GEORGIA INSTITUTE OF TECHNOLOGY
OFFICE OF CONTRACT ADMINISTRATION
SPONSORED PROJECT INITIATION

Date: November 16, 1979

Project Title: Optical, Thermal and Stress Analysis of Ceramic Receiver

Project No: A-2503

Project Director: Mr. Tom B. Elfe

Sponsor: Fairchild Stratos Division; Manhattan Beach, California 90266

Agreement Period: From 10/12/79 Until 11/15/79

Type Agreement: Purchase Order No. H-E0530 under Prime No. NAS 7-100

Amount: Not to exceed $15,986.64 (includes funding from C.O. #1)

Reports Required: Draft Reports; Detail Report

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Defense Priority Rating: None

Assigned to: ERL/SRB XXXXXXX(School/Laboratory)

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CA-3 (3/76)

GEORGIA INSTITUTE OF TECHNOLOGY
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SPONSORED PROJECT TERMINATION

Date: 2/5/80

Project Title: Optical, Thermal and Stress Analysis of Ceramic Receiver

Project No: A-2503

Project Director: Tom Elfe

Sponsor: Fairchild Stratos Division; Manhattan Beach, CA 90266

Effective Termination Date: 2/1/80

Clearance of Accounting Charges: 2/1/80

Grant/Contract Closeout Actions Remaining:

_x_ Final Invoice ~~and Closing Documents~~

_ Final Fiscal Report

_ Final Report of Inventions

_ Govt. Property Inventory & Related Certificate

_ Classified Material Certificate

_ Other _____

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CA-4 (1/79)

FINAL REPORT

PROJECT A-2503

CERAMIC SOLAR RECEIVER FEASIBILITY STUDY

By

T. B. Elfe

J. F. Kinney

J. H. Murphy

December 1979

Prepared for

Fairchild Stratos Division
Manhattan Beach, CA 90266

Engineering Experiment Station
Georgia Institute of Technology
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OPTICAL ANALYSIS

An optical analysis was performed to establish the solar flux pattern on the receiver surface. The concentrator used for the analysis was the JPL Test Bed Concentrator, masked for 67 kW reflected power. The masking scheme was that worked out by Dr. Peter Poon of JPL when Dr. Poon visited Georgia Tech in August. The 67 kW is slightly low, but was used to make correlations with earlier receiver work more direct.

One alteration was made to the optical analysis program. Previously, the systematic slope error produced by approximating a paraboloid by spherical facets had been put into the program as a parabolic approximation which passed through the actual errors at the edges of each facet and the assumed zero error in the center of the facet. With the parabolic fit, there is no inflection point in the systematic error for a given facet. In the present model, the systematic error is a cubic fit, wherein the amplitude is different on each side of facet center. This approximation is more realistic than the parabolic approximation, in that there is an inflection point at the facet center and the slope is maximum at the two ends.

The flux pattern from the masked Test Bed Concentrator thus modeled is shown in Figure 1. Qualitatively, it is similar to the pattern presented in the Design Review Report. One significant difference is that the double peak in the earlier pattern has disappeared. It would be surprising if the change from parabolic to cubic systematic error could produce such a change. Since it did not appear that the accuracy of the thermal model would be seriously affected by relatively small flux pattern differences, this phenomenon was not investigated further.

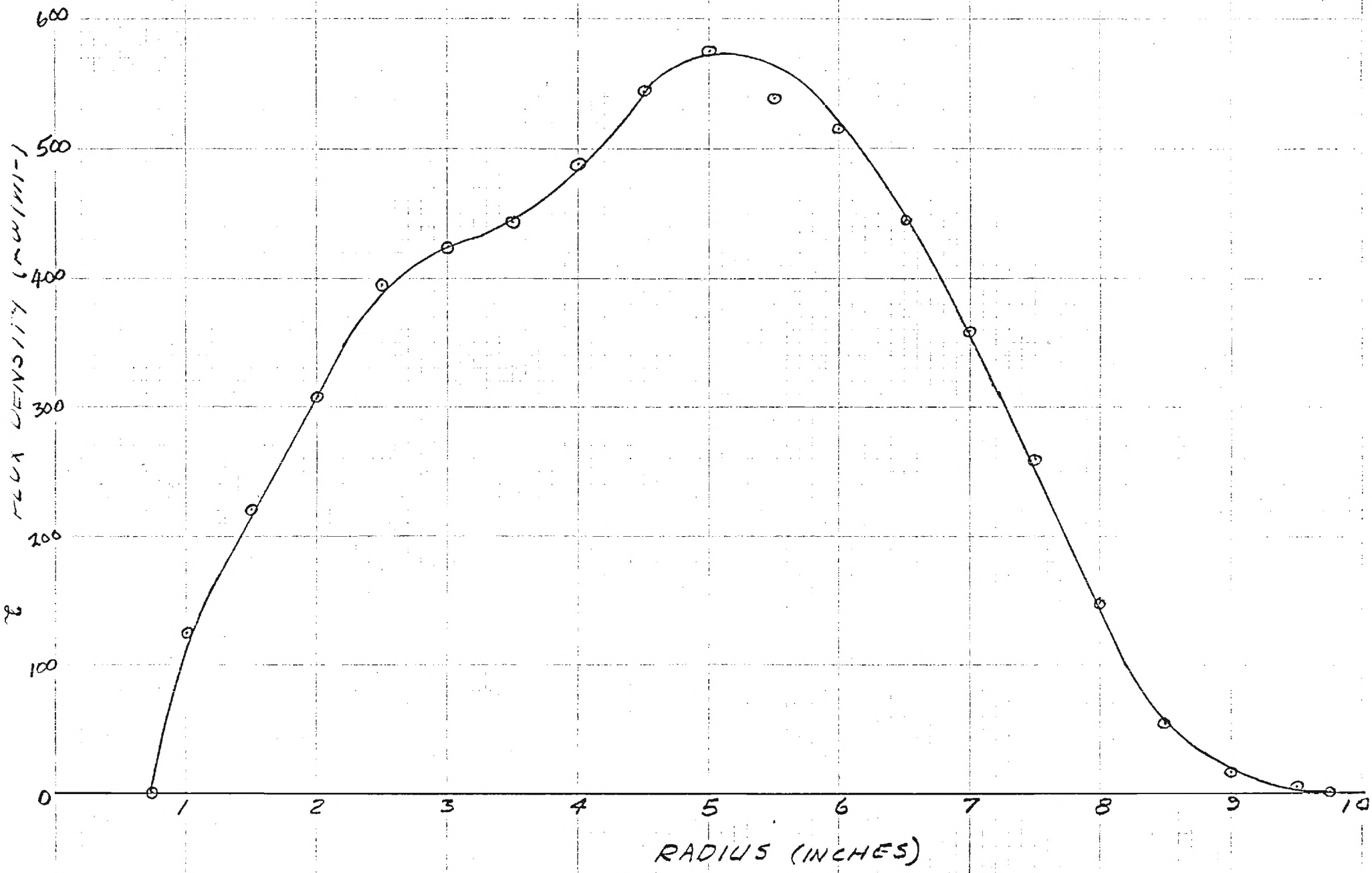


FIGURE 1
FLUX ON RECEIVER SURFACE

CERAMIC RECEIVER 1500 DEG. FLUID REGENERATOR TUBE OCTOBER 26 VERSION 100% COMBUSTOR MODE

++NOTE++ EBALNA(.100000) HAS BEEN MET ON ITERATION 164.

TIMEN = .0	EBALSC = -.883829	CSGMIN(0) = .0	DRLXCC(0) = .0
TSTEPU = .0	EBALNC(2) =-8.854360E-02	CSGMAX(0) = .0	ARLXCC(2) =-7.202451E-02
	ITERCT = 164	DMXTCC(0) = .0	AMXTCC(0) = .0

DIFFUSION NODES
++NONE++

ARITHMETIC NODES

T 1= 1749.63	T 2= 1764.44	T 3= 1776.68	T 4= 1787.28	T 5= 1796.73	T 6= 1749.24
T 7= 1764.01	T 8= 1776.21	T 9= 1786.70	T 10= 1795.97	T 11= 1748.27	T 12= 1762.98
T 13= 1775.04	T 14= 1785.34	T 15= 1794.38	T 16= 1746.86	T 17= 1761.41	T 18= 1773.30
T 19= 1783.41	T 20= 1792.21	T 21= 1745.01	T 22= 1759.44	T 23= 1771.15	T 24= 1781.02
T 25= 1789.58	T 26= 1742.90	T 27= 1757.16	T 28= 1768.63	T 29= 1778.28	T 30= 1786.62
T 31= 1740.58	T 32= 1754.65	T 33= 1765.90	T 34= 1775.30	T 35= 1783.40	T 36= 1738.18
T 37= 1752.03	T 38= 1763.01	T 39= 1772.11	T 40= 1779.90	T 41= 1735.84	T 42= 1749.47
T 43= 1760.15	T 44= 1768.91	T 45= 1776.31	T 46= 1733.75	T 47= 1747.17	T 48= 1757.56
T 49= 1765.96	T 50= 1772.99	T 51= 1732.08	T 52= 1745.32	T 53= 1755.44	T 54= 1763.52
T 55= 1770.19	T 56= 1730.99	T 57= 1744.10	T 58= 1754.01	T 59= 1761.84	T 60= 1768.19
T 61= 1730.61	T 62= 1743.67	T 63= 1753.50	T 64= 1761.19	T 65= 1767.34	T 66= 1695.70
T 67= 1707.43	T 68= 1717.26	T 69= 1725.86	T 70= 1733.64	T 71= 1695.37	T 72= 1707.05
T 73= 1716.77	T 74= 1725.18	T 75= 1732.66	T 76= 1694.46	T 77= 1706.01	T 78= 1715.51
T 79= 1723.63	T 80= 1730.74	T 81= 1693.12	T 82= 1704.51	T 83= 1713.76	T 84= 1721.54
T 85= 1728.30	T 86= 1691.51	T 87= 1702.73	T 88= 1711.71	T 89= 1719.21	T 90= 1725.64
T 91= 1689.77	T 92= 1700.83	T 93= 1709.61	T 94= 1716.88	T 95= 1723.06	T 96= 1688.02
T 97= 1698.93	T 98= 1707.55	T 99= 1714.63	T 100= 1720.64	T 101= 1686.36	T 102= 1697.14
T 103= 1705.59	T 104= 1712.51	T 105= 1718.36	T 106= 1684.87	T 107= 1695.52	T 108= 1703.82
T 109= 1710.58	T 110= 1716.28	T 111= 1683.61	T 112= 1694.14	T 113= 1702.29	T 114= 1708.91
T 115= 1714.47	T 116= 1682.63	T 117= 1693.09	T 118= 1701.15	T 119= 1707.64	T 120= 1713.04
T 121= 1682.02	T 122= 1692.43	T 123= 1700.39	T 124= 1706.77	T 125= 1712.05	T 126= 1681.81
T 127= 1692.18	T 128= 1700.11	T 129= 1706.46	T 130= 1711.68	T 131= 3449.26	T 132= 3399.98
T 133= 3352.11	T 134= 3305.58	T 135= 3260.35	T 136= 3216.37	T 137= 3152.48	T 138= 3071.63
T 139= 2995.30	T 140= 2923.24	T 141= 2855.21	T 142= 2806.04	T 143= 2773.72	T 144= 2742.29
T 145= 2711.74	T 146= 2682.05	T 147= 2653.19	T 148= 2625.17	T 149= 2611.36	T

HEATER NODES
++NONE++

BOUNDARY NODES

T 150= 3500.00	T 151= 1500.00 T

Table I. Calculated Temperatures for Regenerator Tubes.

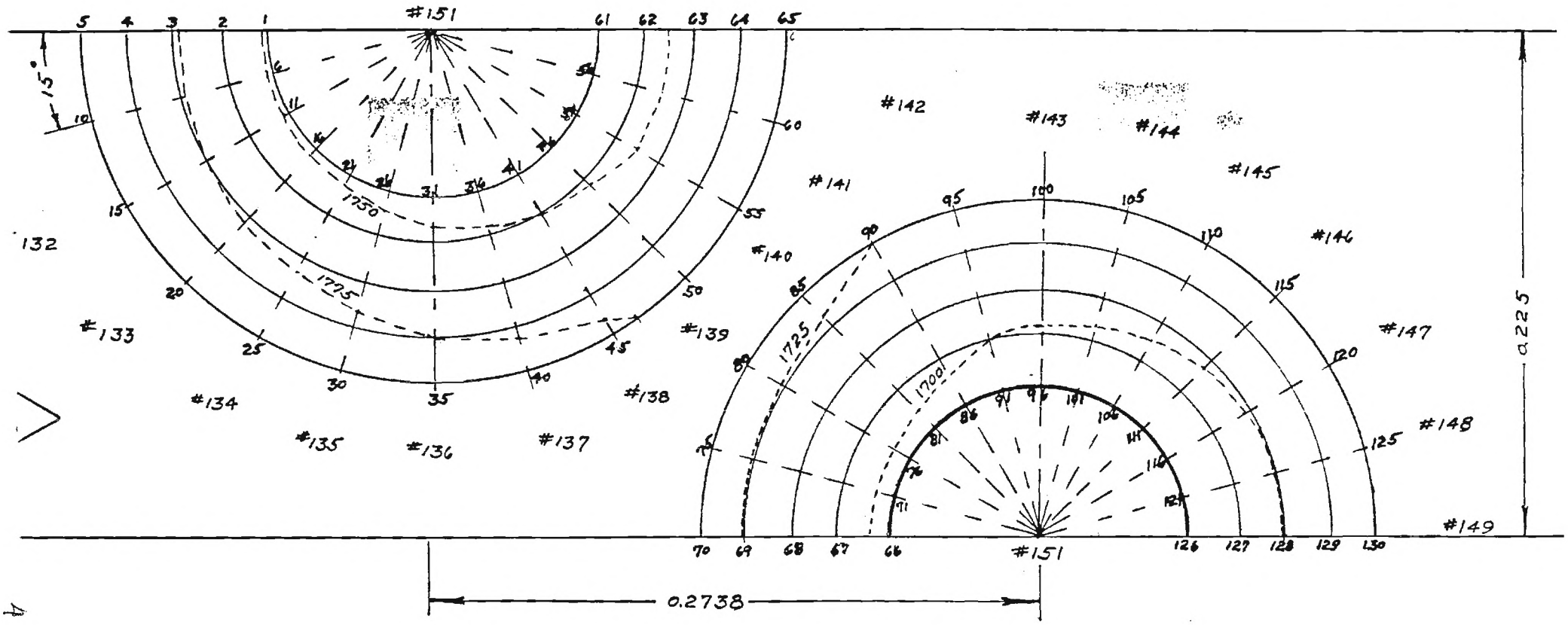


Figure 2.

