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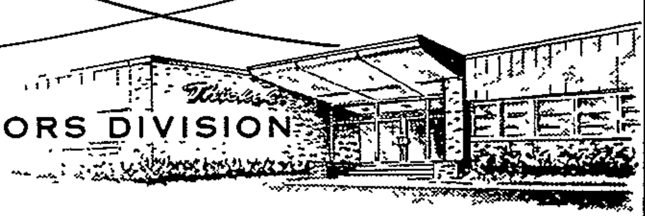
Thiokol CHEMICAL CORPORATION

RMD 6062-F

FINAL REPORT

OF_2/Diborane Thrust Chamber Assemblies

17 April 1969



REACTION MOTORS DIVISION
DENVILLE, NEW JERSEY

Thiokol
REACTION MOTORS DIVISION
DENVILLE, NEW JERSEY

RMD 6062-F

FINAL REPORT

OF_2/Diborane Thrust Chamber Assemblies

17 April 1969

RMD Project No. 6062
JPL Purchase Order 952296

Prepared by: L. VanDerJagt
L. VanDerJagt
Engineering Specialist

Approved by: M. J. Webb
M. J. Webb
Product Engineering
Section Chief

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I. INTRODUCTION

This report was prepared as the Final Technical Report for Jet Propulsion Laboratory, Pasadena, California, under Purchase Order 952296 to the Reaction Motors Division, Thiokol Chemical Corporation. The objectives of the program were to design, fabricate and deliver two thrust chamber assemblies to JPL for evaluation with OF_2/B_2H_6 propellant combination. This report describes the effort conducted by Thiokol-RMD during the period from 12 September 1968 through 1 May 1969.

The unique thrust chamber approach selected to fulfill the JPL specified requirements is termed the Radiabatic concept (Figure 1). This thrust chamber approach provides increased chamber durability over a wide range of operating conditions with the presently operational and advanced high energy, high flame temperature propellants.

As shown in Figure 1, the Radiabatic concept employs solid pyrolytic graphite pieces as the chamber heat transfer medium analagous to the propellant coolant of a regenerative engine design. In the nozzle region, the heat input from the combustion gases is partially transferred by conduction through the "heat pipes" of anisotropic pyrolytic graphite, arranged to provide high radial and axial conductivity so that the heat is conducted forward toward the injector, where it is rejected to the cool boundary provided by the injector.

There have been a number of concepts in the past which employed solid state multi-dimensional heat transfer. Unfortunately, these approaches have failed, in general, to acknowledge the shortcomings of the anisotropic material, i.e., a tendency toward delamination in a combustion environment and high thermal growth. The Radiabatic concept presented herein uses the best characteristics of pyrolytic graphite and overcomes its shortcoming by proper design. Figure 2 shows a photograph of the two deliverable thrust chambers.

II. DESCRIPTION AND DESIGN SUMMARY

1. Requirements

The purchase order requires that two thrust chamber assemblies be designed and fabricated to meet the following conditions and constraints.

Conditions

. Propellants	OF_2/B_2H_6
. Thrust	200 lb
. Chamber Pressure	100 psia
. Duration	1000 seconds
. Core Mixture Ratio	3.0
. Boundary Mixture Ratio	1.0

Constraints

- Chamber is to interface with JPL injector as defined by Control Drawing No. 10022030, Revision A, dated February 5, 1968
- Chamber internal dimensions shall conform to JPL Control Drawing No. 10022020, Revision B, dated March 1, 1968
- Minimum external dimension. Skin temperature not to exceed 600°F during firing
- Minimum weight
- Adaptable to future flightweight 60:1 expansion area ratio nozzle
- Chambers shall be fabricated from one of the following materials or combination thereof:
  1) Graphite
  2) Pyrolytic Graphite
  3) Reinforced Carbon Fibers
  4) Any other carbonaceous composites

2. Design Description

The Radiabatic thrust chamber, shown in Figure 1, presents the concept that Thiokol-RMD delivered for the JPL requirements. The interfaces, weight and envelope dimensions are defined in Figure 3. Figure 1 defines the significant features of the Radiabatic thrust chamber which are discussed below.

Liner Assembly

The Radiabatic thrust chamber liner was fabricated from ATJS Graphite. This is a premium grade ATJ graphite and provides a minimum throat erosion. The material is essentially flaw free and, in addition, has excellent thermal shock resistance. The liner is one continuous structure that is retained at the injector end by pyrolytic graphite plates and is permitted to grow axially at the nozzle end. The liner I.D. was contoured as defined in the JPL interface drawing. The liner O.D. was match contoured to the pyrolytic graphite wedges to provide maximum thermal contact.

This improved ATJ type graphite was developed to provide a fine grain with higher physical properties and increased resistance to thermal shock and erosion. The improvements in physical properties is reflected by an increase in density, tensile strength, flexure strength and compressive strength. A lower modulus is a significant factor in the high thermal shock resistance of this grade. Coupled with these physical improvements is a decrease in permeability achieved through fewer pores of decreased diameter. Each of these factors contributes to greater erosion resistance. The liner thickness is increased in the throat area to provide for throat erosion if experienced. Figure 4 shows a photo of the finished liner assembly.

Axial Heat Conduction Wedges

The axial heat conduction wedges were fabricated out of plate pyrolytic graphite with the highly conductive A-B planes oriented parallel to the axial centerline. The graphite liner will conduct the heat into the wedges from whence the heat will be conducted into the outer insulation and transferred back into the chamber gases at the cooler injector end of the chamber. The axial heat is blocked at the injector end by P.G. wafers to provide acceptable temperatures at the interface. The pyrolytic graphite wedges were fabricated in 1/2 inch plates by depositing pyrolytic graphite on a flat mandrel. Pyrolytic graphite plate fabricated in this manner is substrate nucleated with the cone growth from the deposited surface through the plate. This thickness plate can be fabricated with basically no delaminations. Grafoil crushable tape was provided between the wedges to provide for thermal expansion during operation and precise spacing during fabrication. Figure 5 shows a photo of a finished wedge along with a strip of grafoil tape. Figure 6 shows a photo of the wedge assembly.

Liner/Pyrolytic Graphite Wedge Assembly

It is essential to achieve good thermal transfer from the ATJS liner to the pyrolytic graphite wedges. The following fabrication procedure was followed for this interface:

1) Machine the liner to the required contour

2) Match contour wedge assembly using liner as a templet

3) Lap the interface surfaces between the liner and wedge assembly to obtain intimate contact

4) Cement the parts together utilizing compression tooling.

Crushable Retainer Ring

The crushable retainer ring was fabricated from grafoil tape. This ring is designed to retain the pyrolytic graphite wedges against the graphite liner during the thermal transients and will provide a cushion to take up the thermal growth of the pyrolytic graphite radial insulator which is retained on the O.D. by the chamber shell. The grafoil tape crushing strength is considerably less than pyrolytic graphite indicating that the tape will be the component that crushes as is desired.

Radial Insulation Cylinder

The radial insulation cylinder was made from a single piece of pyrolytic graphite. This cylinder provides high temperature insulation between the hot wedges and the chamber shell. The cylinder is designed so that the temperature gradient is sufficient to permit the use of conventional materials for the outer insulation and the chamber shell. Radial thermal expansion was compensated for by the fabrication technique of the pyrolytic graphite and an expansion joint.

The pyrolytic graphite used for the internal insulation was fabricated on a male mandrel. This structure is stress free at 4000F and when it cooled it delaminated in the circumferential direction. This pyrolytic has a slightly lower density and thermal conductivity than a similar part fabricated on the I.D. of a mandrel. This fabrication technique was ideal for this application. When the unit is fired these delaminations will act as spring and reduce the thermal growth loads against the chamber wall. Figure 7 shows a photo of the pyrolytic graphite internal insulation cylinder.

Chamber Jacket Assembly

The chamber jacket assembly was fabricated from C-103 columbium alloy, a medium strength refractory material selected primarily on the basis of its suitability for the application, its excellent fabrication characteristics and its weldability.

A silicide protective coating was applied to provide oxidization and carbide protection for operating temperatures up to 3200°F.

The C-103 columbium alloy has a recrystallization temperature range of 2200F and a brittle ductile transition point below -320F. Since the design temperatures of the columbium approach the recrystallization temperature, the physical properties of recrystallized material will be used. This yields a conservative design.

Figure 8 shows a photo of the jacket assembly with a piece of the outer insulation and the outer shell.

Outer Insulation

The outer diameter insulation was fabricated using Johns-Manville Dyna-Flex. Dyna-Flex is a strong, long fiber, flexible thermal insulation suitable for continuous operating temperatures up to 2700°F. Dyna-Flex is formed from alumina-silica-chromia fibers having a melting point well over 3000°F, and the ability to retain a soft fibrous structure at 2700°F. The material is protectived by a thin stainless steel cylinder.

The outer skin at the injector end is insulated by a silica phenolic ring.

Gaskets

A grafoil gasket is encompassed between the silica phenolic insulator and the thrust chamber liner assembly. This gasket provides sealing during thermal expansion of the assembly. Figure 9 shows the mechanical properties of the gasket.

A silicone gasket is installed between the injector adapter flange and the silica phenolic insulator to provide sealing and additional thermal expansion capability.

Other photos of the assembly and details are included as Figures 10 through 16, and are defined as follows:

Figure 10	Thrust Chamber Assembly
Figure 11	Thrust Chamber Liner Assembly
Figure 12	Injector Flange/Insulator/Grafoil Gasket
Figure 13	Thrust Chamber Liner Assembly & Jacket Shell (Injector End)

Figure 14	Thrust Chamber Liner Assembly & Jacket Shell (Nozzle End)
Figure 15	Liner, Wedge Assembly & Radial Insulator
Figure 16	Wedge Assembly

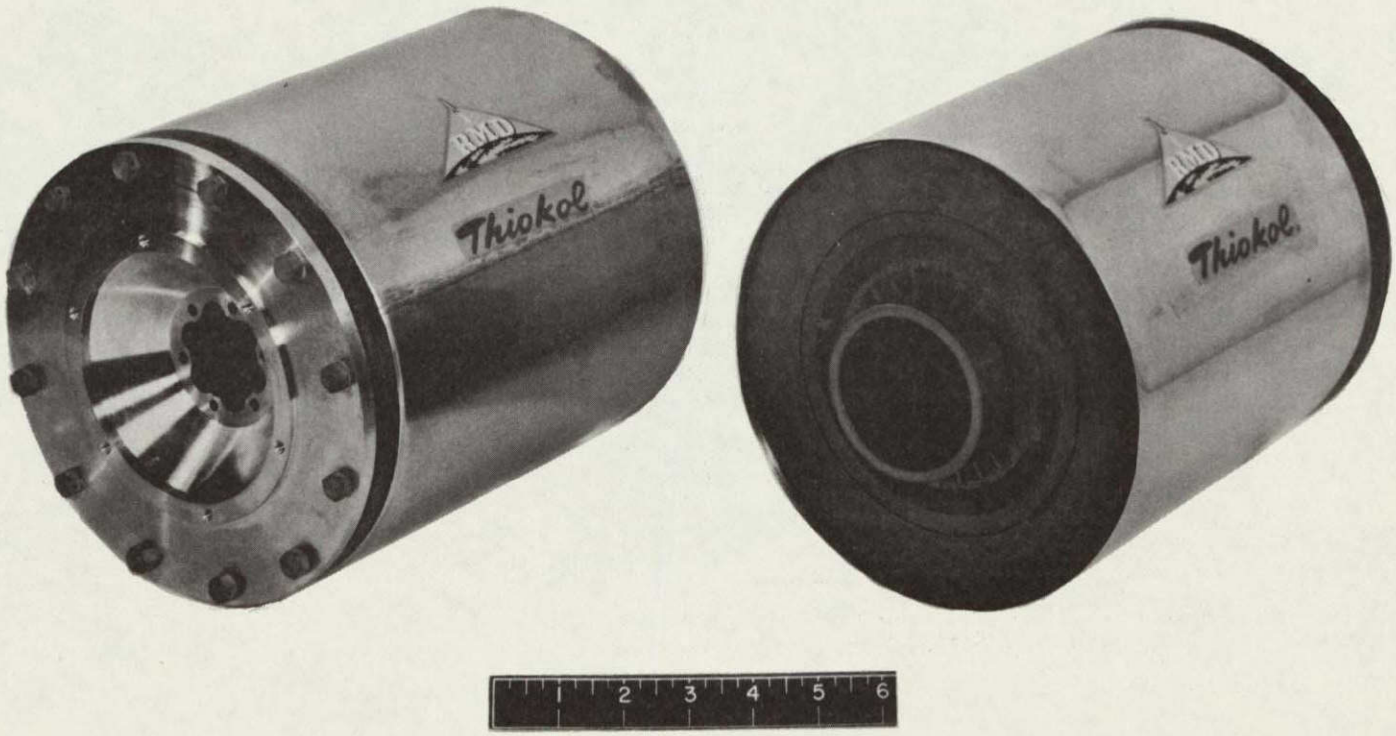
3. Design Analysis

A thermal and stress analysis was performed in conjunction with the design. These reports are included as Appendix A&B and are defined as follows:

Appendix A	DS 100-134	Thermal Analysis of the JPL OF_2/DB Thrust Chamber
Appendix B	DS 100-135	JPL OF_2/DB Thrust Chamber Design Analysis.

III. CONCLUSIONS

Two Radiabatic thrust assemblies were designed and fabricated to meet the JPL specified conditions and constraints. These thrust chambers will be subjected to experimental testing with OF_2/B_2H_6 at JPL later this year.



