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DEVELOPMENT OF A TURBOJET COMBUSTOR WITH A SEGMENTALLY CONSTRUCTED LINER

by

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prepared for

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION

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CURTISS-WRIGHT CORPORATION

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FINAL SUMMARY REPORT

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Contract NAS 3-7908

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ABSTRACT

Durability of conventionally designed combustor liners is compromised due to the thermal stresses encountered in the severe combustor environment. The large temperature gradients and thermal cycling induce thermal stresses which can cause buckling and local plastic flow or liner cracks. Severely warped liners with abnormal temperature distribution can cause burned turbine blades and possible engine loss.

The development effort reported herein resulted in a unique liner design directed toward alleviating the thermal stresses. The liners were segmented in both the axial and circumferential direction. The segmented liners, by permitting unrestrained thermal expansion of adjoining elements, reduced thermal stresses. This should result in an extended service life. Further, the individual segments can be replaced, where necessary, without the need for an entire new liner assembly.

The liner assemblies were successfully tested to combustor air inlet temperature and pressure of 1150°F. and four atmospheres, with combustor gas outlet temperature of 2200°F. Ten percent of total airflow was used for liner cooling. This flow provided .0036 pounds coolant/sec/in^2 of liner surface at the four atmosphere condition.

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1.0 SUMMARY

1.1 Object

The continuing development of aviation, encompassing the operation of both military and civil aircraft, has always been paced by the availability of suitable powerplants. One of the major technical areas of concern with respect to the powerplants to be used in advanced supersonic aircraft is the durability and reliability of the highly stressed engine parts. Nowhere is the problem more critical than in the combustor, where detail parts such as liners are subjected to a transient and steady state stress environment that is difficult to analyze, predict and provide for.

NASA had recognized this as an area of vital concern and had been engaged in exploratory work to determine how the stresses could be alleviated. An investigation at Lewis Research Center had indicated that a segmented construction for the combustor liner would minimize the stresses and thereby increase liner life.

Subsequent to this, Curtiss-Wright Corporation, Wood-Ridge Facility, under the sponsorship of The National Aeronautics and Space Administration, Lewis Research Center, undertook the development of a segmentally constructed liner assembly. This work was done for NASA under Contract Number NAS 3-7908.

The objective of the program reported herein was to demonstrate, through actual tests, that the segmented liner concept was feasible.

1.2 Scope of Effort

The first portion of this program was directed toward the development of two candidate combustor liner designs. These were the result of a two-phase effort. The first phase was a preliminary study to arrive at design concepts, with related fabrication and material studies. The second phase was preparation of the final designs. In this effort a detailed design and analysis was performed, and three separate liner designs were prepared. The liners were designed so that each segment would provide film cooling for the following downstream segment. This effort also included design of the test combustor and the test sector rig.

Upon completion, and approval of two designs by NASA, fabrication of the components was initiated. This was followed by tests to verify the designs. Liner modifications, based upon the test results, were accomplished during this period.

1.3 Results

As outlined in the scope of work, two final designs were fabricated and tested.

The liners were tested for structural durability and performance for a total of 112 hours, of which 46 hours were hot runs. Tests were run to 1150°F inlet temperature and a pressure level of 4 atmospheres. Further tests scheduled for 6 atmospheres were terminated due to sector rig malfunctions (side plates burned through).

During the testing some liner problems were encountered. Local hot spots which occurred on the liners caused some degree of downstream edge melting, though no failures occurred. In addition, there was excessive warpage of the liner trailing edges, which caused blockage of the film cooling slots and overheating. The combustor rig experienced development problems associated with air flow distribution and side plate durability.

Design modifications to the combustor rig and liners were incorporated into the test builds, and the final tests verified that the modifications markedly improved the liner durability. Liner temperatures in the upstream regions were within specification (1600°F). The downstream liner temperatures were slightly higher (1750°F max.). However, there was little warpage and no local metal degradation such as had previously been observed. Analysis and extrapolation of the test data indicates that the liner performance would be equivalent at the six atmosphere level.

1.4 Principal Conclusions

The segmented liner program demonstrated the following:

1. That such a design could be readily fabricated utilizing "state of the art" materials and manufacturing techniques.
2. That such a design reduced liner thermal stresses. Throughout the program there were no indications of structural distress. The liners worked and were durable under the extreme environment experienced in a combustor.
3. That such a design could provide reduced operational costs, since individual sectors could be readily replaced. During the entire test program the liner segments were repeatedly removed and reinstalled. No problems were encountered during these operations.

This program verified the basic concept of liner segmentation. As compared to conventional liners, the segmented liners can provide a more durable and reliable structure due to the reduced liner thermal stresses.

1.5 Recommendations

A segmented liner configuration should be considered for incorporation in a demonstration or development engine. The following is recommended for continuation of this program:

1. Modify liner design, based on the final test results, to further optimize liner performance.
2. Evaluate a full combustor incorporating the improved liner assembly on a full round combustor test rig at operating conditions determined by the development engine requirements. This should include cyclic testing in a duty cycle which reflects engine operating conditions.

2.0 INTRODUCTION

As noted in the summary section of this report, current combustor liners are subject to extremely high thermal stresses due to the thermal growth limitations inherent in their structural designs.

The objective of this program was to design and experimentally evaluate a unique liner concept directed toward alleviating the thermal stresses. The segmented liners were designed to operate in an advanced turbine engine at a Mach 3 flight condition. The liner designs were tested and evaluated as a method of improving durability and maintaining combustor performance. Based upon the results of these evaluations, one liner configuration was reworked to improve its performance and subjected to further testing. This work was performed in accordance with the following program plan:

Task I - Preliminary Design Study

A literature survey was performed to evaluate all previous work and relate the accumulated data to the program. Conceptual studies were carried out to arrive at candidate liner configurations. The designs generated were submitted to NASA for approval.

Task II - Detailed Combustor Liner Design

Two liner configurations were selected, and detailed designs were prepared. Stress, aerodynamic and heat transfer analyses of these designs were performed. These designs were submitted to NASA for approval.

Task III - Design and Fabrication of Test Hardware

Layout drawings were prepared for test ducts, instrumentation and combustor. These were submitted to NASA for approval.
All equipment was fabricated.

Task IV - Testing

Two combustor liner configurations were tested. Units were revised based on tests and test verification was completed.

The Program Plan for these tasks is shown in Figure 1. The Program progressed through Task IV and concluded with successful tests.

The significance of this effort was that it demonstrated, through actual combustor tests, that the segmented liner concept is feasible.

The program reported herein has shown that such liners, through proper design, can be readily fabricated, installed and maintained, and that the segmented liner concept is durable when subjected to the extreme environment of an advanced combustor. The results of the above design and development program are discussed and summarized in the following sections of this final summary report.

The report summarizes the overall program as follows:

1. Review of the liner design effort including stress and heat transfer inputs.
2. Review and summary of the liner development effort
3. Conclusions
4. Recommendations

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PROGRAM SCHEDULE - SEGMENTED LINER DEVELOPMENT

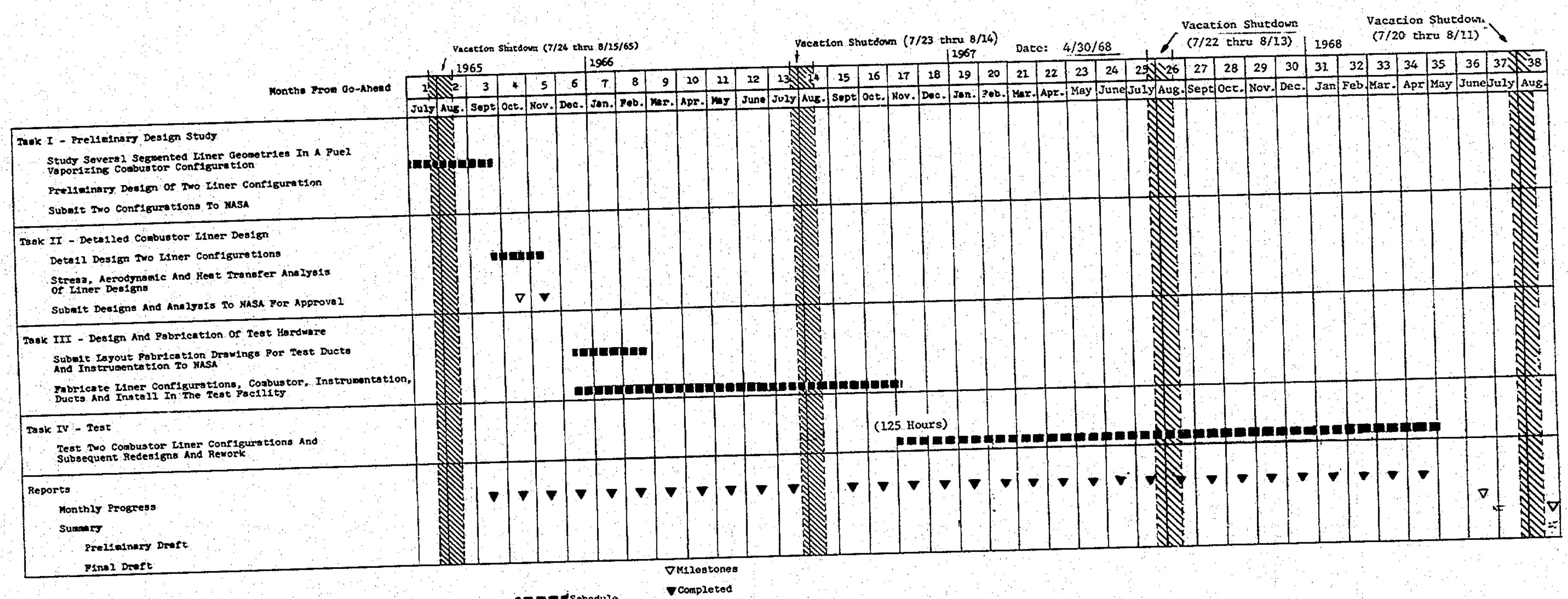


Figure 1

3.0 DESIGN

The design effort covered the segmented liner design and associated test hardware such as the combustor and sector test rig.

The major effort was directed toward the segmentally constructed liner design. This included a survey of existing literature, conceptual design studies and the selection of the two most promising concepts. Final design included material and manufacturing studies and performance of thermal and structural analyses.

Concurrent with this was the design of other items such as the overall combustor configuration and the sector rig for the evaluation tests.

3.1 Design Specifications

The specifications for the combustor design are those stated in Exhibit "A" of NASA Contract Statement NAS 3-7908. These constraints were adhered to in the design of the combustor assembly and other hardware associated with the sector rig tested.

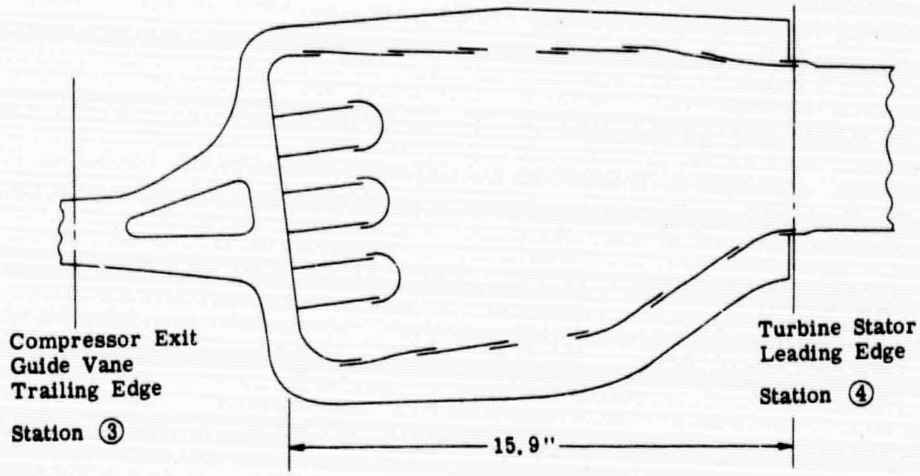
The combustor design and performance specifications are listed in Figure 2. The combustor is designed to operate on an advanced turbine engine at a Mach 3 flight condition.

3.2 Segmented Liner Design

The segmented liner forms the inner and outer walls of the combustor. The two liners are assemblies of individual formed sheet metal panels that are overlapped in shingle fashion both axially and circumferentially. The liner assembly is shown schematically in Figure 3. Segmented liners offer the following advantages over full hoop liner designs:

1. Elimination of large diametral changes due to thermal growth.
2. Allowance for free thermal expansion of adjacent liner panels regardless of temperature distribution.

DESIGN AND PERFORMANCE SPECIFICATIONS



Combustor Size	
Overall Length ③ to ④ - inches	22.5
Primary Zone Length, l_p - inches	7.0
Combustion Chamber Length - inches	15.9
Reference Area, A_{Ref} - in^2	1070.6
Inlet Conditions - Station ③	
Air Flow (Full Round), W_{a3} - pps	143.0
Total Pressure, P_{T3} - in. Hg Abs.	183.0
Total Temperature T_{T3} - ^oR	1610.0
Mach Number - M_3	0.514
Compressor Exit O.D., D_{o3} - inches	29.0
Compressor Exit I.D., D_{i3} - inches	25.2
Compressor Exit Area, A_3 - in^2	160.0
Combustor Exit Conditions - Station ④	
Total Pressure, P_{T4} - in. Hg Abs.	168.2
Total Temperature, T_{T4} - ^oR	2660.0
Turbine Inlet O.D., D_{o4} - inches	37.4
Turbine Inlet I.D., D_{i4} - inches	27.8
Turbine Inlet Area, A_4 - in^2	491.0
Combustor Performance	
Fuel-Air Ratio - F/A	0.0172
Temperature Ratio, T_{T4}/T_{T3} - $^oR/^oR$	1.65
Combustion Efficiency, η_b - %	99.0
Combustor Total Pressure Loss:	
Percent of Inlet Velocity Head, $\Delta P_{T3-4}/q_3$ - %	51.6
Percent of Inlet Total Pressure, $\Delta P_{T3-4}/P_{T3}$ - %	8.1
Overall Combustor Heat Release Rate - Btu/Hr/Atmos./Ft^3	5.4×10^6
Reference Velocity, V_{Ref} - Ft/Sec	145.0
Primary Zone Residence Time - milliseconds	4.85

Figure 2

SCHEMATIC OF SEGMENTED LINER ASSEMBLY

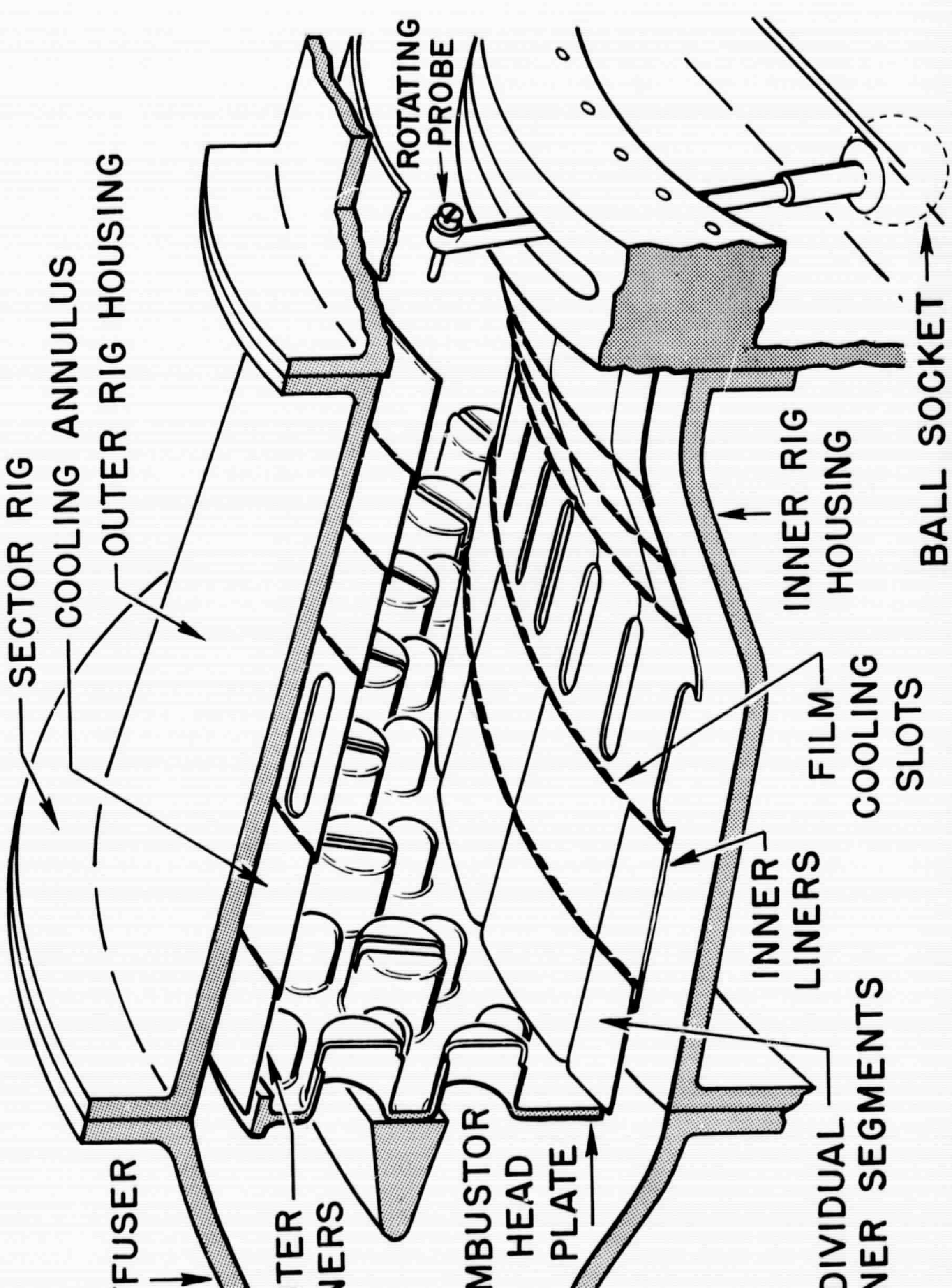


Figure 3

3. Reduction of thermal stresses to a level below the plastic range of the material, thus eliminating low cycle fatigue problems usually associated with hoop designs.
4. Close control of air inlet metering areas without imposing thermal restraints.
5. Reduction of service and maintenance costs, in that only individual segments need be replaced when required.

3.2.1 General Liner Design Criteria

The segmented liner design activity encompassed a preliminary study phase, and a detail design effort. During the preliminary phase, numerous segmentally constructed liner configurations were conceived and studied. A historical literature survey was conducted to ascertain previous development experience with segmentally constructed combustor liners. Experience had been gained by the contractor in this field during the development of large ram-jet and afterburning turbo-jet engines. This background of practical experience was particularly useful in the generation of new segmental configurations. The following basic concepts were generated as a result of this survey.

1. The attachment of the segments must permit unrestricted thermal growth of individual segments both longitudinally and circumferentially. This would significantly reduce the thermally induced liner stress levels.
2. The design would provide film cooling.
3. The attachment of support hangers to the liner segments should be accomplished with a "tee" section butt weld. This type of attachment would eliminate the interfaces which result with conventional sheet-metal lap joints. Lap joints are undesirable because the insulating layer of air formed at the metal interface creates high local metal temperatures.

Three of the most promising segmented liner configurations were selected for evaluation from the numerous liner and attachment geometries conceived during the initial design studies. Each of the selected concepts incorporated the following design features:

1. The liners were segmented both longitudinally and circumferentially to permit unrestrained thermal expansion.
2. The segments were supported from longitudinal hangers attached to the combustor housings. The liner supports were slotted to minimize longitudinal stiffening of the segments.
3. Slip joint seals were provided along the longitudinal edges of the segments to control leakage and permit circumferential thermal expansion.
4. Close tolerance control of the film cooling metering area was obtained by machining recesses in the downstream edge of the liner segments. Machined lands between the recesses maintain control of the cooling slot height. "L" shaped hooks welded to the recessed ends of the segments are used to hold the machined lands in contact with the mating surface of the overlapped liner segment.
5. The design of the support members would be such that they would cause minimum obstruction of the coolant air flow to the liners.

Typical segmented panels incorporating these features are shown schematically in Figures 4 and 5.

At the completion of the preliminary study phase, two of the three segmented liner configurations were selected for the detail design effort. These were configurations 1 and 3. These liner assemblies are shown in Figures 6, 7, 8, and 9. The selection was based upon minimum complexity, minimum aerodynamic blockage, and ease of fabrication. A detailed description of each of the two configurations, and the stress analysis with these designs is presented in the sections which follow.

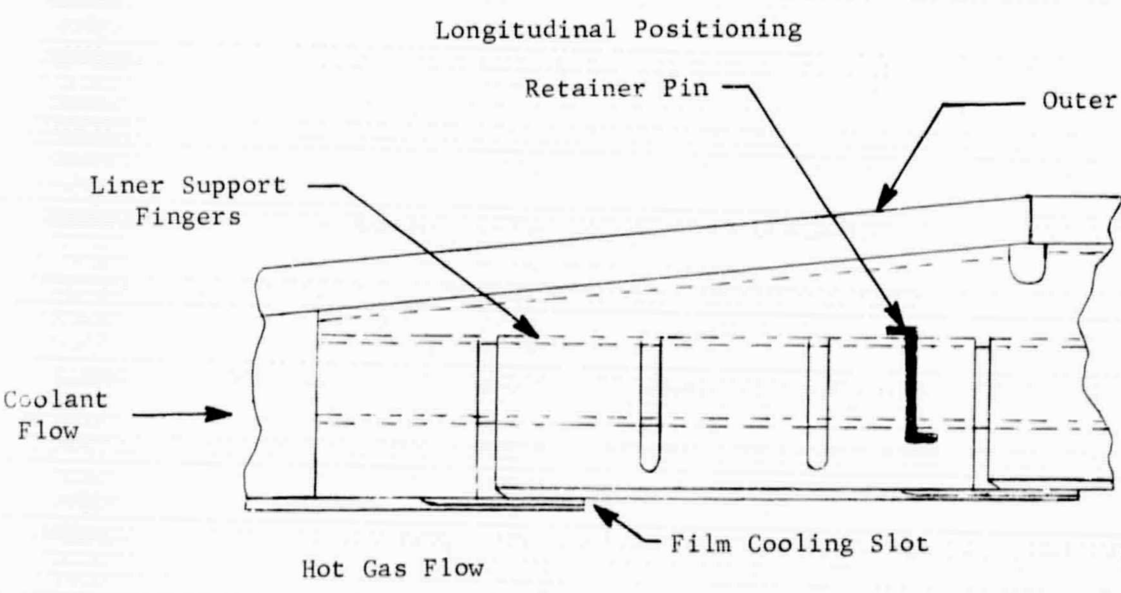
3.2.2 Segmented Liner Configuration No. 1.

A schematic of the Segmented Liner Configuration No. 1 design is shown in Figure 4. The liners are shown assembled in Figures 6 and 7. The basic intent of Configuration No. 1 is to hold one longitudinal edge of the liner segment in a relatively fixed position, and allow the other edge freedom to expand circumferentially. A spring pin is used to hold the fixed edge of the segment in position. The resilient action of the pin holds the segment in the proper

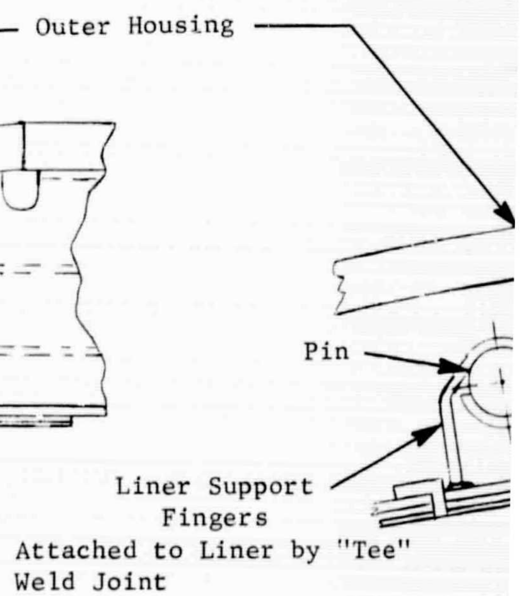
SCHEMATIC OF OUTER LINER ASSEMBLY -

"L'

"L" Hook S



SECTION A-A



Slip Joint

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FOLDOUT FRAME 1

BLY - CONFIGURATION NO. 1

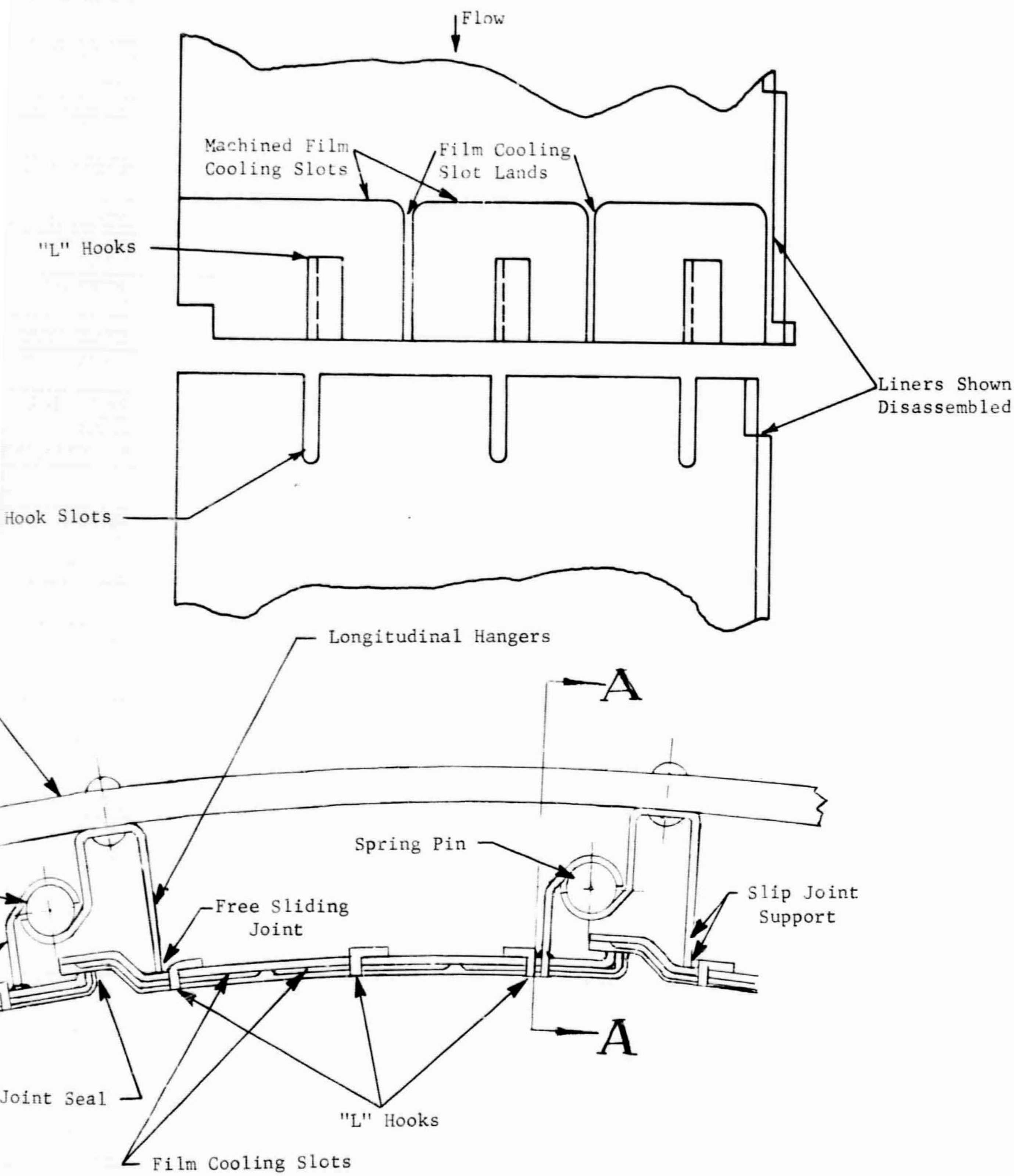
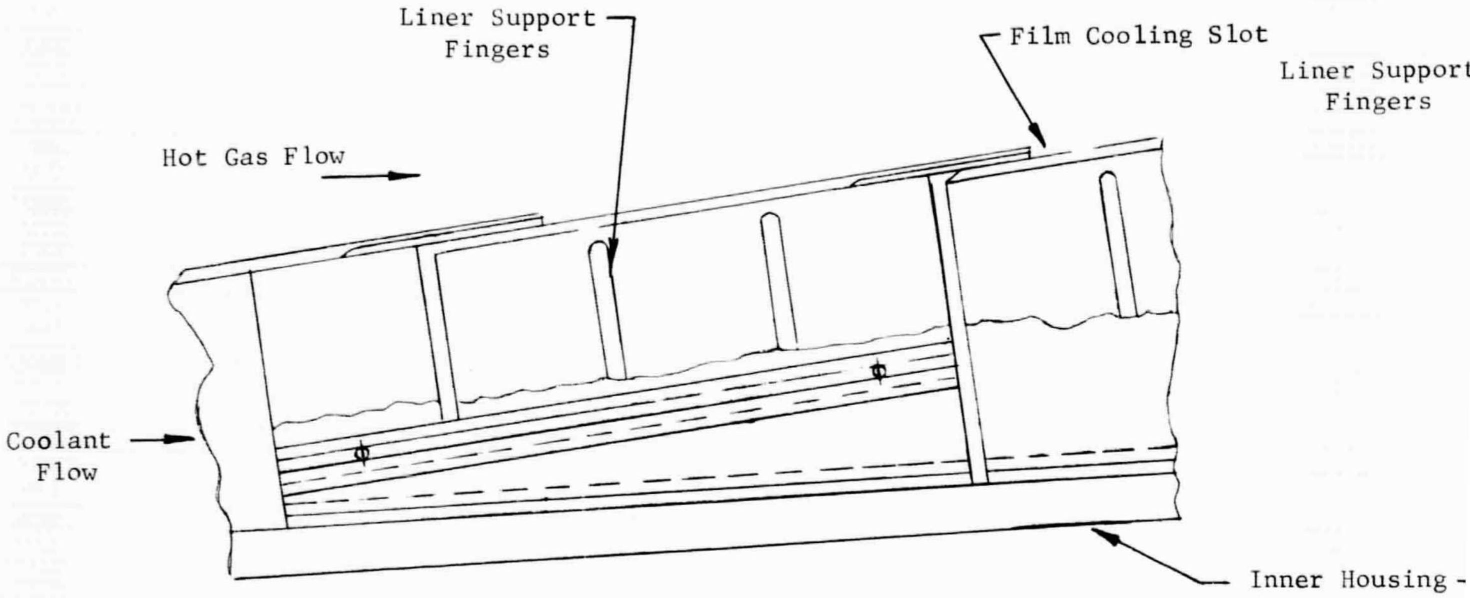


Figure 4

FOLDOUT FRAME 2

SCHEMATIC OF INNER LINER ASSEMBLY -

Slip Joint



SECTION C-C

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EMBLY - CONFIGURATION NO. 3

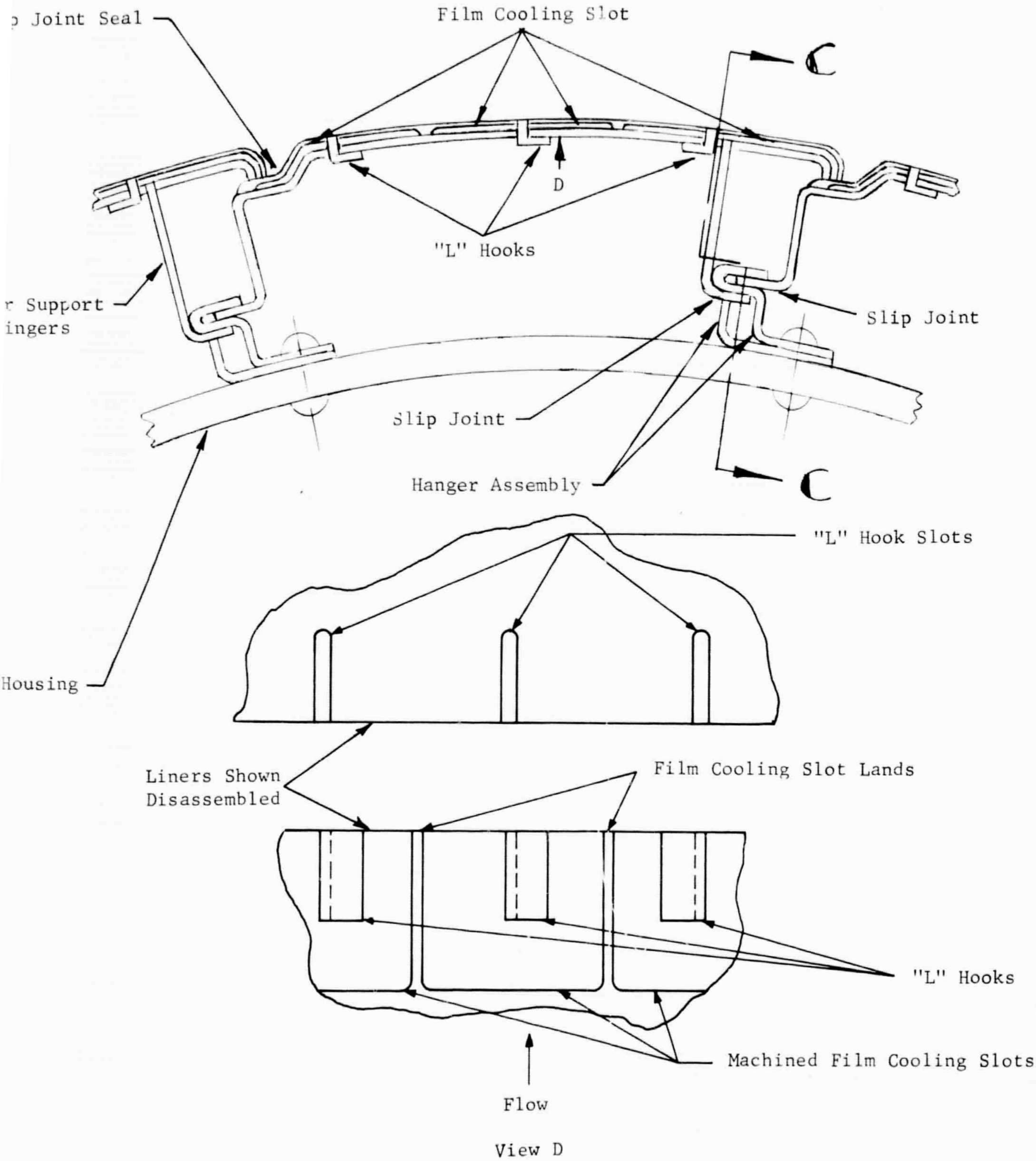


Figure 5

OUTER LINER CONFIGURATION NO. 1
(LOOKING UPSTREAM)

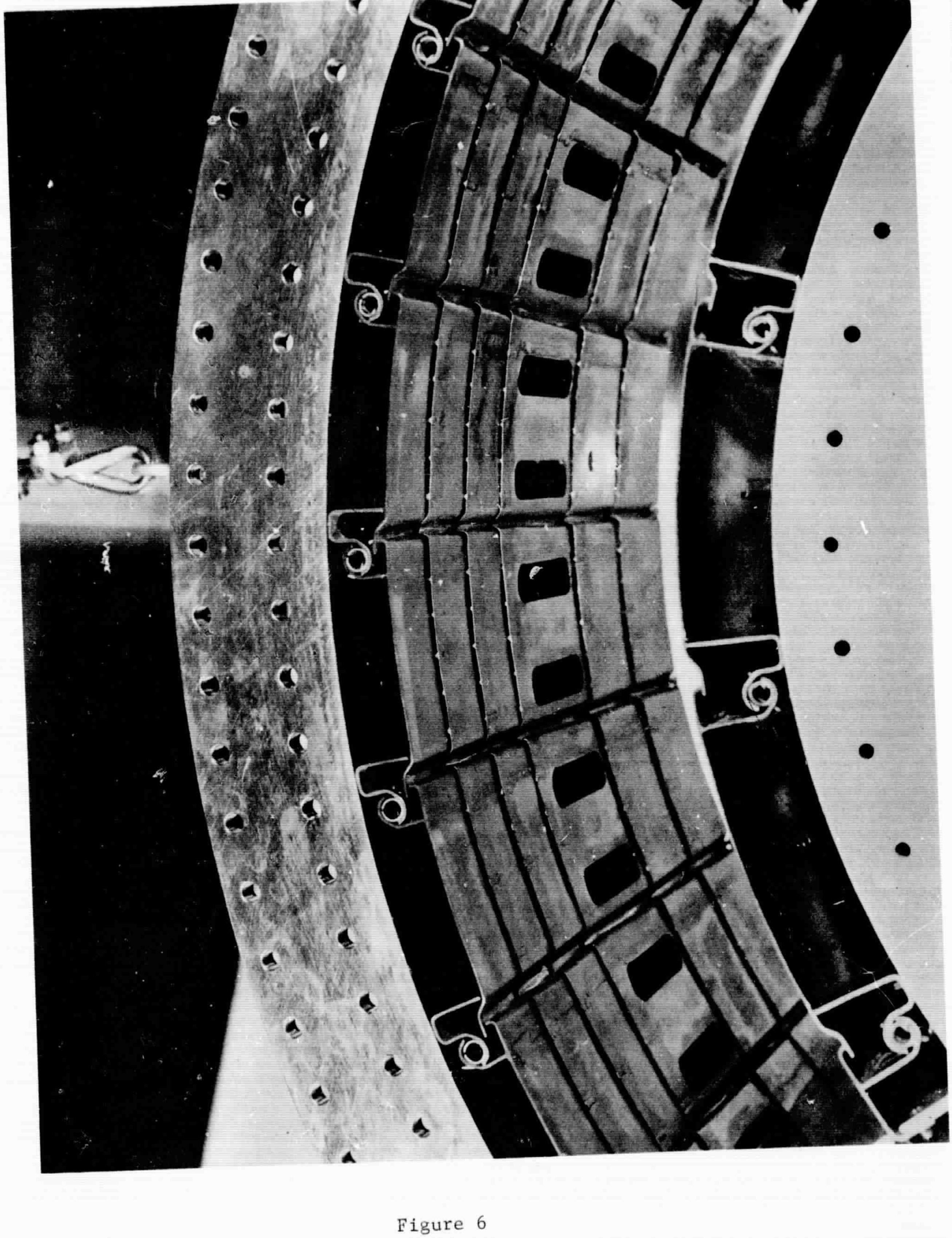
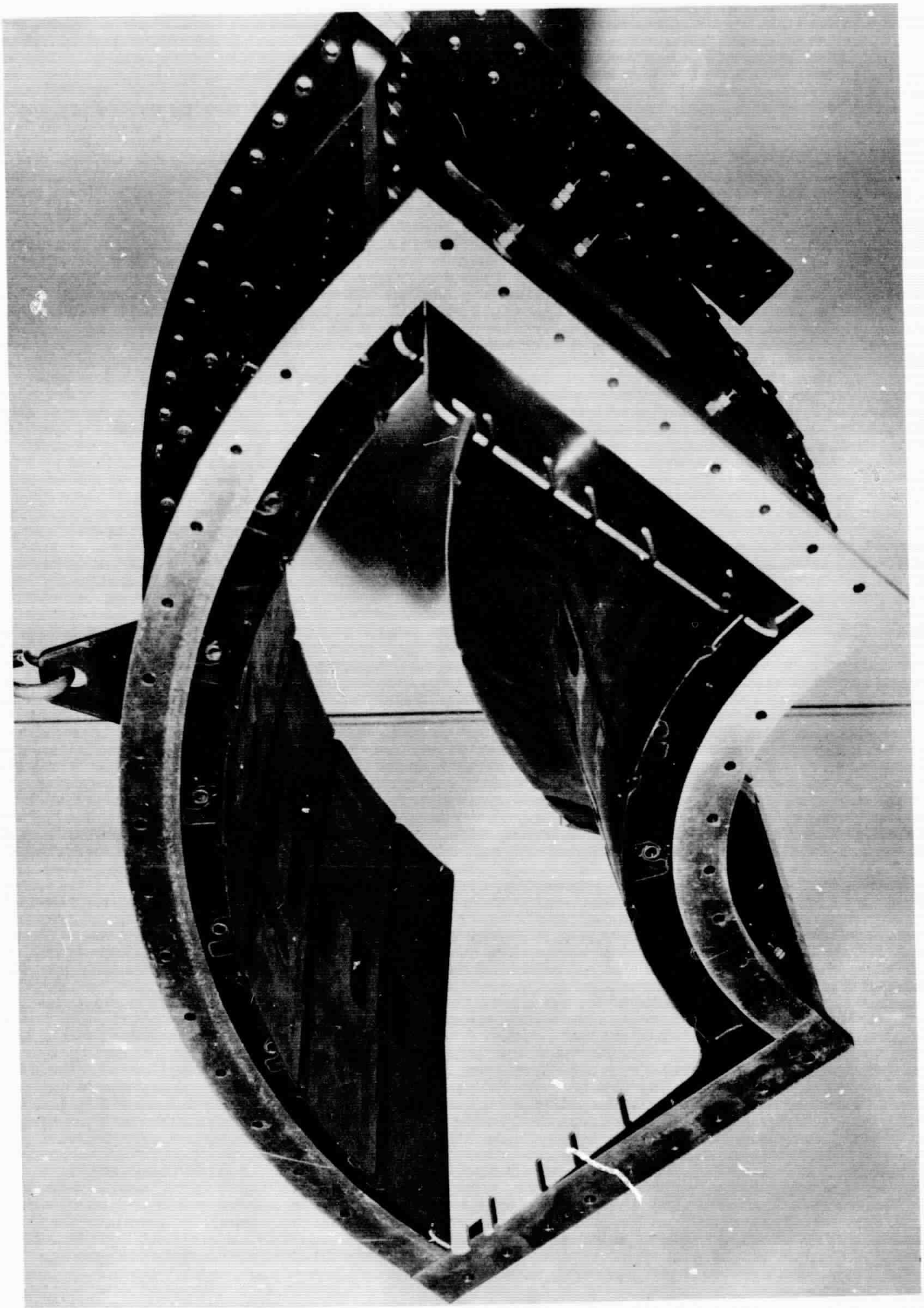


Figure 6



INNER LINER CONFIGURATION NO. 1
(LOOKING DOWNSTREAM)

Figure 7

INNER LINER CONFIGURATION NO. 3
(LOOKING DOWNSTREAM)

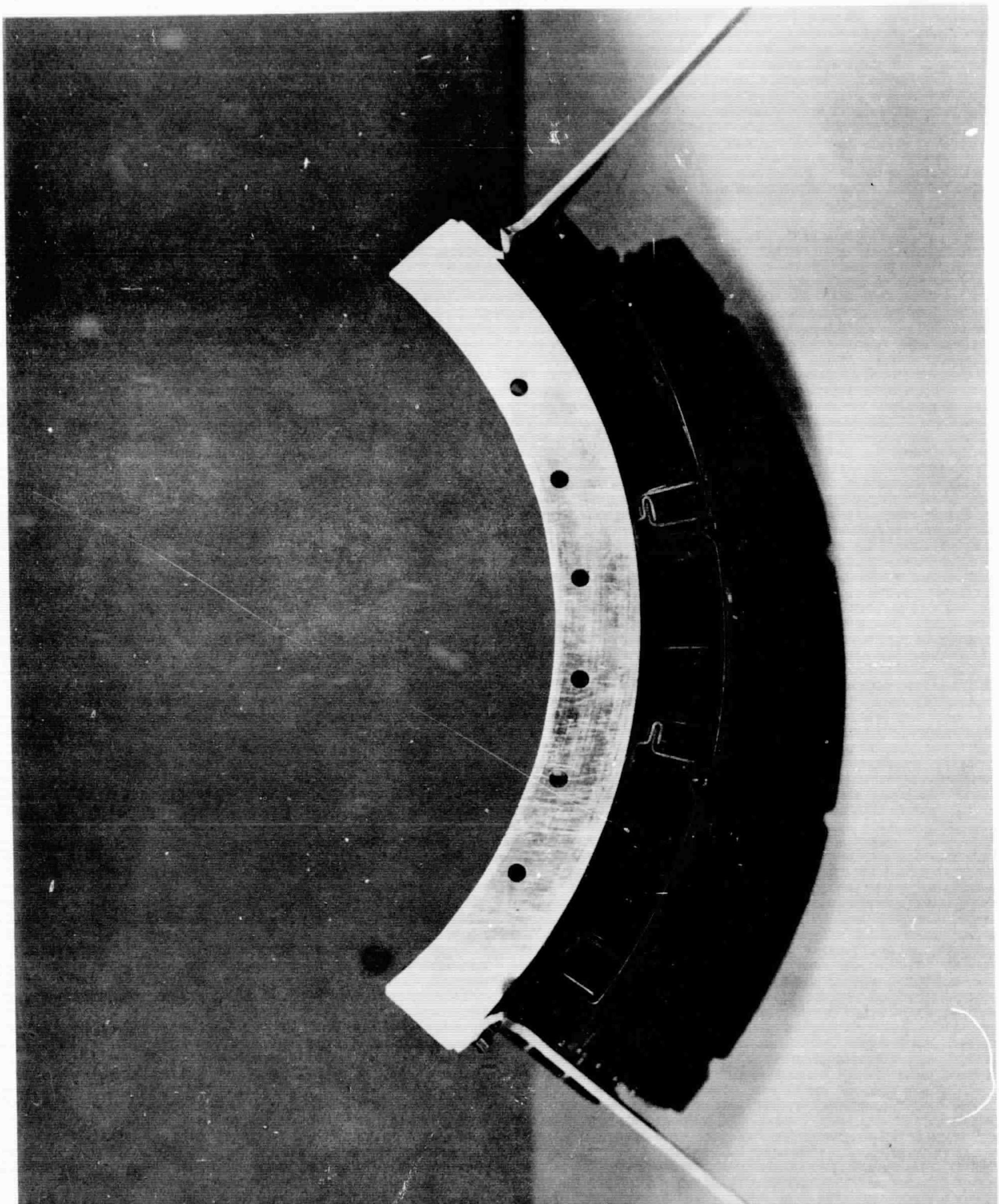


Figure 8

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OUTER LINER CONFIGURATION NO. 3
(LOOKING UPSTREAM)

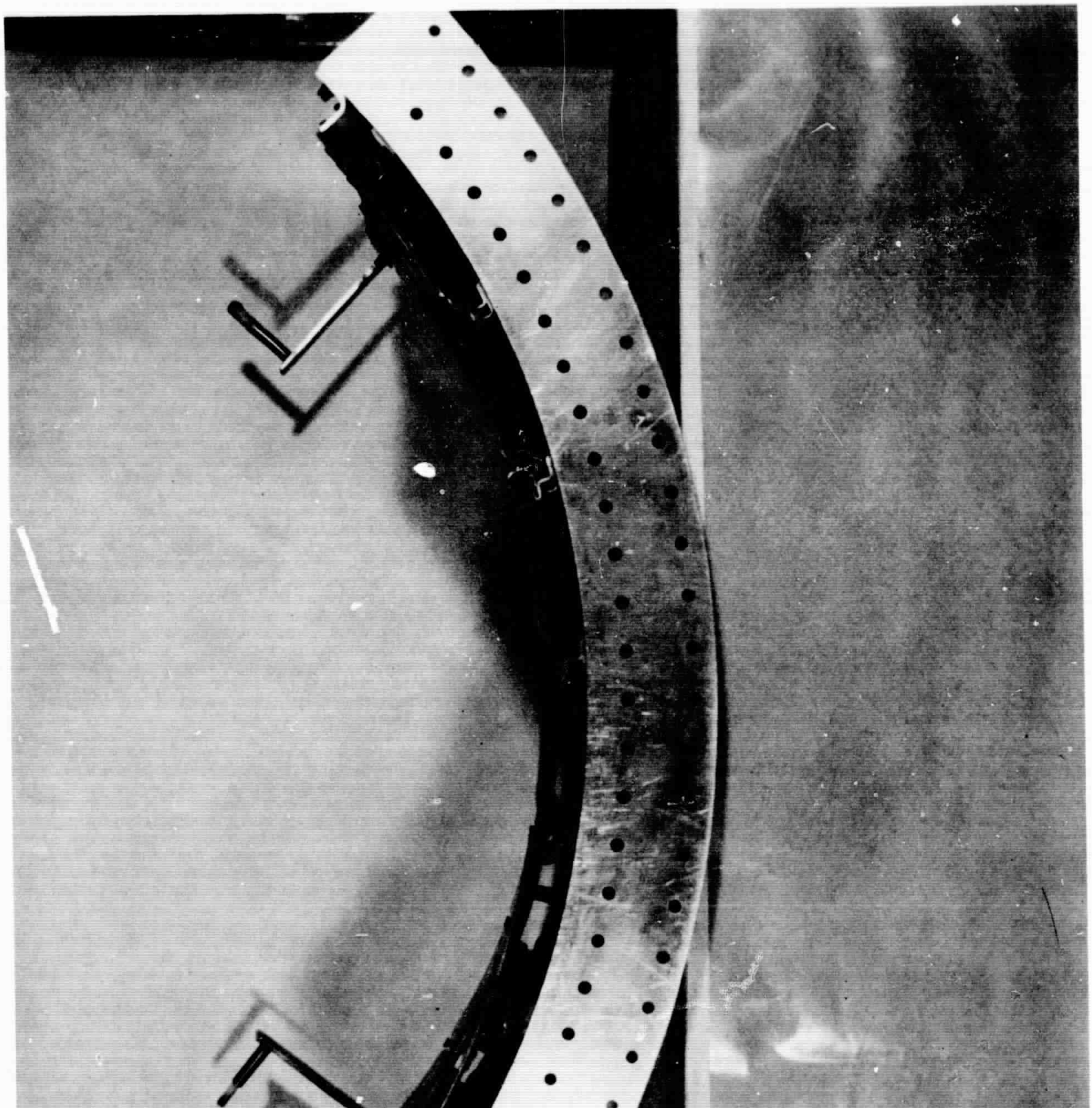


Figure 9

radial position, and provides a sealing force at the slip joints along the fixed longitudinal edge of the segment. This force also holds the free longitudinal edge of the adjacent segment against the slip joint support, without restricting circumferential expansion. The spring pin is located in the relatively cool air passage between the liner and the combustion chamber housing. The longitudinal position of the segment is maintained by a retainer pin through the hanger, spring pin and liner support finger. The retainer pin is located in the downstream support finger of each segment, which permits each segment to grow longitudinally toward the headplate. The liner support is slotted along its axial length to reduce stiffness and to permit thermal growth in an axial direction.

This configuration provides a smooth surface on the hot side of the liner, which is desirable for maintaining the film of cooling air. The concept also provides for good control of the cooling film slot height and good sealing for minimum air leakage. There are no interfaces which could cause local hot spots.

3.2.3 Segmented Liner Configuration No. 3

A schematic of the Segmented Liner Configuration No. 3 design is shown in Figure 5. The liners are shown assembled in Figures 8 and 9. This configuration incorporates the same desirable features as Configuration No. 1. It differs in that circumferential thermal growth of the liner is permitted in both directions. The liner support fingers are held in double slip joint supports which are attached to the combustor housings. Sealing is maintained at the slip joint along the longitudinal edges of the segments, by close dimensional control of the liner support fingers. The support legs are slotted to permit thermal growth in the axial direction.

3.2.4 Materials

The liner segments and support hangers are made of Rene 41 material (WAD 7816 - Heat Treatment W7817 HT92 after welding). This choice was based upon the thermal and structural requirements of the design as related to a minimum life capability of 600 hours, and to achieving the desired flight weight objectives.

Rene 41 is a vacuum melted nickel base alloy with high strength properties and good oxidation resistance at elevated temperatures. It is quite formable in the solution treated condition, and can be welded. The material is aged to obtain the desired mechanical properties. This aging process includes an intermediate solution treatment to lessen the chance of cracks developing during welding operations.

The liner segments were built satisfactorily according to blueprint and performed successfully in the test rig, without developing faults related to the fabrication methods.

Other materials also considered for liner segment application were Hastelloy X and Stellite No. 25. Both are suitable as combustor materials, but have insufficient strength to meet the structural and flight weight requirements of the design. The cost saving by not requiring a heat treatment was also recognized.

The burner headplate, primary air fuel vaporizing tubes and air cups were made of Hastelloy X material, which has excellent oxidation resistance, formability and weldability. All external rig housing hardware was of heavyweight construction. The inner and outer walls, and the side covers, were treated as hot section components, and were made from Hastelloy X material. The inlet and diffuser sections were made with AISI 321 stainless steel material.

3.2.5 Stress Analysis

The stress analysis of the segmented liner (Configurations 1 and 3) was conducted to establish the adequacy of the structure under the mechanical and thermal loads as presented in other sections of this report. The induced stresses were calculated on the basis of steady state conditions, and assumed no restraint due to thermal expansion in either the longitudinal or circumferential directions. In addition to the mechanical properties exhibited by the liner material (Rene 41; WAD 7816) at operating pressures and temperatures, consideration was given to the isothermal stress-time relations of 0.2% creep based on the Larson-Miller method, and stress rupture predicted by the Manson-Haferd method.

The calculated stresses and the material allowables, based on yield and 600 hrs. of 0.2% creep and stress rupture, are tabulated in Figures 10 and 11, and are shown for each segmented element of both liner configurations. Figures 12 and 13 show the maximum stresses induced in the hanger support systems for each liner configuration.

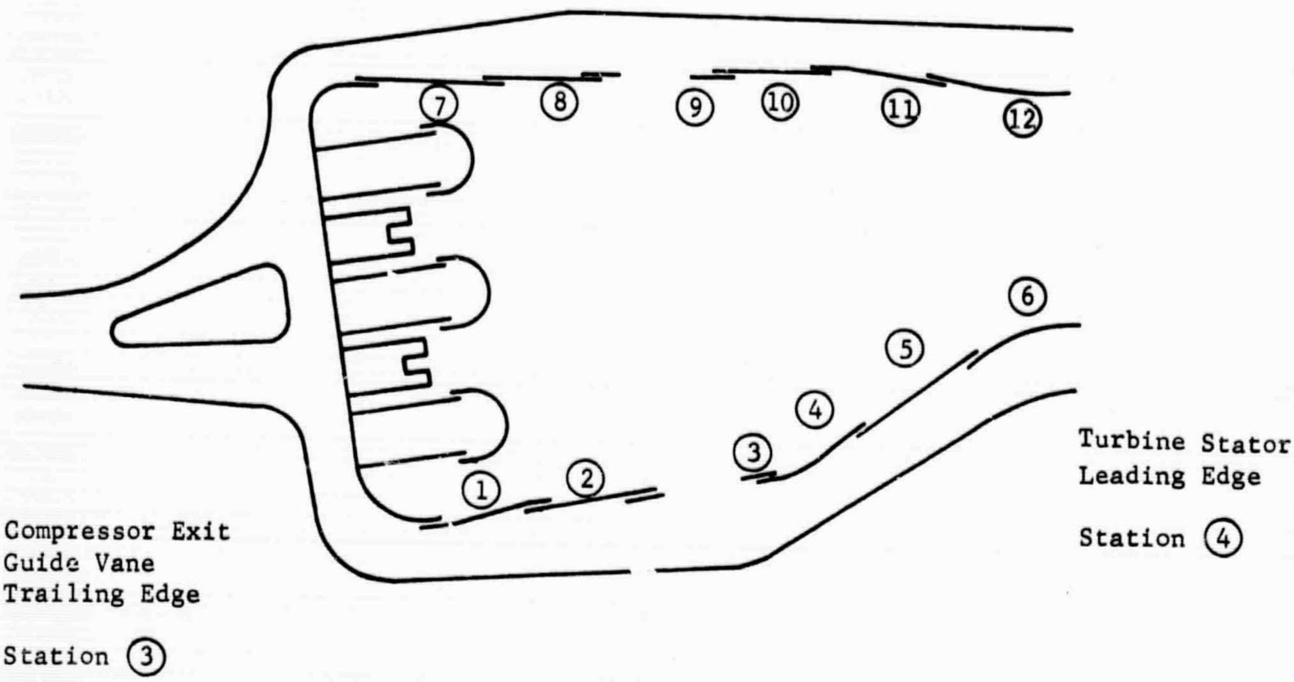
The combustor liner section properties and the pressure differentials used to calculate mechanical stresses are shown in Figure 14. The material allowable stresses used in this analysis are shown in Figures 15, 16 and 17. The calculated stresses and the material allowables show that the segmented liner designs are structurally adequate under the specified pressure and thermal loads imposed on the structure. A discussion of the analytical procedure used to determine the stresses due to mechanical and thermal loads is presented in Appendix 7.1. A sample calculation is included with that discussion.

3.2.6 Transient Heat Transfer Analysis

A three dimensional heat transfer analysis was conducted to obtain a mapping of the steady state and transient surface temperatures of the combustor housings, liner support systems, and segmental elements. The operating conditions which were used to simulate the transient operation are shown in Figures 18 and 19. The fuel-air ratio was assumed to vary linearly from 0.01 at ignition to 0.0172 at the Mach 3 operating condition, which was attained 10 seconds after ignition. A sketch of the combustor is shown in Figure 20 and the operating conditions at ignition and at the Mach 3 design point are listed in Table I.