Node Configuration for Regenerator Tubes.

TEMPERATURE DISTRIBUTION IN SILICON CARBIDE RECEIVER

The steady state temperature distribution in the section of the regenerator tube was estimated using part of the Mitas program, input combustion gas temperature of 3500° F, a constant helium gas temperature of 1500° and a constant value of the thermal conductivity for silicon carbide of 14 Btu/hr-ft-^{o}F. The variation of the temperature of the combusion gases as they pass through the modeled section was estimated using $\dot{W}Cp$ as the gas conductivity, where

$\dot{W}$ = combustion gas to model section, pounds/hour

Cp = combustion gas heat capacity, Btu/lb-^{o}F.

With 340 pounds/hour of combustion gases in the non-solar mode, and 48 sets of three regenerator tubes each,

$$\dot{W} = \frac{340}{3 \times 48} = 2.36 \text{ lb/hr}$$

$$Cp = 0.42 \text{ Btu/lb-}^{o}\text{F}$$

$$\dot{W}C = 0.977 \text{ Btu/}^{o}\text{F}$$

In this analysis, the combustion gases were assumed to be completely mixed at each gas node.

A total of 130 nodes in the tube sections and 21 combustion gas nodes were chosen. The temperatures produced by the steady state Mitas calculation are shown in Table I. Four isothermal lines are sketched in on Figure 2

The temperature of the combustion gases leaving the regenerator tubes was used as the temperature of the gases entering the cone, both for the solar and non-solar cases.

SUMMARY OF MAXIMUM TEMPERATURE AND GRADIENT DATA

	Maximum Temperature (^{o}F)	Maximum Gradient	Nodes
Solar + 10% Comb.	2154	$1400^{o}F/in.$	135-136
100% Comb.	1860	$< 300^{o}/in.$	
100% Comb., no gas to plane #7	1640	$< 300^{o}/in.$	

Seven planes in the cone were also examined in the steady-state with the Mitas program. These planes were cut as shown in Figure 3 using a width of 1/96 of the circle, 49 nodes on each plane plus the constant temperature helium node and five combustion gas nodes. The sinusoidal shape of the combustion gas passage in the rear of the cone was modeled as shown in Figures 6-10.

A radial depth of 2 mm for the combustion gas passage was used in estimating the gas velocity in the cone passage. However, since velocity is inversely proportional to the width of the passage, Reynold's number is virtually a constant value in the cone, and a constant value of the convective coefficient* was used in these calculations.

*100% Combustion; $h = 70$ Btu/hr-ft^2-^{o}F
Solar plus 10% combustion; $h = 26$ Btu/hr-ft^2-^{o}F.

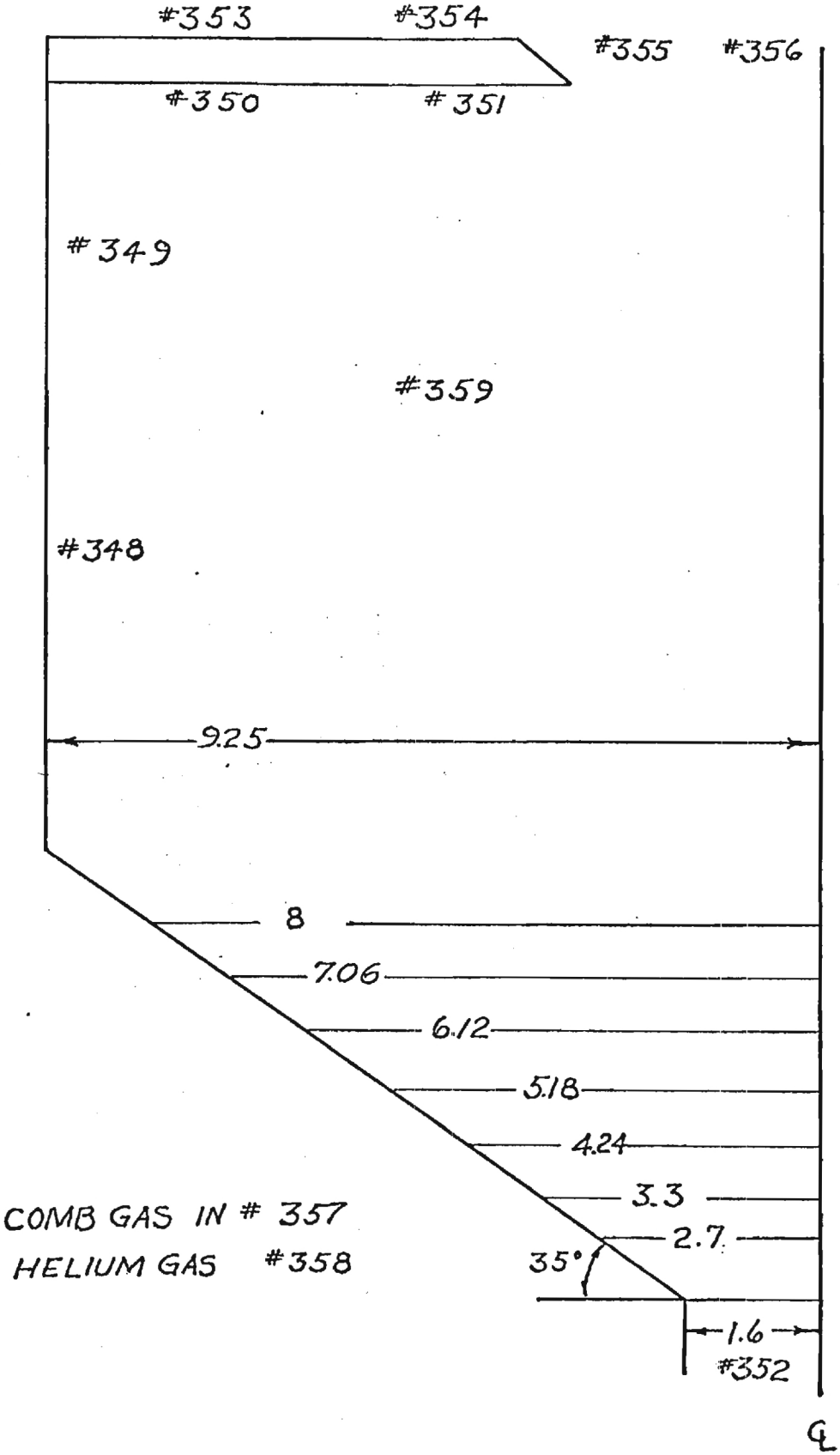


Figure 3.

Geometric Location of Planes.

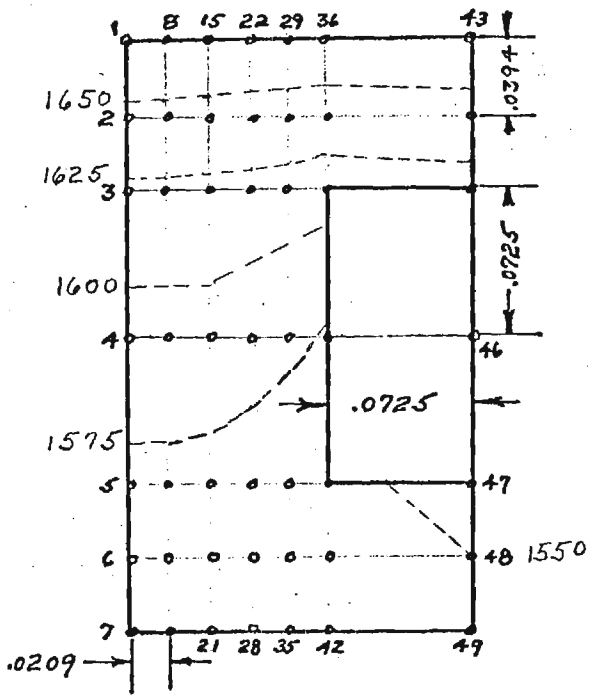


Figure 4.

Plane 1
Solar Plus 10 Percent Combustion Gas.

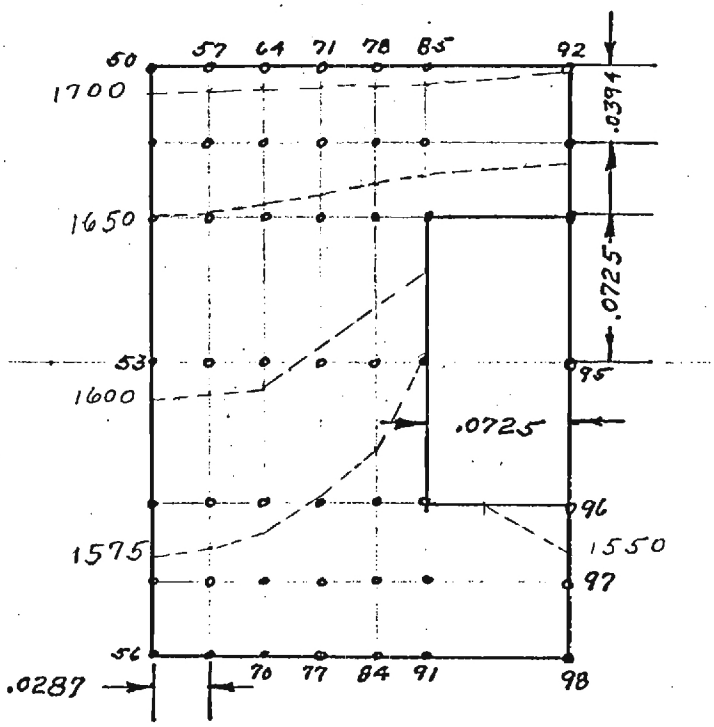


Figure 5.

Plane 2
Solar Plus 10 Percent Combustion Gas.

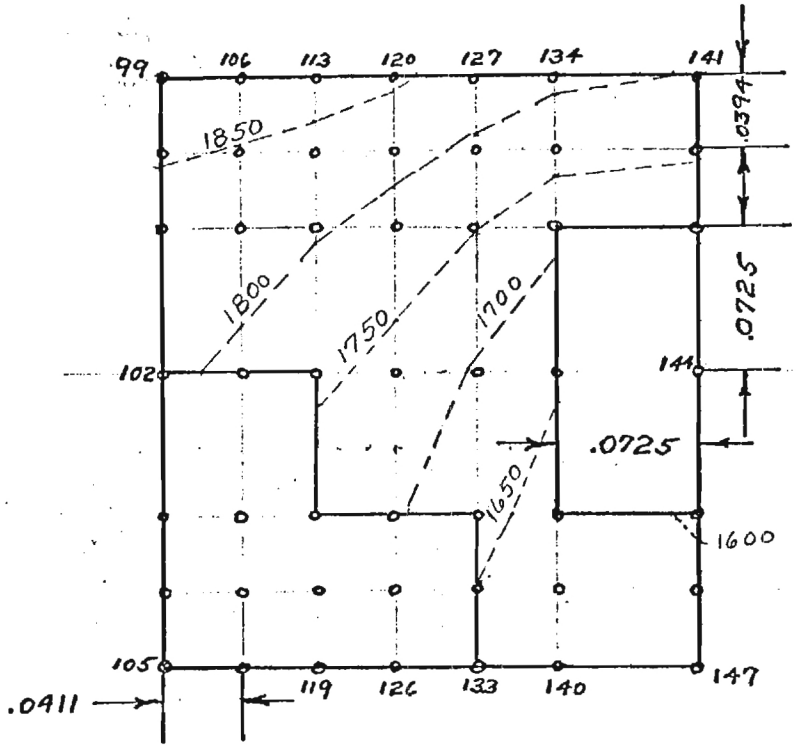


Figure 6.

Plane 3
Solar Plus 10 Percent Combustion Gas.

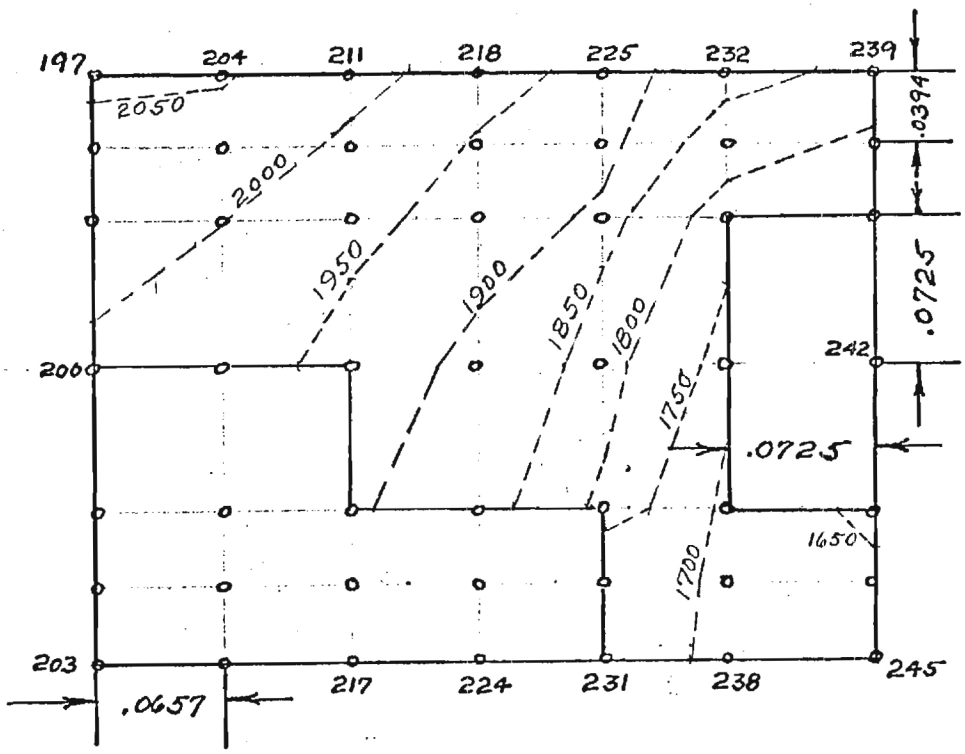


Figure 7.

Plane 4
Solar Plus 10 Percent Combustion Gas.