6062-13

FIGURE 2. JPL OF_2/B_2H_6 THRUST CHAMBER ASSEMBLIES

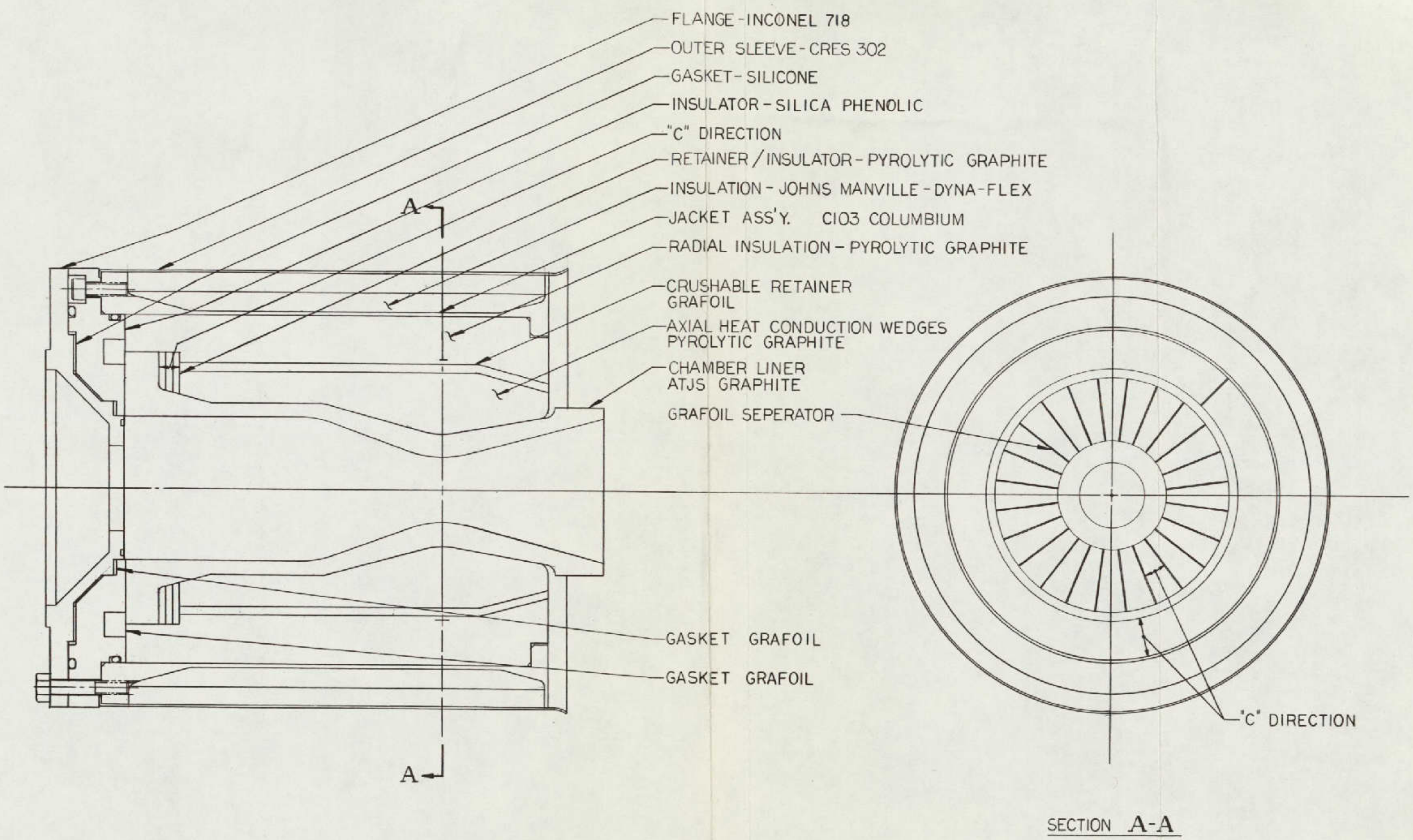


FIGURE 1. RADIABATIC THRUST CHAMBER DESIGN

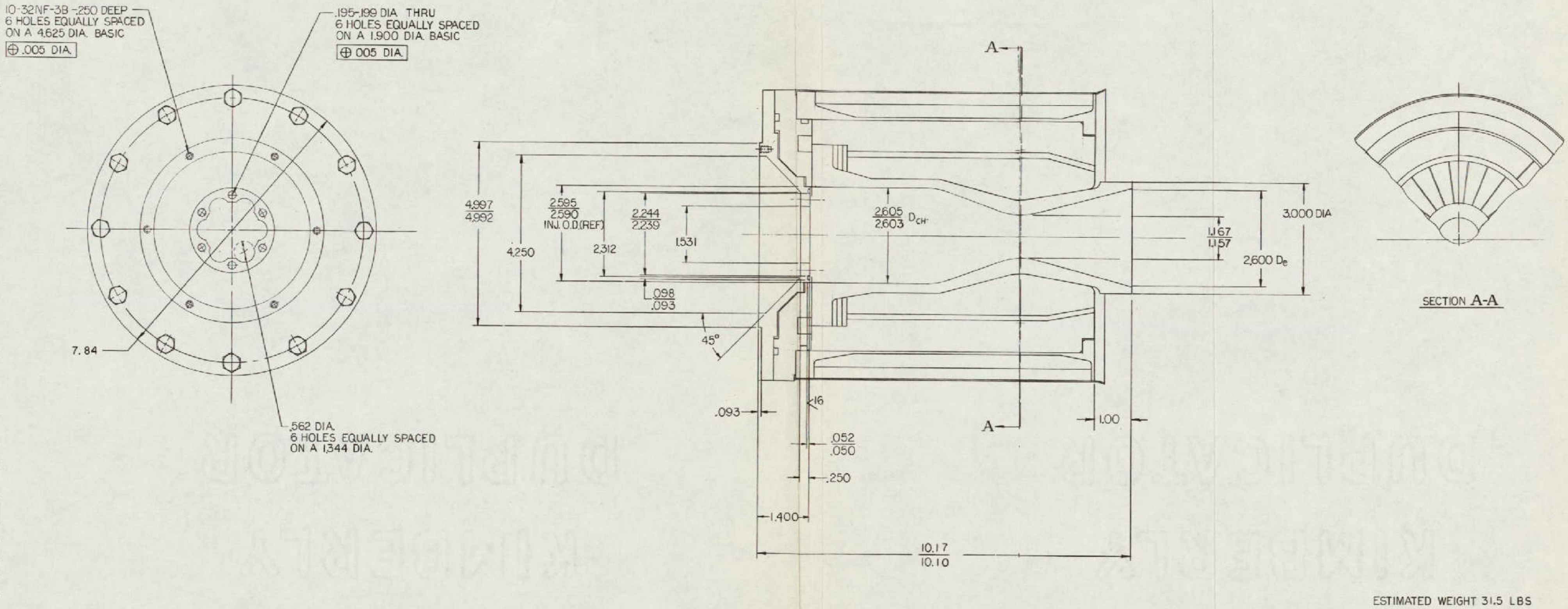


FIGURE 3. RADIABATIC THRUST CHAMBER INTERFACES

FOLDOUT FRAME

FOLDOUT FRAME

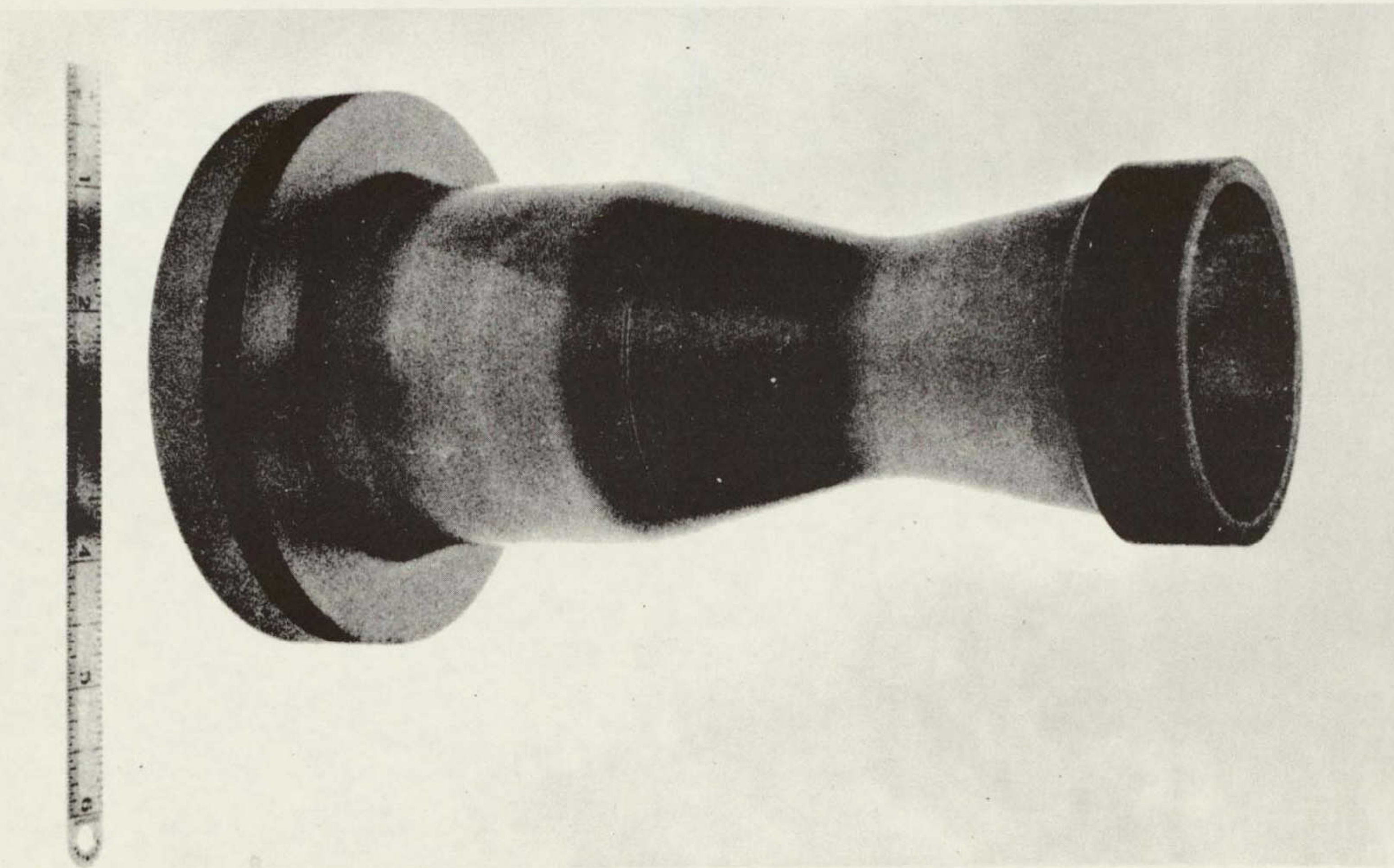


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FIGURE 4. LINER ASSEMBLY

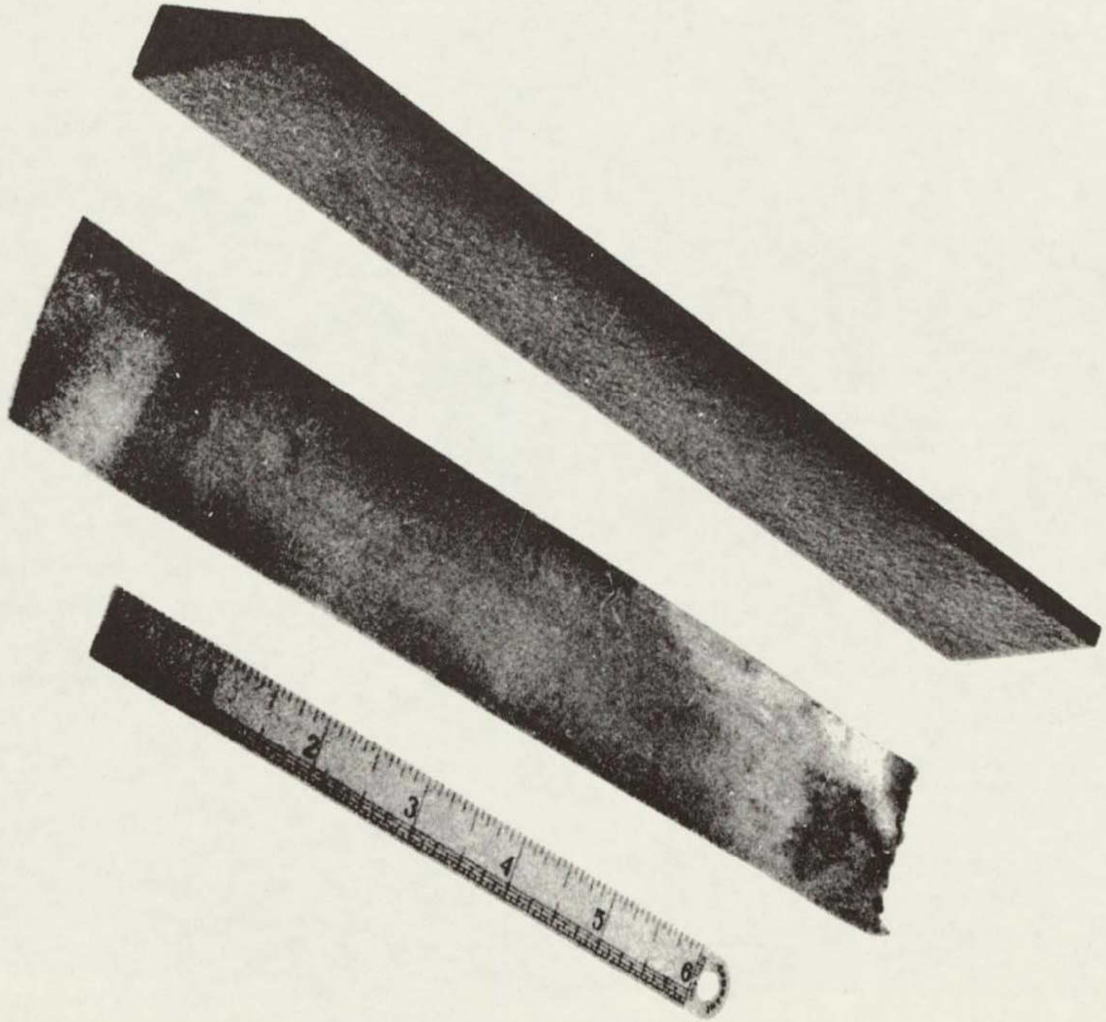

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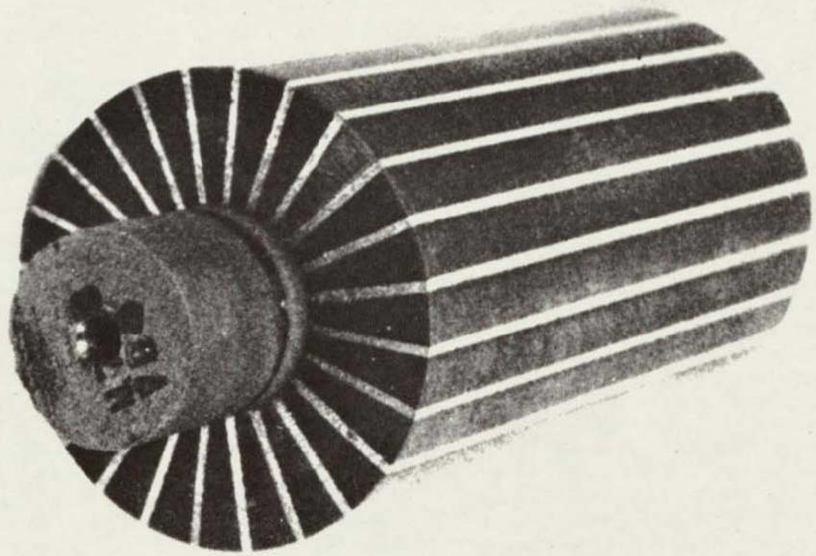
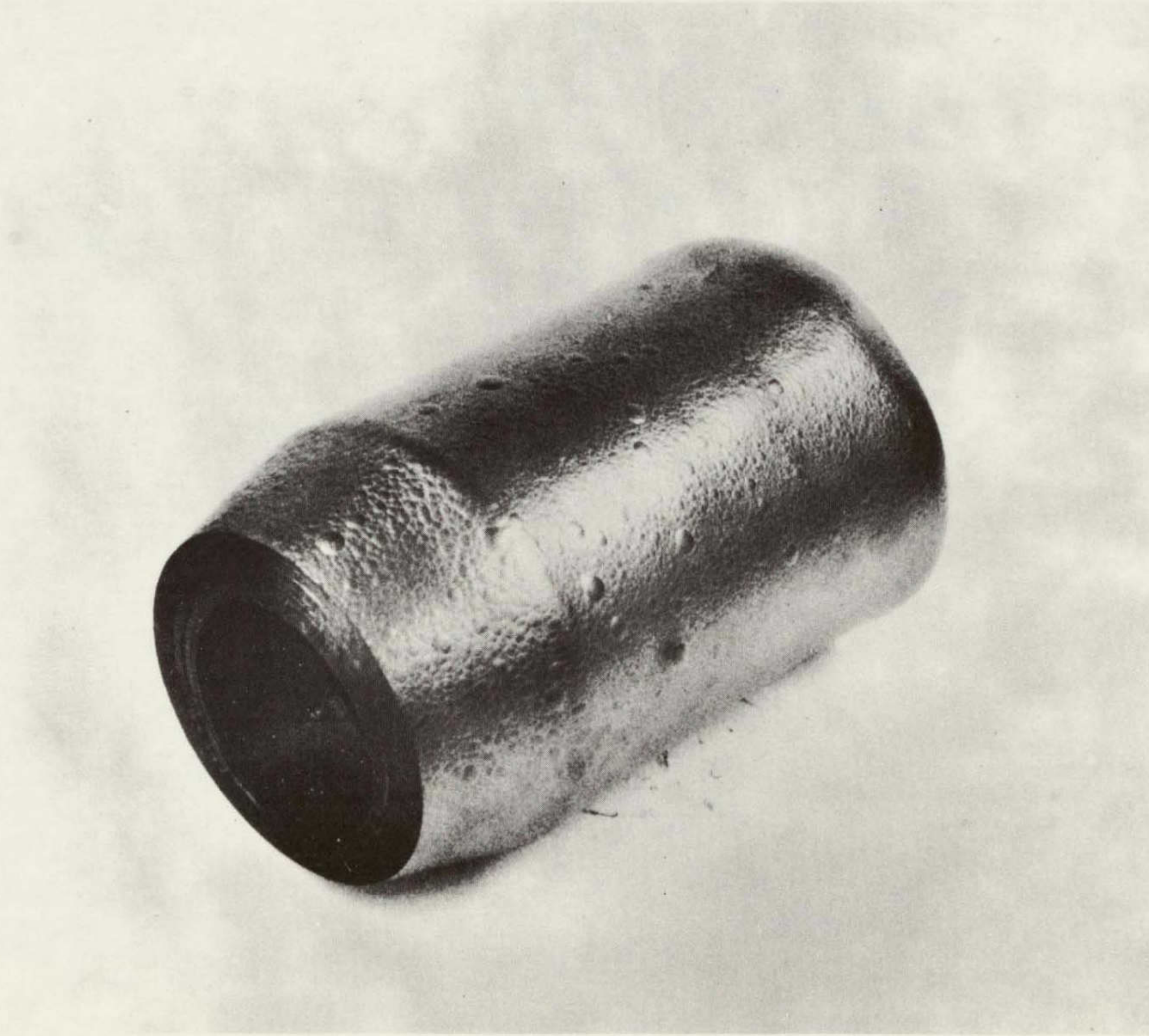
FIGURE 5. AXIAL HEAT CONDUCTION WEDGE AND GRAFOIL STRIP



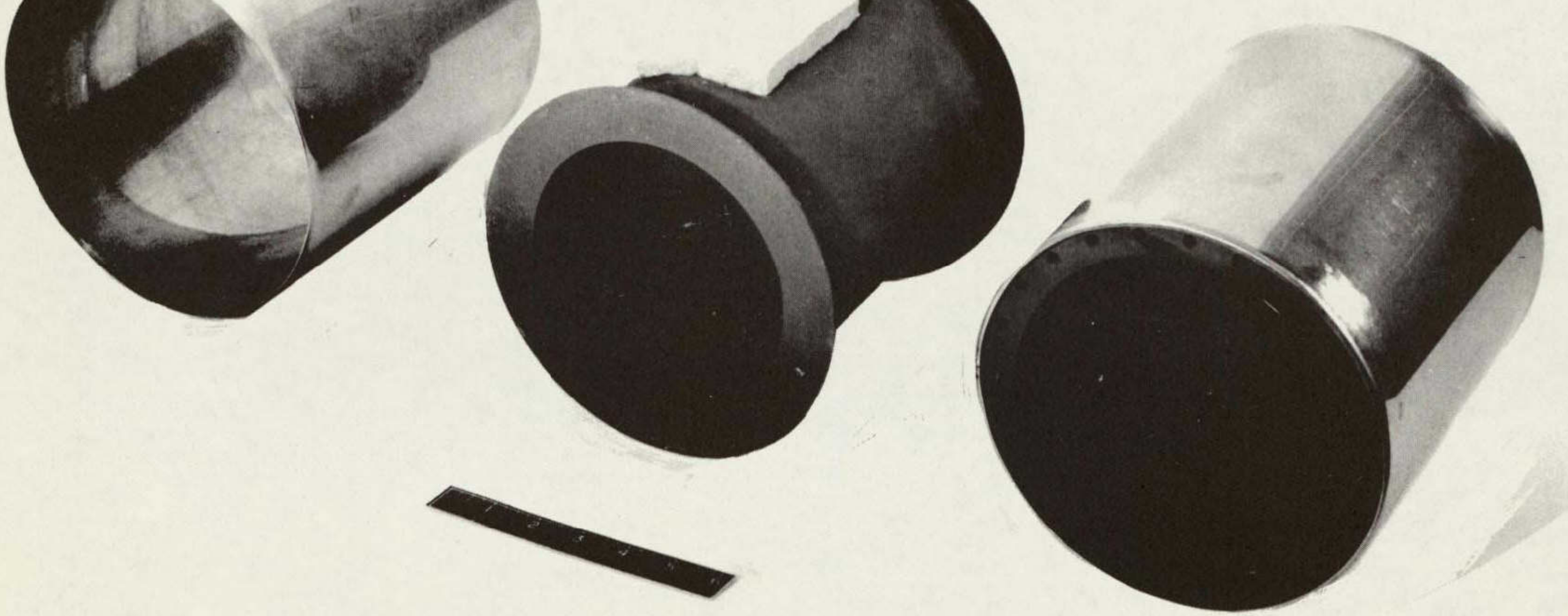
6062-2

FIGURE 6. AXIAL HEAT CONDUCTION WEDGE ASSEMBLY



6062-4

FIGURE 7. RADIAL INSULATION CYLINDER



6062-8

FIGURE 8. JACKET/INSULATION/SHELL ASSEMBLY

Compression Relaxation

Grafoil Laminate, Grade GHA

Typical Density 70 lbs/$_{ft}$3

Thiokol Order C 33876
HTMD No. 4644

Data

Free Height: .500 in (Ref)
* Installed Height: .380 in
Height @200 psi (Rm temp.): .414 in
* Height @200 psi @ 3100°F: .432

*Design Criteria

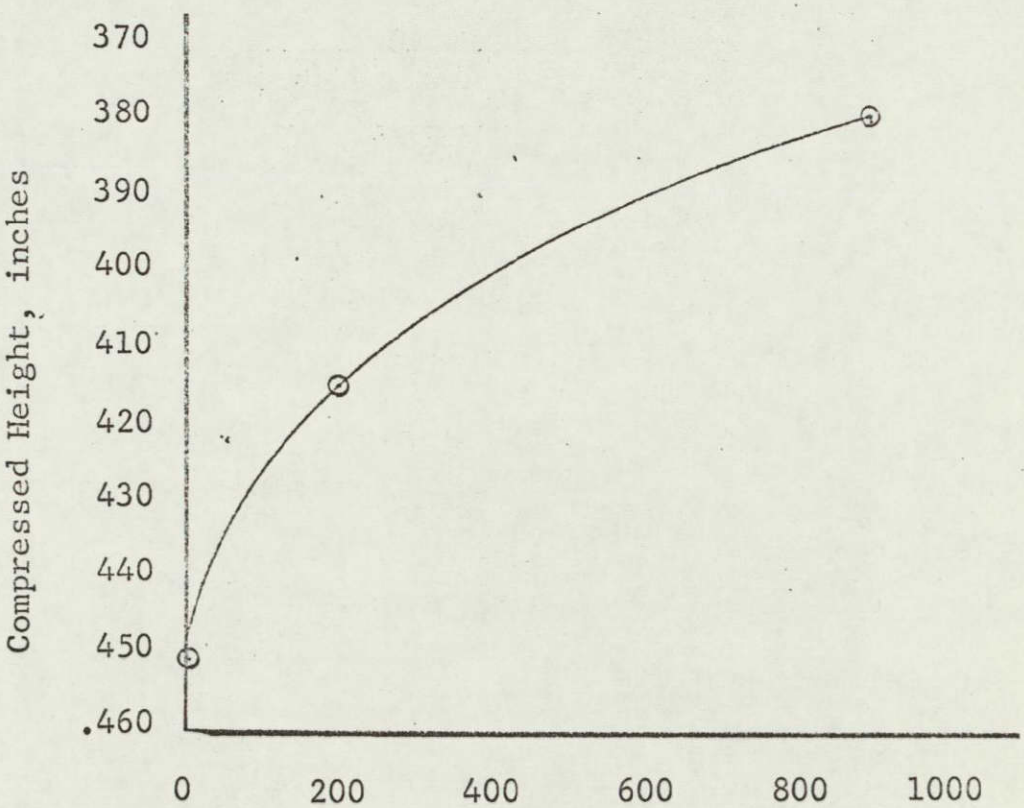
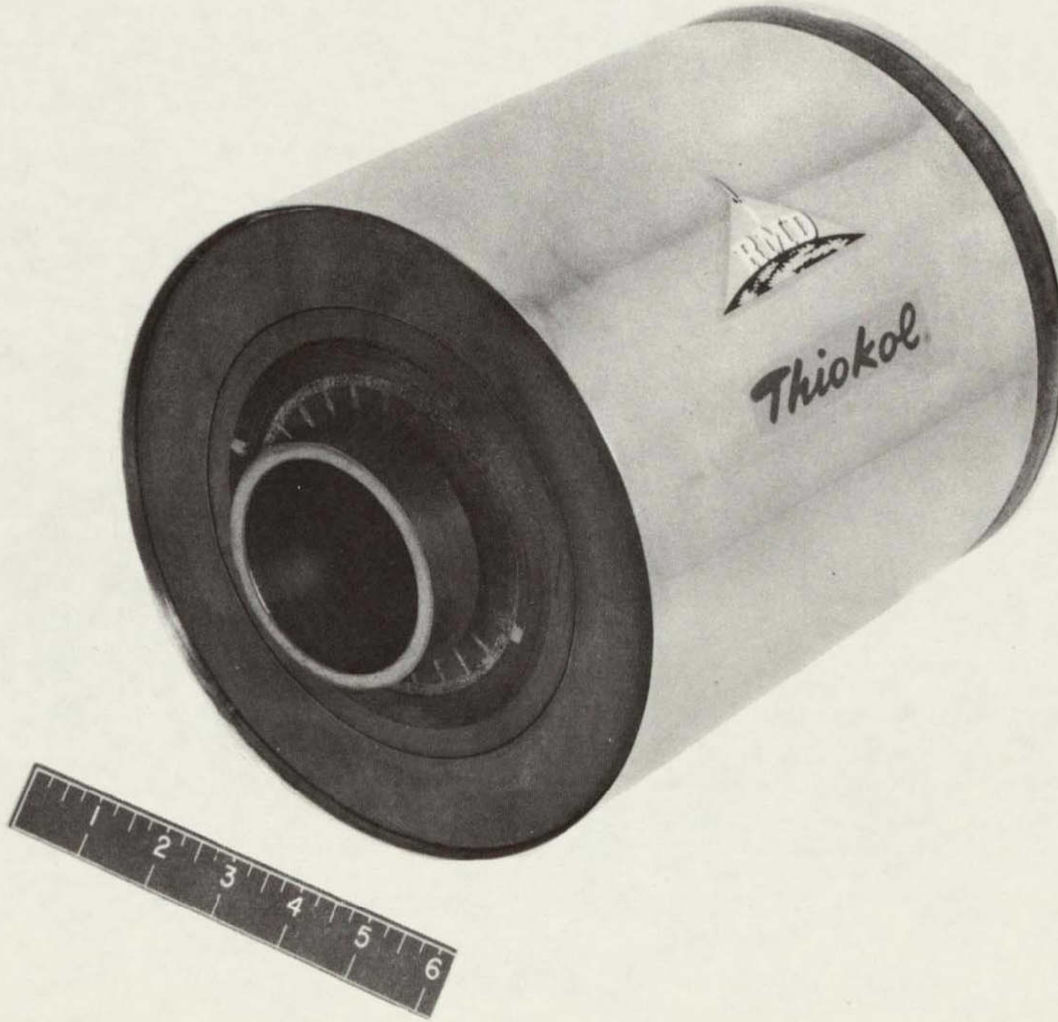
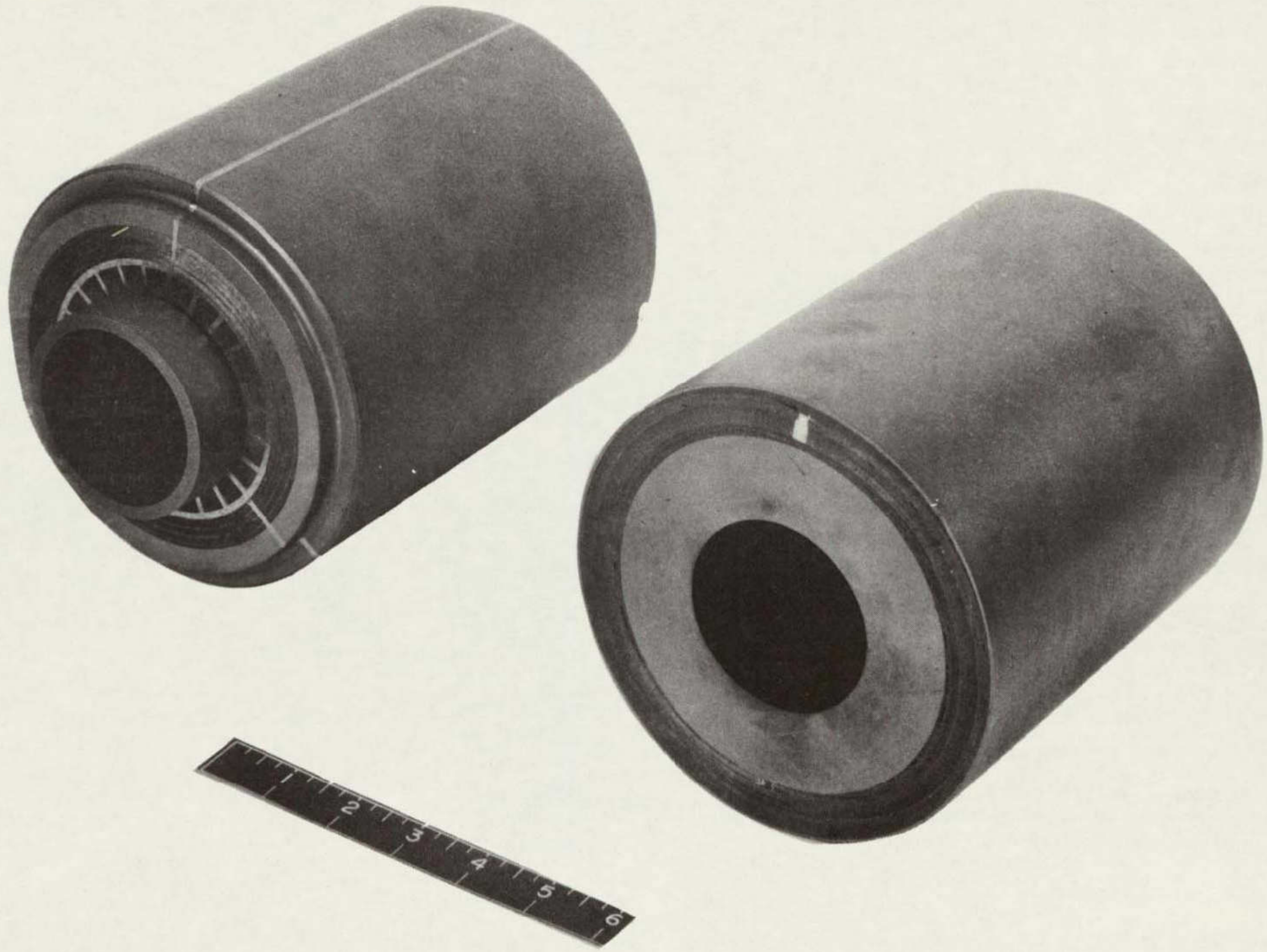