The temperature distribution was determined by a balance between the various heat inputs and heat losses. These heat fluxes, and the analytical methods used for their determination, are discussed in Appendix 7.2 of this report. For this analysis, the value of luminous radiation from the flame in the primary zone was assumed to vary from 25,000 BTU/Hr-Ft^2 at ignition, to 123,000 BTU/Hr-Ft^2 at the Mach 3 design point. The flame front was assumed to be arrested at the downstream end of the primary zone by injection of the diluent air. Based upon this assumption, the value of luminous radiation in the secondary zone was estimated to be 20 to 60% of the value in the primary zone.

STRESS INDUCED IN SEGMENTAL ELEMENTS - CONFIGURATION NO. 1

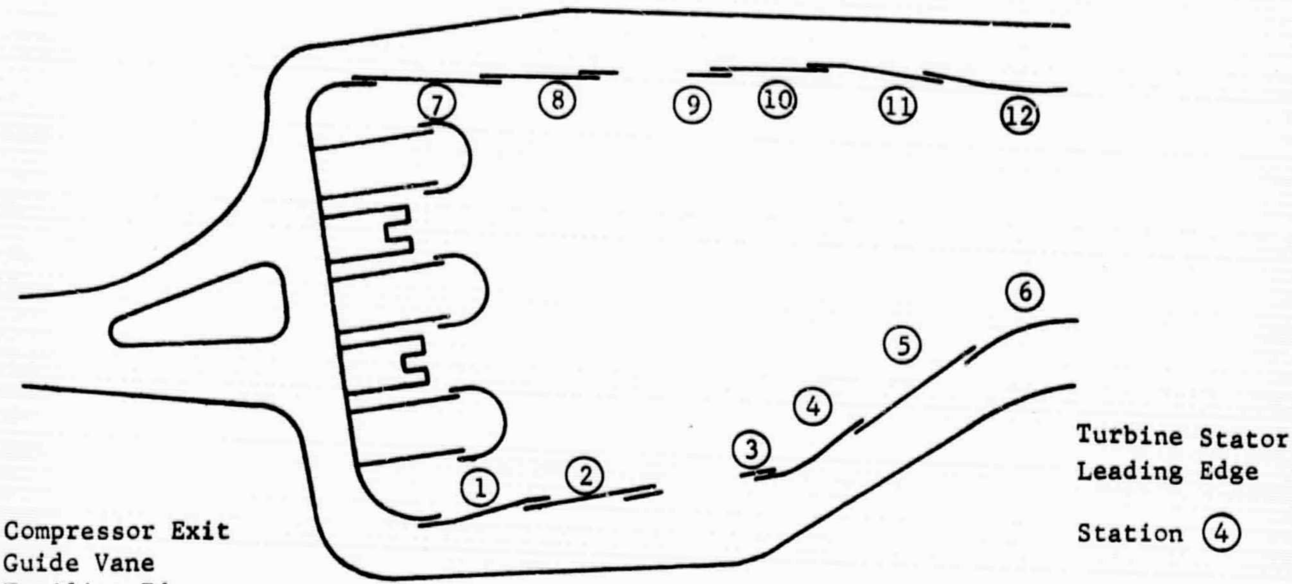


σ_B ≡ Maximum Bending Stress At Center Of Segment Element Due To ΔP

Segment Element No.	Average Temp. °F	σ_B ± Psi	Allowable Stress (Psi)		
			.2% Yield	.2% Creep At 600 Hrs.	600 Hr. Rupture
1	1520	9,850	88,000	20,000	23,000
2	1520	15,750	88,000	20,000	23,000
3	1400	26,300	109,000	33,000	43,000
4	1300	30,030	115,000	48,000	76,000
5	1250	42,470	117,000	60,000	92,000
6	1275	560	115,000	54,000	84,000
7	1520	8,380	88,000	20,000	23,000
8	1550	10,960	78,000	16,000	18,000
9	1380	8,100	111,000	36,000	50,000
10	1270	17,430	116,000	54,000	84,000
11	1225	19,900	118,000	68,000	102,000
12	1190	16,760	118,000	77,000	110,000

Figure 10

STRESS INDUCED IN SEGMENTAL ELEMENTS - CONFIGURATION NO. 3



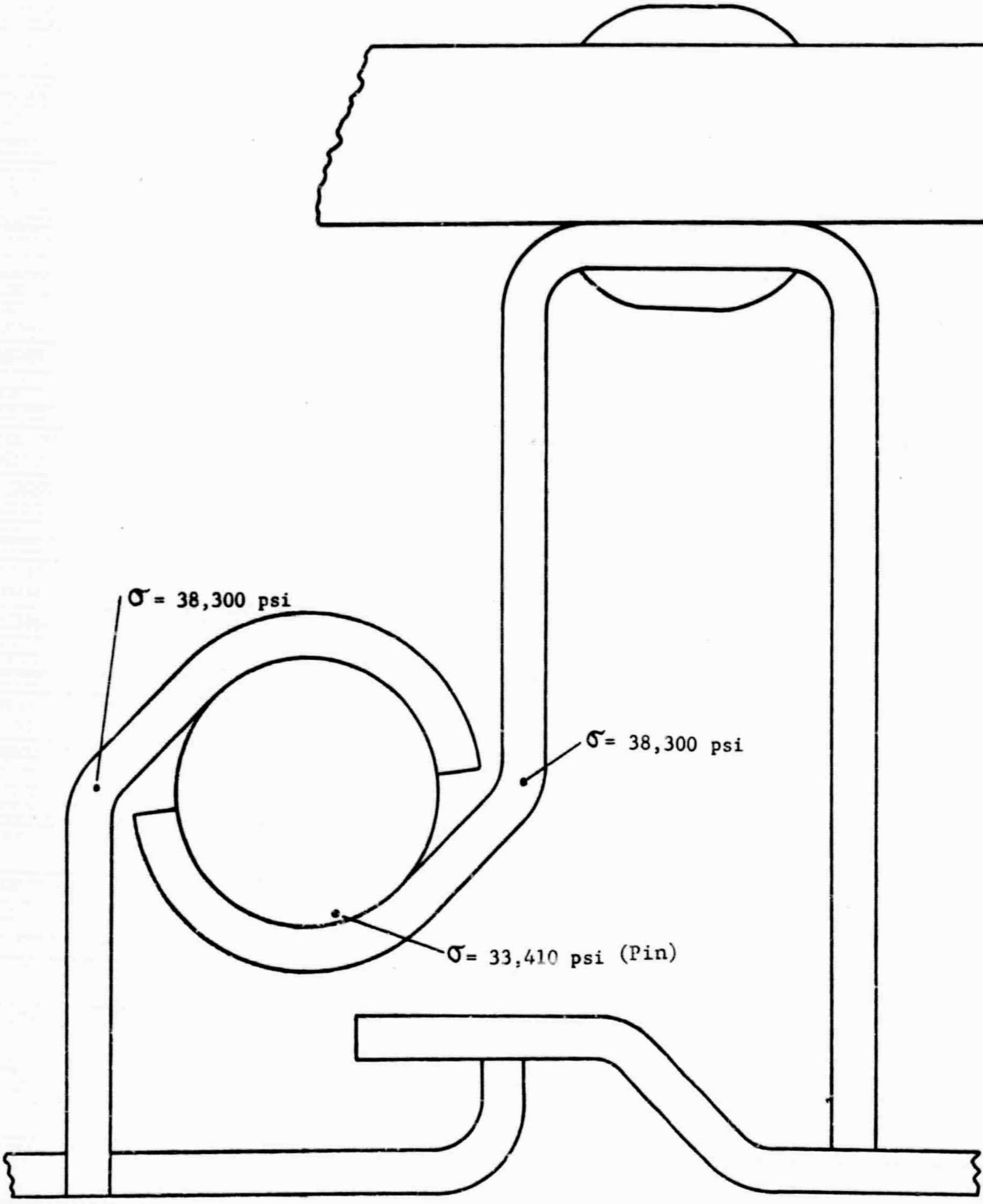
σ_B ≡ Maximum Bending Stress At Center Of Segment Element Due To ΔP

Segment Element No.	Average Temp. °F	σ_B (± Psi)	Allowable Stress (Psi)		
			.2% Yield	.2% Creep At 600 Hrs.	600 Hr. Rupture
1	1520	10,420	88,000	20,000	23,000
2	1520	17,630	88,000	20,000	23,000
3	1400	8,900	109,000	33,000	43,000
4	1300	32,350	115,000	48,000	76,000
5	1250	45,600	117,000	60,000	92,000
6	1275	610	115,000	54,000	84,000
7	1520	8,860	88,000	20,000	23,000
8	1550	11,940	78,000	16,000	18,000
9	1380	7,000	111,000	36,000	50,000
10	1270	18,700	116,000	54,000	84,000
11	1225	22,000	118,000	68,000	102,000
12	1190	18,440	118,000	77,000	110,000

Figure 11

MAXIMUM STRESSES INDUCED IN HANGER SUPPORT SYSTEM

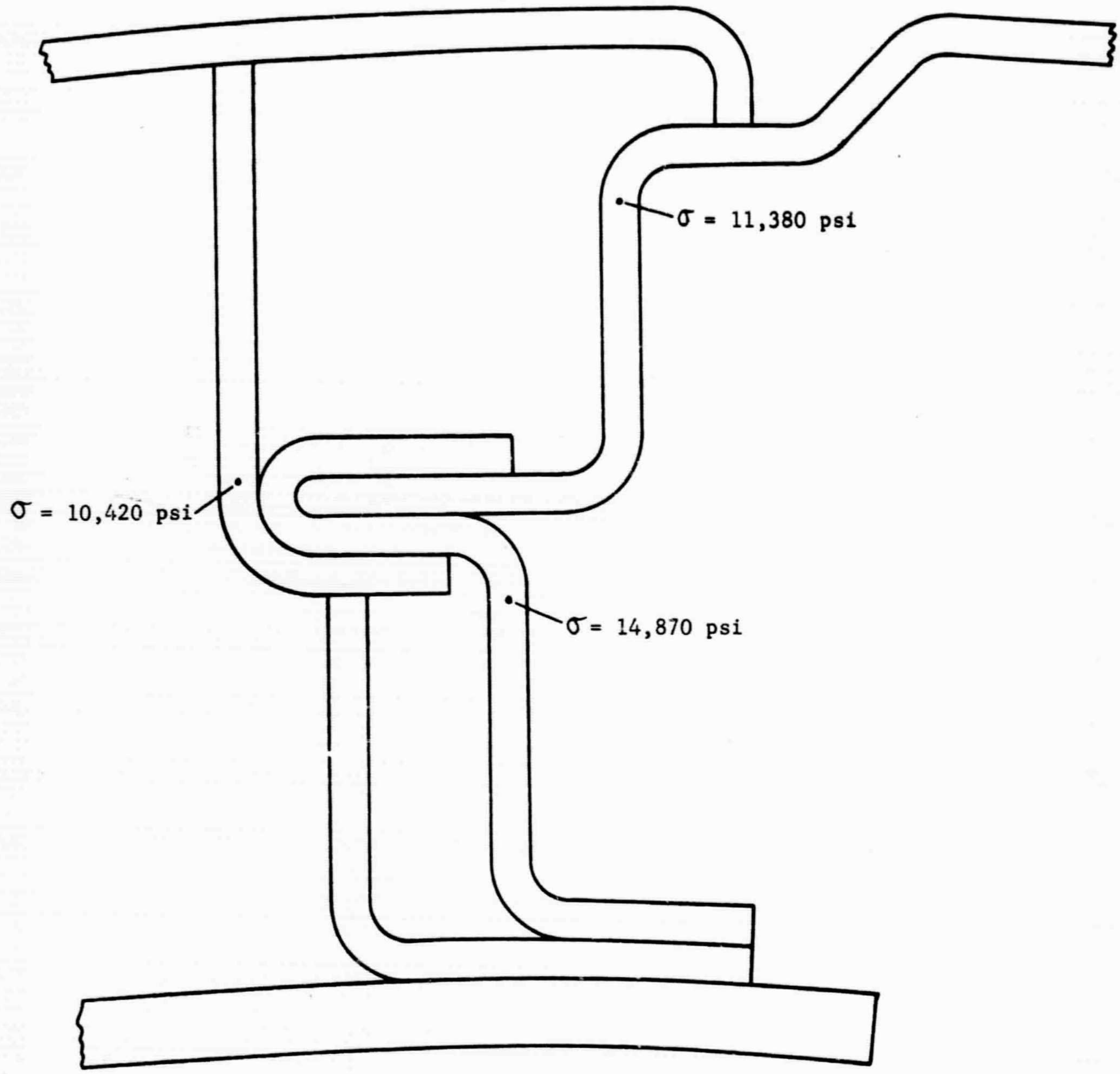
Configuration No. 1



Hanger And Pin Material - WAD 7816
Average Temperature = 1200°F
.2% Yield = 130,000 psi
.2% Creep In 600 Hours = 74,000 psi
Rupture Strength In 600 Hours = 110,000 psi

Figure 12

MAXIMUM STRESSES INDUCED IN HANGER SUPPORT SYSTEM
Configuration No. 3

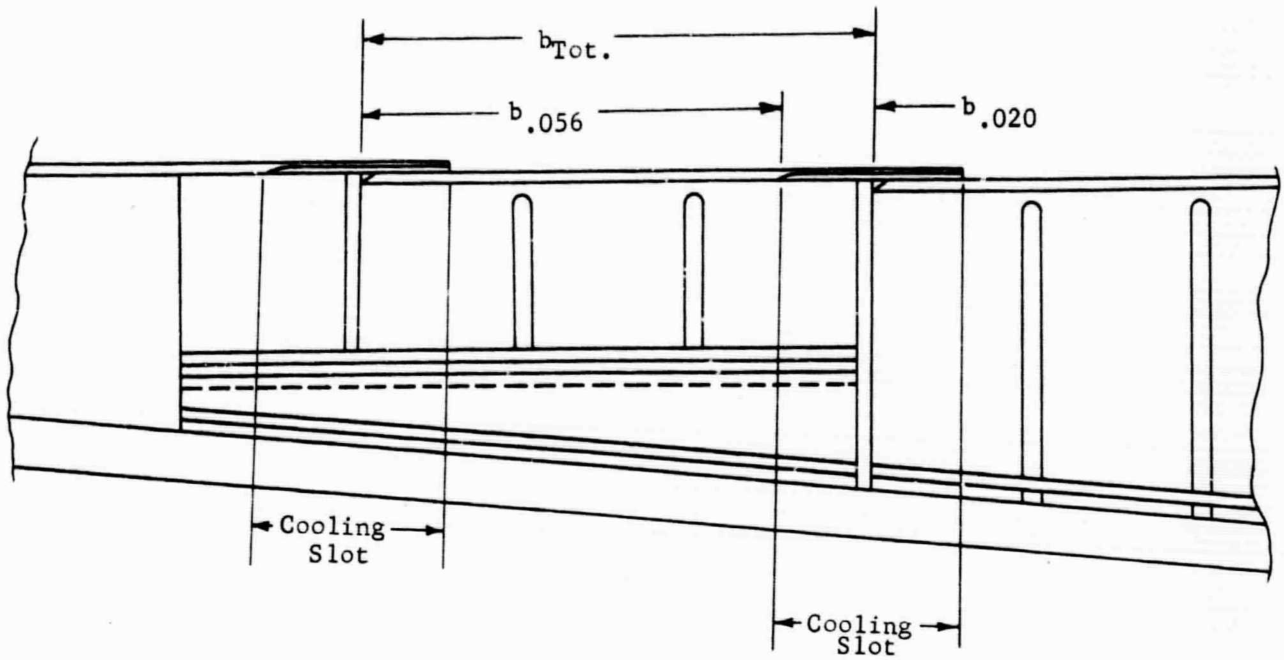


Hanger Material - WAD 7816

Average Temperature	**= 1200°F**
.2% Yield	**= 130,000 psi**
.2% Creep In 600 Hours	**= 74,000 psi**
Rupture Strength In 600 Hours	**= 110,000 psi**

Figure 13

STRESS ANALYSIS - SECTIONAL PROPERTIES AND IMPOSED LOADING



Segment Element No.	L in.	ΔP psi	Configuration 1 $b_{.056}$ in.	$b_{.020}$ in.	$b_{Tot.}$ in.	I x10^6 in.^4	Configuration 3 $b_{.056}$ in.	$b_{.020}$ in.	b_{Tot} in.	I x10^6 in.^4
1	4.18	2.79	2.1	0.50	2.60	31.03	2.3	0.46	2.76	33.91
2	4.30	4.21	2.13	0.48	2.61	31.52	2.3	0.50	2.80	33.93
3	4.46	5.68	3.75	0.60	4.35	55.2	-	-	-	-
4	4.88	5.00	1.08	0.50	1.58	16.13	1.1	0.47	1.57	16.41
5	5.32	5.88	1.15	0.50	1.65	17.16	1.15	0.50	1.65	17.12
6	5.80	6.70	-	-	-	23,190	-	-	-	23,190
7	3.99	2.65	2.0	0.50	2.50	29.66	2.0	0.40	2.40	29.57
8	4.00	3.55	2.2	0.46	2.66	32.51	2.52	0.50	3.02	37.23
9	4.01	4.46	3.44	0.48	3.92	50.51	-	-	-	-
10	4.01	4.92	1.48	0.43	1.91	21.99	1.40	0.50	1.90	20.83
11	3.98	5.83	1.38	0.50	1.88	20.53	1.35	0.50	1.85	20.08
12	3.95	6.71	2.25	0	2.25	32.9	2.25	0	2.25	32.9

Figure 14

RELATION OF TENSILE STRENGTH TO TEMPERATURE FOR .062 SHEET

Rene 41

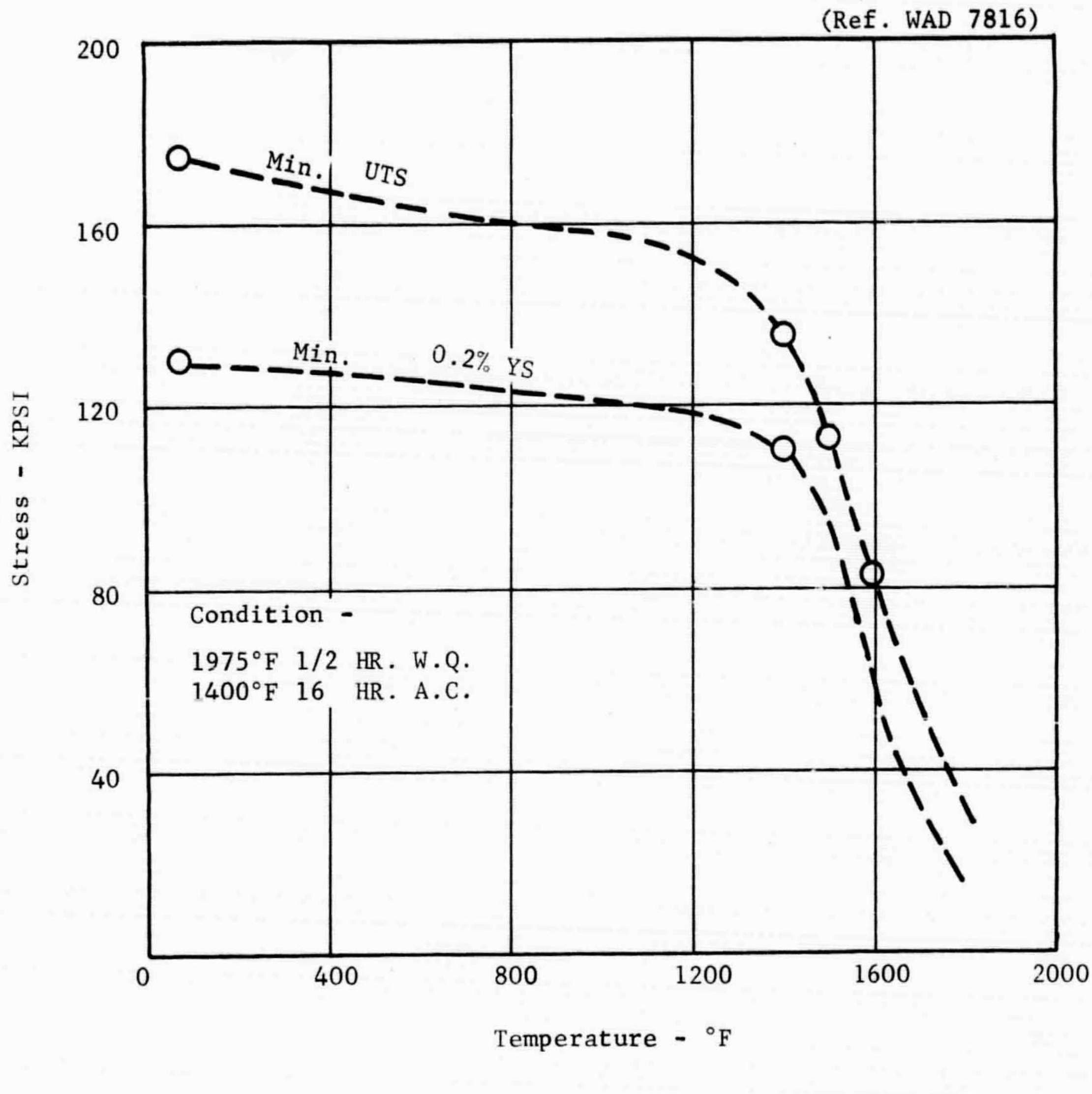


Figure 15

ISOTHERMAL STRESS-TME RELATION FOR STRESS RUPTURE

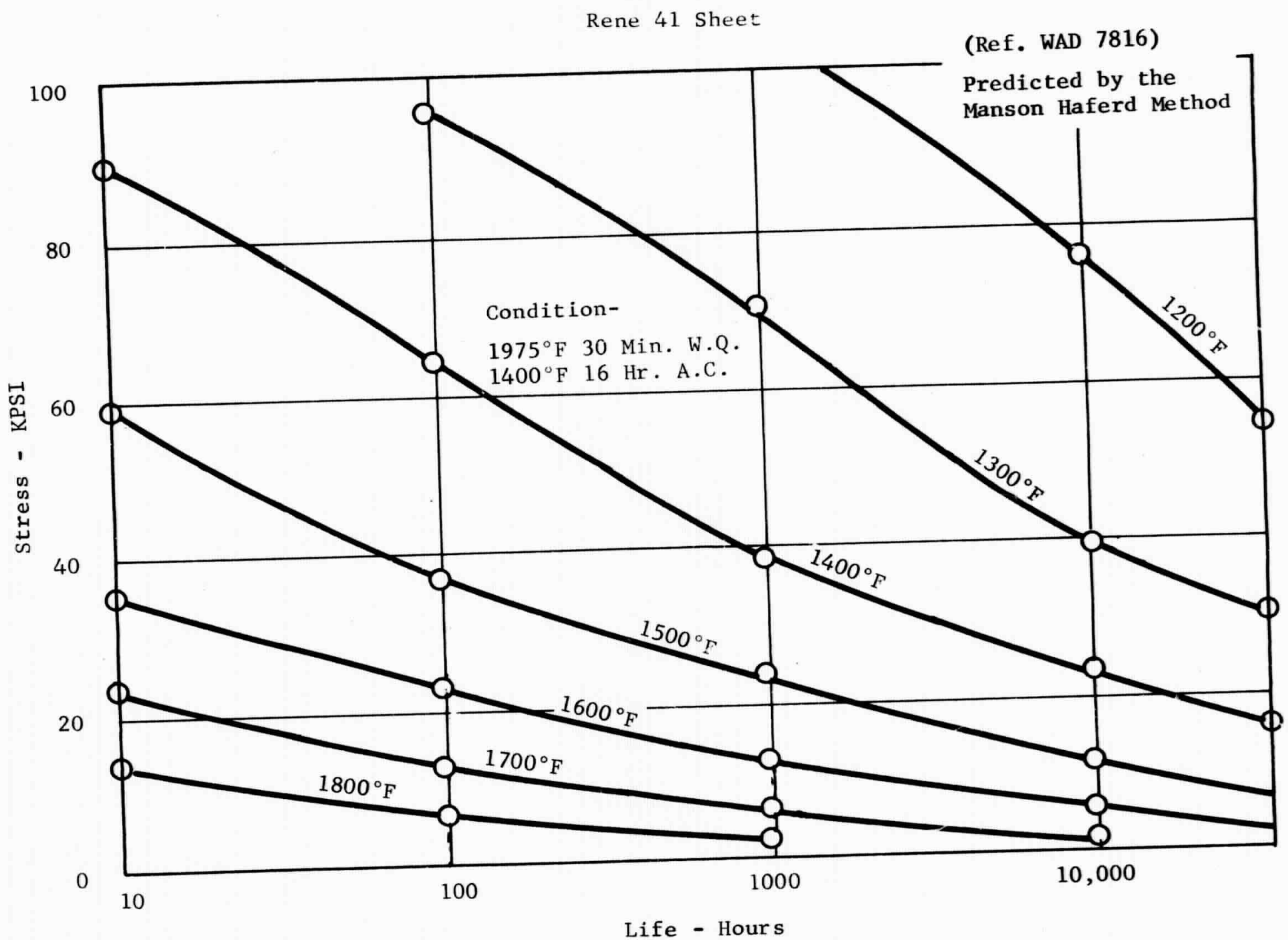


Figure 16

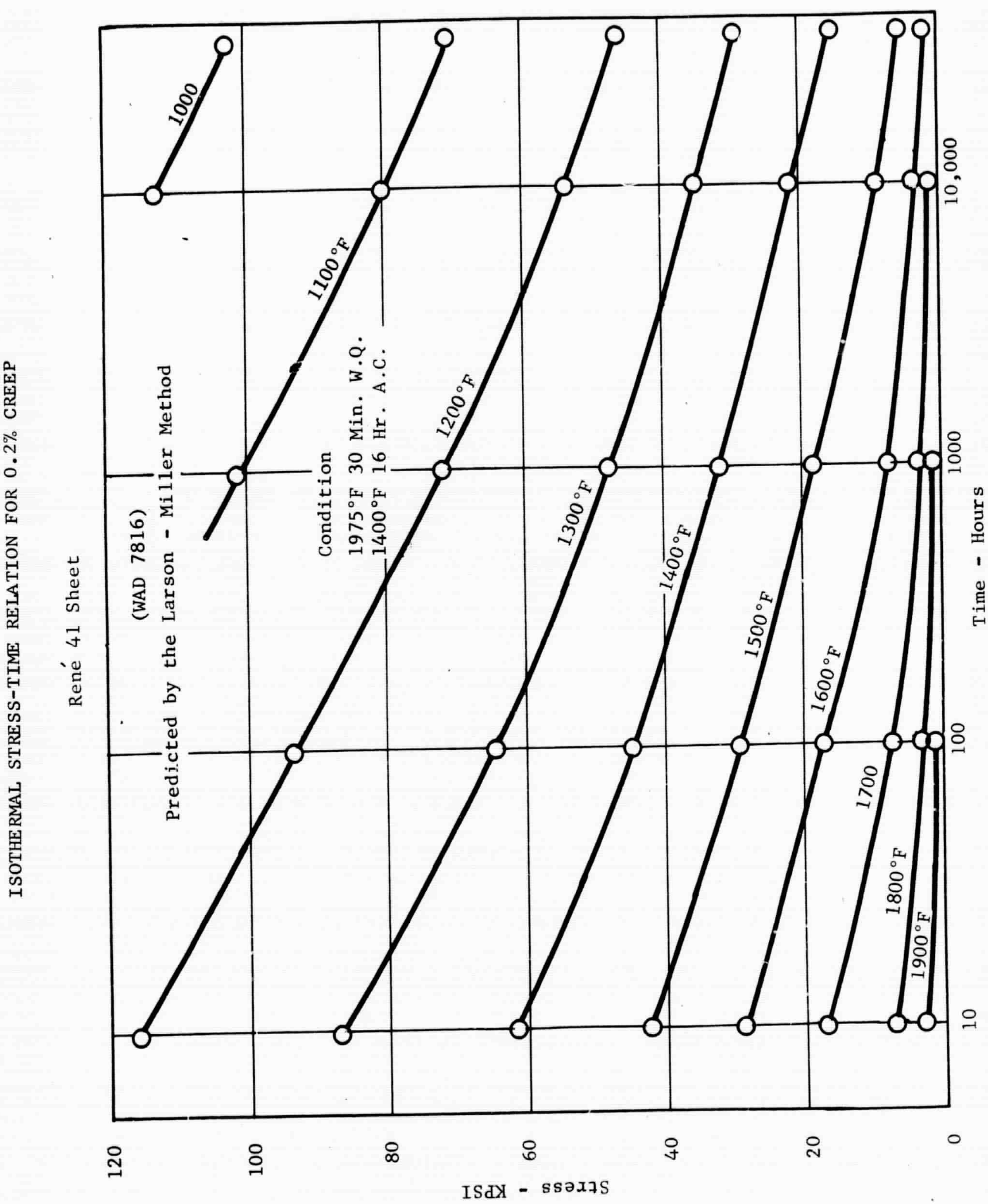

ISOTHERMAL STRESS-TIME RELATION FOR 0.2% CREEP
René 41 Sheet
(WAD 7816)
Predicted by the Larson - Miller Method
Condition
1975°F 30 Min. W.Q.
1400°F 16 Hr. A.C.
1000
1100°F
1200°F
1300°F
1400°F
1500°F
1600°F
1700
1800°F
1900°F
Stress - KPSI
0
20
40
60
80
100
120
Time - Hours
10
100
1000
10,000

Figure 17

SEGMENTED LINER TRANSIENT OPERATION

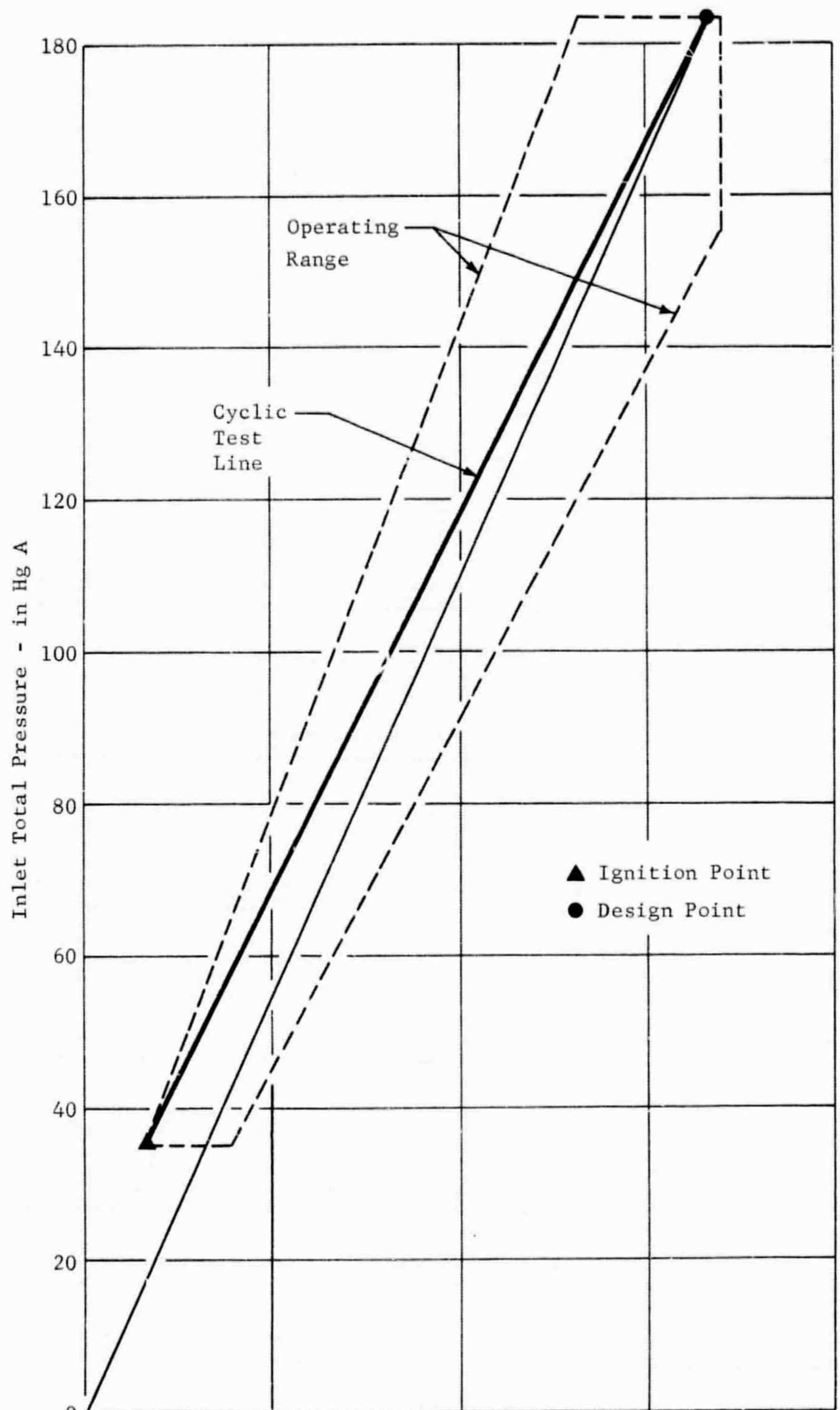


Figure 18

SEGMENTED LINER TRANSIENT OPERATION

Inlet Conditions

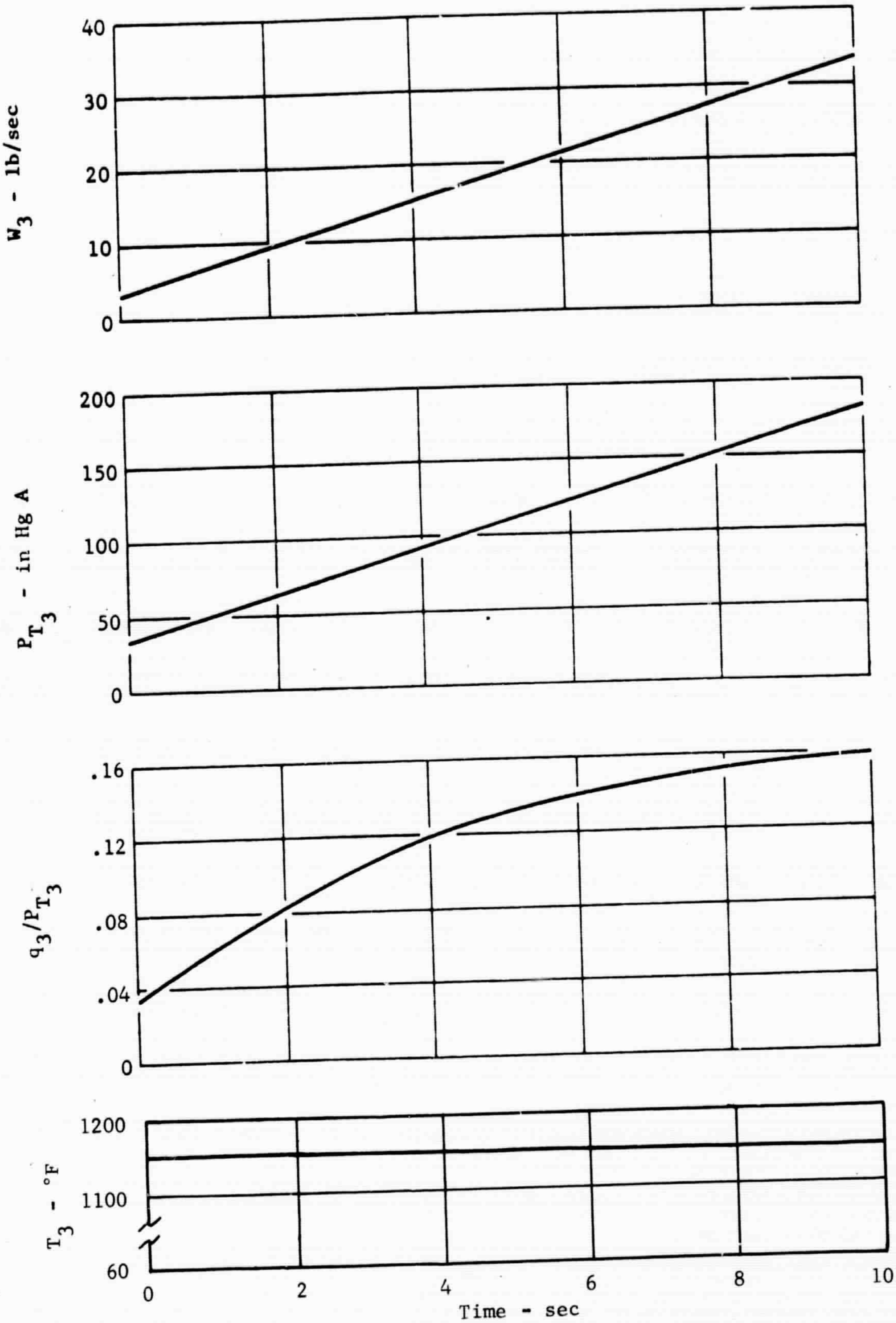
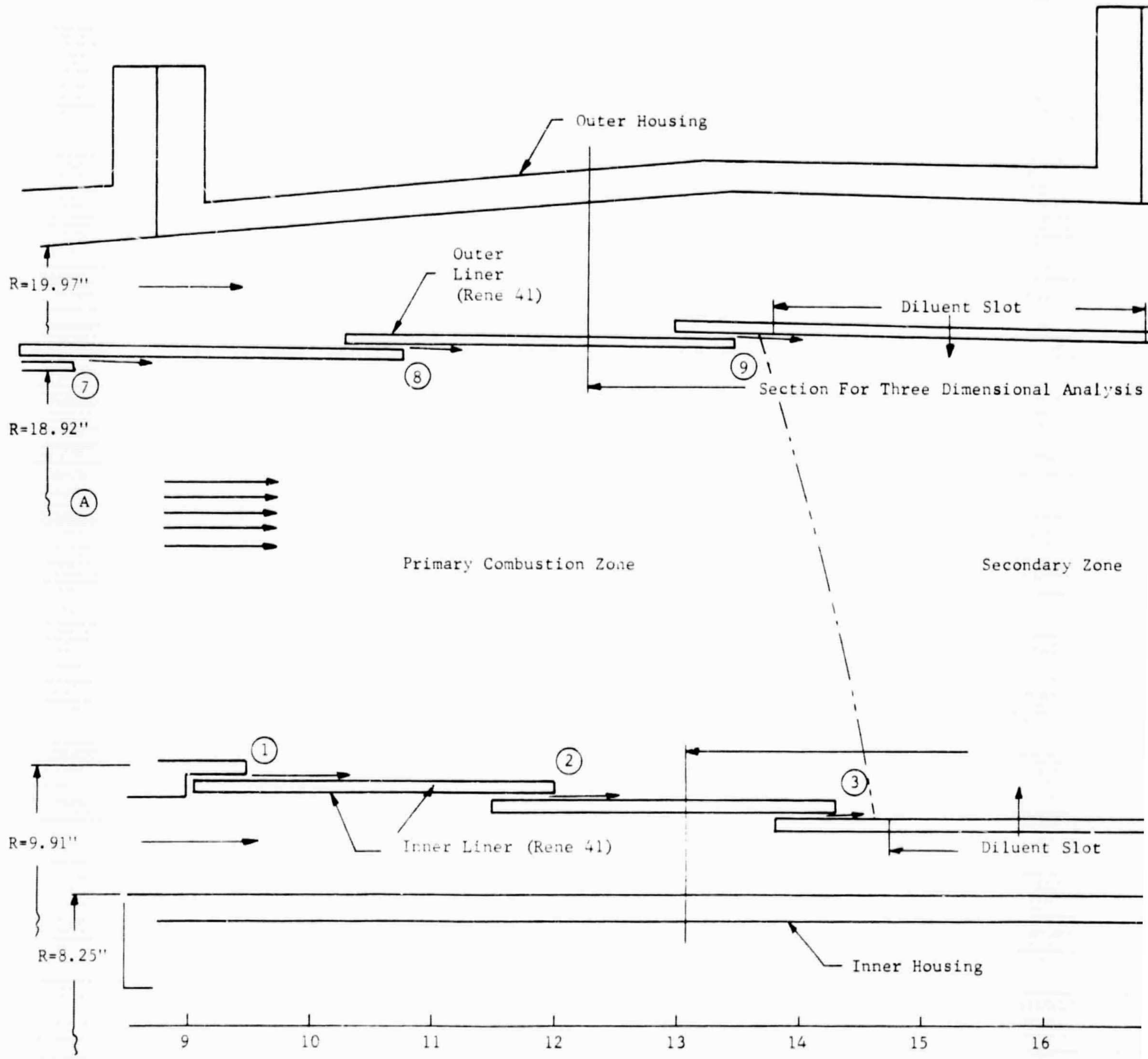


Figure 19

TRANSIENT HEAT TRANSFER ANALYSIS - COMBUS



Axial Distance From Compressor Exit Gu

68-3279

FOLDOUT FRAME 1

S - COMBUSTOR LINERS AND HOUSINGS

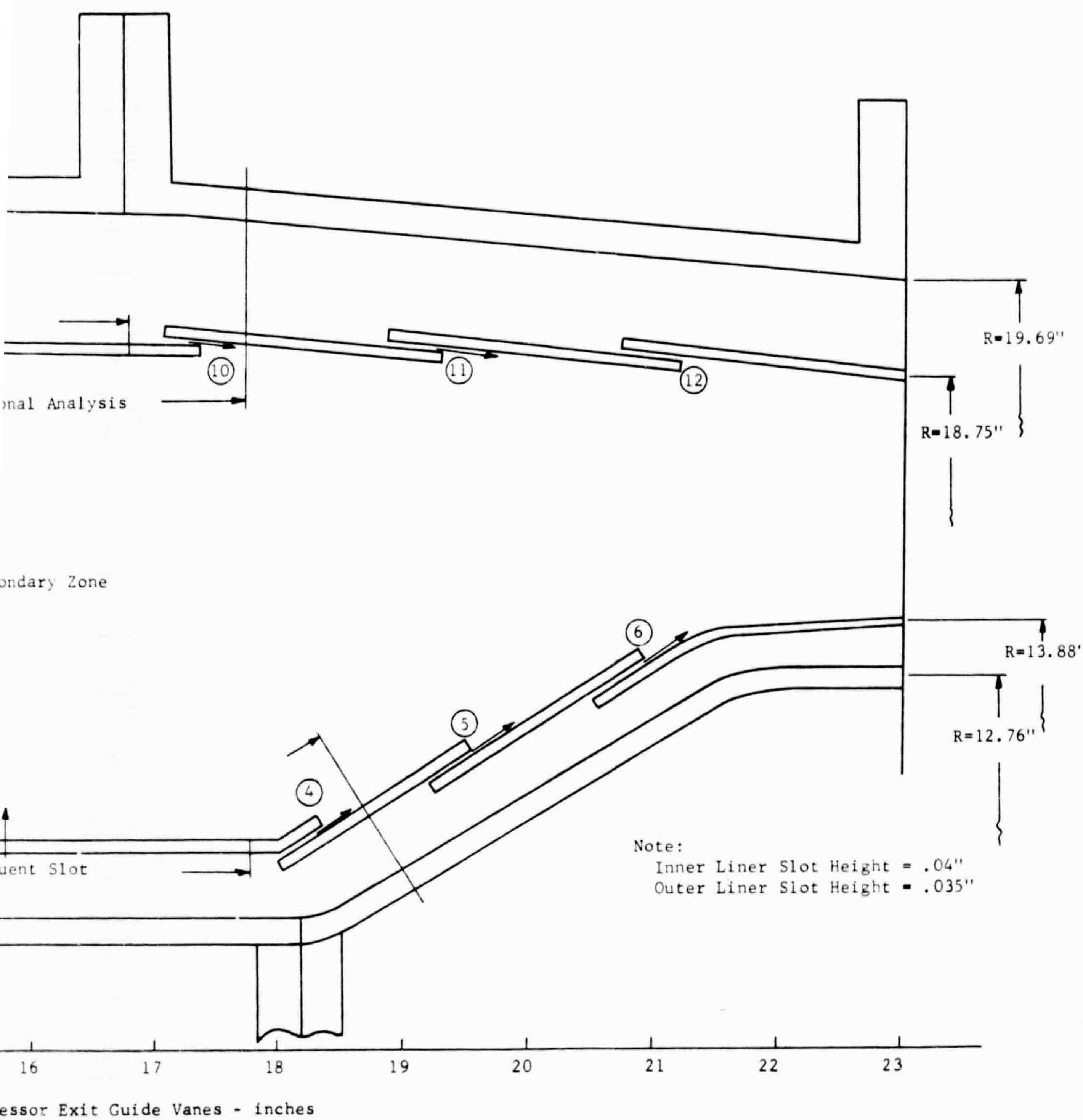


Figure 20

A two dimensional transient analysis was first conducted to obtain longitudinal temperature distributions from the headplate to the combustor exit in a plane midway between the diluent slots. The results of this analysis are presented in Figures 21 through 24. The analysis was then extended circumferentially in the area of the diluent slots, where the thermal environment is the most severe. The analyses encompassed the combustor liners, liner supports, hangers and housings for both liner configurations, and extended circumferentially from the longitudinal centerline of one diluent slot, to the longitudinal centerline of the next adjacent diluent slot. This area has been indicated in Figure 20.

Configuration No. 1 outer liner assembly is shown in Figure 25. The node points at which the temperatures were determined for this outer liner assembly are shown on the detail pieces and the temperatures at each node point are tabulated in Table II. Data for the Configuration 1 inner liner and the Configuration 3 liners are presented in a similar manner. The following is a summary of this data:

Configuration	Node Point Location	Temperature Data
1 - Outer	Figure 25	Table II
3 - Outer	Figure 26	Table III
1 - Inner	Figure 27	Table IV
3 - Inner	Figure 28	Table V

This analysis indicated that temperature gradients in the circumferential direction are small relative to the longitudinal temperature gradients computed in the two dimensional analysis.

3.3 Combustor Design and Performance Analysis

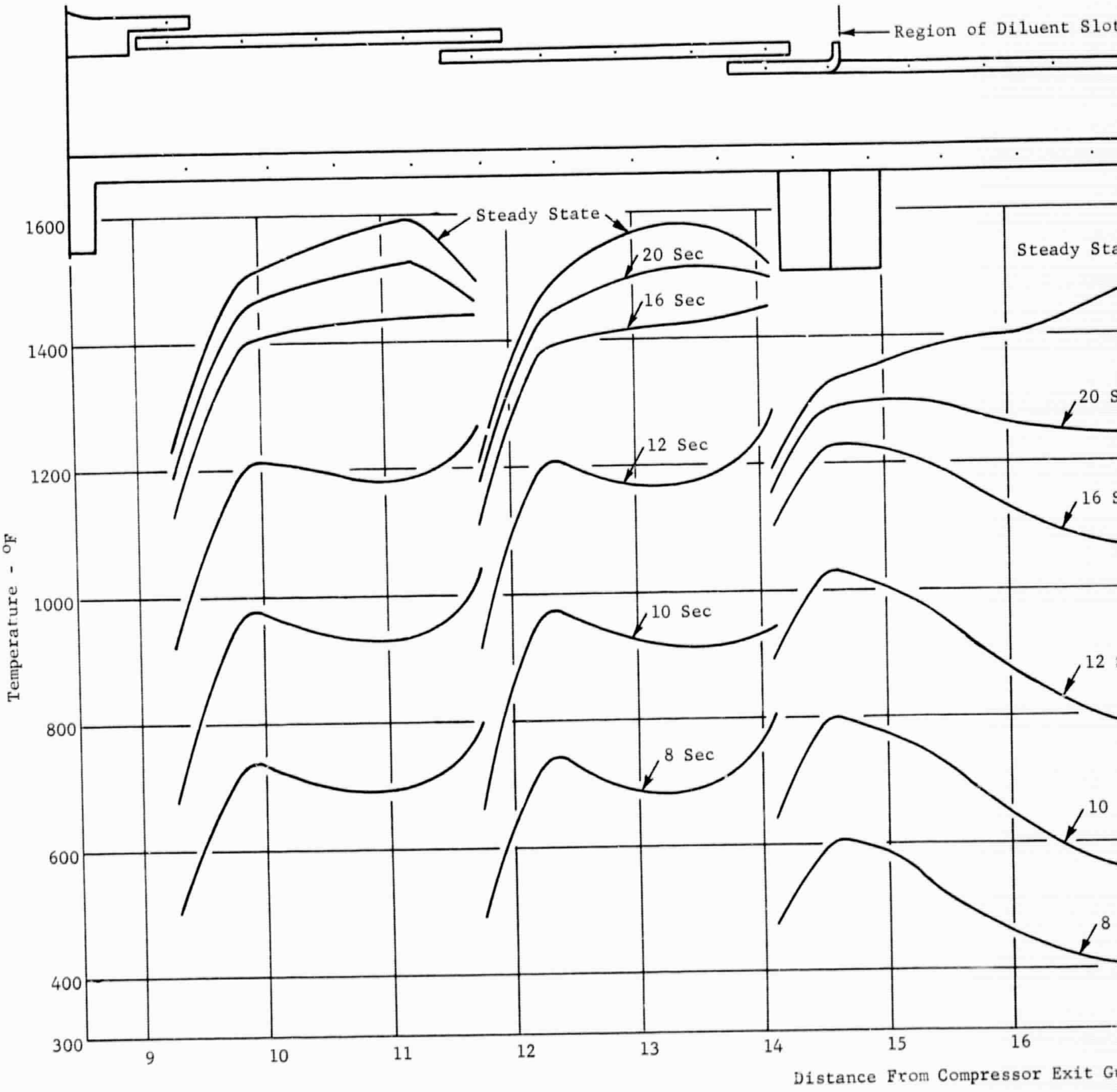
An annular vaporizing type combustor was utilized in the sector test rig. A table of the combustor operating conditions, design performance, and significant dimensions is presented in Figure 2. A more detailed description of the design geometry and performance is contained in the subsequent paragraphs.