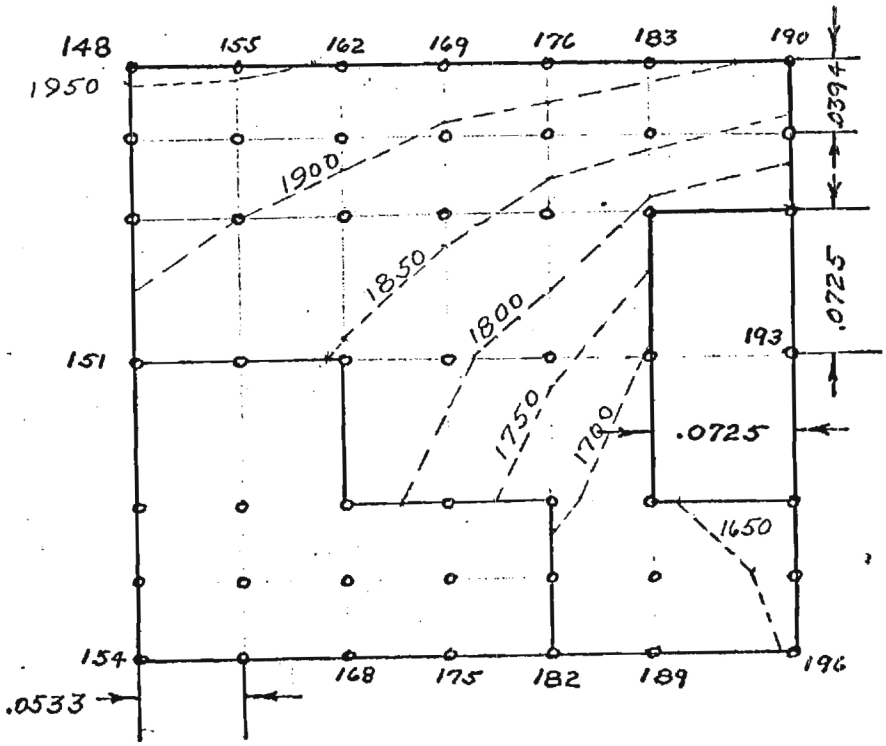


Figure 8.

Plane 5
Solar Plus 10 Percent Combustion Gas.

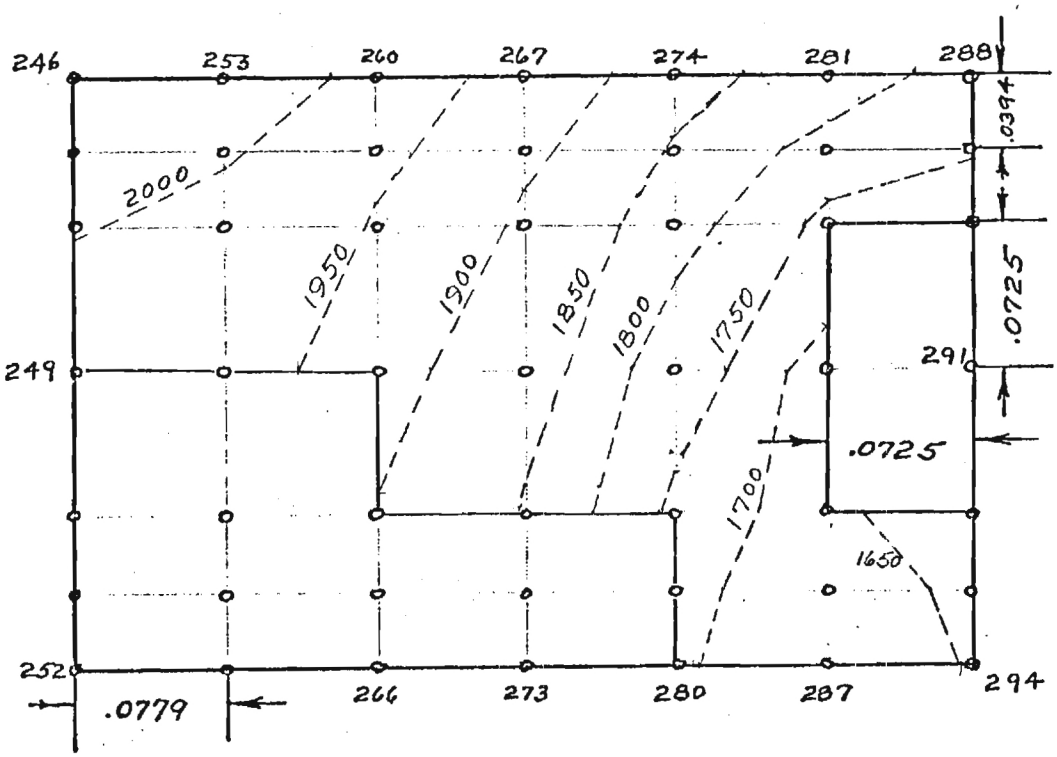


Figure 9.

Plane 6
Solar Plus 10 Percent Combustion Gas.

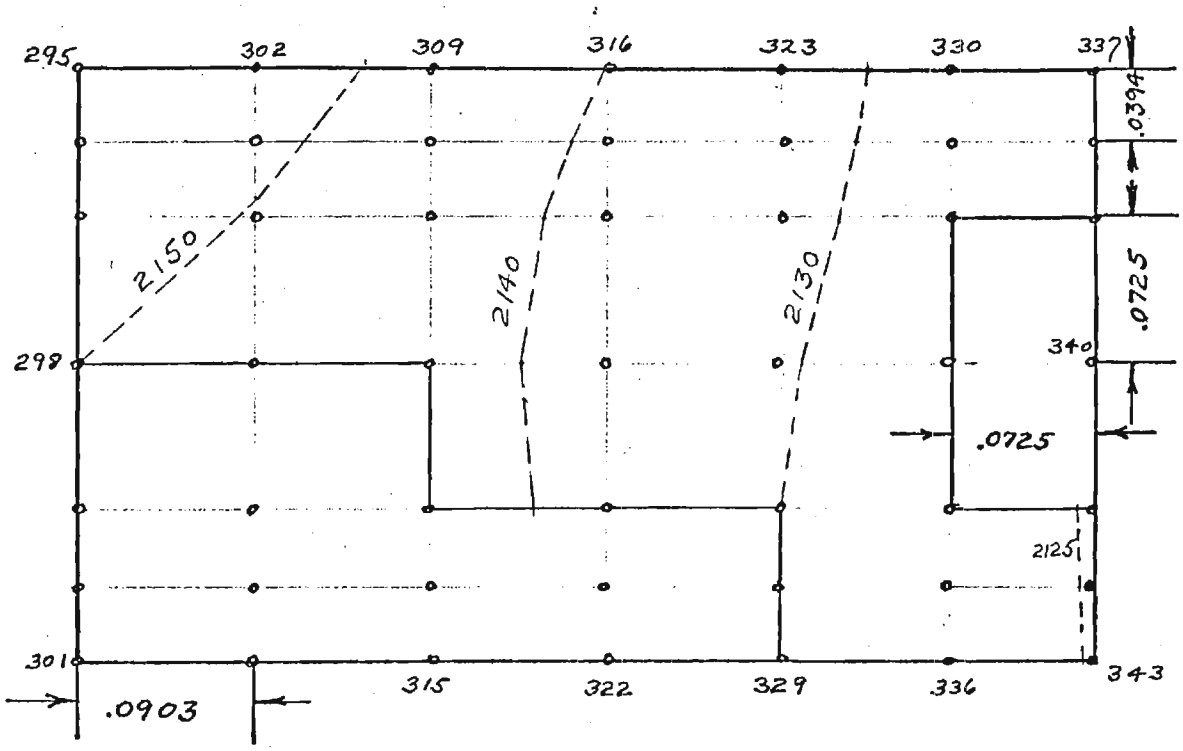


Figure 10.

Plane 7
Solar Plus 10 Percent Combustion Gas.

CERAMIC RECEIVER 1500 DEG. FLUID SPENT COMBUSTOR GAS USEDSOLAR+10% COMBUSTOR NOV. 7 CONFIGURATION

++NOTE++ EBALLA(.100000) HAS BEEN MET ON ITERATION 375.

TIMEN = .0	EBALSC = .609734	CSGMIN(0) = .0	DRLXCC(0) = .0
TSTEPU = .0	EBALNC(323) =-7.566643E-02	CSGMAX(0) = .0	ARLXCC(330) =-3.211902E-02
	ITERCT = 375	DMXTCC(0) = .0	AMXTCC(0) = .0

DIFFUSION NODES
++NONE++
ARITHMETIC NODES

T	1=	1668.85	T	2=	1644.87	T	3=	1622.61	T	4=	1589.01	T	5=	1570.34	T	6=	1565.95
T	7=	1664.63	T	8=	1668.66	T	9=	1644.62	T	10=	1622.20	T	11=	1588.38	T	12=	1569.77
T	13=	1665.52	T	14=	1564.26	T	15=	1668.13	T	16=	1643.88	T	17=	1620.98	T	18=	1586.48
T	19=	1668.02	T	20=	1564.25	T	21=	1563.18	T	22=	1667.38	T	23=	1642.74	T	24=	1618.91
T	25=	1583.23	T	26=	1565.03	T	27=	1562.20	T	28=	1561.49	T	29=	1666.63	T	30=	1641.34
T	31=	1115.94	T	32=	1578.52	T	33=	1560.62	T	34=	1559.56	T	35=	1559.39	T	36=	1665.20
T	37=	1639.95	T	38=	1611.96	T	39=	1572.18	T	40=	1554.50	T	41=	1556.67	T	42=	1557.19
T	43=	1655.44	T	44=	1640.96	T	45=	1617.01	T	46=	1601.82	T	47=	1544.71	T	48=	1550.17
T	49=	1551.78	T	50=	1711.23	T	51=	1676.64	T	52=	1649.99	T	53=	1608.32	T	54=	1581.31
T	55=	1571.01	T	56=	1568.73	T	57=	1711.02	T	58=	1676.27	T	59=	1649.12	T	60=	1607.10
T	61=	1580.51	T	62=	1570.65	T	63=	1568.53	T	64=	1710.42	T	65=	1675.18	T	66=	1646.39
T	67=	1603.28	T	68=	1578.00	T	69=	1569.61	T	70=	1567.96	T	71=	1709.56	T	72=	1673.50
T	73=	1641.46	T	74=	1596.43	T	75=	1573.43	T	76=	1567.98	T	77=	1567.10	T	78=	1708.58
T	79=	1671.43	T	80=	1633.50	T	81=	1585.92	T	82=	1566.06	T	83=	1565.95	T	84=	1566.08
T	85=	1707.68	T	86=	1669.42	T	87=	1620.88	T	88=	1570.90	T	89=	1554.52	T	90=	1563.89
T	91=	1569.07	T	92=	1702.28	T	93=	1663.91	T	94=	1621.56	T	95=	1501.88	T	96=	1543.19
T	97=	1553.64	T	98=	1556.74	T	99=	1688.13	T	100=	1852.44	T	101=	1825.43	T	102=	1804.45
T	103=	1726.98	T	104=	1694.81	T	105=	1688.17	T	106=	1884.30	T	107=	1847.81	T	108=	1819.54
T	109=	1793.94	T	110=	1722.16	T	111=	1690.45	T	112=	1683.57	T	113=	1871.50	T	114=	1834.37
T	115=	1802.32	T	116=	1759.46	T	117=	1715.71	T	118=	1681.58	T	119=	1673.98	T	120=	1853.49
T	121=	1814.96	T	122=	1780.08	T	123=	1731.41	T	124=	1701.11	T	125=	1666.19	T	126=	1659.01
T	127=	1832.55	T	128=	1791.66	T	129=	1750.97	T	130=	1697.49	T	131=	1668.43	T	132=	1648.10
T	133=	1844.31	T	134=	1813.00	T	135=	1768.13	T	136=	1713.01	T	137=	1655.77	T	138=	1625.78
T	139=	1630.70	T	140=	1631.74	T	141=	1798.58	T	142=	1753.78	T	143=	1700.46	T	144=	1503.66
T	145=	1593.70	T	146=	1610.48	T	147=	1615.26	T	148=	1957.75	T	149=	1921.14	T	150=	1905.38
T	151=	1893.23	T	152=	1832.14	T	153=	1797.44	T	154=	1789.55	T	155=	1955.51	T	156=	1917.95
T	157=	1899.75	T	158=	1882.63	T	159=	1825.41	T	160=	1789.94	T	161=	1781.34	T	162=	1948.25
T	163=	1938.82	T	164=	1863.20	T	165=	1849.30	T	166=	1816.27	T	167=	1773.51	T	168=	1763.10
T	169=	1938.15	T	170=	1895.47	T	171=	1860.50	T	172=	1809.51	T	173=	1785.62	T	174=	1739.38
T	175=	1728.31	T	176=	1927.11	T	177=	1879.77	T	178=	1829.02	T	179=	1759.02	T	180=	1711.16
T	181=	1674.80	T	182=	1671.36	T	183=	1917.90	T	184=	1865.16	T	185=	1782.29	T	186=	1696.46
T	187=	1657.26	T	188=	1667.90	T	189=	1668.41	T	190=	1887.83	T	191=	1835.11	T	192=	1764.89
T	193=	1504.73	T	194=	1619.29	T	195=	1641.22	T	196=	1647.41	T	197=	2061.20	T	198=	2032.62
T	199=	2011.60	T	200=	1995.29	T	201=	1917.63	T	202=	1880.79	T	203=	1873.63	T	204=	2052.68
T	205=	2022.42	T	206=	2000.00	T	207=	1980.50	T	208=	1909.29	T	209=	1871.47	T	210=	1862.88
T	211=	2021.34	T	212=	1991.10	T	213=	1965.79	T	214=	1930.58	T	215=	1903.38	T	216=	1850.80
T	217=	1838.79	T	218=	1977.90	T	219=	1946.65	T	220=	1920.05	T	221=	1885.93	T	222=	1867.99
T	223=	1808.37	T	224=	1792.72	T	225=	1923.45	T	226=	1889.77	T	227=	1859.00	T	228=	1828.52
T	229=	1787.46	T	230=	1729.69	T	231=	1715.75	T	232=	1666.19	T	233=	1825.10	T	234=	1770.47
T	235=	1724.90	T	236=	1686.96	T	237=	1691.35	T	238=	1691.82	T	239=	1839.26	T	240=	1797.30
T	241=	1733.93	T	242=	1504.97	T	243=	1637.95	T	244=	1661.99	T	245=	1668.76	T	246=	2035.30
T	247=	2014.77	T	248=	2000.23	T	249=	1991.02	T	250=	1970.63	T	251=	1943.78	T	252=	1937.86
T	253=	2024.61	T	254=	2002.37	T	255=	1986.35	T	256=	1974.29	T	257=	1957.38	T	258=	1935.10

Table II. Calculated Temperatures for Solar Plus 10 Percent Combustion Gas.