FIGURE 9



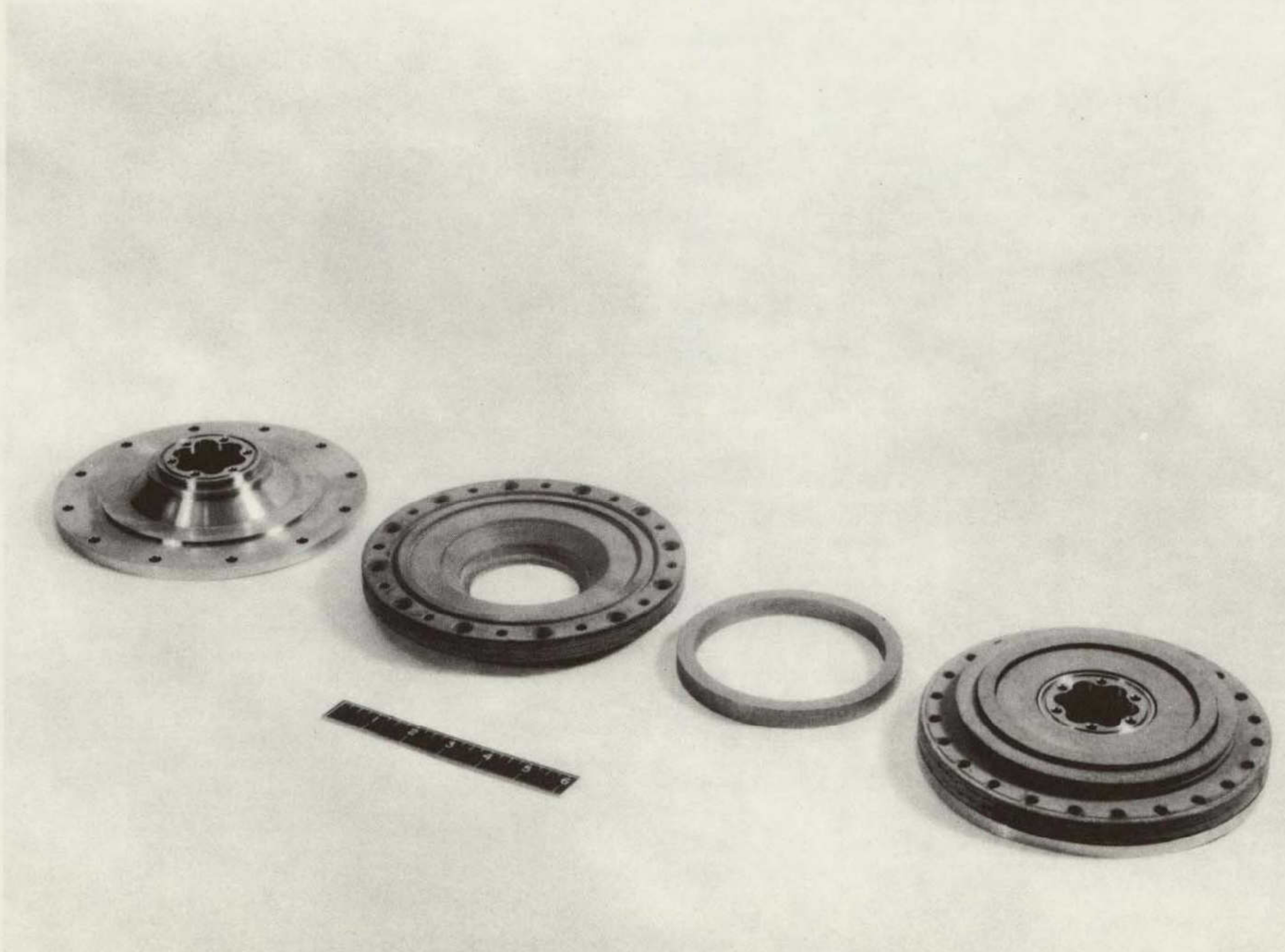
6062-12

FIGURE 10. THRUST CHAMBER ASSEMBLY



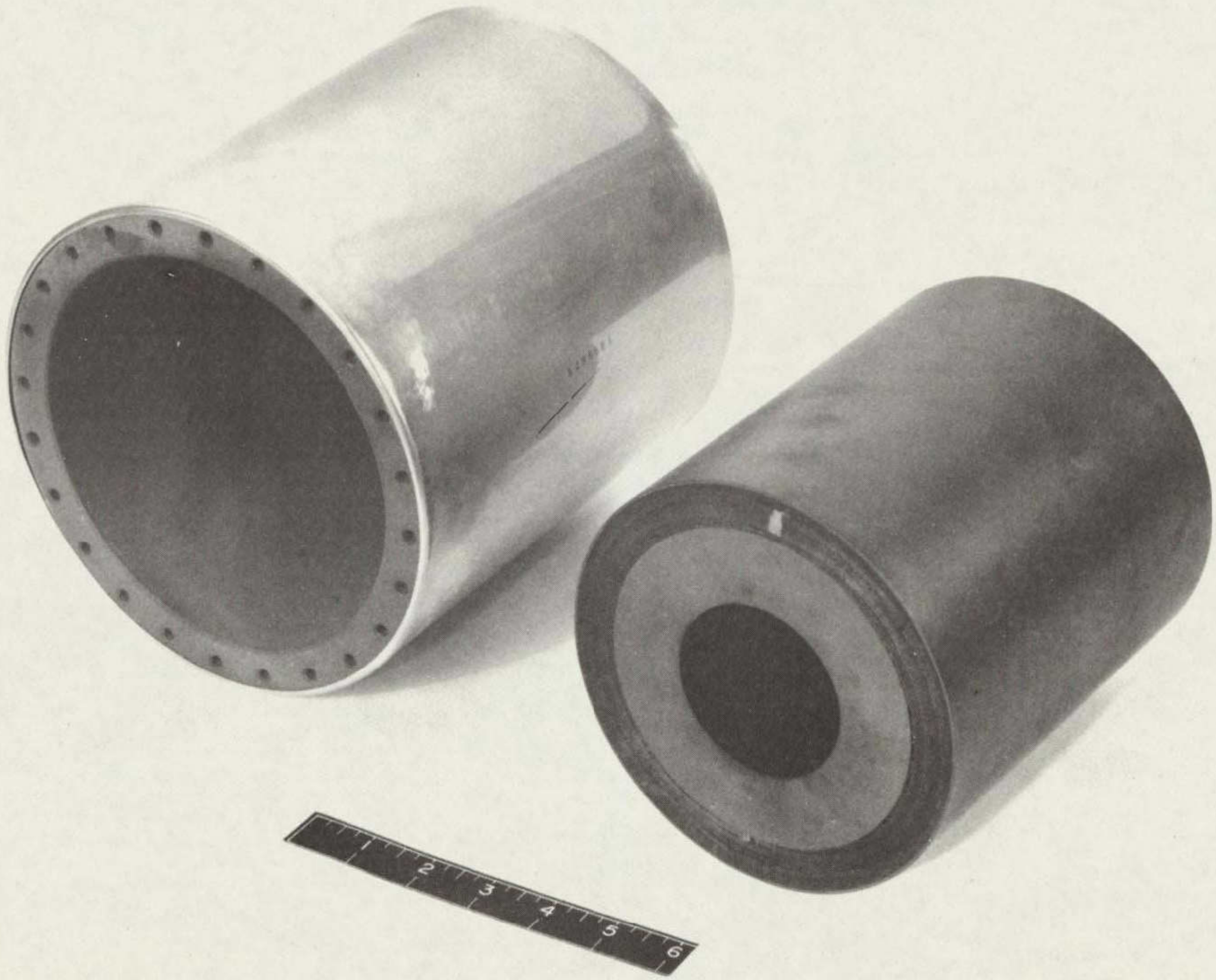
6062-11

FIGURE 11. THRUST CHAMBER LINER ASSEMBLY



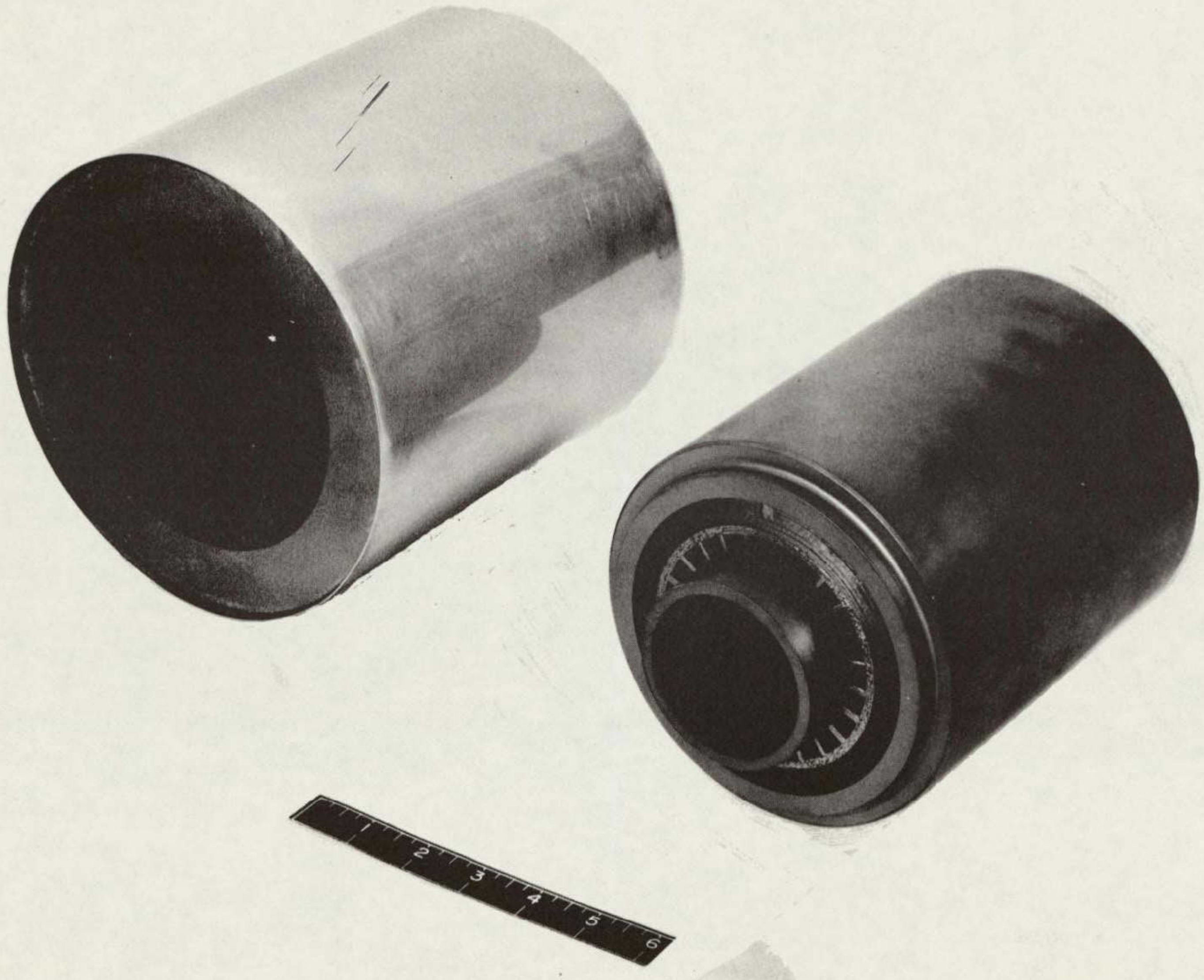
6062-7

FIGURE 12. INJECTOR FLANGE/INSULATOR/GRAFOIL GASKET



6062-9

FIGURE 13. THRUST CHAMBER LINER ASSEMBLY & JACKET SHELL (INJECTOR END)

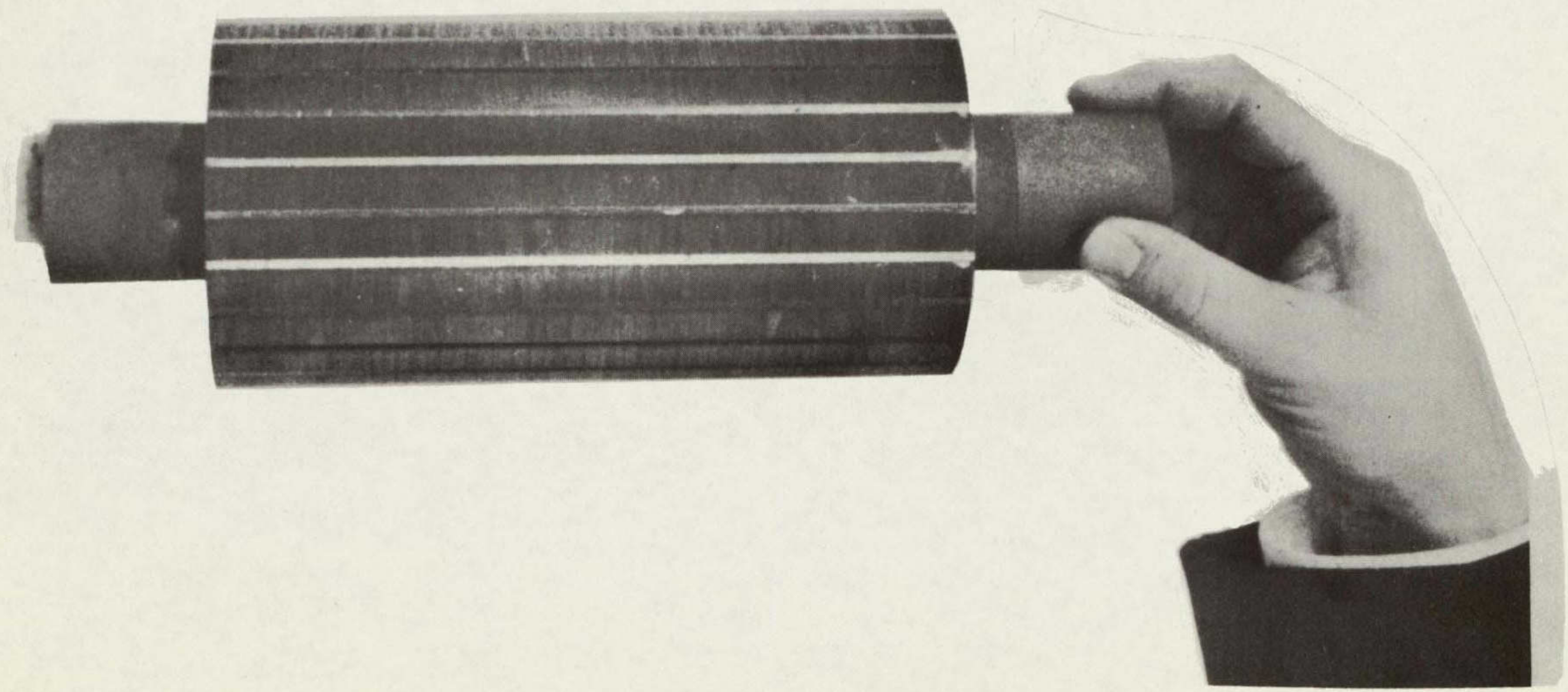


6062-10

FIGURE 14. THRUST CHAMBER LINER ASSEMBLY & JACKET SHELL
(NOZZLE END)

6062-1

FIGURE 15. LINER, WEDGE ASSEMBLY & RADIAL INSULATOR



6062-3

FIGURE 16. WEDGE ASSEMBLY

APPENDIX A

JPL OF_2/DB THRUST CHAMBER

THERMAL ANALYSIS

REACTION MOTORS DIVISION

DENVILLE, NEW JERSEY

Thiokol® CHEMICAL CORPORATION

DS 100-134
REPORT NUMBER

CLASS U

TITLE THERMAL ANALYSIS OF THE JPL OF_2/DB THRUST CHAMBER

REPORT PREPARED BY S. Elkind 10/24/68 (DATE)

REPORT CHECKED BY R. W. Seaman for J. Lovingham — J. J. Lovingham 10/24/68 (DATE)

REPORT APPROVED BY ______ (DATE)

W.O. 6062-11-2000

THIS REPORT INCLUDES 5 PAGES, 3 FIGURES, AND ______ DRAWINGS.

cc: R. W. Seaman
W. Hosek
G. Rabe
C. Nash
R. Novotny
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W. Monagle

REVISIONS AND ADDITIONS

LETTER	DATE	DESCRIPTION	BY	CHECKED	APPROVED

RMD RE 119

TITLE: THERMAL ANALYSIS OF THE JPL OF_2/DB THRUST CHAMBER

REPORT NO. DS 100-134

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TITLE: THERMAL ANALYSIS OF THE JPL OF_2/DB THRUST CHAMBER

REPORT NO. DS 100-134

ABSTRACT

A Thermal Model was made of the JPL OF_2/DB Thrust Chamber, and nodal temperatures computed, Figure 2. Component temperatures are within material capabilities and JPL thermal requirements are met.

TITLE: THERMAL ANALYSIS OF THE JPL OF_2/DB THRUST CHAMBER

REPORT NO. DS 100-134

INTRODUCTION

Thiokol-RMD has designed a thrust chamber for JPL to be used with their OF_2/DB barrier cooled injector. Under WA-6062-11-2000, a study was made to determine whether the RMD design meets JPL's thermal requirements.

DISCUSSION

The JPL OF_2/DB thrust chamber, Figure 1, consists of:

1. An ATJS graphite liner;
2. Pyrolytic graphite wedges with the "a - b" planes in the radial and axial directions;
3. A "Grafoil" foam or "Grafoam" cylinder;
4. A pyrolytic cylinder with the "c" direction radial;
5. A columbium structural shell; and
6. Dyna-quartz insulation held in place by a columbium foil shell.

A silica phenolic block insulates the upstream injector housing from the rest of the chamber.

Operating conditions are:

Propellants	OF_2/DB
Chamber Pressure	100 psia
Propellant Flow Rate	.512 pps
Firing Duration	1000 sec
Chamber Gas Film Temperature	4000°F
Nozzle Gas Film Temperature	7000°F
Maximum Skin Temperature	600°F

METHOD OF ANALYSIS

Component temperatures throughout the OF_2/DB thrust chamber were determined by means of a finite difference numerical analysis. In brief, the method consists of dividing the chamber into regular geometric volumes, and assuming each volume shrinks to a point, or node. Each node is assumed to retain the thermal characteristics of the volume it represents. Heat balance equations are written for each node, resulting in a set of "n" simultaneous equations for "n" nodes. When forward differences (in time) are used, these equations are explicit in nodal temperatures and easily solved on a digital computer. The procedure is repeated for a finite time period, $\Delta\theta$, later and in this way temperature distributions are computed at time 0, $\Delta\theta$, $2\Delta\theta$, ... $m\Delta\theta$. The time step, $\Delta\theta$, depends on: (1) the component material properties; (2) the division into nodes; and (3) the modes of heat transfer considered. It is also subject to a stability criteria, to insure a stable numerical solution.

The proposed OF_2/DB chamber was divided into 96 nodes as indicated in Figure 2. The nodes have been chosen to obtain a good simulation of the problem, e.g., nodes in the converging section 11, 12, and 13, are closer together than in the chamber 8, 9, and 10. Also, nodes in the pyrolytic cylinder, e.g., 31, 38, 45, and 52, are spaced closer than other nodes to allow better simulation of the anisotropic thermal conductivity of the material. A time step, $\Delta\theta$ of one second was used.

RESULTS

Calculated nodal temperatures after a 1000 second firing are presented in Figure 1. The temperature near the throat, Node 13, is 6102F, while the highest combustion chamber node, 10, is 4359F. These temperatures are well within the capability of the ATJS material.

Typical nodes in the pyrolytic cylinder, 34, 41, 48 and 55, attain 4973F, 3295F, 2397F, and 2014F, respectively. This material functions as a high temperature insulator, with a 2900F drop in the "c" direction.

The fibrous insulation, dyna-quartz, drops the temperature from 2014F at Node 55 to 517F at Node 76. All the shell nodes, 71-77, are below the specified maximum of 600°F.

The highest temperature in the columbium structure, 2536F occurs at Node 50. This can be tolerated by columbium. It should be noted that conduction along the columbium was neglected in order to be able to use a time step of one second. In the flight design it may be necessary to insulate the outer flange of the columbium shell to limit the skin temperature to 600F.

The upstream housing that mates to JPL's injector is represented by Nodes 96, 94, and 95. They reach 1674F, 198F, and 169F respectively. While 1674F may be high at Node 96, this analysis does not include the added thermal mass of the injector and any cooling effects due to propellant flow. Very little heat rejection in this area results in tremendous temperature reduction. For example, in a preliminary analysis, neglect of the housing heat capacity resulted in a temperature of 2700F at Node 96. Thus, the addition of the heat capacity dropped the node almost 1100F.

Typical nodal transient temperatures are indicated in Figure 3. Node 13 near the throat is approaching its steady state value, as evidenced by the decrease in slope. Node 11 is not as close to steady state. Due to its large thermal inertia, the thrust chamber is still in a transient after a 1000 second firing.

The JPL OF_2/DB thrust chamber design, Drawing 318281, meets all JPL thermal requirements and is adequate for its application.

Appendix B is a tabulation of the calculated Nodal temperature from start to 1000 seconds.

APPENDIX A

DATA USED IN ANALYSIS

A. Gas convection coefficients were computed by a modified Colburn equation. The resulting coefficients are:

Node	Diameter, inches	hg, BTU/°F.-HR-FT^2
8, 9, 10	2.60	92
11	2.30	115
12	1.70	198
13, 14	1.20	371

B. Material Properties

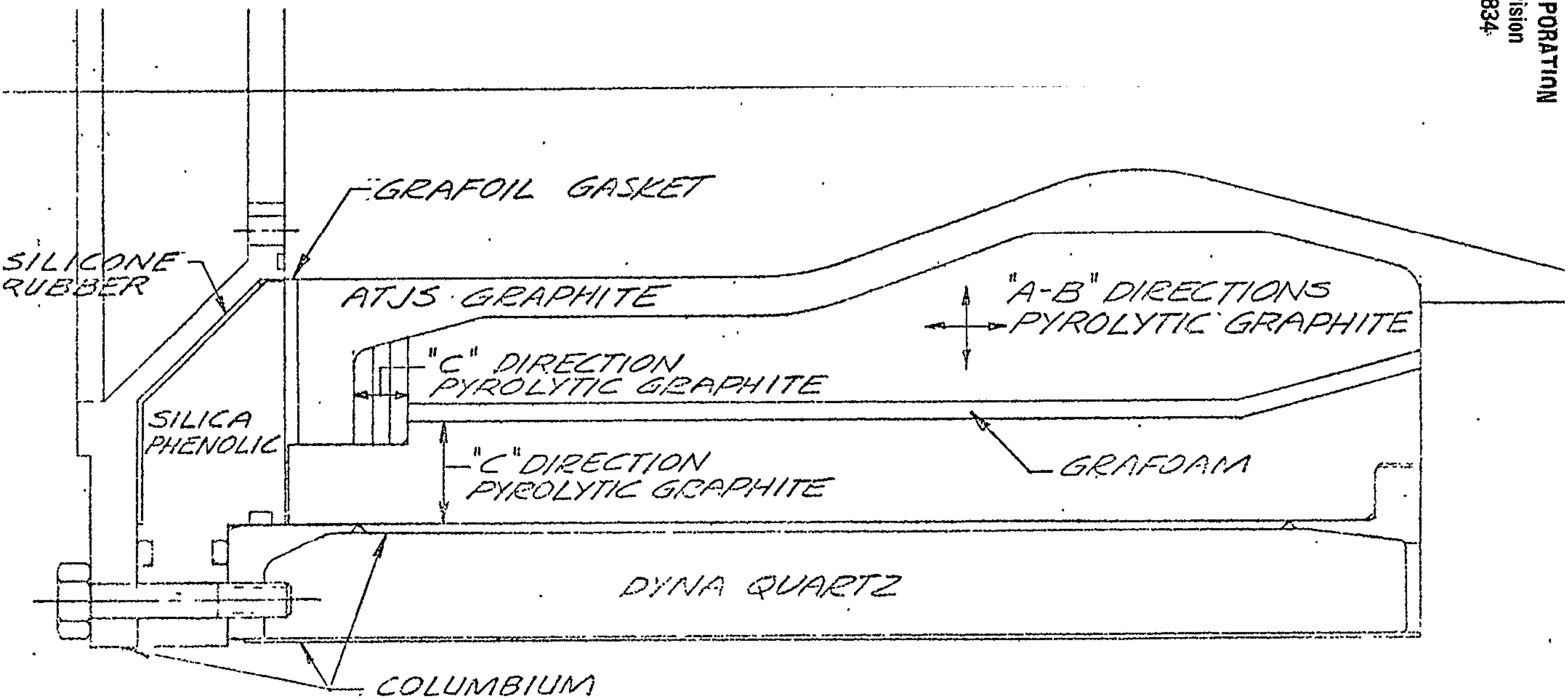
Material	$\overline{T}$	k	ρ	C_p
ATJS	4000	25	114	.50
PYRO "a-b"	4000	40	137	.45
"c"	4000	.5	137	.45
Dyna-Quartz	1800	.085	16	.29
Silica Phenolic	500	.14	108	.30

k = Thermal Conductivity
BTU/HR-FT^2 - Degree

ρ = Density, lbs per cu. ft.

