
	204	0.144 watt-cm./cm.^{2}-deg. C.	400	100 Btu-in./ft.^{2}-hr.-deg. F.
	260	0.152 watt-cm./cm.^{2}-deg. C.	500	106 Btu-in./ft.^{2}-hr.-deg. F.
	316	0.161 watt-cm./cm.^{2}-deg. C.	600	112 Btu-in./ft.^{2}-hr.-deg. F.
	371	0.170 watt-cm./cm.^{2}-deg. C.	700	118 Btu-in./ft.^{2}-hr.-deg. F.
	427	0.180 watt-cm./cm.^{2}-deg. C.	800	125 Btu-in./ft.^{2}-hr.-deg. F.
	482	0.190 watt-cm./cm.^{2}-deg. C.	900	132 Btu-in./ft.^{2}-hr.-deg. F.
	538	0.199 watt-cm./cm.^{2}-deg. C.	1000	138 Btu-in./ft.^{2}-hr.-deg. F.
	593	0.210 watt-cm./cm.^{2}-deg. C.	1100	146 Btu-in./ft.^{2}-hr.-deg. F.
	649	0.219 watt-cm./cm.^{2}-deg. C.	1200	152 Btu-in./ft.^{2}-hr.-deg. F.
	704	0.230 watt-cm./cm.^{2}-deg. C.	1300	160 Btu-in./ft.^{2}-hr.-deg. F.
	760	0.240 watt-cm./cm.^{2}-deg. C.	1400	167 Btu-in./ft.^{2}-hr.-deg. F.
	816	0.251 watt-cm./cm.^{2}-deg. C.	1500	174 Btu-in./ft.^{2}-hr.-deg. F.
	871	0.251* watt-cm./cm.^{2}-deg. C.	1600	174* Btu-in./ft.^{2}-hr.-deg. F.
	927	0.258* watt-cm./cm.^{2}-deg. C.	1700	179* Btu-in./ft.^{2}-hr.-deg. F.
	982	0.272* watt-cm./cm.^{2}-deg. C.	1800	189* Btu-in./ft.^{2}-hr.-deg. F.
	1093	0.294* watt-cm./cm.^{2}-deg. C.	2000	204* Btu-in./ft.^{2}-hr.-deg. F.
	1204	0.305* watt-cm./cm.^{2}-deg. C.	2200	212* Btu-in./ft.^{2}-hr.-deg. F.
Specific Heat	0	0.095 cal./g.-deg. C.	32	0.095 Btu/lb.-deg. F.
	100	0.101 cal./g.-deg. C.	212	0.101 Btu/lb.-deg. F.
	200	0.106 cal./g.-deg. C.	410	0.106 Btu/lb.-deg. F.
	300	0.111 cal./g.-deg. C.	572	0.111 Btu/lb.-deg. F.
	400	0.116 cal./g.-deg. C.	752	0.116 Btu/lb.-deg. F.
	500	0.120 cal./g.-deg. C.	932	0.120 Btu/lb.-deg. F.
	600	0.125 cal./g.-deg. C.	1112	0.125 Btu/lb.-deg. F.
	700	0.129 cal./g.-deg. C.	1292	0.129 Btu/lb.-deg. F.
	800	0.133 cal./g.-deg. C.	1472	0.133 Btu/lb.-deg. F.
	900	0.137 cal./g.-deg. C.	1652	0.137 Btu/lb.-deg. F.
	1000	0.141 cal./g.-deg. C.	1832	0.141 Btu/lb.-deg. F.
	1100	0.145 cal./g.-deg. C.	2012	0.145 Btu/lb.-deg. F.
	1200	0.149 cal./g.-deg. C.	2192	0.149 Btu/lb.-deg. F.
Magnetic Permeability	Room	1.01 at 200 oersteds		

* Calculated.

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Section 2.1.1

FORMABILITY, SHEET

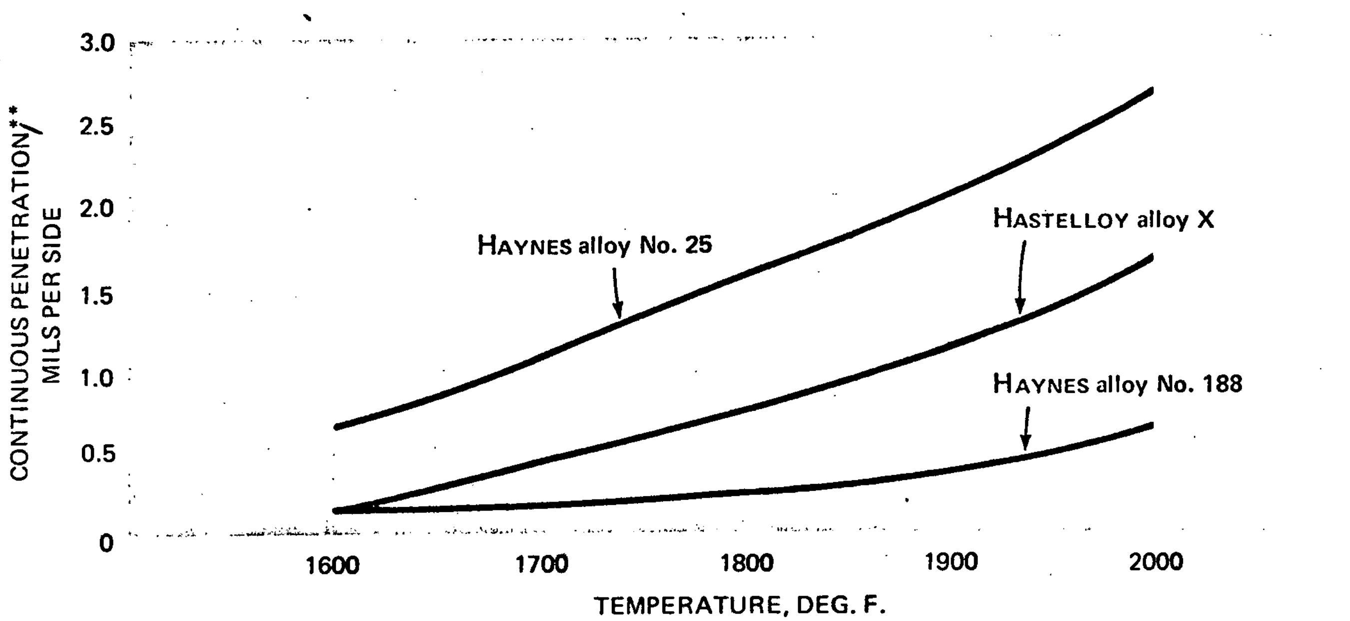
Condition	Thickness, in.	Typical Erichsen Cup Depth	
		mm.	in.
Heat-treated at 2150 deg. F., Water Quenched	0.078	14.3	0.56
	0.063	13.7	0.54
	0.040	12.5	0.49
	0.030	11.9	0.47
	0.020	11.6	0.46

RESISTANCE TO OXIDATION

The outstanding oxidation resistance of HAYNES alloy No. 188 is best illustrated by a comparison with the oxidation resistance of HASTELLOY alloy X and HAYNES alloy No. 25 in the table and graph below.

Test Temp., deg. F.	Oxidation Rate,* Weight Loss, mg/cm²			Oxidation Rate,* Metal Loss, mils/side		
	Alloy No. 188	Alloy X	Alloy No. 25	Alloy No. 188	Alloy X	Alloy No. 25
1600	1.0	1.5	2.1	0.05	0.07	0.09
1800	1.5	2.4	8.5	0.07	0.11	0.37
2000	3.9	5.4	42.4	0.16	0.25	1.83
2100	9.2	9.2	106.1	0.39	0.42	4.57

OXIDATION RESISTANCE IN DRY AIR, 100-HOUR TEST



*Intermittent exposure for 100 hours in dry air based on descaled weight change.
**From original thickness.

IMPACT STRENGTH, 3/4-IN. PLATE

Condition	Specimen Direction	Test Temp., deg. F.	Typical Charpy V-Notch Impact Resistance, ft.-lbs.
Heat-Treated at 2150 deg. F., Water Quenched	Transverse	−300	115
	Longitudinal	−300	117
	Longitudinal	−270	120
	Transverse	−220	112
	Transverse	−150	127
	Longitudinal	−150	134
	Transverse	Room	140
	Longitudinal	Room	145
	Longitudinal	600*	101
	Transverse	1000*	126
	Longitudinal	1000*	108
	Transverse	1300*	87
	Longitudinal	1300*	126
	Longitudinal	1500*	104
Aged for 100 hrs. in Vacuum at:			
1400 deg. F.	Transverse	Room	39
1600 deg. F.	Transverse	Room	35
1800 deg. F.	Transverse	Room	31
Aged at 1700 deg. F in Vacuum for:			
500 hrs.	Transverse	Room	26
500 hrs.	Longitudinal	Room	23
1000 hrs.	Transverse	Room	17
1000 hrs.	Longitudinal	Room	17

DYNAMIC MODULUS OF ELASTICITY**

Test Temp. deg. F.	Dynamic Modulus of Elasticity, psi x 10^6	Test Temp., deg. F.	Dynamic Modulus of Elasticity, psi x 10^6
−300	36.1	600	30.2
−250	35.8	800	28.9
−200	35.4	1000	27.6
−150	35.1	1200	26.2
−100	34.8	1400	24.9
−50	34.4	1600	23.6
86	33.6	1800	22.3
200	32.8	2000	21.0
400	31.5		

* Estimated temperature.

**Average of three tests at each temperature except for cryogenic and 2000 deg. F. tests, which are based on one and two tests, respectively.

EFFECT OF COLD-WORK AND HEAT-TREATMENTS ON ROOM TEMPERATURE HARDNESS OF SHEET *

Heat-Treatment		Average Ra Hardness after indicated per cent of cold reduction				
Temp., deg. F.	Time, minutes	10%	20%	30%	40%	50%
As-Cold Reduced	0	69	71	73	75	76
2200	15	60	58	55	54	54
2100	15	60	62	64	63	62
2100	30	59	59	55	58	55
2100	60	58	58	56	54	51
2000	15	61	62	64	66	66
2000	30	61	61	64	65	62
2000	60	61	62	63	64	64
1900	15	65	64	65	66	66
1900	30	65	63	65	65	67
1900	60	65	64	67	67	67
1800	15	69	68	68	68	69
1800	30	68	67	68	67	69
1800	60	66	65	66	67	68
1700	15	68	70	70	66	69
1700	30	67	71	69	68	69
1700	60	66	68	67	68	69
1600	15	66	72	74	71	70
1600	30	67	72	71	70	69
1600	60	69	71	71	70	69
1500	30	69	74	75	75	72
1500	60	72	72	75	74	72

* Hardness of material prior to cold reduction and/or subsequent heat-treatment was Ra 62.