CERAMIC RECEIVER 1500 DEG. FLUID SPENT COMBUSTOR GAS USEDSOLAR+10% COMBUSTOR NOV. 7 CONFIGURATION

T	254=	1938.39	T	260=	1986.55	T	261=	1964.07	T	262=	1944.82	T	263=	1916.91	T	264=	1896.79
T	265=	1918.80	T	266=	1906.25	T	267=	1935.11	T	268=	1911.34	T	269=	1890.03	T	270=	1859.63
T	271=	1847.91	T	272=	1860.66	T	273=	1855.73	T	274=	1873.28	T	275=	1846.65	T	276=	1819.56
T	277=	1778.06	T	278=	1741.31	T	279=	1711.97	T	280=	1704.58	T	281=	1815.37	T	282=	1780.87
T	283=	1733.43	T	284=	1687.41	T	285=	1658.77	T	286=	1667.09	T	287=	1669.40	T	288=	1788.79
T	289=	1735.25	T	290=	1705.68	T	291=	1504.30	T	292=	1620.82	T	293=	1642.76	T	294=	1649.25
T	295=	2192.82	T	296=	2151.55	T	297=	2150.52	T	298=	2150.12	T	299=	2043.36	T	300=	1994.53
T	301=	1942.20	T	302=	2154.59	T	303=	2151.35	T	304=	2149.46	T	305=	2148.68	T	306=	2058.19
T	307=	1998.78	T	308=	1990.87	T	309=	2146.24	T	310=	2145.01	T	311=	2143.95	T	312=	2142.86
T	313=	2142.77	T	314=	2015.22	T	315=	1993.08	T	316=	2139.94	T	317=	2138.79	T	318=	2137.92
T	319=	2137.12	T	320=	2137.77	T	321=	2030.69	T	322=	2011.74	T	323=	2133.59	T	324=	2132.46
T	325=	2131.68	T	326=	2130.76	T	327=	2130.15	T	328=	2128.07	T	329=	2127.43	T	330=	2125.84
T	331=	2125.36	T	332=	2126.22	T	333=	2125.94	T	334=	2125.89	T	335=	2125.48	T	336=	2125.33
T	337=	2119.68	T	338=	2123.31	T	339=	2124.36	T	340=	2123.86	T	341=	2124.90	T	342=	2124.94
T	343=	2124.91	T	344=	2160.38	T	345=	2377.33	T	346=	2154.51	T	347=	2286.18	T	348=	1750.09
T	349=	1694.39	T	350=	1490.70	T	351=	1427.68	T	352=	310.351	T	353=	1231.42	T	354=	1419.20

HEATER NODES

++NONE++

BOUNDARY NODES

T	355=	-460.000	T	356=	-460.000	T	357=	2611.00	T	358=	1500.00	T	359=	300.000	T		

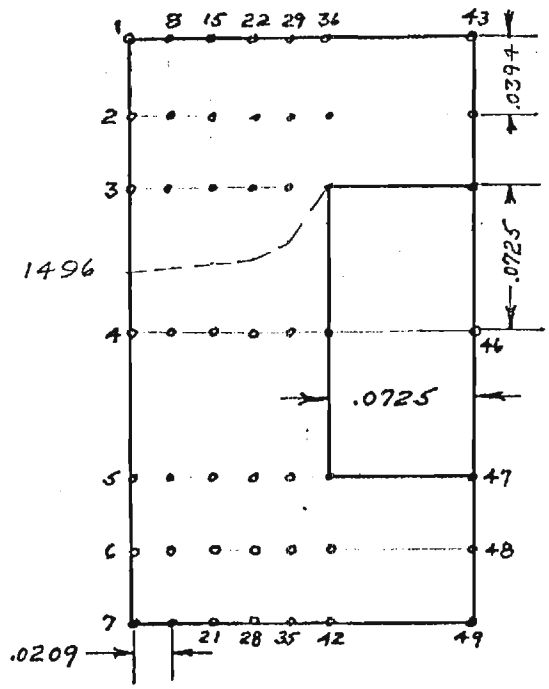
Table II. Calculated Temperatures for Solar Plus 10 Percent Combustion Gas (Continued).

SUMMARY OF HEAT TRANSFERRED

Total Input Desired for System = 251,520 Btu/hr

	Solar + 10% Combustor	C. Gas to #7	No C. Gas to #7
Heat to He Via Regen tubes	12,960	129,120	129,120
Heat to He Via Cone	205,106	58,768	49,323
Total	218,066	187,888	178,443
Cone Losses			
Lost by Radiation	17,622	9,978	6,967
Lost by Convection	16,722	12,808	10,675
	34,344	22,786	17,641
Total Heat to He + Losses	252,410	210,674	196,084

From the above table, it is obvious that not quite enough heat is transferred from the combustor gas to the helium in the 100 percent combustor mode. Since this mode is a less severe stress condition than the solar + 10% combustor mode, we did not go through a second iteration to get a closer heat input. It is also worthy of note that combustor efficiency is higher when the combustor gas leaves the cone at the same radius as the regenerator tubes (column 3).

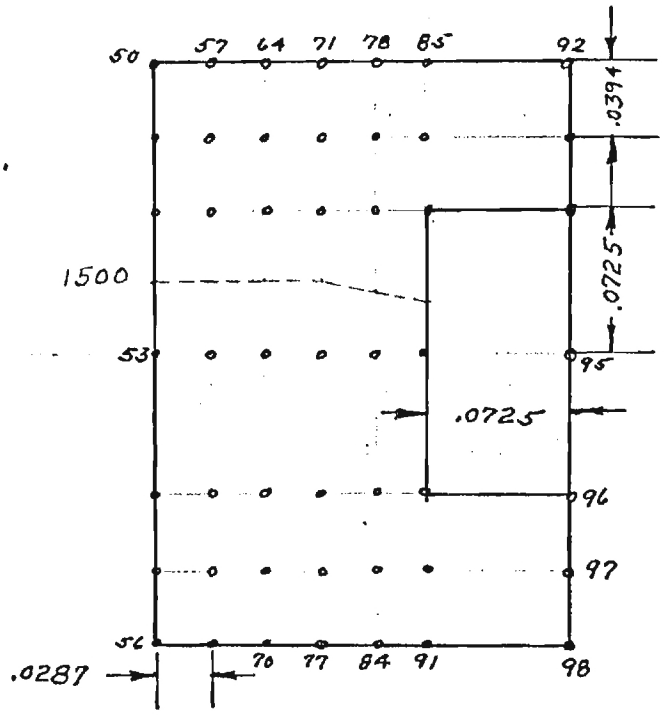


1496.10 $^{+2.24}_{-3.02}$

σ 1.24

Figure 11.

Plane 1
100 Percent Combustion Gas.



$1499.75 \pm {}^{1.72}_{3.41}$

$\sigma = 1.63$

Figure 12.

Plane 2
100 Percent Combustion Gas.

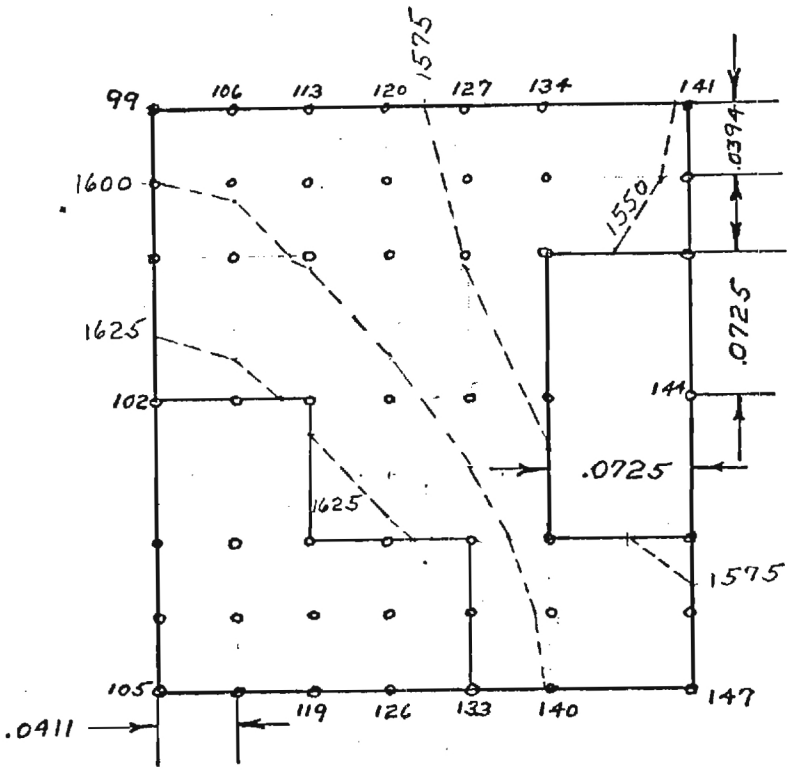


Figure 13.

Plane 3
100 Percent Combustion Gas.

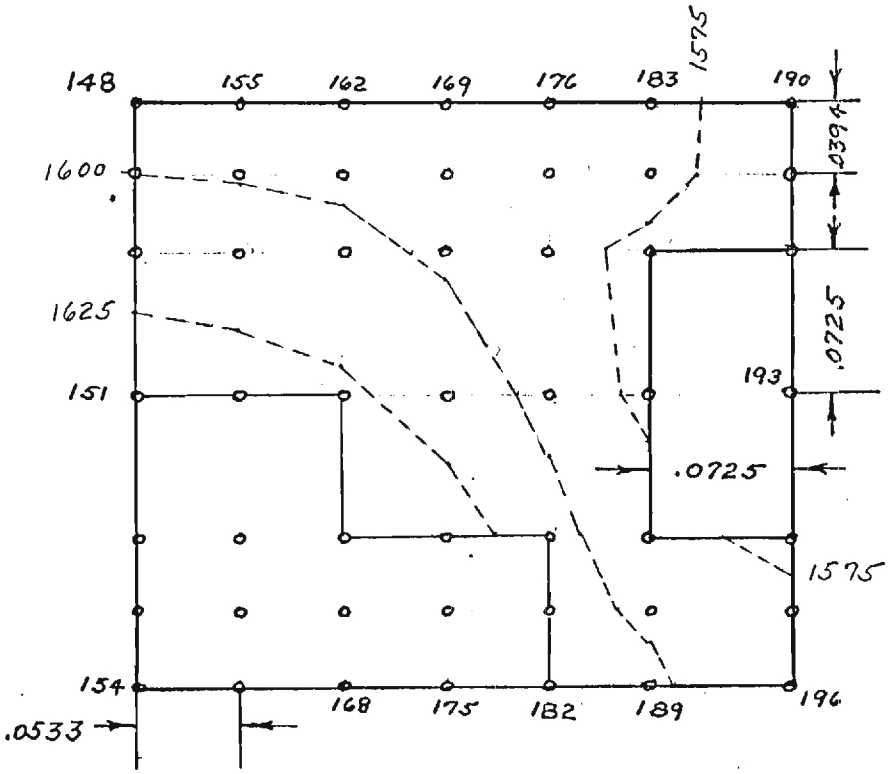


Figure 14.

Plane 4
100 Percent Combustion Gas.

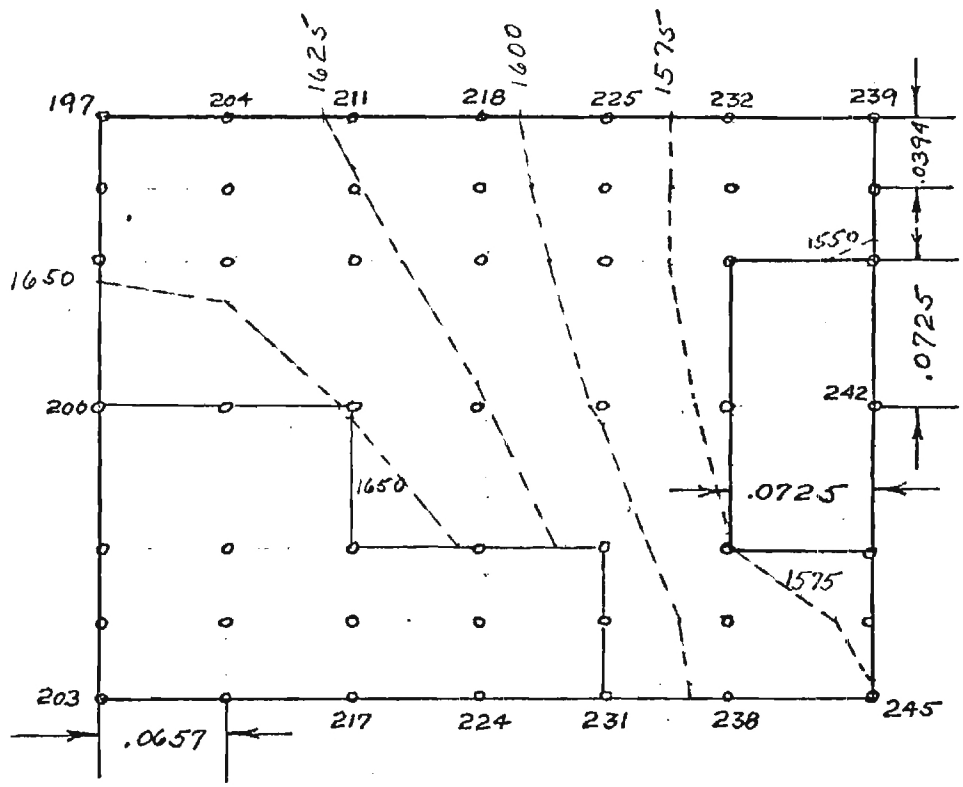


Figure 15.

Plane 5
100 Percent Combustion Gas.