A sketch of the airflow split and the aerodynamic contours of the combustor system is shown in Figure 29. The system includes an inlet diffuser section

TRANSIENT TEMPERATURE DISTRIBUTION OF INNER LINER SEGM

8 SECONDS TO STEADY STATE

Two-Dimensional Analysis



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NNER LINER SEGMENTS VS. AXIAL DISTANCE

STEADY STATE

nal Analysis

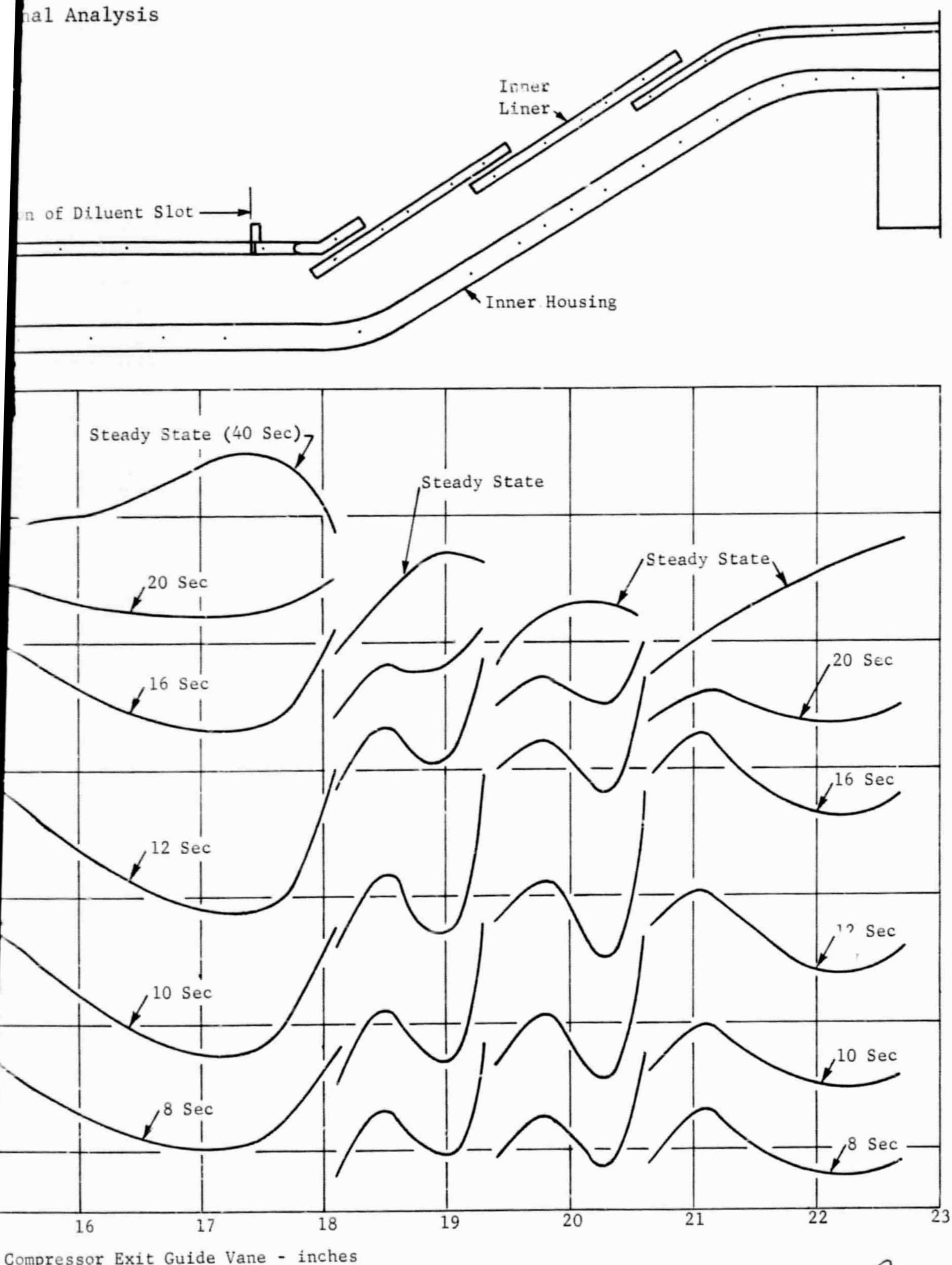

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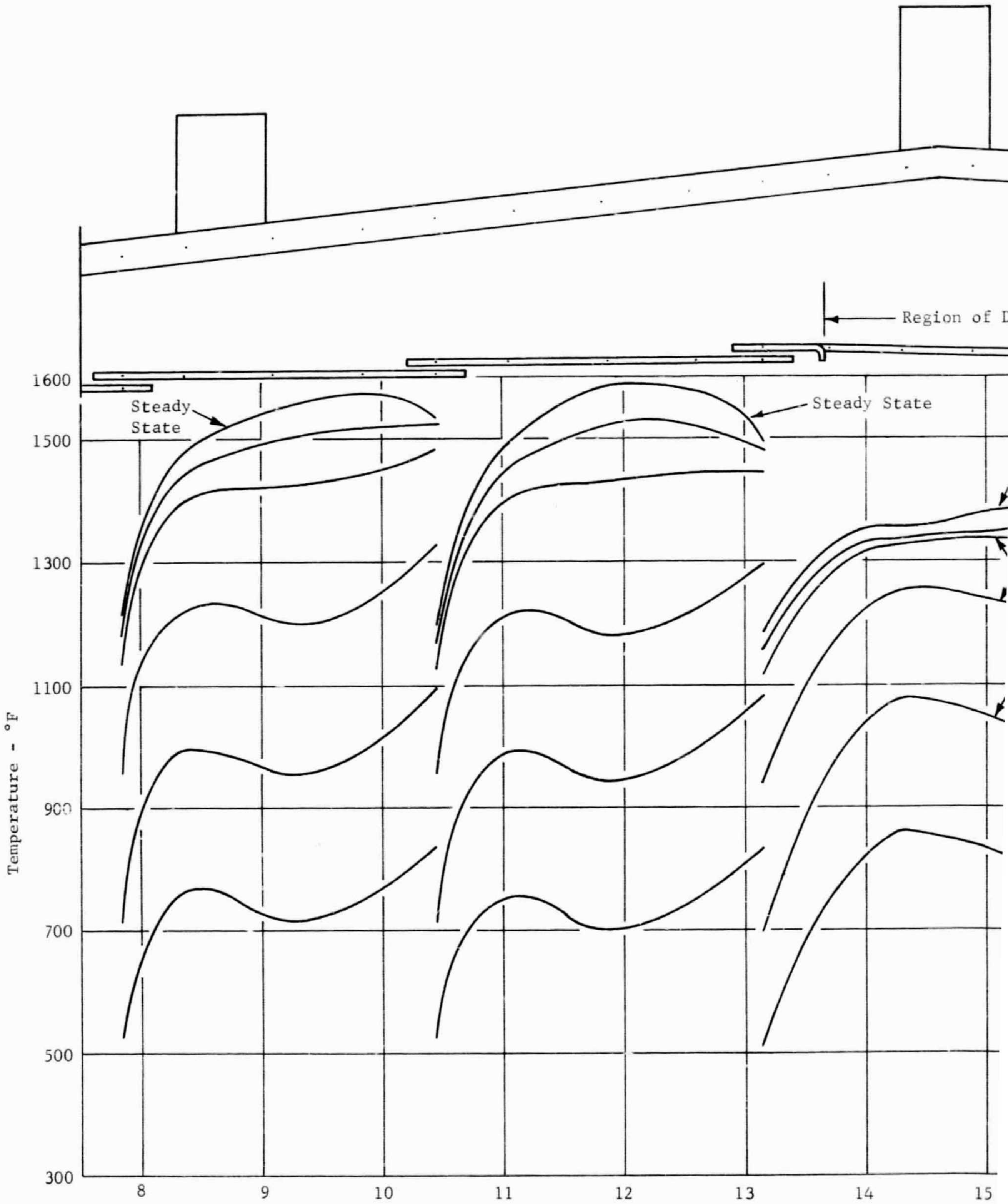
Figure 21

TRANSIENT TEMPERATURE DISTRIBUTION OF OUTE

8 SECONDS TO STEAI

Two Dimensional a



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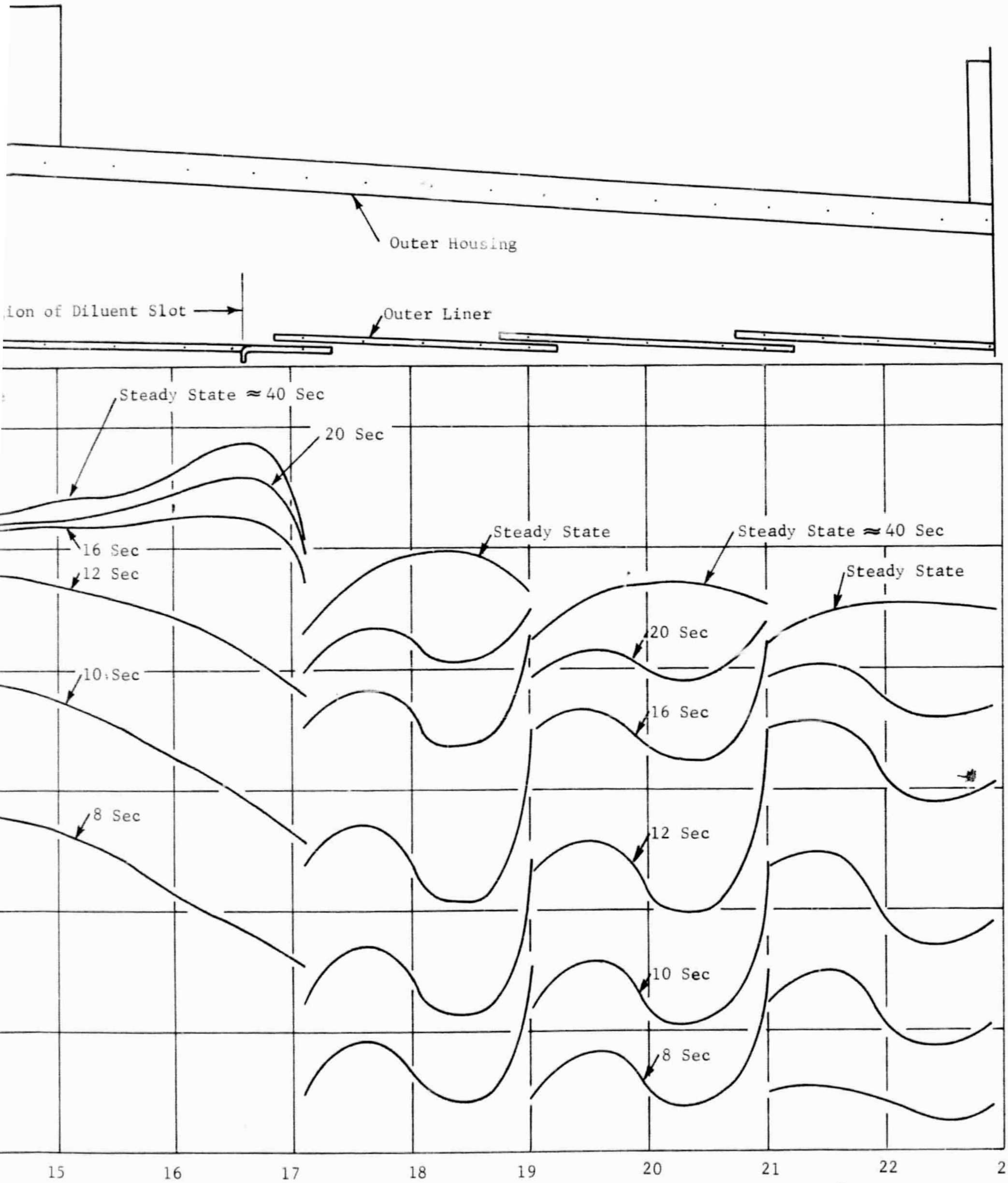
F OUTER LINER SEGMENTS VS AXIAL DISTANCE

) STEADY STATE

.onal analysis



om Compressor Guide Vane - inches

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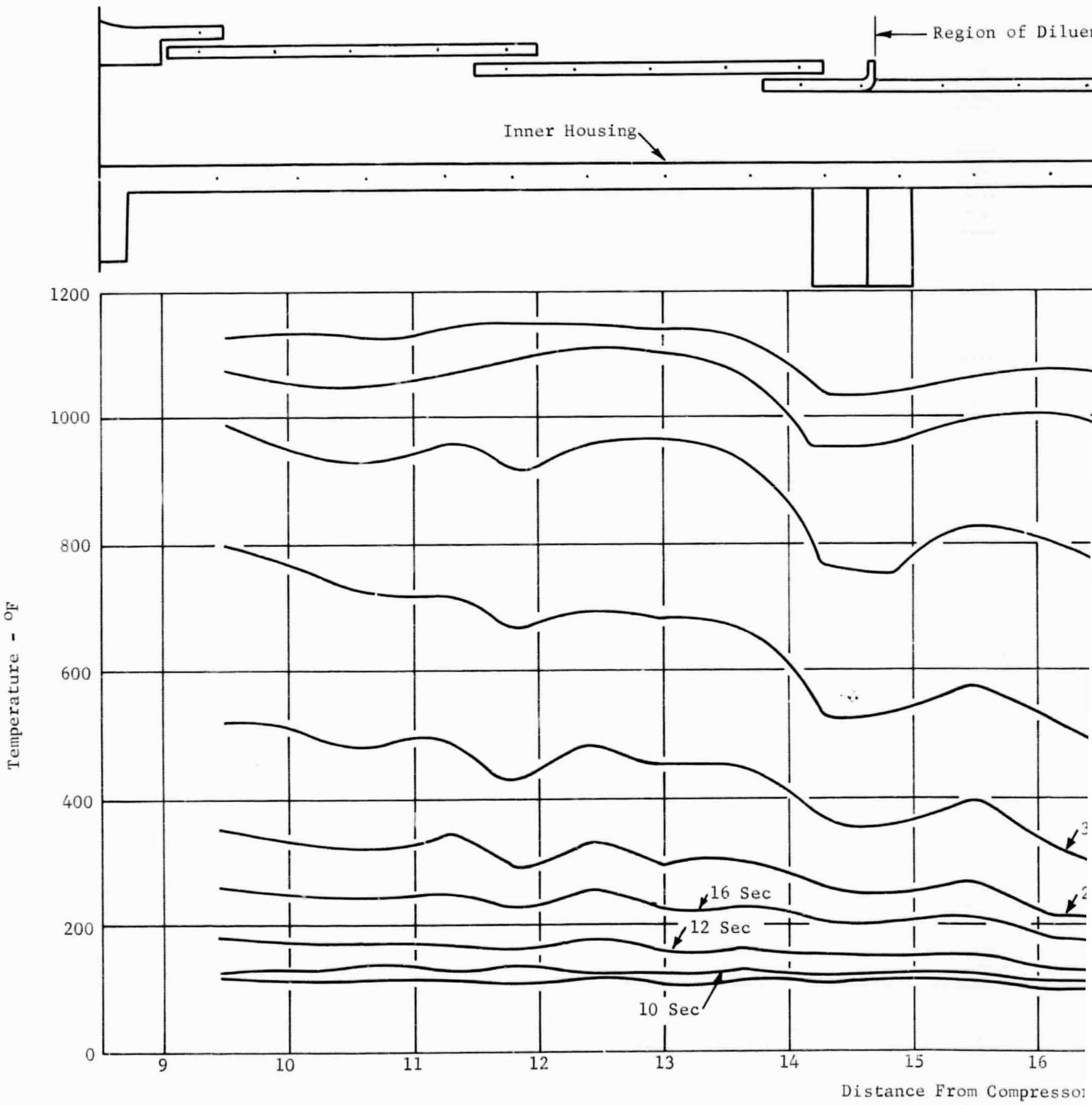
Figure 22

TRANSIENT TEMPERATURE DISTRIBUTION OF INNER HOU

8 SECONDS TO STEADY STAT

Two Dimensional Analysi



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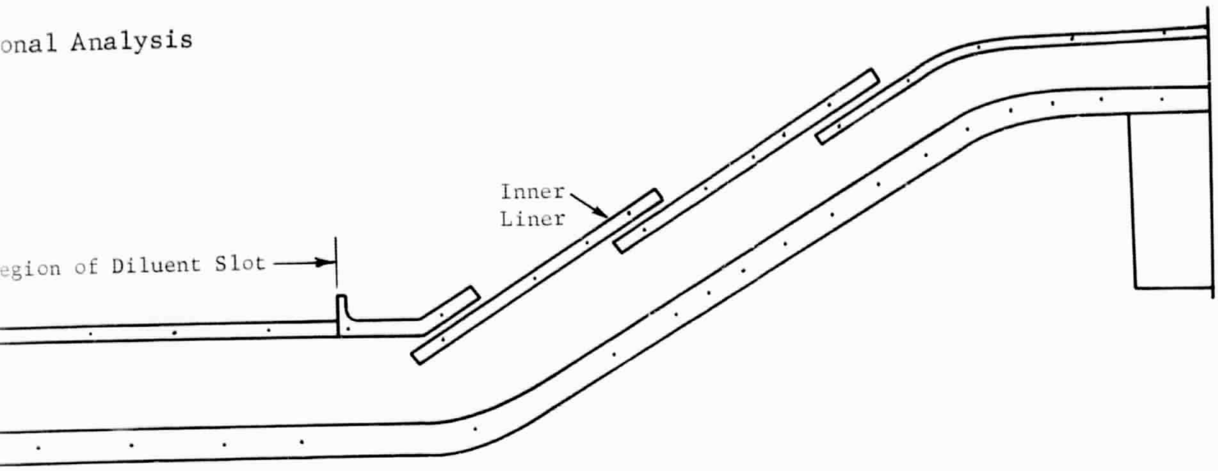
16-077

OF INNER HOUSING VS AXIAL DISTANCE

) STEADY STATE

onal Analysis



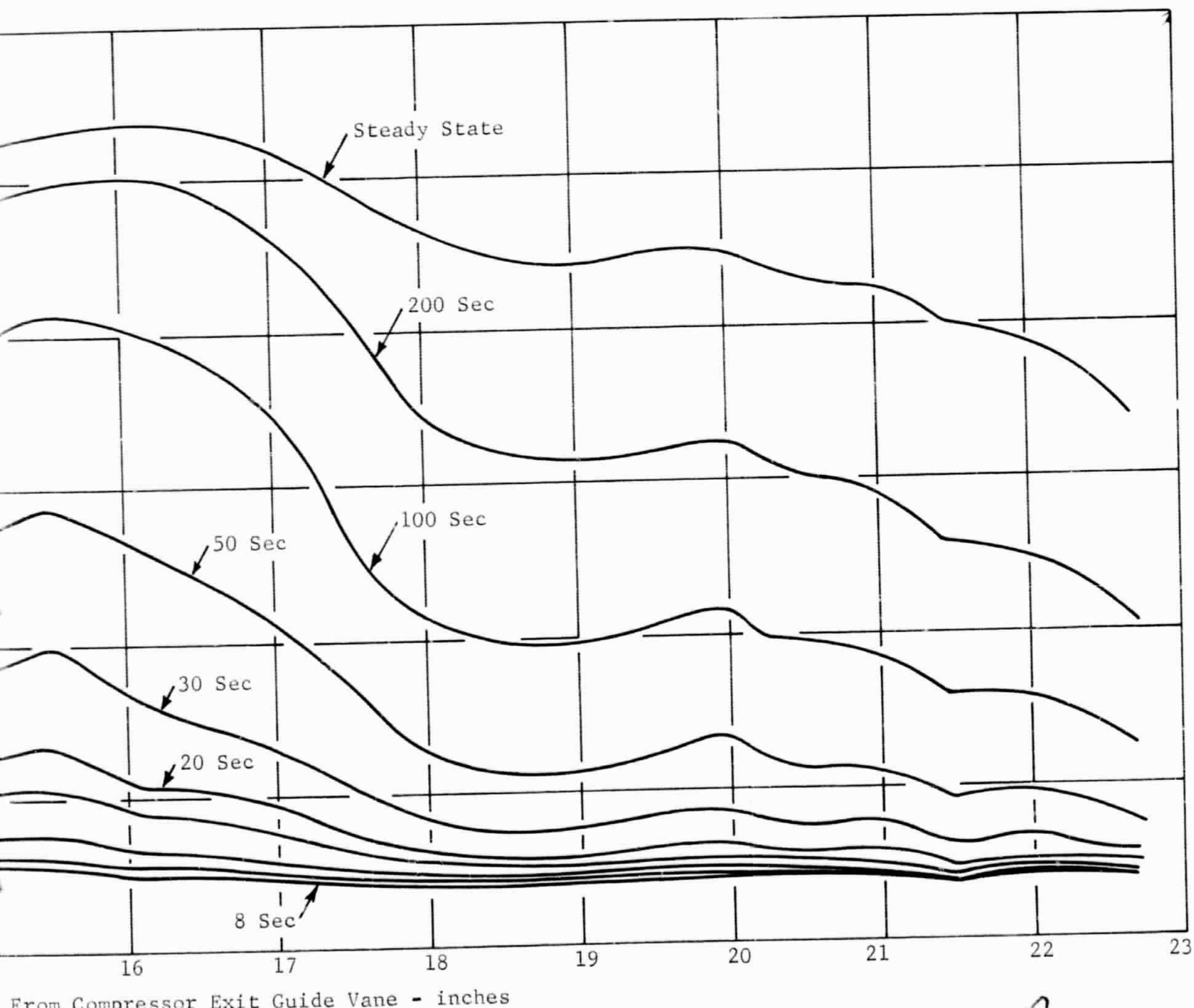


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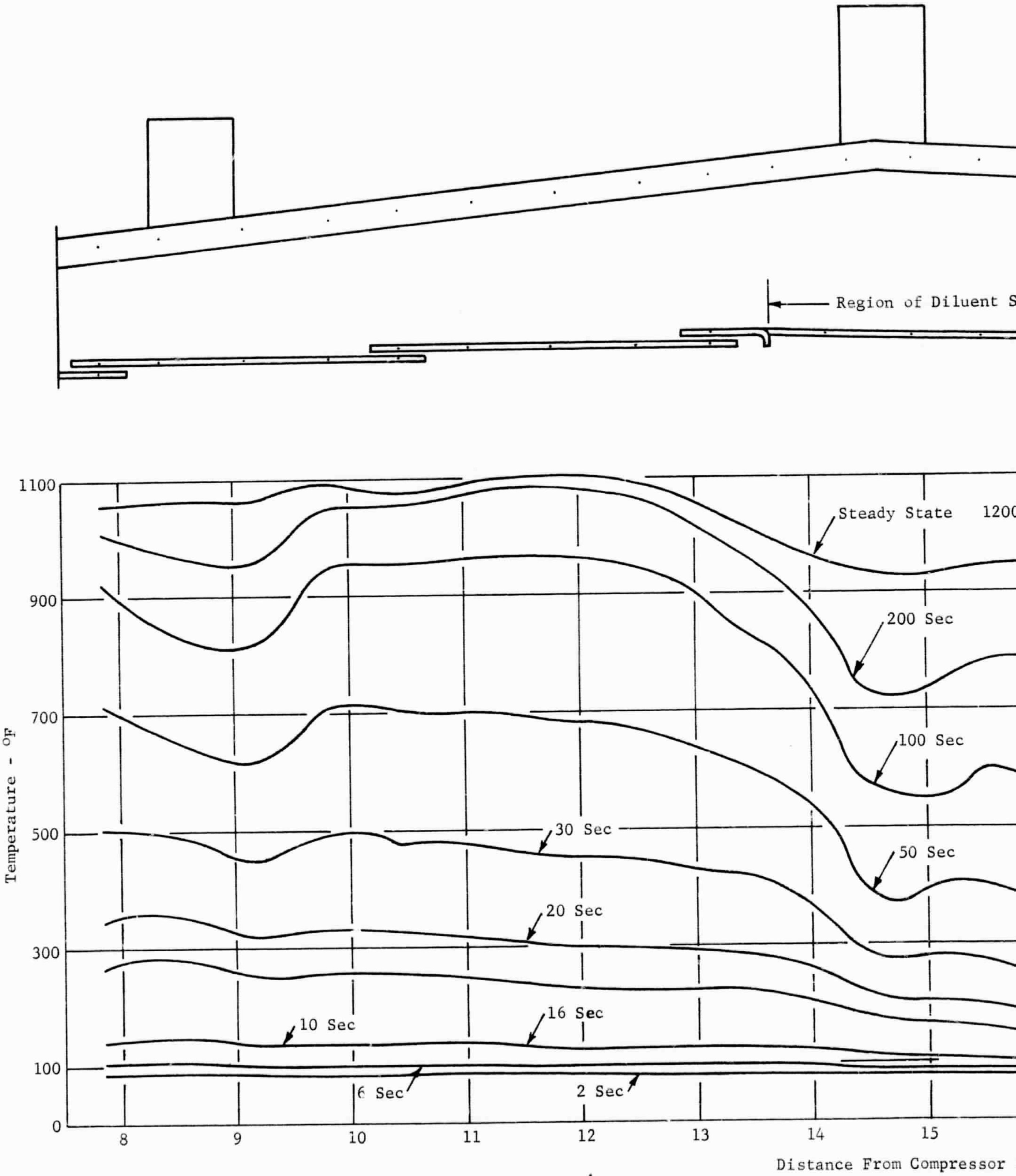
Figure 23

TRANSIENT TEMPERATURE DISTRIBUTION OF OUTE

IGNITION TO STEADY

Two-Dimensional



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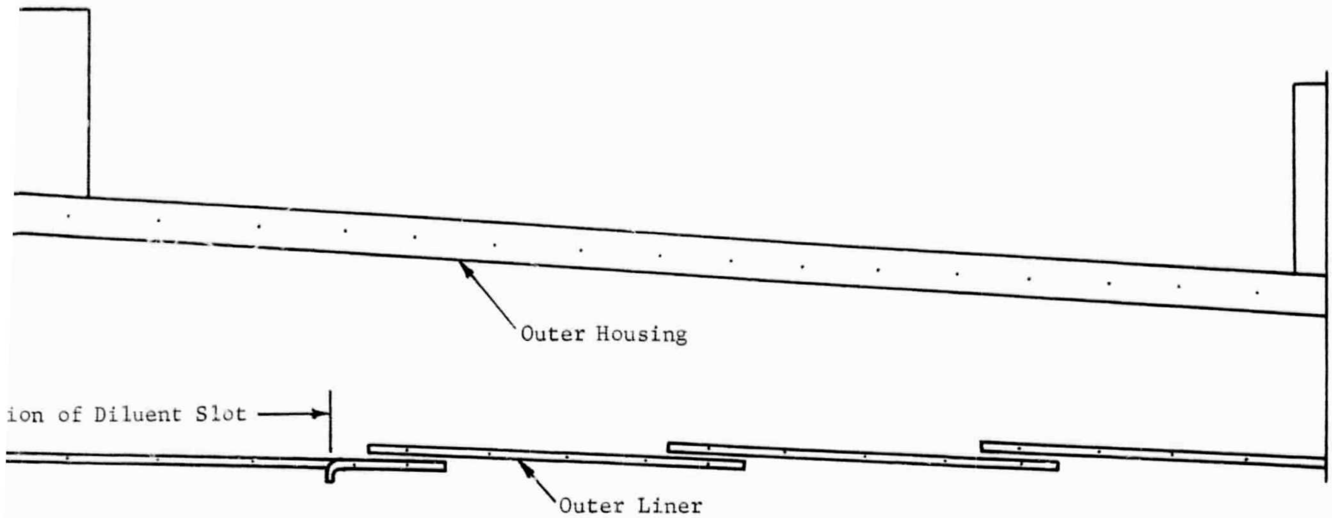
16-091

UTION OF OUTER HOUSING VS. AXIAL DISTANCE

ION TO STEADY STATE

-Dimensional Analysis



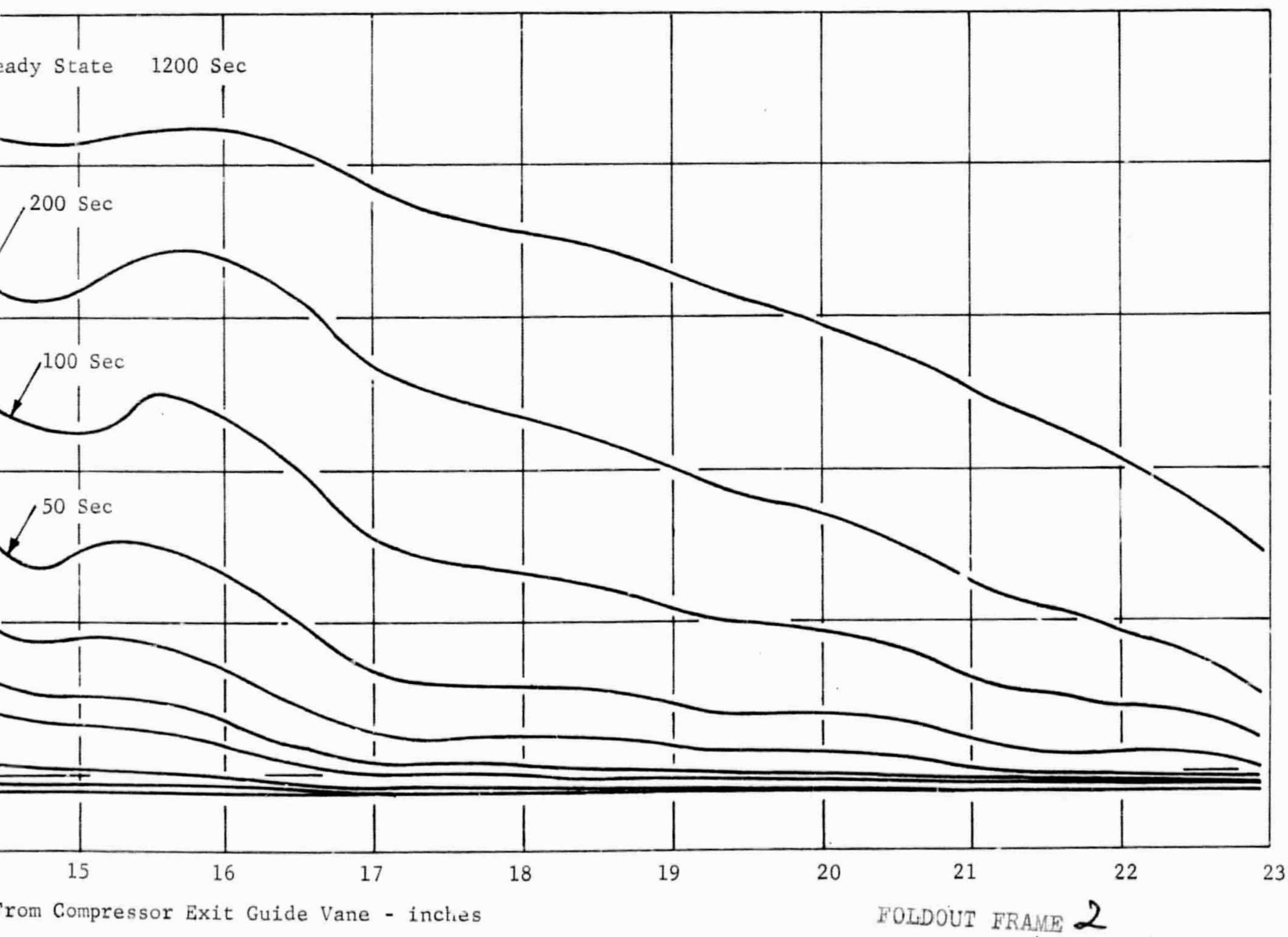


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Figure 24

OUTER LINER HEAT TRANSFER ANALYSIS
NODE POINT LOCATIONS
CONFIGURATION NO. 1

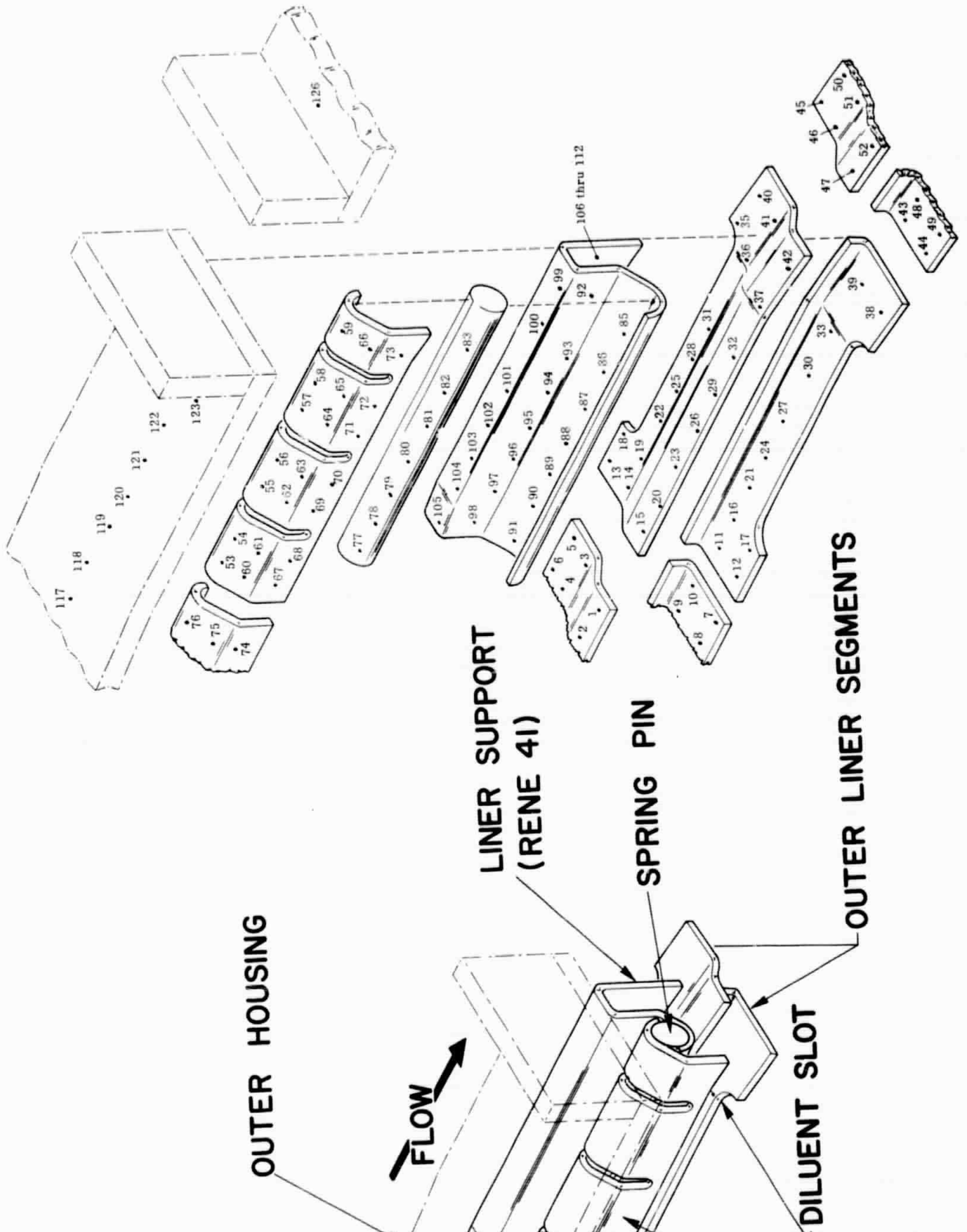


Figure 25

OUTER LINER HEAT TRANSFER ANALYSIS
NODE POINT LOCATIONS
CONFIGURATION NO. 3

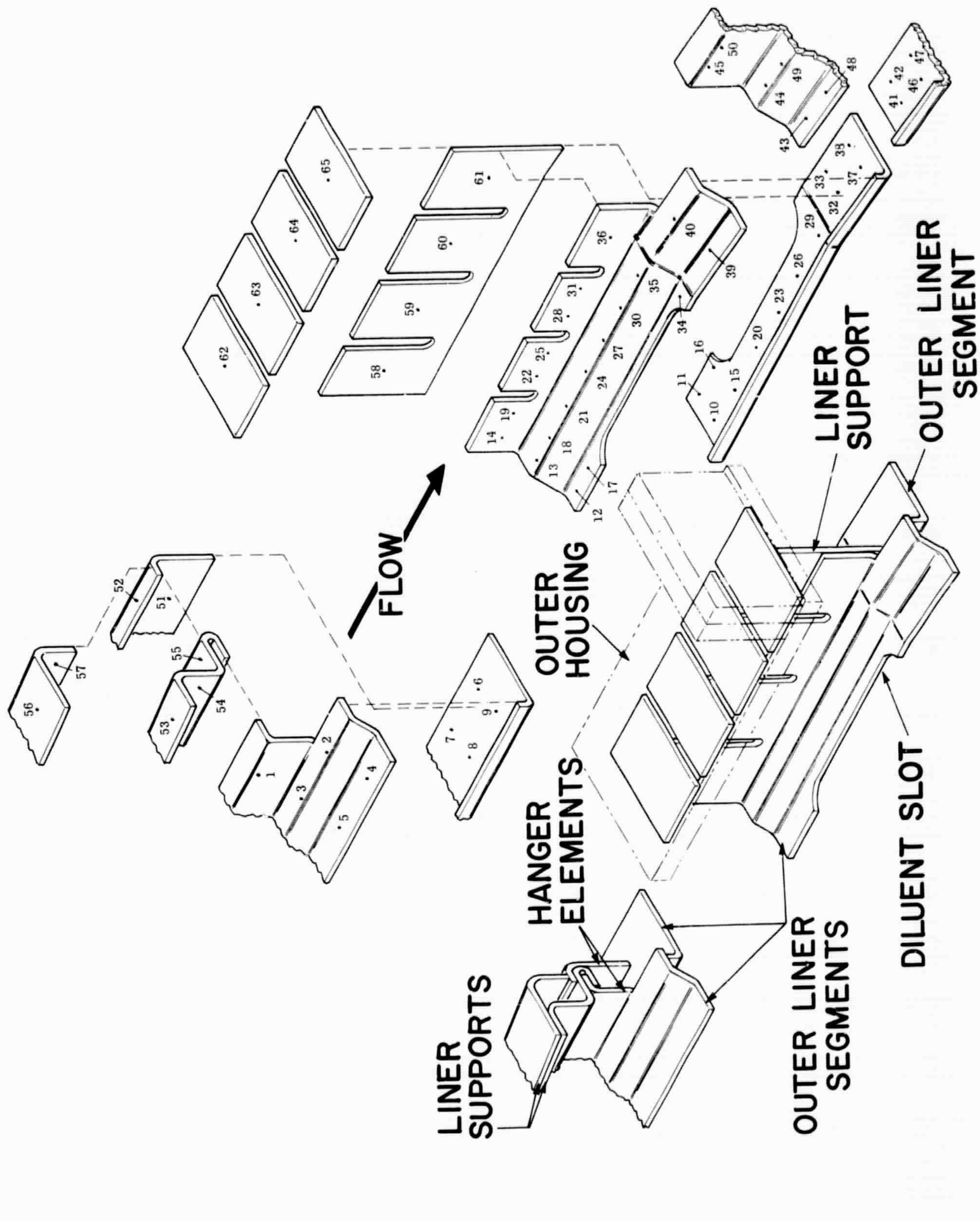


Figure 26

INNER LINER HEAT TRANSFER ANALYSIS
NODE POINT LOCATIONS
CONFIGURATION NO. 1

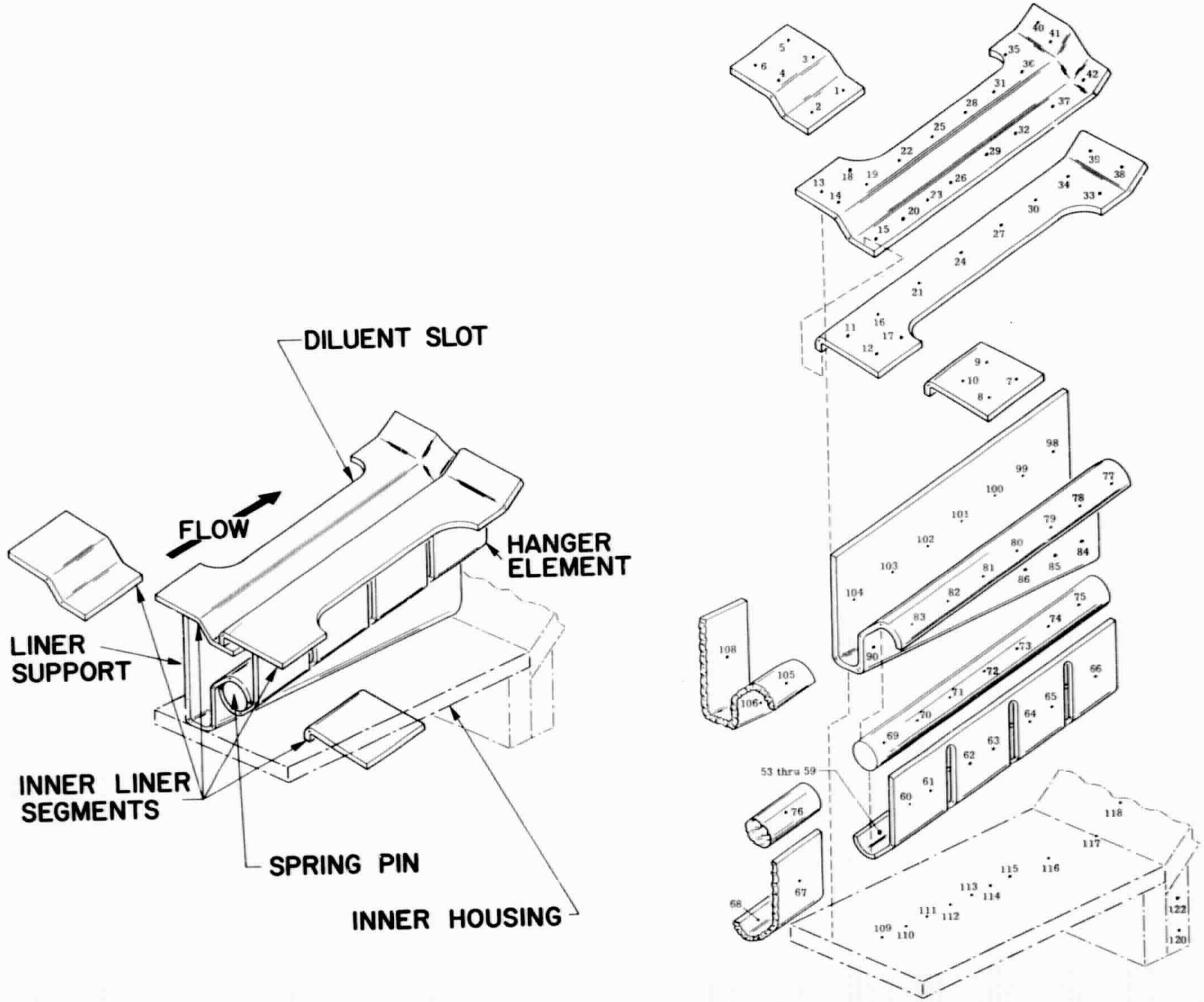


Figure 27

INNER LINER HEAT TRANSFER ANALYSIS
NODE POINT LOCATIONS
CONFIGURATION NO. 3

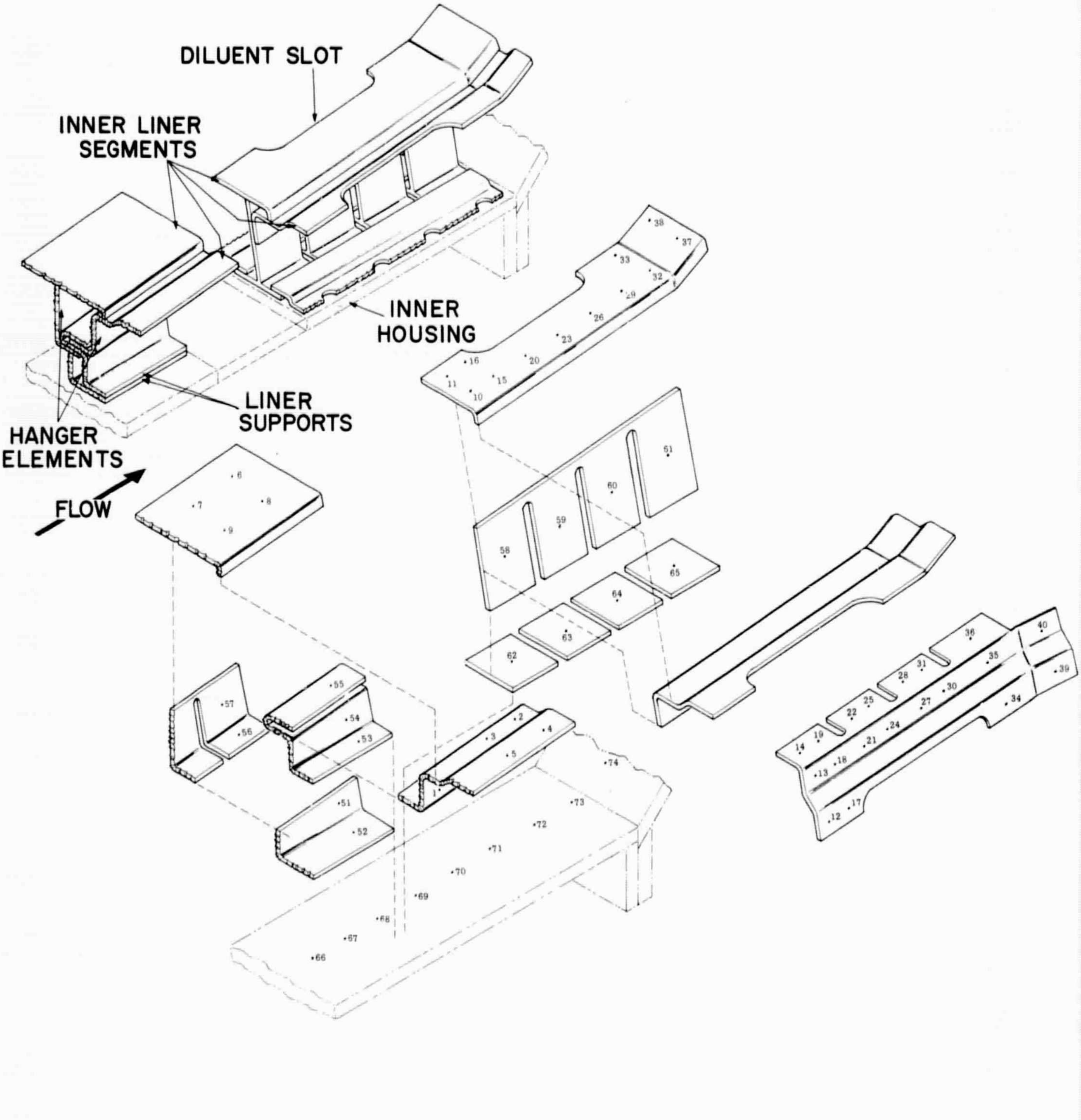


Figure 28

AERODYNAMIC CONTOURS AND DESIGN WEIGHT FLOW SPLIT

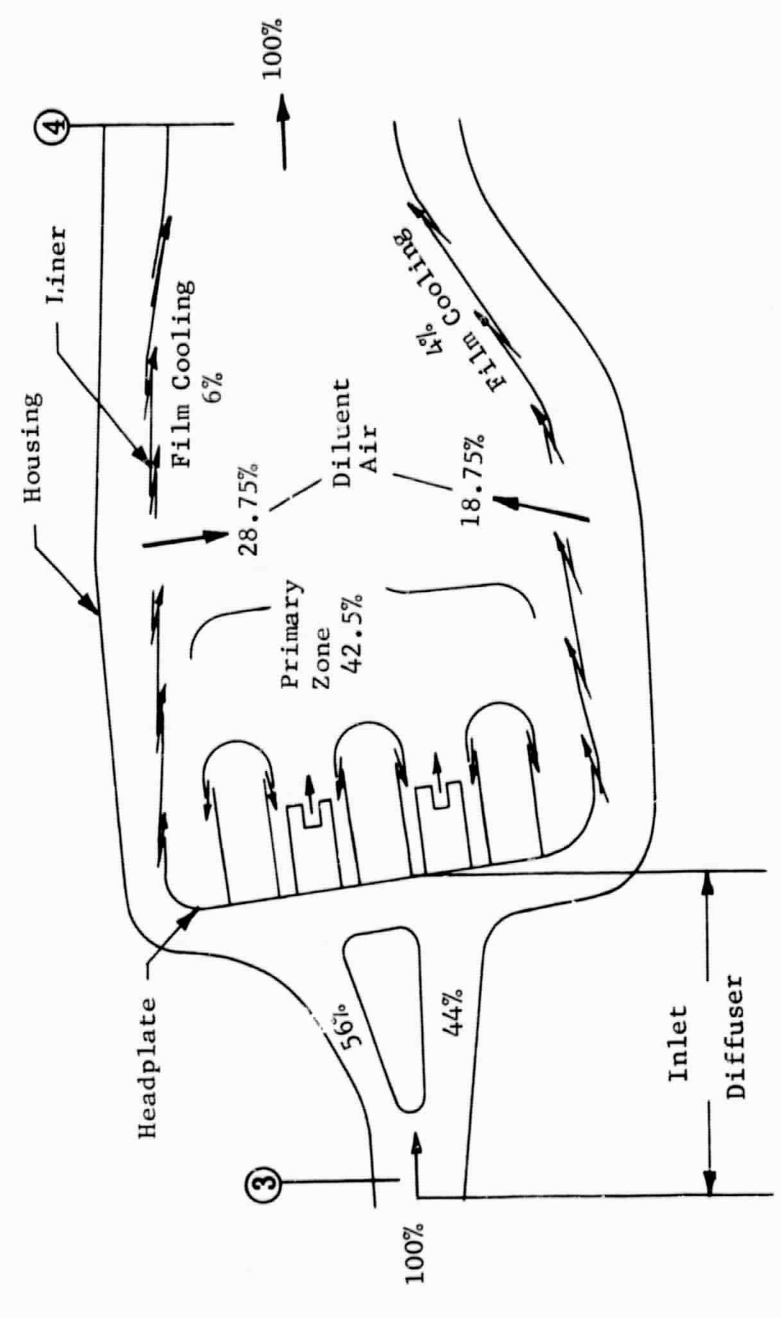
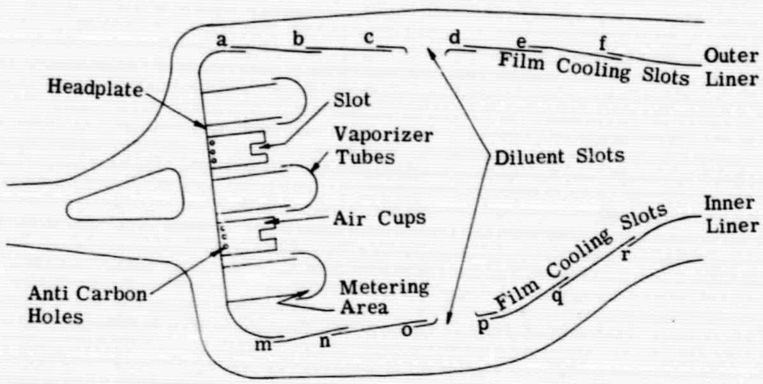


Figure 29

and the combustion chamber proper. Air entering the diffuser section is divided into two concentric annular streams and is diffused through an area ratio of approximately 2:1. The air diffuses to a lower velocity and is delivered against the vaporizer headplate, which is located normal to the diffuser exit. All of the air required for combustion enters the combustion chamber through fuel vaporizer tubes and air metering orifices (aircups) in the headplate. The balance of the air leaving the diffuser section bypasses the headplate, and undergoes additional diffusion as it flows through the annular passages formed by the combustion chamber liners and housings. Part of this air is used to cool the liners, and the remainder is injected into the flow of combustion products as a diluent after combustion is completed. Liner cooling air is introduced through annular slots located strategically along the length of the liners, thereby providing a recurring fresh sheet of film cooling air. A detailed tabulation of the combustion chamber metering areas and airflow distribution is presented in Figure 30.

The primary zone headplate geometry is shown in Figure 31. Externally metered fuel is delivered through individual feed tubes inserted tangentially into the inlets of the vaporizer tubes. The fuel velocity leaving the feed tube is low and helical, to assure complete wetting of the inside diameter of the fuel tube. The fuel is pre-mixed with air inside the vaporizer tube, and this mixture is heated by the combustion process surrounding the tube. The mixture is injected into the primary zone in the upstream direction (toward the headplate) through the metering area at the exit of the tube. The major portion of the primary air enters the combustion chamber through slotted primary aircups also located in the headplate. The fan-shaped air jets issuing axially from the primary aircups divide the flow into sectors, and create a degree of coarseness in the fuel-air mixture within the primary zone that provides combustion stability over a wide operating range. Air for combustion is continually available as required along the edge of these axial jets. The number or pitch of the primary aircups was the determining factor in establishing the length of the primary zone, since mixing requirements were more stringent than residence time requirements. Ignition is accomplished by means of a spark ignitor and primer fuel injector projecting through the outer liner into the primary zone.

DESIGN AIR FLOW DIVISION AND METERING AREAS



AIR PASSAGE	AREA		WEIGHT FLOW	
	Actual - in^2	Effective - in^2	% Wt Total	Wt lb/sec @ Design Point
OUTER LINER	141.90	85.14	33.75	48.26
Diluent Slots	118.20	70.92	27.60	39.46
Film Cooling Slots	23.70	14.22	6.15	8.80
a	3.93	2.36	1.01	1.45
b	3.94	2.36	1.03	1.47
c	3.96	2.38	1.03	1.48
d	3.97	2.38	.97	1.38
e	3.96	2.38	1.03	1.48
f	3.94	2.36	1.08	1.54
INNER LINER	96.61	57.97	23.75	33.96
Diluent Slots	81.06	48.64	19.67	28.13
Film Cooling Slots	15.55	9.33	4.08	5.83
m	2.30	1.38	.610	.871
n	2.37	1.42	.632	.907
o	2.43	1.46	.649	.927
p	2.57	1.54	.630	.899
q	2.82	1.69	.727	1.04
r	3.06	1.84	.832	1.19
HEADPLATE	158.10	94.86	42.50	60.78
Vaporizer Tubes	43.88	26.33	10.66	15.25
Air Cups	114.22	68.53	31.84	45.53
Slot	93.45	56.07	26.84	38.38
Anti Carbon Holes	20.77	12.46	5.00	7.15
COMBUSTOR TOTAL	396.61	237.97	100%	143.00

Revised 11/1/65

Figure 30

PRIMARY ZONE HEADPLATE GEOMETRY

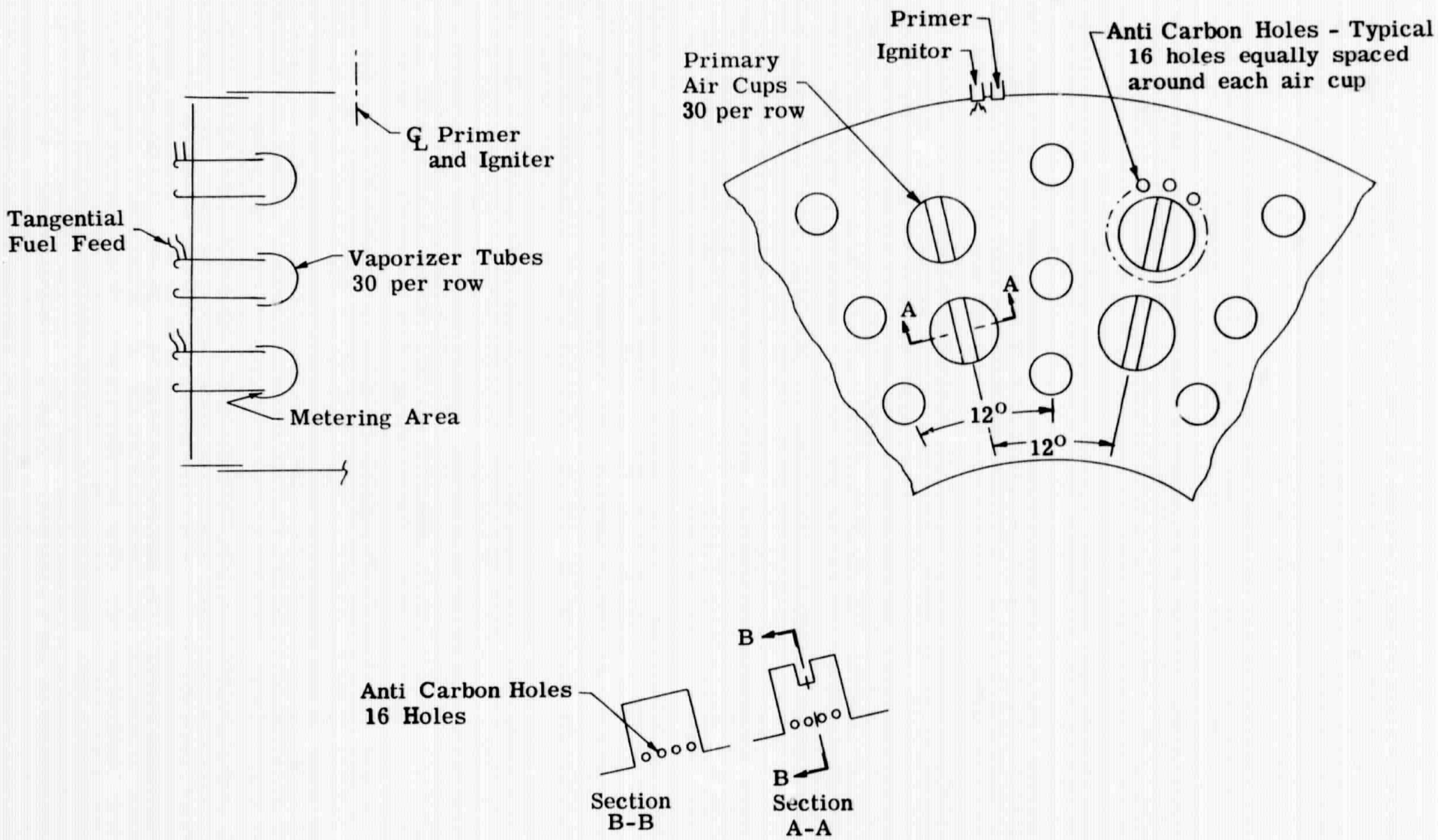


Figure 31

The estimated combustion efficiency characteristic is presented in Figure 32. The primary zone weight flow was selected to meet the operational requirements of the Sea Level Take Off condition, which is representative of the maximum fuel-air ratio that would be encountered in engine operation. From the figure, it can be seen that the fuel-air ratio at the contractual design point is significantly lower than the fuel-air ratio at the sea level take-off condition.

The design combustor total pressure loss characteristics are presented in Figure 33. The characteristic pressure loss, $\Delta P_T/q_3$, (overall total pressure loss/inlet dynamic head) is presented as a function of overall temperature ratio, T_{T4}/T_{T3}, on the right side of the figure. At non-burning conditions (temperature ratio of one) the pressure loss is attributable to the loss in the diffuser and the drop across the combustion chamber orifices. The increased loss with increased overall temperature ratio is the momentum loss arising from heat addition. The overall total pressure loss, expressed as a percent of the inlet total pressure, is shown on the left hand portion of this figure for conditions of Sea Level Take Off and the contractual design point (Flight $M_o = 3.0$).

The design aerodynamic conditions at intermediate stations within the combustor system (between the compressor exit and turbine inlet) are presented in Figure 34. Total pressure loss and static pressure recovery are also plotted as non-dimensional ratios against the combustor inlet dynamic head in Figure 35. Using this figure, the performance can be readily calculated at any operating condition.

3.4 Sector Test Rig.

The rig which was used to evaluate combustor performance, and the two segmented liner configurations are shown in Figure 36. The rig is an 84° sector of a full round annular combustion chamber, and is shown schematically in Figure 37.