HARDNESS AND BEND DUCTILITY, AGED SHEET *

Exposure Temp., deg. F.	Post Aging Bend Angle, deg. Around 2T Radius After Indicated Time at Temp.		Average Hardness, Ra After Indicated Time at Temp.	
	200 hrs.	500 hrs.	200 hrs.	500 hrs.
1850	–	–	62	61
1800	180	180	62	61
1700	180	180	63	63
1600	180	130	63	64
1500	180	180	64	63
1400	180	180	64	63
1300	180	180	64	64
1200	180	180	62	62
1100	180	180	62	61
1000	180	180	61	61
900	180	180	62	61

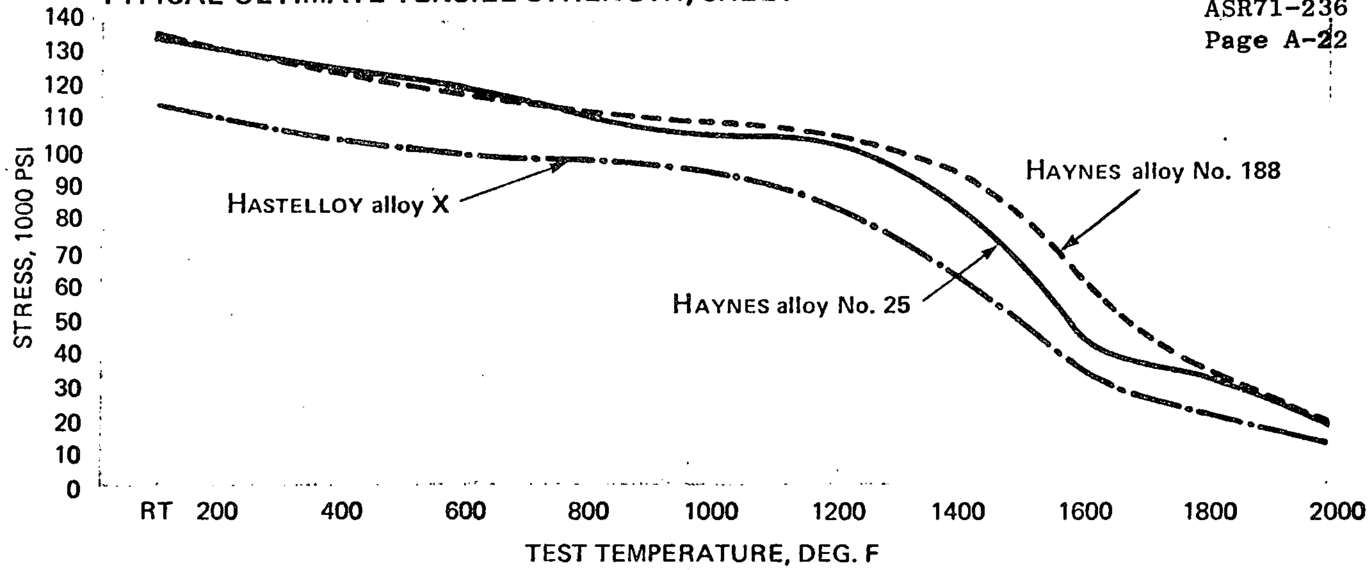
* Material was heat-treated at 2150 deg. F. and water quenched prior to test. Hardness was Ra 60.

AVERAGE SHORT-TIME TENSILE DATA *

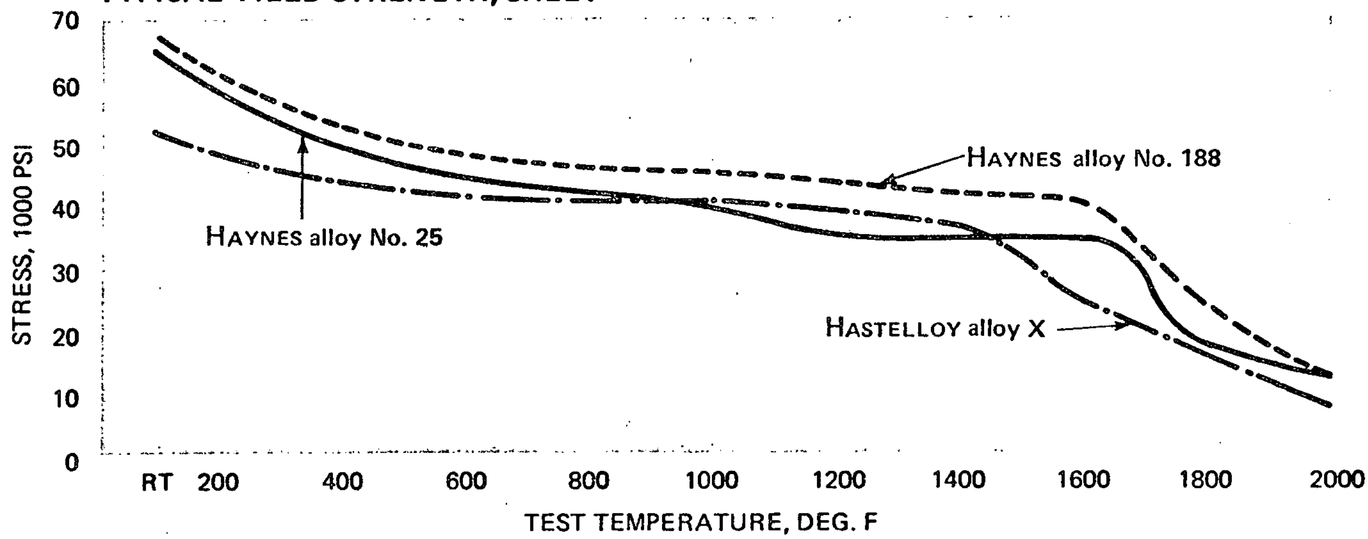
Form	Condition	Test Temp., deg. F.	Ultimate Tensile Strength, psi	Yield Strength at 0.2% offset, psi	Elongation in 1-1/8-in., per cer
Sheet, 0.030-in. to 0.065-in. thick	Heat-treated at 2150 deg. F, Water Quenched	–300	190,200	103,500	48
		–200	166,100	93,700	47
		–100	156,100	82,200	47
		Room	139,400	69,500	56
		600	116,300	48,500	71
		1000	107,200	43,800	70
		1200	103,100	43,900	61
		1400	92,000	42,200	43
		1600	60,700	38,000	73
		1800	36,800	23,500	72
		2000	19,300	11,500	47
		2100	14,000	8,200	37
		2200	11,100	7,000	35
Sheet, 0.109-in. to 0.130-in. thick	Heat-treated at 2150 deg. F, Water Quenched	–300	186,100	99,600	58
		–200	167,000	91,400	62
		–100	158,400	82,000	65
		Room	136,800	67,600	61
		600	117,600	47,500	75
		1000	109,300	45,300	78
		1200	106,200	43,600	73
		1400	95,500	41,600	54
		1600	63,200	40,400	81
		1800	37,700	24,700	86
		2000	20,400	12,700	75
		2100	14,600	8,700	61
		2200	12,100	6,800	48
Plate, 0.250-in. thick	Heat-treated at 2150 deg. F, Water Quenched	Room	139,700	65,200	52
		600	122,900	45,300	61
		1000	117,800	46,400	59
		1400	91,500	40,600	58
		1600	59,000	37,800	69
		2000	18,200	11,000	79

*Test Conditions: Below 1600°F, 0.005 in./in./min. strain rate to 0.6% offset and 0.500 in./min. crosshead velocity to failure. At 1600°F and above, 0.050 in./min. crosshead velocity to 0.6% offset and 0.500 in./min. crosshead velocity to failure.

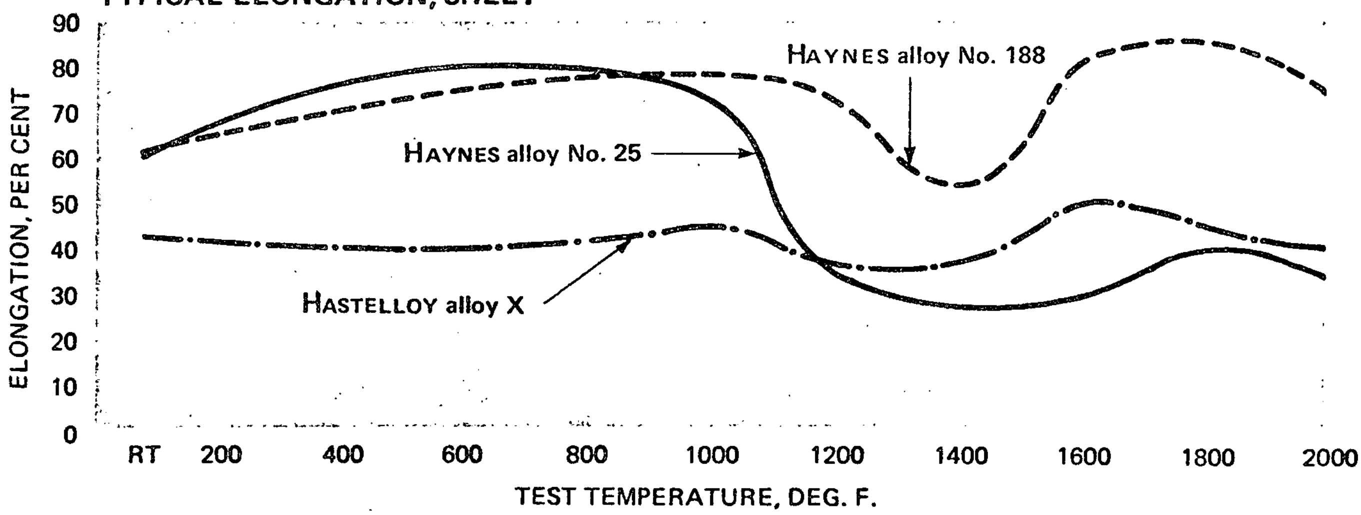
TYPICAL ULTIMATE TENSILE STRENGTH, SHEET



TYPICAL YIELD STRENGTH, SHEET



TYPICAL ELONGATION, SHEET



TENSILE DATA, WELDED

Weld Method and Material	Test Temp., deg. F.	Ultimate Tensile Strength, psi	Yield Strength at 0.2% Offset, psi	Elongation, per cent
Gas-Tungsten Arc (TIG) Sheet, 0.060-in.	Room	124,200	70,000	31
	1000	83,900	44,800	28
	1600	58,700	35,400	34
	1800	36,400	21,200	27
	2000	19,000	10,700	29
Gas-Tungsten Arc (TIG) All weld metal	Room	117,300	79,400	39
Electron Beam, (No filler) Sheet, 0.060-in.	Room	133,400	72,800	46
Resistance Sheet, 0.060-in.	Room	131,800	70,800	44

TENSILE DATA, AS COLD-REDUCED SHEET

Test Temp., deg. F.	Cold-Reduction, per cent	Ultimate Tensile Strength, psi	Yield Strength at 0.2% Offset, psi	Elongation, per cent
Room	10	158,000	129,600	43
	20	190,400	185,800	12
	30	212,000	209,800	9
	40	235,200	215,800	6
	50	246,400	220,100	4
600	10	133,400	98,400	40
	20	152,100	127,500	25
	30	179,000	145,800	6
	40	199,000	174,500	4
	50	215,000	193,000	2
800	10	127,400	86,100	52
	20	148,500	122,500	35
	30	176,100	154,500	6
	40	197,100	184,100	4
	50	220,000	198,500	2
1000	10	125,500	86,100	60
	20	146,600	131,400	10
	30	173,500	151,300	7
	40	201,500	188,000	4
	50	230,000	213,400	2