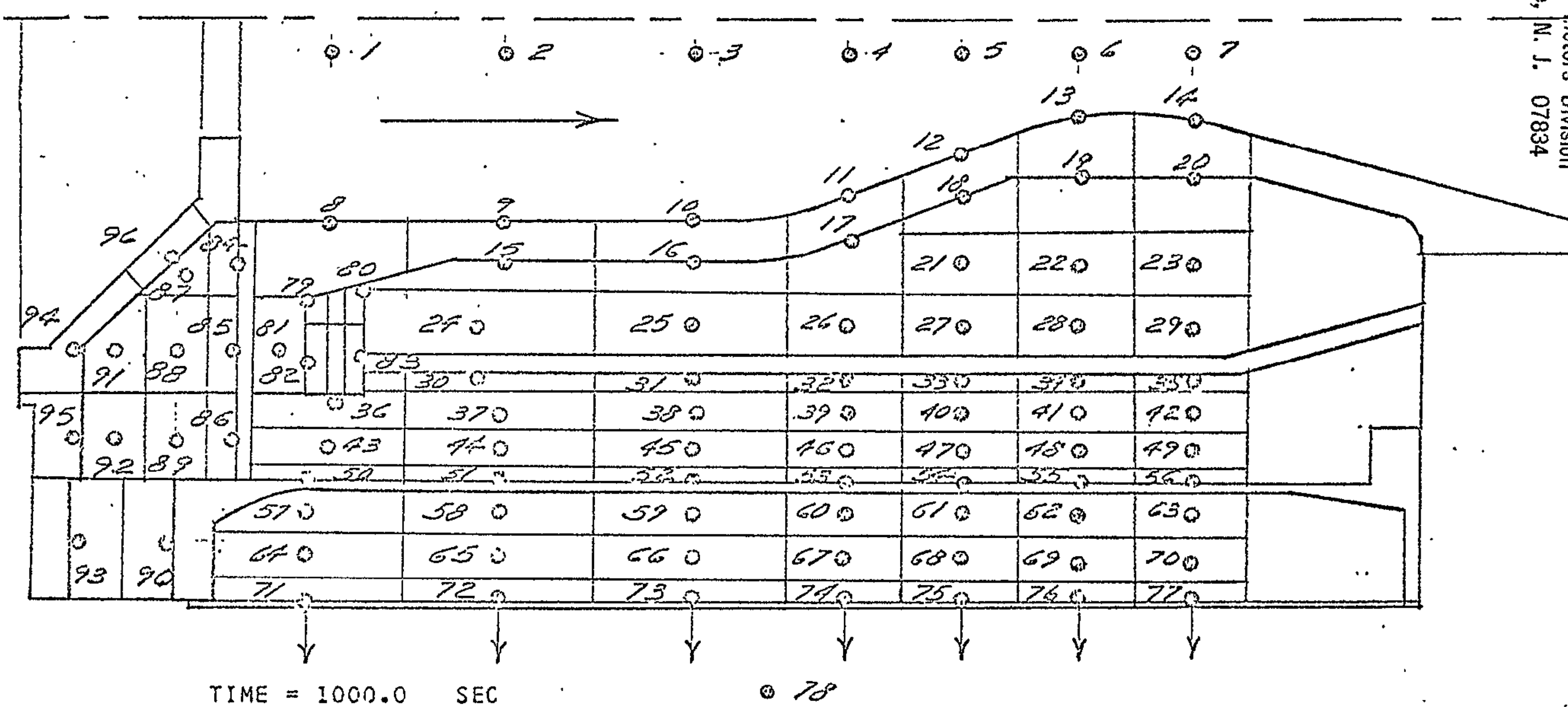
C_p = Specific Heat, BTU/lb - degree

$\overline{T}$ = Average Temperature - °F



JPL OF_2/DB THRUST CHAMBER

FIGURE 1



TIME = 1000.0 SEC

	1	2	3	4	5	6	7	8	9	10
0	4000.0	4000.0	4000.0	7000.0	7000.0	7000.0	7000.0	3515.9	3800.3	4359.0
10	5178.5	5722.0	6102.4	6184.6	3785.8	4357.6	5017.3	5521.2	5733.8	5826.6
20	5337.8	5520.4	5613.1	3764.5	4347.1	4906.3	5235.0	5427.0	5520.3	3648.9
30	4144.3	4550.7	4804.7	4972.9	5056.2	3105.1	3073.6	3128.2	3201.6	3254.6
40	3295.1	3317.0	2742.8	2567.6	2461.1	2419.3	2402.5	2396.7	2398.5	2535.6
50	2274.2	2112.6	2043.9	2016.9	2014.0	2036.8	1605.7	1528.5	1407.9	1352.3
60	1329.2	1325.6	1333.1	982.8	971.5	896.3	859.5	844.0	843.8	842.3
70	562.8	562.3	532.6	517.2	510.7	516.6	509.5	100.0	3234.6	3549.8
80	3193.6	3172.4	3363.9	3484.6	3140.1	2819.7	1970.4	1259.0	1011.2	292.6
90	382.5	308.3	150.4	198.3	168.5	1673.8				

DIVISION OF CHAMBER INTO NODES, AND
NODAL TEMPERATURES AFTER 1000 SEC.

FIGURE 2

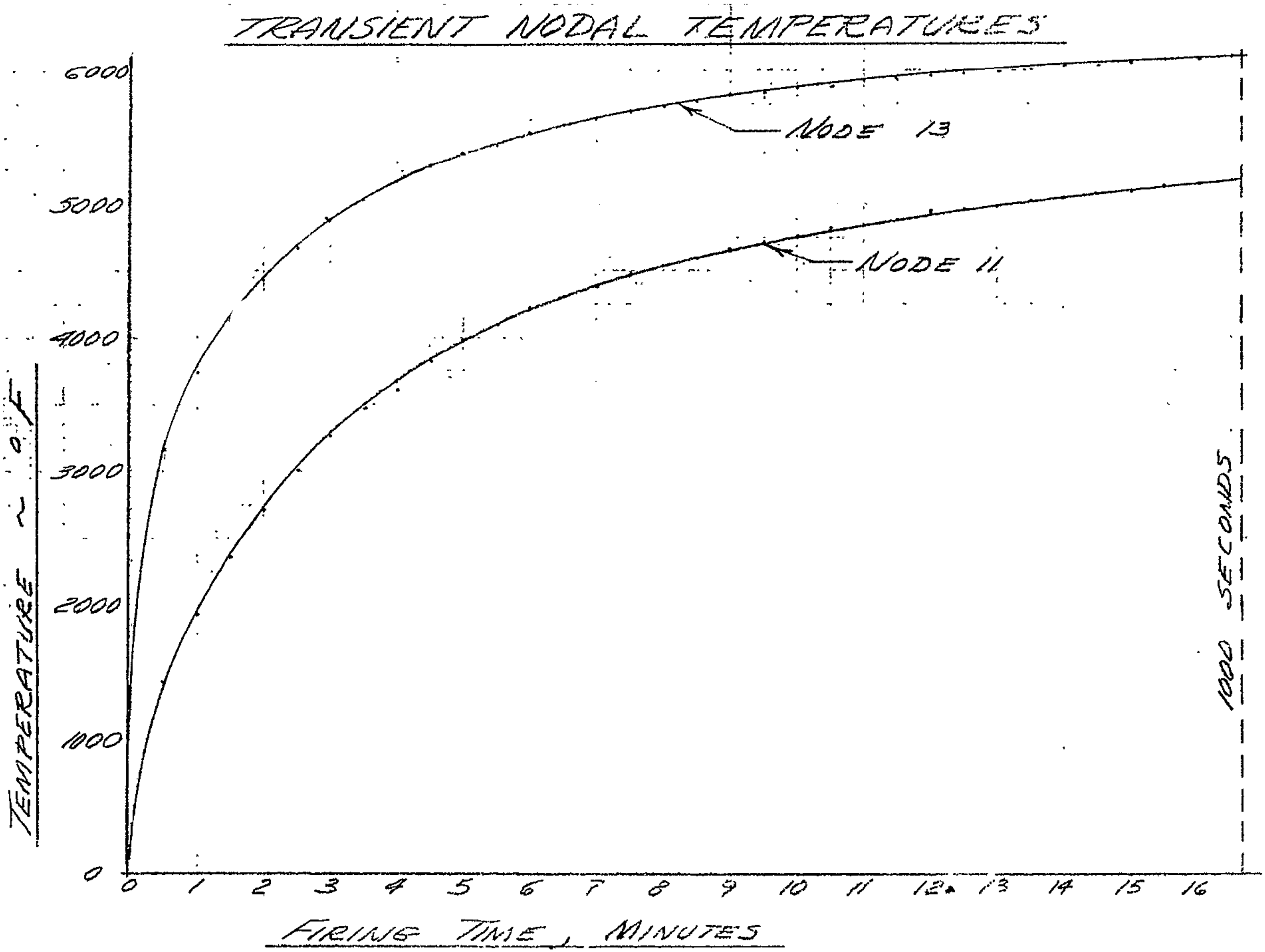

TRANSIENT NODAL TEMPERATURES
TEMPERATURE ~ °F
6000
5000
4000
3000
2000
1000
0
NODE 13
NODE 11
1000 SECONDS
0
1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
16
FIRING TIME, MINUTES

FIG. 3

CALC TIME = 1.0 SEC, PRINTOUT = 30.0 SEC, TOTAL RUN=1000.0
NO OF ITERATIONS = 0

APPENDIX B

TIME = 30.0 SEC

	1	2	3	4	5	6	7	8	9	10
0	4000.0	4000.0	4000.0	7000.0	7000.0	7000.0	7000.0	779.9	560.8	638.3
10	1412.9	2247.8	3167.9	3277.5	446.4	513.9	925.6	1523.4	1726.0	1783.4
20	974.0	967.8	977.9	357.2	419.6	633.6	713.1	709.4	708.6	202.9
30	218.0	277.7	296.2	290.8	286.3	198.1	117.5	105.2	105.4	105.6
40	105.2	105.0	114.3	101.7	100.2	100.2	100.3	100.7	101.6	106.7
50	100.6	100.1	100.3	101.1	103.6	109.8	100.3	100.0	100.0	100.0
60	100.1	100.4	101.3	100.0	100.0	100.0	100.0	100.0	100.0	100.1
70	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	343.2	393.8
80	287.4	261.4	256.7	703.1	220.4	134.9	127.9	101.3	100.3	100.0
90	100.0	100.0	100.0	100.0	100.0	101.4				

TIME = 60.0 SEC

	1	2	3	4	5	6	7	8	9	10
0	4000.0	4000.0	4000.0	7000.0	7000.0	7000.0	7000.0	1057.8	854.0	1030.2
10	1928.5	2838.5	3741.4	3873.0	743.8	916.4	1478.1	2192.0	2468.0	2564.0
20	1678.4	1771.2	1827.1	652.3	825.4	1200.5	1419.5	1513.5	1558.7	440.1
30	529.9	702.7	807.8	862.0	884.9	354.4	189.3	145.0	145.6	149.3
40	151.9	153.0	176.0	119.3	105.2	103.4	103.5	104.2	105.4	144.3
50	109.4	102.0	101.9	103.5	107.3	114.6	105.4	100.9	100.2	100.2
60	100.6	101.5	103.4	100.5	100.1	100.0	100.0	100.1	100.2	100.6
70	100.1	100.0	100.0	100.0	100.0	100.0	100.1	100.0	551.1	653.5
80	483.9	448.9	467.4	1005.6	418.1	224.3	185.8	108.7	102.7	100.0
90	100.1	100.0	100.0	100.0	100.0	110.1				

TIME = 90.0 SEC

	1	2	3	4	5	6	7	8	9	10
0	4000.0	4000.0	4000.0	7000.0	7000.0	7000.0	7000.0	1255.0	1117.2	1391.9
10	2350.9	3273.0	4129.7	4268.0	1013.7	1289.4	1935.7	2692.3	2997.8	3114.0
20	2220.2	2371.7	2457.3	924.7	1205.2	1678.3	1977.1	2132.8	2210.0	692.9
30	874.5	1138.3	1313.5	1422.9	1475.6	505.7	294.0	225.9	228.3	237.8
40	246.4	251.2	260.1	157.4	122.0	115.1	114.1	114.8	116.2	204.3
50	131.9	109.6	106.2	107.3	111.4	119.0	119.1	105.0	101.3	101.0
60	101.5	103.0	105.7	102.8	100.6	100.1	100.1	100.3	100.6	101.3
70	100.6	100.1	100.0	100.0	100.1	100.0	100.4	100.0	723.8	881.6
80	652.3	613.7	666.4	1208.0	590.5	327.8	247.3	121.9	108.1	100.1
90	100.6	100.2	100.0	100.0	100.0	127.0				

TIME = 120.0 SEC

	1	2	3	4	5	6	7	8	9	10
0	4000.0	4000.0	4000.0	7000.0	7000.0	7000.0	7000.0	1424.7	1356.9	1716.2
10	2706.9	3619.9	4429.6	4569.1	1260.1	1624.1	2322.2	3092.5	3410.1	3536.5
20	2656.4	2842.3	2944.8	1174.6	1546.8	2082.8	2428.8	2620.9	2717.1	934.4
30	1199.0	1527.0	1748.5	1894.2	1966.6	651.9	416.3	336.3	342.4	357.7
40	372.4	380.9	353.8	211.7	153.3	139.1	135.7	135.8	137.1	276.4
50	167.0	125.3	115.7	114.7	118.0	125.5	141.5	114.0	104.6	103.0
60	103.3	105.0	108.3	108.0	102.4	100.7	100.5	100.7	101.2	102.3
70	102.4	100.7	100.2	100.1	100.2	100.2	100.9	100.0	880.9	1090.2
80	807.1	766.8	853.5	1379.1	746.0	436.2	308.3	139.8	116.6	100.3
90	101.5	100.6	100.0	100.1	100.0	150.9				

TIME = 150.0 SEC

	1	2	3	4	5	6	7	8	9	10
0	4000.0	4000.0	4000.0	7000.0	7000.0	7000.0	7000.0	1579.9	1574.9	2002.4
10	3008.4	3903.2	4669.1	4806.9	1484.5	1919.5	2649.7	3419.4	3740.2	3871.2
20	3013.9	3220.0	3332.1	1402.8	1848.4	2425.7	2799.8	3013.5	3120.7	1158.9
30	1491.7	1863.9	2115.3	2283.7	2368.2	794.3	548.2	464.7	475.5	496.0
40	515.7	527.2	452.9	278.1	198.3	176.0	169.4	168.2	169.2	355.9
50	212.4	149.7	132.2	127.7	129.4	136.4	171.3	128.4	111.0	107.1
60	106.7	108.3	111.9	116.9	106.1	102.1	101.4	101.5	102.2	103.7
70	106.1	102.1	100.6	100.4	100.5	100.5	101.7	100.0	1029.5	1282.8
80	954.3	913.0	1029.8	1534.6	892.6	547.0	368.9	161.7	128.1	100.8
90	102.9	101.2	100.0	100.1	100.1	180.7				

TIME = 180.0 SEC

	1	2	3	4	5	6	7	8	9	10
0	4000.0	4000.0	4000.0	7000.0	7000.0	7000.0	7000.0	1723.9	1772.7	2253.1
10	3264.6	4137.4	4863.8	4998.7	1688.1	2178.3	2928.1	3689.7	4009.0	4141.6
20	3310.2	3528.1	3645.3	1610.1	2112.8	2717.1	3107.8	3334.3	3447.7	1365.5
30	1752.2	2154.9	2425.4	2608.0	2699.9	932.7	684.6	602.7	618.3	643.2
40	666.7	680.4	555.6	354.0	255.3	224.9	214.8	211.8	212.1	440.6
50	266.1	182.9	156.4	147.7	147.2	153.4	207.3	148.5	121.5	114.1
60	112.4	113.6	117.2	129.6	112.3	104.9	103.2	103.0	103.7	105.5
70	112.2	104.8	101.7	101.1	101.2	101.2	102.6	100.0	1171.4	1460.8
80	1095.5	1053.8	1195.6	1678.9	1033.1	659.0	429.3	187.0	142.4	101.5
90	104.9	102.2	100.1	100.3	100.1	215.4				

TIME = 210.0 SEC

	1	2	3	4	5	6	7	8	9	10
0	4000.0	4000.0	4000.0	7000.0	7000.0	7000.0	7000.0	1858.1	1951.7	2472.5
10	3483.2	4333.0	5024.2	5155.7	1872.7	2404.9	3165.8	3915.5	4230.9	4363.2
20	3558.1	3782.7	3902.4	1798.3	2344.3	2965.8	3366.0	3599.7	3716.4	1554.9
30	1983.3	2406.8	2689.5	2880.7	2977.0	1066.7	821.9	744.5	764.7	793.2
40	819.6	834.9	660.3	437.2	322.2	284.3	270.5	265.5	265.0	528.9
50	326.9	224.3	188.5	175.3	172.2	177.4	248.4	173.9	136.3	124.7
60	121.3	121.7	125.2	146.2	121.5	109.5	106.3	105.6	106.2	108.2
70	120.9	109.2	103.8	102.5	102.3	102.5	104.0	100.0	1307.0	1625.1
80	1230.9	1189.1	1351.3	1813.3	1168.0	771.1	490.0	215.4	159.5	102.6
90	107.5	103.6	100.1	100.5	100.2	254.2				

TIME = 240.0 SEC

	1	2	3	4	5	6	7	8	9	10
0	4000.0	4000.0	4000.0	7000.0	7000.0	7000.0	7000.0	1983.0	2113.7	2664.8
10	3670.8	4497.9	5157.9	5285.9	2039.8	2603.5	3370.0	4105.8	4416.0	4547.1
20	3767.5	3995.3	4116.0	1968.8	2547.4	3179.5	3584.3	3821.7	3939.9	1728.2
30	2188.4	2626.0	2916.2	3112.6	3211.4	1195.8	957.8	886.3	910.7	942.0
40	970.5	987.1	766.0	525.7	397.1	352.3	335.1	328.0	326.7	619.8
50	393.6	273.1	228.4	210.6	204.8	209.0	293.8	204.4	155.7	139.4
60	133.9	133.2	136.4	166.4	133.7	116.3	111.1	109.7	110.1	112.1
70	132.3	115.8	107.1	104.8	104.3	104.8	106.0	100.0	1436.2	1776.6
80	1360.3	1318.6	1497.1	1938.6	1297.2	882.2	550.9	246.4	179.0	104.0
90	110.8	105.4	100.2	100.9	100.4	296.4				

TIME = 270.0 SEC

	1	2	3	4	5	6	7	8	9	10
0	4000.0	4000.0	4000.0	7000.0	7000.0	7000.0	7000.0	2099.2	2260.5	2833.9

10	3832.9	4638.2	5270.5	5395.1	2191.2	2778.2	3546.5	4267.7	4572.2	4701.5
20	3945.9	4174.9	4295.5	2123.5	2726.1	3364.2	3770.5	4009.3	4128.1	1886.7
30	2371.1	2817.8	3112.3	3311.5	3411.7	1319.7	1090.5	1025.6	1053.8	1087.3
40	1117.5	1134.9	871.6	618.1	478.3	427.5	407.0	398.0	395.8	712.2
50	465.1	328.6	275.5	253.2	244.9	248.2	342.7	239.6	179.7	158.5
60	150.5	148.6	151.5	190.0	149.3	125.6	118.1	115.7	115.8	117.6
70	146.1	124.5	112.0	108.3	107.3	108.2	108.9	100.0	1558.9	1916.3
80	1483.7	1442.3	1633.5	2055.2	1420.5	991.8	612.1	279.8	200.9	105.9
90	114.8	107.7	100.4	101.4	100.7	341.7				

TIME = 300.0 SEC

	1	2	3	4	5	6	7	8	9	10
0	4000.0	4000.0	4000.0	7000.0	7000.0	7000.0	7000.0	2207.3	2393.6	2983.3
10	3973.8	4758.5	5366.3	5487.5	2328.6	2932.5	3700.0	4406.6	4705.1	4832.5
20	4099.1	4327.9	4447.9	2264.1	2884.1	3524.8	3930.6	4169.5	4287.9	2031.9
30	2534.2	2986.7	3283.4	3483.8	3584.5	1438.1	1219.0	1161.0	1192.5	1227.8
40	1259.2	1277.2	976.3	712.9	564.1	508.1	484.7	473.9	470.9	805.4
50	540.5	389.9	329.1	302.7	291.9	294.4	394.6	279.0	208.3	181.9
60	171.5	168.2	170.6	216.7	168.2	137.8	127.4	123.8	123.6	125.1
70	162.3	135.7	118.8	113.3	111.6	113.2	113.0	100.0	1675.2	2045.2
80	1600.9	1560.0	1761.0	2163.8	1537.8	1099.1	673.5	315.1	225.0	108.2
90	119.5	110.5	100.6	102.1	101.0	389.5				

TIME = 330.0 SEC

	1	2	3	4	5	6	7	8	9	10
0	4000.0	4000.0	4000.0	7000.0	7000.0	7000.0	7000.0	2307.9	2514.6	3115.8
10	4097.2	4862.5	5448.5	5566.5	2453.6	3069.6	3834.4	4526.8	4819.3	4944.5
20	4231.8	4459.5	4578.5	2392.1	3024.4	3665.5	4069.4	4307.3	4425.0	2165.0
30	2680.6	3136.2	3433.6	3634.2	3734.9	1551.1	1342.7	1291.6	1326.1	1362.9
40	1395.2	1413.6	1079.4	809.1	653.3	592.9	567.1	554.7	551.0	898.5
50	618.9	456.1	388.4	358.4	345.4	347.3	448.8	322.4	241.2	209.7
60	196.7	192.2	194.0	246.1	190.4	152.9	139.4	134.4	133.9	134.9
70	180.4	149.1	127.5	120.1	117.5	119.9	118.5	100.0	1785.3	2164.3
80	1712.1	1671.8	1880.3	2264.9	1649.3	1203.8	734.9	352.0	250.9	111.1
90	124.9	113.8	100.9	102.9	101.5	439.5				

TIME = 360.0 SEC

	1	2	3	4	5	6	7	8	9	10
0	4000.0	4000.0	4000.0	7000.0	7000.0	7000.0	7000.0	2401.5	2624.9	3234.1
10	4205.8	4953.1	5519.6	5634.7	2567.6	3191.9	3952.9	4631.5	4918.3	5041.3
20	4347.6	4573.6	4691.3	2509.0	3149.6	3789.6	4190.7	4427.0	4543.7	2287.3
30	2812.5	3269.5	3566.5	3766.6	3866.8	1658.8	1461.3	1417.0	1454.2	1492.2
40	1525.1	1543.8	1180.5	905.8	744.7	680.8	652.8	639.1	634.8	991.2
50	699.5	526.3	452.7	419.4	404.6	406.1	504.7	369.1	278.1	241.7
60	226.2	220.4	221.7	277.8	215.6	171.0	154.3	147.8	146.9	147.2
70	200.2	164.8	138.4	128.7	125.3	128.4	125.6	100.0	1889.5	2274.6
80	1817.5	1778.0	1991.9	2359.1	1755.1	1305.5	796.2	390.4	278.5	114.4
90	131.0	117.7	101.3	104.0	102.1	491.2				

TIME = 390.0 SEC

	1	2	3	4	5	6	7	8	9	10
0	4000.0	4000.0	4000.0	7000.0	7000.0	7000.0	7000.0	2488.8	2725.9	3340.1
10	4302.2	5032.7	5581.7	5694.0	2672.0	3301.6	4058.0	4723.4	5004.6	5125.5
20	4449.3	4673.4	4789.7	2616.0	3262.0	3899.7	4297.4	4531.6	4647.2	2400.0
30	2931.9	3389.0	3684.9	3883.9	3983.6	1761.3	1574.8	1537.0	1576.7	1615.7
40	1649.2	1668.1	1279.3	1002.2	837.4	770.7	741.1	726.2	721.5	1082.8
50	781.5	599.9	521.2	485.2	468.7	470.1	562.0	418.8	318.8	277.6

60	259.7	252.8	253.6	311.4	243.7	192.1	172.0	163.9	162.7	162.3
70	221.2	182.5	151.4	139.4	134.9	138.9	134.5	100.0	1988.0	2376.8
80	1917.5	1878.7	2096.5	2447.0	1855.4	1404.1	857.3	429.8	307.6	118.3
90	137.8	122.1	101.8	105.2	102.8	544.5				

TIME = 420.0 SEC

	1	2	3	4	5	6	7	8	9	10
0	4000.0	4000.0	4000.0	7000.0	7000.0	7000.0	7000.0	2570.4	2818.6	3435.7
10	4388.1	5103.0	5636.2	5746.0	2767.8	3400.4	4151.9	4804.7	5080.6	5199.4
20	4539.4	4761.2	4876.0	2714.4	3363.4	3997.9	4391.9	4623.9	4738.2	2504.2
30	3040.4	3496.7	3791.0	3988.7	4087.6	1859.0	1683.1	1651.8	1693.7	1733.5
40	1767.5	1786.6	1375.5	1097.9	930.7	861.9	831.0	815.3	810.2	1173.1
50	864.5	675.9	593.1	554.7	537.1	538.5	620.1	471.1	362.8	317.2
60	297.1	289.2	289.4	346.6	274.4	216.0	192.5	182.9	181.4	180.1
70	243.0	201.9	166.3	152.1	146.6	151.4	145.4	100.0	2081.3	2471.8
80	2012.2	1974.2	2194.7	2529.1	1950.6	1499.6	918.1	470.2	338.1	122.7
90	145.2	127.0	102.4	106.8	103.7	599.0				

TIME = 450.0 SEC

	1	2	3	4	5	6	7	8	9	10
0	4000.0	4000.0	4000.0	7000.0	7000.0	7000.0	7000.0	2646.8	2903.9	3522.2
10	4465.2	5165.6	5684.5	5791.9	2856.1	3490.0	4236.1	4877.1	5147.9	5264.8
20	4619.7	4839.1	4952.4	2805.2	3455.2	4086.2	4476.2	4705.8	4818.8	2600.8
30	3139.6	3594.4	3886.8	4082.9	4180.9	1952.0	1786.6	1761.3	1805.3	1846.0
40	1880.3	1899.6	1469.0	1192.3	1023.9	953.7	921.9	905.5	900.2	1261.8
50	947.9	753.9	667.7	627.5	609.0	610.6	678.7	525.4	409.8	360.2
60	338.1	329.2	329.1	382.9	307.4	242.7	215.9	204.7	203.1	200.8
70	265.2	222.8	183.2	166.7	160.2	165.9	158.2	100.0	2169.6	2560.4
80	2102.1	2065.0	2287.0	2606.0	2040.9	1591.9	978.6	511.3	369.7	127.6
90	153.3	132.5	103.2	108.6	104.8	654.5				