The intake to the sector rig is a bell shaped annular section, followed by a constant area annular duct which is instrumented to record the inlet air conditions. The bell portion of this duct is located inside the inlet plenum chamber, and the constant area portion of the duct extends through a blanking

PREDICTED COMBUSTOR EFFICIENCY VS. FUEL/AIR RATIO

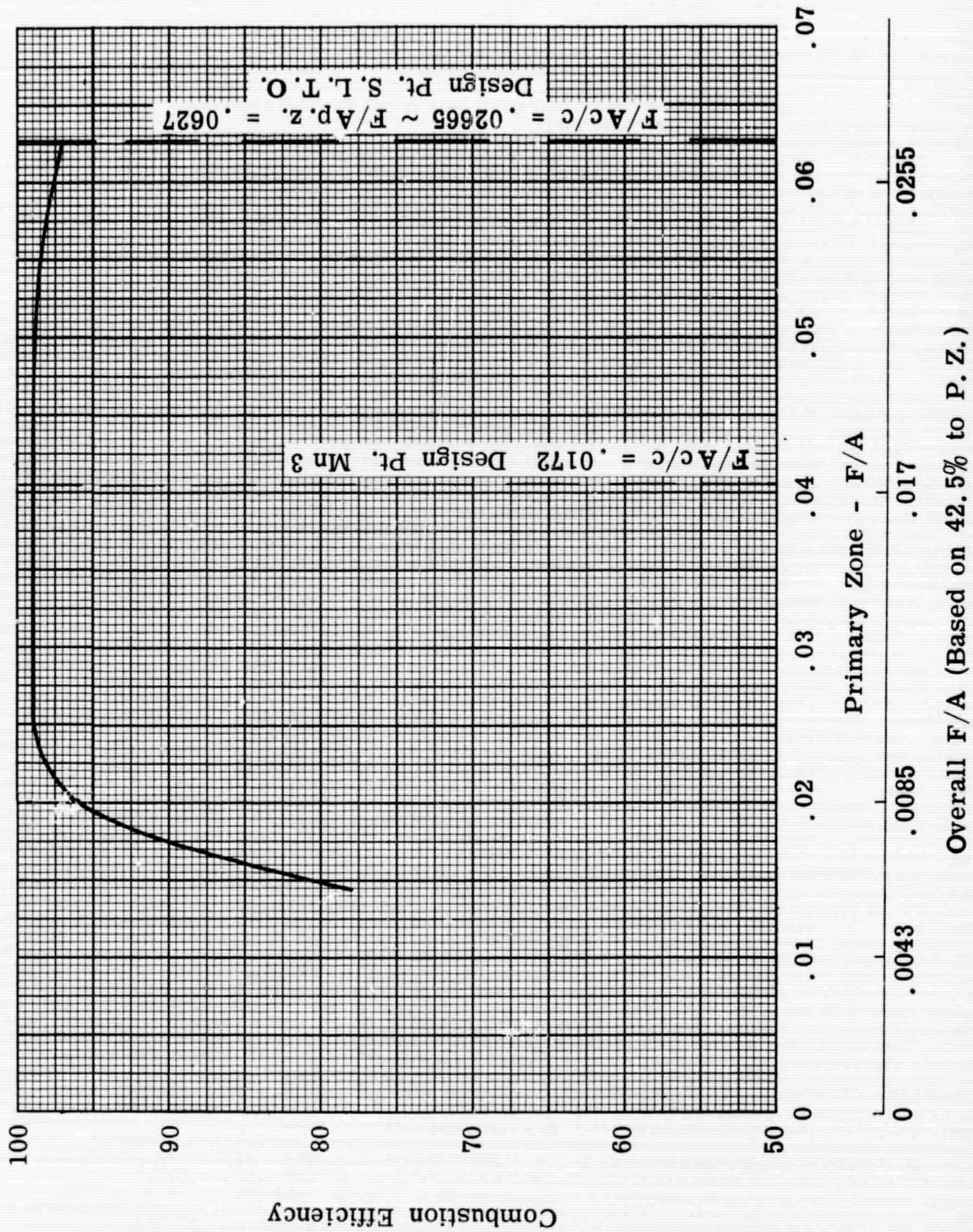


Figure 32

DESIGN TOTAL PRESSURE LOSS CHARACTERISTICS

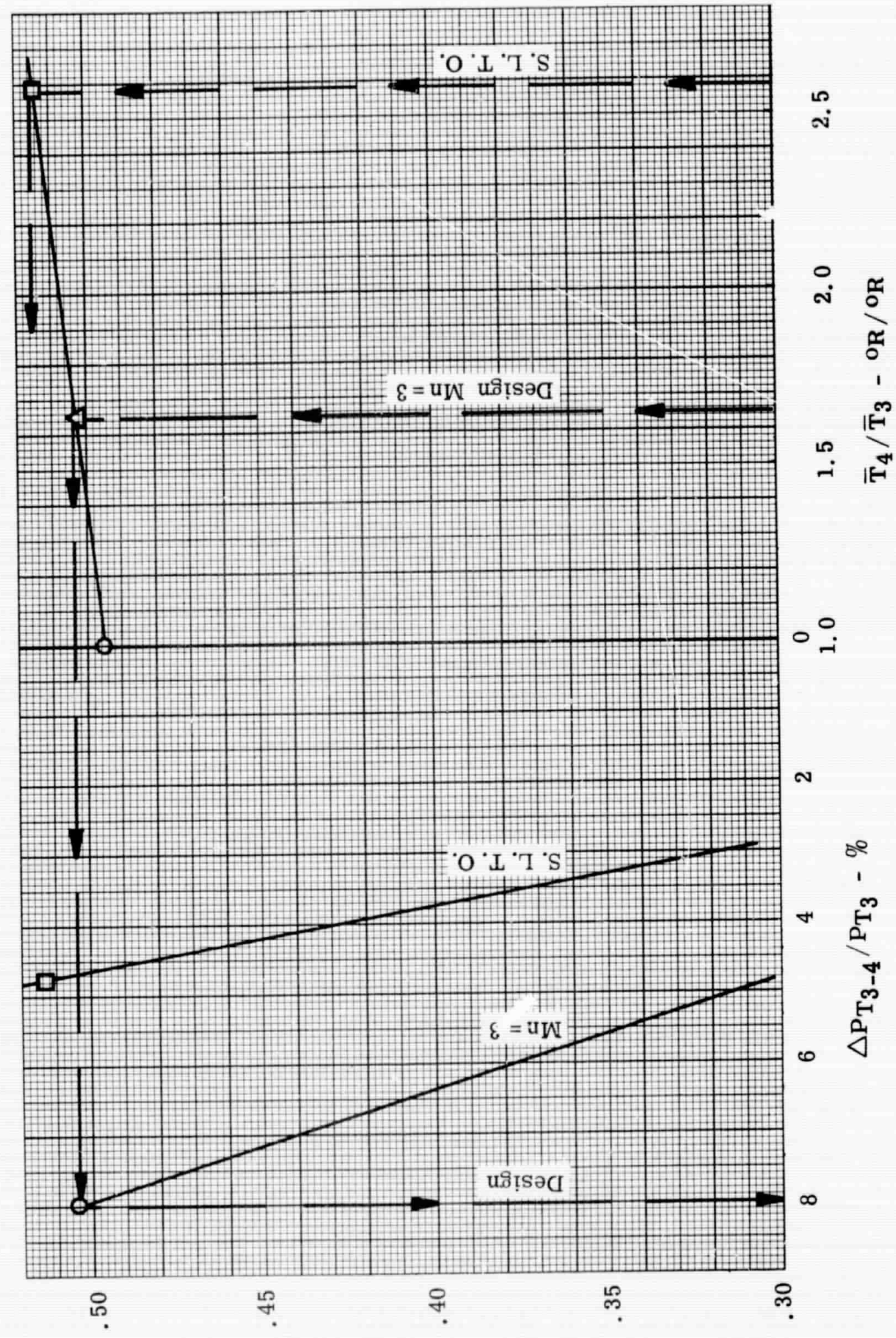
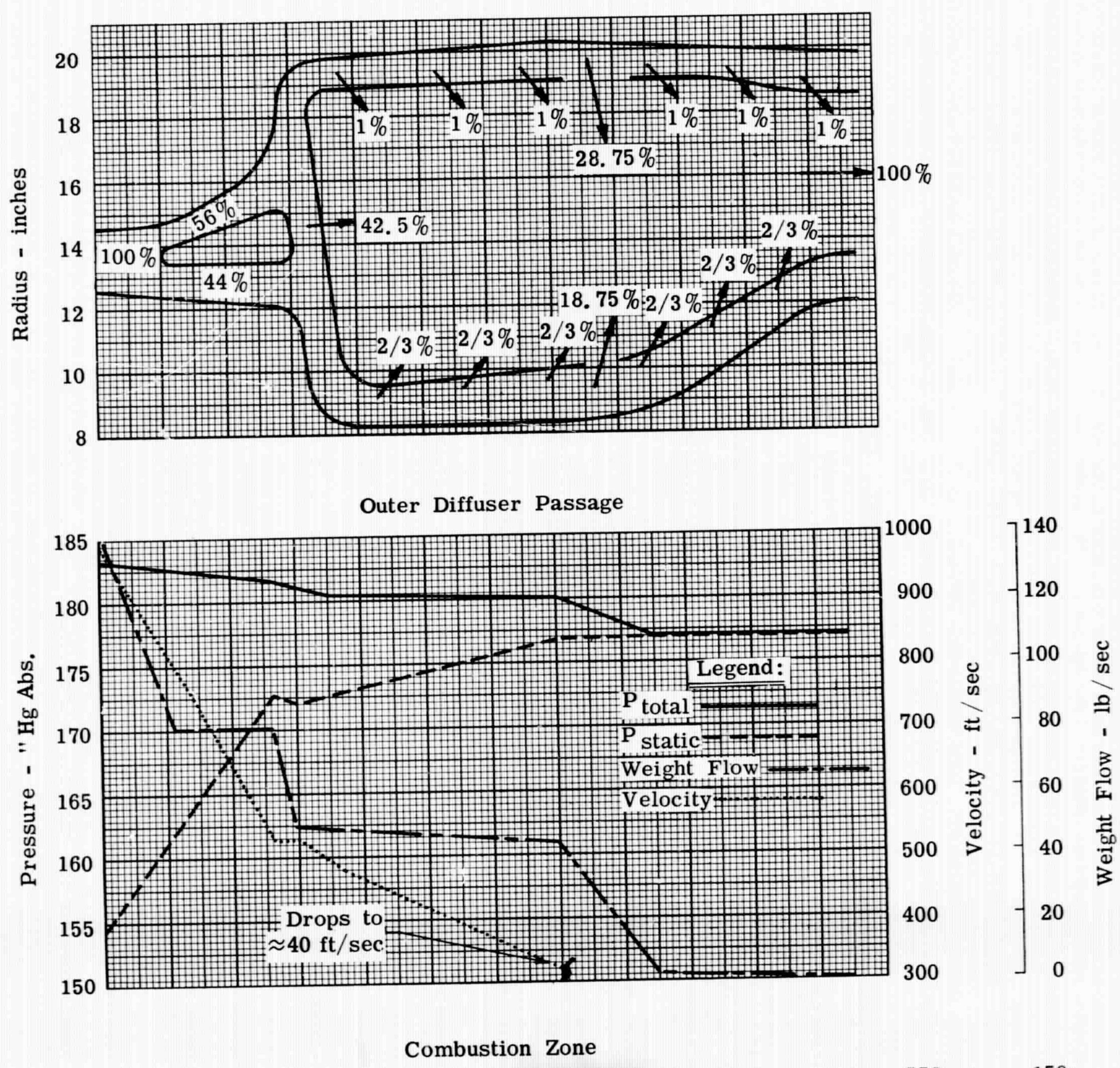


Figure 33

DESIGN POINT STATE CONDITIONS



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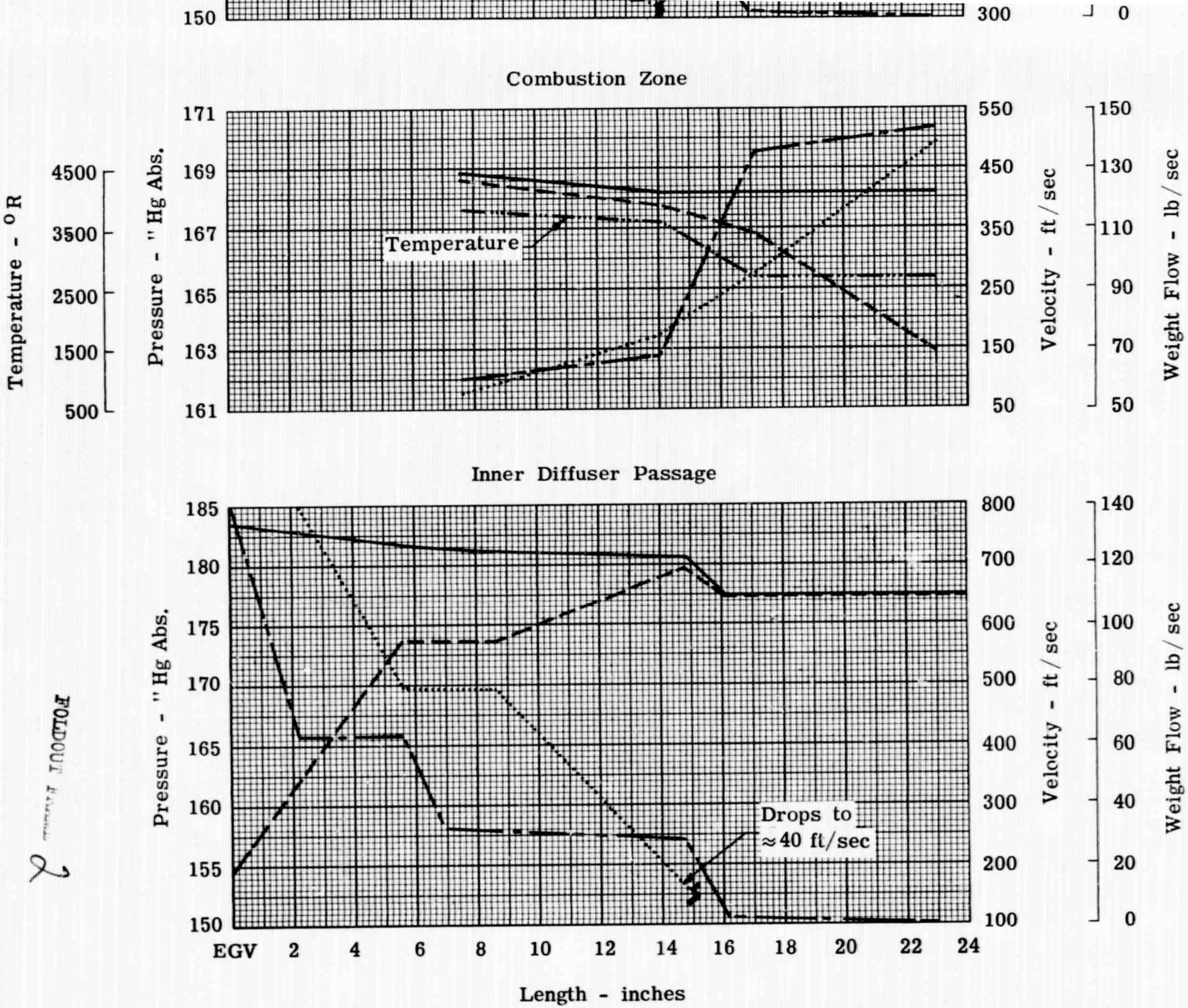

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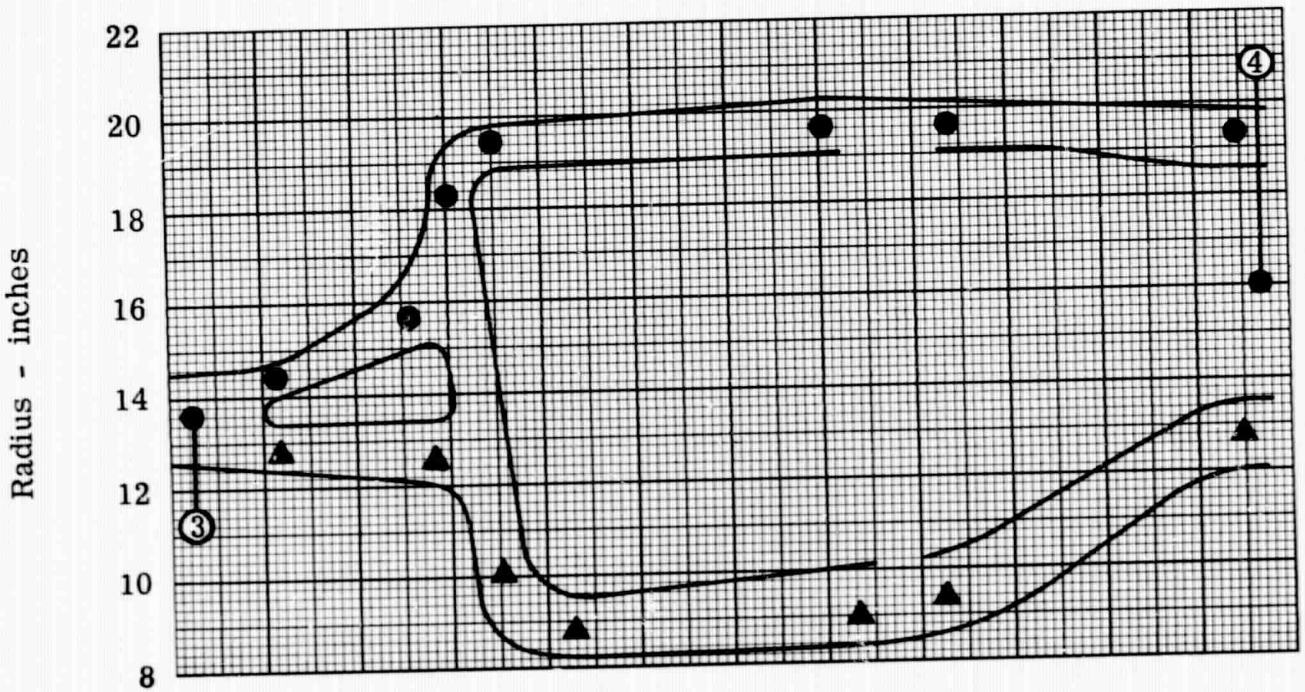
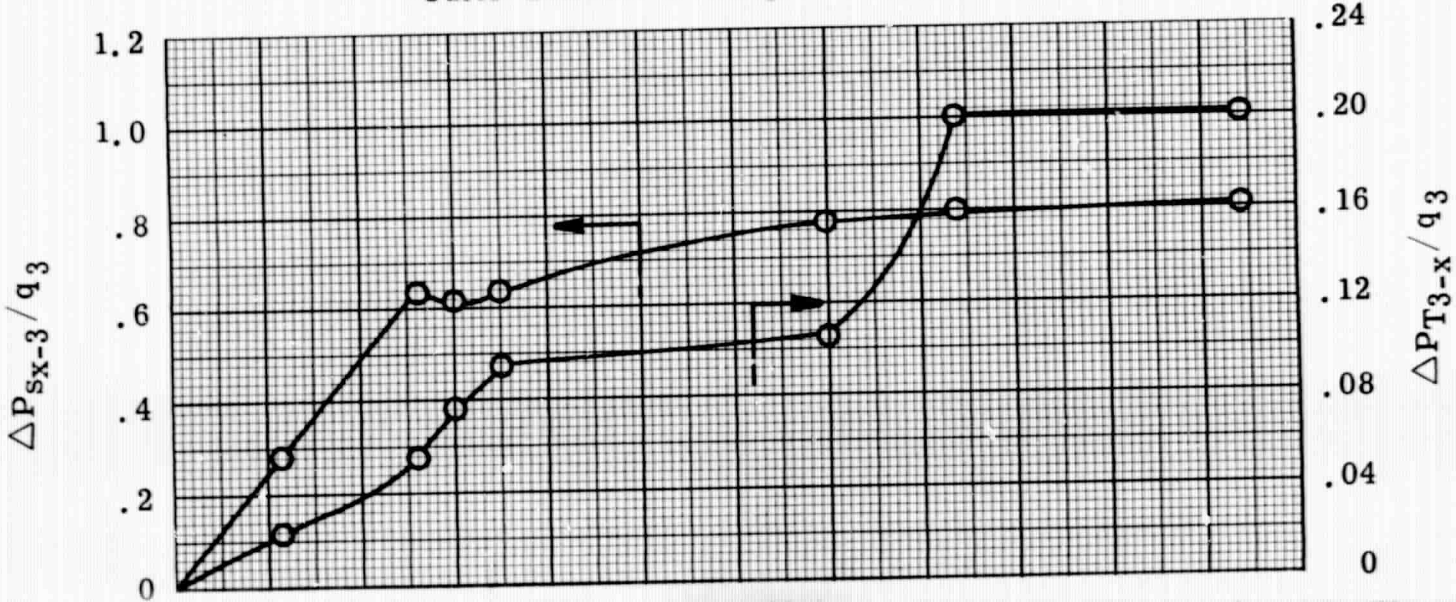
Figure 34

DESIGN DIFFUSER PERFORMANCE



Outer Diffuser Passage Performance



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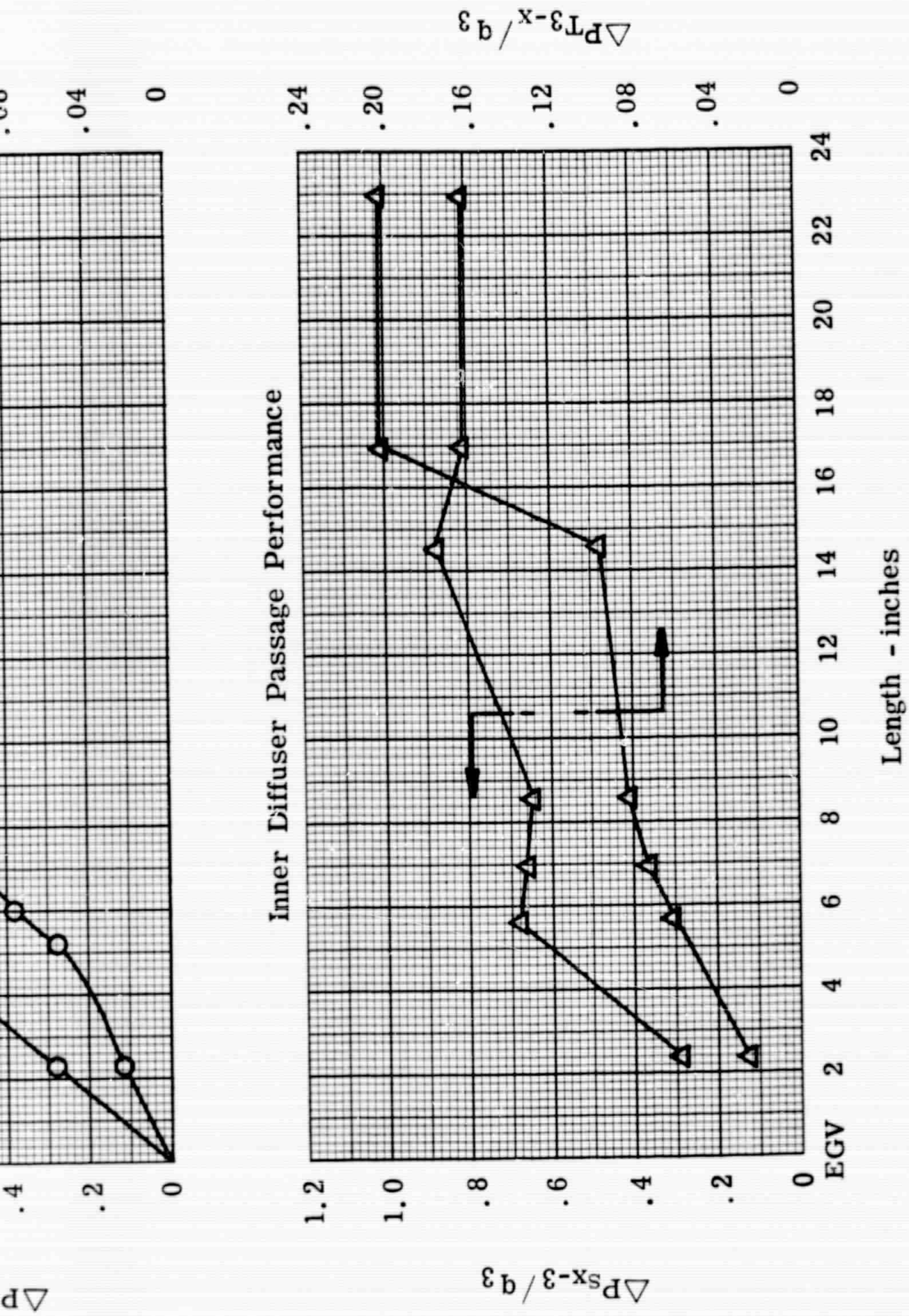

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Figure 35

SECTOR RIG INLET DUCTING, DIFFUSER SECTION AND EXIT PROBE HOUSING

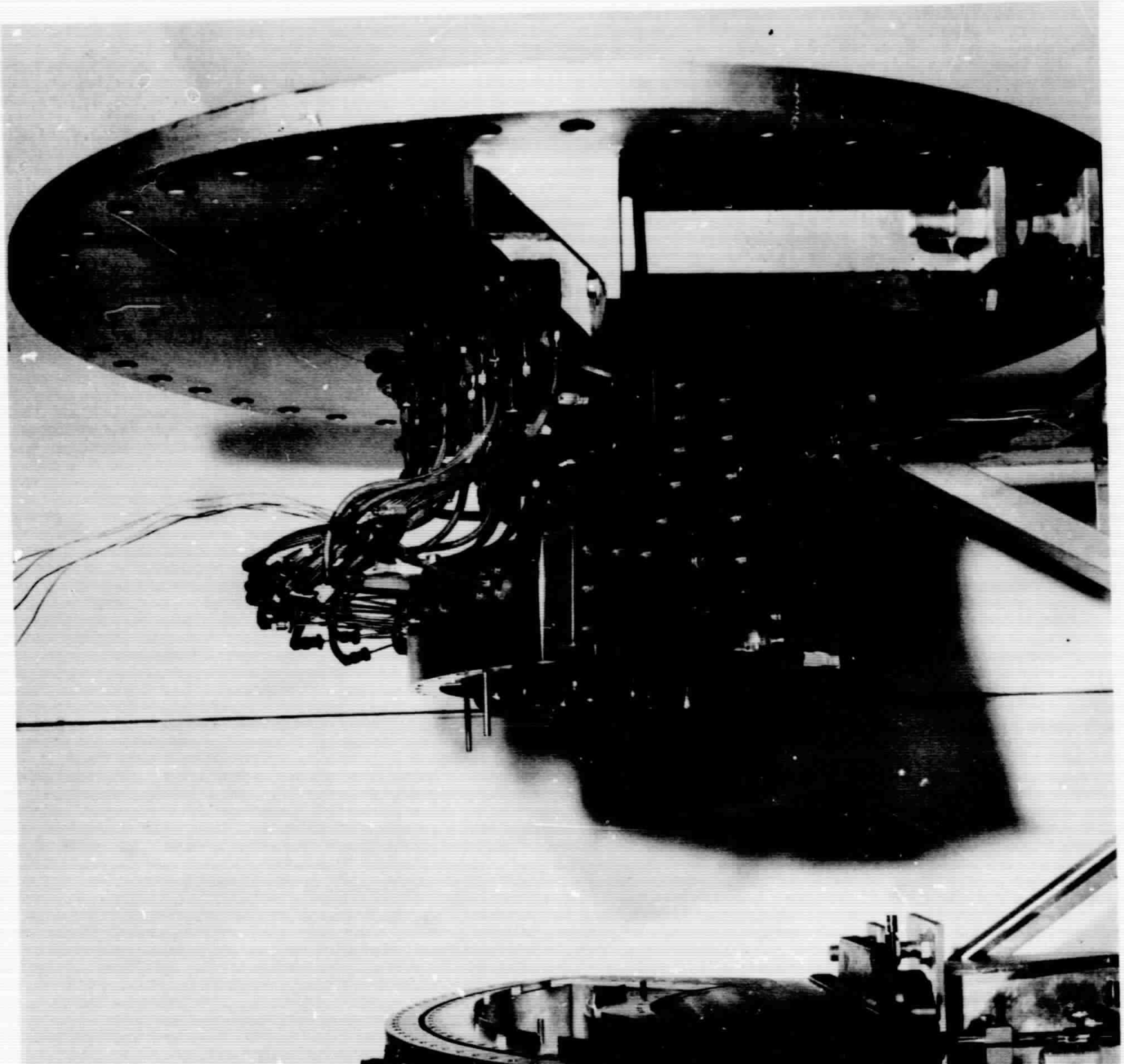


Figure 36

SECTOR RIG TEST FACILITY INSTALLATION SCHEMATIC

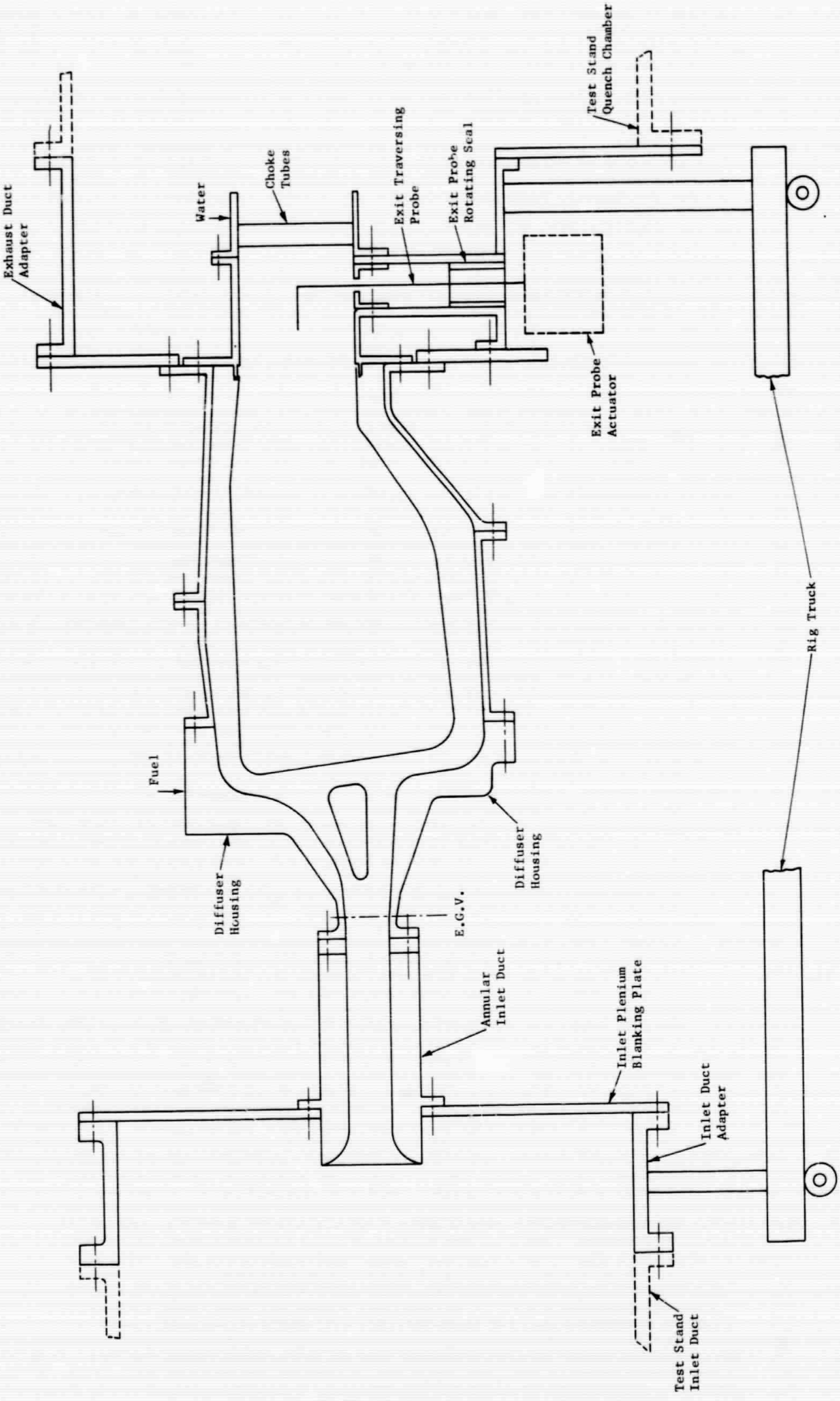


Figure 37

plate bolted to the plenum chamber. The diffuser housings are bolted to the downstream flanges of the duct and support the segmented liner housings. The downstream flanges of the liner housings bolt to the exhaust probe housing which mates with the test stand quench chamber. With this arrangement the combustor section and the rig instrumentation is readily accessible for service and maintenance work.

The upper diffuser housing is fitted with pads to accommodate the fuel feed tube assemblies. Each of these assemblies is fitted with three fuel tubes which feed fuel tangentially into the inlets of three radially stacked vaporizer tubes. The headplate assembly is supported with pins slipped into spherical bearings in the inner and outer diffuser housings. This assembly is shown installed in the sector rig in Figure 38.

The diffuser splitter shown in Figure 39 is supported from the headplate by a slip joint attachment to permit relative thermal growth between the splitter and the headplate. The external side walls of the combustion chamber sector were designed to withstand the internal pressure loading exerted under back pressure conditions. The internal side walls are unrestrained Rokide coated metal plates. Heat Losses are minimized by inserting asbestos insulation between the internal side walls and the external side housings.

The exit probe housing, shown schematically in Figure 40, incorporates a removable flow constriction for obtaining sonic or near sonic flow at a station a few inches downstream from the combustor exit traversing probe. This device consists of a series of radial tubes which are spaced so that the open flow area between the tubes produces sonic flow. Thirteen 1.20 inch O.D. tubes produce the required sonic flow, and are convectively cooled with high pressure water. The outer duct is cooled by water spray. The inner duct is convectively cooled with a water jacket, which eliminates the generation of steam in the high pressure plenum below the traversing probe, and provides a double radiant heat shield for the probe seal. The traversing probe seal is located at the axial centerline of the rig, and is the pivot for the probe. The ball bearing type seal is shown in Figure 41. The ball is held in a fixed axial plane with a pin which permits circumferential sweeps of the probe. The probe is moved radially in the guide tube for obtaining circumferential sweeps at various

HEADPLATE ASSEMBLY INSTALLED IN SECTOR RIG

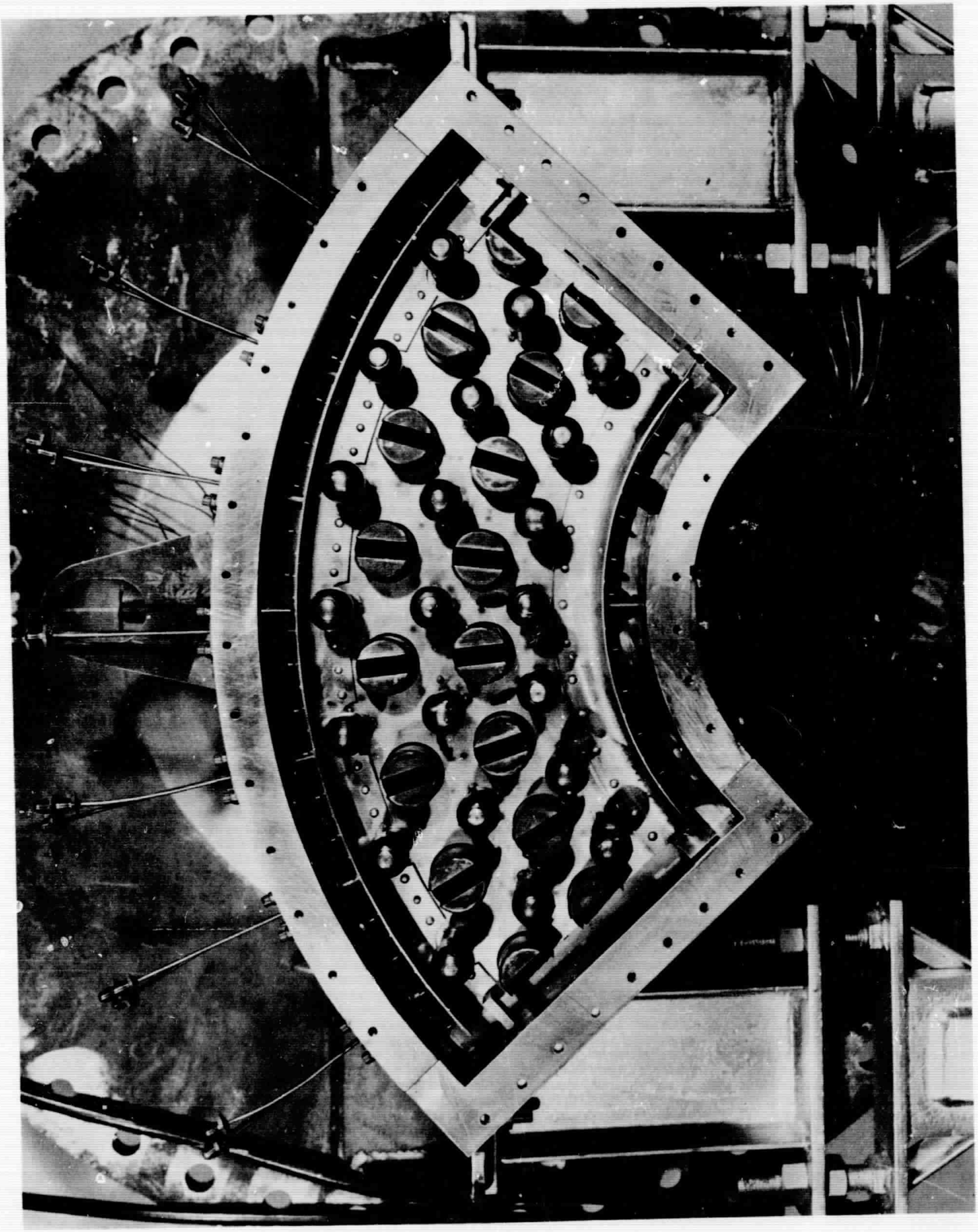


Figure 38

68-0969

DIFFUSER SPLITTER AND HEADPLATE ASSEMBLY

(Note Masking Over Anti-choke Holes for Initial Airflow Split Determination)

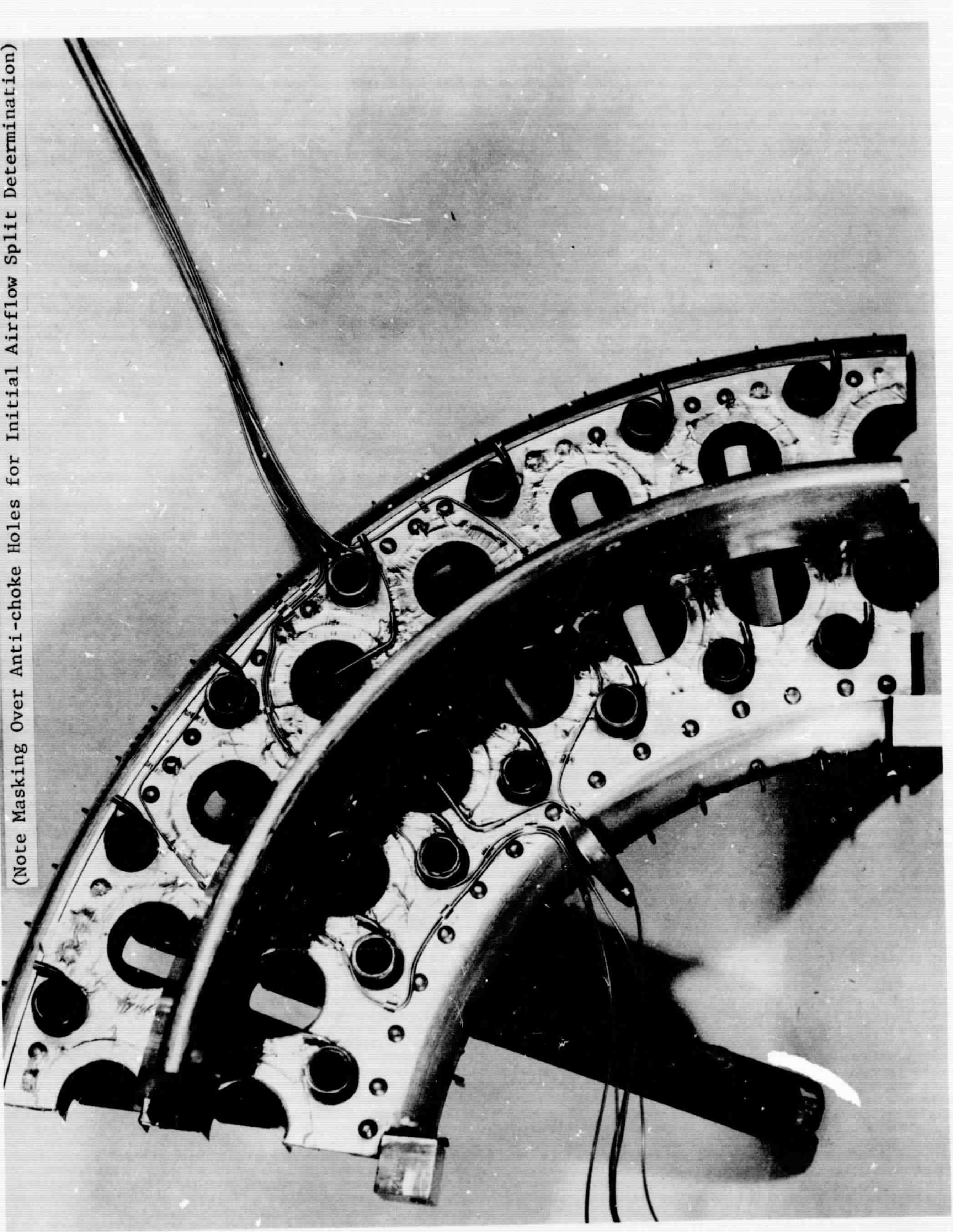
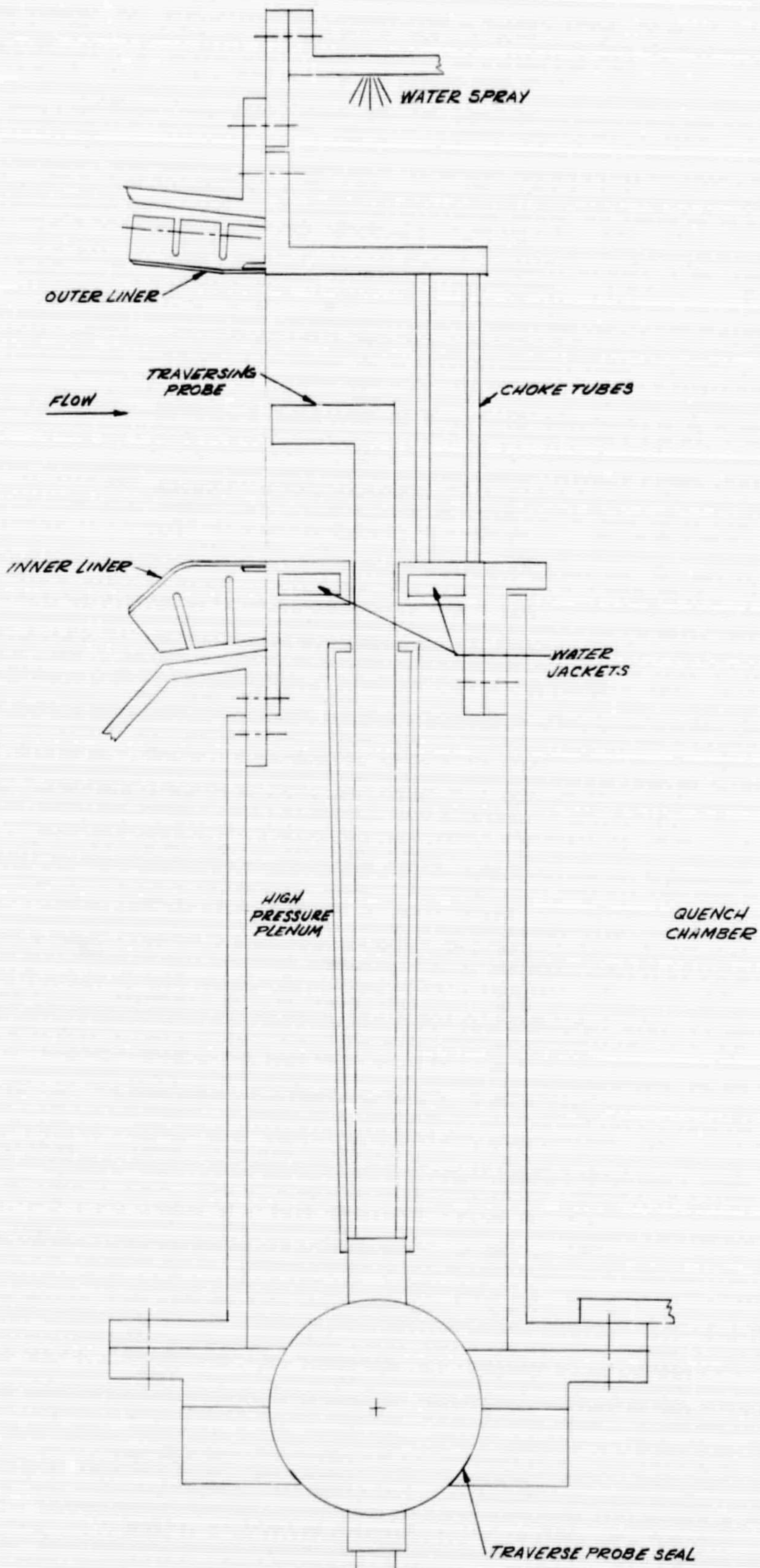


Figure 39

66-726

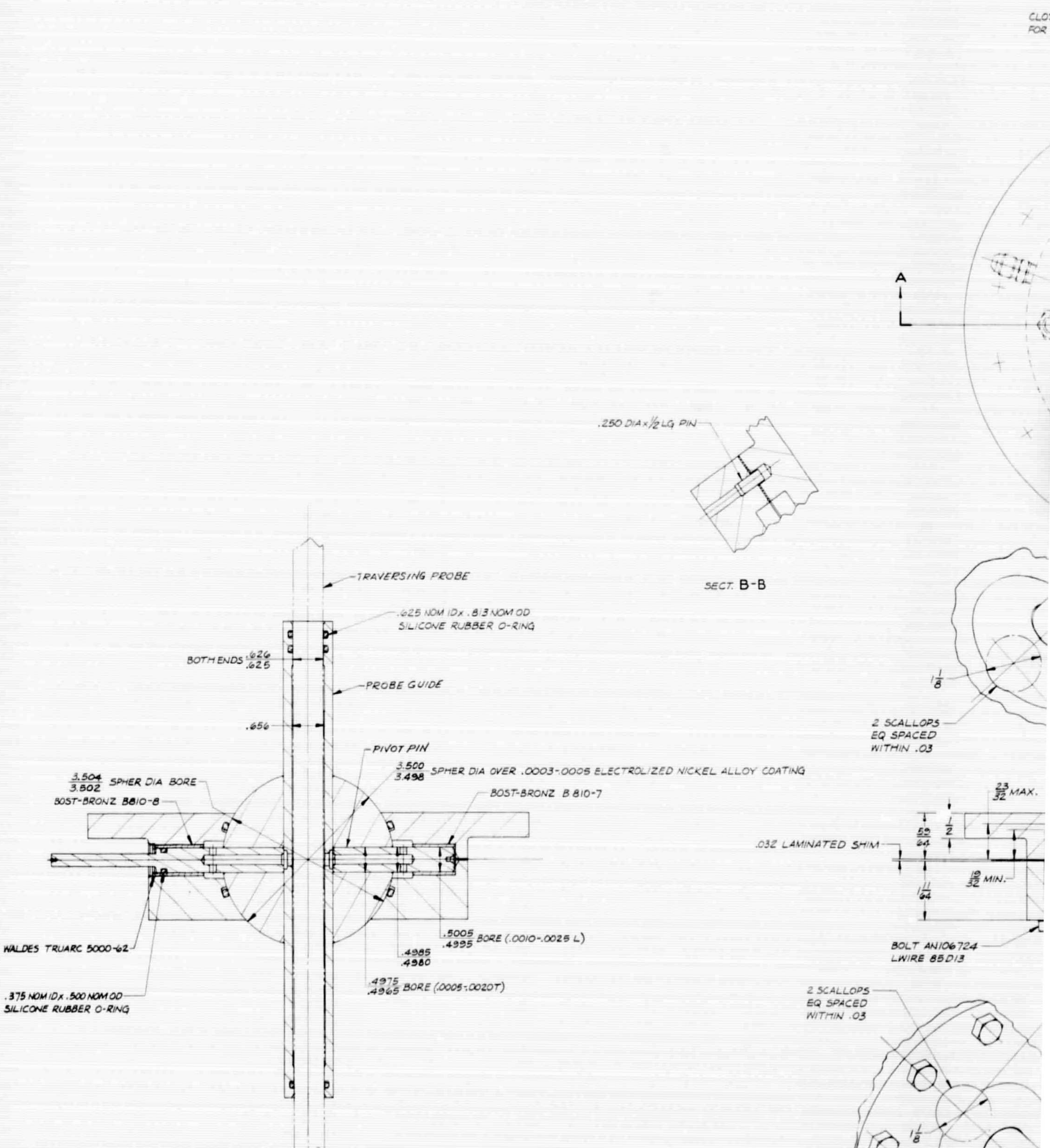
COMBUSTOR EXIT TRAVERSING PROBE HOUSING



17-655

Figure 40

COMBUSTOR EXIT TRAVERSING PROBE SEAL DESI



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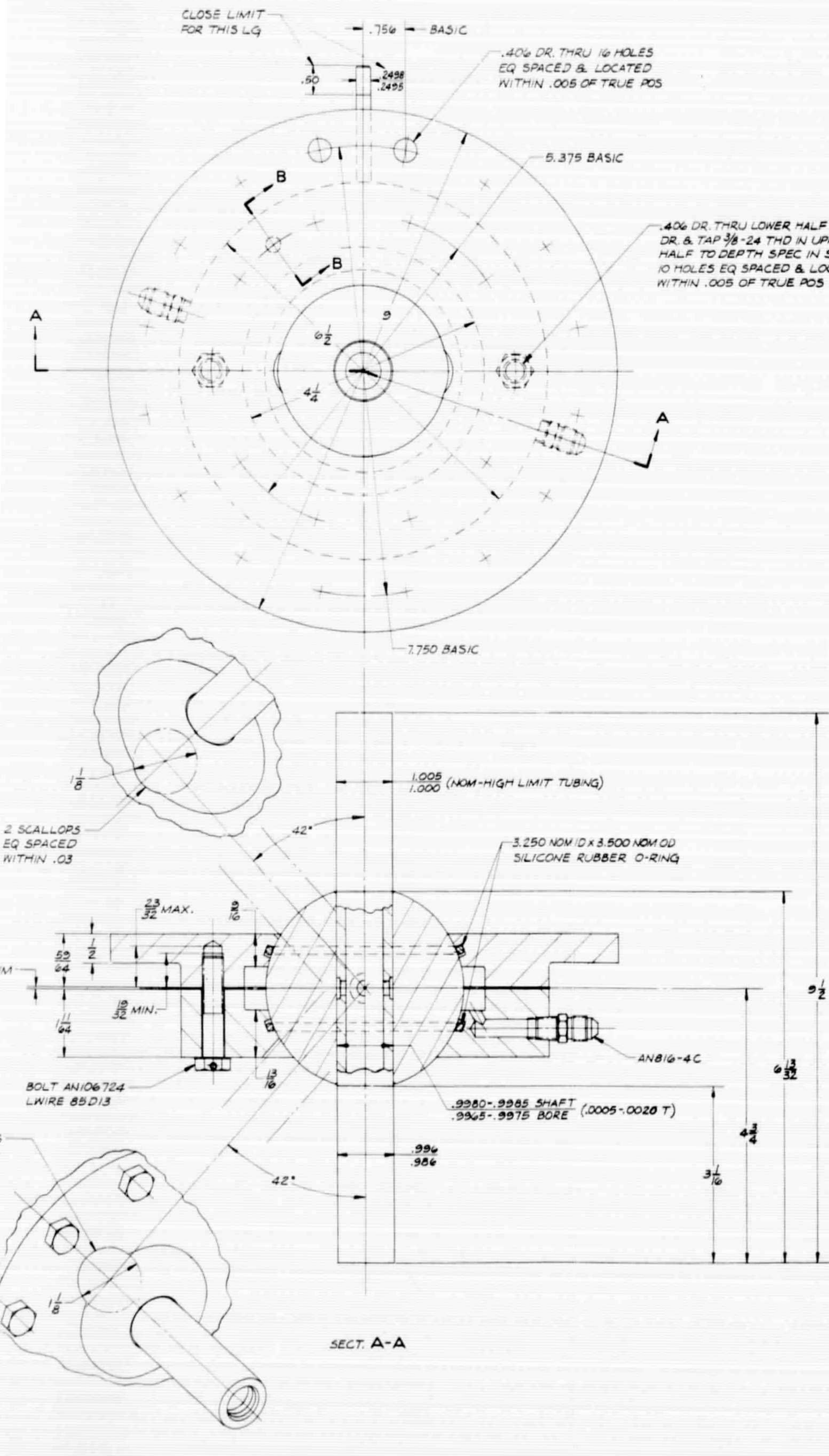
; PROBE SEAL DESIGN



FOLDOUT FRAME 2

Figure 41

radial heights. High pressure air passages are provided to minimize leakage of hot gases past the O-ring seals on the ball bearing and guide tube. This design permits the electrical actuation mechanism to be located outside the quench chamber for improved durability and accessibility.

3.5 Combustor and Segmented Liner - Detail Designs

The following drawings represent the layout and detail fabrication drawings of the final hardware configurations.

Drawing Number	Description
LS 32620	Segmentally Constructed Combustor Liner - Configuration No. 1
LS 32621 Sheets 1 and 2	Segmentally Constructed Combustor Liner - Configuration No. 3
LS 32622 Sheets 1 - 15	84° Combustor Sector Rig and Details
	Configuration No. 1
ES 156803	Liner Assembly Detail - Outer
ES 156821	Liner Assembly Detail - Inner
ES 156867	Liner Assembly Detail - Outer Ends
ES 156868	Liner Assembly Detail - Inner Ends
	Configuration No. 3
ES 156801	Liner Assembly Detail - Outer
ES 156820	Liner Assembly Detail - Inner
ES 156865	Liner Assembly Detail - Outer Ends
ES 156866	Liner Assembly Detail - Inner Ends

3.6 Design Modifications

As a result of development testing, the following modifications were made to both liner configurations and related test rig hardware:

3.6.1 Liners

A. Wire spacer pins were added to prevent the film cooling air slots from closing due to thermal distortions within the individual segments. (See Figure 42.)

B. The width of the axial slots, which engage the "L" shaped hooks, was enlarged at the film cooling air slots to permit unrestrained circumferential thermal expansion of the overlapped liner segments relative to one another. (See Figure 42.)

C. Liner segment length was reduced by one-quarter inch at the film cooling slot to remove thin distressed areas. These had warped excessively during testing. (See Figure 42.)

D. Increased the film cooling air supply over the inner panels in the primary combustion zone by locally opening the air slots on the I.D. of the burner headplate.

3.6.2 Test Rig Hardware

A. Decreased the primary combustion air through the headplate by 35 percent by reducing the aircup metering slot size. This richened the F/A mixture, and moved the flame front away from the vaporizer tubes and aircups in the headplate. Burning of the vaporizer tubes, as shown in Figure 43, had been encountered during test. The aircup slot was also reshaped to redirect the incoming fan of air so that its impingement on the liner segments in the primary zone (outer liners in particular) would not break up the film cooling air (See Figure 44). This was done since thermal distress patterns on the outer liners were found to coincide with each air cup.

B. Increased aircup wall thickness for greater structural integrity at design operating temperatures. Bulging of aircups at high inlet pressure and temperature conditions, with high fuel-air ratio, had been encountered during test. (See Figure 45.)

C. Removed three of the six vaporizer tubes on the inner row of the burner headplate to provide more fuel flow per tube in the remaining vaporizers, thus improving cooling of the vaporizers (Figures 44 and 45).