STRESS RUPTURE DATA *

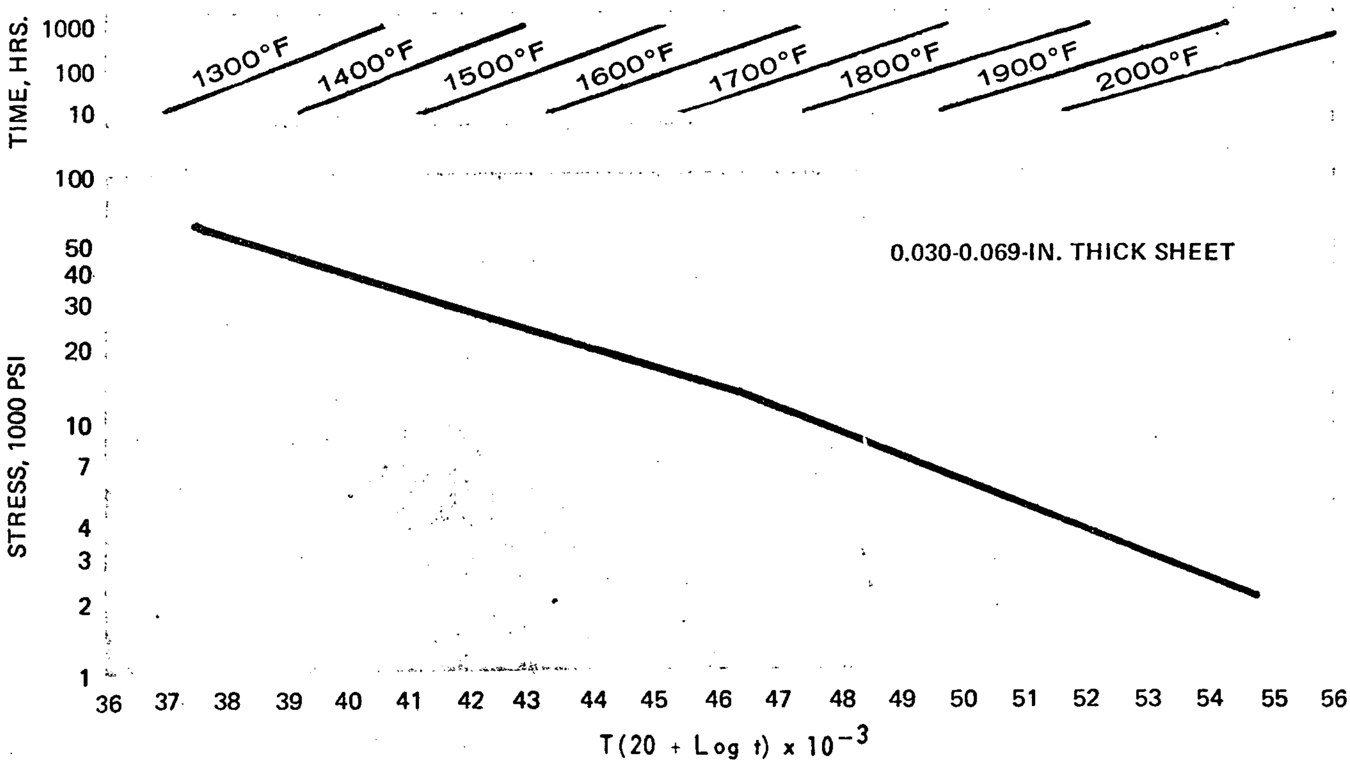
Form	Condition	Test Temp., deg. F.	Average Initial Stress (psi) for Rupture in:		
			10 hrs.	100 hrs.	1000 hrs.
Sheet 0.030 to 0.069-in., thick	Heat-treated at 2150 deg. F., Water Quenched	1300	65,000	47,300	34,800
		1400	44,600	32,400	23,600
		1500	31,100	22,300	16,000
		1600	21,800	15,300	10,100
		1700	15,300	9,700	6,000
		1800	9,900	6,000	3,600
		1900	6,200	3,700	2,200
		2000	3,900	2,200	–

RUPTURE DATA, SHEET

Condition	Test Temp., deg. F.	Stress, psi	Life, hrs.	Elongation, per cent
TIG Welded**	1500	24,000	94.4	28
Unwelded typical	1500	24,000	60.8	36
TIG Welded**	2000	3,200	28.5	7
Unwelded typical	2000	3,200	21.1	21

*Taken from the Larson-Miller Plot.
**Average of two tests.

STRESS RUPTURE DATA, SHEET (LARSON–MILLER PLOT)



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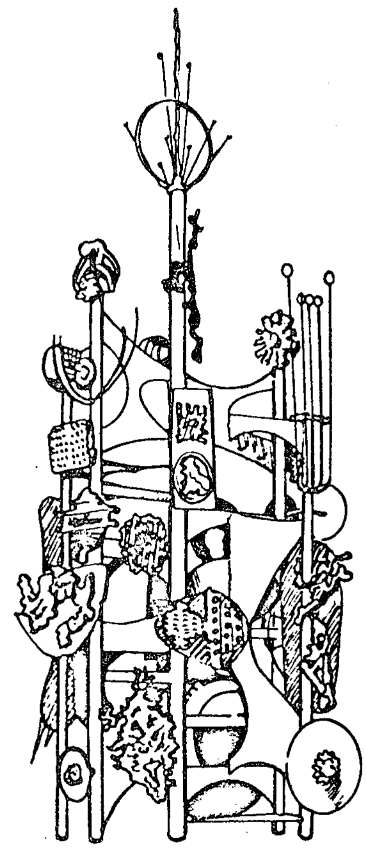

Kalpa-Tarou

The Hindu mythological "tree of imagination" from which man can gather whatever he desires. Every part of this sculpture was "found" at the Stellite plant. It stands in front of the Main Office in Kokomo, Indiana.

For more information on the products produced by Stellite Division, contact:

In the United States

	Phone
Kokomo, Indiana 46901 1020 W. Park Avenue	317-457-8411

Outside the United States

Western Hemisphere:	Cabot Interamerica, Inc. P. O. Box 746 Kokomo, Indiana 46901 Phone: 317-459-5697
United Kingdom and Europe:	Stellite Division Cabot Belgium S.A. 113/115 Rue Defacqz Brussels, Belgium Phone: 37 31 50
Other Locations:	Stellite Division, Cabot Corporation International Department Kokomo, Indiana 46901 Phone: 317-457-8411

STELLITE DIVISION
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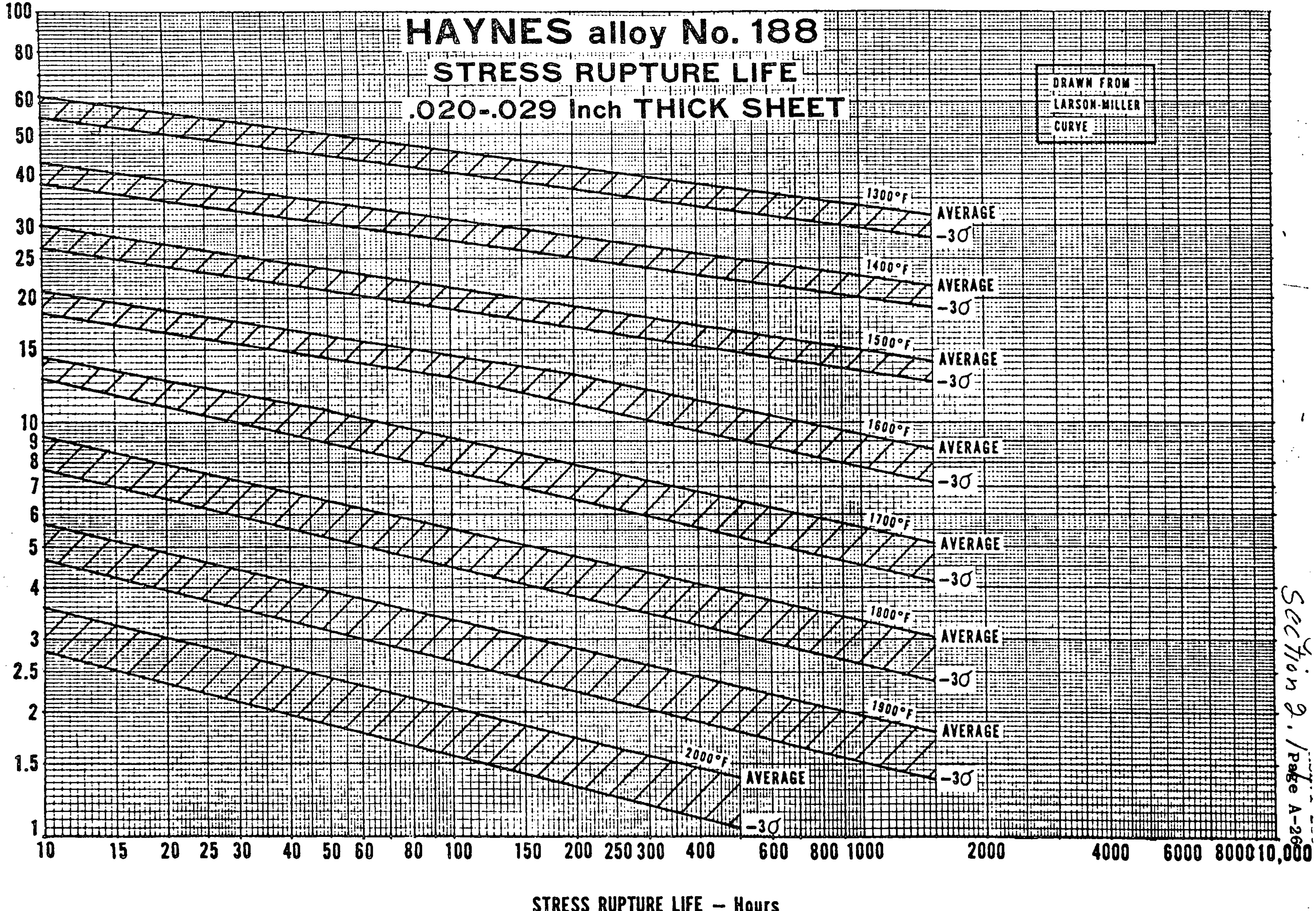