TIME = 480.0 SEC

	1	2	3	4	5	6	7	8	9	10
0	4000.0	4000.0	4000.0	7000.0	7000.0	7000.0	7000.0	2718.4	2982.8	3601.0
10	4534.8	5221.7	5727.5	5832.7	2937.8	3571.6	4312.1	4941.9	5208.0	5322.9
20	4691.6	4908.6	5020.5	2889.1	3538.9	4165.9	4551.9	4779.1	4890.7	2690.6
30	3230.6	3683.4	3973.6	4168.1	4265.1	2040.6	1885.4	1866.0	1911.9	1953.4
40	1988.0	2007.3	1559.7	1285.1	1116.6	1045.6	1013.1	996.3	990.9	1348.8
50	1031.2	833.2	744.3	702.8	683.7	685.7	737.4	581.3	459.4	406.2
60	382.2	372.7	372.1	419.9	342.4	271.9	242.0	229.3	227.5	224.3
70	287.5	244.7	201.7	183.2	175.7	182.2	172.8	100.0	2253.3	2643.2
80	2187.4	2151.2	2373.9	2678.2	2126.7	1681.0	1038.5	553.0	402.3	133.1
90	162.0	138.5	104.0	110.6	106.1	710.7				

TIME = 510.0 SEC

	1	2	3	4	5	6	7	8	9	10
0	4000.0	4000.0	4000.0	7000.0	7000.0	7000.0	7000.0	2785.8	3056.0	3673.0
10	4598.0	5272.2	5766.1	5869.3	3013.6	3646.2	4381.2	5000.4	5261.9	5375.0
20	4756.6	4971.1	5081.5	2967.1	3615.5	4238.3	4620.3	4844.9	4955.2	2774.4
30	3314.5	3764.9	4052.8	4245.6	4341.7	2125.1	1979.7	1965.9	2013.7	2055.9
40	2090.8	2110.3	1647.7	1376.2	1208.3	1137.0	1104.3	1087.3	1081.8	1433.8
50	1114.0	913.3	822.5	780.1	760.6	763.2	796.0	638.6	511.1	454.8
60	429.3	419.2	418.3	457.4	379.0	303.4	270.6	256.4	254.5	250.4
70	309.7	267.3	221.5	201.2	192.9	200.2	189.3	100.0	2332.8	2720.8
80	2268.5	2233.2	2456.0	2746.1	2208.2	1767.0	1098.0	595.0	435.7	139.1
90	171.2	145.0	105.1	113.0	107.6	767.5				

TIME = 540.0 SEC

	1	2	3	4	5	6	7	8	9	10
0	4000.0	4000.0	4000.0	7000.0	7000.0	7000.0	7000.0	2849.2	3124.1	3739.2
10	4655.6	5318.1	5801.0	5902.2	3084.1	3714.7	4444.2	5053.4	5310.7	5422.0
20	4815.5	5027.6	5136.6	3039.8	3685.9	4304.4	4682.4	4904.6	5013.5	2852.7
30	3392.1	3839.8	4125.5	4316.5	4411.6	2205.8	2069.7	2061.4	2111.0	2153.9
40	2189.1	2208.6	1732.8	1465.3	1298.9	1227.8	1195.0	1177.9	1172.6	1516.7
50	1196.2	993.8	901.8	858.7	839.2	842.5	854.1	696.8	564.8	505.7
60	478.8	468.3	467.2	495.0	416.8	336.8	301.4	286.0	284.0	279.1
70	331.4	290.3	242.5	220.7	211.6	219.5	207.4	100.0	2408.4	2793.7
80	2345.6	2311.4	2533.6	2810.1	2285.9	1849.9	1156.9	637.2	469.8	145.5
90	181.0	152.0	106.3	115.7	109.3	824.7				

TIME = 570.0 SEC

	1	2	3	4	5	6	7	8	9	10
0	4000.0	4000.0	4000.0	7000.0	7000.0	7000.0	7000.0	2909.1	3187.7	3800.3
10	4708.4	5359.8	5832.6	5932.1	3150.0	3778.0	4502.0	5101.7	5354.9	5464.6
20	4869.3	5079.0	5186.6	3107.6	3750.9	4365.0	4739.0	4958.8	5066.5	2926.2
30	3464.2	3909.2	4192.4	4381.6	4475.9	2282.9	2155.9	2152.7	2204.1	2247.6
40	2283.1	2302.8	1815.3	1552.3	1388.0	1317.4	1284.8	1267.9	1262.7	1597.6
50	1277.4	1074.3	981.6	938.3	919.0	923.1	911.6	755.5	619.8	558.5
60	530.5	519.8	518.5	532.5	455.6	371.9	334.2	317.7	315.7	310.0
70	352.5	313.3	264.2	241.2	231.5	240.0	226.8	100.0	2480.4	2862.3
80	2419.2	2385.8	2607.2	2870.6	2359.9	1930.0	1215.2	679.5	504.4	152.5
90	191.4	159.5	107.7	118.6	111.3	882.1				

TIME = 600.0 SEC

	1	2	3	4	5	6	7	8	9	10
0	4000.0	4000.0	4000.0	7000.0	7000.0	7000.0	7000.0	2965.8	3247.2	3856.9
10	4757.1	5398.1	5861.5	5959.3	3211.8	3836.7	4555.3	5146.0	5395.4	5503.5
20	4918.6	5126.0	5232.3	3171.3	3811.1	4420.9	4791.1	5008.5	5114.9	2995.3
30	3531.4	3973.5	4254.4	4441.9	4535.2	2356.7	2238.2	2240.1	2293.2	2337.4
40	2373.2	2393.0	1895.1	1637.2	1475.5	1405.9	1373.7	1357.0	1352.1	1676.4
50	1357.5	1154.4	1061.6	1018.3	999.5	1004.5	968.3	814.4	676.0	612.9
60	584.1	573.3	571.9	569.6	494.8	408.3	368.6	351.2	349.2	343.0
70	372.8	336.0	286.3	262.6	252.4	261.3	247.3	100.0	2548.9	2927.1
80	2489.4	2457.0	2677.0	2927.8	2430.5	2007.3	1272.9	721.9	539.5	159.9
90	202.2	167.5	109.2	121.9	113.4	939.6				

TIME = 630.0 SEC

	1	2	3	4	5	6	7	8	9	10
0	4000.0	4000.0	4000.0	7000.0	7000.0	7000.0	7000.0	3019.6	3303.2	3909.6
10	4802.2	5433.3	5888.0	5984.2	3269.8	3891.3	4604.6	5186.8	5432.6	5539.1
20	4964.1	5169.2	5274.2	3231.1	3867.2	4472.6	4839.1	5054.1	5159.3	3060.5
30	3594.3	4033.5	4312.1	4497.8	4590.2	2427.3	2317.1	2323.8	2378.6	2423.5
40	2459.6	2479.5	1972.3	1719.9	1561.3	1492.8	1461.2	1445.0	1440.4	1753.1
50	1436.3	1234.1	1141.6	1098.6	1080.3	1086.4	1023.9	873.3	733.0	668.5
60	639.1	628.3	627.1	606.1	534.4	445.7	404.5	386.3	384.4	377.7
70	392.2	358.2	308.6	284.4	274.0	283.1	268.6	100.0	2614.4	2988.5
80	2556.4	2524.9	2743.4	2982.1	2497.9	2081.9	1329.9	764.2	575.0	167.8
90	213.6	175.9	111.0	125.6	115.9	997.0				

TIME = 660.0 SEC

	1	2	3	4	5	6	7	8	9	10
0	4000.0	4000.0	4000.0	7000.0	7000.0	7000.0	7000.0	3070.7	3355.9	3958.7
10	4844.0	5465.9	5912.5	6007.2	3324.4	3942.2	4650.5	5224.5	5466.8	5572.0

20	5006.1	5209.0	5312.9	3287.5	3919.6	4520.7	4883.5	5096.3	5200.4	3122.1
30	3653.3	4089.6	4365.9	4549.9	4641.4	2495.1	2392.8	2404.1	2460.6	2506.1
40	2542.5	2562.5	2046.9	1800.4	1645.2	1578.2	1547.4	1531.7	1527.4	1827.7
50	1513.6	1312.9	1221.1	1178.6	1161.1	1168.4	1078.5	932.0	790.5	725.0
60	695.2	684.6	683.5	642.0	573.9	483.8	441.5	422.7	420.8	413.9
70	410.7	379.8	330.8	306.4	295.9	305.1	290.4	100.0	2677.0	3046.6
80	2620.5	2590.0	2806.7	3033.7	2562.5	2153.8	1386.2	806.3	610.6	176.1
90	225.3	184.7	112.9	129.5	118.6	1054.4				

TIME = 690.0 SEC

	1	2	3	4	5	6	7	8	9	10
0	4000.0	4000.0	4000.0	7000.0	7000.0	7000.0	7000.0	3119.3	3405.7	4004.8
10	4883.0	5496.2	5935.1	6028.4	3376.1	3990.0	4693.2	5259.6	5498.6	5602.4
20	5045.2	5246.0	5348.7	3340.9	3968.7	4565.6	4924.9	5135.5	5238.4	3180.5
30	3708.9	4142.3	4416.3	4598.7	4689.3	2560.0	2465.3	2481.1	2539.3	2585.4
40	2622.2	2642.3	2119.2	1878.7	1727.2	1661.9	1632.0	1616.9	1613.0	1900.1
50	1589.4	1390.7	1300.0	1258.3	1241.7	1250.1	1131.8	990.1	848.1	782.1
60	752.1	741.8	741.1	677.0	613.1	522.4	479.2	460.1	458.2	451.2
70	428.3	400.6	352.6	328.4	317.8	327.1	312.4	100.0	2736.9	3101.9
80	2681.9	2652.3	2867.1	3082.9	2624.3	2223.4	1441.7	848.3	646.4	184.8
90	237.5	193.9	115.1	133.8	121.6	1111.5				

TIME = 720.0 SEC

	1	2	3	4	5	6	7	8	9	10
0	4000.0	4000.0	4000.0	7000.0	7000.0	7000.0	7000.0	3165.7	3452.8	4048.1
10	4919.6	5524.4	5956.2	6048.2	3425.0	4034.9	4733.3	5292.3	5528.2	5630.7
20	5081.8	5280.5	5382.0	3391.4	4014.9	4607.7	4963.5	5172.0	5273.8	3236.0
30	3761.3	4191.9	4463.7	4644.5	4734.3	2622.4	2535.0	2555.2	2614.9	2661.7
40	2698.8	2719.1	2189.1	1954.8	1807.3	1743.9	1714.9	1700.6	1697.1	1970.5
50	1663.6	1467.4	1378.0	1337.3	1321.7	1331.4	1183.9	1047.4	905.7	839.6
60	809.6	799.6	799.3	711.1	651.9	561.0	517.4	498.1	496.3	489.3
70	445.0	420.5	373.8	350.0	339.6	348.8	334.3	100.0	2794.2	3154.5
80	2740.8	2712.1	2924.8	3129.8	2683.7	2290.5	1496.5	889.9	682.3	193.8
90	250.1	203.5	117.5	138.5	124.8	1168.3				

TIME = 750.0 SEC

	1	2	3	4	5	6	7	8	9	10
0	4000.0	4000.0	4000.0	7000.0	7000.0	7000.0	7000.0	3210.0	3497.6	4088.9
10	4953.9	5550.9	5975.9	6066.6	3471.5	4077.2	4770.9	5322.9	5555.9	5657.1
20	5116.0	5312.7	5413.1	3439.4	4058.5	4647.2	4999.7	5206.2	5306.9	3288.8
30	3811.0	4238.7	4508.3	4687.6	4776.6	2682.4	2602.0	2626.4	2687.7	2735.2
40	2772.6	2793.0	2256.7	2028.8	1885.4	1824.0	1796.1	1782.6	1779.6	2038.9
50	1736.2	1542.8	1455.1	1415.4	1401.0	1412.0	1234.7	1103.9	963.0	897.0
60	867.2	857.7	858.0	744.3	690.0	599.6	555.8	536.5	534.8	528.0
70	460.8	439.4	394.4	371.2	361.0	370.0	356.0	100.0	2849.3	3204.7
80	2797.3	2769.5	2980.1	3174.6	2740.6	2355.4	1550.6	931.2	718.3	203.3
90	263.1	213.5	120.0	143.5	128.3	1224.7				

TIME = 780.0 SEC

	1	2	3	4	5	6	7	8	9	10
0	4000.0	4000.0	4000.0	7000.0	7000.0	7000.0	7000.0	3252.4	3540.2	4127.5
10	4986.2	5575.7	5994.4	6083.8	3515.7	4117.3	4806.4	5351.7	5581.8	5681.9
20	5148.1	5342.9	5442.3	3485.0	4099.6	4684.5	5033.7	5238.3	5338.0	3339.1
30	3858.2	4283.0	4550.6	4728.4	4816.6	2740.2	2666.5	2694.9	2757.7	2805.9
40	2843.7	2864.3	2322.2	2100.7	1961.5	1902.3	1875.6	1862.8	1860.4	2105.2
50	1807.0	1616.9	1530.9	1492.6	1479.3	1491.7	1284.1	1159.4	1019.8	954.3
60	924.9	915.9	916.8	776.5	727.3	637.8	594.2	575.0	573.4	566.9

70	475.7	457.4	414.1	391.7	381.9	390.6	377.2	100.0	2902.2	3252.7
80	2851.6	2824.7	3033.0	3217.5	2795.3	2418.1	1603.8	972.2	754.1	213.0
90	276.4	223.8	122.9	148.8	132.1	1280.7				

TIME = 810.0 SEC

	1	2	3	4	5	6	7	8	9	10
0	4000.0	4000.0	4000.0	7000.0	7000.0	7000.0	7000.0	3293.0	3580.7	4164.1
10	5016.8	5599.1	6011.7	6100.1	3557.8	4155.2	4839.9	5378.8	5606.2	5705.1
20	5178.4	5371.4	5469.7	3528.6	4138.7	4719.7	5065.9	5268.5	5367.2	3387.2
30	3903.0	4325.1	4590.7	4767.0	4854.4	2795.8	2728.5	2760.9	2825.2	2874.1
40	2912.2	2933.0	2385.5	2170.5	2035.7	1978.7	1953.3	1941.4	1939.5	2169.7
50	1876.2	1689.5	1605.6	1568.5	1556.6	1570.4	1332.2	1213.8	1075.9	1011.2
60	982.3	973.9	975.5	807.7	763.8	675.6	632.4	613.4	612.0	605.9
70	489.8	474.4	433.1	411.5	402.1	410.5	397.8	100.0	2953.0	3298.6
80	2903.9	2877.8	3083.8	3258.6	2847.9	2478.7	1656.3	1012.8	789.9	223.1
90	290.0	234.4	125.9	154.5	136.2	1336.2				

TIME = 840.0 SEC

	1	2	3	4	5	6	7	8	9	10
0	4000.0	4000.0	4000.0	7000.0	7000.0	7000.0	7000.0	3332.0	3619.5	4198.8
10	5045.8	5621.2	6028.1	6115.3	3598.0	4191.3	4871.7	5404.4	5629.2	5727.1
20	5207.1	5398.2	5495.6	3570.2	4175.8	4753.1	5096.2	5297.0	5394.8	3433.2
30	3945.7	4365.2	4628.8	4803.7	4890.4	2849.4	2788.3	2824.4	2890.3	2939.8
40	2978.4	2999.3	2446.9	2238.3	2107.9	2053.2	2029.1	2018.1	2016.8	2232.2
50	1943.6	1760.5	1678.8	1643.2	1632.6	1647.8	1378.9	1266.9	1131.2	1067.5
60	1039.3	1031.5	1033.9	837.9	799.3	712.7	670.1	651.5	650.2	644.7
70	503.1	490.5	451.1	430.5	421.5	429.5	417.6	100.0	3001.9	3342.6
80	2954.2	2928.9	3132.6	3298.1	2898.6	2537.4	1708.1	1052.9	825.5	233.4
90	303.9	245.4	129.1	160.5	140.5	1391.2				

TIME = 870.0 SEC

	1	2	3	4	5	6	7	8	9	10
0	4000.0	4000.0	4000.0	7000.0	7000.0	7000.0	7000.0	3369.4	3656.5	4231.9
10	5073.3	5642.2	6043.6	6129.8	3636.5	4225.6	4901.8	5428.7	5651.0	5747.8
20	5234.2	5423.7	5520.1	3609.9	4211.1	4784.8	5125.1	5324.1	5421.0	3477.2
30	3986.5	4403.4	4665.0	4838.6	4924.6	2901.0	2846.0	2885.8	2953.1	3003.3
40	3042.2	3063.3	2506.3	2304.1	2178.2	2125.9	2103.1	2093.0	2092.3	2292.9
50	2009.3	1830.1	1750.6	1716.5	1707.3	1724.0	1424.2	1318.8	1185.5	1123.0
60	1095.6	1088.6	1091.8	867.1	833.8	749.0	707.3	689.1	688.0	683.2
70	515.6	505.7	468.2	448.6	440.1	447.7	436.7	100.0	3049.0	3384.8
80	3002.6	2978.2	3179.5	3336.0	2947.5	2594.1	1759.0	1092.6	860.9	244.0
90	318.1	256.6	132.6	166.9	145.1	1445.5				

TIME = 900.0 SEC

	1	2	3	4	5	6	7	8	9	10
0	4000.0	4000.0	4000.0	7000.0	7000.0	7000.0	7000.0	3405.3	3692.0	4263.4
10	5099.4	5662.1	6058.3	6143.5	3673.3	4258.3	4930.6	5451.8	5671.7	5767.5
20	5260.1	5447.8	5543.4	3648.1	4244.8	4815.0	5152.4	5349.7	5445.8	3519.5
30	4025.5	4439.9	4699.7	4871.9	4957.3	2950.9	2901.6	2945.0	3013.8	3064.6
40	3103.9	3125.2	2563.8	2367.9	2246.6	2196.7	2175.2	2166.2	2166.0	2351.7
50	2073.2	1898.0	1820.9	1788.4	1780.6	1798.7	1468.3	1369.5	1238.8	1177.7
60	1151.2	1144.9	1149.0	895.4	867.3	784.6	743.8	726.2	725.2	721.1
70	527.5	520.0	484.5	465.8	457.8	465.0	454.9	100.0	3094.4	3425.3
80	3049.3	3025.7	3224.7	3372.4	2994.5	2649.0	1809.1	1131.8	896.0	254.9
90	332.6	268.1	136.3	173.6	150.1	1499.3				

TIME = 930.0 SEC

	1	2	3	4	5	6	7	8	9	10
0	4000.0	4000.0	4000.0	7000.0	7000.0	7000.0	7000.0	3439.9	3726.0	4293.6
10	5124.4	5681.0	6072.3	6156.5	3708.7	4289.6	4958.0	5473.8	5691.4	5786.2
20	5284.7	5470.8	5565.5	3684.6	4277.1	4843.9	5178.5	5374.2	5469.4	3560.1
30	4062.9	4474.7	4732.8	4903.8	4988.5	2999.0	2955.3	3002.2	3072.4	3123.9
40	3163.5	3185.0	2619.5	2429.9	2313.1	2265.6	2245.5	2237.4	2237.8	2408.8
50	2135.5	1964.3	1889.7	1858.8	1852.4	1872.0	1511.0	1418.7	1290.9	1231.3
60	1205.8	1200.3	1205.4	922.7	899.8	819.2	779.5	762.5	761.7	758.4
70	538.8	533.6	499.8	482.2	474.6	481.5	472.3	100.0	3138.2	3464.3
80	3094.4	3071.5	3268.2	3407.5	3040.0	2702.1	1858.4	1170.6	930.9	265.9
90	347.3	279.9	140.3	180.6	155.3	1552.4				

TIME = 960.0 SEC

	1	2	3	4	5	6	7	8	9	10
0	4000.0	4000.0	4000.0	7000.0	7000.0	7000.0	7000.0	3473.3	3758.7	4322.4
10	5148.3	5699.1	6085.6	6168.9	3742.6	4319.6	4984.2	5494.7	5710.1	5804.0
20	5308.1	5492.7	5586.5	3719.8	4307.9	4871.4	5203.4	5397.5	5491.9	3599.1
30	4098.7	4508.2	4764.5	4934.2	5018.3	3045.5	3007.2	3057.4	3129.0	3181.2
40	3221.2	3242.8	2673.5	2490.1	2377.7	2332.7	2314.0	2306.9	2307.9	2464.3
50	2196.0	2028.9	1956.9	1927.6	1922.7	1943.7	1552.4	1466.7	1341.9	1283.9
60	1259.4	1254.7	1260.8	949.0	931.2	852.9	814.4	798.0	797.4	794.9
70	549.4	546.3	514.4	497.7	490.7	497.1	488.8	100.0	3180.5	3501.9
80	3137.9	3115.8	3310.2	3441.3	3083.9	2753.6	1906.9	1208.8	965.5	277.2
90	362.3	291.9	144.5	188.0	160.7	1604.9				

TIME = 990.0 SEC

	1	2	3	4	5	6	7	8	9	10
0	4000.0	4000.0	4000.0	7000.0	7000.0	7000.0	7000.0	3505.4	3790.1	4350.1
10	5171.1	5716.4	6098.3	6180.8	3775.2	4348.3	5009.2	5514.8	5728.0	5821.0
20	5330.5	5513.6	5606.6	3753.5	4337.5	4897.8	5227.3	5419.7	5513.3	3636.7
30	4133.2	4540.2	4794.9	4963.4	5046.9	3090.5	3057.3	3110.8	3183.8	3236.6
40	3277.0	3298.7	2725.8	2548.5	2440.5	2397.9	2380.7	2374.6	2376.2	2518.0
50	2254.9	2091.9	2022.4	1994.8	1991.4	2013.8	1592.6	1513.3	1391.6	1335.4
60	1312.0	1308.1	1315.2	974.5	961.6	885.6	848.4	832.6	832.3	830.6
70	559.5	558.4	528.2	512.5	505.8	511.9	504.5	100.0	3221.3	3538.0
80	3179.9	3158.5	3350.7	3473.9	3126.3	2803.4	1954.7	1246.6	999.8	288.7
90	377.4	304.1	148.9	195.6	166.5	1656.7				

TIME = 1000.0 SEC

	1	2	3	4	5	6	7	8	9	10
0	4000.0	4000.0	4000.0	7000.0	7000.0	7000.0	7000.0	3515.9	3800.3	4359.0
10	5178.5	5722.0	6102.4	6184.6	3785.8	4357.6	5017.3	5521.2	5733.8	5826.6
20	5337.8	5520.4	5613.1	3764.5	4347.1	4906.3	5235.0	5427.0	5520.3	3648.9
30	4144.3	4550.7	4804.7	4972.9	5056.2	3105.1	3073.6	3128.2	3201.6	3254.6
40	3295.1	3317.0	2742.8	2567.6	2461.1	2419.3	2402.5	2396.7	2398.5	2535.6
50	2274.2	2112.6	2043.9	2016.9	2014.0	2036.8	1605.7	1528.5	1407.9	1352.3
60	1329.2	1325.6	1333.1	982.8	971.5	896.3	859.5	844.0	843.8	842.3
70	562.8	562.3	532.6	517.2	510.7	516.6	509.5	100.0	3234.6	3549.8
80	3193.6	3172.4	3363.9	3484.6	3140.1	2819.7	1970.4	1259.0	1011.2	292.6
90	382.5	308.3	150.4	198.3	168.5	1673.8				

APPENDIX B

JPL OF_2/DB THRUST CHAMBER

DESIGN ANALYSIS

REACTION MOTORS DIVISION

DENVILLE, NEW JERSEY

Thiokol® CHEMICAL CORPORATION

DS 100-135
REPORT NUMBER

CLASS U

TITLE JPL OF_2/DB THRUST CHAMBER DESIGN ANALYSIS

REPORT PREPARED BY C. F. Nash C. F. Nash 3/13/69 (DATE)

REPORT CHECKED BY (DATE)

REPORT APPROVED BY R. H. Sawyer R. H. Sawyer 3/13/69 (DATE)

THIS REPORT INCLUDES 50 PAGES, ___ FIGURES, AND ___ DRAWINGS.