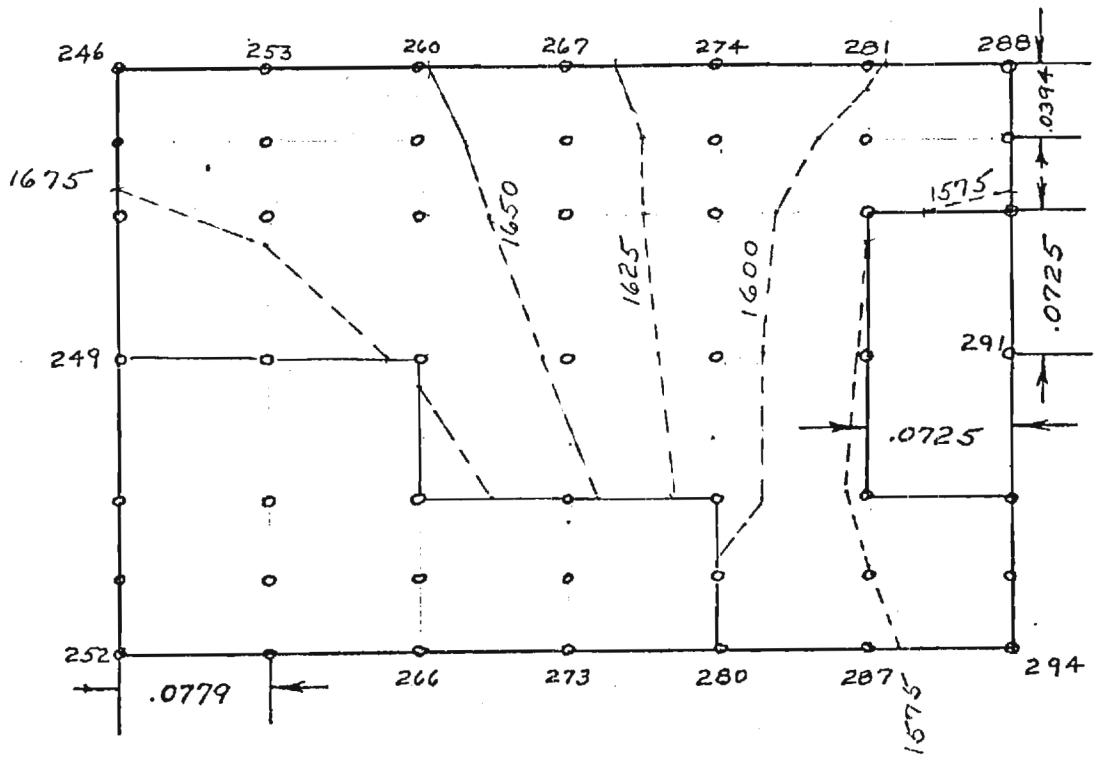


Figure 16.

Palne 6
100 Percent Combustion Gas.

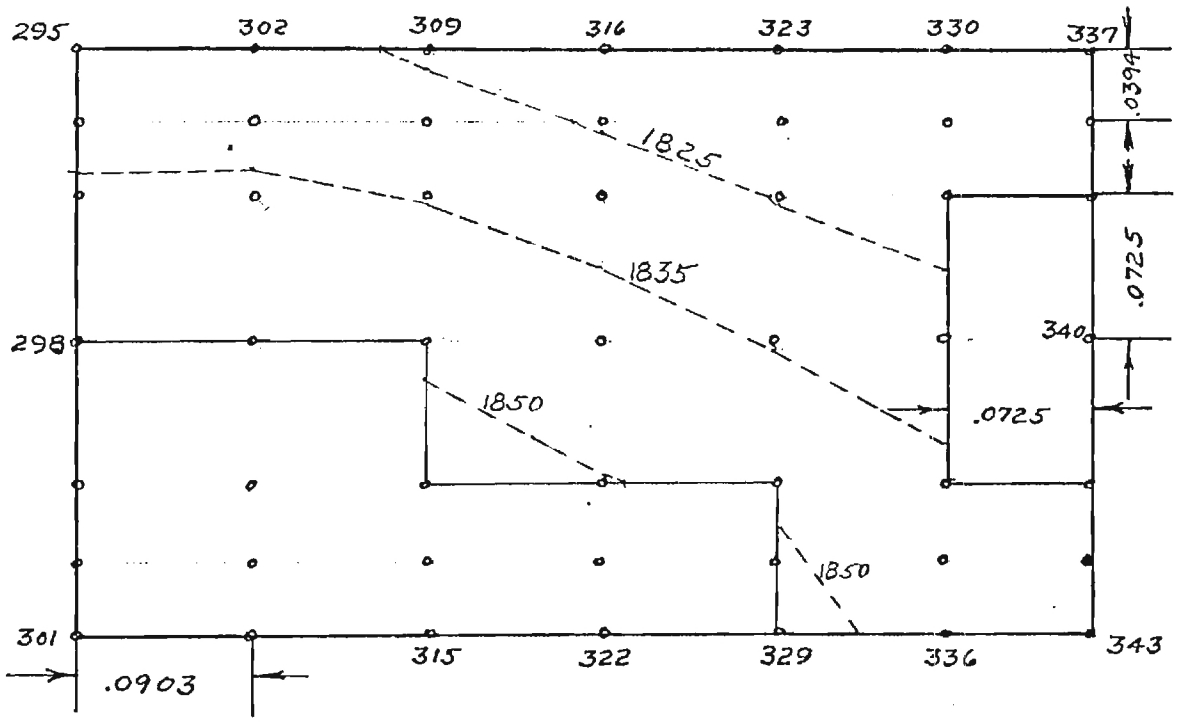


Figure 17.

Plane 7
100 Percent Combustion Gas.

CERAMIC RECEIVER 1500 DEG. FLUID SPENT COMBUSTOR GAS USED100% COMBUSTION. NOV. 7 CONFIGURATION

++NOTE++ EBALNA(.100000) HAS BEEN MET ON ITERATION 276.

TIMEN =	.0	EBALSC	= .204218	CSGMIN(	0) =	.0	DRLXCC(	0) =	.0
TSTEPU =	.0	EBALNC(	51) = 6.028265E-02	CSGMAX(	0) =	.0	ARLXCC(	56) =	1.718044E-02
		ITERCT	= 276	DMXTCC(	0) =	.0	AMXTCC(	0) =	.0

DIFFUSION-NODES
++NONE++
ARITHMETIC NODES

T 1=	1493.08	T 2=	1494.17	T 3=	1495.15	T 4=	1496.56	T 5=	1497.35	T 6=	1497.53
T 7=	1497.59	T 8=	1493.14	T 9=	1494.19	T 10=	1495.16	T 11=	1496.59	T 12=	1497.37
T 13=	1497.55	T 14=	1497.60	T 15=	1493.07	T 16=	1494.22	T 17=	1495.22	T 18=	1496.66
T 19=	1497.43	T 20=	1497.60	T 21=	1497.64	T 22=	1493.08	T 23=	1494.28	T 24=	1495.31
T 25=	1496.79	T 26=	1497.55	T 27=	1497.67	T 28=	1497.71	T 29=	1493.17	T 30=	1494.39
T 31=	1495.45	T 32=	1496.98	T 33=	1497.72	T 34=	1497.78	T 35=	1497.79	T 36=	1493.69
T 37=	1494.55	T 38=	1495.62	T 39=	1497.22	T 40=	1497.96	T 41=	1497.89	T 42=	1497.87
T 43=	1493.69	T 44=	1494.59	T 45=	1495.49	T 46=	1499.93	T 47=	1498.34	T 48=	1498.14
T 49=	1498.08	T 50=	1497.11	T 51=	1498.27	T 52=	1499.36	T 53=	1500.64	T 54=	1501.02
T 55=	1501.15	T 56=	1501.19	T 57=	1497.12	T 58=	1498.27	T 59=	1499.35	T 60=	1500.66
T 61=	1501.04	T 62=	1501.16	T 63=	1501.20	T 64=	1497.06	T 65=	1498.25	T 66=	1499.32
T 67=	1500.67	T 68=	1501.11	T 69=	1501.18	T 70=	1501.22	T 71=	1497.01	T 72=	1498.21
T 73=	1499.25	T 74=	1500.63	T 75=	1501.17	T 76=	1501.20	T 77=	1501.24	T 78=	1496.99
T 79=	1498.16	T 80=	1499.15	T 81=	1500.56	T 82=	1501.14	T 83=	1501.23	T 84=	1501.28
T 85=	1497.00	T 86=	1498.12	T 87=	1499.01	T 88=	1500.47	T 89=	1501.02	T 90=	1501.25
T 91=	1501.31	T 92=	1496.34	T 93=	1497.62	T 94=	1498.47	T 95=	1500.00	T 96=	1501.08
T 97=	1501.32	T 98=	1501.47	T 99=	1595.95	T 100=	1599.97	T 101=	1607.98	T 102=	1635.06
T 103=	1584.77	T 104=	1566.60	T 105=	1560.50	T 106=	1594.30	T 107=	1597.91	T 108=	1605.51
T 109=	1631.39	T 110=	1593.62	T 111=	1570.66	T 112=	1562.25	T 113=	1588.12	T 114=	1591.71
T 115=	1598.30	T 116=	1619.58	T 117=	1640.38	T 118=	1581.66	T 119=	1566.75	T 120=	1579.38
T 121=	1582.40	T 122=	1567.47	T 123=	1604.66	T 124=	1628.70	T 125=	1587.12	T 126=	1576.69
T 127=	1569.04	T 128=	1571.02	T 129=	1573.51	T 130=	1587.72	T 131=	1610.96	T 132=	1617.25
T 133=	1619.96	T 134=	1559.06	T 135=	1559.20	T 136=	1555.67	T 137=	1568.04	T 138=	1584.12
T 139=	1595.89	T 140=	1599.65	T 141=	1549.10	T 142=	1548.28	T 143=	1541.07	T 144=	1501.49
T 145=	1566.33	T 146=	1579.97	T 147=	1584.32	T 148=	1595.11	T 149=	1600.02	T 150=	1612.16
T 151=	1639.21	T 152=	1627.56	T 153=	1615.93	T 154=	1609.21	T 155=	1594.31	T 156=	1598.90
T 157=	1610.53	T 158=	1636.92	T 159=	1633.49	T 160=	1618.66	T 161=	1610.03	T 162=	1591.52
T 163=	1595.61	T 164=	1605.50	T 165=	1629.25	T 166=	1658.48	T 167=	1623.87	T 168=	1610.92
T 169=	1587.01	T 170=	1590.53	T 171=	1596.74	T 172=	1613.25	T 173=	1637.58	T 174=	1617.23
T 175=	1608.97	T 176=	1583.25	T 177=	1584.44	T 178=	1584.59	T 179=	1592.98	T 180=	1607.55
T 181=	1594.38	T 182=	1606.65	T 183=	1579.51	T 184=	1578.68	T 185=	1567.10	T 186=	1569.38
T 187=	1582.72	T 188=	1598.16	T 189=	1601.98	T 190=	1564.94	T 191=	1563.35	T 192=	1552.76
T 193=	1501.59	T 194=	1567.20	T 195=	1581.60	T 196=	1586.23	T 197=	1637.07	T 198=	1640.82
T 199=	1647.11	T 200=	1665.84	T 201=	1664.40	T 202=	1657.61	T 203=	1651.94	T 204=	1634.13
T 205=	1637.29	T 206=	1643.29	T 207=	1661.69	T 208=	1665.70	T 209=	1657.99	T 210=	1651.09
T 211=	1622.41	T 212=	1625.90	T 213=	1631.56	T 214=	1648.45	T 215=	1671.62	T 216=	1656.28
T 217=	1647.43	T 218=	1605.38	T 219=	1608.39	T 220=	1612.90	T 221=	1626.07	T 222=	1646.02
T 223=	1641.44	T 224=	1636.11	T 225=	1584.56	T 226=	1586.63	T 227=	1588.97	T 228=	1598.06
T 229=	1610.80	T 230=	1618.70	T 231=	1619.03	T 232=	1563.89	T 233=	1563.92	T 234=	1559.82
T 235=	1566.99	T 236=	1575.50	T 237=	1585.69	T 238=	1588.82	T 239=	1552.36	T 240=	1551.86
T 241=	1544.16	T 242=	1501.45	T 243=	1559.64	T 244=	1571.76	T 245=	1575.66	T 246=	1667.77
T 247=	1671.43	T 248=	1676.79	T 249=	1691.62	T 250=	1705.30	T 251=	1697.78	T 252=	1692.19
T 253=	1664.56	T 254=	1667.48	T 255=	1672.44	T 256=	1686.92	T 257=	1705.01	T 258=	1698.61

Table III. Calculated Temperatures for 100 Percent Combustion Gas.

CERAMIC RECEIVER 1500 DEG. FLUID SPENT COMBUSTOR GAS USED100% COMBUSTION NOV. 7 CONFIGURATION

T	259=	1691.83	T	260=	1650.94	T	261=	1654.24	T	262=	1658.85	T	263=	1671.56	T	264=	1689.14
T	265=	1695.30	T	266=	1688.26	T	267=	1631.97	T	268=	1634.57	T	269=	1637.51	T	270=	1645.36
T	271=	1659.21	T	272=	1674.33	T	273=	1670.41	T	274=	1611.37	T	275=	1612.04	T	276=	1610.99
T	277=	1610.59	T	278=	1610.42	T	279=	1597.50	T	280=	1595.35	T	281=	1602.43	T	282=	1594.56
T	283=	1580.41	T	284=	1573.62	T	285=	1570.32	T	286=	1575.18	T	287=	1576.63	T	288=	1580.43
T	289=	1577.66	T	290=	1564.46	T	291=	1501.65	T	292=	1554.16	T	293=	1564.26	T	294=	1567.31
T	295=	1826.94	T	296=	1831.68	T	297=	1836.47	T	298=	1845.84	T	299=	1767.68	T	300=	1735.17
T	301=	1731.51	T	302=	1828.45	T	303=	1831.99	T	304=	1836.37	T	305=	1845.84	T	306=	1784.39
T	307=	1743.73	T	308=	1735.31	T	309=	1823.90	T	310=	1828.88	T	311=	1834.33	T	312=	1846.18
T	313=	1859.79	T	314=	1765.18	T	315=	1745.07	T	316=	1819.36	T	317=	1824.35	T	318=	1829.63
T	319=	1840.03	T	320=	1850.49	T	321=	1782.10	T	322=	1767.14	T	323=	1814.36	T	324=	1819.34
T	325=	1824.62	T	326=	1834.92	T	327=	1846.54	T	328=	1853.36	T	329=	1855.46	T	330=	1808.32
T	331=	1813.98	T	332=	1819.68	T	333=	1829.06	T	334=	1837.06	T	335=	1839.63	T	336=	1840.57
T	337=	1804.19	T	338=	1812.11	T	339=	1818.13	T	340=	1827.06	T	341=	1835.02	T	342=	1837.80
T	343=	1833.73	T	344=	2149.38	T	345=	2262.57	T	346=	2373.09	T	347=	2489.58	T	348=	1427.43
T	349=	1364.00	T	350=	1176.18	T	351=	1151.02	T	352=	305.869	T	353=	1023.17	T	354=	1145.49

HEATER NODES

++NONE++

BOUNDARY NODES

T	355=	-460.000	T	356=	-460.000	T	357=	2611.00	T	358=	1500.00	T	359=	300.000	T		

Table III. Calculated Temperatures for 100 Percent Combustion Gas (Continued).