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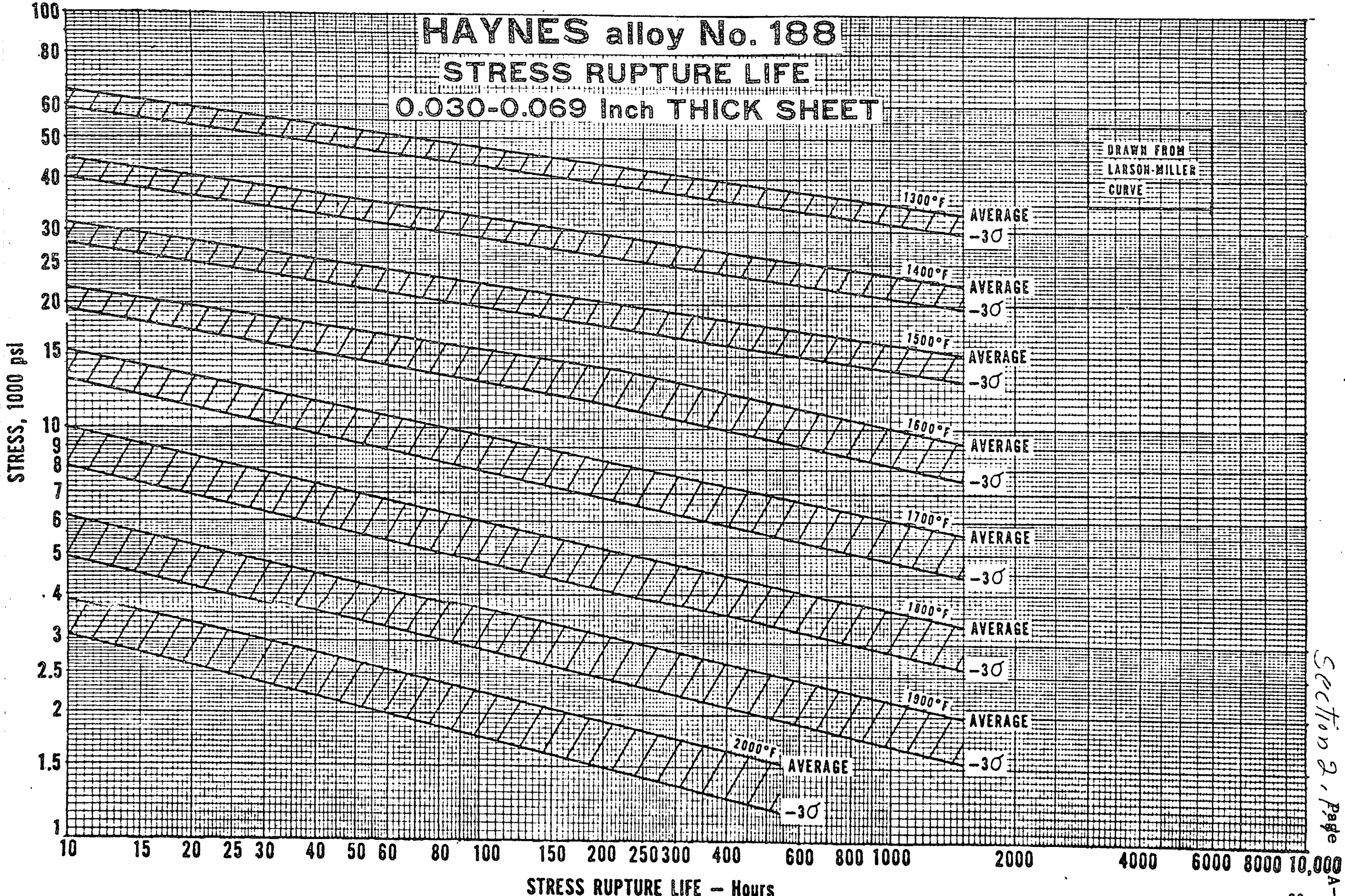

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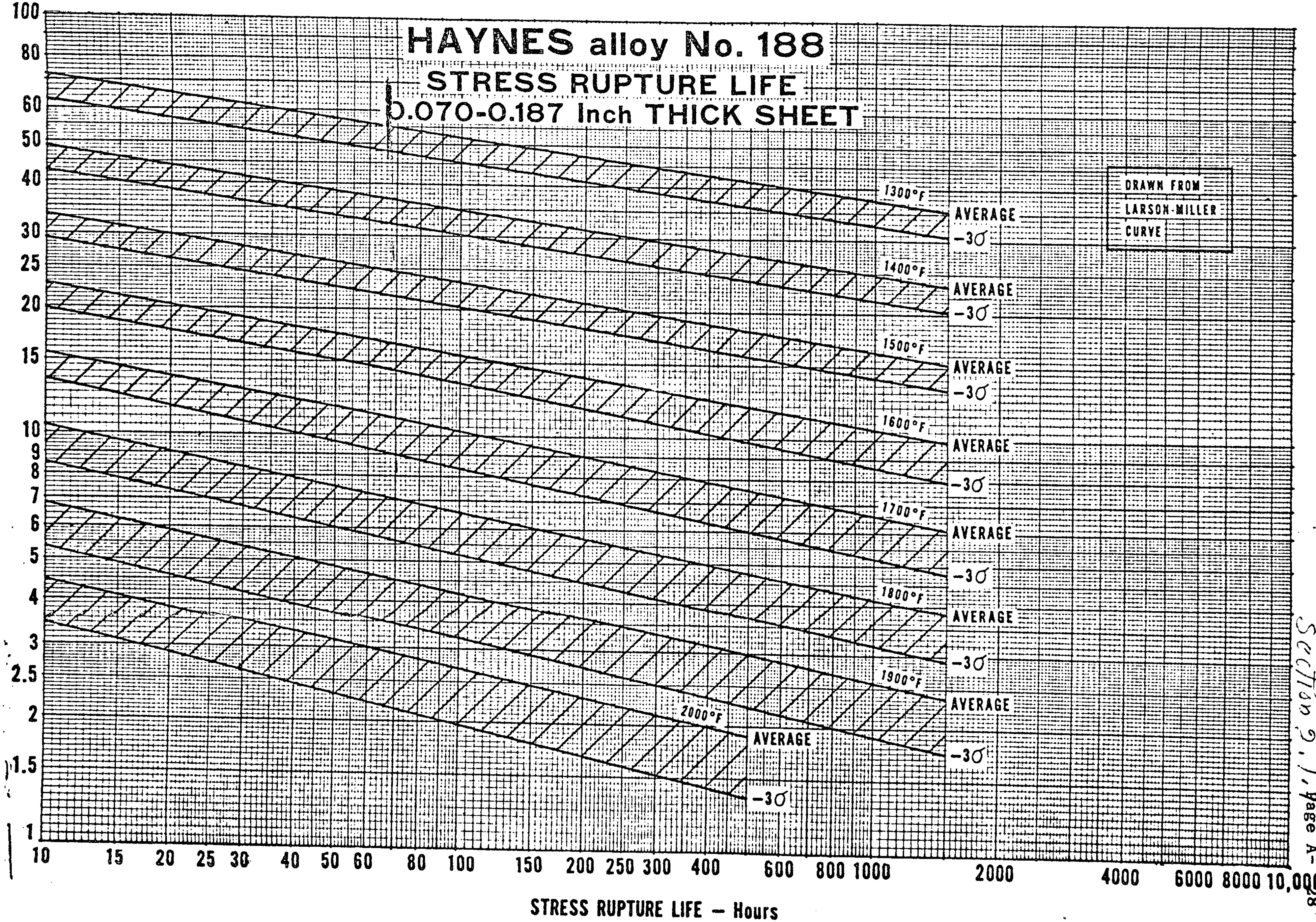

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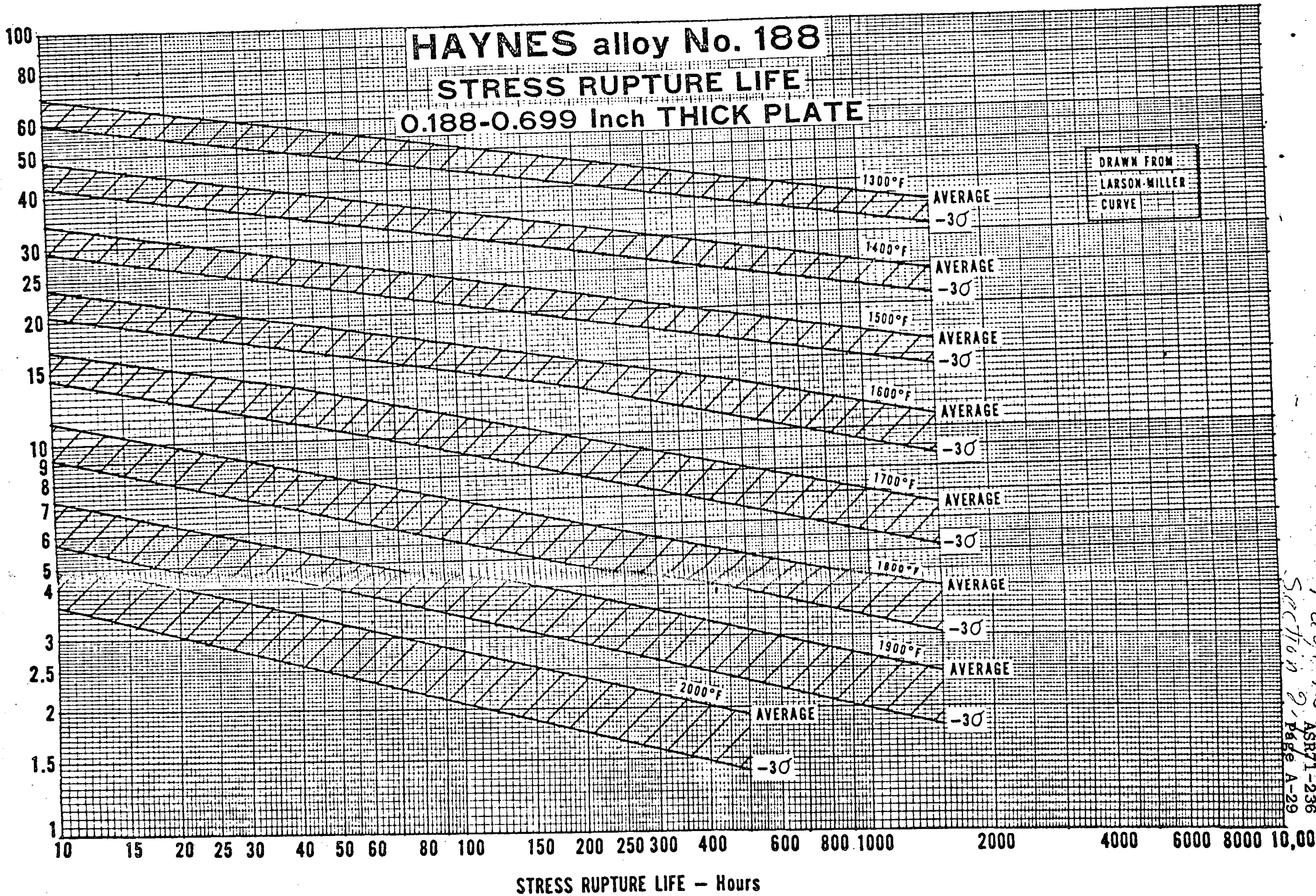