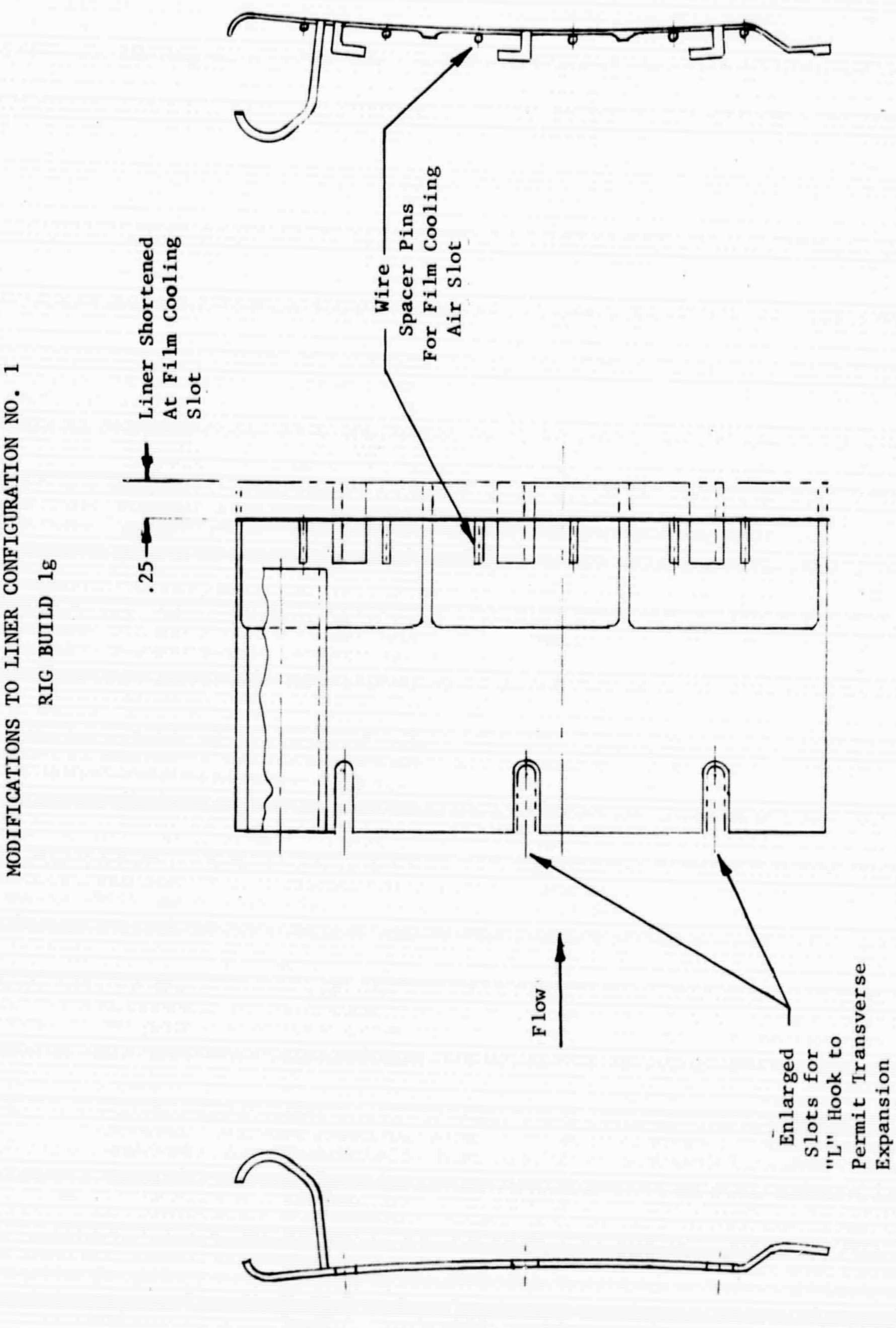
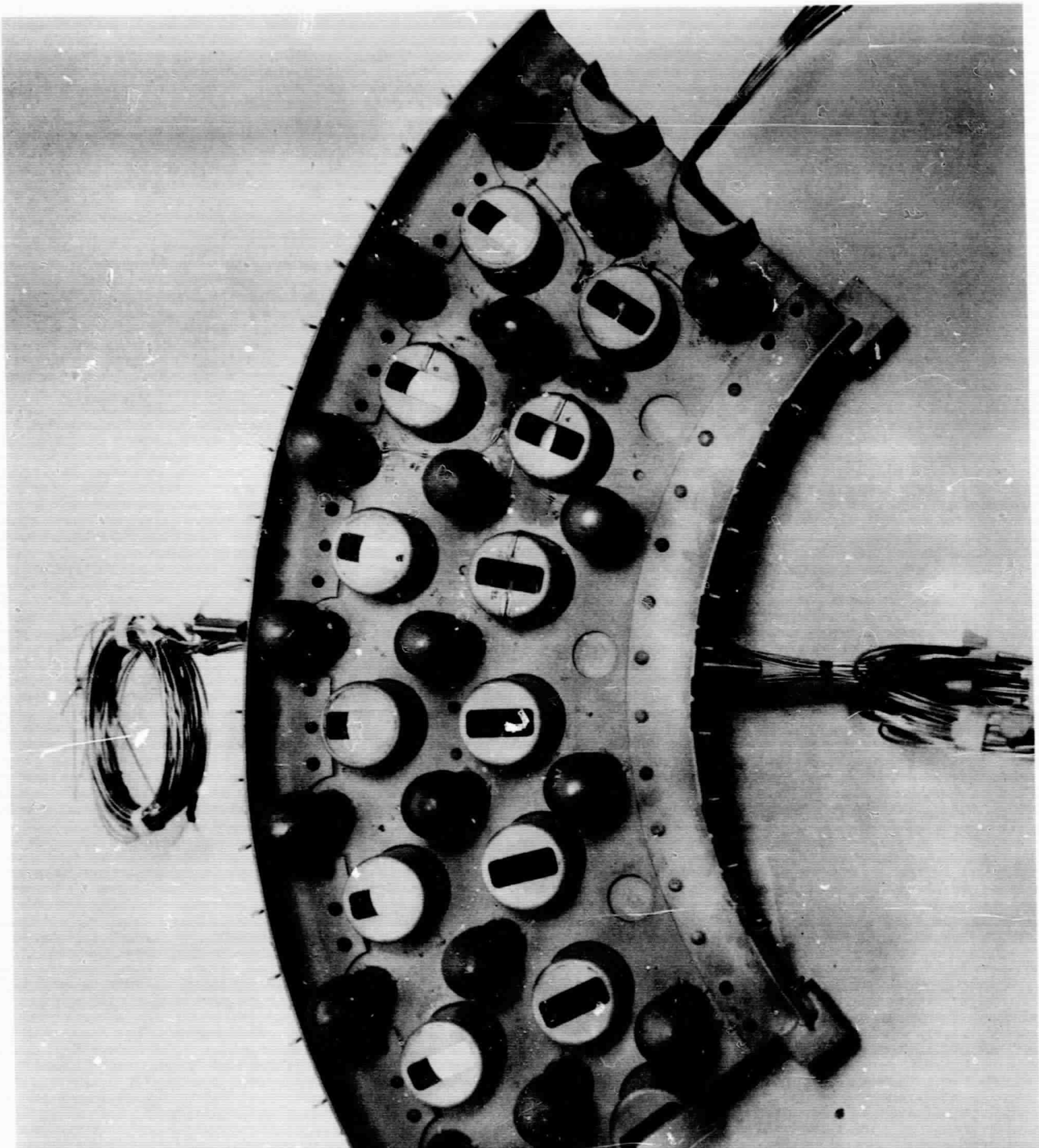

MODIFICATIONS TO LINER CONFIGURATION NO. 1
RIG BUILD 1g
.25
Liner Shortened At Film Cooling Slot
Wire Spacer Pins For Film Cooling Air Slot
Flow
Enlarged Slots for "L" Hook to Permit Transverse Expansion

Figure 42

CLOSE UP OF HEADPLATE, SHOWING BURNED VAPOR TUBES - RIG BUILD 1a

Figure 43

68-3285



MODIFIED HEADPLATE ASSEMBLY, SHOWING REDUCTION IN AIRCUP SLOTS - RIG BUILD 1g

Figure 44

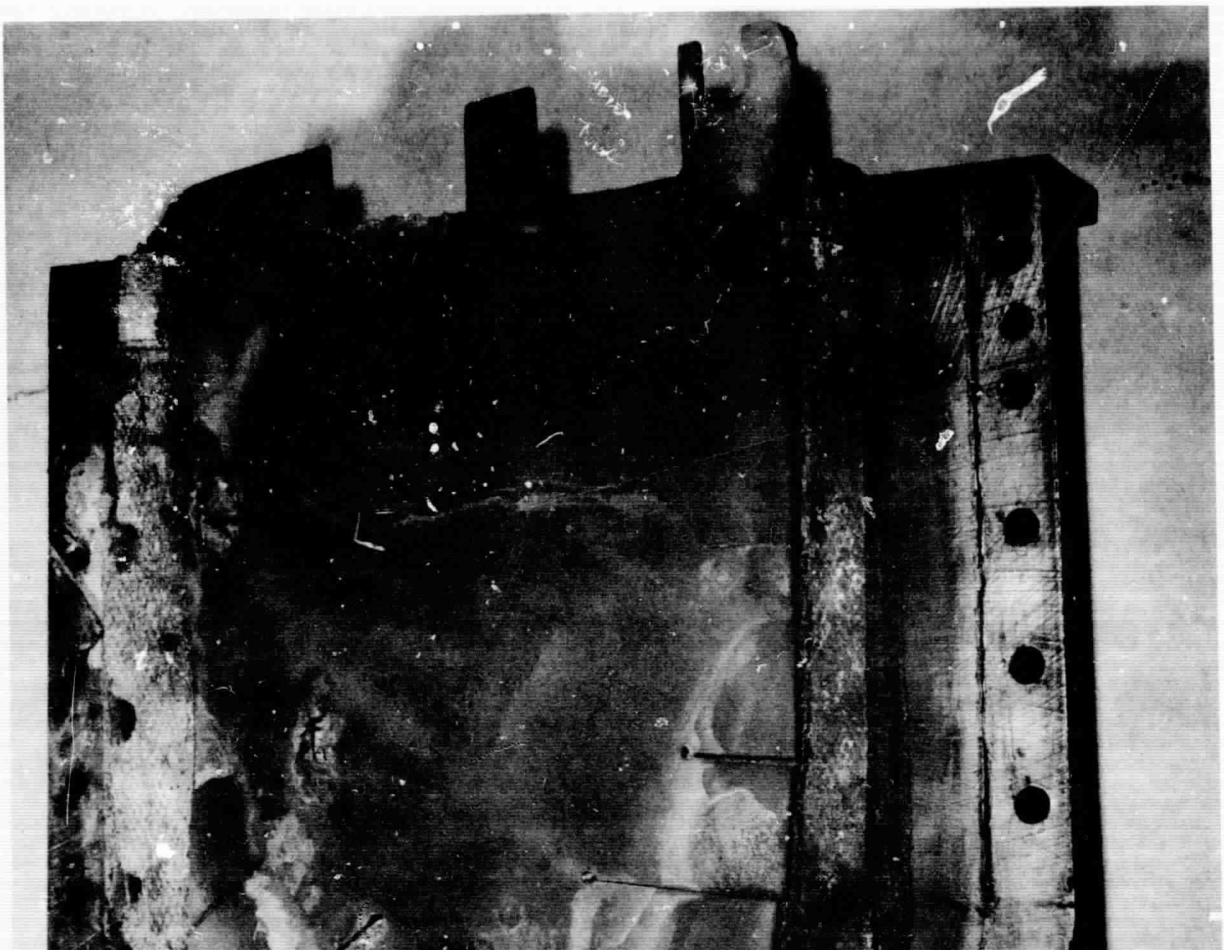
CLOSE UP OF HEADPLATE, SHOWING BULGED AIRCUPS - RIG BUILD 1e

Figure 45

D. Modified the vaporizer tubes to incorporate sliding radial dome support pins. This was done to eliminate the thermal stresses which develop due to relative thermal expansion between the vaporizer dome and the center tube.

E. Replaced the Hastelloy X side plates with a higher melting temperature alloy, Inconel 600, and coated the hot side with a thin layer of zirconium oxide insulation. The side plates were also slotted to prevent warpage due to thermal distortion. For typical damage to side plates during test, see Figure 46.

The following section of this report summarizes the development effort.



COMBUSTOR SIDEPLATE, SHOWING BURNED HOLES NEAR INNER LINER - RIG BUILD 1e

Figure 46

4.0 LINER DEVELOPMENT PROGRAM

This part of the report summarizes the test development effort. The section contains a brief review of the test facility and test instrumentation, and a test history. This is followed by a review of those items which affect the liner performance, such as air inlet pressure, air flow distribution, and radiation. The Liner review concludes with a comparison of liner configurations 1 and 3, including a discussion of the steps taken to optimize the liners during the program.

The final part of this section reviews those changes made to the combustor to improve the liner temperatures and a general review of the combustor development.

4.1 Test Facility

All testing was done at the Curtiss-Wright Corporation Development Laboratory. The control room of the facility is shown in Figures 47 and 48, and the test cell interior is shown in Figure 49. Air supply for the test program was provided by a compressor system. Air preheat was accomplished with a large indirect-fired air preheater system which has a supply capacity of 35 lb/sec of air at an outlet temperature of $1150^{\circ}F \pm 15^{\circ}$.

4.2 Instrumentation

The instrumentation incorporated into the combustor sector rig provided data for full evaluation of the liner and combustor performance. This instrumentation is tabulated and shown schematically in Figure 50. The inlet total and static pressures were measured at a plane simulating the axial position of the last stage of the compressor. Inlet total pressure measurements were recorded at five (5) radial positions at each of five (5) circumferential positions using Kiel head pressure rakes. Total temperature measurements were recorded at the same inlet station, using bare junction stagnation thermocouples. Static pressure taps were also installed at this inlet station on the inner and outer duct walls. Total pressure, total

CONTROL ROOM - COMBUSTOR TEST FACILITY
CONTROL CONSOLE

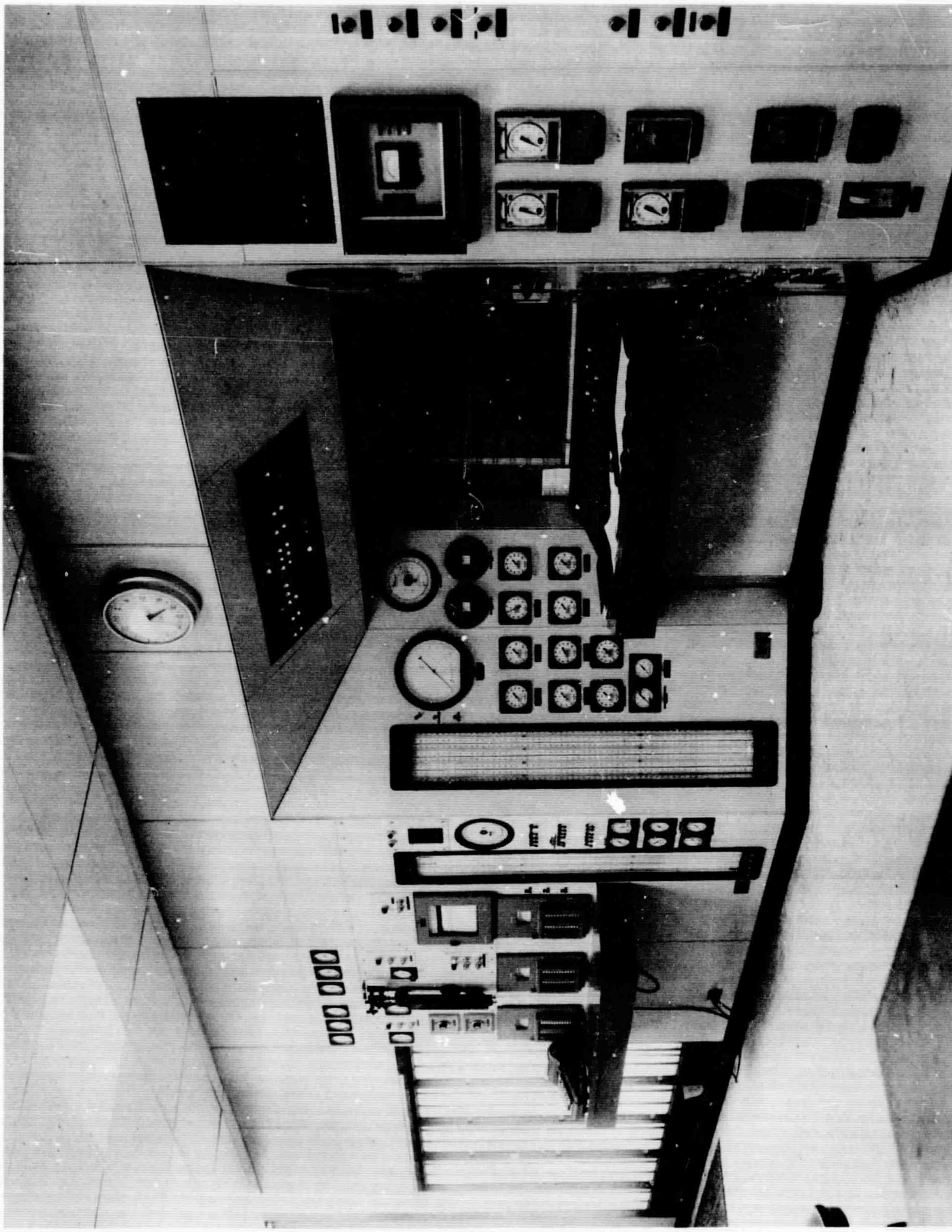


Figure 47

CONTROL ROOM - COMBUSTOR TEST FACILITY
RECORDING EQUIPMENT

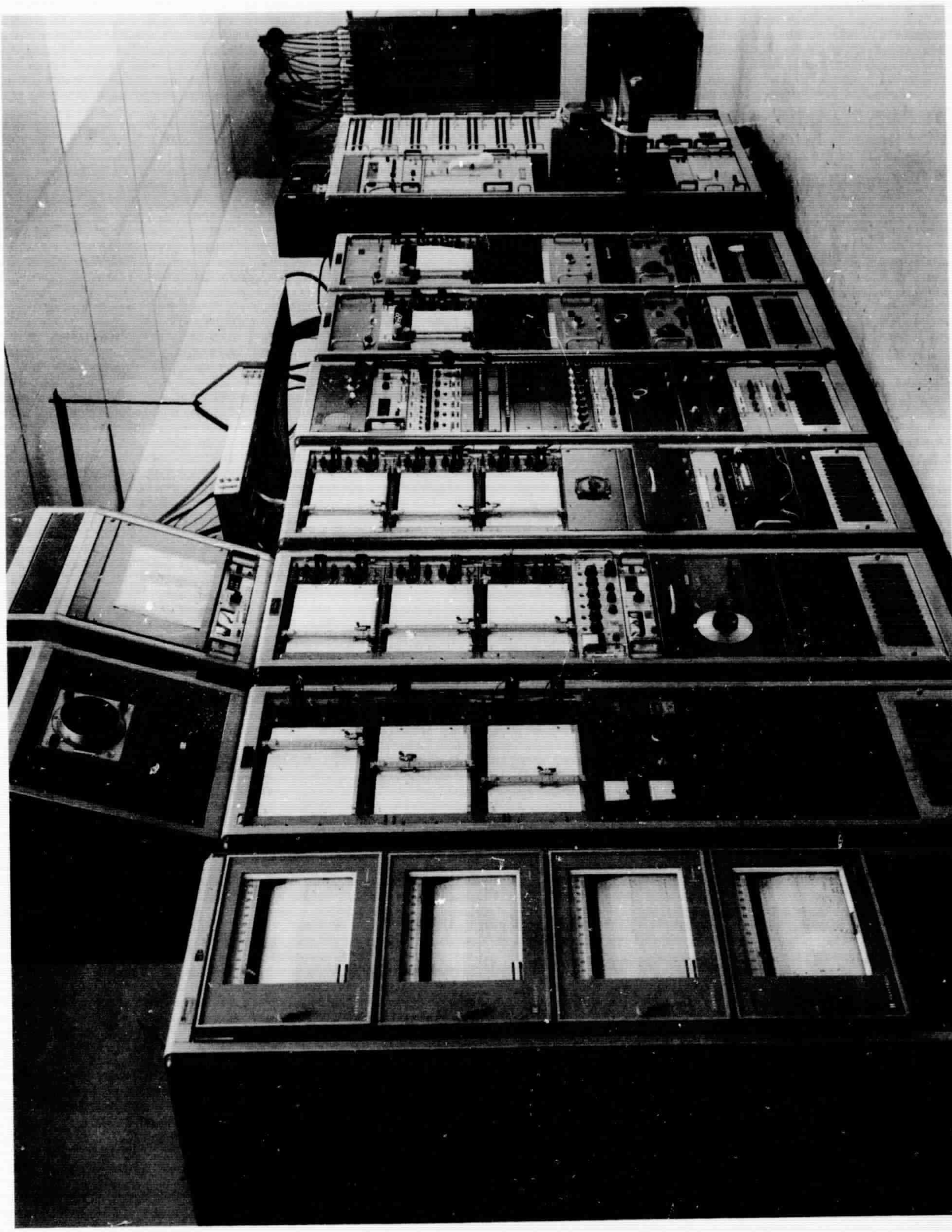


Figure 48

COMBUSTOR TEST CELL

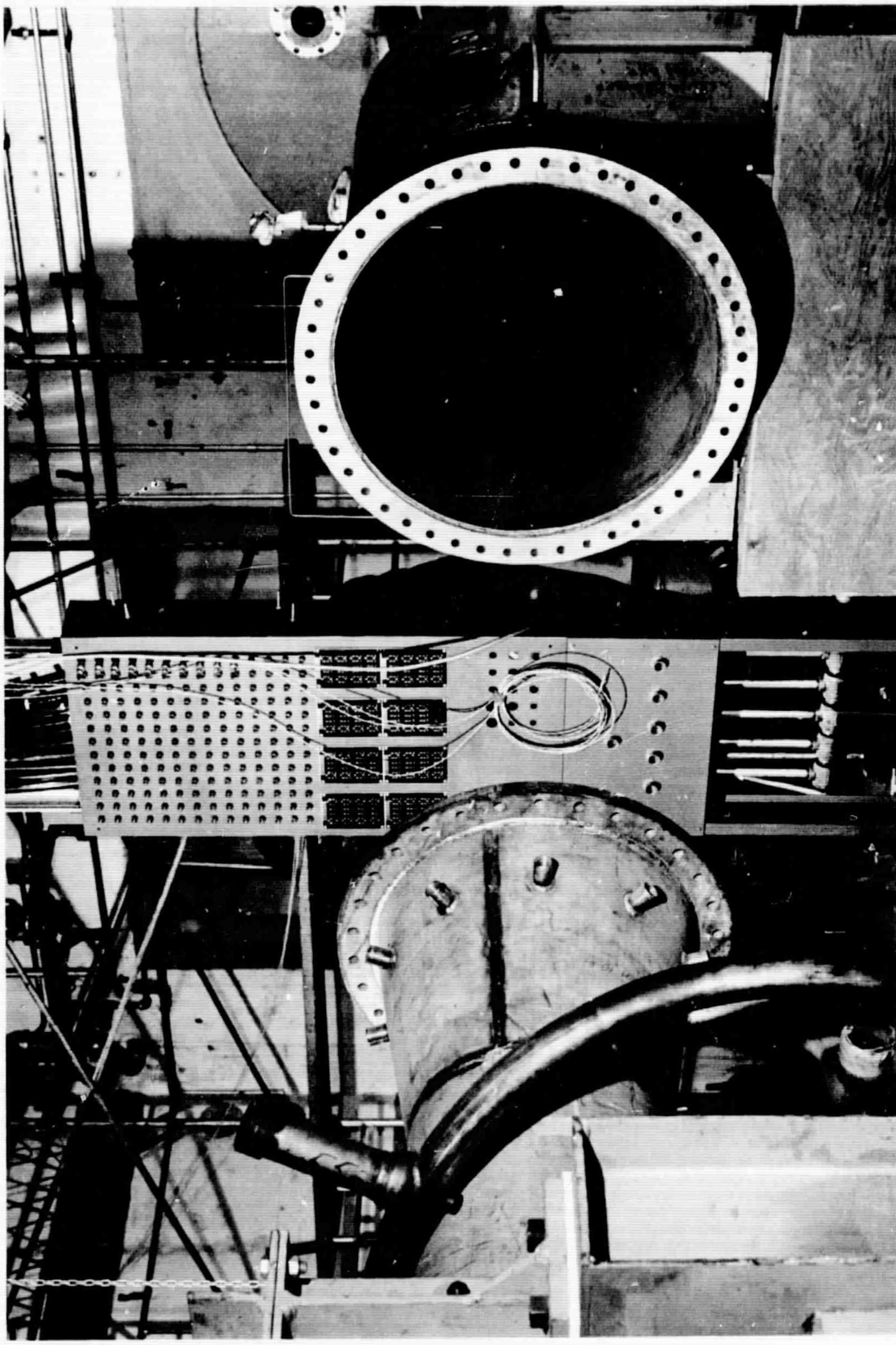
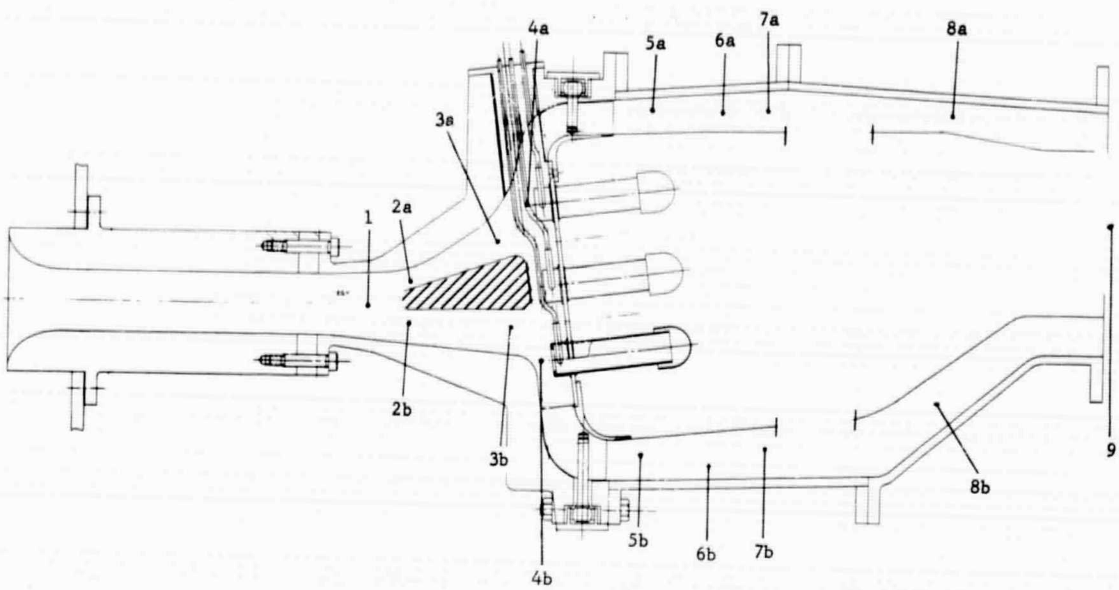


Figure 49

SECTOR RIG SCHEMATIC, SHOWING INSTRUMENTATION STATIONS



Station Description	Station Number	Instrument Type	Number Of Circumfer. Locations	Readings Per Location	Radial Location
Compressor Exit	1	P_t	5	5	C.O.E.A.
		P_s	5	2	Outer and Inner Walls
		T_t	2	1	Mid Duct
Diffuser Inlet	2a & 2b	P_t	2	3	C.O.E.A.
		P_s	2	2	Outer and Inner Walls
Diffuser Section	3a & 3b	P_t	2	3	C.O.E.A.
		P_s	2	2	Outer and Inner Walls
Headplate	4a & 4b	P_t	1	1	Primary Air Cup Inlet
Diffuser Exit	5a & 5b	P_t	2	3	C.O.E.A.
		P_s	2	1	Outer Wall
Diluent Section	6a	T_t	1	1	Mid-Passage
	6b	T_t	1	1	Mid-Passage
Diluent Section	7a & 7b	P_t	2	3	C.O.E.A.
		P_s	2	1	Outer Wall
End of Diluent Section	8a & 8b	P_t	2	3	C.O.E.A.
		P_s	2	1	Outer Wall
Turbine Inlet	9	P_t	Rotating	5	C.O.E.A.
		T_t	Rotating	5	C.O.E.A.
		P_s	5	2	Outer and Inner Wall

<u>Legend</u>

P_t = Total Pressure Rake

P_s = Static Pressure

T_t = Total Temperature

C.O.E.A. = Centers Of Equal Areas

Figure 50

temperature and static pressures were measured with similar instrumentation through the diffuser passages and along the inner and outer cooling passages.

The total temperature and total pressure profiles at the combustor exit were measured using a remotely operated traversing probe which permitted continuous travel in a circumferential sweep and radial span. Continuous data was recorded at a minimum of five (5) radial heights and plotted directly on x-y recorders. The sensing head was a single element sonic-aspirating type Platinum/Platinum-Rhodium thermocouple with an attached total pressure sensor. The design of this probe is shown in Figure 41. The exit probe actuator system is shown in Figure 51.

Segmented liner metal temperatures were evaluated with bare-wire chromel-alumel thermocouples tack-welded to the cooled sides of the liner segments in 34 locations. Positioning of these thermocouples is shown in Figure 52. Relationship of the thermocouple locations to vaporizer and aircup locations is shown in Figure 53. Twenty-four of the liner thermocouple readings were recorded directly on a Honeywell strip chart recorder. The remaining ten were read visually from a Brown multi-channel meter on the control console.

4.3 Test History

In order to minimize the chances for a major rig failure, the test program was carefully planned and sequenced to arrive at the design conditions through a series of steps. These were as follows:

1. Cold Flow tests to evaluate liner air distribution, and to provide check points for setting the rig in later tests.
2. Preheater tests, with no combustion, to evaluate instrumentation and general rig performance.
3. Hot tests, with combustion, with progressive increases in air inlet pressure and temperature to approach the critical design conditions in controllable increments.

EXIT PROBE ACTUATOR SYSTEM

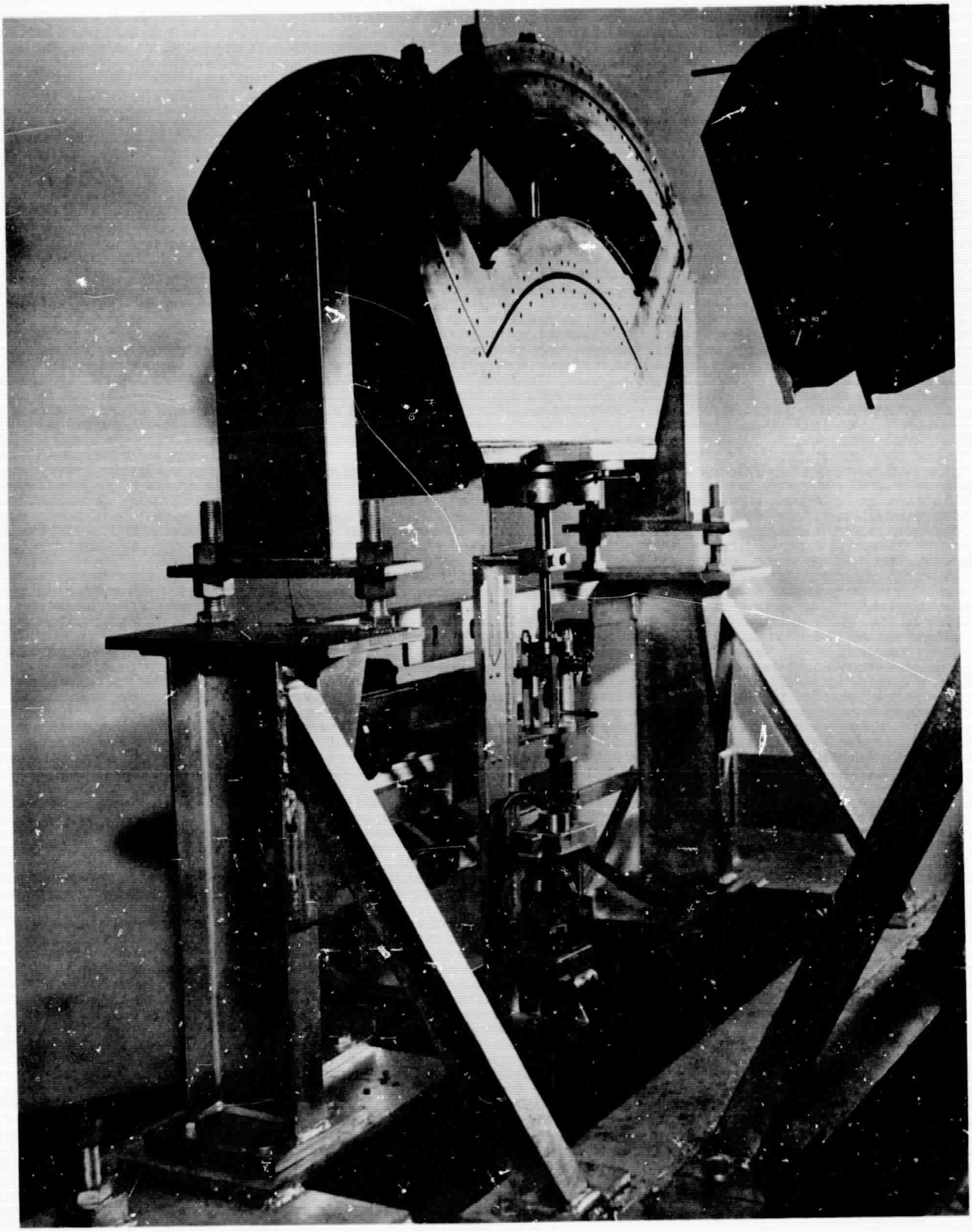
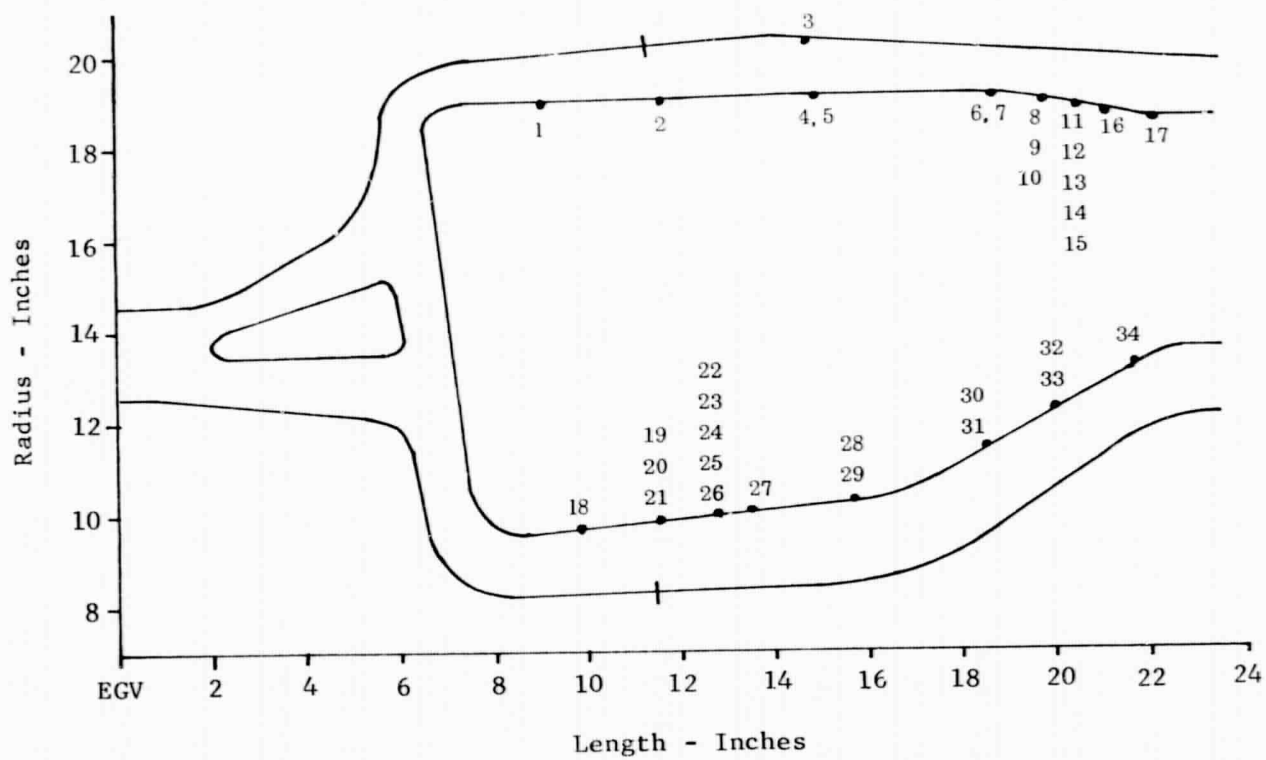
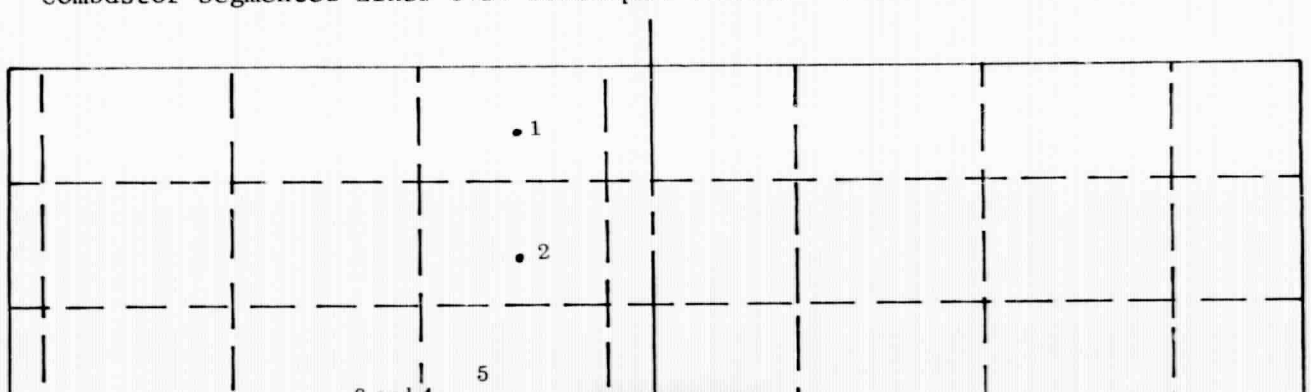


Figure 51

LINER THERMOCOUPLE LOCATIONS



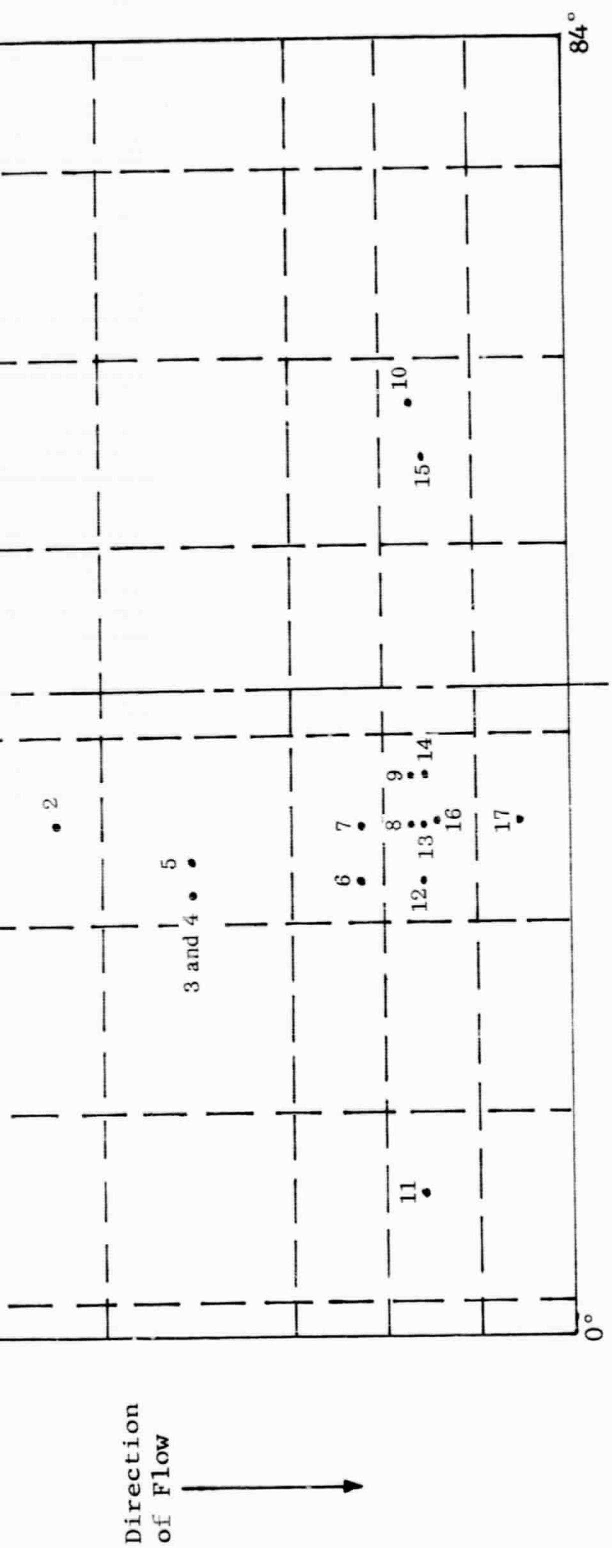
Combustor Segmented Liner O.D. Developed Surface - Viewed From Above



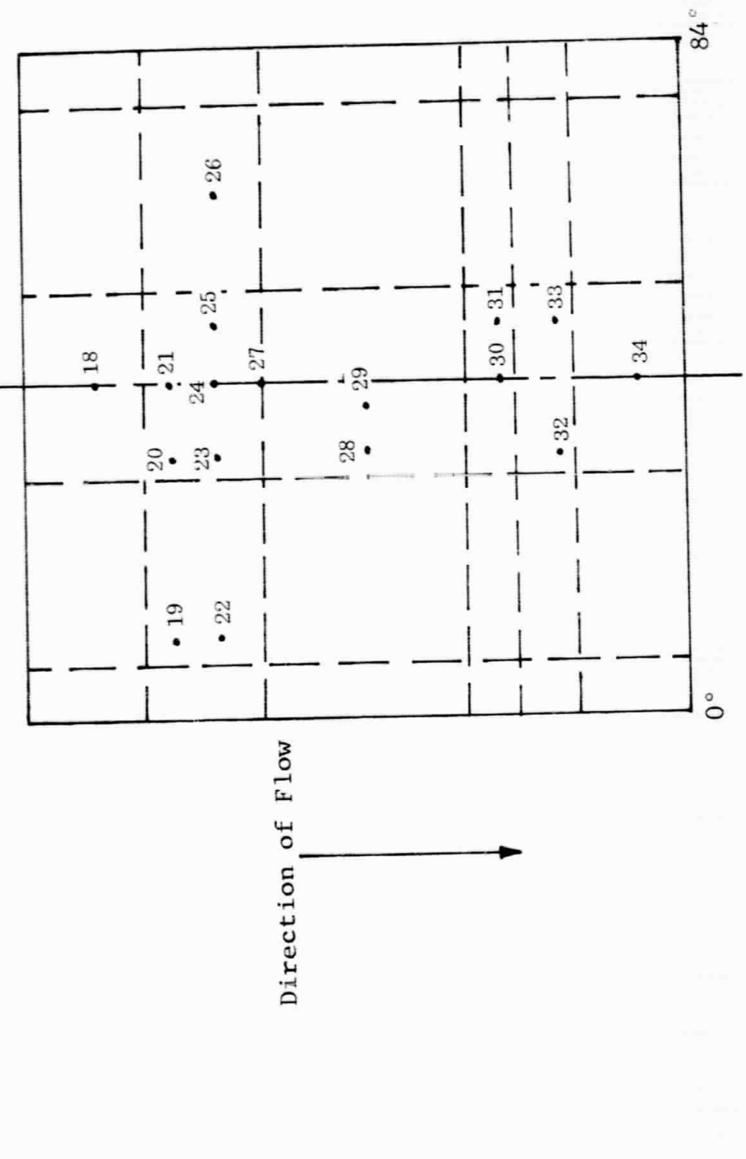
Direction of Flow

FOLDOUT FRAME

43



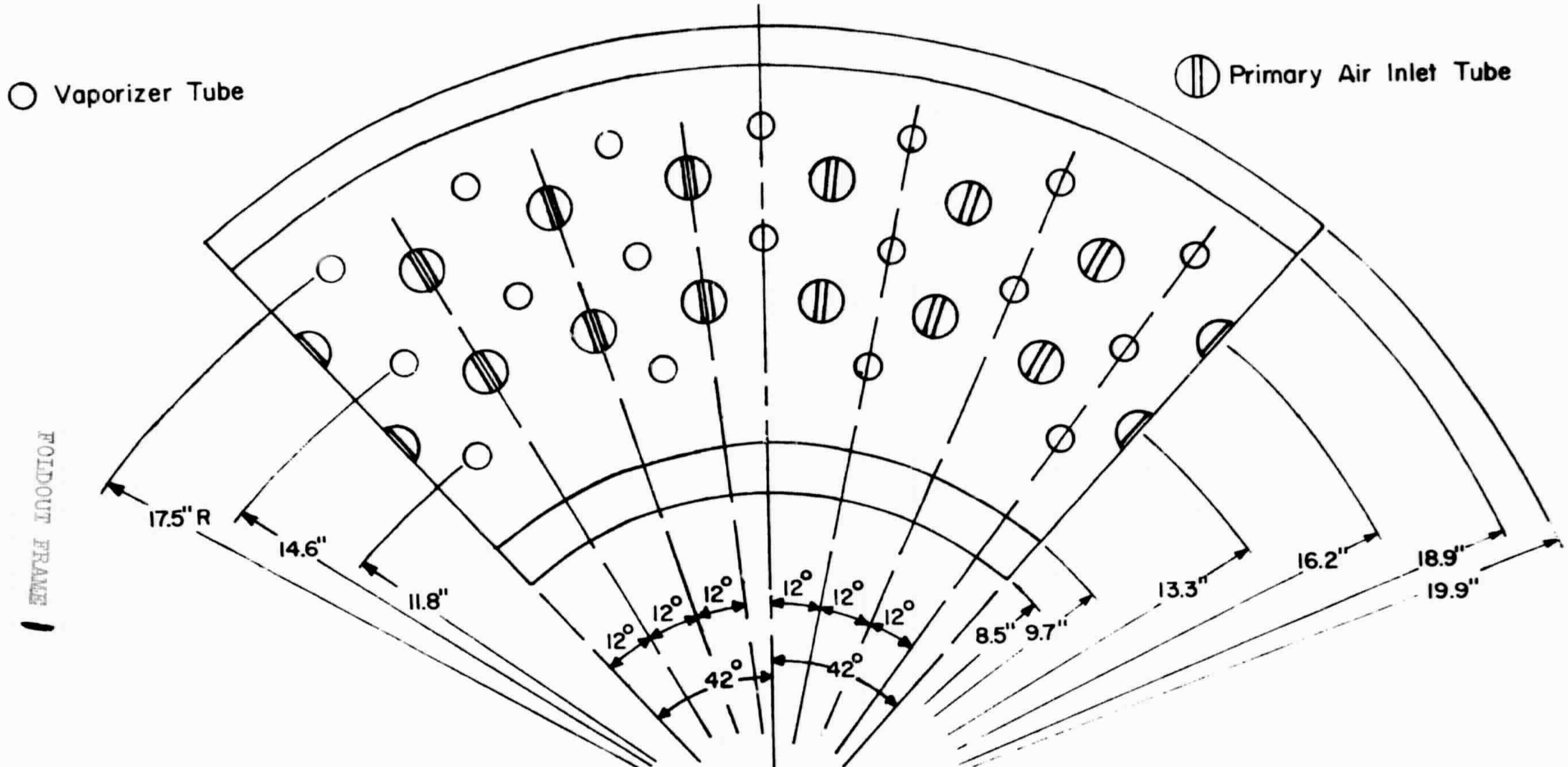
Combustor Segmented Liner I.D. Developed Surface - Viewed From Above



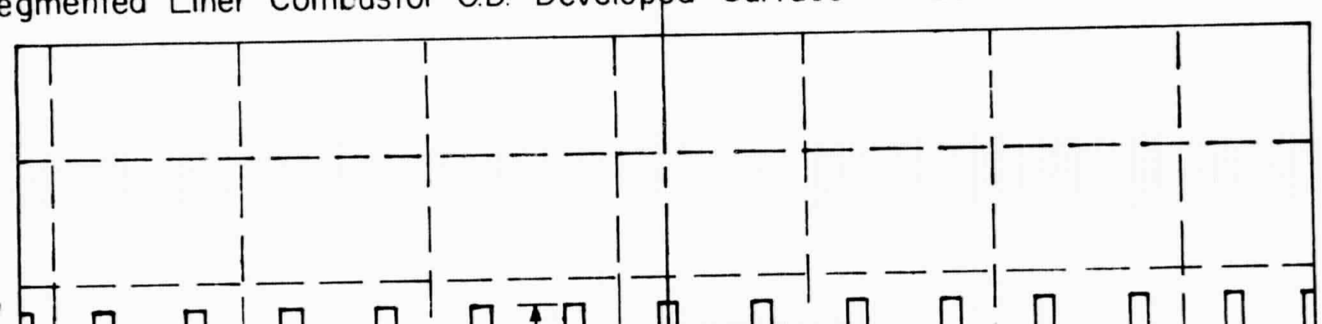
FOLDOUT FRAME 2

Figure 52

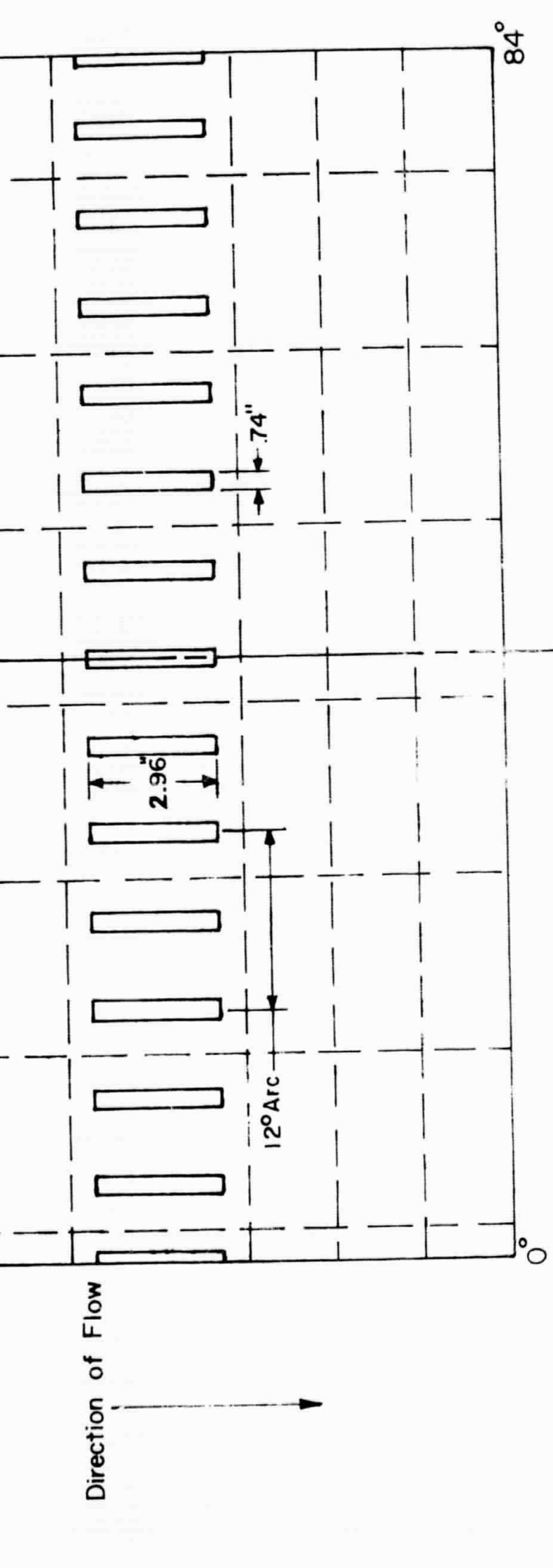
COMBUSTOR HEADPLATE - VAPORIZER AND PRIMARY AIRCUP ARRANGEMENT



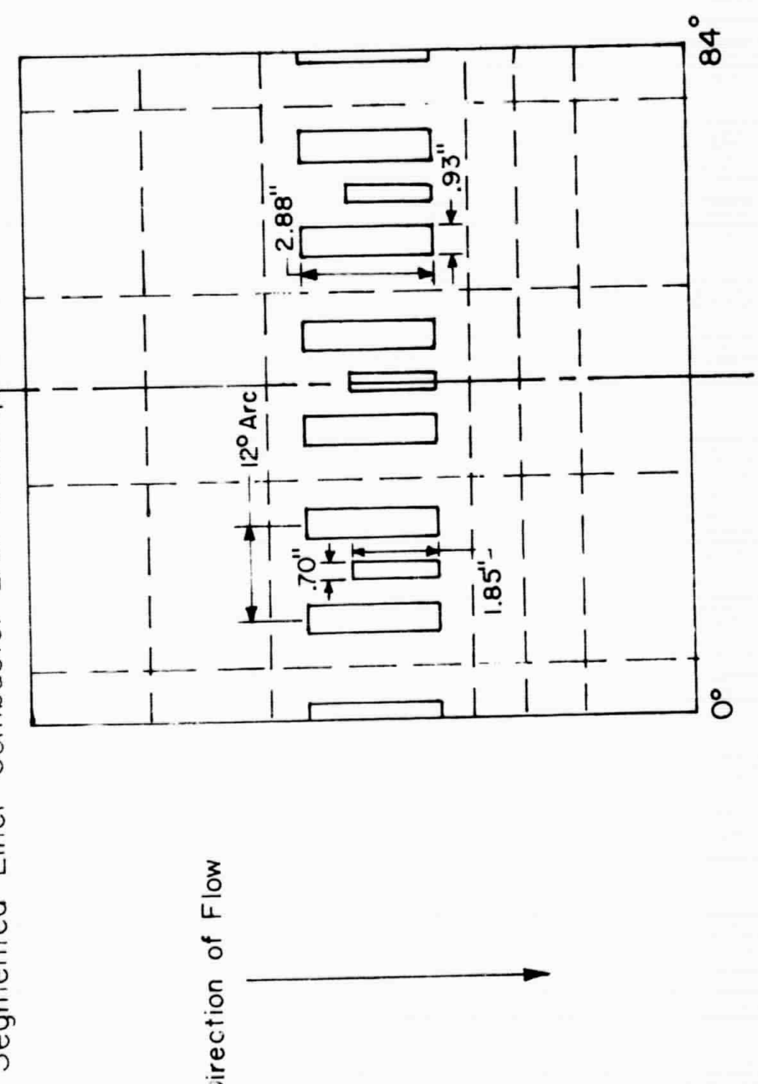
Segmented Liner Combustor O.D. Developed Surface — Location of Diluent Slots



FOLDOUT FRAME 1



Segmented Liner Combustor I.D. Developed Surface — Location of Diluent Slots



FOLDOUT FRAME 2

Figure 53

Accumulated testing time for the program was 112 hours, of which 46 were hot. Eight builds were tested. Running times, test objectives and results are listed in Tables VI and VII. A detailed breakdown of the test runs, with all operating conditions defined, is contained in Table VIII.

Details of the development effort encompassed by builds 1 through 1d, and the modifications incorporated in the hardware in the course of those builds, are thoroughly documented in the monthly progress reports. This effort will not be repeated here except as it pertains to clarification of the final results reported herein. The performance of the segmented liners, and performance improvements resulting from development efforts, are demonstrated in the testing conducted with rig builds 1e, 1f and 1g.

Rig builds 1e, 1f and 1g were extensively tested at inlet air pressures of 2 and 4 atmospheres, inlet air temperatures of 570, 860 and 1150°F, and fuel-air ratios of .015, .017 and .020. Rig builds 1e and 1g incorporated liner configuration #1. Build 1f incorporated liner configuration #3. A general description of these builds, and the testing associated with them, follows:

Build 1e - Liner Configuration #1

This build incorporated all modifications applied to earlier builds, plus an adjustment to the headplate air flow areas to optimize air flow distribution. Twenty-seven test points were run, covering the full range of air inlet temperatures and overall fuel-air ratios, at 2 and 4 atmospheres. Testing was discontinued due to deterioration of the rig side plates (See Figure 46).

The liner assembly was inspected and post test photographs were taken. These are presented in Figures 54 through 57. The light colored areas which appear on the liner inner and outer assemblies are calcium deposits that occurred as a result of a water leak in the exhaust duct during a post-test equipment check-out. During this check-out, 1150°F air passed through the rig with no burning. The discolorations have no bearing on liner condition.