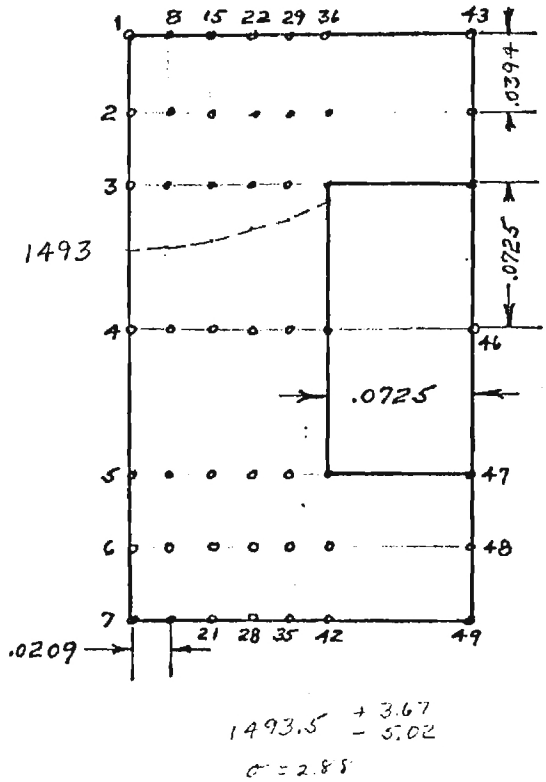
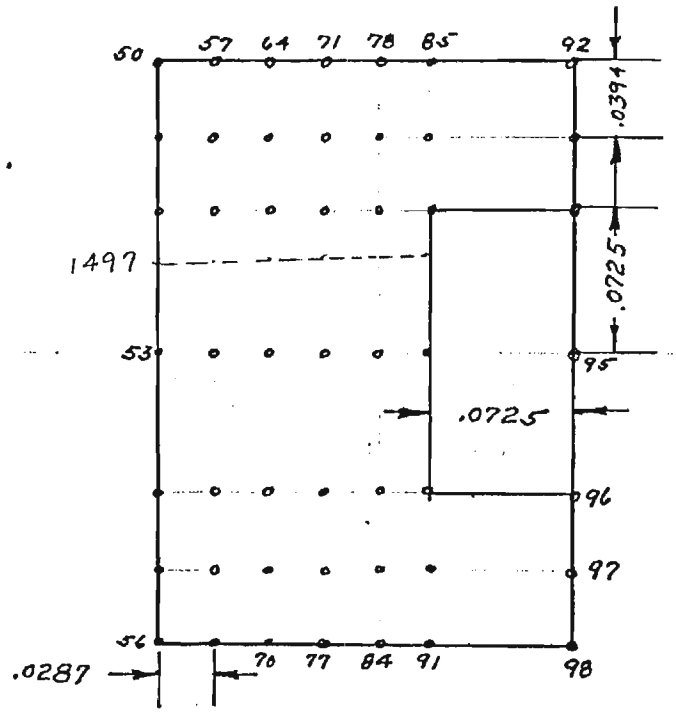


Figure 18.

Plane 1
100 Percent Combustion Gas
(No Gas to Plane 7)



1497.18 ± 3.15 / 5.45
σ = 2.94

Figure 19.

Plane 2
100 Percent Combustion Gas
(No Gas to Plane 7)

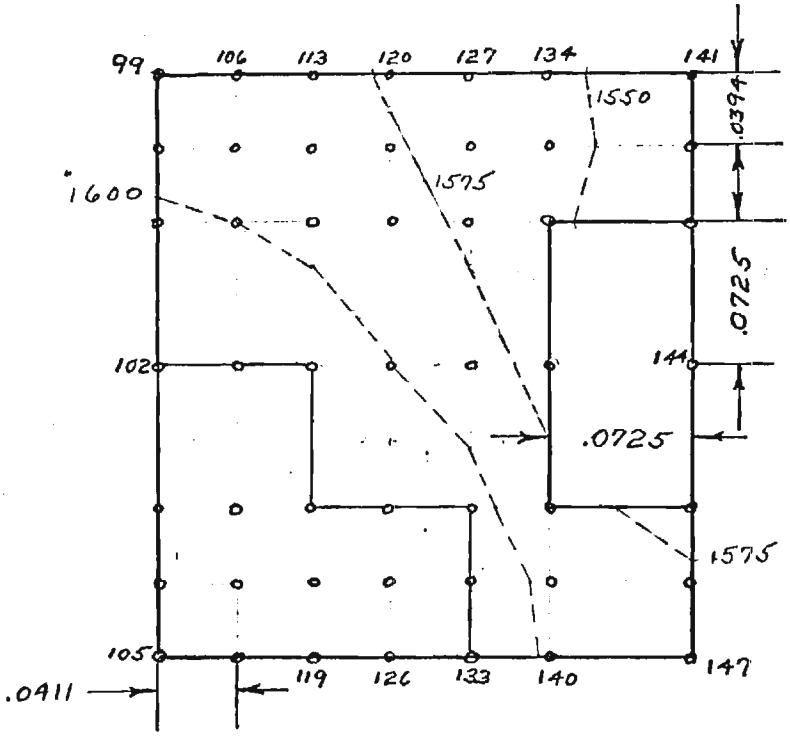


Figure 20.

Plane 3
100 Percent Combustion Gas
(No Gas to Plane 7)

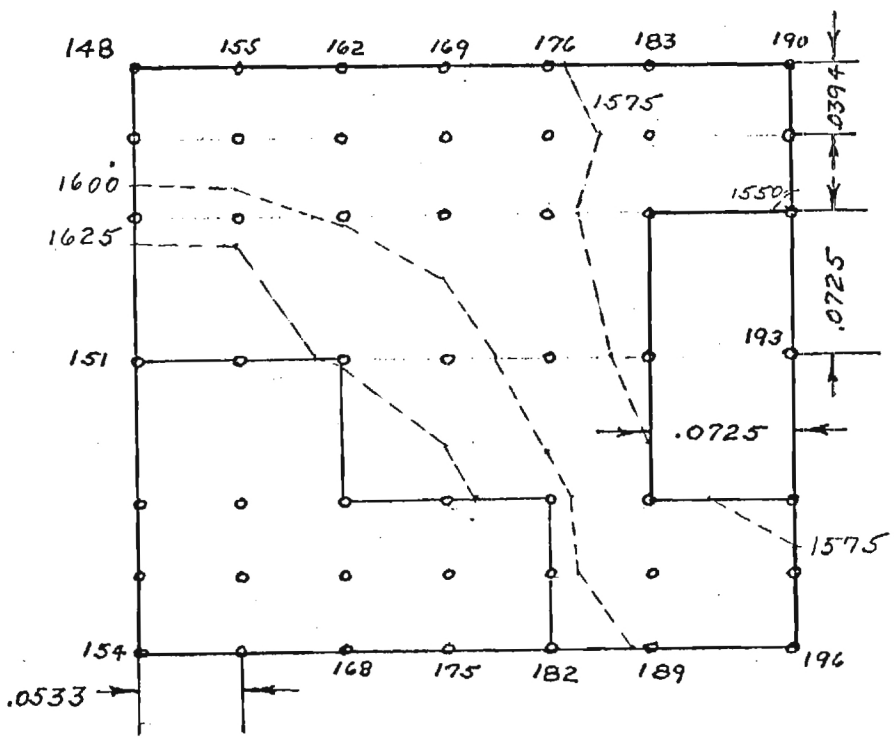


Figure 21.

Plane 4
100 Percent Combustion Gas
(No Gas to Plane 7)

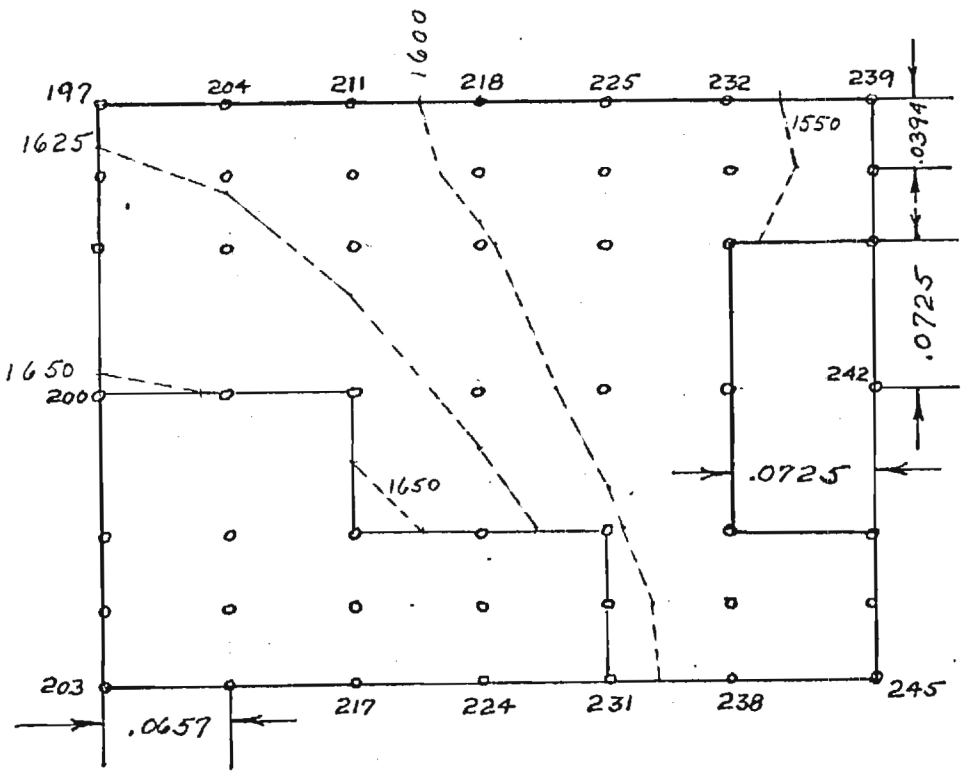


Figure 22.

Plane 5
100 Percent Combustion Gas
(No Gas to Plane 7)

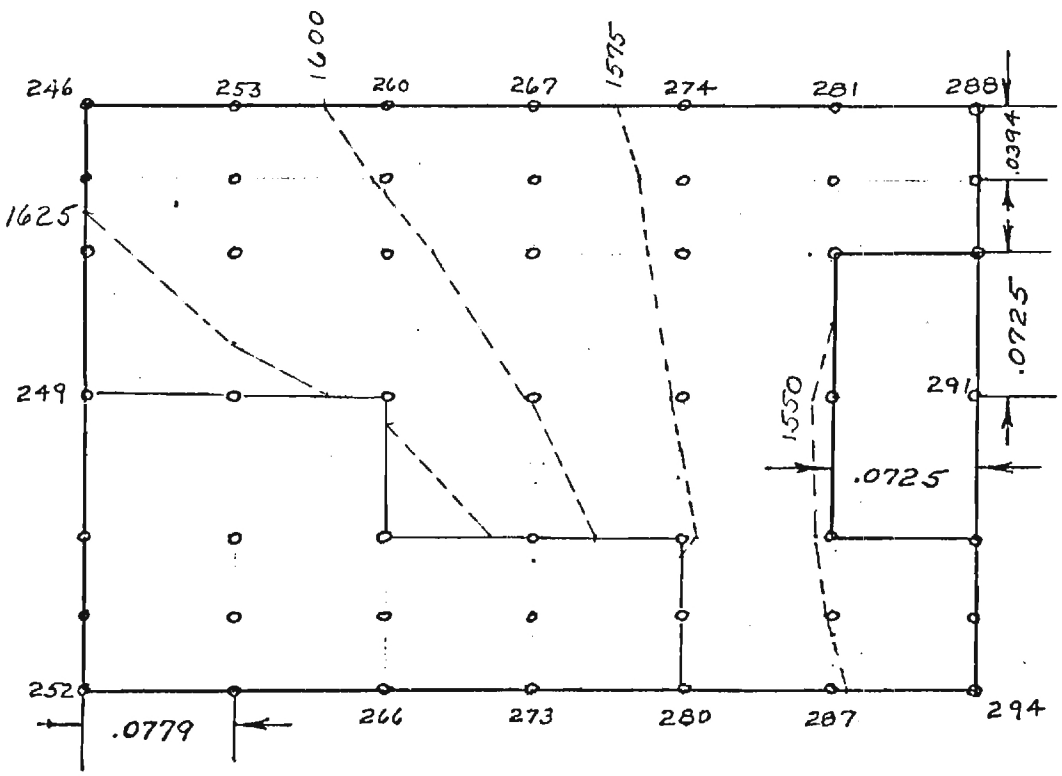
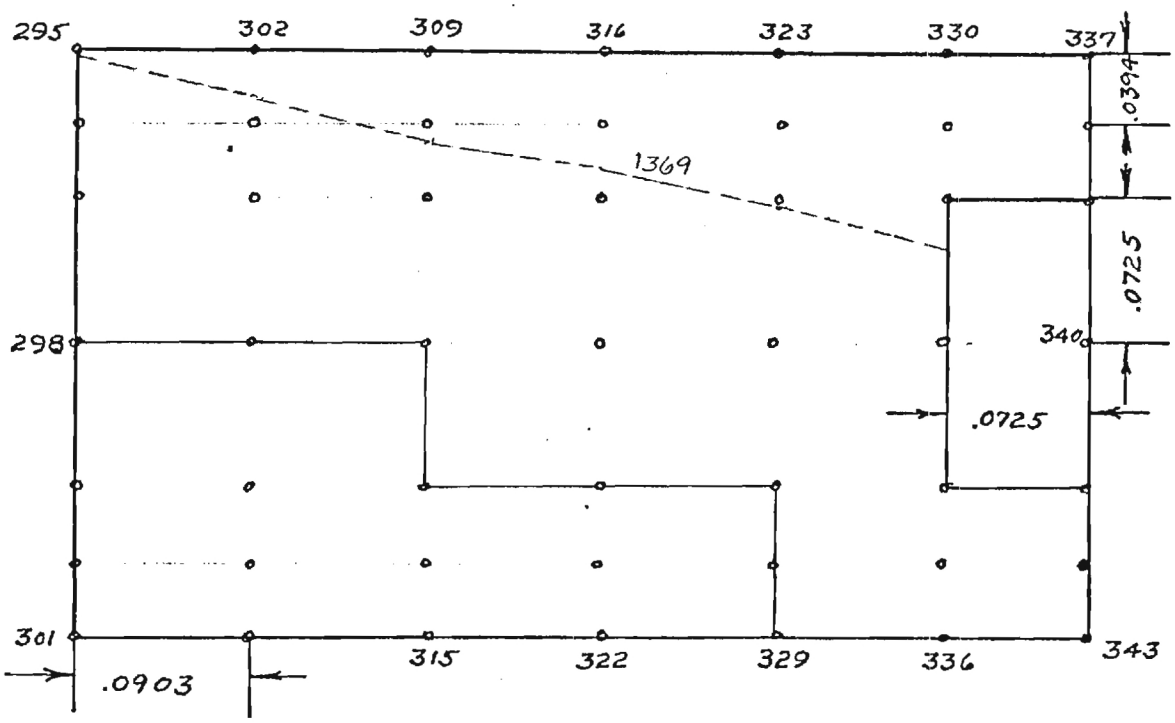


Figure 23.