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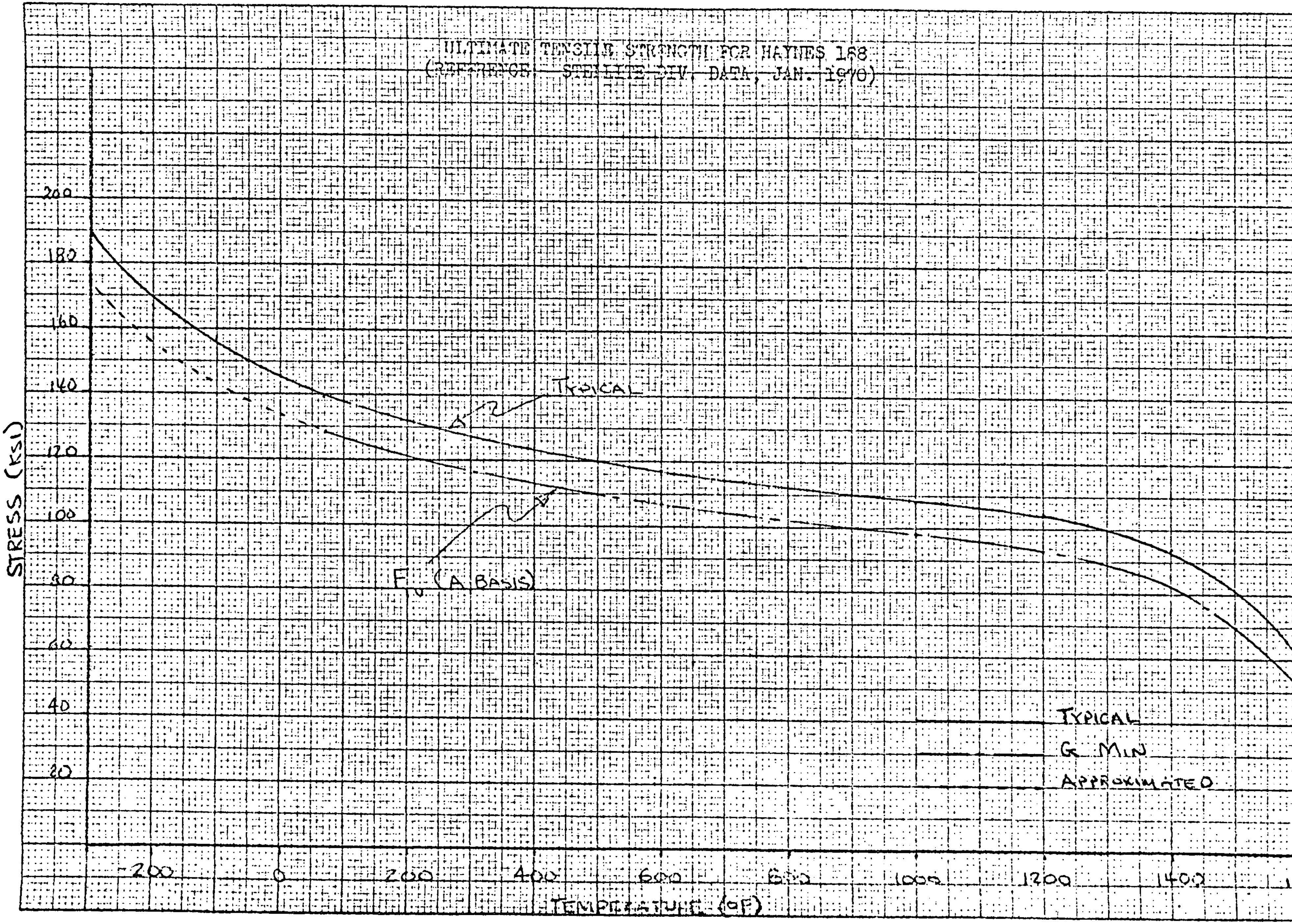

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FIG 2

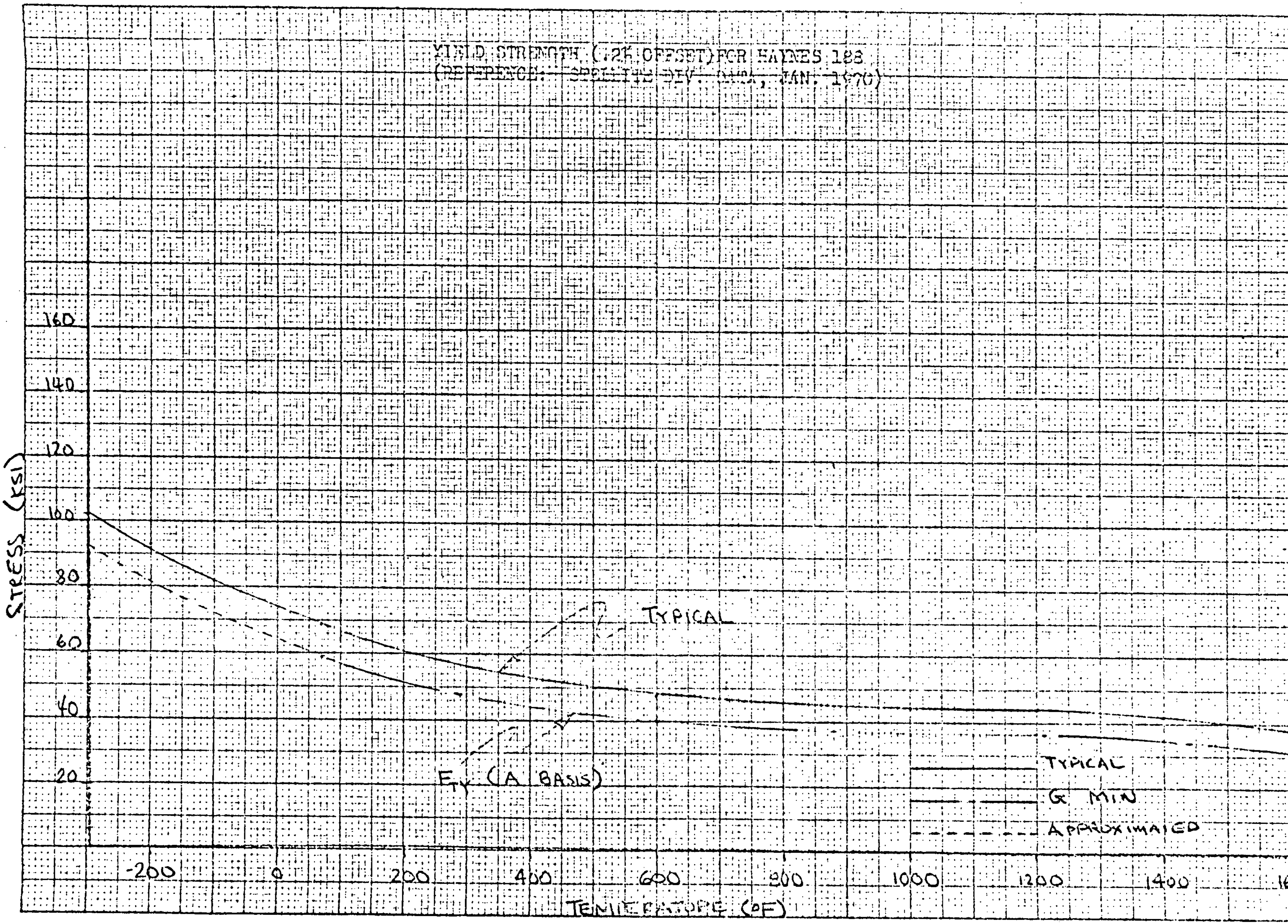

FIG. 8

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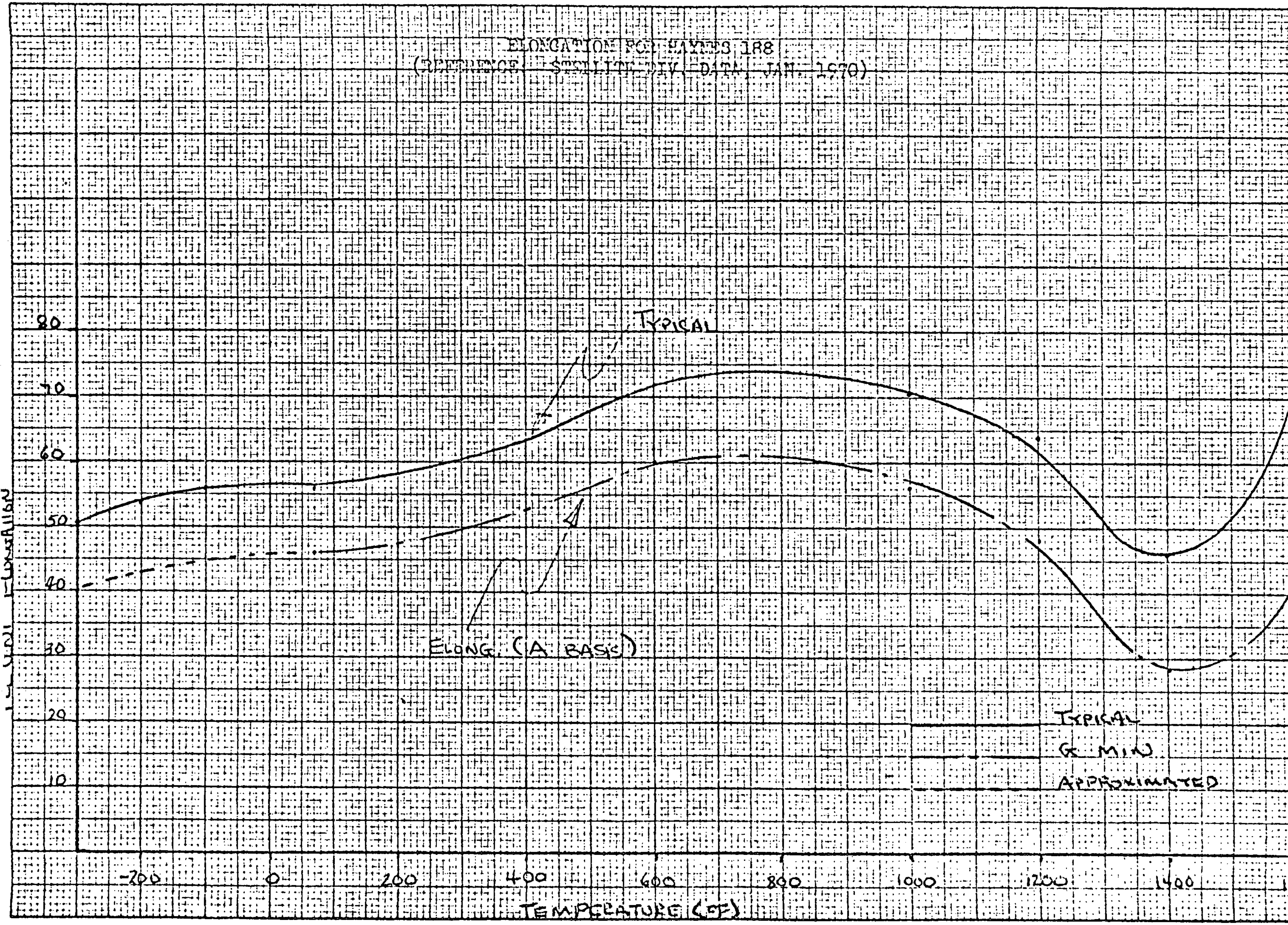
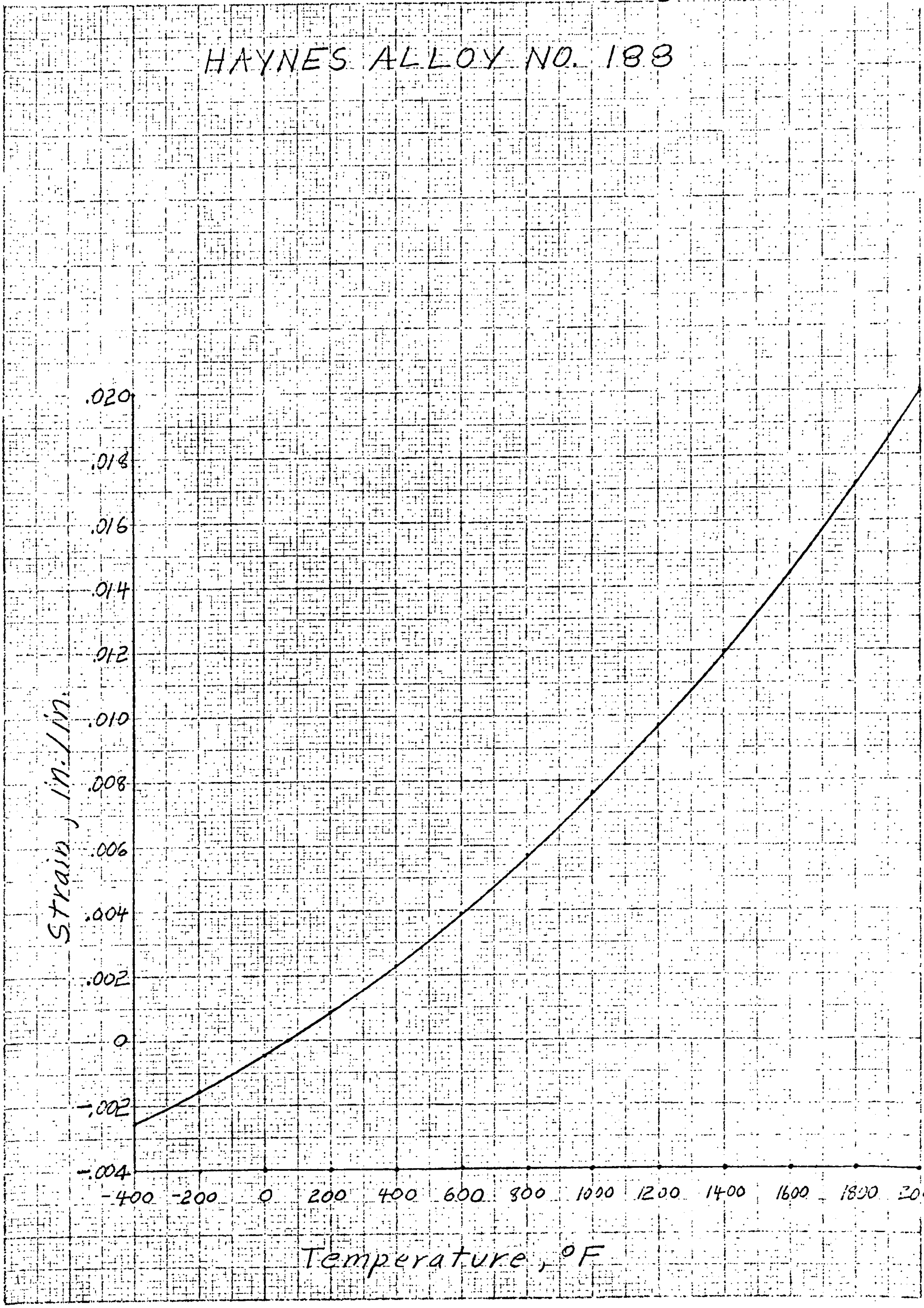