LINER CONFIGURATION NO. 1
INNER LINER ASSEMBLY
BUILD 1e: POST-TEST

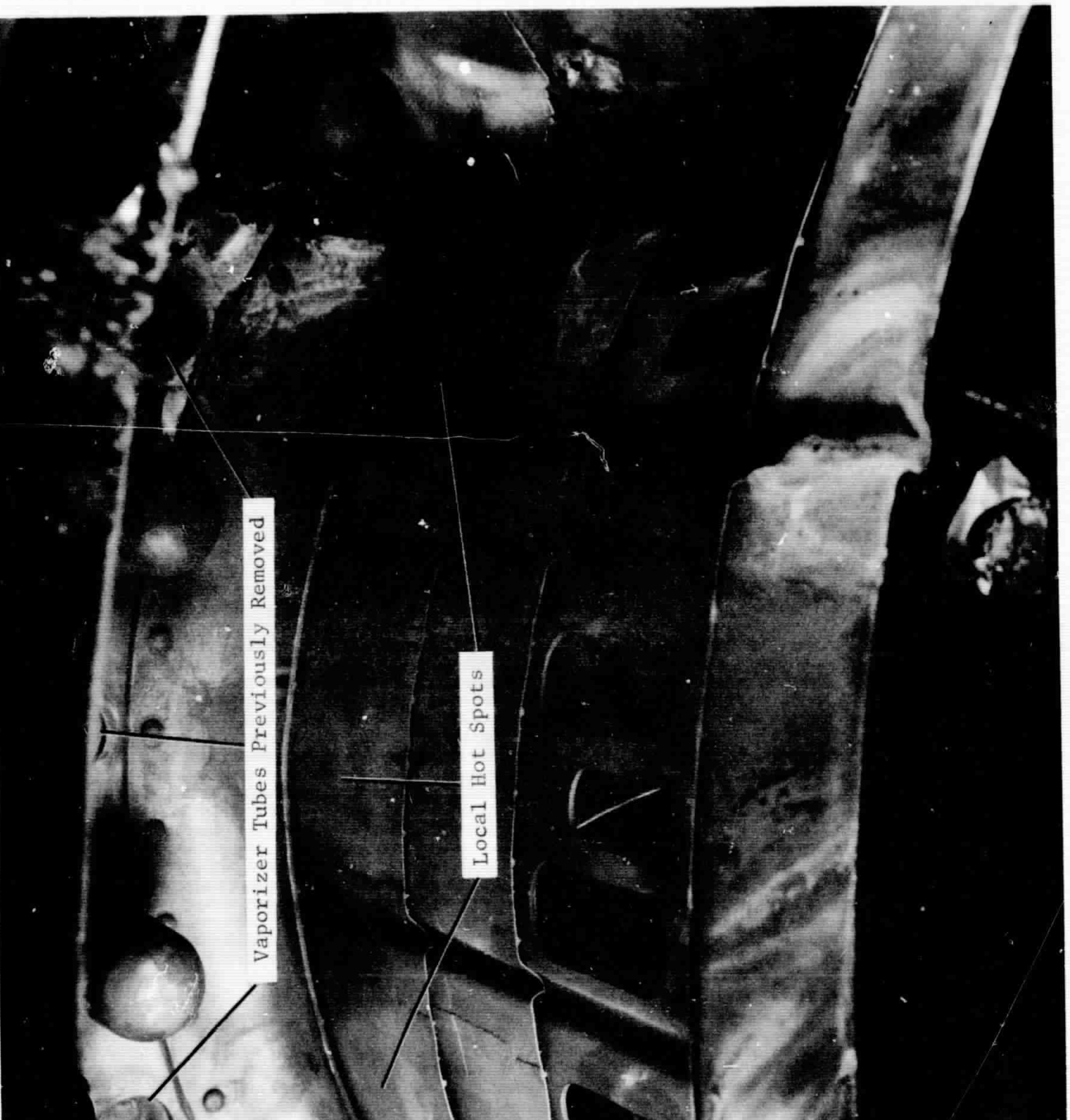


Figure 54

LINER CONFIGURATION NO. 1
INNER LINER ASSEMBLY
BUILD 1e: POST-TEST

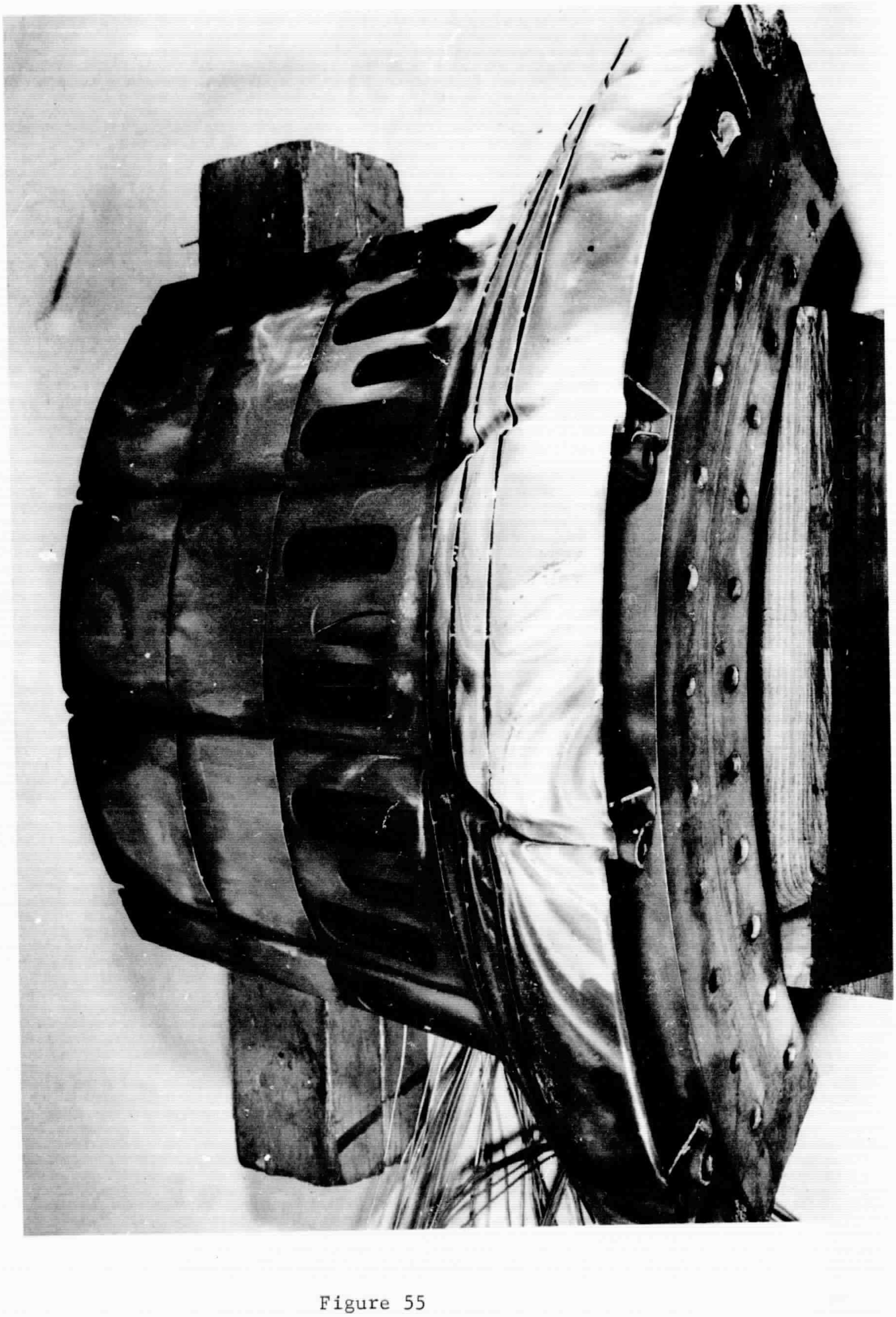


Figure 55

LINER CONFIGURATION NO. 1
OUTER LINER ASSEMBLY
BUILD 1e: POST-TEST

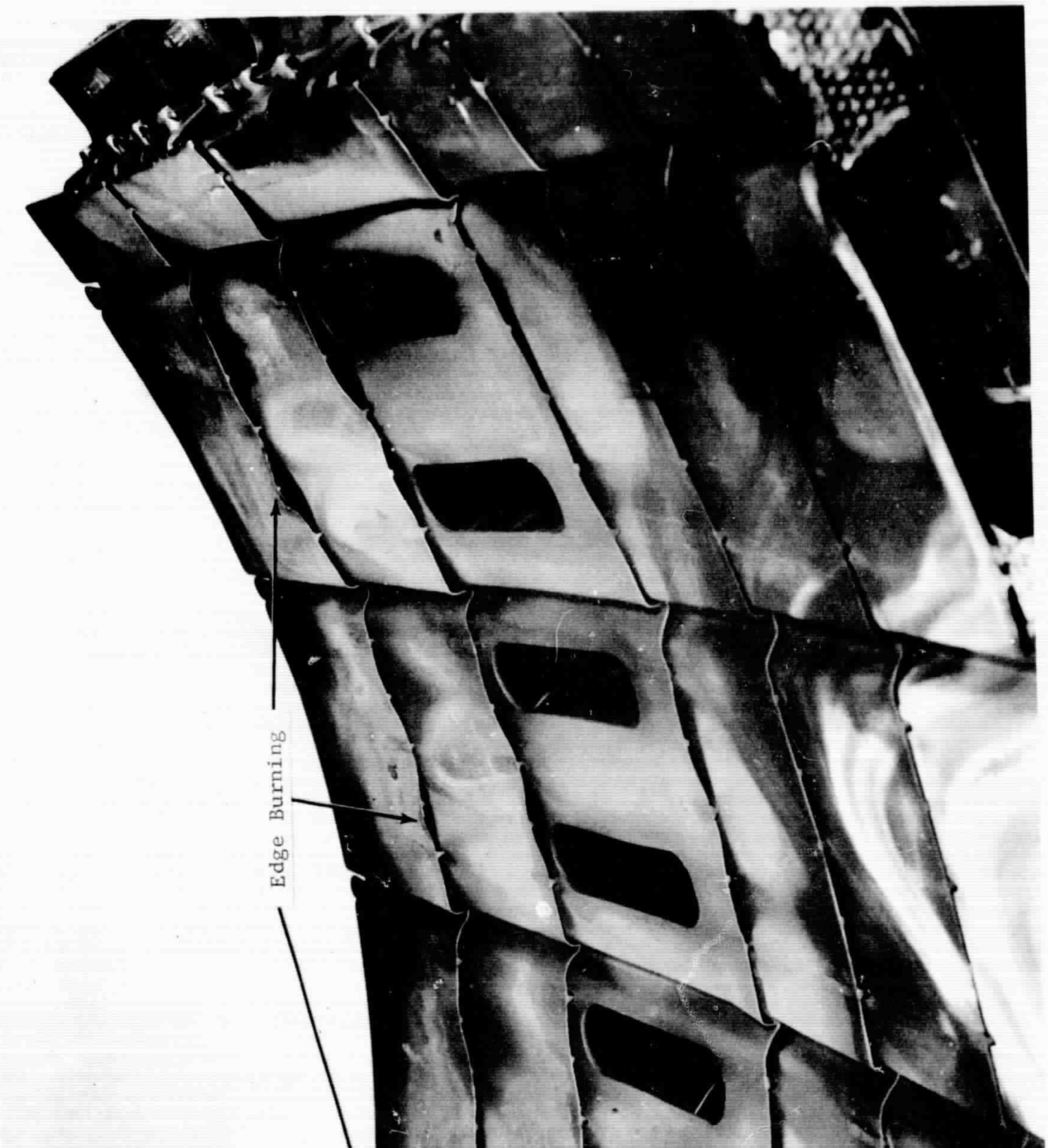


Figure 56

LINER CONFIGURATION NO. 1
OUTER LINER ASSEMBLY
BUILD 1e: POST-TEST

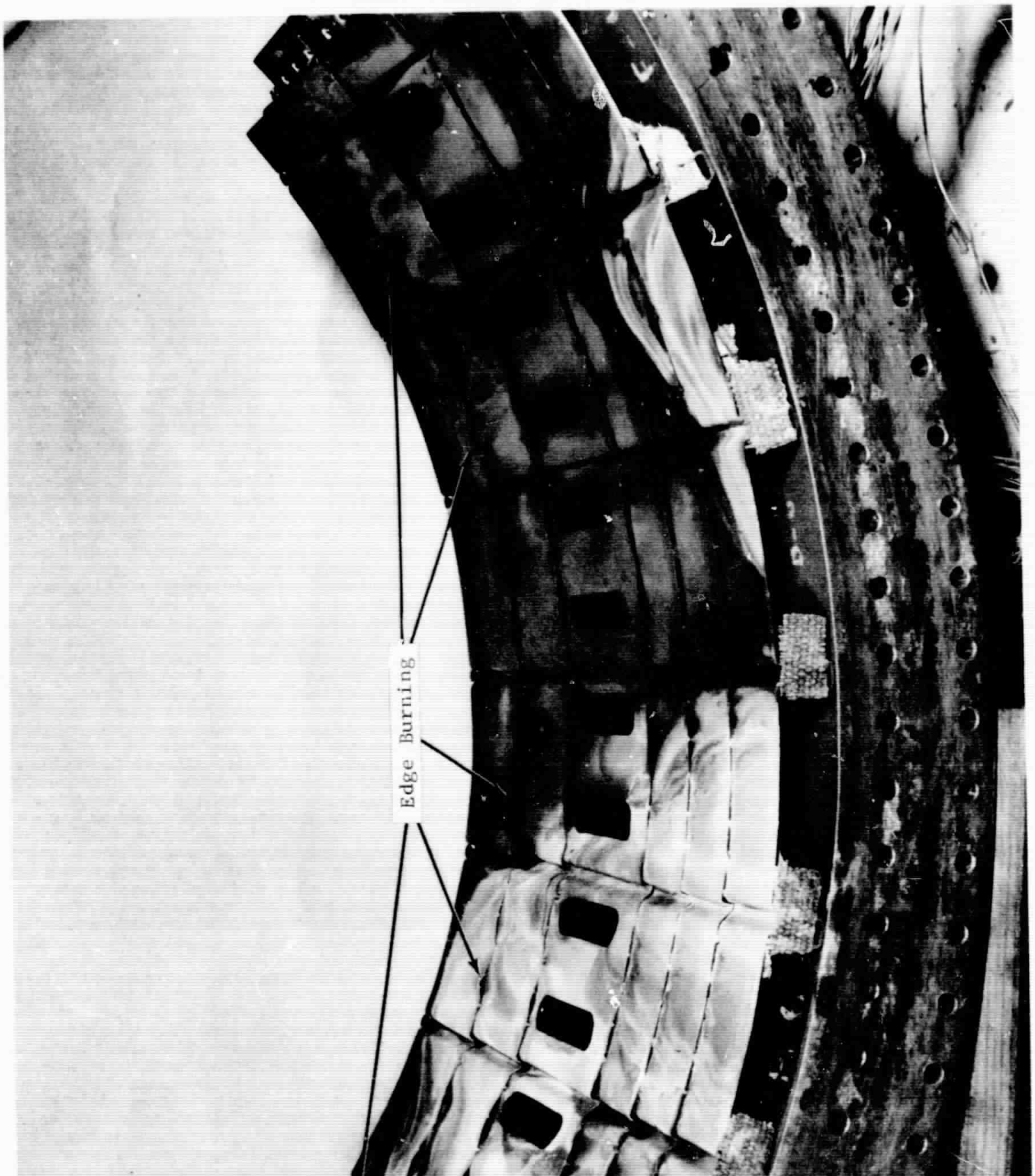


Figure 57

Inner liner post-test photographs are presented in Figures 54 and 55. It can be seen that no evidence of warpage or closing of the film cooling slots occurred. However, surface discoloration and oxidation on the first row of segments, located in the combustor primary zone, were evident. These areas occurred in line with the "two-in-a-row" vaporizer positions (Figure 53), the result of which is a high local temperature due to a localized lean fuel-air mixture. Recorded liner metal temperatures reached a maximum at this location. The maximum temperature ran 150^{o} higher than the predicted design value of $1600^{o}F$.

Outer liner post-test photographs are presented in Figures 56 and 57. From these figures, it is readily evident that warpage and liner distortion took place, especially in the primary zone. Downstream edge burning on the segments, as noted, occurred at locations in line with the air cups where air flow is high, fuel-air lean, and temperature high.

Warping of the liners in the primary zone resulted in very large film cooling slot openings, causing disturbance of the coolant film. Outer liner surfaces and film cooling slots were in good shape downstream of the diluent slots.

Post-test examination of the headplate revealed aircup damage due to pressure effects at the elevated temperatures tested (See Figure 45). It was determined that the aircups would have to be strengthened before attempting hot tests at six atmospheres.

While awaiting a modified headplate, with new aircups, it was decided to run comparative tests on liner configuration #3. This done on build 1f.

Rig Build 1f - Liner Configuration #3

The existing hardware for liner configuration #3 was instrumented identically to configuration #1 and installed in the rig.

A total of 12 hours 15 minutes of hot running was successfully conducted at 2 and 4 atmosphere pressure levels, with a burner inlet temperature of 570°F, and 2 atmosphere pressure level with a burner inlet temperature of 860°F. Radiant heat flux evaluations were also conducted during this hot running.

Build 1f test results indicated that total pressure losses ($\Delta P_T/Q_3$) were of the same magnitude as the total pressure losses obtained running with Liner Configuration No. 1. Typical data is presented in Figure 58. Liner metal thermocouple results showed that, in general, liner temperatures for Configuration No. 3 ran about the same as those for Configuration No. 1. This data is contained in Tables X and XI.

During this test the liners were subjected to excessive temperatures, and to loads well in excess of design conditions. This occurred due to facility malfunctions, and it is quite important to note that the liners withstood these conditions with only minor damage.

In the first malfunction, a sudden depression in air flow caused by a seal failure produced a momentary fuel-air ratio of .024 prior to fuel cut-off. Inspection revealed that the liners had not been damaged by the high fuel-air ratio and resulting high combustor temperature.

The second malfunction, a back-pressure valve failure, also produced a very high fuel-air ratio, accompanied by a high combustor overpressure. This condition lasted 5 to 10 seconds. In that time, liner metal temperatures increased as much as 700°F. Post-test inspection revealed downstream edge damage to a number of liner segments. Typical damage is visible in Figures 59, 60 and 61. However, it is noted that the damage was restricted to the thin trailing edges of the liners, and that no liner or hanger structural failures occurred.

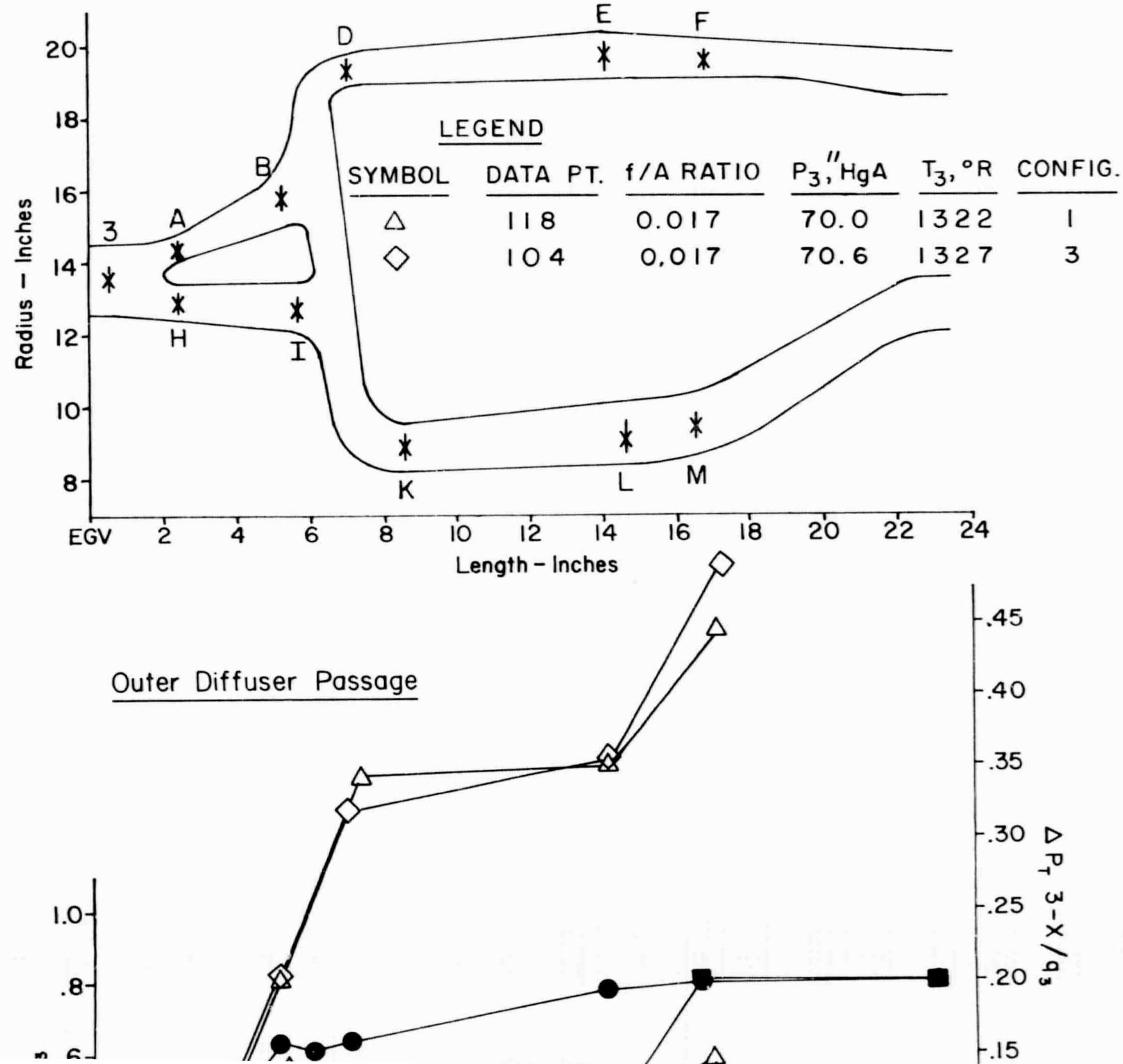
Enough data points had been accumulated to provide an adequate comparison with liner configuration #1. The data obtained indicated no noticeable difference in operating temperatures or pressure characteristics between the two configurations.

Rig Build 1g - Liner Configuration #1

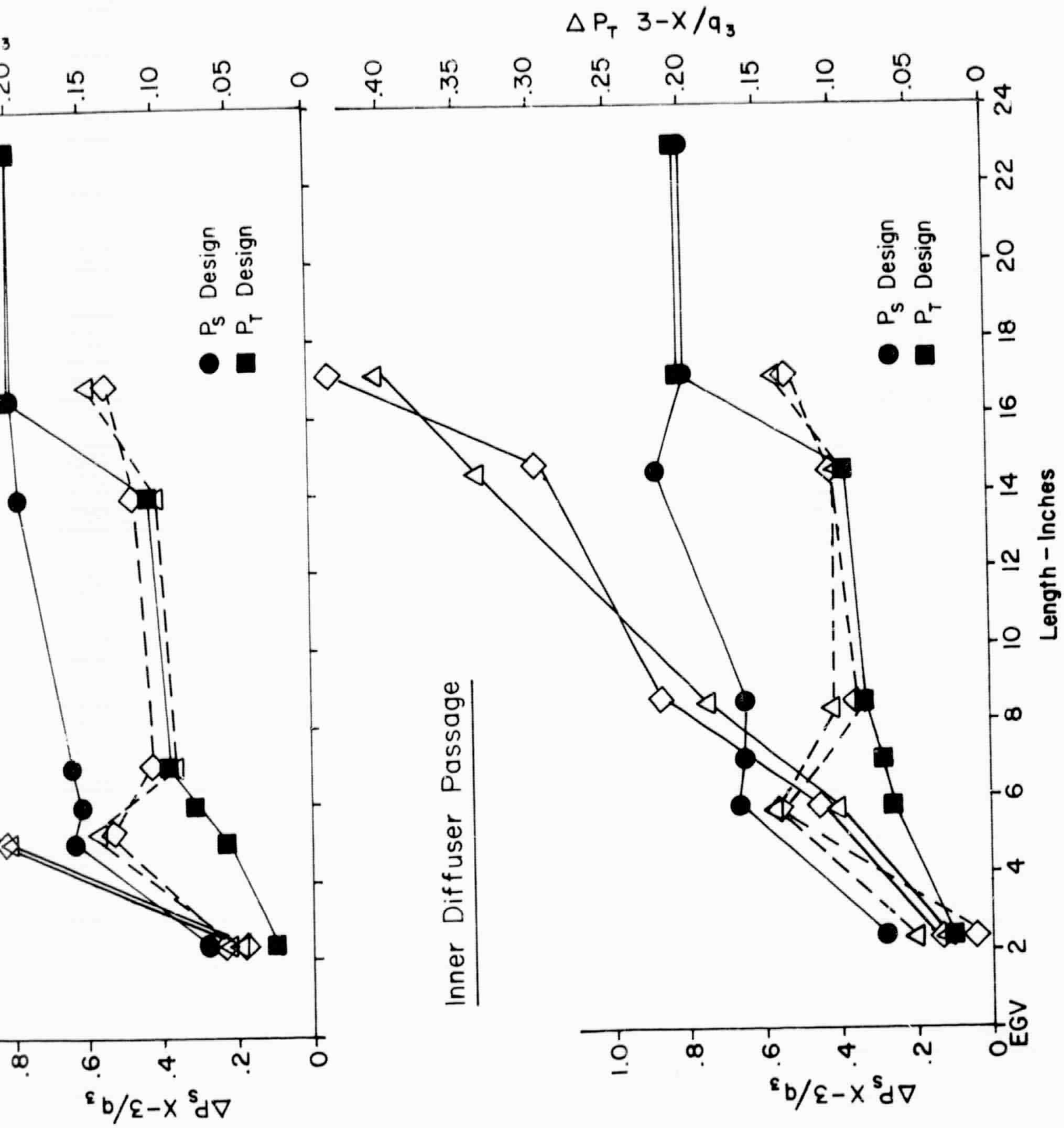
A physical inventory and inspection of the liner segments for both Configuration No. 1 and No. 3 showed that Configuration No. 1 had more useable back-up liners available. Therefore, Configuration No. 1 was selected and

DIFFUSER PERFORMANCE

build Ie vs If

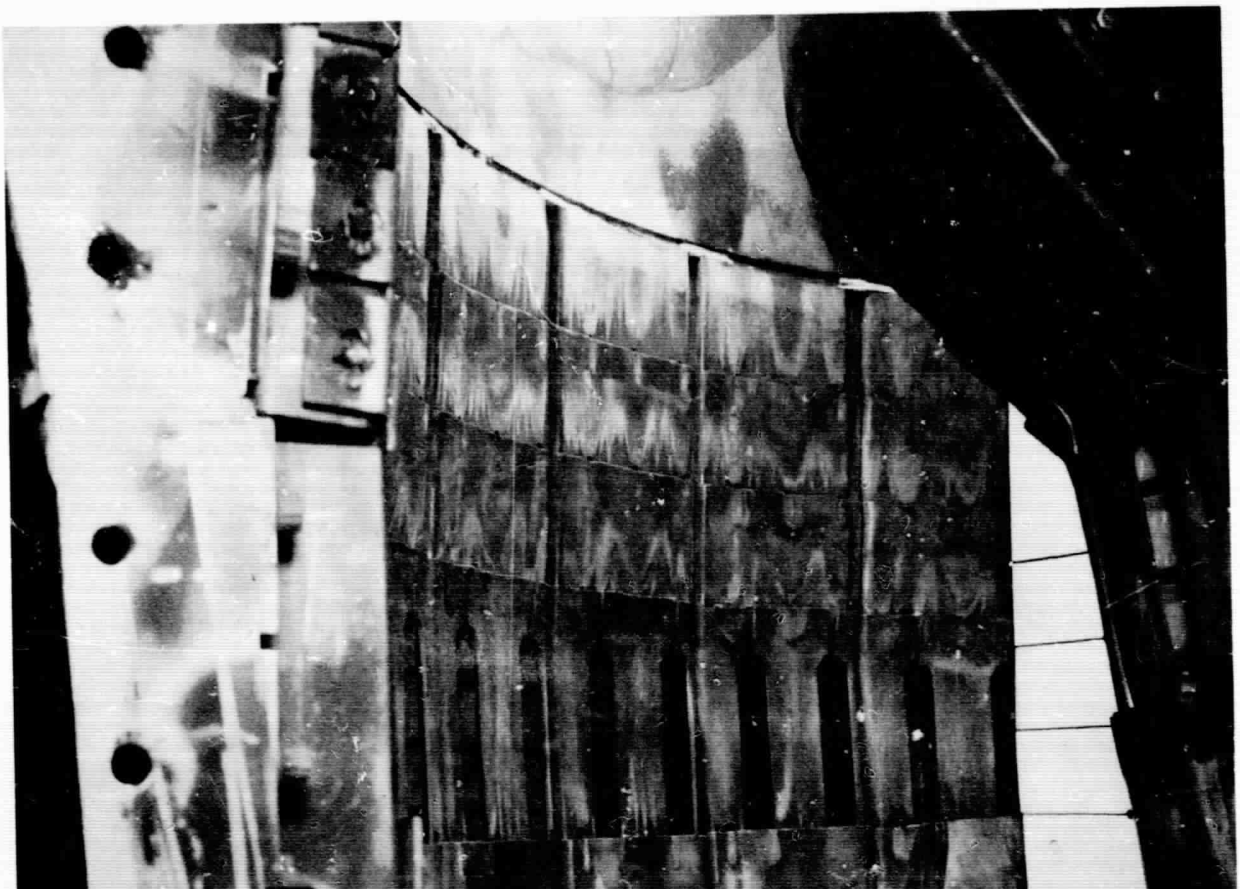


FOLDOUT FRAME 1



FOLDOUT FRAME 2

Figure 58



LINER CONFIGURATION NO. 3 SECTOR RIG ASSEMBLY
BUILD 1f: POST-TEST

Figure 59

LINER CONFIGURATION NO. 3
INNER LINER ASSEMBLY
BUILD 1f: POST-TEST

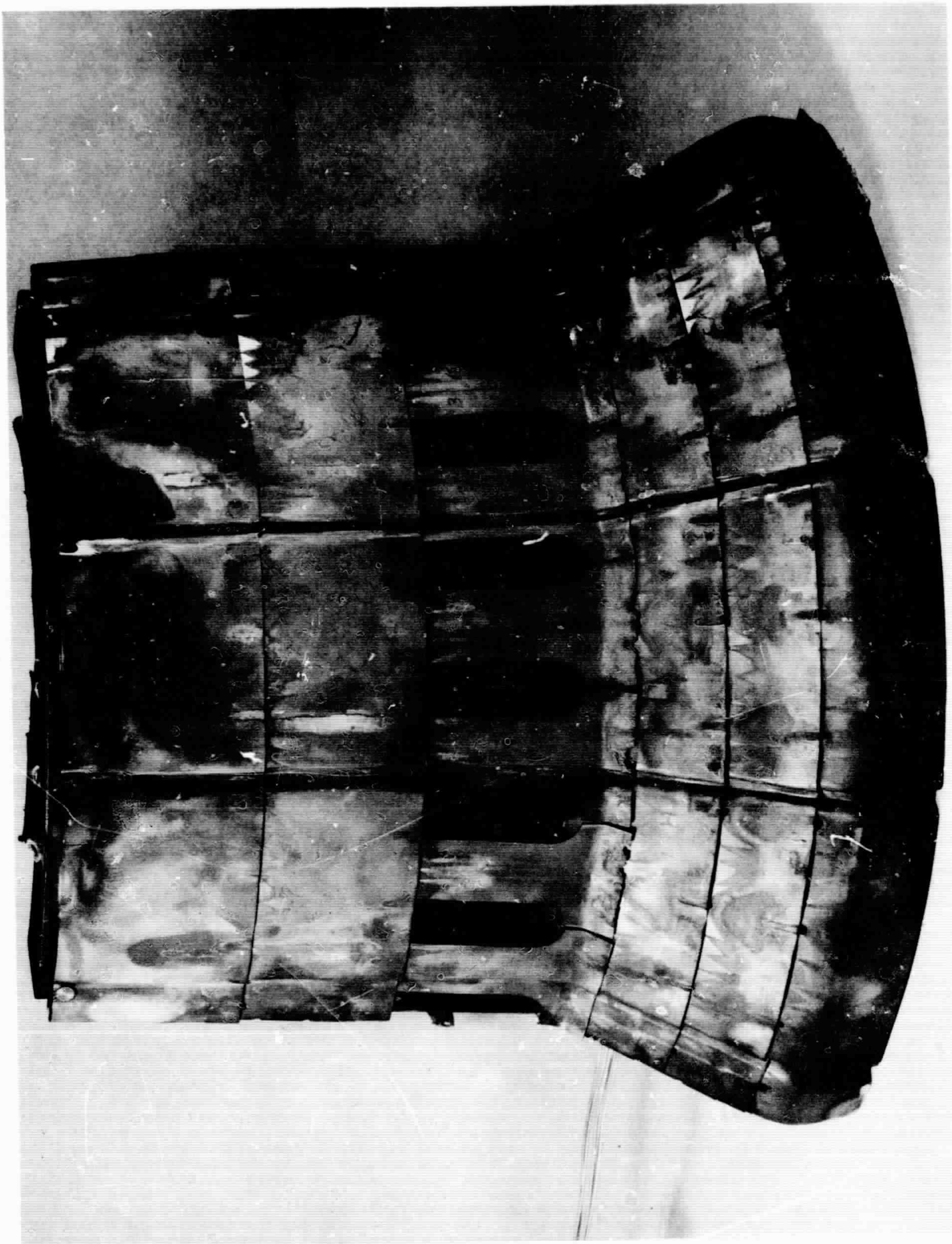


Figure 60

LINER CONFIGURATION NO. 3
OUTER LINER DETAIL
BUILD 1f: POST-TEST

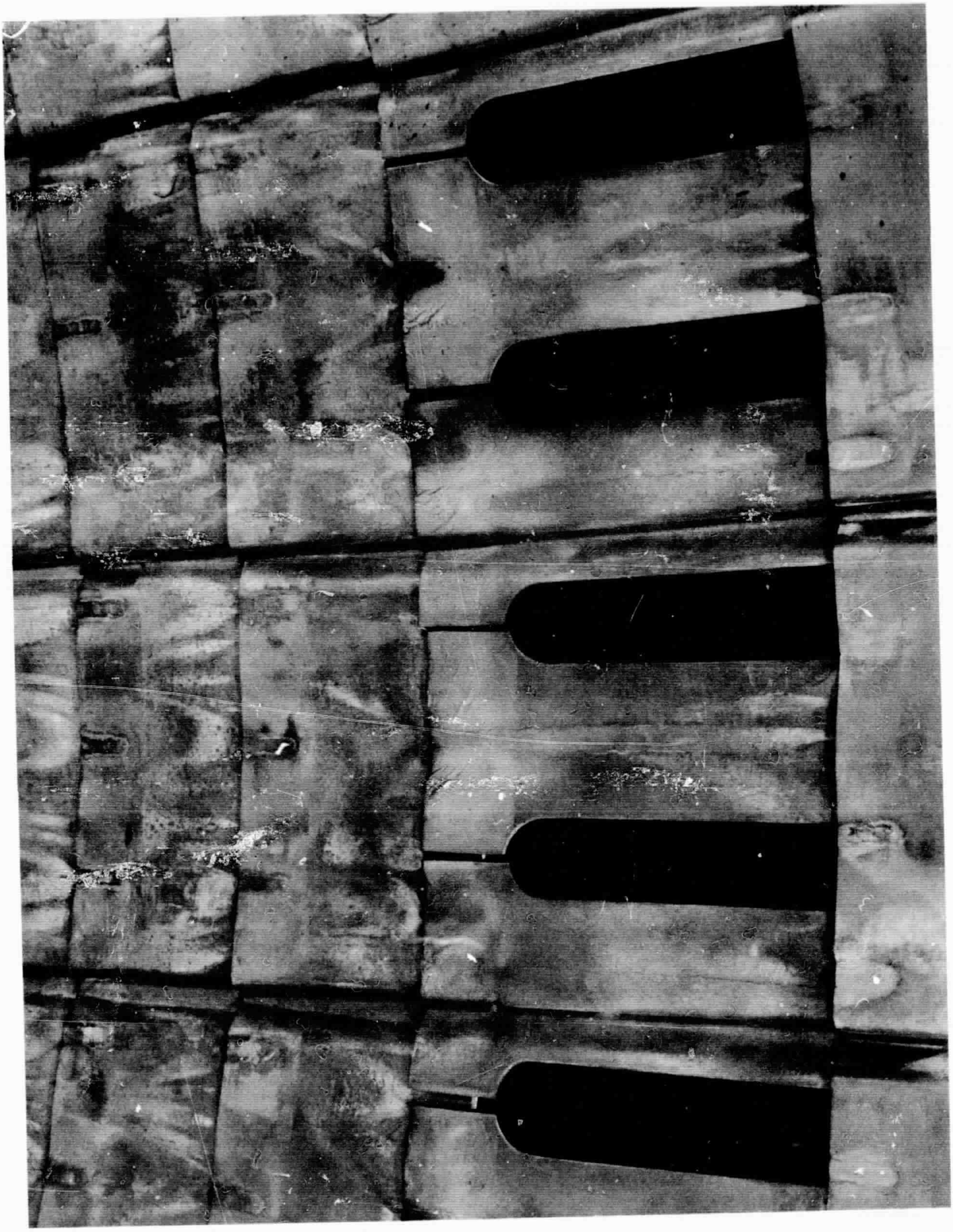


Figure 61

approved by the NASA Project Engineer for the next build, 1g. It was expected that Task IV could be completed with this build.

Since Task IV was to verify the segmented liner concepts, all optimized fixes were incorporated into the build as follows:

1. Headplate Assembly (See Figure 44)
   a. Newly designed fuel tubes
   b. Heavier air cups
2. Liner Segments (See Figure 42)
   a. Increased liner hanger slots to accomodate thermal stresses
   b. More "land" supports added in film air cooling slots to maintain desired slot thickness.
   c. Liner segment length reduced 1/4 inch at the liner trailing edge to remove the thin distressed areas.
   d. Patches added over the exposed portion of the hanger slots resulting from the liner cut back, to prevent an over-supply of secondary or diluent air in the combustor zone.

The liner segments were instrumented with metal temperature thermocouples in the same configuration as for builds 1e and 1f. (See Figure 52).

A total of 16 hours of testing was conducted, including 5 hours of burning time. Hot testing was conducted at inlet air pressures of 2 and 4 atmospheres for inlet air temperatures of 570°, 860° and 1150°F, with fuel-air ratios of .015, .017 and .020. Twenty-one test points were recorded in all.

Periodic rig inspections were made throughout this testing. The inspection performed following the four atmosphere test points revealed severe damage to the combustor sideplates, of the same nature as encountered in build 1e. The segmented liners themselves were in excellent condition. Post-test photographs of the inner and outer liner assemblies are presented in Figures 62, 63 and 64.

The condition of the liners should be noted, and compared with the post-test condition of the liners in build 1e (Figures 54 through 57). Due to the

LINER CONFIGURATION NO. 1
OUTER LINER ASSEMBLY
BUILD 1g: POST-TEST

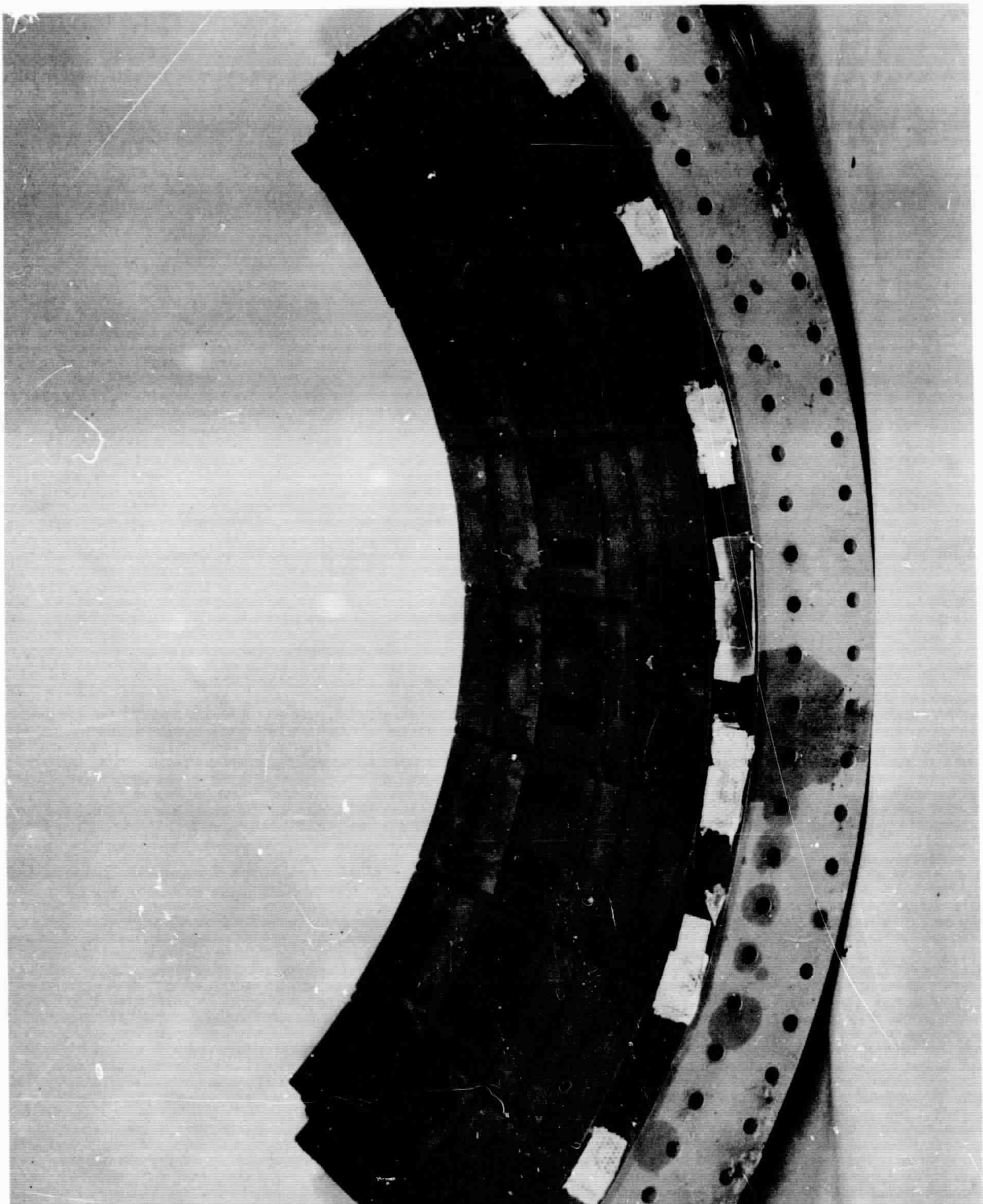


Figure 62

LINER CONFIGURATION NO. 1
OUTER LINER ASSEMBLY
BUILD 1g: POST-TEST

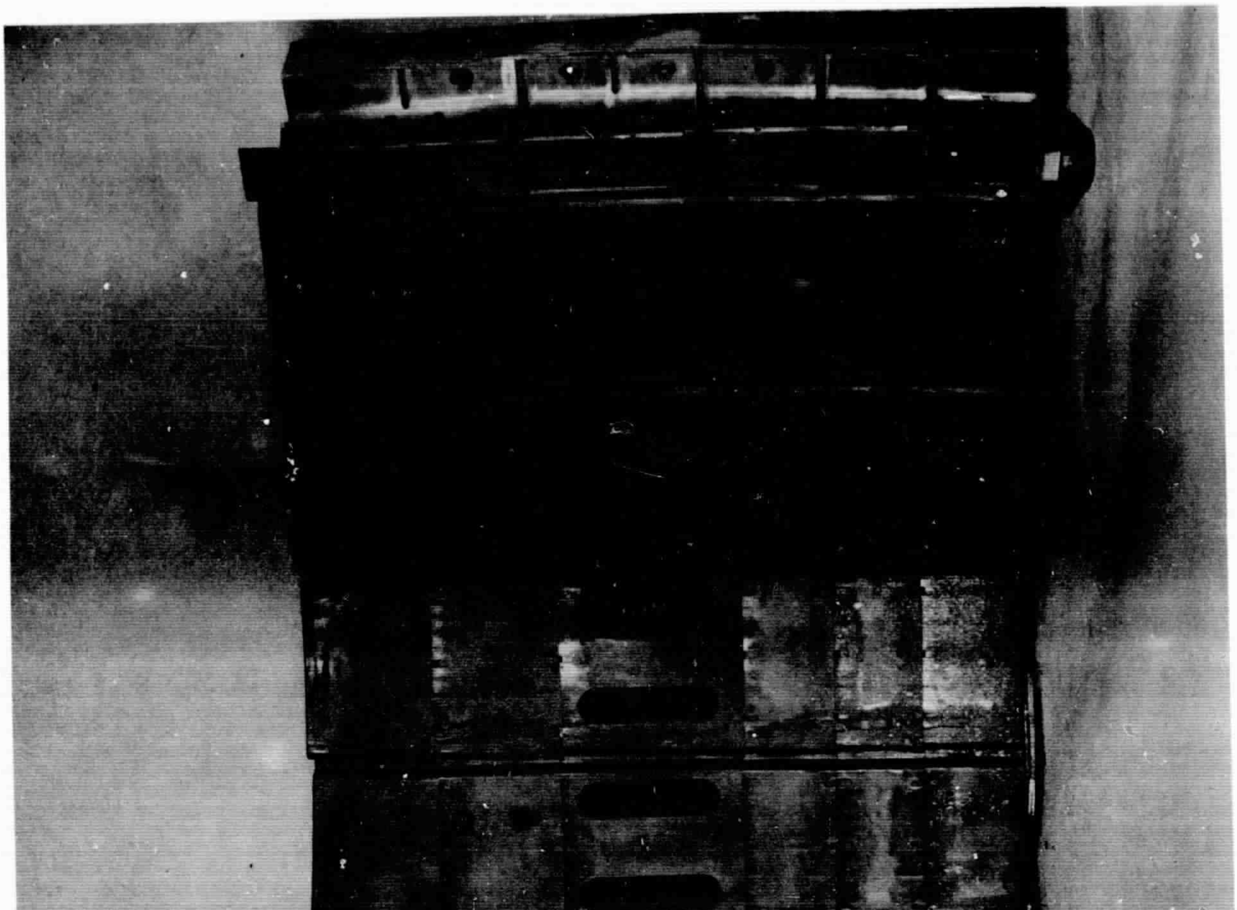


Figure 63

LINER CONFIGURATION NO. 1
INNER LINER ASSEMBLY
BUILD 1g: POST-TEST

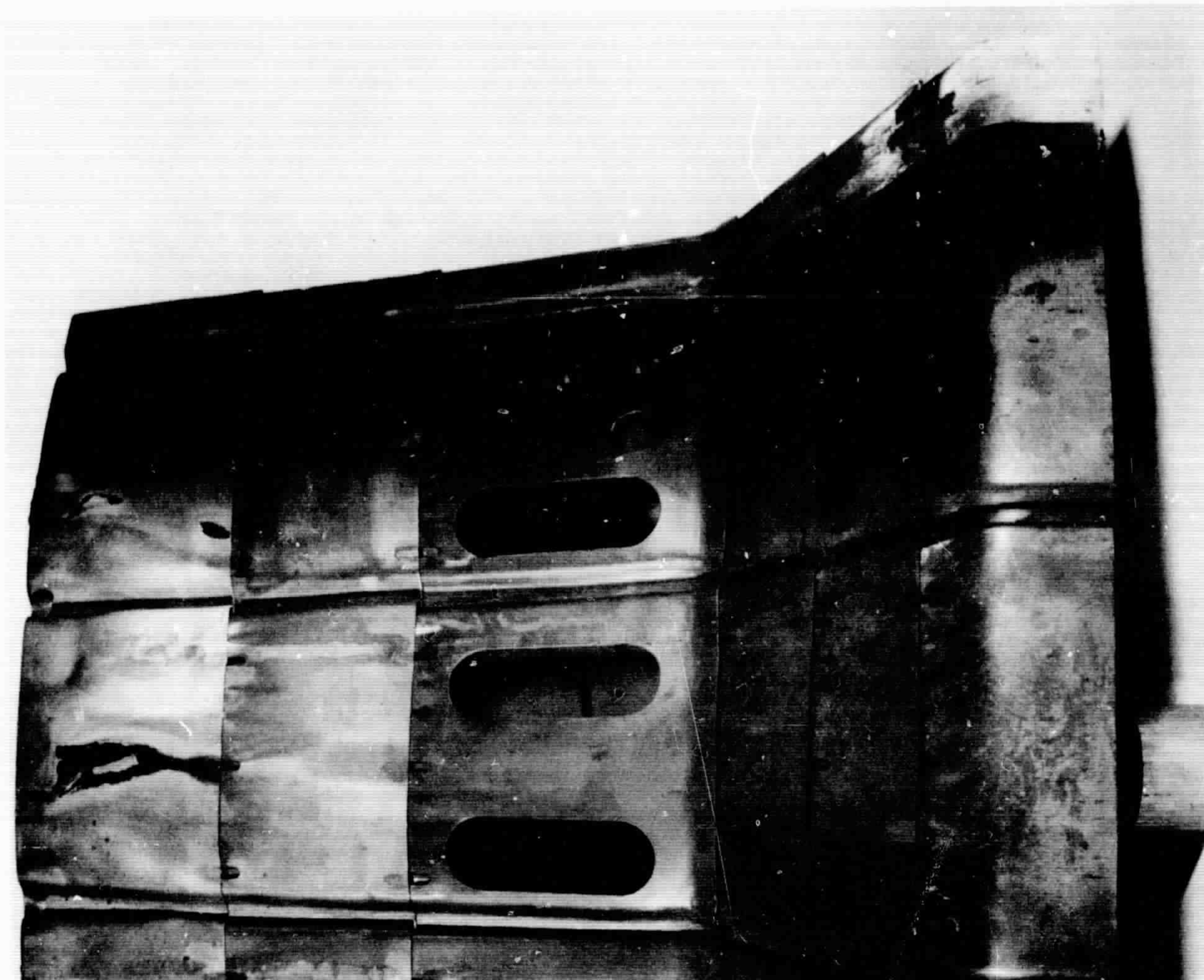


Figure 64

liner improvements incorporated in build 1g, there was no warping of liner trailing edges, nor is there any evidence of liner damage due to overheating in the vicinity of the headplate. The dark patches on the inner liner in the primary zone (visible in Figure 64) are carbon deposits. Sufficient data had been collected which demonstrated the segmented liner concept. Accordingly, the decision was made by NASA and Curtiss-Wright to discontinue further test program activities.

4.4 Test Results

Evaluation of the feasibility of the segmented liner concept hinged on three primary factors:

a. Structural integrity, or the ability of the segments, and of the liner assembly, to withstand the thermal and structural loads imposed on them;

b. Durability, as related to:
   1. Liner metal temperatures (tendency to develop local hot spots)
   2. Liner warpage, especially in the region of the film cooling slots

c. Maintainability, in terms of the ability to disassemble and reassemble the individual segments after prolonged exposure to high temperatures.

The test program conclusively demonstrated items (a) and (c), in the following sense:

1. Throughout the program, there was never a structural failure of any liner segment.
2. No difficulty was experienced at any time during the program in disassembling the liners, or in separating a single liner segment from the assembly.

Item (b) is a function of liner design, liner coolant flow and combustor operating characteristics. As such, it is far more subject to development than the other considerations. The following sections are related primarily to the evaluation of liner durability, including the factors which affect it.

4.4.1 Liner Metal Temperature Distribution

The bulk of testing directed toward liner optimization was conducted with rig builds 1e, 1f and 1g.

The liner temperature data obtained in testing of builds 1e (liner configuration 1), 1f (liner configuration 3), and 1g (shortened liner configuration 1) are contained in Tables IX, X, and XI, respectively. The following discussion is restricted to those data points run at the design fuel-air ratio of .017. For reference, a typical variation of liner temperature with fuel-air ratio is shown in Figure 65.

4.4.1.1 Variation with Air Inlet Pressure

No runs were made at six atmosphere inlet pressure. It was observed in the 2 and 4 atmosphere tests that the liner temperature increases slightly with increase in pressure level from 2 to 4 atmospheres. Figure 66 presents the variation of liner temperature with pressure for three typical inner liner stations. It is observed that the variation of liner temperature with air inlet pressure never exceeds 100°F, and is generally much less than that. On the basis of this small increase in liner temperature between 2 and 4 atmospheres, the data obtained at 4 atmospheres is considered to be representative of the temperatures which would exist at the design point of six atmospheres. The quantitative liner temperature evaluations presented are based on comparisons between predicted temperatures at six atmospheres and measured temperatures at four atmospheres.

4.4.1.2 Air Flow Distribution

The diffuser air distribution cold flow testing and analysis indicated that flows to the liner cooling passages were lower than originally specified (See Table XII). A heat transfer analysis was performed which utilized the cold flow data, and it was concluded that the liner temperatures would be somewhat higher than desired, though not seriously so. Further, it was felt that this factor could most accurately be determined by actual hot tests. Combustion testing was therefore begun, and all tests have been conducted with the original air supply configuration. The liners did run

67-2849

EFFECT OF FUEL-AIR RATIO ON LINER TEMPERATURE

Rig Build 1e

(Based on Thermocouple T_M-34 Located at 42°, 6th Segment Row, Inner Liner)

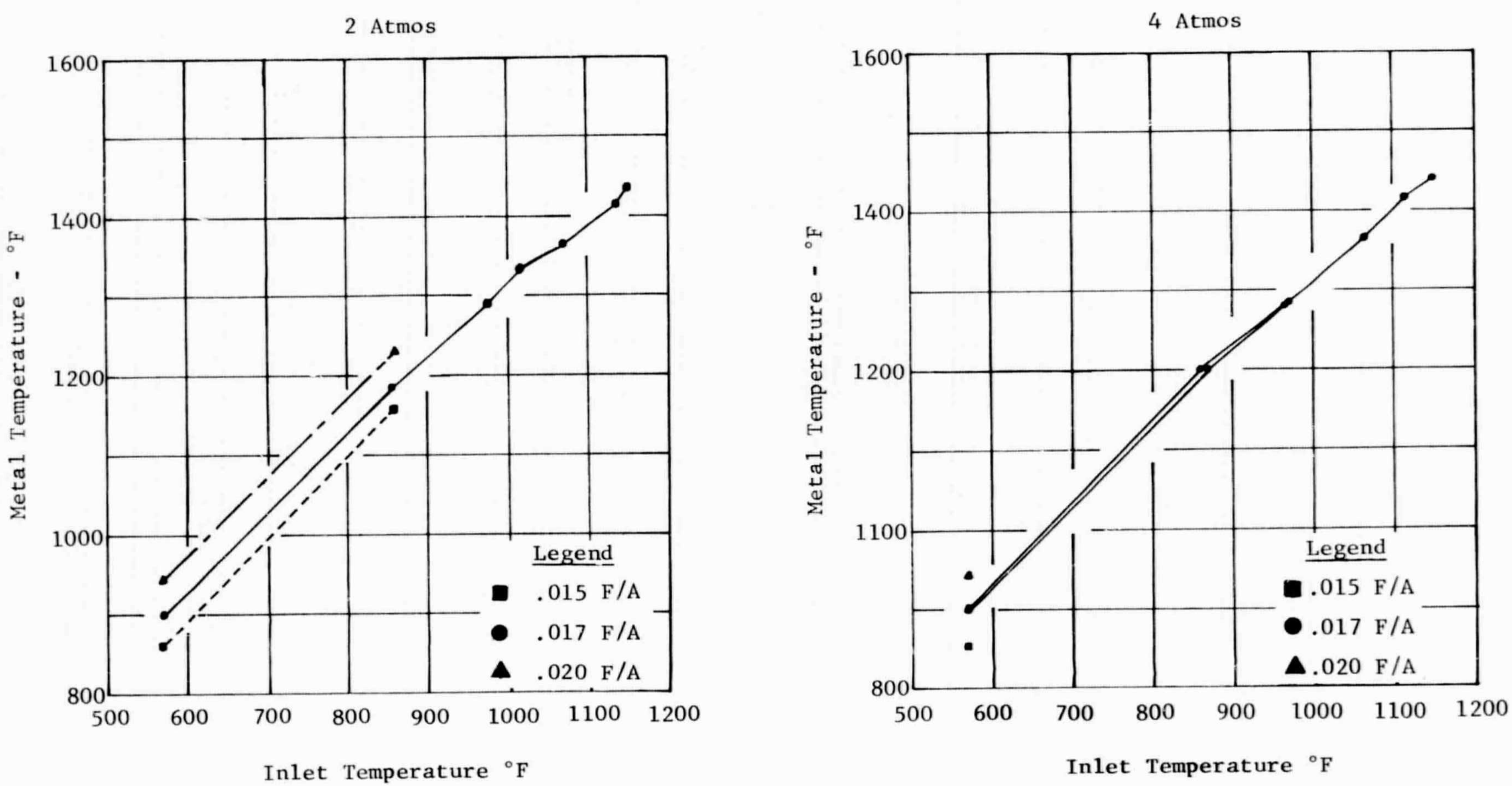
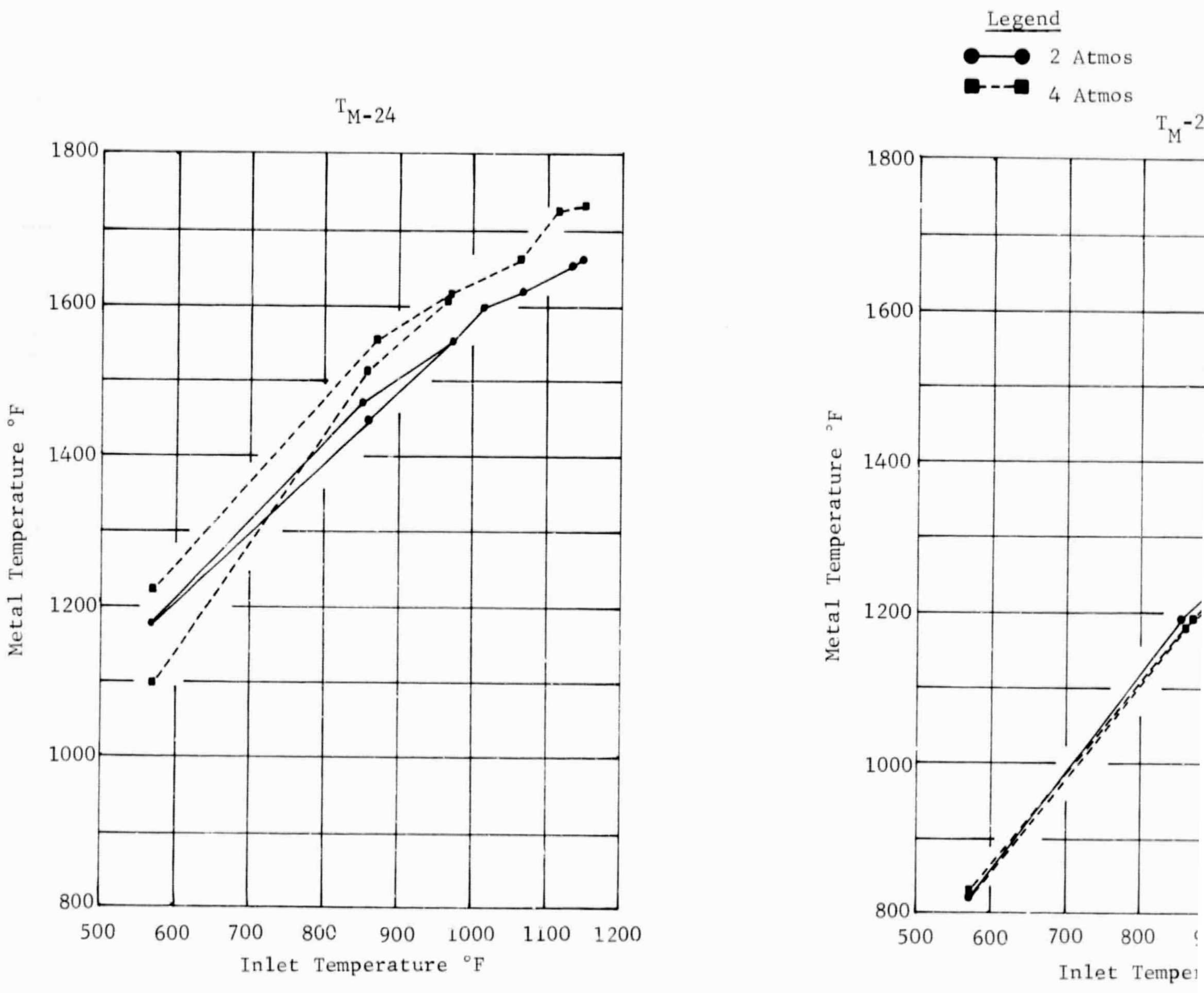


Figure 65

EFFECT OF PRESSURE LEVEL ON LINER

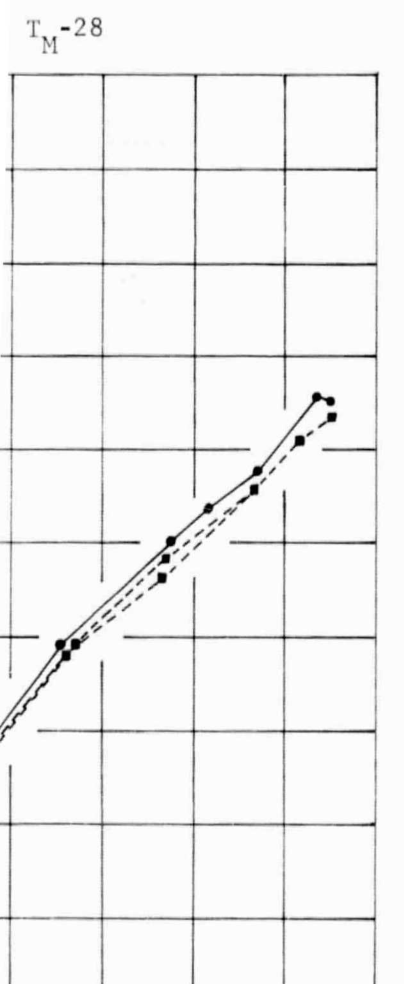
Rig Build

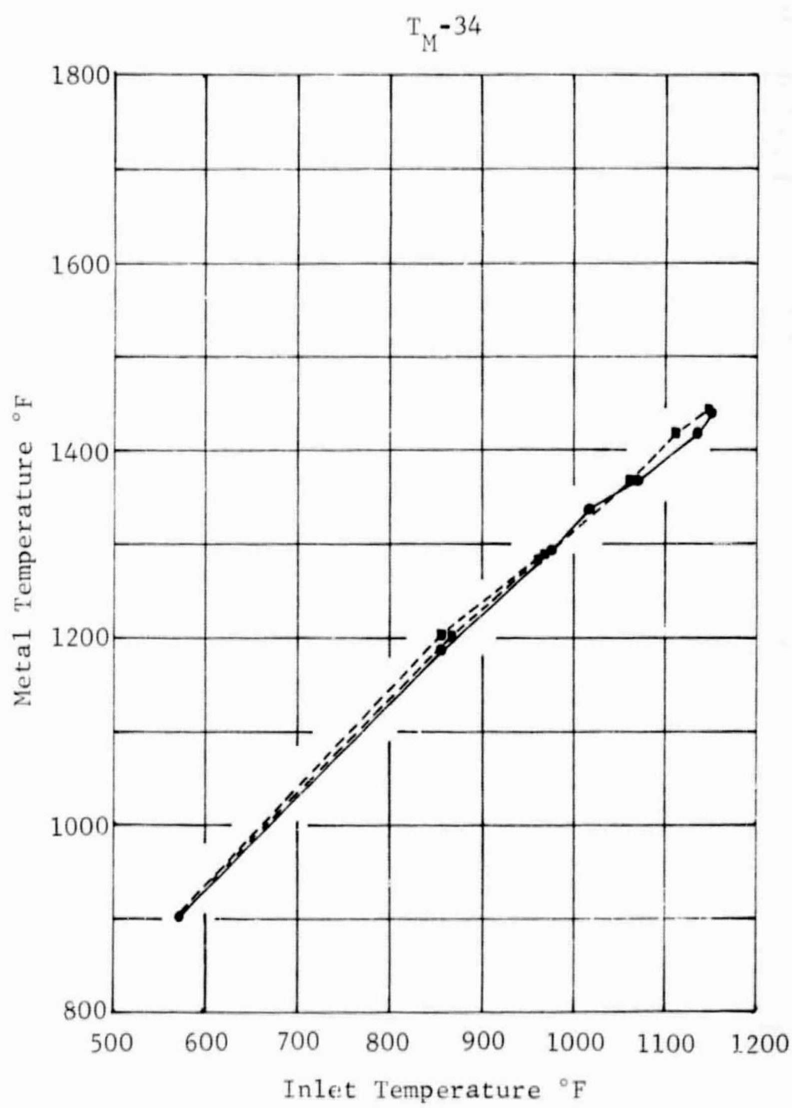


FOLDOUT FRAME /

INER TEMPERATURES AT F/A = .017

uild le





FOLDOUT FRAME 2

Figure 66

somewhat hotter than the design values, but the average increase was less than 100°F, and the liner overtemperature did not materially affect the execution of the test program. Detailed commentary on liner temperature is contained in a later section of this report.