Plane 6
100 Percent Combustion Gas
(No Gas to Plane 7)



1369.35 $^{+2.25}_{-3.89}$
σ = 1.87

Figure 24.

Plane 7
100 Percent Combustion Gas
(No Gas to Plane 7)

COMBUSTOR GAS STOPS AFTER PLANE 6. CERAMIC RECEIVER 1500 DEG. FLUID SPENT COMBUSTOR GAS USED100% COMBUSTION

++NOTE++ EBALNA(.100000) HAS BEEN MET ON ITERATION 627.

TIMEN =	.0	EBALSC	= -.844417	CSGMIN(	0) =	.0	DRLXCC(	0) =	.0		
TSTEPU =	.0	EBALNC(	303) =-5.451537E-02	CSGMAX(	0) =	.0	ARLXCC(	246)	=-6.472379E-02		
		ITERCT	= 627	DMXTCC(	0) =	.0	AMXTCC(	0) =	.0		

DIFFUSION NODES
++NONE++
ARITHMETIC NODES

T	1=	1488.50	T	2=	1490.31	T	3=	1491.91	T	4=	1494.23	T	5=	1495.51	T	6=	1495.81
T	7=	1495.90	T	8=	1488.62	T	9=	1490.33	T	10=	1491.94	T	11=	1494.28	T	12=	1495.55
T	13=	1495.84	T	14=	1495.92	T	15=	1488.48	T	16=	1490.38	T	17=	1492.04	T	18=	1494.40
T	19=	1495.66	T	20=	1495.92	T	21=	1495.99	T	22=	1488.51	T	23=	1490.50	T	24=	1492.20
T	25=	1494.62	T	26=	1495.85	T	27=	1496.05	T	28=	1496.10	T	29=	1488.68	T	30=	1490.71
T	31=	1492.43	T	32=	1494.93	T	33=	1496.14	T	34=	1496.22	T	35=	1496.24	T	36=	1489.63
T	37=	1490.99	T	38=	1492.74	T	39=	1495.34	T	40=	1496.54	T	41=	1496.41	T	42=	1496.38
T	43=	1489.65	T	44=	1491.09	T	45=	1492.57	T	46=	1499.88	T	47=	1497.17	T	48=	1496.83
T	49=	1496.73	T	50=	1492.26	T	51=	1494.29	T	52=	1496.02	T	53=	1498.28	T	54=	1499.32
T	55=	1499.71	T	56=	1499.81	T	57=	1492.29	T	58=	1494.28	T	59=	1496.02	T	60=	1498.32
T	61=	1499.36	T	62=	1499.73	T	63=	1499.82	T	64=	1492.21	T	65=	1494.28	T	66=	1496.04
T	67=	1498.42	T	68=	1499.48	T	69=	1499.76	T	70=	1499.85	T	71=	1492.18	T	72=	1494.27
T	73=	1496.07	T	74=	1498.53	T	75=	1499.64	T	76=	1499.82	T	77=	1499.89	T	78=	1492.21
T	79=	1494.27	T	80=	1496.15	T	81=	1498.68	T	82=	1499.77	T	83=	1499.89	T	84=	1499.95
T	85=	1492.30	T	86=	1494.27	T	87=	1496.29	T	88=	1496.92	T	89=	1499.89	T	90=	1499.95
T	91=	1500.00	T	92=	1491.73	T	93=	1493.90	T	94=	1495.71	T	95=	1499.96	T	96=	1500.20
T	97=	1500.23	T	98=	1500.33	T	99=	1589.01	T	100=	1593.81	T	101=	1602.42	T	102=	1630.21
T	103=	1570.77	T	104=	1545.79	T	105=	1536.98	T	106=	1587.58	T	107=	1591.83	T	108=	1600.04
T	109=	1626.71	T	110=	1582.53	T	111=	1552.41	T	112=	1540.87	T	113=	1581.30	T	114=	1585.73
T	115=	1593.06	T	116=	1615.46	T	117=	1637.34	T	118=	1568.59	T	119=	1549.76	T	120=	1572.73
T	121=	1576.67	T	122=	1562.54	T	123=	1600.94	T	124=	1625.84	T	125=	1578.86	T	126=	1565.97
T	127=	1562.72	T	128=	1565.63	T	129=	1569.02	T	130=	1584.52	T	131=	1608.57	T	132=	1615.33
T	133=	1618.14	T	134=	1553.16	T	135=	1554.19	T	136=	1551.78	T	137=	1565.49	T	138=	1582.34
T	139=	1594.12	T	140=	1597.89	T	141=	1543.05	T	142=	1543.31	T	143=	1537.20	T	144=	1501.43
T	145=	1565.04	T	146=	1578.46	T	147=	1582.76	T	148=	1587.06	T	149=	1592.65	T	150=	1605.20
T	151=	1632.77	T	152=	1596.02	T	153=	1569.04	T	154=	1557.27	T	155=	1586.34	T	156=	1591.58
T	157=	1603.66	T	158=	1630.66	T	159=	1608.58	T	160=	1576.96	T	161=	1562.08	T	162=	1583.53
T	163=	1588.40	T	164=	1598.83	T	165=	1623.62	T	166=	1653.72	T	167=	1593.38	T	168=	1571.64
T	169=	1579.69	T	170=	1583.49	T	171=	1590.45	T	172=	1608.14	T	173=	1633.20	T	174=	1597.59
T	175=	1583.47	T	176=	1575.46	T	177=	1577.61	T	178=	1578.77	T	179=	1588.67	T	180=	1604.32
T	181=	1601.83	T	182=	1604.19	T	183=	1571.85	T	184=	1572.05	T	185=	1562.03	T	186=	1566.08
T	187=	1580.32	T	188=	1595.69	T	189=	1599.52	T	190=	1557.09	T	191=	1556.86	T	192=	1547.70
T	193=	1501.51	T	194=	1565.41	T	195=	1579.50	T	196=	1584.05	T	197=	1622.20	T	198=	1626.67
T	199=	1633.53	T	200=	1652.94	T	201=	1598.92	T	202=	1569.11	T	203=	1557.93	T	204=	1619.81
T	205=	1623.50	T	206=	1630.02	T	207=	1649.18	T	208=	1611.61	T	209=	1576.24	T	210=	1561.40
T	211=	1608.40	T	212=	1612.69	T	213=	1619.09	T	214=	1637.24	T	215=	1661.54	T	216=	1591.78
T	217=	1568.67	T	218=	1592.35	T	219=	1596.24	T	220=	1601.57	T	221=	1616.01	T	222=	1636.69
T	223=	1594.80	T	224=	1578.82	T	225=	1572.87	T	226=	1575.90	T	227=	1579.23	T	228=	1589.78
T	229=	1603.52	T	230=	1611.54	T	231=	1609.84	T	232=	1553.50	T	233=	1554.70	T	234=	1552.25
T	235=	1561.02	T	236=	1570.25	T	237=	1579.80	T	238=	1582.56	T	239=	1541.75	T	240=	1542.91
T	241=	1537.07	T	242=	1501.31	T	243=	1555.44	T	244=	1566.73	T	245=	1570.33	T	246=	1607.22
T	247=	1611.29	T	248=	1617.22	T	249=	1633.51	T	250=	1564.86	T	251=	1543.49	T	252=	1535.81
T	253=	1605.42	T	254=	1608.67	T	255=	1614.25	T	256=	1630.38	T	257=	1575.19	T	258=	1546.56

Table IV. Calculated Temperatures for 100 Percent Combustion Gas (No Combustion Gas to Plane 7).

COMBUSTOR GAS STOPS AFTER PLANE 6. CERAMIC RECEIVER 1500 DEG. FLUID SPENT COMBUSTOR GAS USED100% COMBUSTION

T	259=	1535.92	T	260=	1595.16	T	261=	1599.07	T	262=	1604.64	T	263=	1620.27	T	264=	1641.26
T	265=	1556.03	T	266=	1536.60	T	267=	1581.76	T	268=	1585.05	T	269=	1588.98	T	270=	1599.14
T	271=	1615.03	T	272=	1552.38	T	273=	1538.08	T	274=	1568.83	T	275=	1570.42	T	276=	1570.83
T	277=	1573.32	T	278=	1577.36	T	279=	1567.61	T	280=	1567.34	T	281=	1568.49	T	282=	1562.18
T	283=	1551.84	T	284=	1547.41	T	285=	1546.71	T	286=	1549.75	T	287=	1550.75	T	288=	1548.39
T	289=	1548.20	T	290=	1540.15	T	291=	1501.04	T	292=	1535.01	T	293=	1541.54	T	294=	1543.52
T	295=	1368.00	T	296=	1369.08	T	297=	1369.81	T	298=	1370.36	T	299=	1473.20	T	300=	1501.05
T	301=	1495.12	T	302=	1368.49	T	303=	1369.25	T	304=	1369.86	T	305=	1370.41	T	306=	1456.47
T	307=	1492.41	T	308=	1490.11	T	309=	1367.62	T	310=	1368.77	T	311=	1369.64	T	312=	1370.58
T	313=	1371.13	T	314=	1467.90	T	315=	1477.24	T	316=	1367.16	T	317=	1368.36	T	318=	1369.34
T	319=	1370.59	T	320=	1371.09	T	321=	1442.68	T	322=	1450.51	T	323=	1366.59	T	324=	1367.83
T	325=	1368.91	T	326=	1370.39	T	327=	1371.16	T	328=	1371.49	T	329=	1371.60	T	330=	1365.46
T	331=	1366.96	T	332=	1368.28	T	333=	1370.14	T	334=	1371.10	T	335=	1371.42	T	336=	1371.52
T	337=	1364.34	T	338=	1366.54	T	339=	1368.02	T	340=	1370.14	T	341=	1371.05	T	342=	1371.39
T	343=	1371.50	T	344=	2253.86	T	345=	2254.19	T	346=	2371.26	T	347=	2489.03	T	348=	1231.20
T	349=	1183.30	T	350=	996.871	T	351=	991.808	T	352=	304.554	T	353=	891.619	T	354=	987.478

HEATER NODES
++NONE++
BOUNDARY NODES

T	355=	-460.000	T	356=	-460.000	T	357=	2611.00	T	358=	1500.00	T	359=	300.000	T		

Table IV. Calculated Temperatures for 100 Percent Combustion Gas (No Combustion Gas to Plane 7) (Continued).

THERMAL STRESSES

A preliminary analysis was performed in order to evaluate stresses produced in the receiver by the temperature variations. The analysis is preliminary in the sense that only steady state operating conditions were considered. It is to be expected that more severe stresses will be produced during some transient condition since the variations in temperature in the receiver will be greater. The steady state temperatures used in this stress analysis were those obtained from the MITAS computer calculations. Furthermore, the stress analysis is preliminary in that only hand calculations were made using standard thermal stress solutions. This applies particularly to the receiver cone where the stress equation used was "one-dimensional" solution, it will be desirable to refine this stress prediction by a numerical computer analysis. However, an effort was made to identify the areas of highest stress and to obtain a good estimate of their value. It is not expected that a more refined stress analysis will reveal stresses significantly different from those obtained from the present analysis.

Thermal stresses are produced in a component by unequal expansion of the material if the temperature is unequal throughout the material. This can be true even if the component is free and not attached to any other component. However, additional stresses are produced by the unequal expansion of components attached to each other but at different temperatures. The most severe steady state condition is that of full solar plus 10 percent combustor. During this operating mode the temperature variations through the receiver cone are greatest. Also, the difference in temperature between the receiver cone and the helium tubes connecting the cone to the engine head

are greatest. The receiver cone was analyzed for the stresses produced in it by the temperature variation through the material. The helium tubes were analyzed for stresses produced by the temperature variation and also for stresses produced from the unequal expansions of the tubes and the cone. These are the only components for which good temperature estimates were obtained. It is believed that these are the most critical components, but other components should be considered. The engine head will have temperature variation through the material and also will undoubtedly be constrained by other components. Although it is felt that the engine head will not be subject to as severe a condition as the receiver cone, the fact that the head is relatively thick may result in significant stresses.

Tensile stresses on the order of 30,000 to 40,000 psi were found. The only data available during this analysis was that given on a Carborundum data sheet for Sintered Alpha Silicon Carbide. The Carborundum data sheet gives the flexural (bending test data) strength as 50,000 psi. It is not stated if this is a minimum, average or mean value. In general, ceramic type materials show a high scatter in values of strength determined from tests. This is due to the inherent brittleness of these materials and their high notch sensitivity. Failure of the material is associated with high localized tensile stresses. It is usually necessary therefore to accept some level of failure probability and to set an allowable stress limit from a statistical analysis of strength test data. Stresses of 30,000 to 40,000 psi are significant and would appear to represent a higher failure rate than desirable.