ELONGATION FOR HAYNES 188
(REFERENCE: STELLITE DIV. DATA, JAN. 1970)
TYPICAL
ELONG. (A BASIS)
% ELONGATION
80
70
60
50
40
30
20
10
-200
0
200
400
600
800
1000
1200
1400
1600
TEMPERATURE (°F)
TYPICAL
G MIN
APPROXIMATED

FIG 9 7


HAYNES ALLOY NO. 188
Strain, in./in.
.020
.018
.016
.014
.012
.010
.008
.006
.004
.002
0
-.002
-.004
-400
-200
0
200
400
600
800
1000
1200
1400
1600
1800
2000
Temperature, °F

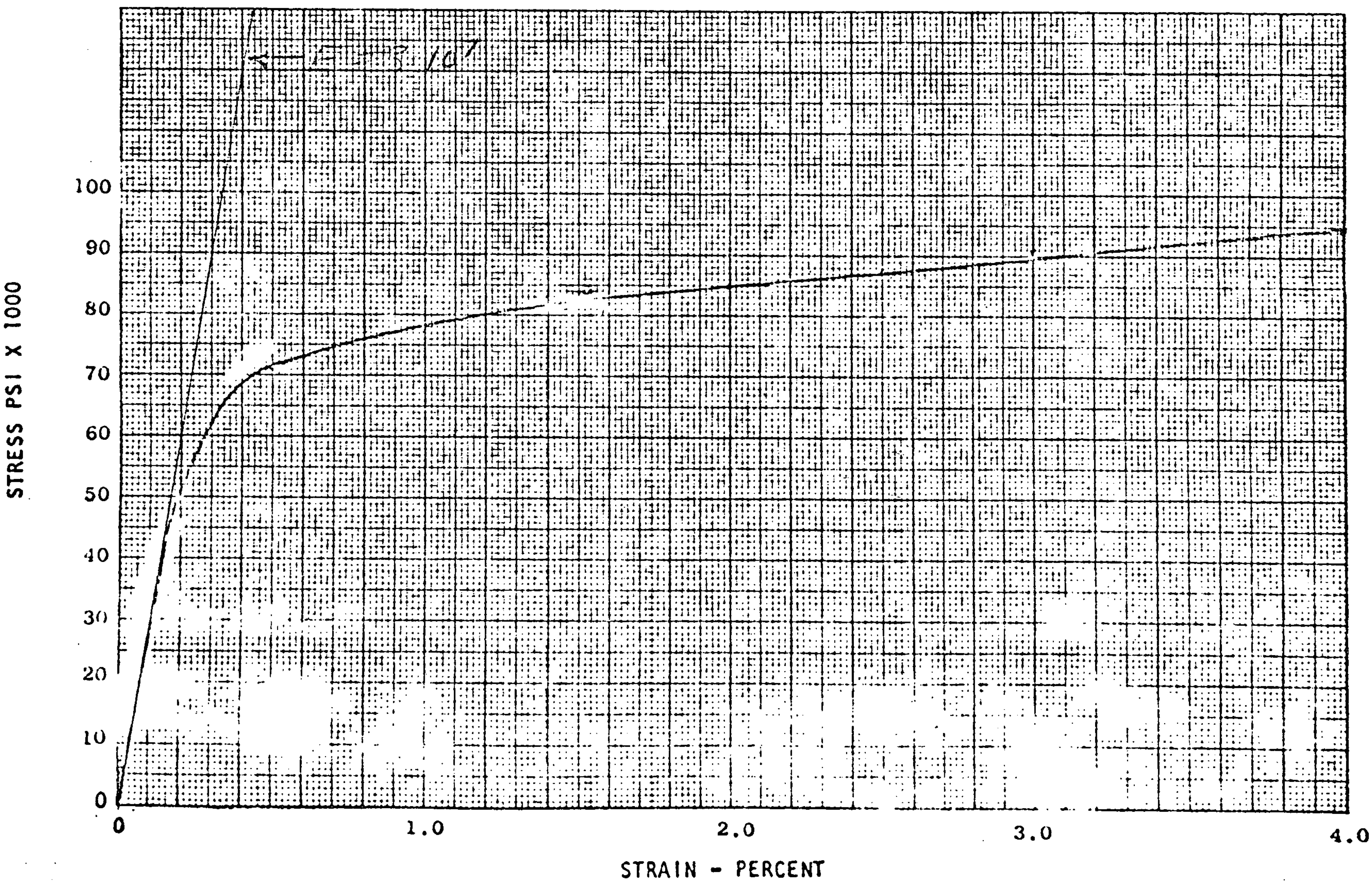
Rocketdyne
North American Rockwell

ISSUED BY MATERIALS
AND PROCESSES DEPT.
DRAWN BY E. F. Green
APPROVED
DATE 10-9-70

STRESS—STRAIN DIAGRAM

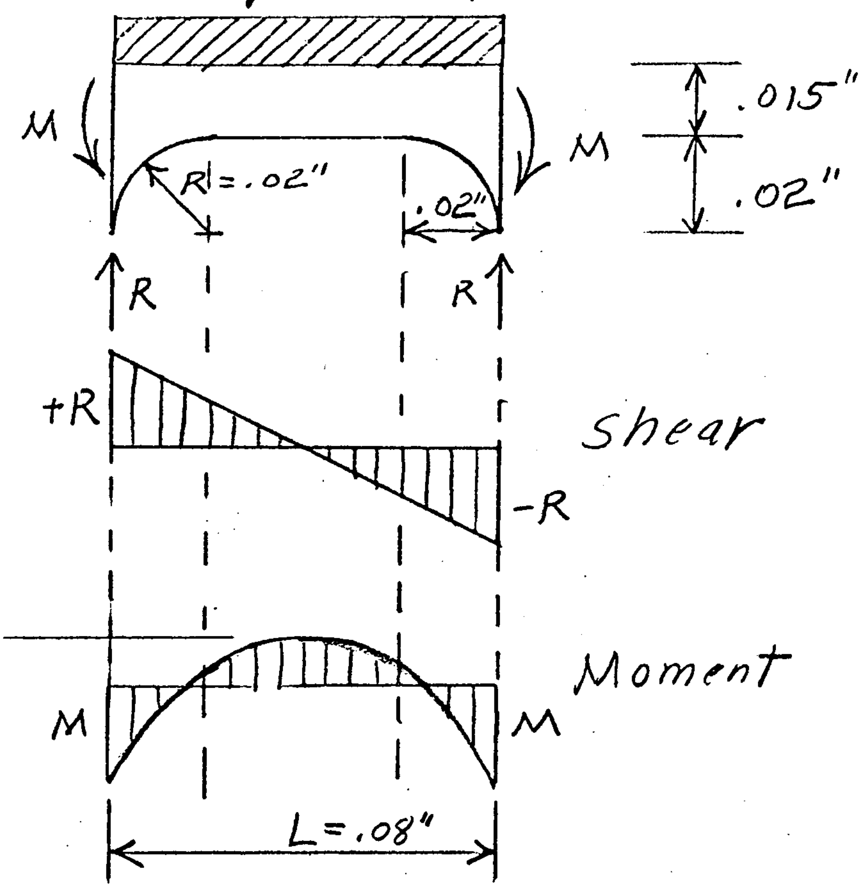
CHART NO. 9-13-7-1
MATERIAL Haynes No. 188
TEST TEMPERATURE 70 F
FORM Bar
CONDITION ANN
SPECIFICATION

NOTES: YS - 70KSI, UTS - 154KSI, EL % - 4D - 55.0, RA - 51.4%
Cr - 22.0, W - 14.0, Ni - 22.0, Fe - 1.5, La - .08%, C - .08, Co - Balance



Channel Wall

Pressure Bending Stress



$M = pL^2 \div 12$

$℄ \text{ stress} = \sigma_{℄} = \frac{6M_{℄}}{t^2} = \frac{6}{t^2}\frac{pL^2}{24} = \frac{pL^2}{4t^2}$

$\sigma_{℄} = \frac{(2100)(.08)(.08)}{(4)(.015)(.015)}$

$\sigma_{℄} = 14.9$ ksi = Max. bending stress

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Channel Wall

Material Study

On page 3 of section 4.2.2 it is stated that $(F_{TY})_W t_W$ must equal $(F_{TY})_B t_B$ if the thermal strain analysis is to be valid. When $(F_{TY})_W t_W = (F_{TY})_B t_B$ the $\alpha \Delta T$ from back wall to Hot wall will be split 1/2 to each wall. This is important in order to minimize thermal strain in each wall. As indicated on page 2 of section 4.2.2 a preliminary estimate of allowable ϵ_e for Haynes 188 is 0.0056 in./in. The following tabulation of material data was prepared to aid in studying material selection. It appears that 304L or 347 CRES at -200 to -300 °F for the back wall will match the Haynes and ARMCO alloys reasonably well at 500 to 600 °F. Thicknesses can be adjusted to optimise matching depending on exact temperatures.

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Material	Temp. °F	F_{TU} Ksi	F_{TY} Ksi	RA. %	ϵ_e * For 42000 ~ in/in
304L	-300	180	45	53	.0069
	-200	154	44	56	
	1700	12	8	—	—
347	-300	190	51	65	.0075
	-200	160	49	67	
	1700	15	10	—	—
Haynes Alloy No. 188	400	123	53	57	.0054
	600	117	48	55	
	1700	45	33	—	—
ARMCO 21-6-9	400	90	42	65	.0048
	600	86	38	60	
	1700	15	14	—	—
ARMCO 22-13-5	400	101	49	64	.0053
	600	98	46	63	
	1700	18	15	—	—

* Universal slopes equation used.