4.4.1.3 Radiation to the Liners

Radiation to the outer combustor liners was measured at 2 and 4 atmospheres with an L. & N. Rayotube radiometer in build 1f. Location of the instrumentation and results of the tests are shown in Figures 67 and 69. A compilation and an extrapolation of the radiation test results to the design conditions (P_3= 6 atmospheres, T_3= 1150°F and F/A = .0172) is shown in Figure 70. Good agreement exists between the radiation used in the thermal design and the extrapolated radiation measurements.

There is one apparent deviation from the design conditions in the combustor radiation characteristics. It was assumed in the design that combustion would be completed in the primary zone of the combustor, and that the introduction of diluent air would effectively quench the combustion process. The radiation level measured at the diluent slots equalled the average primary zone radiation at the design fuel-air ratio. On the basis of this measurement, it appears that the combustion process persisted into the secondary zone. Thus, the radiation level in the secondary zone was probably higher than the 20 to 60% assumed in the design, which was based on the view factors of the secondary zone surfaces relative to the primary zone.

4.4.1.4 Comparison of Liner Configurations 1 and 3

Configuration 3 was tested at 2 and 4 atmospheres over a .015 to .020 range in fuel-air ratios. Table X summarizes the liner metal temperatures for all tests with Configuration 3. The thermocouple locations were identical to those used in Configuration 1 tests. A comparison of liner temperatures for Configurations 1 and 3 can be obtained from examination of Tables IX and X for identical operating conditions. From these tables it can be seen that the liner temperatures, in general, are about the same for both configurations.

RADIATION TEST RESULTS

TEST CONDITIONS

P_{t3} = 70" HgA

T_{t3} = 570°F

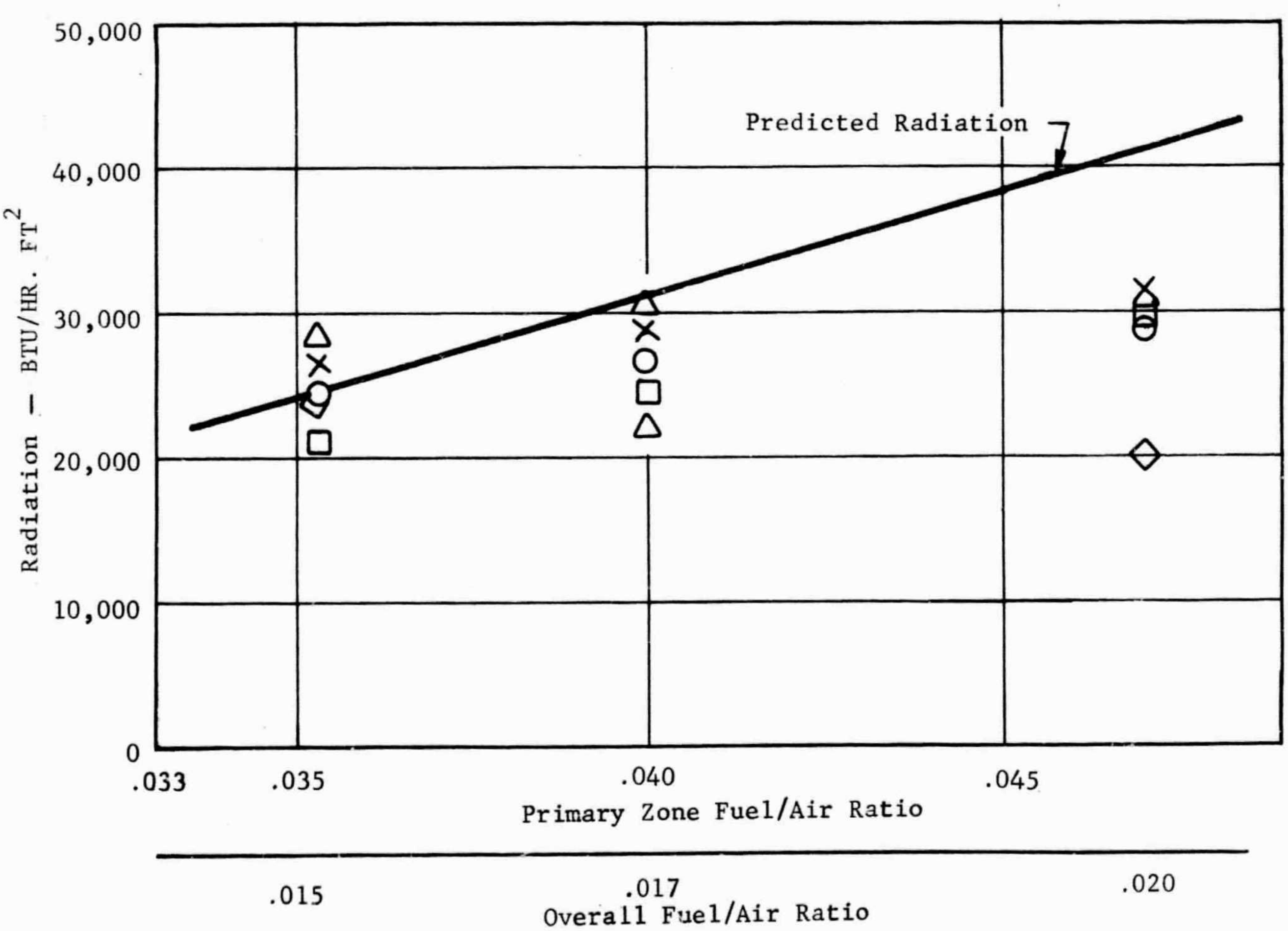


Figure 67

RADIATION TEST RESULTS

DOWNSTREAM OF TWO AIRCUPS

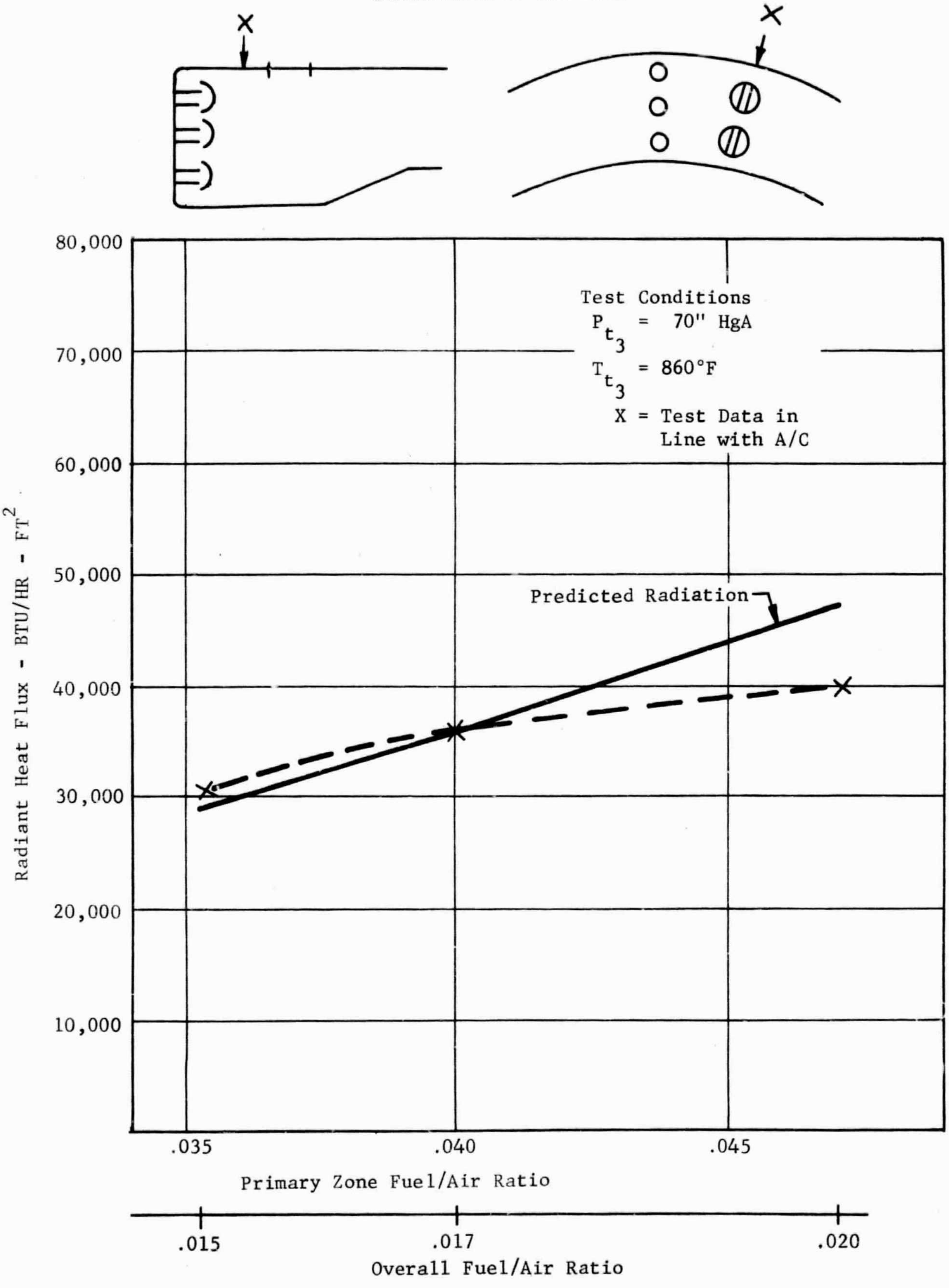


Figure 68

RADIATION TEST RESULTS

DOWNSTREAM OF MID-DISTANCE BETWEEN THREE VAPORIZER TUBES AND TWO AIRCUPS

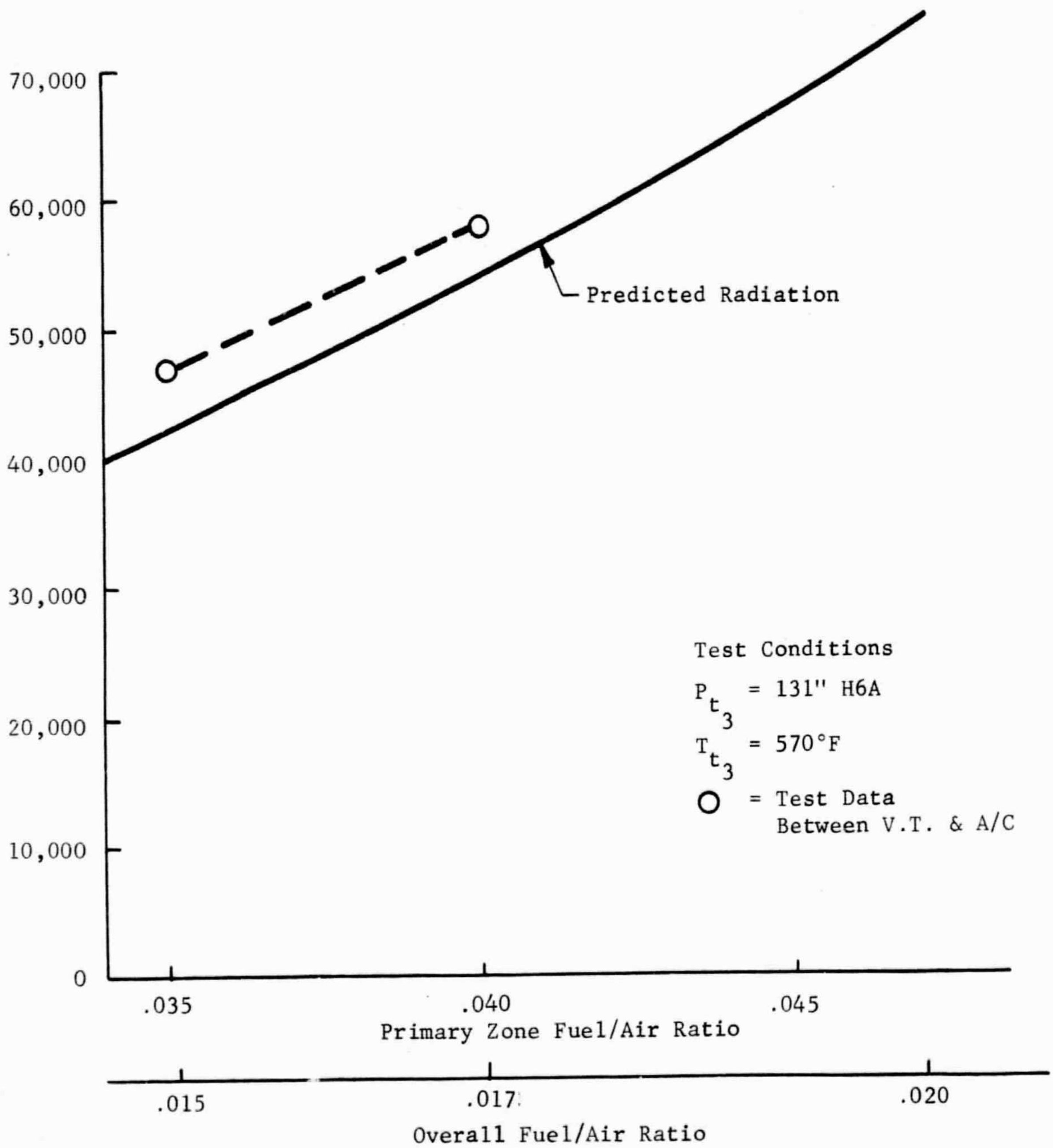


Figure 69

COMPARISON OF MEASURED VS. PREDICTED RADIATION TO LINERS

LEGEND

Symbol	P_{t_3}, atm.	T_{t_3}, °F
○	4	570
●	2	860
+	2	570

Range of Tests

Pressure - 2 to 4 Atmospheres
Inlet Air Temp. - 570 to 860°F
(F/A) o.a. - .015 to .020
(F/A) p.z. -.035 to .047

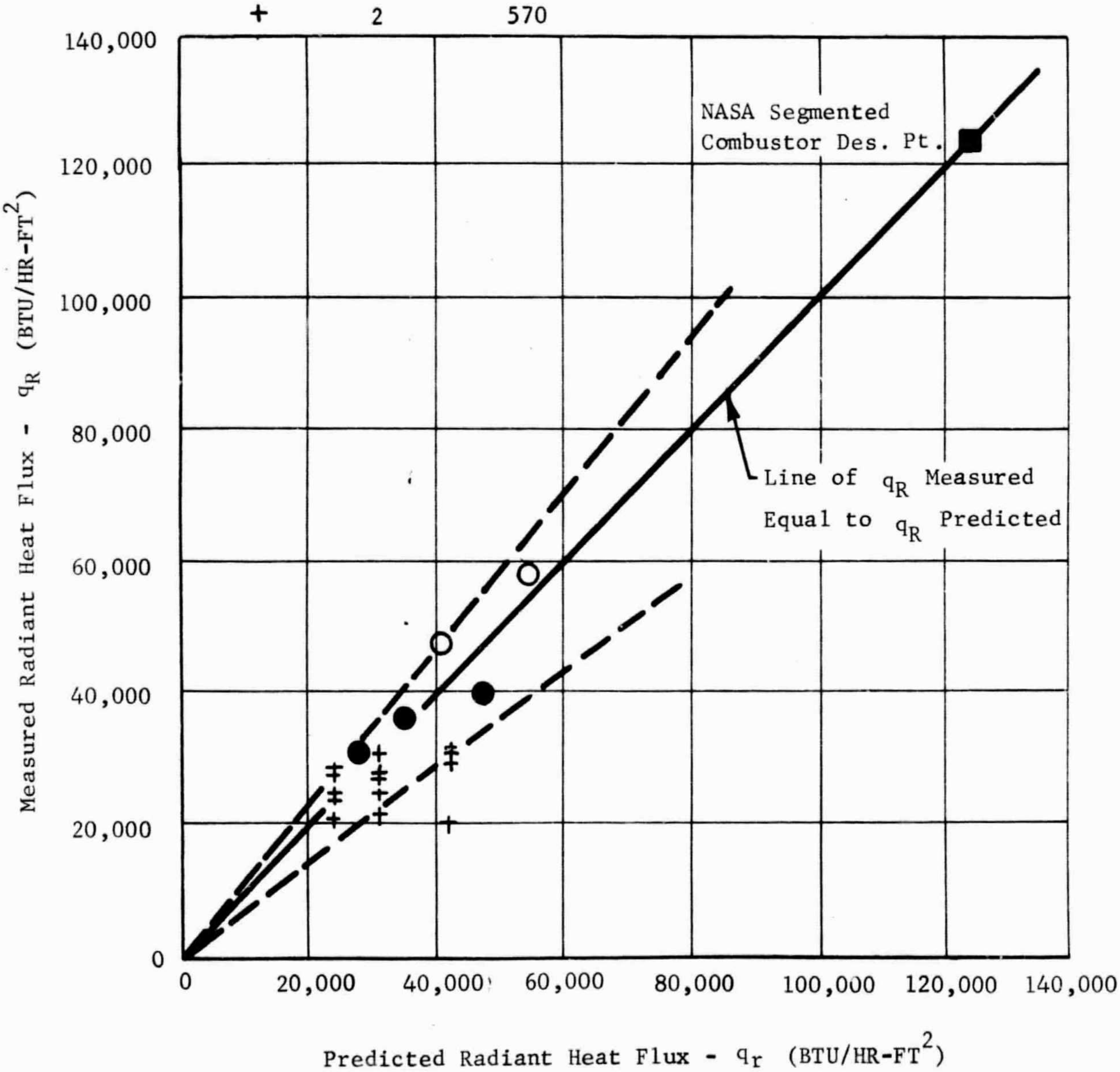


Figure 70

4.4.1.5 Optimization of Liner Configuration No. 1

The final test series (build 1g) showed significant improvement in the upstream inner liner temperatures when compared with build 1e. A detailed examination of Figure 71, with reference to the specific changes of configuration whose effects are visible, yields the following information:

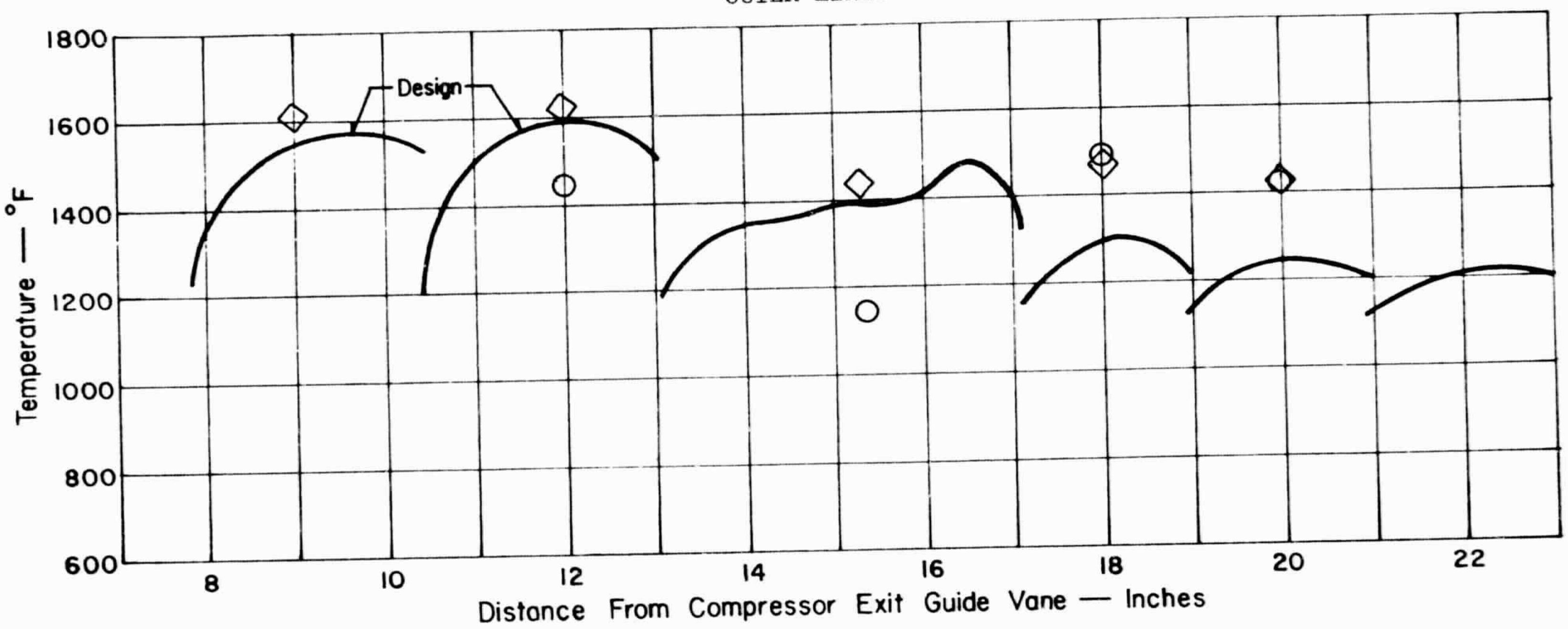
1. In the primary zone area just downstream of the headplate, the outer liner temperatures were below design and the inner liner temperatures were over design on build 1e. On build 1g, the cooling slots between the headplate and the first inner liner segment were opened up, with a resultant decrease in inner liner temperature to within the specifications. This was accompanied by an increase in outer liner temperature to the design limits, and was due to transfer of available film cooling air from the outer liner region to the inner region.
2. In the inner liner area downstream of the diluent slots, build 1e liner temperatures are close to the design value. This configuration had additional diluent slots which increased inner diluent air by 25%. Build 1g was assembled with existing segments which had not been modified to include the additional diluent air. Due to the decreased inner liner diluent flow, higher secondary zone inner liner temperatures were anticipated on build 1g. These higher temperatures clearly demonstrate the effect of the additional diluent air. The temperature increase was not a cause for concern, as it had already been demonstrated that the condition could be corrected.
3. The outer liner temperatures downstream of the diluent slots are in excess of design values, reaching a maximum value of 1750°F, compared to the design limit of 1600°F. Extrapolation of the averaged test data to six atmospheres indicates the liners could experience an additional temperature rise of approximately 100°F. Reduction of the overtemperature, on the outer liners in the secondary zone, to the design limit of 1600°F would require modification of the coolant air supply passages to increase the air flow.

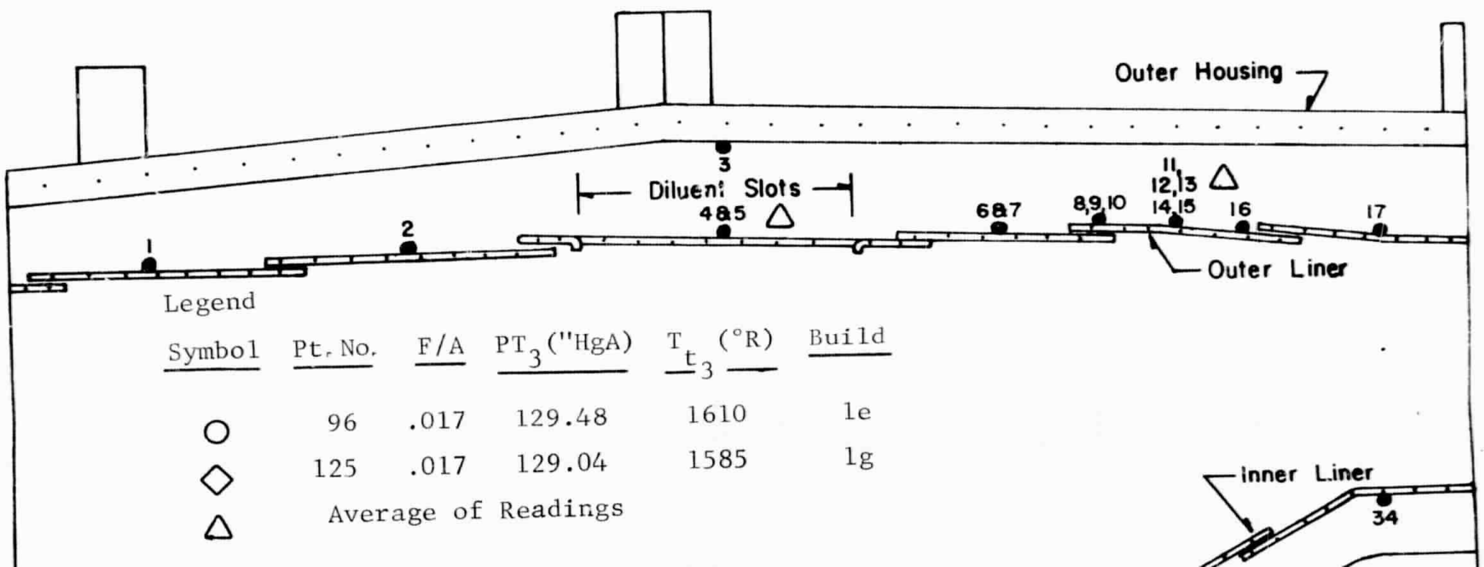
AVERAGED STEADY STATE LINER SEGMENT OPERATING TEMPERATURES

Liner Configuration No. 1

Rig Builds 1e and 1g

OUTER LINER



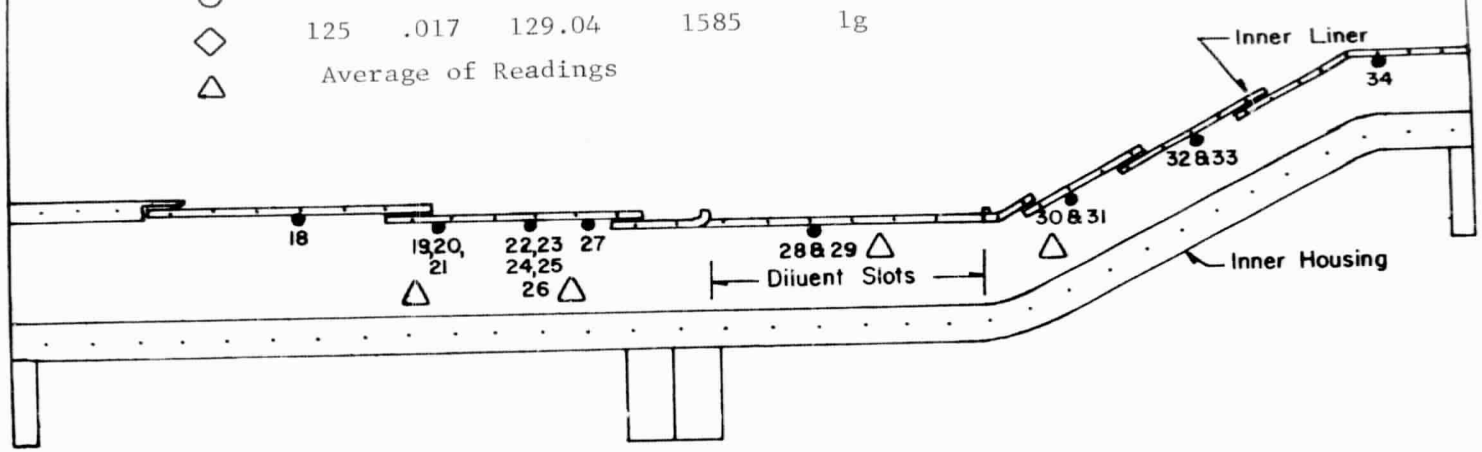


Legend

Symbol	Pt. No.	F/A	PT_3 ("HgA)	T_{t_3} (°R)	Build
○	96	.017	129.48	1610	1e
◇	125	.017	129.04	1585	1g
△	Average of Readings				

◇ 125 .017 129.04 1585 1g

△ Average of Readings



INNER LINER

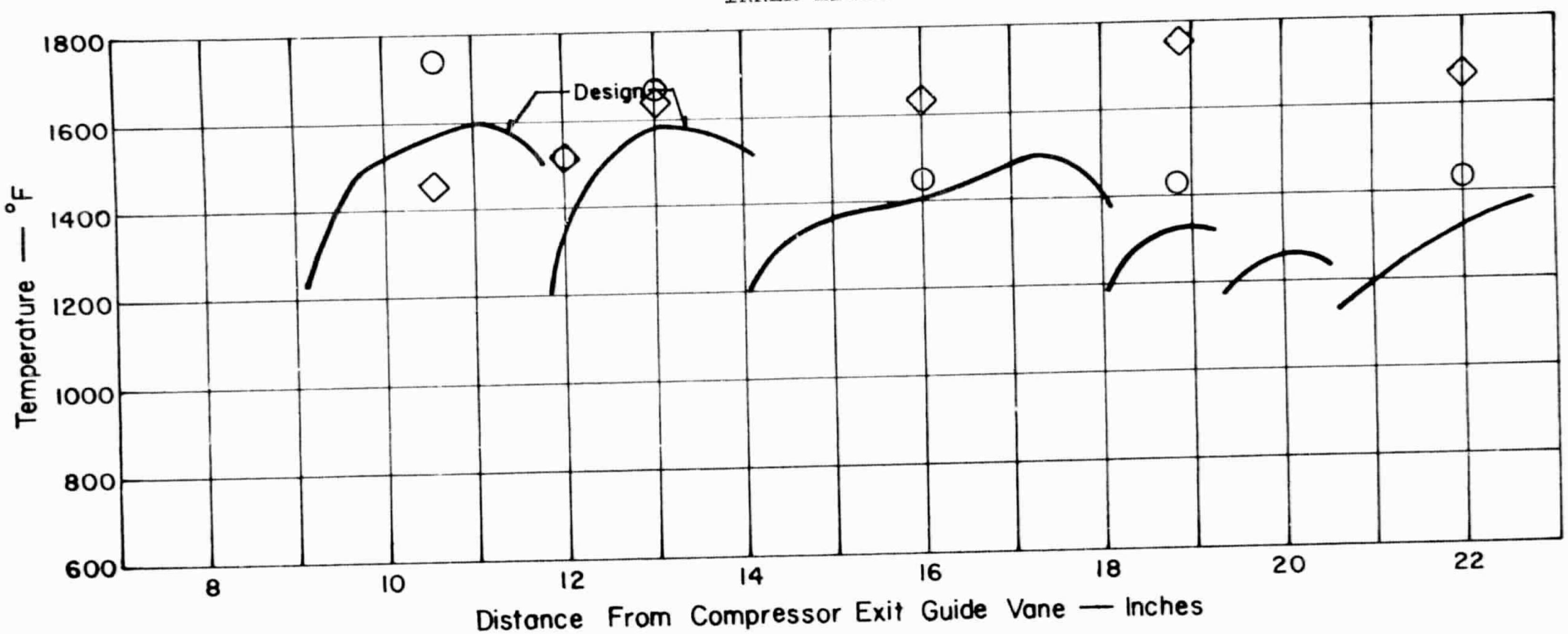


Figure 71

FOLDOUT FRAME 2

4. Liner Trailing Edge Distortion

The tests conducted with build 1e showed that the liner trailing edges were warping. The trailing edges incorporate the film cooling slots and are thinner than the main surfaces of the liners, with a correspondingly lower heat sink capacity. It was concluded that the thin slot sections were not sufficiently supported. Testing had also shown that the overlap of the segments was greater than necessary and could be reduced, shortening the thin sections of the liners. Both changes were made in the liners fitted to build 1g.

The tests conducted with build 1g conclusively demonstrated that the warping which had occurred on build 1e could be corrected. The liner trailing edges showed very little distortion after exposure to the full design temperature environment at four atmospheres inlet pressure. This improvement in durability is clearly visible in a comparison of Figures 62 through 64 (build 1g) with figures 54 through 57 (build 1e).

4.4.1.6 Liner Transverse Temperature Variations

Figures 72 through 77 show the build 1e and 1g distribution of inner and outer liner temperatures in meridional planes downstream of (1) the mid-distance between three vaporizer tubes and two air cups, (2) two air cups, (3) two vaporizer tubes, and (4) three vaporizer tubes. Figure 53 presents the positions of the vaporizer tubes and air cups and the developed views of the inner and outer liners, while Figure 52 presents the locations and identification numbers of the thermocouples. The hottest sections of the outer liners are in the meridional plane downstream of the mid-distance between three vaporizer tubes and two air cups. In this plane the outer liner temperatures are generally between 1400°F and 1600°F, with 1650°F being the maximum. The hottest sections of the inner liners are in the meridional plane downstream of two air cups. In this plane the inner liners operated near 1800°F in two locations. This high temperature occurred on build 1g, which did not have the 25% increase in inner liner diluent slot area. The equivalent liner temperature on build 1e, which did have the additional diluent area, was approximately 1400°F.

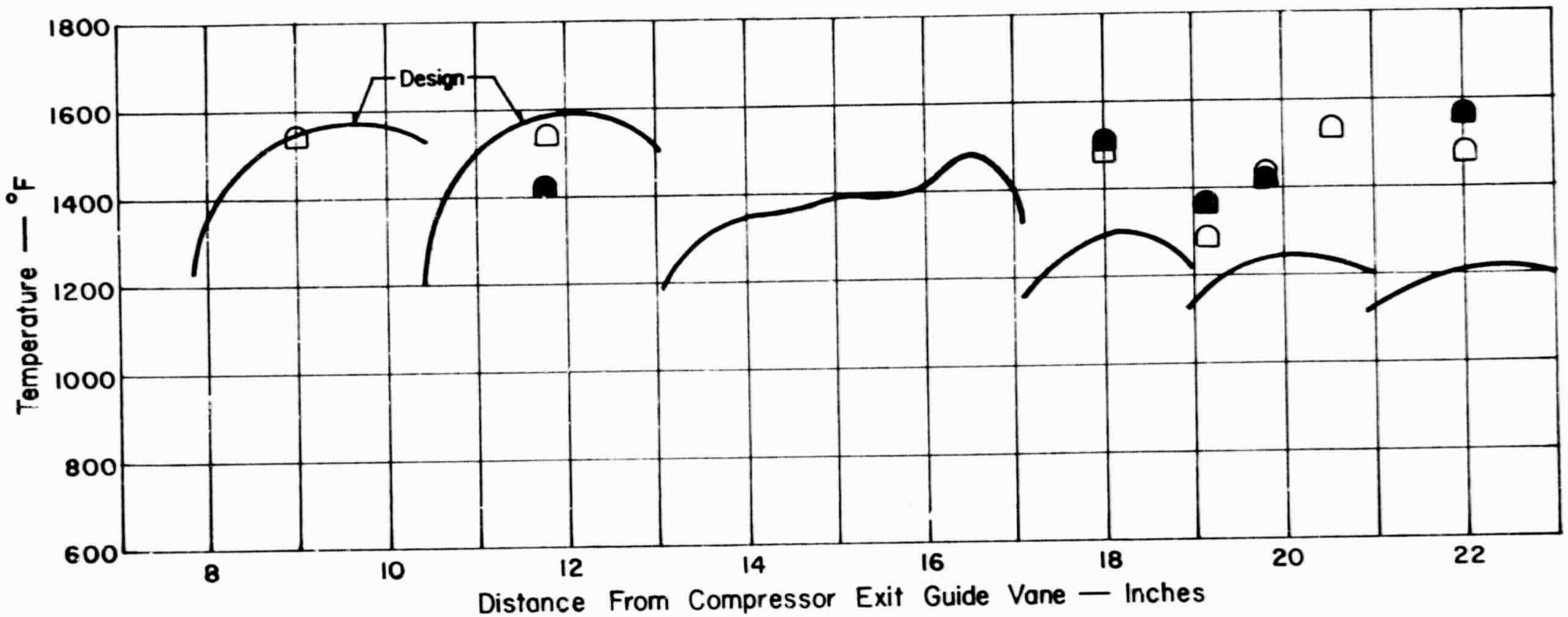
STEADY STATE LINER SEGMENT OPERATING TEMPERATURES

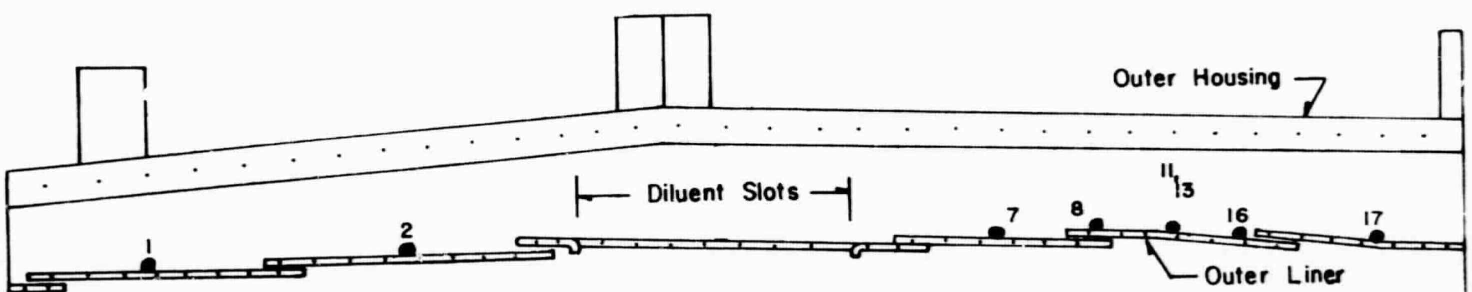
DOWNSTREAM OF MID-DISTANCE BETWEEN THREE VAPORIZER TUBES AND TWO AIRCUPS

TWO ATMOSPHERES

Rig Builds 1e and 1g

OUTER LINER



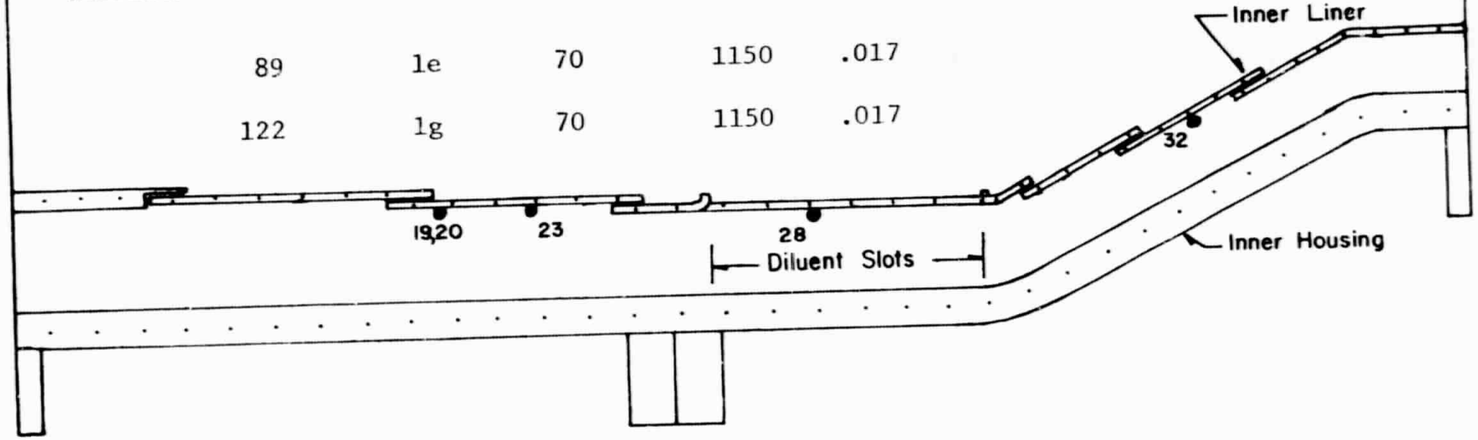


LEGEND

Symbol Pt. No. Build P_{t_3}, "HgA T_{t_3}, °F F/A

FOLDOUT FRAME 1

Symbol	Pt. No.	Build	P_{t_3}, "HgA	T_{t_3}, °F	F/A
	89	1e	70	1150	.017
	122	1g	70	1150	.017



INNER LINER

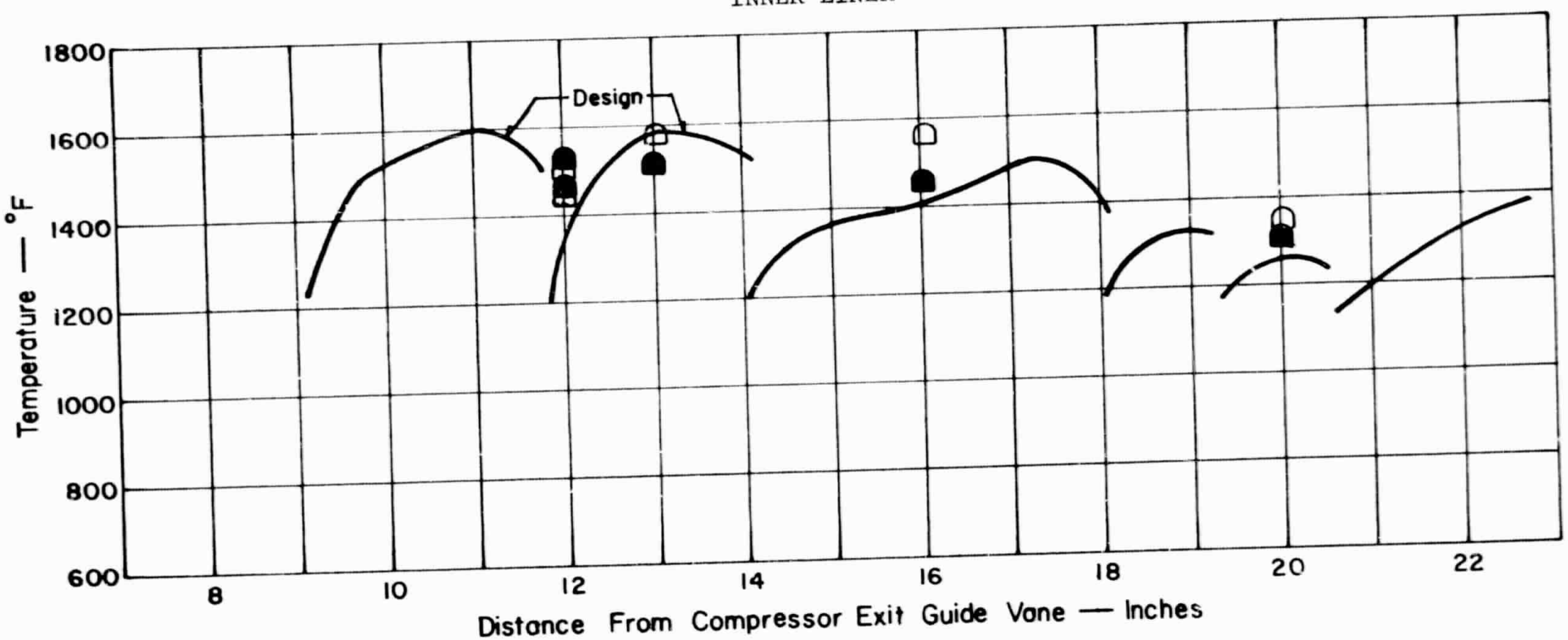


Figure 72

FOLDOUT FRAME 2

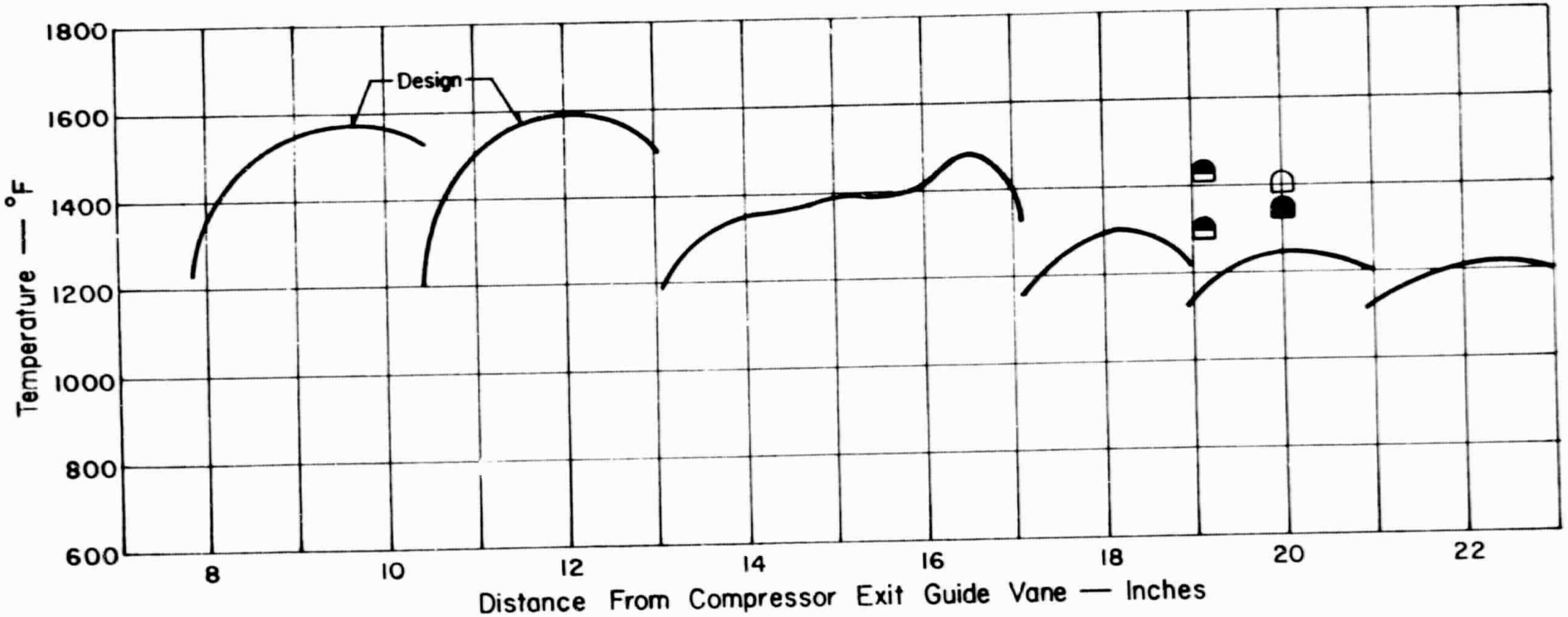
STEADY STATE LINER SEGMENT OPERATING TEMPERATURES

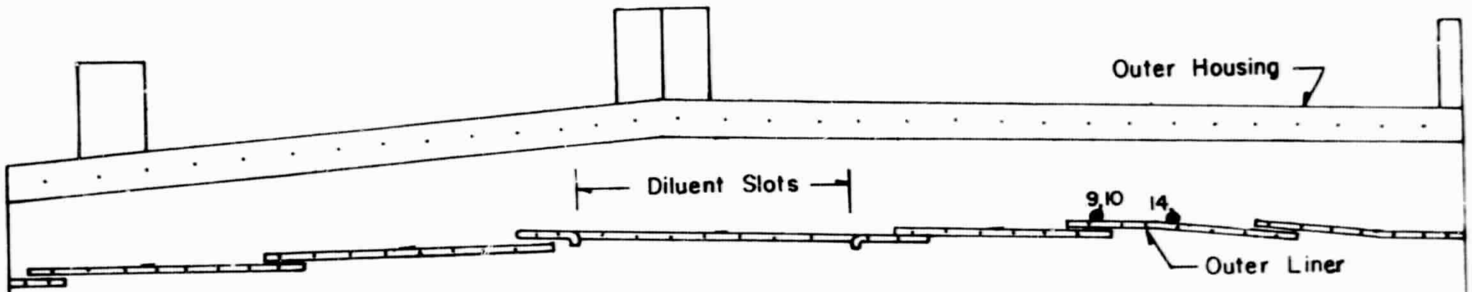
DOWNSTREAM OF TWO AIRCUPS

TWO ATMOSPHERES

Rig Builds 1e and 1g

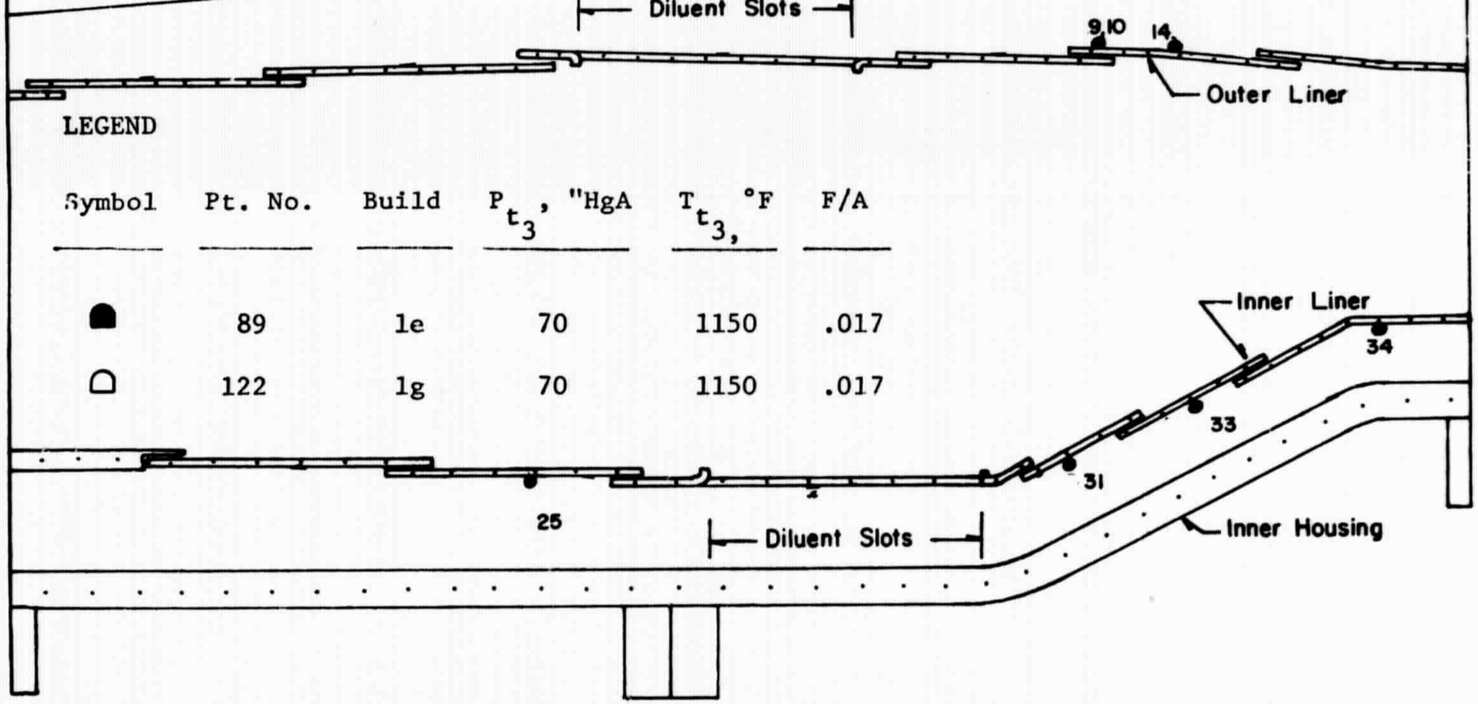
OUTER LINER





LEGEND

Symbol	Pt. No.	Build	P_{t_3}, "HgA	T_{t_3}, °F	F/A



LEGEND

Symbol	Pt. No.	Build	P_{t_3}, "HgA	T_{t_3}, °F	F/A
●	89	1e	70	1150	.017
◯	122	1g	70	1150	.017