Receiver Cone

Stresses in the receiver cone were estimated by treating it as a flat plate with a temperature variation through its thickness. Since the cone is attached at its base, it is treated as a cantilever free to bend and expand along its length. The curvature of the cone and the fact that it is attached to the helium tubes will add to its bending resistance and will therefore serve to increase the stresses above the values calculated. However, the maximum tensile stresses occur adjacent to the helium passages which are close to the neutral axis (centroid) of the cross-section and therefore the added bending constraint may not cause a significant stress increase. The stresses calculated are the normal stresses in the length direction of the cone. Since the temperature varies around the circumference as well as through the thickness, circumferential stresses will also exist. A two-dimensional numerical analysis will be required to establish values of the circumferential stresses but they are not expected to be as large as the stresses in the length direction.

Referring to Figure 25, the normal stresses in the length direction were computed from the equation*

$$\sigma = \frac{E\,\alpha}{1-\nu}\left(\frac{\int T dA}{A} + \frac{y \int T y dA}{I} - T\right)$$

where

E = Modulus of elasticity,

α = Thermal coefficient of expansion,

ν = Poisson's Ratio,

*For example, Boley, B. A. and Weiner, J. H., Theory of Thermal Stresses, John Wiley and Sons, 1960, Chapter 12.

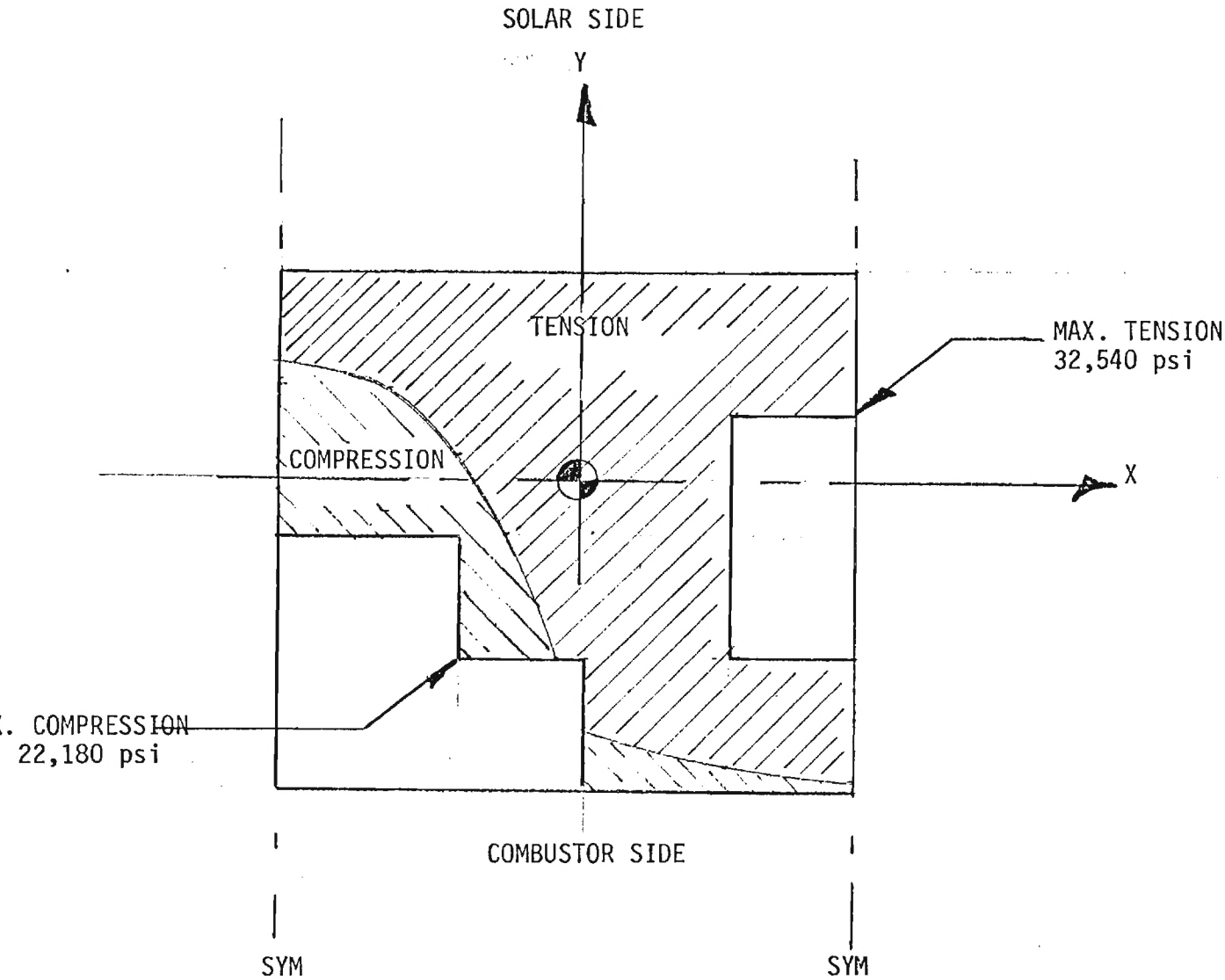


Figure 25. Typical Thermal Stress Distribution in Receiver Cone Cross-Section.

A = Cross sectional area,

I = Cross-sectional area moment of inertia about centroid.

T = Temperature at a point.

The integrals are taken over the cross-sectional area and were evaluated numerically using the MITAS temperature predictions. Material properties were taken from the Carborundum data sheet at the mean temperature with the exception of Poisson's ratio which was assumed as 0.3.

Figure 25 shows the general stress state in the cross-section at station four. This is typical of all the stations. The maximum tensile stress of 32,540 psi occurs adjacent to the helium passage where the temperature gradient from the solar heated surface to the helium passage is greatest.

Helium Tubes

The greatest temperature variations in the helium tubes occur during full combustor operation. Stresses associated with this condition were calculated using a standard solution for thermal stresses in a tube with a radial temperature distribution.* Although the actual temperature distribution is not simply radial, the variation from a radial distribution is small and the effect is believed to be negligible. Tensile stresses occur at the cooler insider tube surface and were found to be about 9,000 psi maximum.

The proposed design for the helium tubes is in the shape of a hair pen with the geometry as shown in Figure 26. Under the condition of full solar plus 10 percent combustor the average temperature of the receiver cone material, up to the point where the helium tubes are joined, is about 1800° F.

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*Boley and Weiner, Chapter 9.

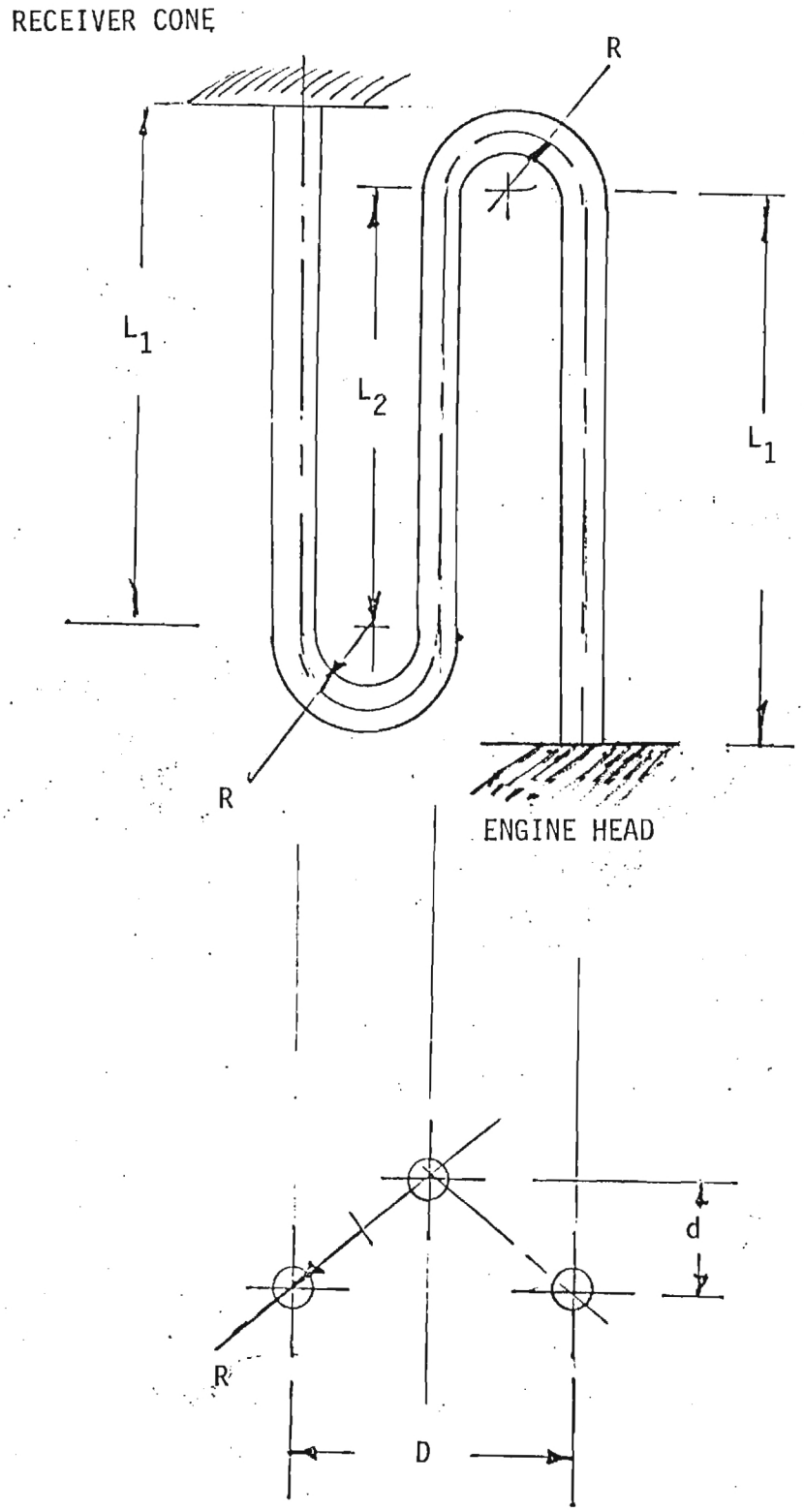

Figure 26. Helium Tube Configuration.

The tubes however will be at a temperature of approximately 1500^{0} F. Therefore, the cone will be 300^{0} hotter than the tubes and will expand more (relative to the engine head). This will cause a pulling and bending of the tubes which will produce tensile stresses. These stresses will be particularly significant at the points of attachment of the tubes to the cone and engine and in the curved portion where stress intensification will occur.

The helium tubes were approximated by a two-dimensional configuration (the fact that the three straight portion are not in the same plane was neglected) and the pulling and bending loads estimated using a standard piping flexibility analysis.* The assumed geometry and the resulting loads are shown in Figure 27. The maximum tensile stress is given by:

$$\sigma = \frac{P}{A} + k\frac{MC}{I}$$

where

P = The 75 pound load,

M = The 30 inch pound moment,

A,C & I = The tube cross-sectional area properties,

k = Stress intensification factor assumed as 3.5.

With the values determined, a tensile stress of 37,000 psi was obtained. It is not known how good is the assumed value of 3.5 for the stress intensification factor. Special consideration should be given to the attachment points in the final design.

The above stress occurs on the outside surface of the tubes and since the tensile stresses associated with the temperature variation through the tube

*Seely, F. B. and Smith, J. O., Advanced Mechanics of Materials, John Wiley and Sons, 1952, Chapter 16.

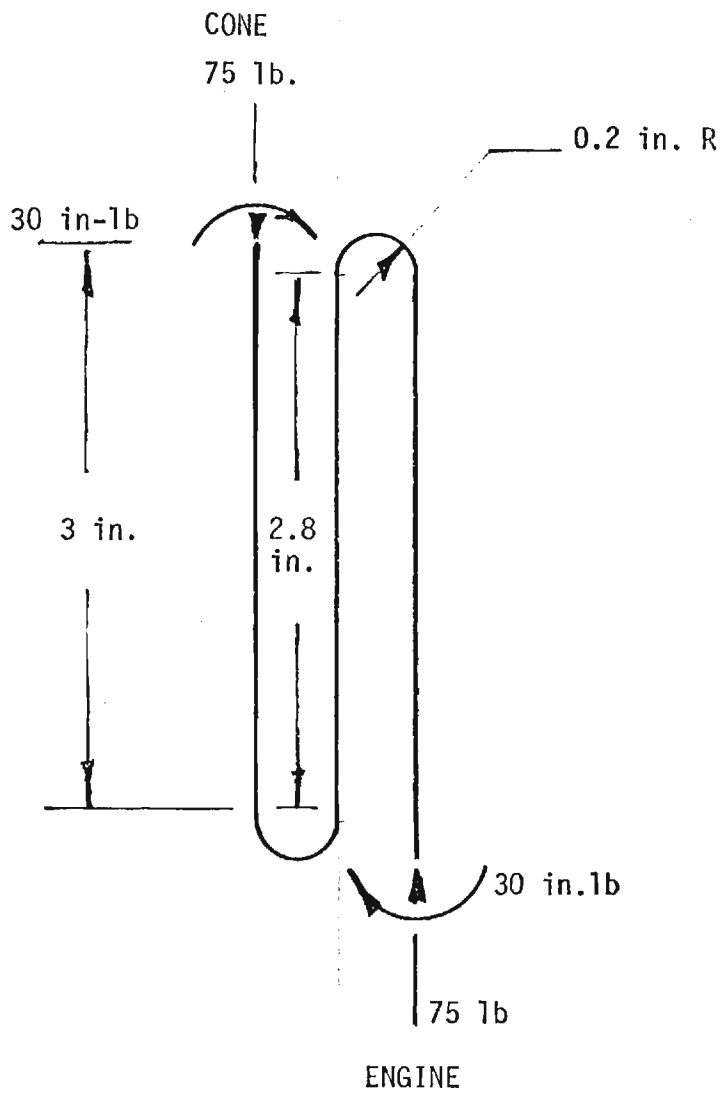

Figure 27. Loads and Moments at Helium Tube Attachments.

wall occur on the inside surface they will not add to these stresses from the end reactions. In fact, stresses on the outside surface due to the temperature variation will be compressive and therefore will serve to off-set this high tensile stress to some degree.