Note: Data above are typical values.

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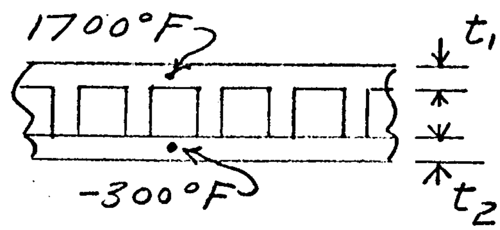
Worst Case Malfunction

Assume:

1. Channel Design



$t_1 = t_2$

2. Haynes Alloy No. 188
3. Temperatures as shown in sketch

Hot Wall Thermal Strain

$\alpha \Delta T (70°F \text{ to } 1700°F) = (9.65)(10^{-6})(1630) = .0157$ in./in.

$\alpha \Delta T (70°F \text{ to } -300°F) = (5.6)(10^{-6})(370) = \underline{.0021}$ in./in.

$\Sigma\ \alpha \Delta T (-300°F \text{ to } 1700°F) = .0178$ in/in.

E @ $1700°F = 23 \cdot 10^6 = E_W$

E @ $-300°F = 36 \cdot 10^6 = E_B$

$t_W = t_B$

$$K_W = \frac{t_B E_B}{t_W E_W + t_B E_B} = \frac{E_B}{E_W + E_B}$$

$$K_W = \frac{36}{23 + 36}$$

$$K_W = .61$$

$$\epsilon_{WT} = K_W \Sigma \alpha \Delta T$$

$$\epsilon_{WT} = (.61)(.0178) = .0109 \text{ in/in.}$$

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Worst Case Malfunction (Cont.)

Hot Wall Thermal Strain (Cont.)

~~$\epsilon_{we} = 2\epsilon_w = (2)(.0109)$~~

~~$\epsilon_{we} = .0218$ in./in.~~

Pressure Load Strain

Assume pressure stress = 23 Ksi

$$\epsilon_{wp} = \frac{2.3000 \cdot 10^4}{23 \cdot 10^6}$$

$$\epsilon_{wp} = 10^{-3} = .001$$

Combined Thermal & Pressure Load Strain

$$\Sigma\epsilon_w = \epsilon_{wT} + \epsilon_{wp} = .0109 + .001$$

$$\Sigma\epsilon_w = .0119 \text{ in./in.}$$

A biaxial state of strain exists

Assume $\epsilon_{wa} = \epsilon_{wl}$

Then $\epsilon_{we} = 2\Sigma\epsilon_w = (2)(.0119)$

$\epsilon_{we} = .0238$ in./in.

Life Expected:

Using Universal Slopes data, a life of more than 500 cycles is predicted at the above value for ϵ_{we}.

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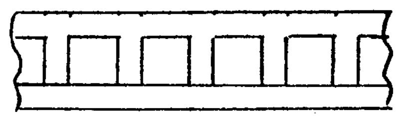
Estimated Allowable Temperatures

Assumptions

1. Channel Design



2. Haynes Alloy No. 188
3. Nominal operating pressure = 1600 psia

Creep Damage Fraction

Pressure loading stress only will be considered for creep damage. Yield strength of Haynes 188 at 1700 °F will approximate the allowable pressure stress at nominal operating pressure.

Assume $\sigma_p = 25000$ psi

At typical expected operating temperatures (less than 1000 °F) the time to rupture at 25 Ksi is greater than 5000 hours.

With 50 hours fireing time

$$\phi_c = \frac{50}{5000} = 0.01$$

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Estimated Allowable Temperatures

Fatigue Damage Fraction

$$4\phi_c + 4\phi_f = 1$$

$$\phi_c = \cancel{.05}\ .01$$

$$.04 + 4\phi_f = 1$$

$$\phi_f = .24 \text{ max.}$$

$$n = 10{,}000$$

$$\phi_f = \frac{n}{N_f} = .24 = \frac{10000}{N_f}$$

$$N_f = 42{,}000 \text{ cycles}$$

Allowable Strain Range

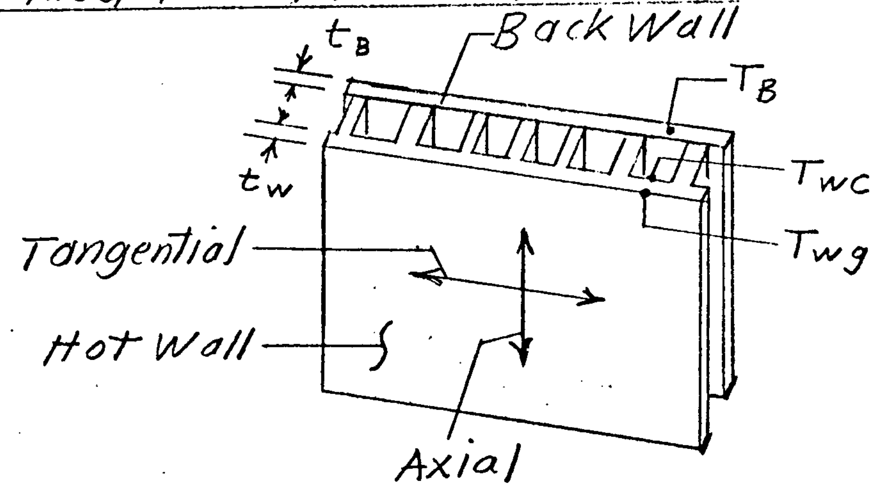
Universal Slopes equation data will be used.

For $N_f = 42{,}000$ and temperature between 0 and 1000°F $\epsilon_e \cong .0056$

Assume $\epsilon_e = 0.0056$ allowable

Estimated Allowable Temperatures

Calculation Method For Thermal Strain



Assume $\epsilon_{Ta} = \epsilon_{T\ell}$

$$\epsilon_{WT} = \pm \frac{\alpha_w}{2}(T_{wg} - T_{wc}) - \left[\alpha_w\left(\frac{T_{wg}+T_{wc}}{2} - T_A\right) - \alpha_B(T_B - T_A)\right]\left[\frac{1}{2}\right]$$

$$\epsilon_{BT} = \left[\alpha_W\left(\frac{T_{wg}+T_{wc}}{2} - T_A\right) - \alpha_B(T_B - T_A)\right]\left[\frac{1}{2}\right]$$

The above equations apply if $(F_{TY})_W t_W = (F_{TY})_B t_B$

Calculation Method For Pressure Strain

Assume $\sigma_p = 25$ ksi (page 1)

Assume $E = 30 \cdot 10^6$

$$\epsilon_p = \frac{25 \cdot 10^3}{30 \cdot 10^6}$$

$\epsilon_p = 0.00083$ in/in.

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Estimated Allowable Temperatures

Calculation Method For Equivelant Uniaxial Strain

Assume $\epsilon_a = \epsilon_\ell$

$\epsilon_a = \epsilon_T + \epsilon_p$

Assume a biaxial state of applied strain

$\epsilon_e \cong \epsilon_a$ for all elastic strain

$\epsilon_e = 2\,\epsilon_a$ for highly plastic strain

Assume $\epsilon_e = 1.5\,\epsilon_a$ for this analysis.

Equivelant Uniaxial Strain - Hot Wall

$$\epsilon_{WT} = -\frac{\alpha_W}{2}(T_{wg} - T_{wc}) - \left[\alpha_W\left(\frac{T_{wg}+T_{wc}}{2} - T_A\right) - \alpha_B(T_B - T_A)\right]\left[\tfrac{1}{2}\right]$$

$$= -\frac{\alpha_W T_{wg}}{2} + \frac{\alpha_W T_{wc}}{2} - \frac{\alpha_W T_{wg}}{4} - \frac{\alpha_W T_{wc}}{4} + \frac{\alpha_W T_A}{2} + \frac{\alpha_B T_B}{2} - \frac{\alpha_B T_A}{2}$$

$$\epsilon_{WT} = -\frac{3}{4}\alpha_W T_{wg} + \frac{\alpha_W T_{wc}}{4} + \frac{\alpha_W T_A}{2} + \frac{\alpha_B T_B}{2} - \frac{\alpha_B T_A}{2}$$

αT_A will be made $= 0$

$$\epsilon_{WT} = -\frac{3}{4}\alpha_W T_{wg} + \frac{\alpha_W T_{wc}}{4} + \frac{\alpha_B T_B}{2}$$

$\epsilon_{WP} = 0.00083$ in/in

$\epsilon_e = 0.0056$ allowable for required life

$\epsilon_e = 1.5(\epsilon_{Wa}) = 1.5(\epsilon_{WT} + \epsilon_{WP})$

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Estimated Allowable Temperatures

Equivelant Uniaxial Strain - Hot Wall

$$-.0056 = 1.5\left(-\frac{3}{4}\alpha_w T_{wg} + \frac{\alpha_w T_{wc}}{4} + \frac{\alpha_B T_B}{2} - .00083\right)$$

$$.00373 = \frac{3}{4}\alpha_w T_{wg} - \frac{\alpha_w T_{wc}}{4} - \frac{\alpha_B T_B}{2} + .00083$$

$$.00290 = \frac{3}{4}\alpha_w T_{wg} - \frac{\alpha_w T_{wc}}{4} - \frac{\alpha_B T_B}{2}$$

$$.01160 = 3\alpha_w T_{wg} - \alpha_w T_{wc} - 2\alpha_B T_B$$

Values of T_{wg} will be assumed and allowable corresponding values of T_{wc} and T_B calculated.

$T_{wg} = 600$:

$$3\alpha_w T_{wg} = 0.01176$$

$$+.00016 = +\alpha_w T_{wc} + 2\alpha_B T_B$$

T_B	$2\alpha_B T_B$	$\alpha_w T_{wc}$	T_{wc}
~~-400~~	~~-.00508~~	~~.00524~~	~~760~~
~~-300~~	~~-.00420~~	~~.00436~~	~~660~~
-200	-.00314	.00330	530
-100	-.002	.00216	380
0	-.000868	.00103	230
+70	0	.00016	90

$T_{wg} = 500$:

$$3\alpha_w T_{wg} = .00935$$

$$-.00225 = +\alpha_w T_{wc} + 2\alpha_B T_B$$

T_B	$2\alpha_B T_B$	$\alpha_w T_{wc}$	T_{wc}
-300	-.00420	.00195	360
-200	-.00314	.00089	210
-100	-.002	-.00025	30
-400	-.00508	.00283	470
0	-.000868	-.00138	-160

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Estimated Allowable Temperatures