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LETTER	DATE	DESCRIPTION	BY	CHECKED	APPROVED

RMD RE 119

TITLE: JPL OF_2/DB THRUST CHAMBER DESIGN ANALYSIS

REPORT NO. DS 100-135

SUMMARY

The JPL OF_2/DB Thrust Chamber Assembly meets the design requirements of JPL as specified by RMD WA 6062-11-3000.

INTRODUCTION

This report documents the design analysis performed to assure the structural integrity of the JPL OF_2/DB Thrust Chamber Assembly defined by RMD Drawing 318281, and Figure 1 of this report.

DESIGN CRITERIA

The assembly has been analyzed for the following conditions as outlined by WA 6062-11-3000:

a. Thermal Effects

- Expansion
- Heat Transfer (Thermal Gradients)

b. Pressure Loads

- Ignition Spike (200 psia for 5 millisecs)
- Steady State (100 psia at 1000 sec. temperature profile)

The heat transfer analysis is found in RMD Report DS 100-134. Figure 2 of Appendix A of this report presents the critical temperature profile.

TITLE: JPL OF_2/DB THRUST CHAMBER DESIGN ANALYSIS

REPORT NO. DS 100-135

DISCUSSION

The design analysis presented in Appendix A was performed in conjunction with the design layout and, therefore, represents the analysis leading to the final design.

One of the major problems in the design of a high temperature system made up of several individual elements is to provide for differential thermal growth.

Radial growth has been allowed for by using a crushable Grafoil Laminate cylinder which readily deforms without creating any significant forces.

The same solution was provided to account for circumferential thermal growth; i.e., Grafoil Laminate is used as an expansion media for the inner P.G. wedges and the outer P.G. split ring.

Differential thermal growth in the axial direction tends to alleviate the compression in the Grafoil gasket used to seal the combustion gases. The calculated seal backoff is 0.05 inches maximum. This has been allowed for by providing a gasket that requires a 900 psi compressive force at room temperature and maintains a 330 psi compressive force after a 0.05 inch backoff. Note that this compressive force is well above the 100 psi operating pressure and should provide an adequate seal.

The inner ATJS liner has been analyzed with regard to thermal stresses. The most critical area is the nozzle throat at t = 30 seconds which is the time at which the thermal gradient is the highest and the strength is still relatively low (strength increases with temperature). The calculations indicate adequate margins of safety.

DISCUSSION (continued)

The detailed design analysis, found in Appendix A, shows adequate margins of safety for all structural components.

Vibratory problems are not anticipated.

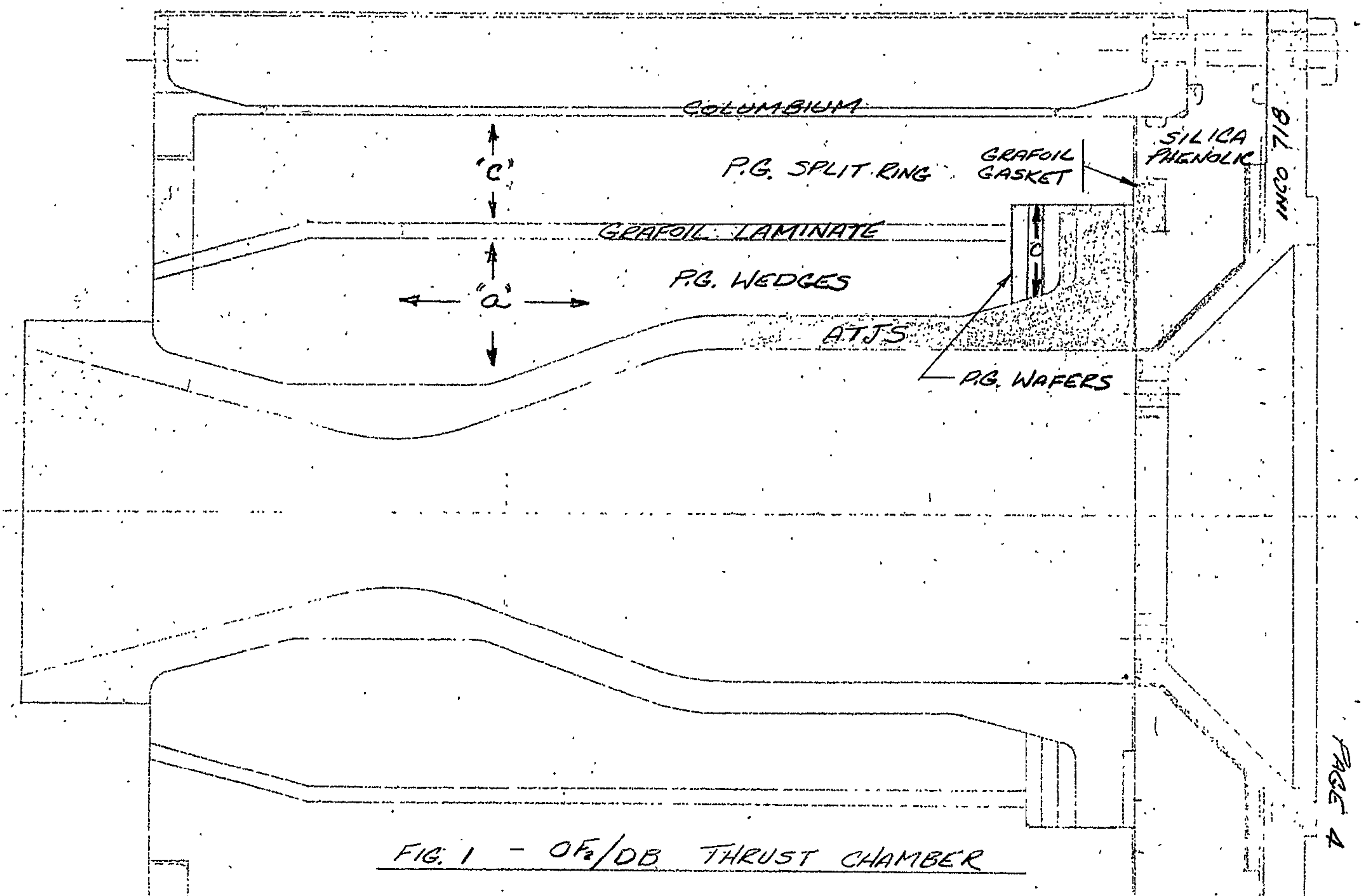


FIG. 1 - OF_2/DB THRUST CHAMBER

APPENDIX A

DESIGN ANALYSIS

TITLE:

LONGITUDINAL AVERAGE TEMPERATURES (REFER TO FIG. 2)

ATJS FROM A TO B

7991 ← NODAL PT. 5447 3823

$$\frac{8+9+79+15}{4}(2.23)+\left(\frac{10+16}{2}\right)1.25+\left(\frac{11+17}{2}\right)(.75)$$

4216 4438 4503

$$+\left(\frac{12+18}{2}\right)(.75)+\left(\frac{13+19}{2}\right)(.75)+\left(\frac{14+20}{2}\right)(.75)$$

6296

$$+\frac{12+18}{2}(1.12)=\overline{T}_{AV}L_T$$

$\overline{T}_{AV} L_T = 36,716$

$L_T = 7.60$

$T_{AV} = 4831\ °F$ FOR PURPOSE OF DETERMINING AXIAL GROWTH BETWEEN A & B

P.G. FROM C TO B

5063 5441 3721

$$\frac{15+24}{2}(1.5)+\frac{16+25}{2}(1.25)+\frac{17+26}{2}(.75)$$

4023 4170

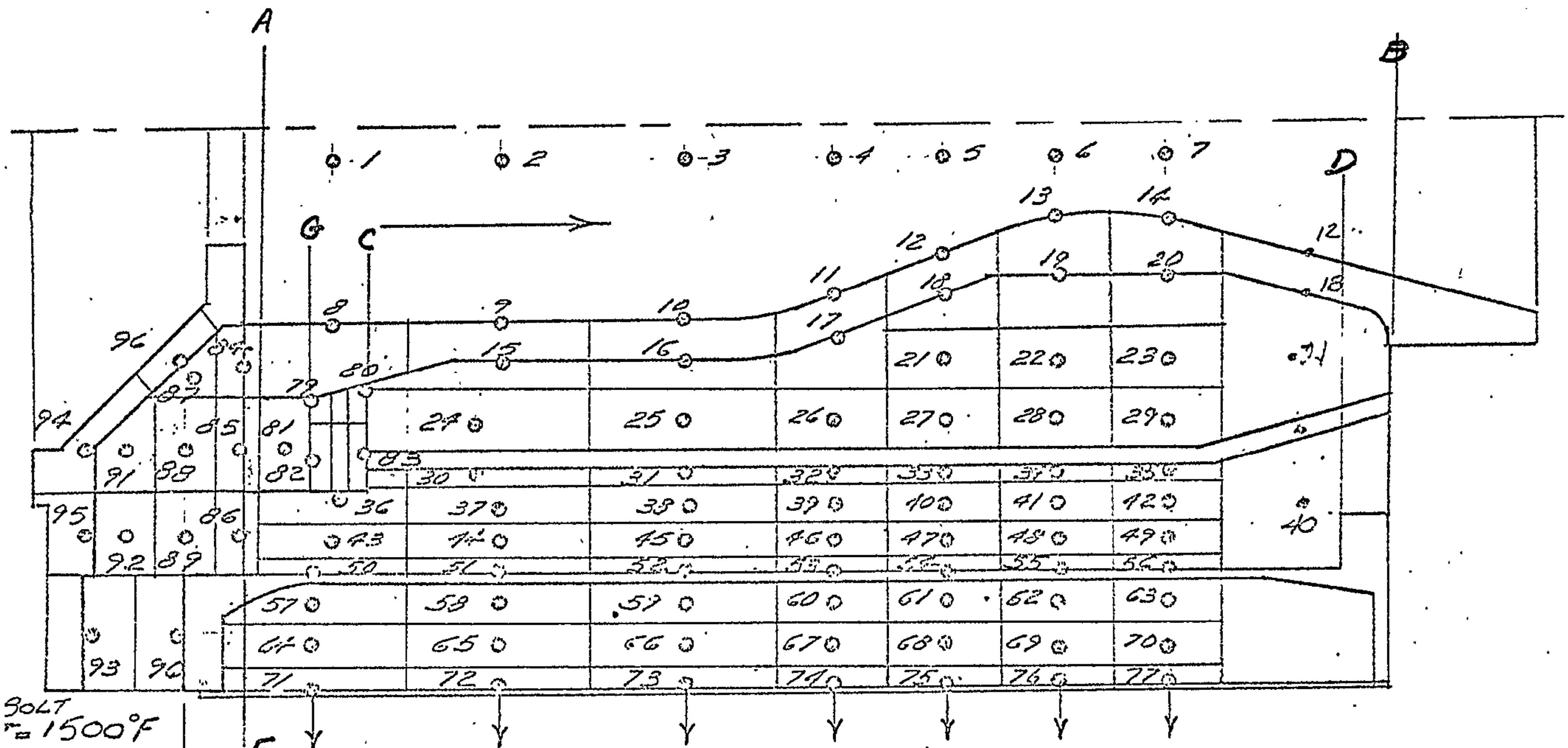
$$+\frac{18+21+27}{3}(.75)+\frac{19+22+28}{3}(.75)+$$

4118 6296

$$+\frac{20+23+29}{3}(.75)+\frac{18+12}{2}(1.12)=\overline{T}_{AV}L_T=33,432$$

$L_T = 6.87$

$\therefore T_{AV} = 4866\ °F$



TIME = 1000.0 SEC

	1	2	3	4	5	6	7	8	9	10	
0	4000.0	4000.0	4000.0	7000.0	7000.0	7000.0	7000.0	3515.9	3800.3	4359.0	0
10	5178.5	5722.0	6102.4	6184.6	3785.8	4357.6	5017.3	5521.2	5733.8	5826.6	10
20	5337.8	5520.4	5613.1	3764.5	4347.1	4906.3	5235.0	5427.0	5520.3	3648.9	20
30	4144.3	4550.7	4804.7	4972.9	5056.2	3105.1	3073.6	3128.2	3201.6	3254.6	30
40	3295.1	3317.0	2742.8	2567.6	2461.1	2419.3	2402.5	2396.7	2398.5	2535.6	40
50	2274.2	2112.6	2043.9	2016.9	2014.0	2036.8	1605.7	1528.5	1407.9	1352.3	50
60	1329.2	1325.6	1333.1	982.8	971.5	896.3	859.5	844.0	843.8	842.3	60
70	562.8	562.3	532.6	517.2	510.7	516.6	509.5	100.0	3234.6	3549.8	70
80	3193.6	3172.4	3363.9	3484.6	3140.1	2819.7	1970.4	1259.0	1011.2	292.6	80
90	382.5	308.3	150.4	198.3	168.5	1673.8	—	—	—	—	90

FIG. 2 - TEMPERATURE PROFILE t= 1000 SEC.

FIG. 1

GRAFOIL FOAM FROM C TO B

$$30(1.5) + 31(1.25) + 32(.75) + 33(.75) + 34(.75) + 35(.75) + \frac{(7+8)}{2}(1.12) = 31,163$$

$L_T = 6.87$

$T_{AV} = 4536$

AXIAL FORCES BETWEEN ATJS AND INNER P.G. LINER

Δl_{ATJS}

$\Delta T = 4831 - 70 = 4761°F$

$L = 7.25$

$\Delta = 11\times10^{-3}\ \frac{IN}{IN}$

REF.- UNION CARBIDE CORP. ; TECH. INF. BULLETIN # 463-201 IG

$\Delta l = 11\times10^{-3}\times 7.25 = .0797\ IN$

$\Delta l_{P.G.\ LINER}$

$\Delta T = 4866 - 70 = 4796°F$

$L = 6.87$

$\Delta_{a''} = .0068\ \frac{IN}{IN}$

REF. - SUPER-TEMP CORP. PYROLYTIC GRAPHITE

$\Delta l_{a''} = .0068 \times 6.87 = .0468$

$\Delta l_{P.G.\ WAFERS}$

$\Delta T = \frac{79 + 80 + 82 + 83}{4} = 3330$

$L = 7.25 - 6.87 = .38$

$\Delta_{c''} = .051\ \frac{IN}{IN}$

REF. - HIGH TEMPERATURE MATERIALS INC. - P.G. DATA SHEET

$\Delta l_{z} = .051(.38) = .0194$ IN.

$\therefore$ ATJS $\Delta l = .0797$ IN.

P.G. LINER + WAFERS = .0468 + .0194 = .0662 IN.

$\therefore$ NO INTERFERENCE & NO FORCES

GASKET COMPRESSION

AVERAGE TEMP OF OUTER P.G. FROM C TO D

$$\overset{842}{\frac{30+36+43+50}{4}}(.28) + \overset{3614}{\frac{30+37+44+51}{4}}(1.25) + \overset{3702}{\frac{31+38+45+52}{4}}(1.25)$$

$$+ \overset{2291}{\frac{32+39+46+53}{4}}(.75) + \overset{2340}{\frac{33+40+47+54}{4}}(.75)$$

$$+ \overset{2377}{\frac{34+41+48+55}{4}}(.75) + \overset{2402}{\frac{35+42+49+56}{4}}(.75)$$

$$\overset{2604}{+ 40(.8)} = 20172$$

$L_T = 6.58 \quad \therefore T_{AV} = 3066°F$

AVERAGE TEMP OF COLUMBIUM FROM E TO D

$$50(1.5) + 51(1.25) + 52(1.25) + 53(.75) + 54(.77)$$

$$+ 55(.77) + 56(1.51) = 17000$$

$L_T = 7.8 \qquad T_{AV} = 2180°F$

TITLE:

AVERAGE T OF P.G. WAFERS = 3330°F

AVERAGE T OF SILICA PHENOLIC FROM E TO F

$$\frac{84+87+85+88+86+89}{6} = 2281\ °F$$

AVERAGE T OF ATJS FLANGE = 81 = 3194°F

GAP AT GASKET:

$$-(l_{CD}+\Delta l_{CD})_{PG} - (l_{CG}+\Delta l_{CG})_{WAFERS} - (l_{AG}+\Delta l_{AG})_{ATJS}$$

$$-(l_{EF}+\Delta l_{EF})_{SILICA\ PHENOLIC} + (l_{ED}+\Delta l_{ED})_{COLUMBIUM} = G$$

$$l_{CD}+l_{CG}+l_{GA}+l_{EA} = l_{ED}$$

OR
$$-(\Delta l_{CD})_{PG} - (\Delta l_{CG})_{WAFERS} - (\Delta l_{AG})_{ATJS}$$

$$-(\Delta l_{EF})_{SP} + (\Delta l_{ED})_{COL.} = G$$

$(\Delta l_{CD})_{PG}$

$\Delta T = 3066 - 70 = 2996\ °F$

$l = 6.44$

$\Delta_{\alpha} = .002\ \frac{IN}{IN}$ — REF.- HIGH TEMPERATURE MATERIAL INC. - P.G. DATA SHEET

$$\therefore (\Delta l_{CD})_{PG} = .002(6.44) = .01288$$

TITLE:

$(\Delta l_{CG})_{WAFERS} = .0194\text{ IN.}$ (TOP OF p.9)

$(\Delta l_{AG})_{ATJS}$

$\Delta T = 3194 - 70 = 3124°F$

$l = .58$

$\Delta = 6 \times 10^{-3}\ \frac{IN}{IN}$

REF. - UNION CARBIDE CORP. - TECHNICAL INFORMATION BULLETIN No. 465-201[illegible]

$\therefore (\Delta l_{AG})_{ATJS} = 6 \times 10^{-3} \times .58 = .00348\text{ IN.}$

$(\Delta l_{EF})_{SP}$

$\Delta T = 2281 - 70 = 2211°F$

$l = .4$

$\alpha = 3 \times 10^{-6}$

REF. - POLYMERIC CHEMICALS INC. DATA SHEET FM-5067

$\therefore (\Delta l_{EF})_{SP} = .4(3)10^{-6}(2211) = .00265$

$(\Delta l_{ED})_{COL.}$

$\Delta T = 2180 - 70 = 2110°F$

$l = 7.80$

$\alpha = 4.5 \times 10^{-6}$

WAH CHANG ALBANY C-103 DATA

$\therefore (\Delta l_{ED})_{COL} = 7.8(2110)(4.5 \times 10^{-6}) = .07406$

$GAP = -(.01288 + .0194 + .00348 + .00265) + .07406$
$= +.0356$

TITLE:

RADIAL THERMAL GROWTHS (THROAT SECTION)

CHECK PLANE OF NODAL PTS. 14 & 77

ATJS AV. TEMP = 6185
5827
2 | 12012
6006 °F $\Delta T = 5936$

$R_o = 1$ $t = .42$

$\Delta = .018 \frac{IN}{IN}$ EXTRAPOLATED

$\Delta R = .018(1) = .018$ IN.   REF. UNION CARBIDE CORP. TECH INFO BUL. 463-201 IG

INNER P.G.   AV. TEMP = 5827
5613
5520
3 | 16960
5653 $\Delta T = 5583\ ^\circ F$

$t = 1.15$

$\Delta_{a''} = .008 \frac{IN}{IN}$ EXTRAPOLATED
REF. SUPER-TEMP CORP.

$\Delta t = .008(1.15) = .0092$ IN.

OUTER P.G.   AV. TEMP = 5056
3317
2399
2037
4 | 12809
3202 °F

$t = .85$

$\Delta t = .050 \frac{IN}{IN}$ { REF. - HIGH TEMPERATURE MATERIALS INC P.G. DATA SHEET

$\Delta t = .85(.05) = .0425$ IN.

COLUMBIUM $T = 2037°F$ $\Delta T = 1967°F$

$\alpha = 4.5 \times 10^{-6} \frac{IN}{IN}/°F$ { REF. WAN CHANG ALBANY C-103

$R = 3.18$

$\Delta R = 3.18 \times 4.5 \times 10^{-6} \times 1967 = .028$

ASSUMING NO ELASTIC DEFLECTIONS, THE GRAFOIL FOAM IS CRUSHED

$.018 + .0092 + .0425 - .028 = \underline{\underline{.0417 \text{ IN}}}$

SELECTION OF A LOW DENSITY FOAM WILL LIMIT THE COMPRESSIVE PRESSURES TO LESS THAN 100#/IN²

TITLE:

ATJS THERMAL STRESS

REF. ROARK 3rd ED. p. 338, CASE 16.

OUTER SURFACE

$$S_t = \frac{\Delta T \alpha E}{2(1-\mu)\ln\frac{c}{b}}\left(1 - \frac{2b^2}{c^2-b^2}\ln\frac{c}{b}\right) \quad \text{TENSION}$$

INNER SURFACE

$$S_t = \frac{\Delta T \alpha E}{2(1-\mu)\ln\frac{c}{b}}\left(1 - \frac{2c^2}{c^2-b^2}\ln\frac{c}{b}\right) \quad \text{COMP}$$

b = INNER RADIUS
C = OUTER RADIUS

EXAMINE NODAL PTS. 14 & 20

TIME	ΔT	AV. T
30	1495	2531
60	1309	3219
90	1154	3691
120	1032	
150	936	
180		
210		
240		
270		
1000	357	

THE MAXIMUM THERMAL GRADIENT OCCURS AT t = 30 SEC.

TITLE:

$C = 1.0$ $E = 2.2 \times 10^6$ @ $2500°F$

$b = .58$ $\alpha = \dfrac{(7.0-4.5)10^{-3}}{1000} = 2.5 \times 10^{-6} \frac{IN}{IN/°F}$ @2500°F

$\mu = .12$ (RMD MATERIAL SECTION)

OUTER SURFACE

$$S_t = \frac{1495(2.5)(2.2)}{2 \ln \frac{1}{.58}(.88)}\left(1 - \frac{2 \times .58^2}{1^2 - .58^2} \ln \frac{1}{.58}\right)$$

$= 3840$ psi

INNER SURFACE

$$S_t = \frac{1495(2.5)(2.2)}{2 \ln \frac{1}{.58}(.88)}\left(1 - \frac{2}{1 - .58^2} \ln \frac{1}{.58}\right)$$

$= -5510$ psi

OK

F_{cu} @ 2500°F = −13,000 psi
F_{tu} @ 2500°F = 6800 psi

REF.–UNION CARBIDE CORP., TECH. INF. BULLETIN #463-201

THICKNESS OF COLUMBIUM SHELL

LIMIT THE AXIAL GROWTH OF THE SHELL TO .005 IN. (FOR SEALING PURPOSES)

(DESIRED GASKET PRESSURE @ $t = 1000$)

AXIAL GASKET FORCE $= 330(\pi)(3.64^2 - 2.22^2) = 2190^{\#}$

ASSUMING NO ALLEVIATION.

GAS AXIAL FORCE $= 100\pi(3.13)^2 = 3080^{\#}$

ASSUMING SMALL LEAK PAST GASKET

LET SHELL T = 2500°F (CONSV. - CALCS. SHOW 2274°F MAX LOCALLY)

TIME = 16.7 MIN.

MAX. % ELONGATION ALLOWED $= \dfrac{.005}{6.55} \times 100 = .0763\%$

CREEP DATA FOR .0763% NOT AVAILABLE

CHECK ELASTIC GROWTH FOR 5000 psi STRESS LEVEL

$E = 6.3 \times 10^6$ @ 2500°F (REF. - WAH CHANG)

$$\varepsilon = \frac{5000}{6.3 \times 10^6} = .000795 \ \frac{IN}{IN}$$

$\delta_{AXIAL} = 6.55 \times .000795 = .0052 \ IN$

∴ @ 5000 psi STRESS, THE ELASTIC GROWTH ALONE IS OVER THE DESIGN VALUE.

ESTIMATE ALLOWABLE AXIAL STRESS = 2500 psi AND FIND t

$$t = \frac{(3080 + 2190)}{2500(2)\pi(3.17)} = .105$$

TITLE:

ACTUALLY, THE FORWARD END OF THE COLUMBIUM IS THE ONLY SECTION AT 2500°F AT $\frac{750}{60}$ = 12.5 MIN. THAT SECTION IS AT 2000°F.

∴ SAY THAT 2 IN. OF THE COLUMBIUM IS AT 2500°F FOR 16.7 − 12.5 = 4.2 MIN. THE REST OF THE COLUMBIUM IS AT 2000°F, AND REFERRING TO THE WAH CHANG CATALOG, THERE IS NO CREEP AT 2000°F FOR STRESSES OF < 15,000 psi @ 1 hr.

CONSIDER USING TWO IDENTICAL GASKETS.

LIMIT THE TOTAL GROWTH TO .010

FROM WAH CHANG THE ALLOWABLE STRESS FOR .5% CREEP FOR 5.7 MIN @ 2500°F IS 7000 psi.