Equivelant Uniaxial Strain - Hot Wall

$T_{wg} = 400°$

$3\alpha_w T_{wg} = .00693$

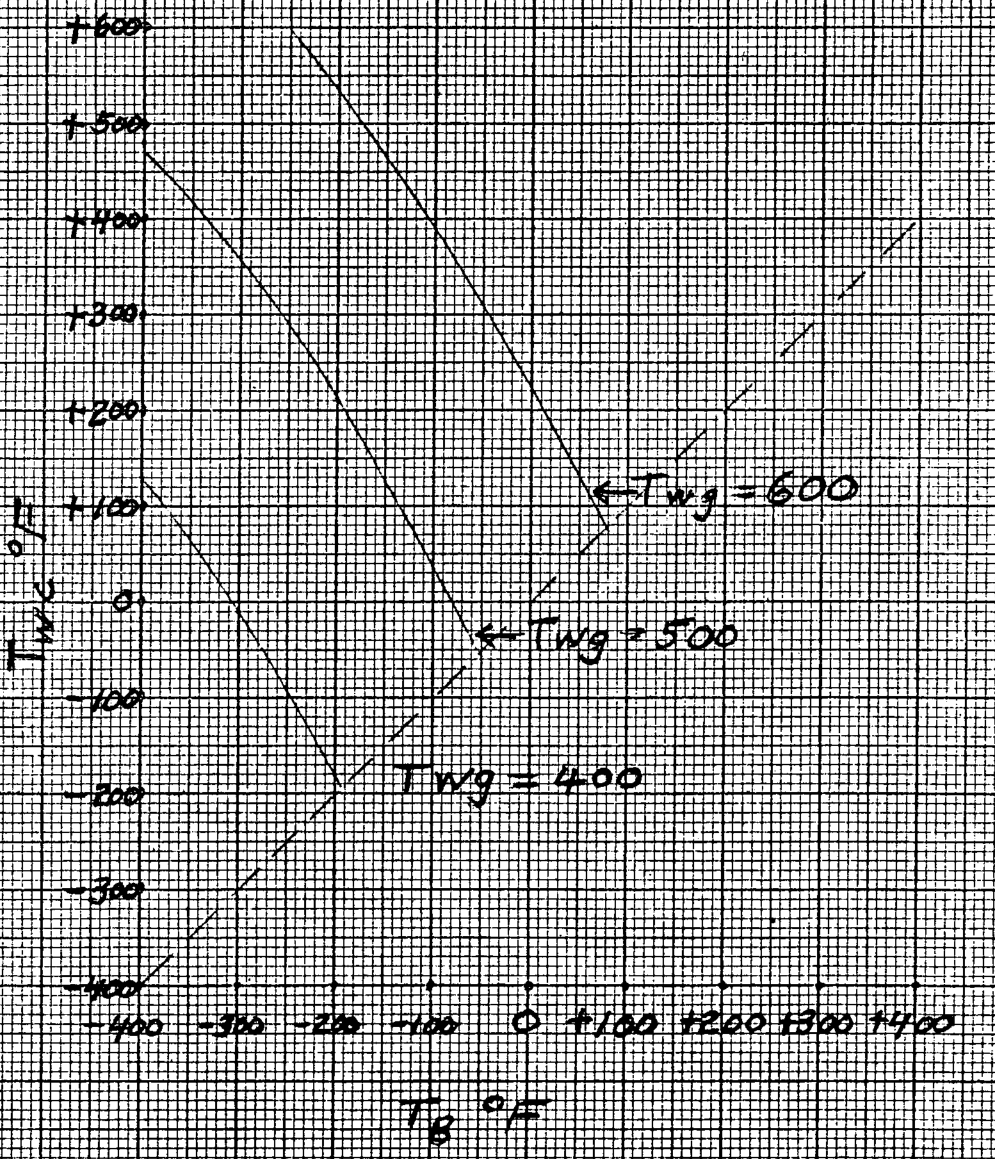
$-.00467 = +\alpha_w T_{wc} + 2\alpha_B T_B$

T_B	$2\alpha_B T_B$	$\alpha_w T_{wc}$	T_{wc}
-400	-.00508	+.00041	130
-300	-.00420	-.00047	-10
-200	-.00314	-.00153	-180
~~100~~	~~-.002~~	~~-.00267~~	
~~0~~	~~-.000868~~		

ESTIMATED ALLOWABLE TEMPERATURES

HAYNES 188

Notes:
1. Practical operating region is to the left of dash line
2. Allowable operating region is to the right and above the solid lines.



APPENDIX B

DEAP COMPUTER PROGRAM

PURPOSE

This computer program is intended to provide a basic tool for the solution of second-order partial differential equations. Parabolic, hyperbolic, and elliptic problems in one, two, or three spatial dimensions can all be solved through use of the Differential Equation Analyzer Program (DEAP). The general hyperbolic differential equation solved by the program can be represented as:

$$\nabla \cdot (K \nabla \varphi) + \vec{W} \cdot \nabla \varphi + s \varphi + q = \lambda \frac{\partial^2 \varphi}{\partial t^2} + \rho c \frac{\partial \varphi}{\partial t} \qquad (1)$$

Normally, several of the coefficients in Eq. 1 will be zero, resulting in the specialization of the equation to a parabolic equation ($\lambda = 0$) or to an elliptic equation ($\lambda = 0$ and $\rho c = 0$). This equation is useful for solution of physical problems relating to mechanical, thermal, mass diffusion, acoustic, magnetic, and electrical physical systems. The DEAP computer program has the capability of solving distributed network problems representing any of these physical systems.

The DEAP computer program solves problems related to the behavior of a continuous physical system through the analogy of a lumped parameter (or nodal) representation that is solved by difference methods. The difference solution method used is a three-time-level method which is a modification of the DuFort Frankel Method that is stable for any computational time increment and is well suited for non-linear problems (where the coefficients of Eq. 1 are functions of the dependent variable).

PROGRAM DESCRIPTION

The DEAP computer program described in this manual is a descendant of the Lockheed Thermal Analyzer Program through the TAP computer program which was obtained from AI. The TAP computer program logic was revised and the program capabilities enlarged at Rocketdyne to produce the DEAP computer program. This program has retained the capability to solve any existing TAP problem with only minor changes to the data deck.

The DEAP computer program can solve problems with up to 999 discrete nodes and 2999 connectors allowing for source terms that can either be constant or variable with the dependent variable value at each node. This manual is divided into two major sections. The first section is ENGINEERING ANALYSIS, where the mathematical model is defined and the difference equations used by the computer program to represent this model are stated. The accuracy and limitations of the solution methods are discussed and a discussion of the stability of the equations is presented. The derivation of several special-purpose boundary-condition treatments is also given, followed by a discussion of program logic. The second section gives USAGE INFORMATION and defines the data input requirements first in general terms and then in detail where each of the 11 input sections is described in terms of its requirements and limitations. The program output is described and a sample problem discussed to illustrate the program features.

With relationship to evaluating thermal conditioners, the DEAP program is currently being employed to determine two-dimensional temperature profiles around the coolant channels. For a given gas temperature, gas-side heat transfer coefficient, coolant bulk temperatures (usually different in adjacent passages) and coolant side film coefficients, as well as channel geometry and thermal conductivity (as a function of temperature), the program determines wall temperature profiles, either steady-state or as a function of time (Fig.B-1).

The program has the capability to utilize the geometry directly to determine thermal resistances and capacitances; in this case, specific instructions are included as part of the input to tell the computer how to determine these variables. The program also has the capability of correcting heat transfer coefficients for all temperature. The output is principally the temperature distribution through the wall. This temperature distribution is used directly in the design in numerous ways. It is used to determine if the life criteria will be met, the average heat flux, the distribution of the heat input between adjacent channels, whether the wall surface temperature is too cold and what the best way is to get around this potential problem, whether the coolant mass velocity can be reduced (thereby saving pressure drop), the effect of geometry tolerances, the effect of coolant bypass, selection of coolant circuit, and other variables associated with the design of the conditioner.

In addition, a more sophisticated geometry is being programmed for the DEAP program which would simulate a full baffle. This is a useful tool for analyzing a given design, as it would be capable of analyzing flow transients and would

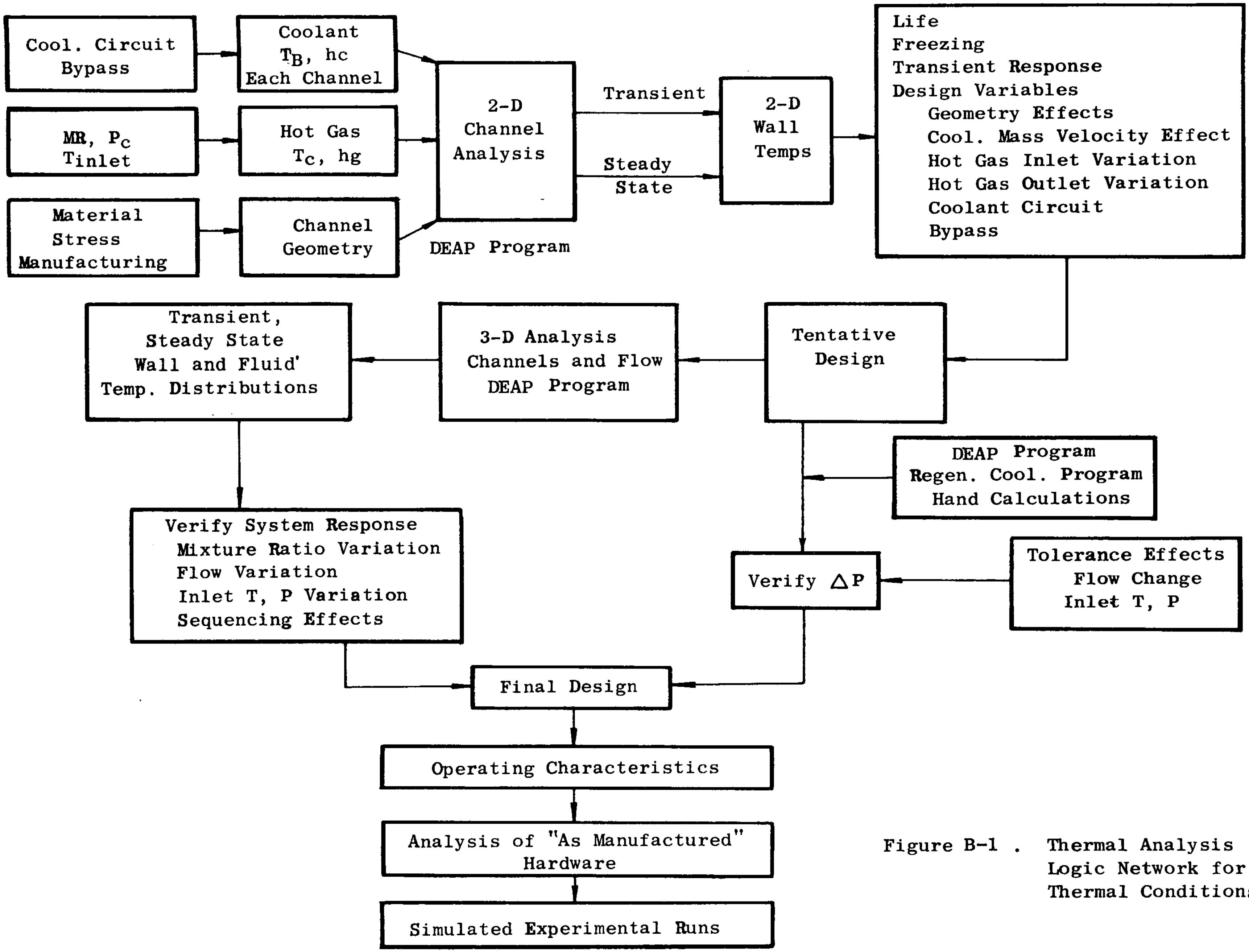


Figure B-1 . Thermal Analysis Logic Network for Thermal Conditions be used to insure that the thermal transient requirement would be satisfied. It is also a handy tool for analyzing the effect of flow or mixture ratio changes. The program is even capable of integrating the rest of the APS system to obtain data on the integrated system. This program is a very versatile tool; it does, however, require a fair amount of time to set up the initial geometry of the problem. Once this is done, it is a simple matter to change lengths, heat transfer coefficients, initial conditions, etc.