LET f = 5000 psi AND CALCULATE THE GROWTH.

$$\Delta_{2500°F} = \frac{5000}{6.3 \times 10^6} \times 2 = .0016$$

$$\Delta_{2000°F} = \frac{5000}{12.3 \times 10^6} \times 4.55 = .0018$$

$$\Delta_{CREEP} = 2 \times .002 = .004$$

FROM WAH CHANG CATALOG
2500°F
5000 psi 5.4 MIN

.0074 IN TOTAL

$$t = \frac{.105}{2} = .0525 \text{ IN.}$$

THE BOLT DEFLECTION MUST BE ADDED TO THE .0074 IN.

BOLT T = 1500°F

DETERMINE THERMAL GROWTH :

REF. AEROSPACE STRUCTURAL METAL HDBK. VOL IIA

MATERIAL Cb-74 (752)

$$\alpha = 4.1 \times 10^{-6} \frac{IN}{IN} / {}^\circ F \quad @1500^\circ F$$

$$l = .35 \text{ (SMALL SUBASSEMBLY BOLTS)}$$

$$\Delta l = .35(4.1)(10^{-6})(1500) = .00215 \text{ IN}$$

THE ADJACENT SILICA PHENOLIC IS AT LOW TEMP AND ∴ THERMAL EXPANSION CAN BE IGNORED.

DETERMINE INITIAL BOLT LOADS TO COMPRESS A 900 psi GASKET (R.T.)

$$P_{AXIAL} = 900\pi(\overline{2.64}^2 - \overline{2.22}^2) = 5770^{\#}$$

~ COMPRESSIVE Δ IN SILICA PHENOLIC IS

$$\Delta = \frac{Pl}{AE} = \frac{7261 \times .62}{\pi(\underbrace{\overline{3.9}^2 - \overline{3.2}^2}_{4.17})\, 2.3 \times 10^6} = .0001 \text{ IN}$$

NEGLIGIBLE

TITLE:

REFER BACK TO PAGE 11 AND REDUE GROWTH ASSUMING NO GASKET LEAK.

AXIAL GASKET FORCE = 2120# @ 330 psi

GAS AXIAL FORCE = $100\pi(2.43)^2 = 1855$#

CENTER OF GASKET

TOTAL AXIAL FORCE = 3975#

LET $t_{SHELL} = .060$ MIN.

AS BEFORE LET 2 IN OF SHELL BE AT 2500°F
" 4.55 IN " " " " 2000°F

$$f_t = \frac{3975}{2\pi(3.17)(.06)} = 3330 \text{ psi}$$

SHELL

$$\Delta_{2500} = \frac{3330}{6.3 \times 10^6} \times 2 = .00106 \text{ IN.}$$

$$\Delta_{2000} = \frac{3330}{12.3 \times 10^6} \times 4.55 = .00123 \text{ IN.}$$

$$\Delta_{CREEP} = 2 \times .0015 = .003 \text{ IN.}$$

EST.

.005 IN TOTAL - SHELL

BOLT (12 1/4 IN) CB 752

$\Delta_{THERMAL} = .00215$ IN. (FROM PAGE 18)

$$\Delta_{STRESS} = \frac{3975 \times .135}{12\frac{\pi}{4}\left(\frac{1}{4}\right)^2 12 \times 10^6} = .0002$$

E ESTIMATED @ 1500°F

SMALL SUB-ASSEMBLY BOLTS

TITLE:

TOTAL DEFLECTION AT GASKET IN THE DIRECTION OF LOOSENESS

```
  .0011
  .0012
  .0030
  .0022
  .0002
  -----
  .0077
+ .0356   FROM PAGE 6
  -----
  .0433 IN
```

CHECK OUT P.G. COMPRESSION

$$\Delta = \frac{4100 \times 6.44}{\pi(\overline{3.12}^2 - \overline{2.28}^2)\,3 \times 10^6} = .0006\text{ IN} \quad \text{OK}$$

∴ ADEQUATE PROVISION WILL HAVE TO BE PROVIDED IN THE GASKET DESIGN FOR A .045IN BACKOFF.

DESIGN WANTS TO MAKE SMALL SUBASSEMBLY BOLTS FROM STAINLESS. ∴ LONG COLUMBIUM BOLTS ARE GOING TO CARRY THE LOAD AT TEMPERATURE. THE NEW DEFLECTION AT THE GASKET TOWARDS LOOSENESS IS

BOLT LENGTH

$$.00215 \times \frac{1}{.35} = .00614$$

p. 18

$$\text{NEW BACKOFF} = \begin{array}{r} .0450 \\ -\,.0022 \\ \hline .0428 \\ +\,.0061 \\ \hline .0489 \end{array} = \underline{.049\text{IN}}$$

BOLT ANALYSIS

LONG COLUMBIUM BOLTS

12 $\frac{1}{4}$ IN. BOLTS $A_t = .0362 \, IN^2$

GASKET PRESSURE @1000 SEC = 330 psi
ASSUME A PRESSURE LEAK PASS THE GASKET JUST PRIOR TO 1000 SEC.

$$\text{TOTAL AXIAL FORCE} = 100\pi(3.3)^2 + 330\pi(2.64^2 - 2.22^2)$$
$$= 3421^{\#} + 2120^{\#} = 5540^{\#}$$

$$\text{FORCE/BOLT} = \frac{5540}{12} = 461^{\#}$$

$$f_t = \frac{461}{.0362} = 12{,}700 \text{ psi}$$

BOLTS CB-74 (752)

ASSUME THREADS ARE AT 2000°F @ 999+ SEC.
FROM VOI-SHAN MANUFACTURING CO. FASTENER CATALOG $F_{tu} = 52{,}000$ psi @ 2000°F

FROM AEROSPACE METALS HANDBOOK

$$\left.\begin{aligned} F_{tu} &= 36{,}000 \text{ psi} \\ F_{ty} &= 28{,}000 \text{ psi} \end{aligned}\right\} @ 2000°F$$

$$\text{M.S. ON YIELD} = \frac{28000}{12700} - 1 = \underline{1.2}$$

TITLE:

REANALYZE BOLTS FOR NEW GRAFOIL GASKET

$$\text{BOLT LOAD @ R.T.} = \frac{13805}{12} = 1150^{\#}$$ (PAGE 28)

$$\text{BOLT LOAD @ 2000°F} = \frac{5540+4602}{12} = 845^{\#}$$ (PAGE 29)

@ R.T. $f_t = \frac{1150}{.0362} = 31,768 \text{ psi}$

FROM AEROSPACE STRUCTURAL METALS HANDBOOK

$P_{ALL} = 2500^{\#}$ FOR A $\frac{1}{4}$-20 COATED BOLT WHICH HAS A SMALLER STRESS AREA THAN THE $\frac{1}{4}$-28.

$\therefore M.S. = \frac{2500}{1150} - 1 = 1.2$ ON ULT.

@ 2000°F

$$f_t = \frac{845}{.0362} = 23,343 \text{ psi}$$

$$F_{ty} = 28,000 \text{ psi}$$

$$M.S._y = \frac{28,000}{23,343} = .20 \text{ ON YIELD}$$

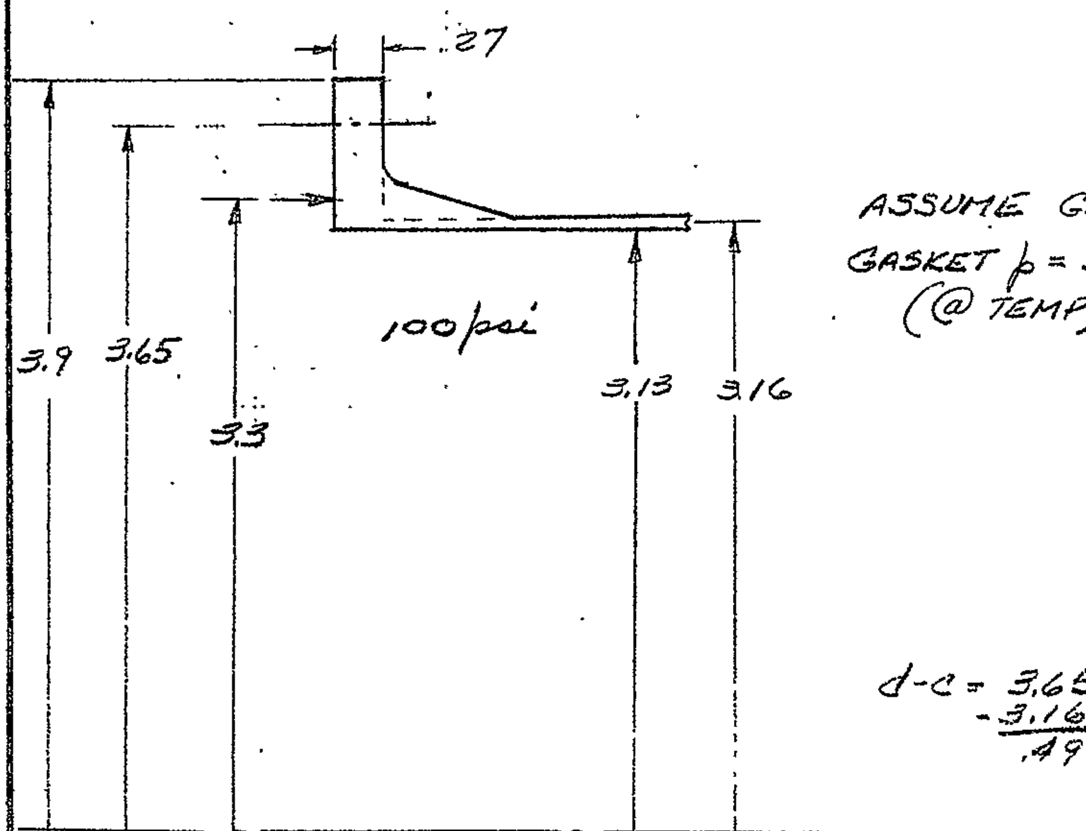
ALSO FROM THE SAME SOURCE AS ABOVE

$$P_{ALL} = 1500^{\#} \text{ @ } 2000°F$$

$$\therefore M.S._u = \frac{1500}{845} - 1 = .77 \text{ ON ULT.}$$

TITLE:

FWD. FLANGE ANALYSIS



ASSUME GASKET LEAK
GASKET $p = 330$ psi
(@ TEMP)

$$d-c = \begin{array}{r} 3.65 \\ -3.16 \\ \hline .49 \end{array}$$

p.16

$$R(d-c) = \frac{5540(.49)}{2\pi(3.16)} = 137$$

$$\beta = \frac{1.285}{\sqrt{.06\times 3.16}} = 2.95 \qquad K = \frac{.455}{(2.95)(3.16)}\left(\frac{.27}{.06}\right)^3 \overset{.223}{\ln\frac{3.9}{3.13}} = .992$$

$$M_0 = \frac{137}{1+\frac{2.95\times .27}{2}+.992} = 57.3 \qquad P_0 = 2.95(57.3) = 169$$

$$f_{c_{FLANGE}} = \frac{-6(57.3)(.992)}{(.27)^2(.223)} - \frac{(169-100\times .27)(3.5)^2}{3.13(.27)(3.9-3.13)}$$

$$= -21{,}000\text{ psi} - 2680\text{ psi} = -23680\text{ psi}$$

N.G. $F_{ty} = 8000$ psi @ 2500°F

LET $h = .4$

$$K = .992\left(\frac{.4}{.27}\right)^3 = 3.23$$

$$M_o = \frac{137}{1 + \frac{2.95(.4)}{2} + 3.23} = 27.8$$

$$P_o = 2.95(27.8) = 82.3$$

$$f_{c_{MOMENT}} = \frac{-6(27.8)(3.23)}{(.4)^2(.223)} = -15100 \text{ psi}$$

MOVE BOLTS IN TO 3.57R, LET $h = .4$

$$R(d-c) = \frac{5540(3.57 - 3.16)}{2\pi(3.16)} = 115$$

$B = 2.95$ $\quad K = 3.23$

$$M_o = 27.8\,\frac{115}{137} = 23.3$$

$$P_o = 2.95(23.3) = 68.8$$

$$f_{c_M} = \frac{-6(23.3)(3.23)}{(.4)^2(.223)} = -12700 \text{ psi}$$

TITLE:

HEAT TRANSFER SECTION ESTIMATES THE FLANGE TEMPERATURE TO BE 2000°F RATHER THAN 2500°F BASED ON CONSERVATIVE CALCULATIONS.

$$@2000°F \quad \left.\begin{array}{l} F_{tu} = 25{,}000\,psi \\ F_{ty} = 18{,}000\,psi \end{array}\right\} \text{MIN. GUAR.}$$

(REF. - WAH CHANG ALBANY)

∴ LETTING $k = .4$ AND BOLT RADIUS = 3.57

$$f_c = -12{,}700 - \frac{(68.8 - 100 \times .40)(3.5)^2}{3.13(.4)(3.9-3.13)}$$

$$f_c = -12{,}700 - 366 = -13{,}066\,psi$$

$$M.S. = \frac{18000}{13066} - 1 = .38 \text{ ON YIELD}$$

SHELL STRESS WILL BE TAKEN CARE OF BY TAPER AT THE WALL,

$$f = \frac{6(23.3)}{(.24)^2} + \frac{5540}{2\pi(3.25)(.24)} = 2430 + 1130 = 3560\,psi$$

OK

TITLE:

FWD. FLANGE ANALYSIS - 900 psi GASKET PRESSURE AND 100 psi LEAK

$$R(d-c) = \frac{115 \times}{5540}\left(3421 + \overset{9203}{2120 \times \frac{900}{330}}\right) = 191$$

$$M_o = 23.3 \times \frac{191}{115} = 38.7$$

$$f_{CM} = -12700 \times \frac{38.7}{23.3} = -21{,}094 \text{ psi}$$

$$f_c = \frac{-(2.95 \times 38.7 - 100 \times .4)(3.5)^2}{3.13(.4)(3.9-3.13)} = -942$$

$$f_{c_{RING}} = -22036 \text{ psi}$$

SHELL

$$f = \frac{6(38.7)}{(.24)^2} + \frac{9203}{2\pi(3.25)(.24)} = 4031 + 1878$$

$$f = 5909 \text{ psi}$$

OK $\left.\begin{array}{l} F_{ty} = 40 \text{ ksi} \\ F_{tu} = 58 \text{ ksi} \end{array}\right\}$ @ R.T. REF. WAH-CHANG ALBANY

FWD. FLANGE ANALYSIS – PROOF PRESSURE

$h = .4 \quad t = .06$

$P = \pi (3.13)^2 (250) = 7694$

$P' = \pi (3.3^2 - 3.13^2) 250 = 859$

8553

$G = .10 (8553) = 855$

$$R(d-c) = \frac{\overset{3770}{(7694)}(.49) + \overset{374}{(859)}\left(\frac{2 \times 3.65 - 3.13 - 3.3}{2}\right) + \overset{299}{(855)}(3.65 - 3.3)}{2\pi (3.16)}$$

$R(d-c) = 224$

$\beta = 2.95 \qquad K = 3.23$

$$M_o = \frac{224}{1 + \frac{2.95 \times .4}{2} + 3.23} = 46.5$$

$P_o = 2.95 (46.5) = 137$

$$f_{CM} = \frac{-6 (46.5)(3.23)}{(.4)^2 (.223)} - \frac{(137 - 250 \times .4)(3.5)^2}{3.13 (.4)(3.9 - 3.13)}$$

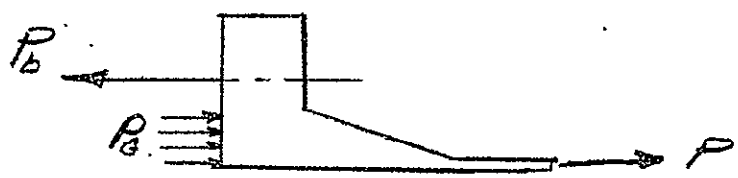
$= -25257 - 470 = -25727$ psi

SHELL STRESS

$$f = \frac{6 (46.5)}{(.24)^2} + \frac{250 \times 3.16}{2 (.24)} = 4844 + 1646 = 6490 \text{ psi}$$

OK $F_{ty} = 40$ ksi $\quad F_{tu} = 58$ ksi @ R.T.

REDESIGNED FLANGE GASKET



1. CHECK BOTH GRAFOIL GASKETS AT 900 psi WITH A LEAK OF 100 psi TO THE OUTSIDE GASKET.

(REF. p 26)

$$P = 9203^{\#}$$

$$P_G = 900\pi\left(\overline{3.38}^2 - \overline{3.13}^2\right) = 4602$$

$$P_b = 13805^{\#}$$

$$R(d-c) = \frac{9203(\overset{3775}{3.57-3.16}) + 4602\left[\frac{\overset{1445}{2(3.57)-3.13-3.38}}{2}\right]}{2\pi(3.16)} = 263$$

$$\beta = 2.95$$

$$h = .42 \qquad f = 3.87$$

$$K = \frac{.455}{2.95(3.16)}\left(\frac{.42}{.06}\right)^3 \ln \overset{.215}{\frac{3.87}{3.13}} = 3.6$$

TITLE:

$$M_o = \frac{263}{1 + \frac{2.95(.42)}{2} + 3.6} = 50.4$$

$$P_o = 2.95(50.4) = 149$$

$$f_{c_{RING}} = \frac{-6(50.4)(3.6)}{(.42)^2(.215)} - \frac{(149 - 100 \times .42)(3.5)^2}{3.13(.42)(3.87 - 3.13)}$$

$$= -28{,}704 - 1347 = -30{,}051 \text{ psi}$$

OK FOR BEGINNING OF RUN, I.E. R.T.

ANALYZE HOT CONDITION WITH OUTER GASKET PRESSURE = 900 #/in² (DESIRED BY DESIGN DEPT) INNER GASKET $p = 330$ #/in², 100 psi LEAK TO OUTER GASKET.

LET $h = .5$

$P = 5540$

$P' = 4602$

$$R(d-c) = \frac{5540(3.57 - 3.16) + 1450}{2\pi(3.16)} = 187$$

$$K = \frac{.455}{2.95(3.16)}\left(\frac{.5}{.06}\right)^3(.215) = 6.08$$

$$M_o = \frac{187}{1 + \frac{2.95 \times .5}{2} + 6.08} = 24$$

TITLE:

$$f_{c_{RING}} = \frac{-6(24)(6.08)}{(.5)^2(.215)} - \frac{(24 \times 2.95 - 100 \times .5)(3.5)^2}{3.13(.5)(3.87-3.13)}$$

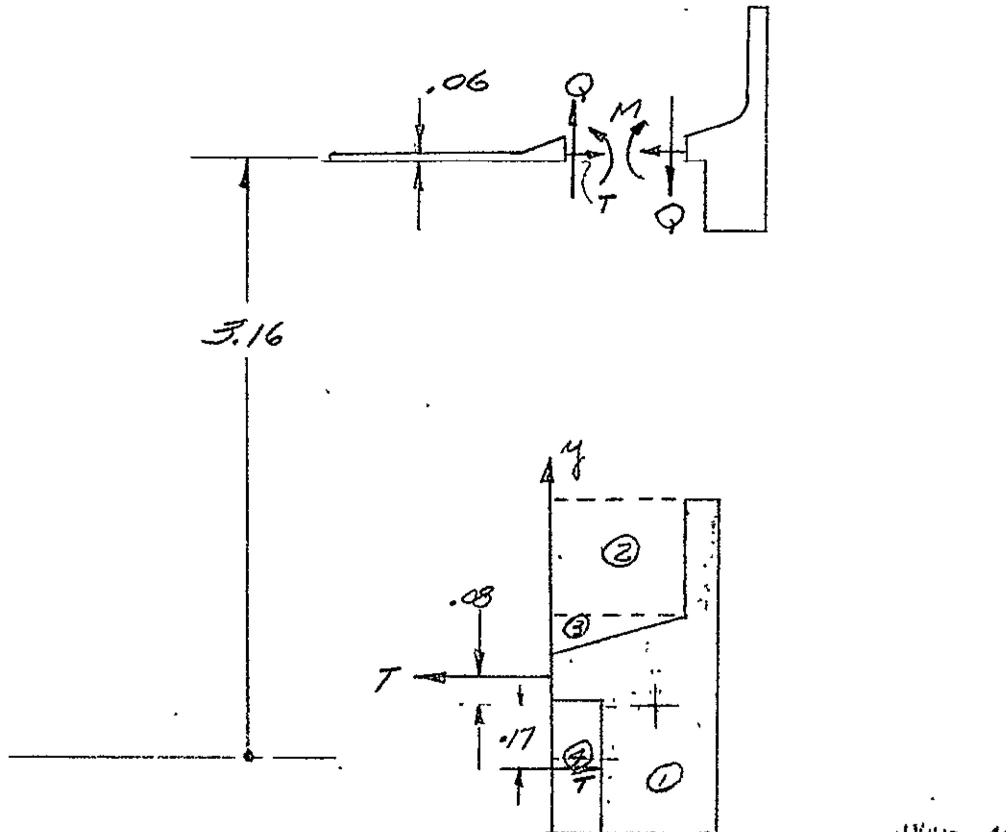
$$= -16288 - 220 = -16,508$$

@ 2000°F $F_{ty} = 18 \text{ ksi}$ OK

$F_{tu} = 25 \text{ ksi}$

TITLE:

AFT FLANGE ANALYSIS



BODY	A	x	y	Ax	A.x²	Ay	I_o
①	.43x.87=.374	.215	.435	.08041	.01729	.16269	$\frac{.43^3 \times .87}{12}$ = .00576
②	.35x.3=-.105	.175	.72	-.01838	-.00322	-.0756	$\frac{.35^3 \times .3}{12}$ = -.00107
③	$\frac{.35}{2}$x.1=-.018	.117	.54	-.00210	-.00025	-.00972	$\frac{.35^3 \times .1}{36}$ = -.00012
④	.13x.35=-.046	.065	.175	-.00299	-.00019	-.00805	$\frac{.13^3 \times .35}{12}$ = -.00006
	.205			.05694	.01363	.06932	.00451

$$I_{yy} = .00451 + .01363 = .01814$$

$$\bar{x} = \frac{.05694}{.205} = .2778$$

$$I_{CG} = .01814 - .205(.2778)^2 = .0023$$

$$\bar{y} = \frac{.06932}{.205} = .3381$$

SHELL:

AXIAL LOAD T

DUE TO PRESSURE (ASSUMES GASKET LEAK) $= \pi(3.3)^2(100) = 3421$

DUE TO NEW GASKET DESIGN $= 330\pi(\overline{2.65}^2 - \overline{2.22}^2) = 2171$

$$T = \frac{5592}{2\pi 3.16} = 282$$

$$\beta = \frac{1.285}{\sqrt{3.16(.06)}} = 2.95 \qquad \frac{D}{E} = \frac{\overline{.06}^3}{10.92} = 19.78\times10^{-6}$$

$$\frac{E}{2D\beta^2} = \frac{10^6}{2(19.78)(2.95)^2} = 2905$$

$$\frac{E}{D\beta} = \frac{10^6}{19.78\times2.95} = 17138$$

$$\frac{E}{2D\beta^3} = 985$$

$$EW_p = -\left[\frac{100(3.16)}{.06} - .3\frac{(282)}{.06}\right](3.16) = -12187$$

$$E\theta = 2905Q + 17138M$$

$$EW = -12187 - 985Q - 2905M$$

TITLE:

RING;

$$\overset{\curvearrowleft +}{M_N} = .25(282) + .28Q - M$$

$$\overset{\downarrow +}{Q_N} = Q$$

$$E\theta = \frac{M_N R^2}{I} = \frac{M_N (3.08)^2}{.0023} = 4125 M_N$$

$$E\theta = 290{,}813 + 1155Q - 4125M$$

$$EW_C = \frac{Q(3.08)^2}{.205} = 46Q$$

$$EW_L = 46Q + .2778(290{,}813 + 1155Q - 4125M)$$

$$= 46Q + 80788 + 321Q - 1146M$$

$$= 367Q - 1146M + 80{,}788$$

EQUATING RING TO SHELL

$$2905Q + 17138M - 1155Q + 4125M - 290813 = 0$$

$$1750Q + 21263M - 290813 = 0$$

$$-12187 - 985Q - 2905M - 367Q + 1146M - 80{,}788 = 0$$

$$-1352Q - 1759M - 92975 = 0$$

$$-1750Q - 2277M - 120{,}345 = 0$$

$$0 \qquad 18986M = 411158$$

$$M = 21.66 \ \frac{\text{IN}-\#}{\text{IN}}$$

TITLE:

$$1750\,Q = 290813 - 21263(21.66)$$

$$Q = -97 \text{ \#/in.}$$

$$EW_L = 367(-97) - 1146(21.66) + 80788$$

$$EW_L = 20{,}367$$

$$EW_R = 46(-97) - .15(290813) - .15(1155)(-97) + .15(4125)(21.66)$$

$$= -17876$$

RING

MAX STRESS $f = \dfrac{-20367}{3.08} = -6613 \text{ psi}$

SHELL

MAX STRESS $f = \dfrac{6(21.66)}{(.10)^2} + \dfrac{292}{.10} = 15{,}816 \text{ psi}$

THICKNESS AT CUT

TEMP = 2000 °F

$F_{ty} = 18{,}000 \text{ psi}$

$F_{tu} = 25{,}000 \text{ psi}$

$$M.S. = \frac{18000}{15816} - 1 = .14 \quad \text{ON YIELD}$$

INCREASE TAPERED SECTION TO GET MORE MARGIN.

C
P

TITLE:

CHECK CONDITION WHERE THE GASKET PRESSURE IS 900 psi (BEGINNING OF RUN)

$$\text{TOTAL AXIAL FORCE} = 900\pi(2.65^2 - 2.22^2) + 3421$$
$$= 5920 + 3421 = 9341^{\#}$$

$$T = \frac{9341}{2\pi(3.16)} = 470\ \#/\text{IN}$$

SHELL:

$$E\theta = 2905Q + 17138M$$

$$EW_p = -\left[100(3.16) - .3(470)\right]\frac{3.16}{.06} = -9217$$

$$EW = -9217 - 985Q - 2905M$$

RING:

$$E\Theta = 484{,}000 + 1155Q - 4125M$$

$$EW_L = 367Q - 1146M + 134800$$

$$367Q - 1146M + 134800 + 9217 + 985Q + 2905M = 0$$
$$1352Q + 1759M + 144017 = 0$$

$$2905Q + 17138M - 484000 - 1155Q + 4125M = 0$$
$$1750Q + 21263M - 484000 = 0$$
$$-14668M = -517942$$
$$M = 35.31$$
$$1352Q = -144017 - 1759(35.31)$$
$$Q = -152.5$$

TITLE:

RING STRESS:

$$\Sigma W_L = 367(-152.5) - 1146(35.31) + 134800$$
$$= 42700$$

$$f = -\frac{42700}{3.08} = -13{,}864 \text{ psi}$$

SHELL STRESS:

$$f = \frac{6(35.31)}{(.1)^2} + \frac{470}{.1} = 25886 \text{ psi}$$

OK $F_{by} = 40{,}000$ psi @ RT (TIME WHEN $P_c = 900$ psi)
$F_{bu} = 58{,}000$ psi

AFT FLANGE

FOR PROOF PRESSURE = 260 #/in²

SHELL

$$E\,w_P = -\frac{.85\,(260)(3.16)^2}{.06} = -36780$$

$$E\Theta = 17138\,M + 2905\,Q$$

$$E\,W = -2905\,M - 985\,Q - 36780$$

RING

$$M_N = \frac{250\overset{98.7}{(3.16)}}{2}(.25) + .28\,Q - M$$

$$E\Theta_L = 4125\,M_N$$

$$= -4125\,M + 1155\,Q + 407344$$

$$E\,W_L = -1196\,M + 367\,Q + .2778\,(407344)$$

$$= -1196\,M + 367\,Q + 113160$$

EQUATING RING TO SHELL

① $21263\,M + 1750\,Q - 407344 = 0$

② $-1759\,M - 1352\,Q - 149940 = 0$

② $\frac{1750}{1352}$ $-2277\,M - 1750\,Q - 194079 = 0$

TITLE:

$$18986\, M = 601423$$

$$M = 31.68 \text{ IN-\#/IN}$$

$$Q = \frac{149960 + 1759(31.68)}{-1352} = -152 \ \#/\text{IN}$$

$$E\,W_L = 21071$$

RING STRESS

$$f_{MAX} = -\frac{21071}{3.08} = -6841 \ \#/\text{IN}^2$$

SHELL STRESS

$$f_{MAX} = \frac{6(31.68)}{(.1)^2} + \frac{260(3.16)}{(2)(.1)}$$

$$= 19010 + 4108 = 23118 \ \#/\text{IN}^2$$

$$M.S._y = \frac{40000}{23118} - 1 = \underline{+.73}$$

TITLE:

RADIAL THERMAL GROWTH IN THE PLANE OF THE ATJS FLANGE

ATJS: $T = \frac{8+79+81}{3} = 3315$

$R_o = 2.45$ (REF. UNION CARBIDE CORP., TECH INF BUL. No. 463-201 IG)

$\Delta = 7.8 \times 10^{-3} \frac{IN}{IN.}$ FOR R_o (ACROSS GRAIN)

$\Delta R = 7.8 \times 10^{-3} \times 2.45 = .019$

P.G. OUTER LINER:

$T = \frac{36+43+50}{3} = 2795$

$t = .7$

$\Delta_{c''} = 40 \times 10^{-3}$ IN/IN (REF. - HIGH TEMPERATURE MATERIALS INC. P.G. DATA SHEET)

$\Delta t = .7 \times 40 \times 10^{-3} = .028$ IN.

COLUMBIUM:

REF. - WAH CHANG ALBANY

$T = 2000°F$ (HEAT TRANSFERS EST. OF ACTUAL T)

$\alpha = 4.0 \times 10^{-6}$ IN/IN/°F $\quad R = 3.13$

$\Delta R = 3.13(4 \times 10^{-6})(2000) = .025$

∴ RADIAL INTERFERENCE = $.019 + .028 - .025 = \underline{.022}$ IN.

PREP. BY C.F. NASH 10-28-68

CHKD. BY G. RABE 10/31/68

SECURITY INFORMATION

CALCULATION OR REPORT NO.

C P

TITLE:

CIRCUMFERENTIAL GROWTH OF P.G.

INNER P.G. IN PLANE OF NOZZLE

INNER CIRC. $= 2\pi(1) = 6.28$

$T = 5827°F$

$\Delta_{c}'' = .09$ REF. HIGH TEMPERATURE MATL INC.

$\Delta C = 6.28 \times .09 = .565$

OUTER CIRC. $= 2\pi(2.15) = 13.51$

$T = 5520°F$

$\Delta_{c}'' = .085$

$\Delta C = 13.51(.085) = 1.15$

CIRCUMFERENTIAL GRAFOIL FILLER SHEETS MUST DEFLECT THESE AMOUNTS TO ALLOW FOR CIRCUMFERENTIAL GROWTH.

OUTER P.G. IN PLANE OF NOZZLE

INNER CIRC $= 2\pi(2.28) = 14.326$

$T = 5056°F$

$\Delta_{a}'' = .007$ REF. - SUPER-TEMP CORP.

$\Delta C = 14.326(.007) = .10$

OUTER CIRC. $= 2\pi(3.12) = 19.60$

$T = 2037$

$\Delta_{a}'' = .0018$ REF. - SUPER-TEMP CORP.

$\Delta C = 19.60 \times .0018 = .035$

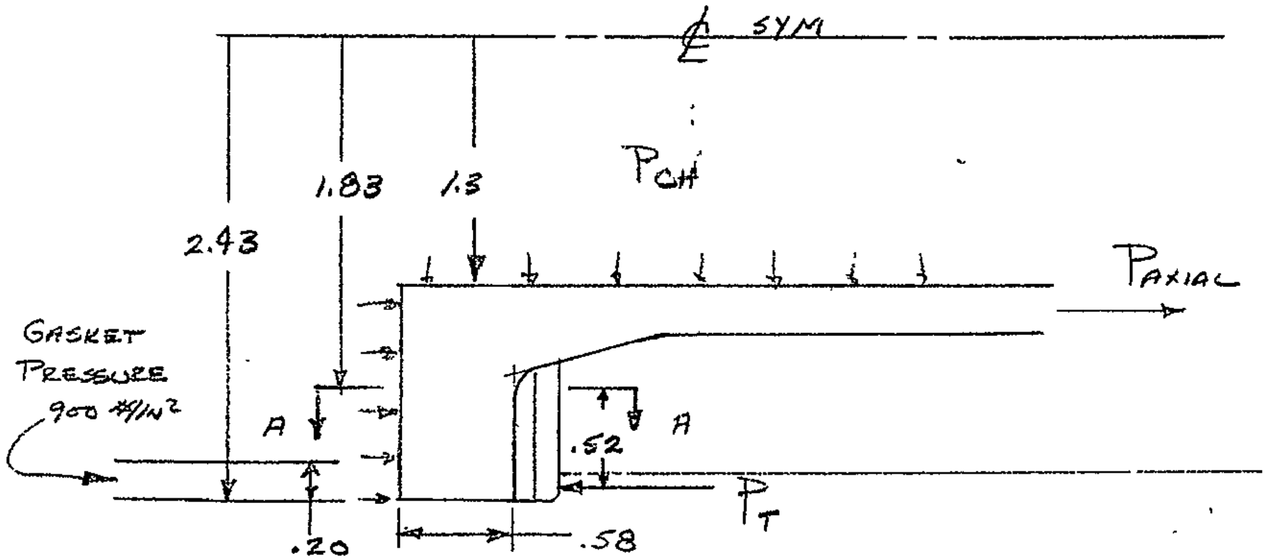
Thiokol CHEMICAL CORPORATION
REACTION MOTORS DIVISION
DENVILLE, NEW JERSEY

SECURITY INFORMATION

RMD RE 256

OGILVIE PRESS INC., BROOKLYN 17, N. Y. REPROVEL NO. 440H

TITLE:



THRUST (SEA LEVEL) = 125#

$P_{CH} = 100 \ \#/in^2$

$P_{AXIAL} = \pi (1.3)^2 (100) - 125 = 531 - 125$

$= 406 \ \#$

AT START $P_{CH} = 200 \ \#/in^2$

$P_{AXIAL} = 812 \ \#$

$$P_T = 812 + (200)\pi\big(\overbrace{2.23^2 - 1.3^2}^{3.28}\big) + (900)\pi\big(\overbrace{2.43^2 - 2.23^2}^{.93}\big)$$

$= 812 + 2060 + 2630 = 5502 \ \#$

TITLE:

Section A-A

$$M_{A-A} = \frac{5502(.52)}{2\pi(1.83)} - \frac{2630(.5)}{2\pi(1.83)} - \frac{200(.4)^2}{2}$$

$$= 249 - 115 - 16 = 118 \text{ in-\#/in}$$

$$f_{b_{A-A}} = \frac{6(118)}{(.58)^2} = 2105 \text{ \#/in}^2$$

Flange Analysis

Dimensions (in.)

$P = 812$ # $b = 1.3$ $h = .58$

$P' = 2060$ # $c = 1.42$ $t = .25$

$G = 2630$ # $d = 2.35$ $a = \frac{2.43 + 1.3}{2} = 1.86$

$e = 2.33$

$f = 2.43$

$$R(d-c) = \frac{812\overset{.93}{(2.35-1.42)} + 2060\overset{.535}{\left(\frac{4.7-1.3-2.33}{2}\right)} + 2630\overset{.02}{(2.35-2.33)}}{2\pi(1.42)}$$

$$= \frac{755 + 1100 + 52.6}{8.93} = \frac{1907.6}{8.93} = 214 \text{ in-\#/in}$$

$$\beta = \frac{1.285}{\sqrt{1.42(.25)}} = 2.16$$

$$K = \frac{.455}{(2.16)(1.42)}\left(\frac{.58}{.25}\right)^3 \ln\frac{2.43}{1.3}$$

$$= .1485\,(12.5)(.625) = 1.16$$

TITLE:

FLANGE ANALYSIS (CONT.)

$$M_0 = \frac{214}{1 + \frac{2.16(.58)}{2} + 1.16} = \frac{214}{2.785} = 76.7 \ \text{IN-\#/IN}$$

$$f_{t\,\text{WALL}} = \frac{6(76.7)}{(.45)^2} + \frac{812}{2\pi(1.42).45}$$

$$= 2280 + 202 = 2482 \ \text{\#/IN}^2$$

$$f_{c\,\text{FLANGE}} = -\frac{6(76.7)\,1.16}{(.58)^2(.625)} - \frac{\left[2.16(76.7) - \overset{50}{200}(.58)\right](1.86)^2}{1.3\,(.58)\,(\underset{1.13}{2.43-1.3})}$$

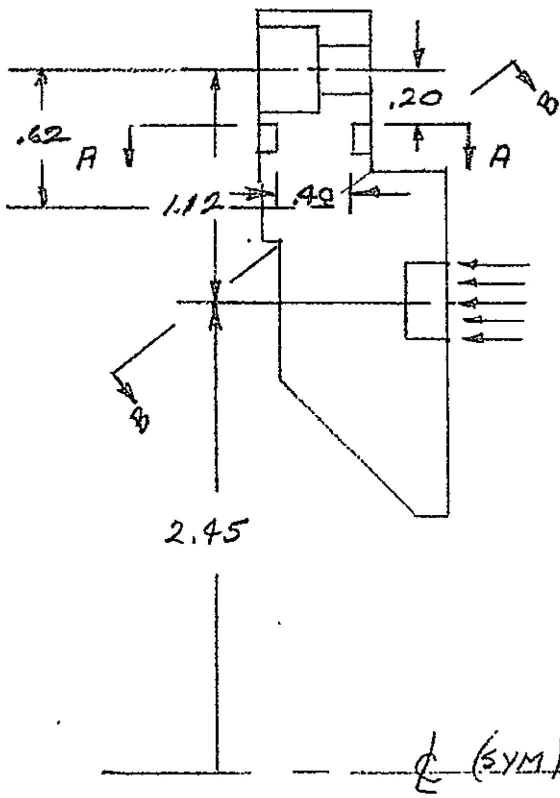
$$= -2540 - 203 = -2743 \ \text{\#/IN}^2$$

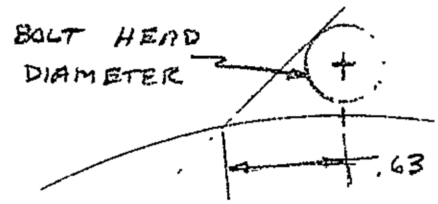
$$M.S._{\text{BENDING}} = \frac{5000}{2482} - 1 = \underline{+1.01}$$

$$M.S._{\text{COMPRESSION}} = \frac{12000}{2743} - 1 = \underline{+3.37}$$

TITLE:

INSULATOR BLOCK DURING INSTALLATION





MATERIAL – SILICA PHENOLIC

$F_{tu} = 14000\ \#/\text{in}^2$ @ R.T.

REF. POLYMERIC CHEM. FM-5067

$$M_{RING} = 900(.4)\,2\pi(2.45)(1.12) = 6207 \text{ IN-\#}$$

$$\frac{I}{C} = \frac{.112}{.50} = .224 \quad (\text{REF. NEXT PAGE})$$

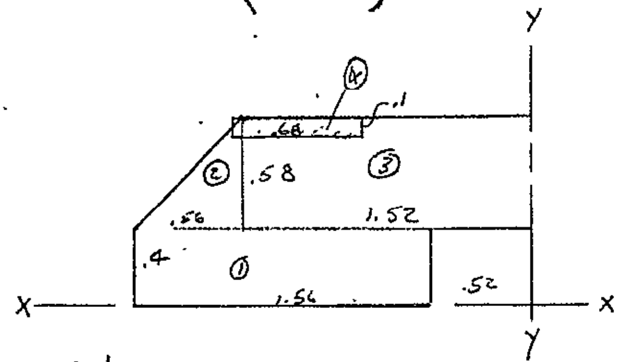
$$f_b = \frac{6207\ \cancel{R_{CG}}}{2\pi R_{CG}(.224)} = 4410\ \#/\text{in}^2$$

{REF. – POLYMERIC CHEMICALS INC. DATA SHEET FM-5067

$$M.S. = \frac{14000}{4410} - 1 = \underline{+\,2.17}$$

TITLE:

INSULATOR BOCK (CONT.)



ITEM	A	x	y	Ax	Ay	Ay^2	I_{ox}
1	(.4)(1.56) = .624	1.30	.2	.811	.1248	.02496	$\frac{1.56(.4)^3}{12} = .00832$
2	$\frac{.58(.56)}{2}$ = .1624	.76	.59	.123	.0958	.05653	$\frac{.56(.58)^3}{36} = .00304$
3	.58(1.52) = .8816	1.71	.69	1.508	.6083	.41973	$\frac{1.52(.58)^3}{12} = .02471$
4	-(.1)(.68) = -.068	1.22	.93	-.083	-.0632	-.05881	$-\frac{.68(.1)^3}{12} = -.00006$
Σ	1.60			2.359	.7657	.44241	.03601

$$\bar{X} = \frac{2.359}{1.6} = 1.474 \text{ in.} \qquad \bar{Y} = \frac{.7657}{1.6} = .4786 \text{ in.}$$

$$I_{xx} = .03601 + .44241 - .4786(.7657) = .112 \text{ in.}^4$$

BOLT STRESS

$$P = \frac{6207}{1.12(12)} = 461 \text{ \#}$$

$$f_t = \frac{461}{.0362} = 12\,800 \text{ \#/in}^2 \quad \text{NOT CRITICAL}$$

C P

TITLE:

INSULATOR BLOCK (CONT.)

SECTION A-A

$$f_{b\,A-A} = \frac{(461)(.20)(6)}{\cancel{2}\,\cancel{(.63)}_{.21}\,(.4)^2} = 2744\ \#/in^2$$

$$M.S. = \frac{14\,000}{2744} - 1 = +\underline{4.10}$$

$$f_s = \frac{461\ (12)}{2\pi\ (3.2)(.4)} = 688\ \#/in^2$$

O.K.

SECTION B-B

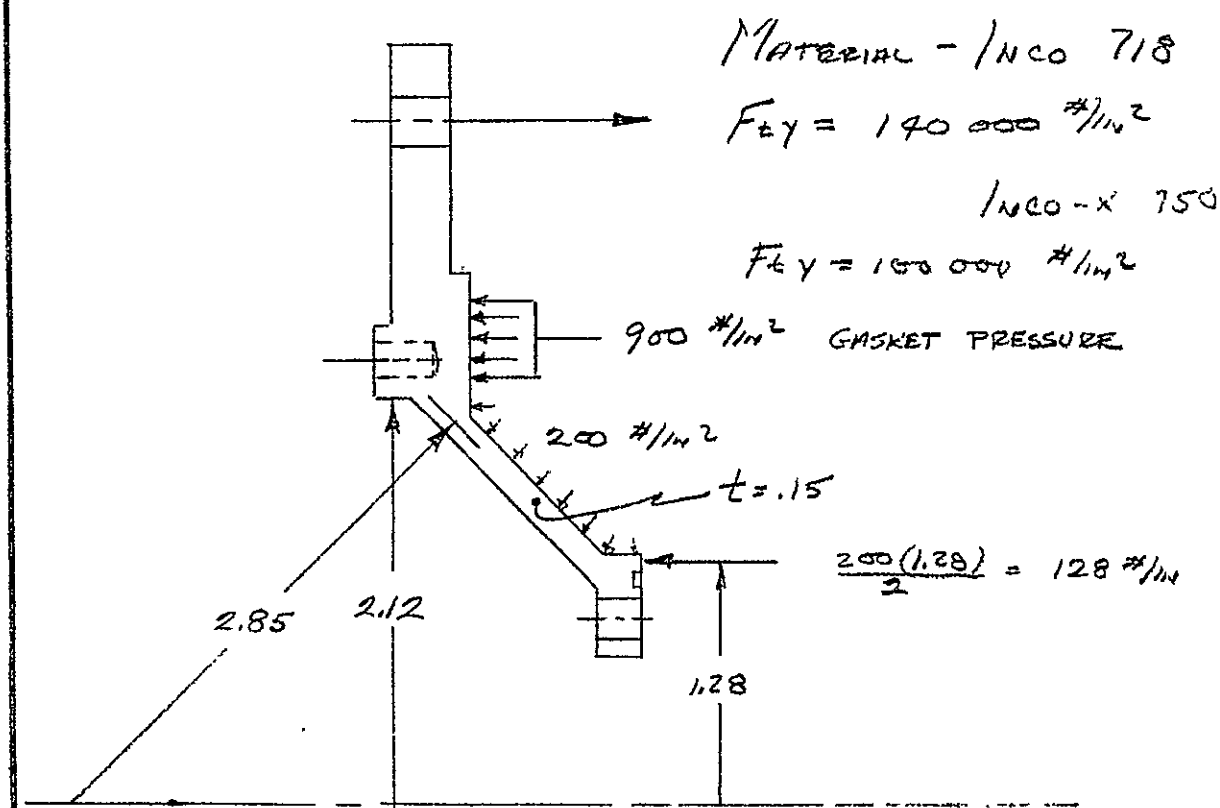
$$f_{b\,B-B} = \frac{461\ (12)(.22)\ 6}{2\pi\ (2.95)(.6)^2} = \pm 3084\ \#/in^2$$

$$f_{a\,B-B} = \frac{461\ (12)\sqrt{.6^2 - .4^2}}{2\pi\ (2.95)(.6)(.6)} = -371\ \#/in^2$$

$$M.S. = \frac{14\,000}{3084 + 371} - 1 = \underline{+3.05}$$

TITLE:

INJECTOR PLATE

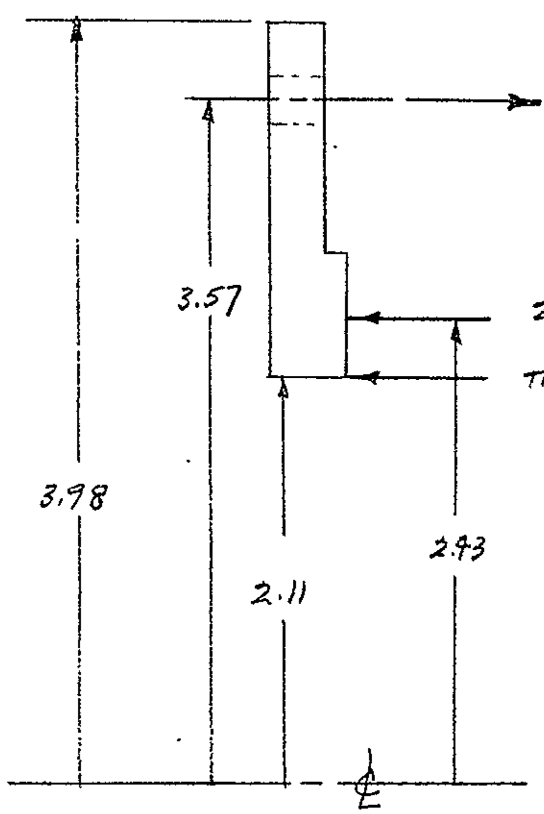


CONE

$$S_2 = \frac{200\,(2.85)}{.15} = 3800 \text{ \#/in}^2 \text{ NOT CRIT.}$$

TITLE:

INJECTOR PLATE (CONT.)



$2\pi(2.43)\,900(.4) = 5490$ #

$\pi(2.11)^2(200) = 2800$ #

FOR LOAD AT INNER EDGE

$$S_t = \frac{3\,(2800)}{2\pi(3.33)\,(.4)^2}\left[\frac{2(3.98)^2\,4.33}{\underbrace{3.98^2 - 2.11^2}_{11.38}}\ln\overset{.525}{\frac{3.57}{2.11}} + 2.33\left(\frac{3.57^2 - 2.11^2}{\underbrace{3.98^2 - 2.11^2}_{11.38}}\right)^2\right]$$

$$= 2500\,(6.38 + 1.70) = 20200 \ \#/\text{in}^2$$

FOR THE GASKET LOAD

$$S_t = \frac{3(5490)}{2\pi(3.33)(.4)^2}\left[\frac{2(3.98)^2(4.33)}{11.38}\ln\overset{.386}{\frac{3.57}{2.43}} + \frac{2.33(3.57^2 - 2.43^2)^2}{11.38}\right]$$

$$= 4920(4.65 + 1.40) = 29800 \ \#/\text{in}^2$$

TITLE:

INJECTOR PLATE (CONT.)

$$S_{t\ \text{TOTAL}} = 20200 + 29800 = 50\,000\ \#/\text{IN}^2$$

$$M.S. = \frac{100\,000}{50\,000} - 1 = \underline{+1.00}$$

TITLE:

PROOF PRESSURE

ASSUME PRESSURE ACTS ON Cb WALL DUE TO GASKET LEAK

$$P_{PROOF} = 100\,(1.15)\,\frac{F_{ty\ RT}}{F_{ty\ 2000°F}}$$

$$P_{PROOF} = \frac{115\,(40\,000)}{18000} = 255\ \#/in^2$$

USE $P_{PROOF} = 250 - 260\ \#/in^2$