INNER LINER

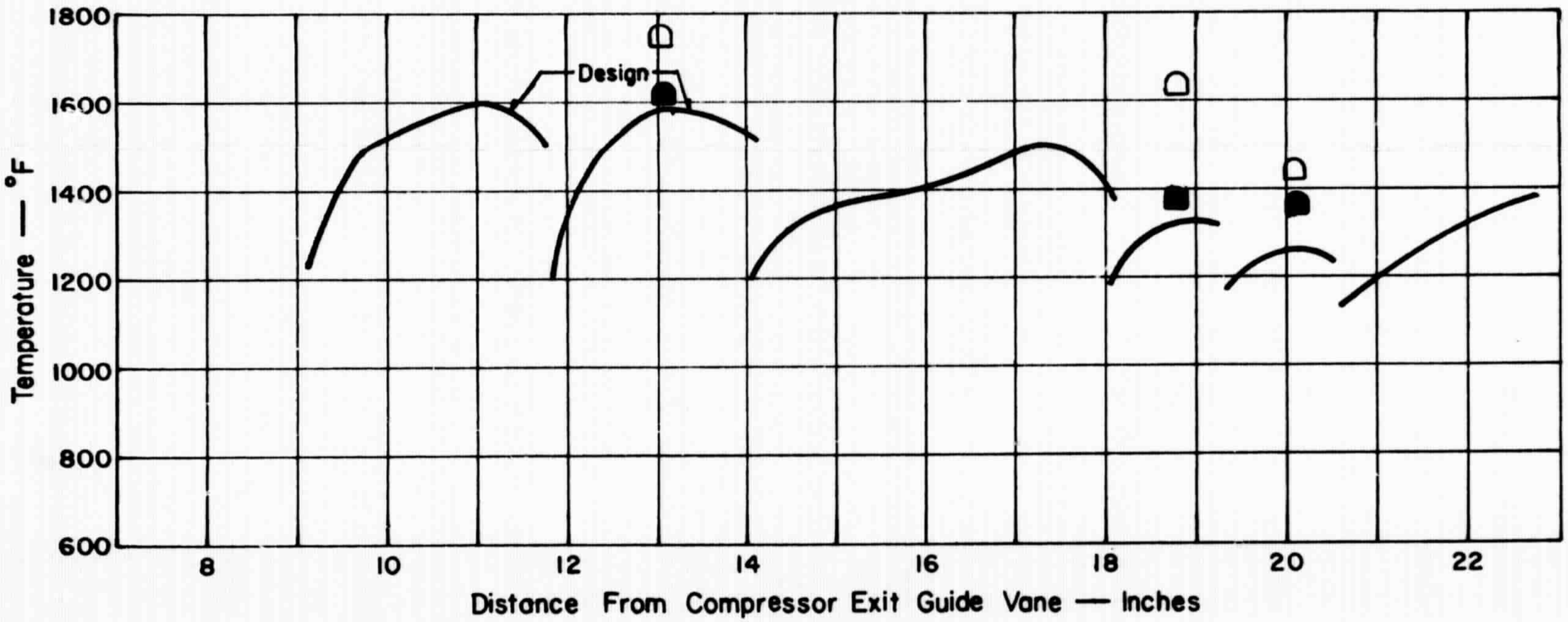


Figure 73

FOLDOUT FRAME 2

STEADY STATE LINER SEGMENT OPERATING TEMPERATURES

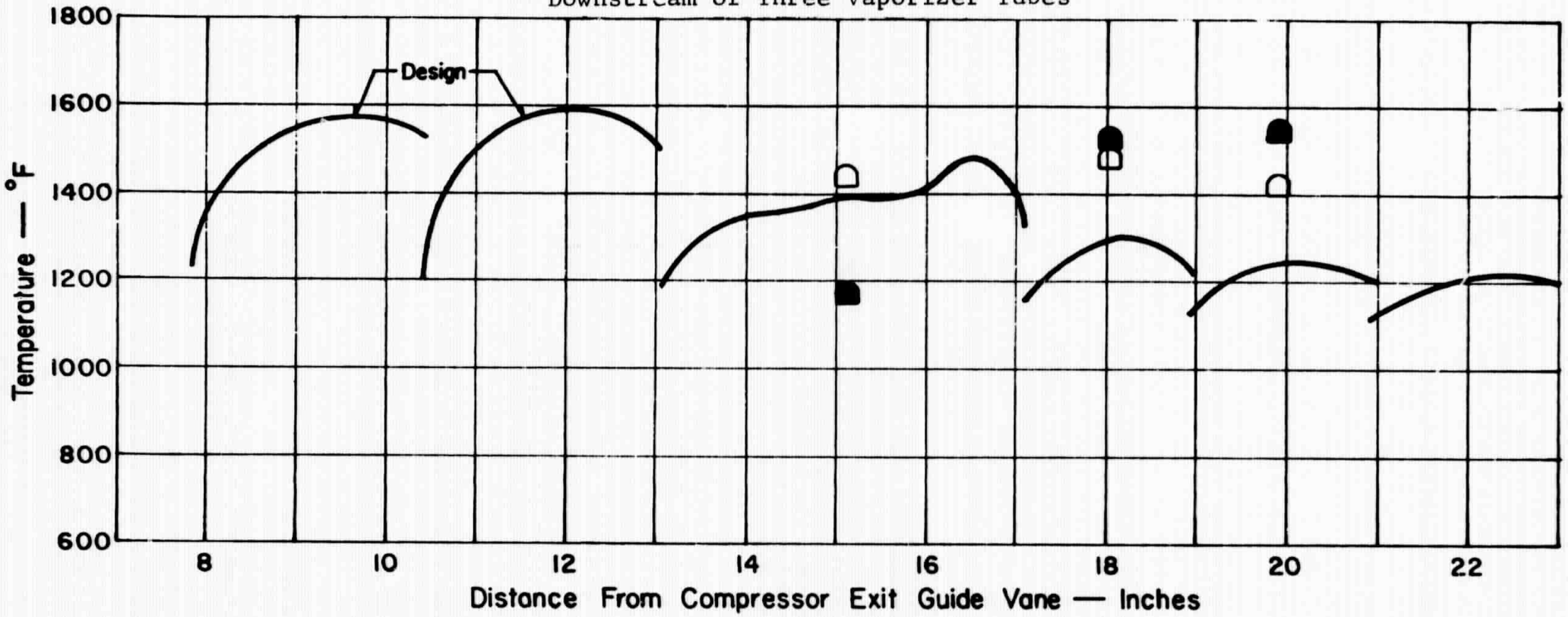
DOWNSTREAM OF VAPORIZER TUBES

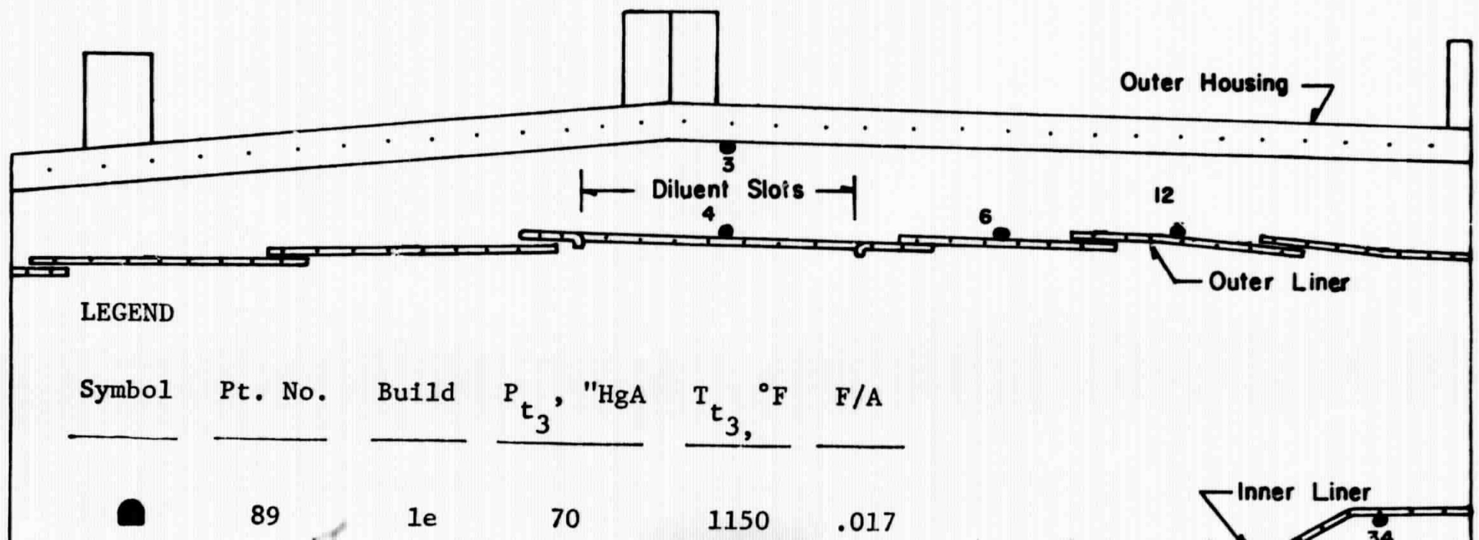
TWO ATMOSPHERES

Rig Builds 1e and 1g

OUTER LINER

Downstream of Three Vaporizer Tubes





LEGEND

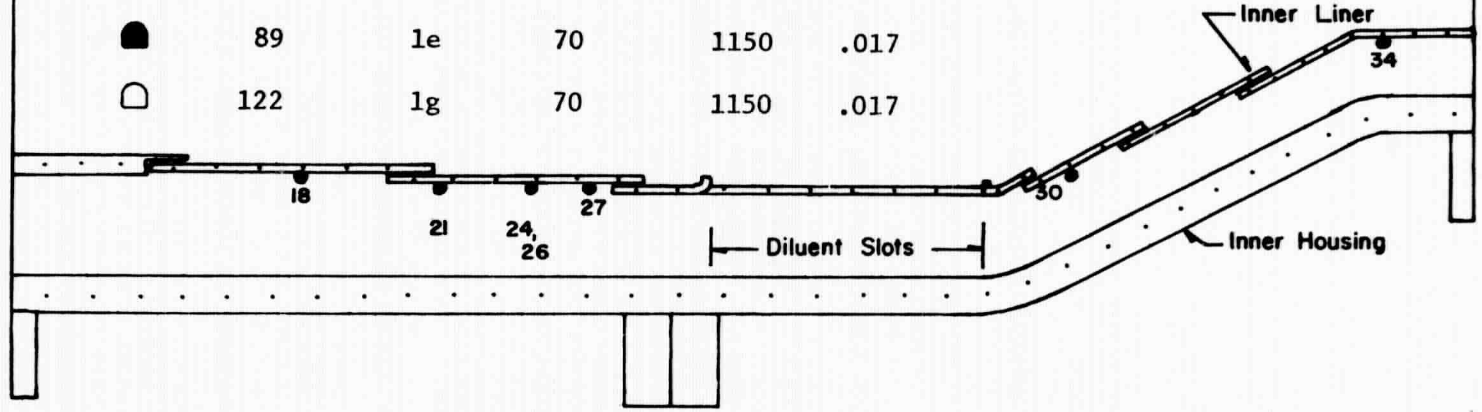
Symbol	Pt. No.	Build	P_{t_3}, "HgA	T_{t_3}, °F	F/A
●	89	1e	70	1150	.017

68-3286

FOLDOUT FRAME

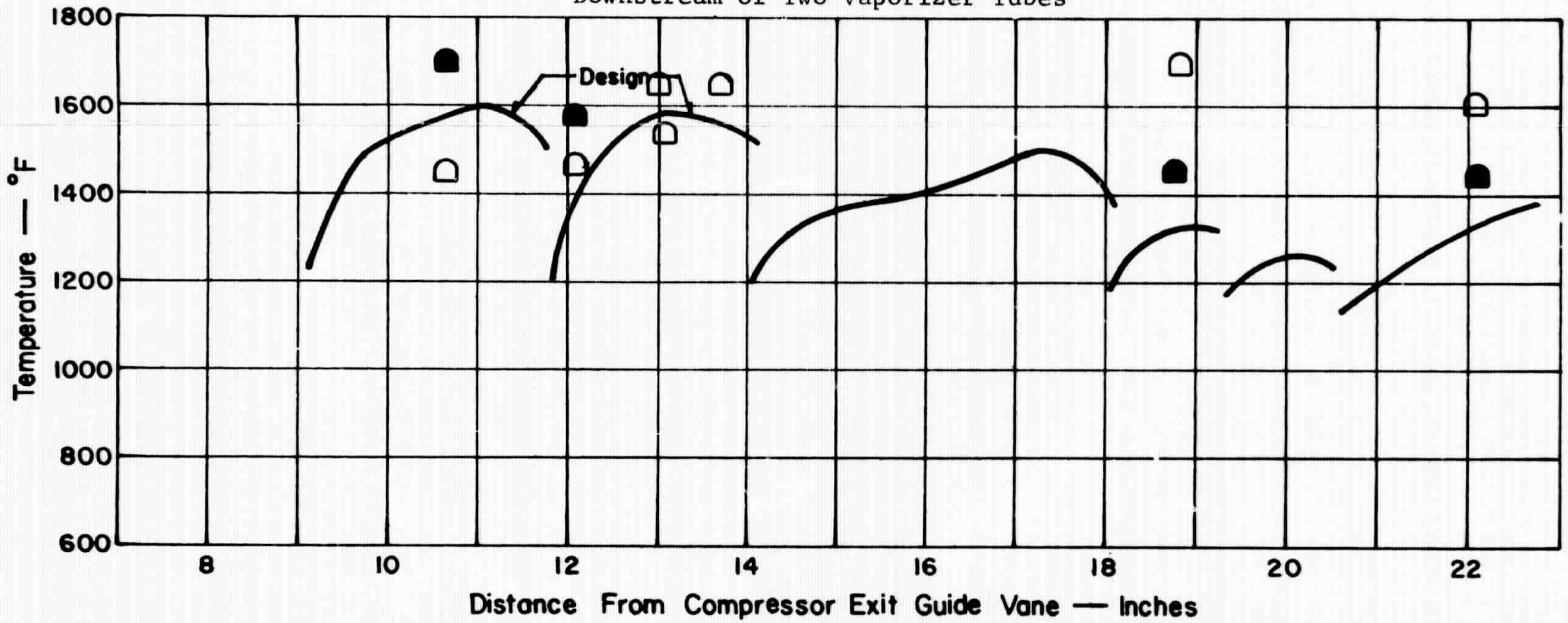
LEGEND

Symbol	Pt. No.	Build	P_{t_3}, "HgA	T_{t_3}, °F	F/A
● (filled)	89	1e	70	1150	.017
○ (open)	122	1g	70	1150	.017



INNER LINER

Downstream of Two Vaporizer Tubes



FOLDOUT FRAME 2

Figure 74

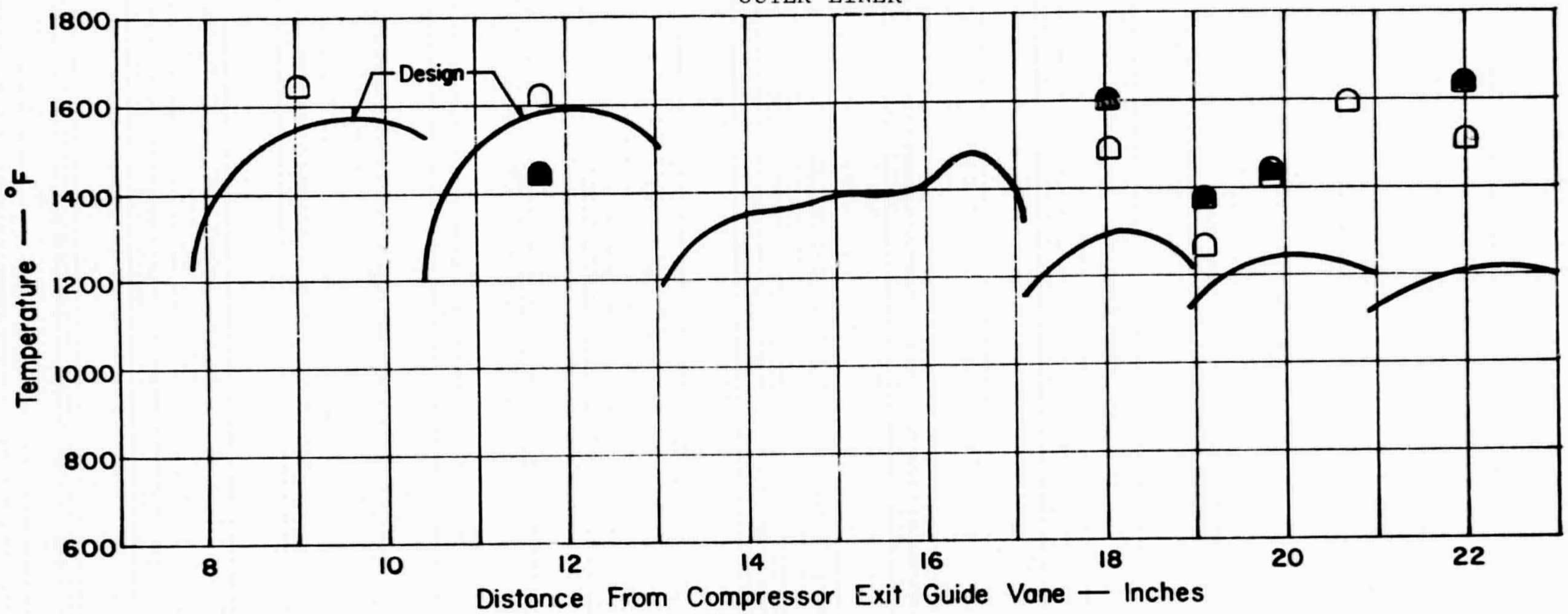
STEADY STATE LINER SEGMENT OPERATING TEMPERATURES

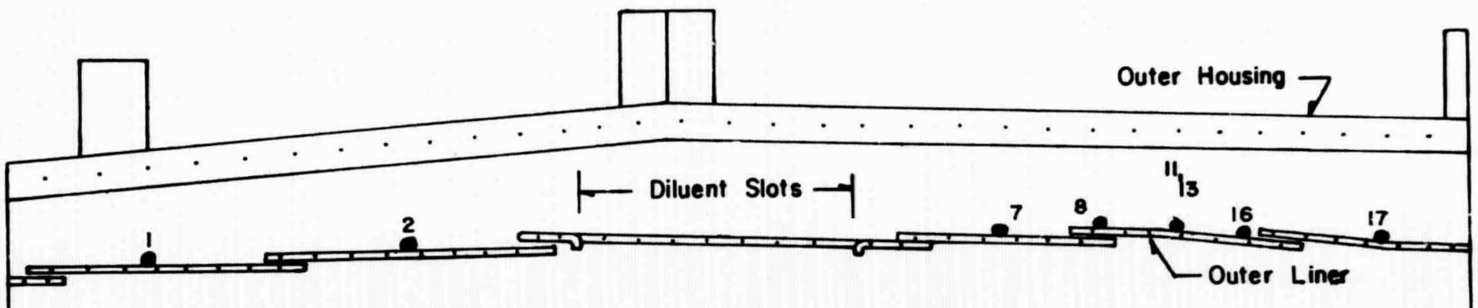
DOWNSTREAM OF MID-DISTANCE BETWEEN THREE VAPORIZER TUBES AND TWO AIRCUPS

FOUR ATMOSPHERES

Rig Builds 1e and 1g

OUTER LINER





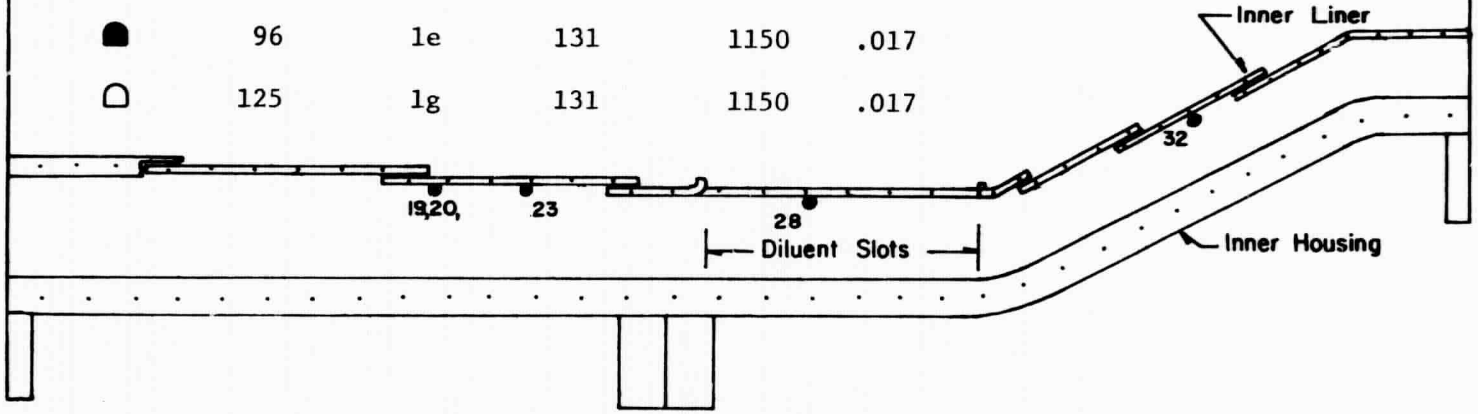
LEGEND

Symbol	Pt. No.	Build	P_{t_3}, "HgA	T_{t_3}, °F	F/A

FOLDOUT FRAME 1

LEGEND

Symbol	Pt. No.	Build	P_{t_3}, "HgA	T_{t_3}, °F	F/A
●	96	1e	131	1150	.017
◯	125	1g	131	1150	.017



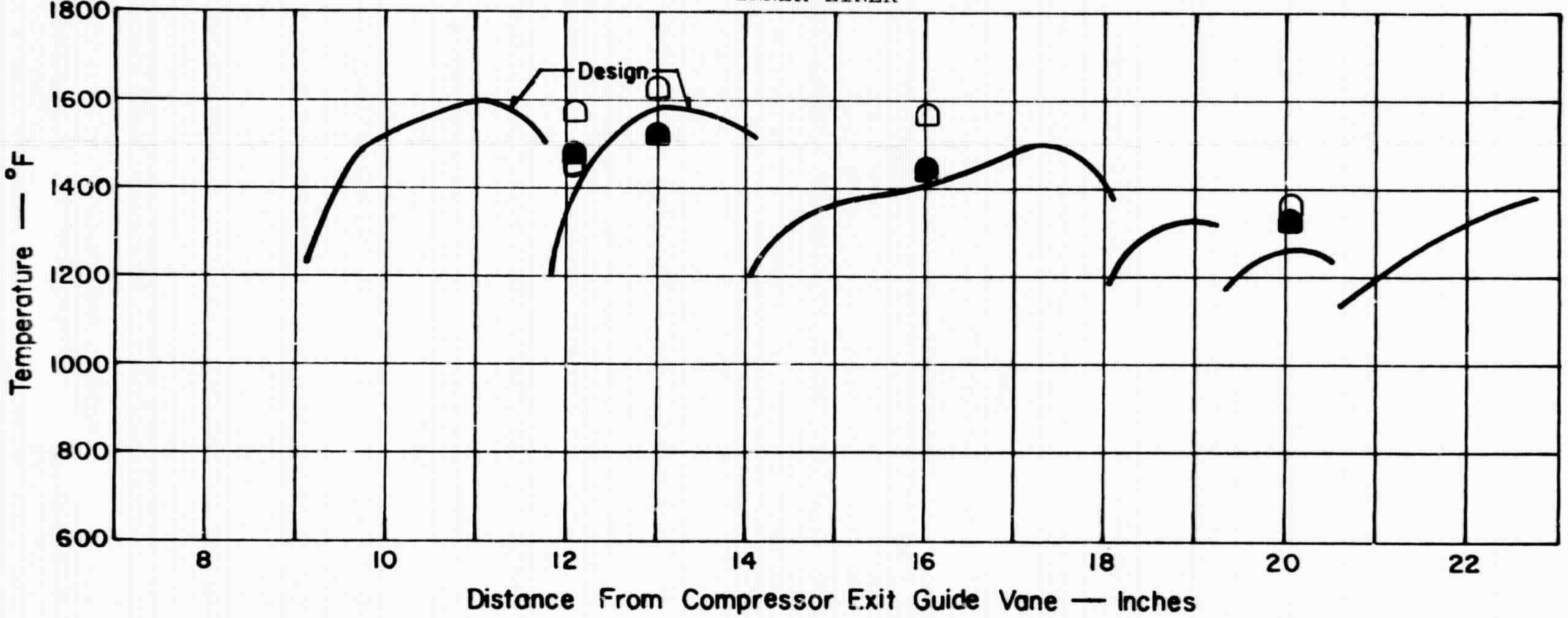


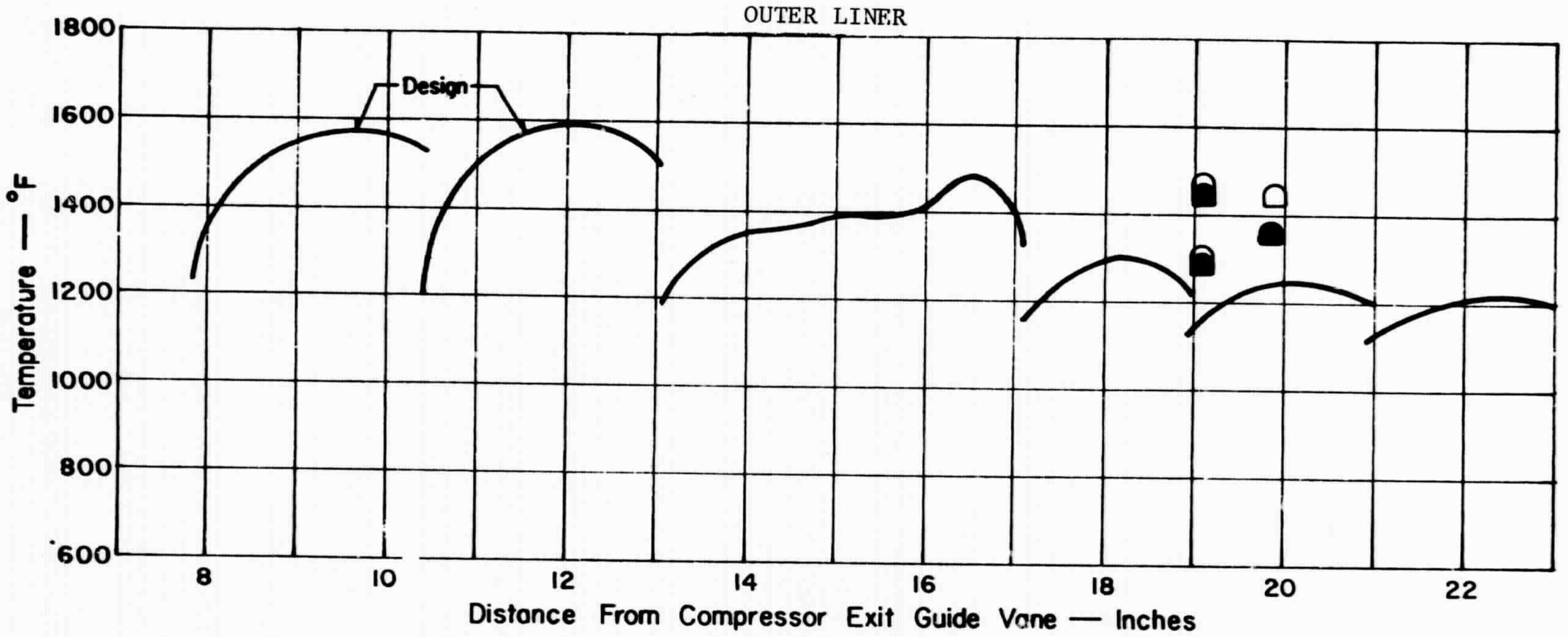
Figure 75

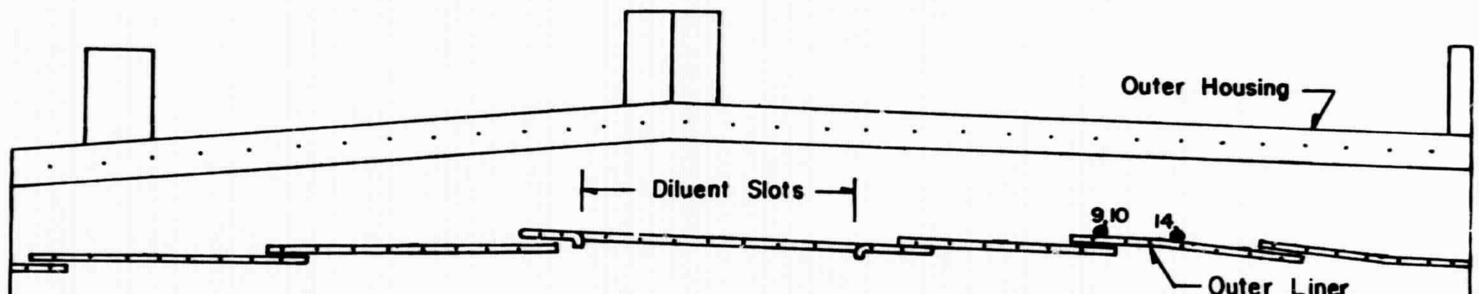
STEADY STATE LINER SEGMENT OPERATING TEMPERATURES

DOWNSTREAM OF TWO AIRCUPS

FOUR ATMOSPHERES

Rig Builds 1e and 1g





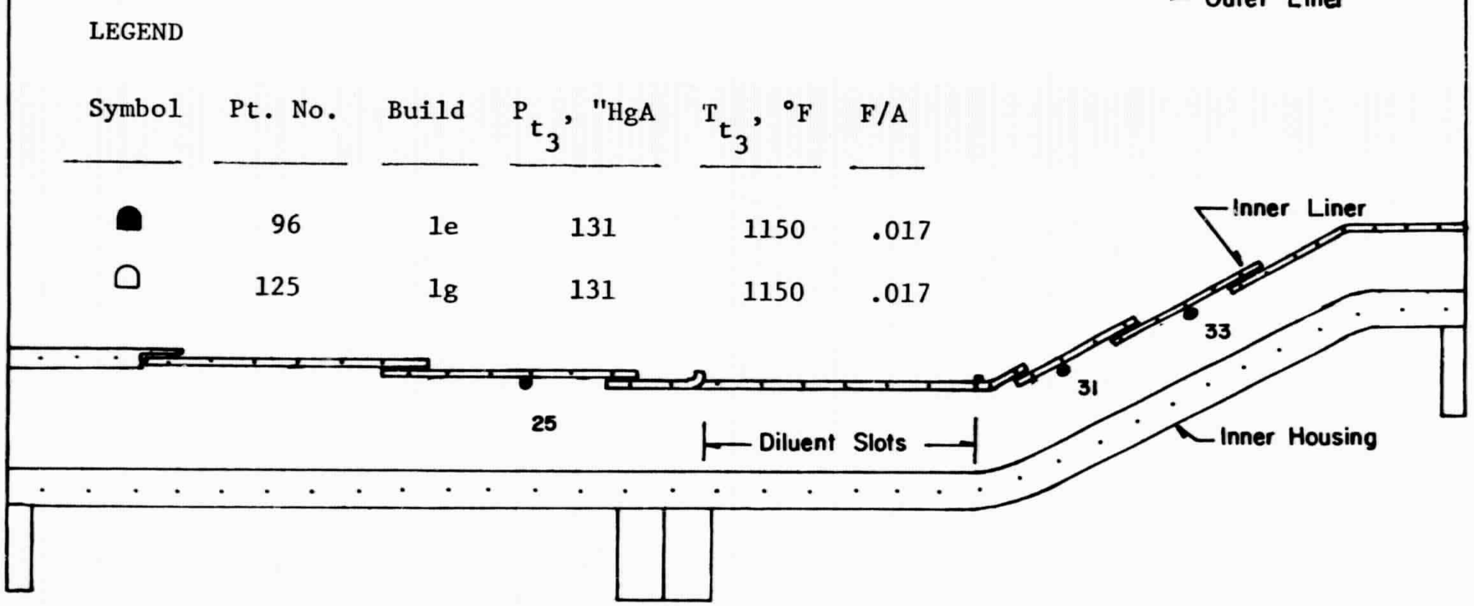
LEGEND

Symbol	Pt. No.	Build	P_{t_3}, "HgA	T_{t_3}, °F	F/A
●	96	1e	131	1150	017

FOLDOUT FRAME

LEGEND

Symbol	Pt. No.	Build	P_{t_3}, "HgA	T_{t_3}, °F	F/A
● (solid)	96	1e	131	1150	.017
○ (open)	125	1g	131	1150	.017



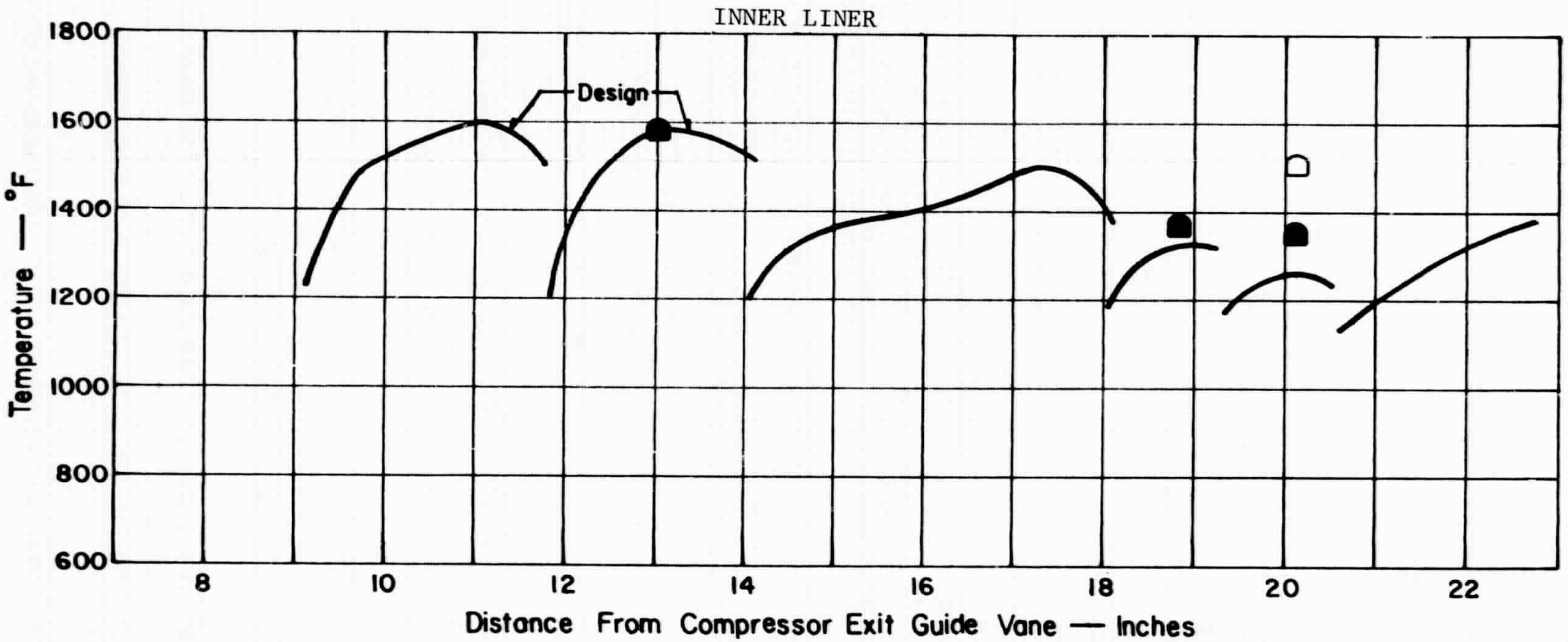


Figure 76

FOLDOUT FRAME 2

STEADY STATE LINER SEGMENT OPERATING TEMPERATURES

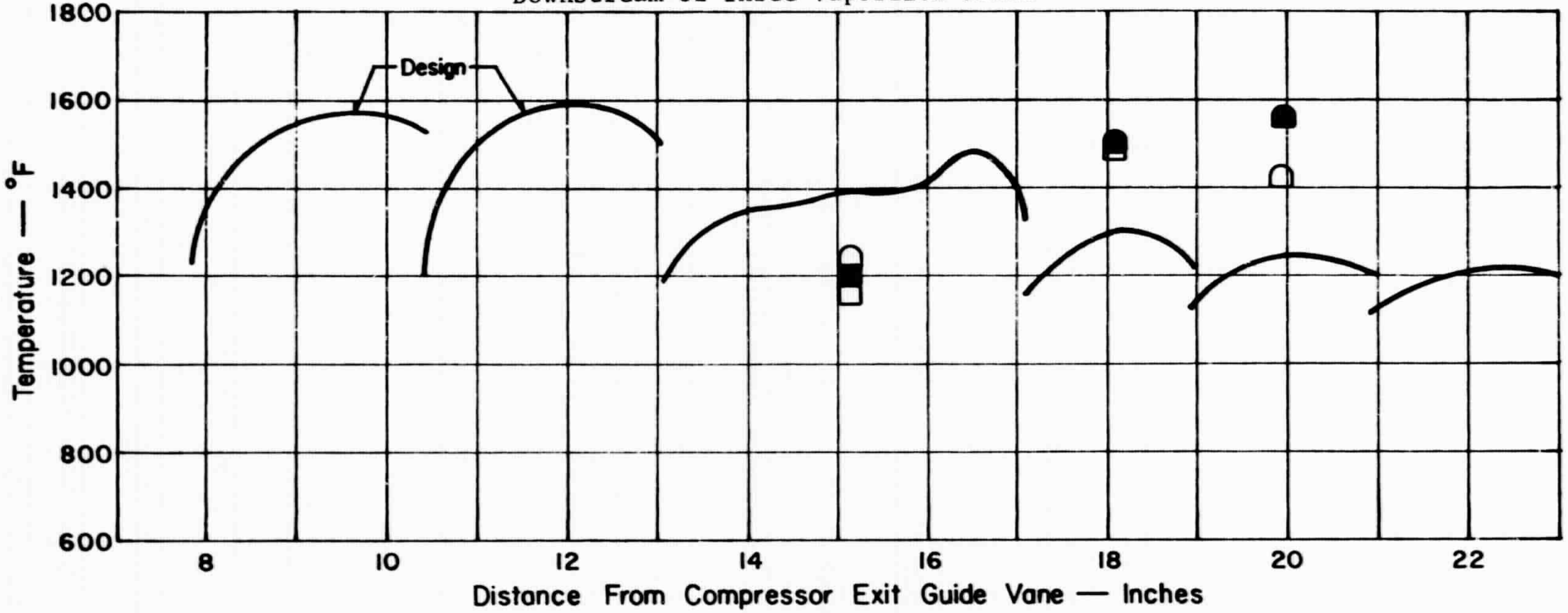
DOWNSTREAM OF VAPORIZER TUBES

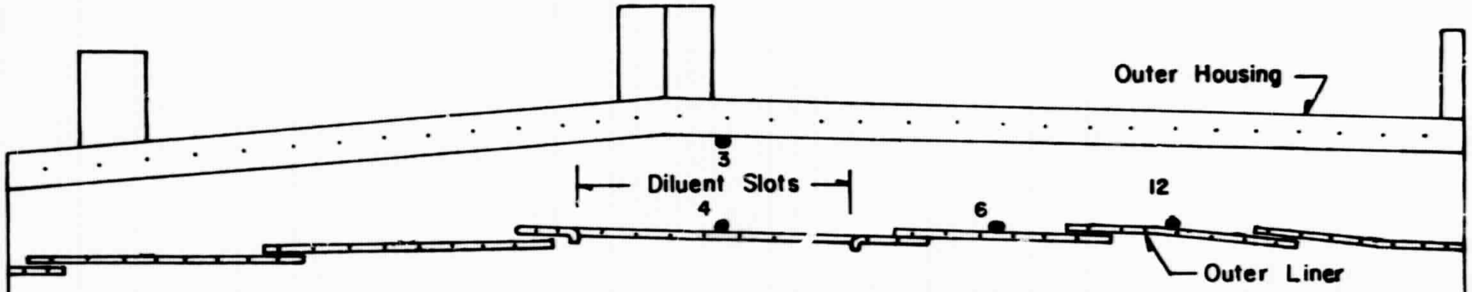
FOUR ATMOSPHERES

Rig Builds 1e and 1g

OUTER LINER

Downstream of Three Vaporizer Tubes

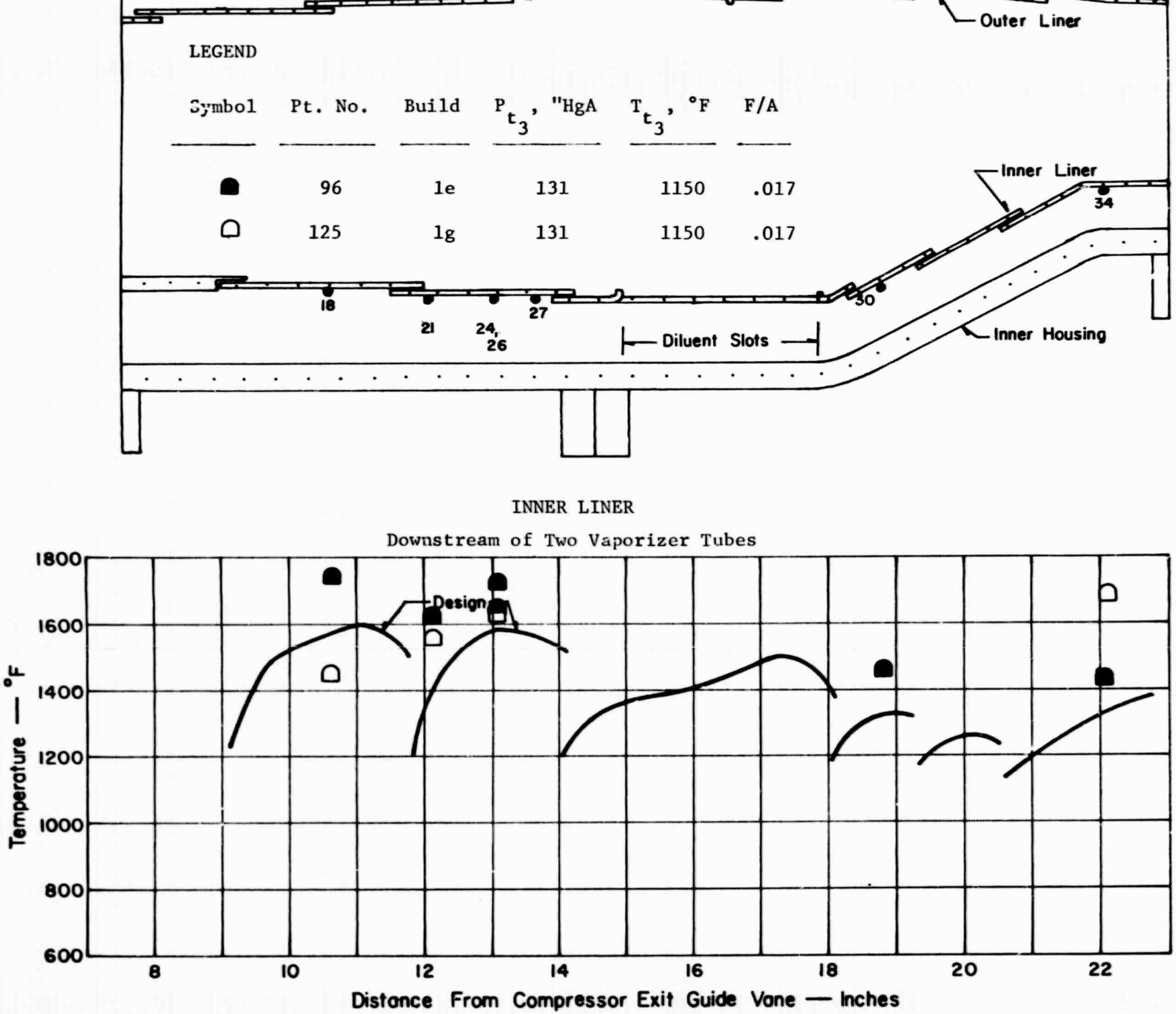




LEGEND

Symbol	Pt. No.	Build	P_{t_3}, "HgA	T_{t_3}, °F	F/A
●	96	1e	131	1150	.017

FOLDOUT FRAME 1



LEGEND

Symbol	Pt. No.	Build	P_{t_3}, "HgA	T_{t_3}, °F	F/A
● (filled)	96	1e	131	1150	.017
○ (open)	125	1g	131	1150	.017

Figure 77

4.5 Combustor Sector Rig Evaluation

Liner development is always related to the associated combustor. This was true in this program, and some degree of modification was necessary to combustor components other than the liners in the course of the experimental program.

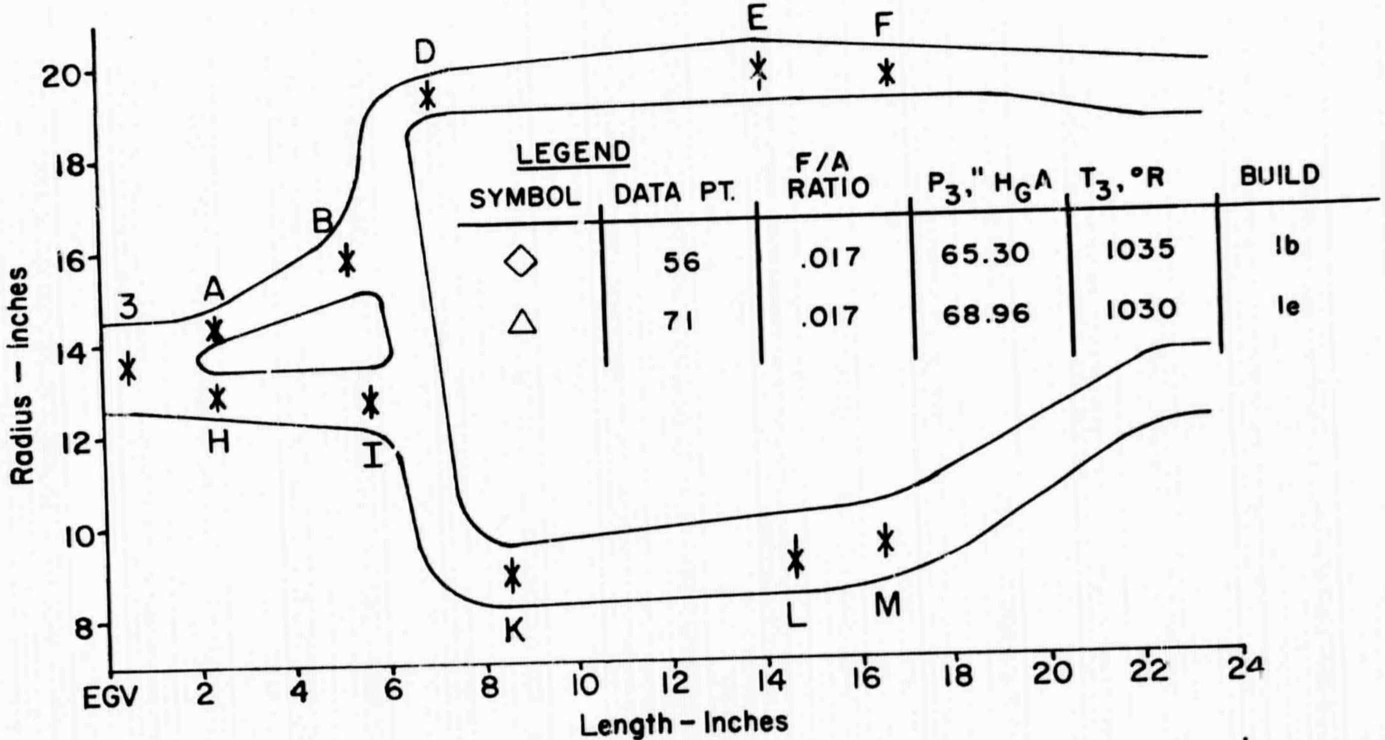
The combustor rig was designed to meet contractual performance specifications, and reflected the operating environment and predicted performance requirement of an advanced turbojet engine operating at a Mach 3 flight condition. The primary combustor performance requirements in the contract were operation at an inlet pressure and temperature of six atmospheres and 1150°F, respectively, with 98% efficiency and 2200°F exit temperature. The design assumed an overall diffuser-combustor total pressure loss of 8%.

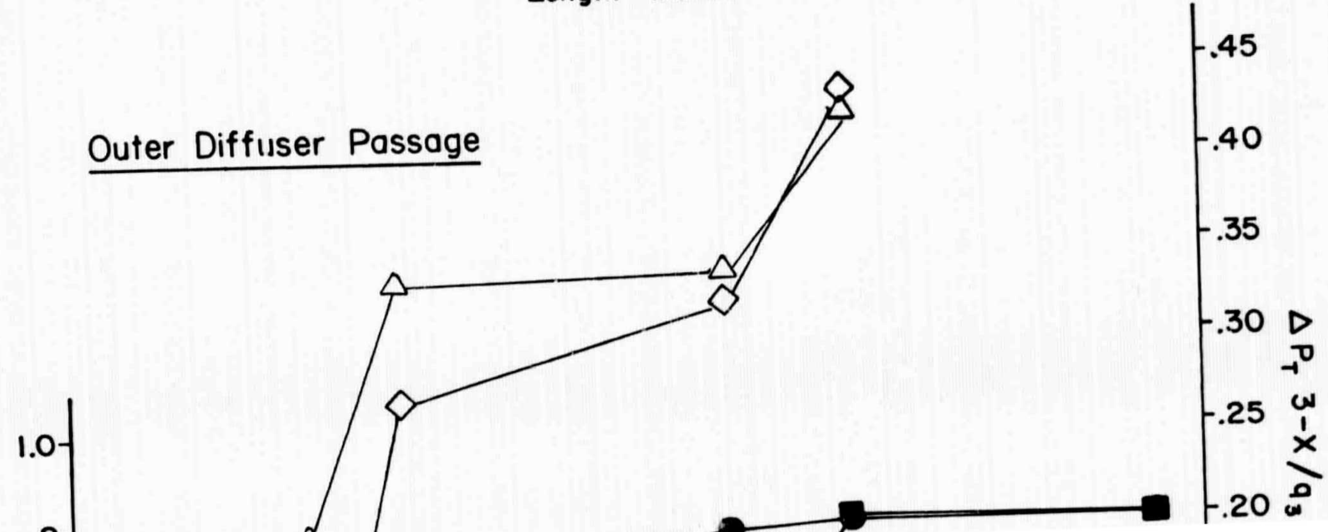
Combustor Rig performance was evaluated on the basis of efficiency, pressure loss characteristics and exit temperature profiles. The testing verified that the overall Combustor Rig efficiency was within specifications as shown in Figure 32.

The inlet-diffuser configuration was not as satisfactory. Combustion total pressure loss is essentially the sum of an aerodynamic or mixing loss and a thermodynamic loss associated with the addition of heat. The thermodynamic loss was a relatively small percentage of the overall loss. The aerodynamic loss was higher than desired, and the pressure loss characteristics indicated that this was due to the diffuser. The actual diffuser performance compared with design is shown in Figures 78 and 79. As shown in the figure, actual total pressure losses were as much as twice the design target, and static pressure recovery was one-half to two-thirds the predicted value. This affected the tests in several ways. As previously mentioned, it caused reductions in coolant air flow capability of 10 to 20%. It is also apparent from Figures 78 and 79 that the diffuser turning passages which fed air to the headplate were at least partially stalled. This condition led to uneven air supply to the headplate and a distorted exit temperature profile.

DIFFUSER PERFORMANCE - BUILD Ib vs. Ie

(CONFIGURATION NO. 1)





FOLDOUT FRAME 1

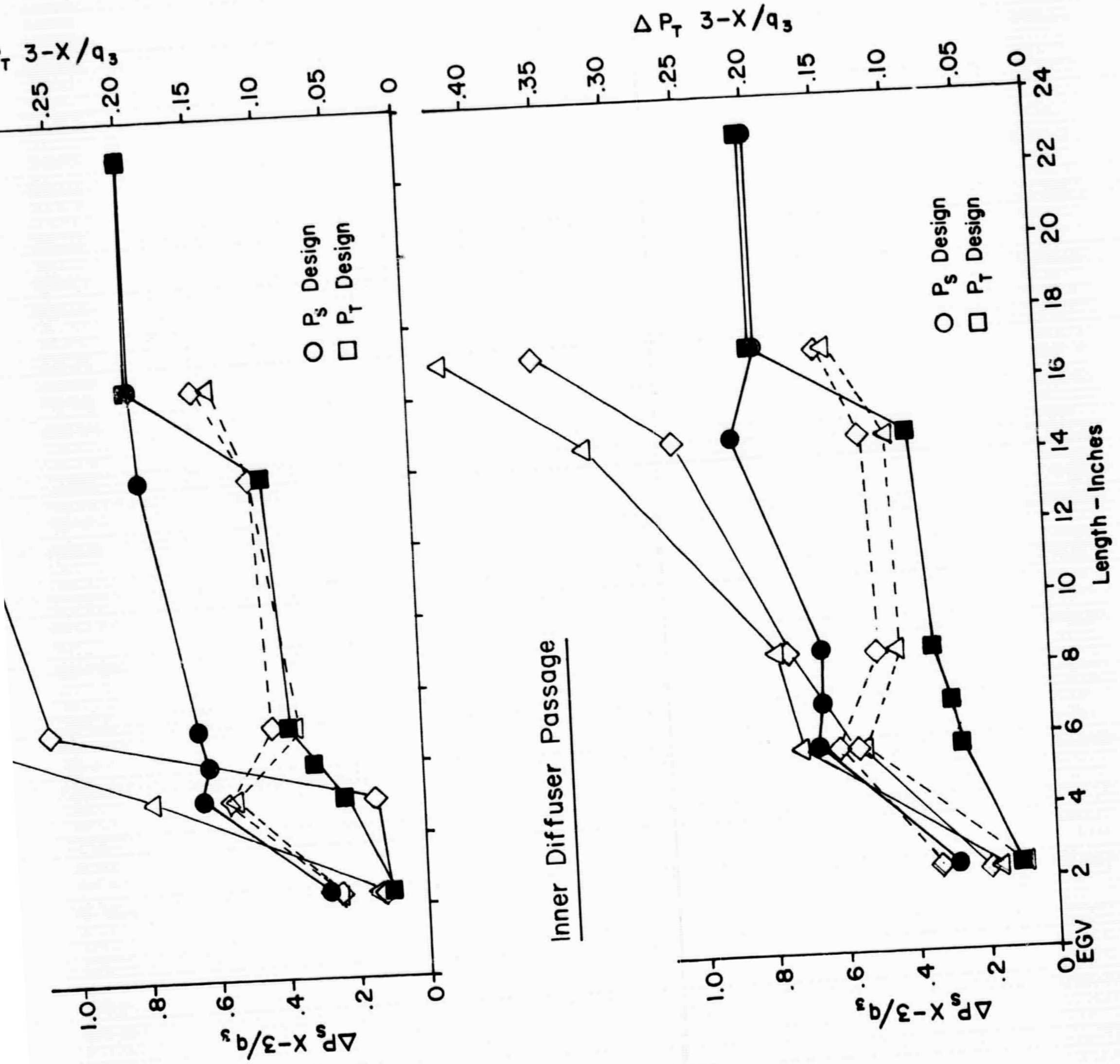
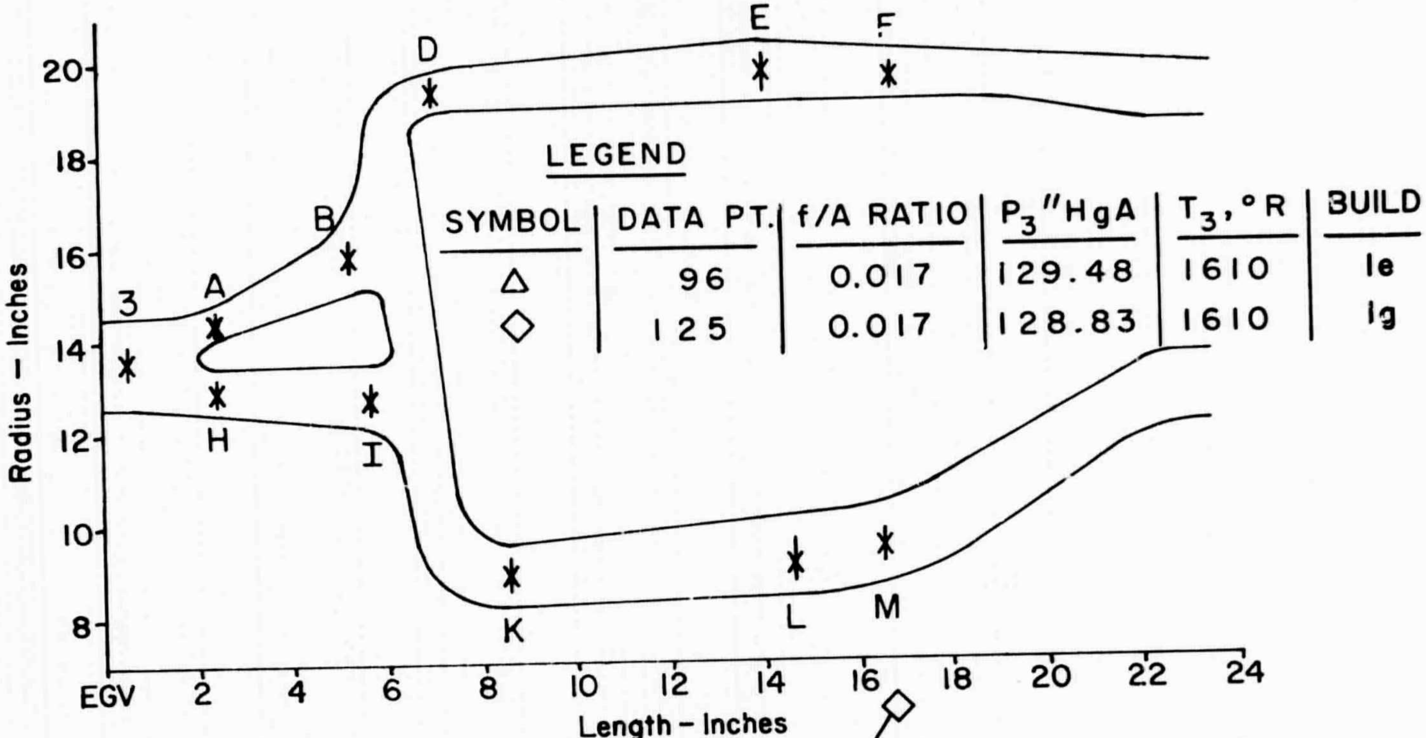


Figure 78

FOLDOUT FRAME 2

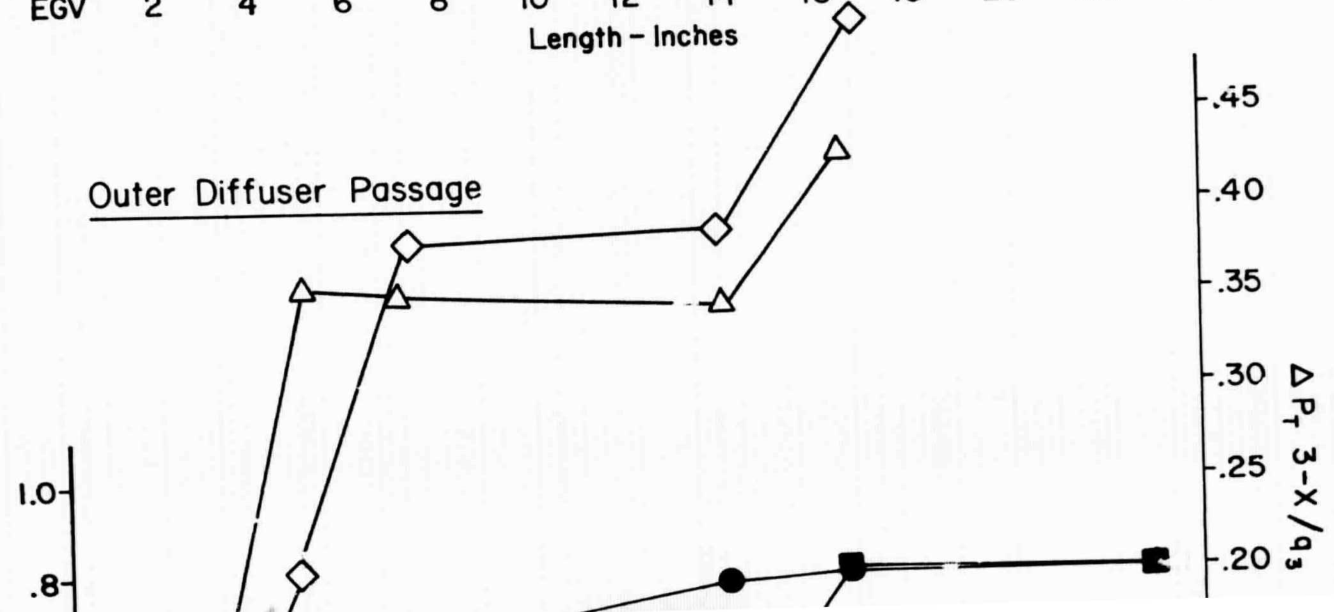
DIFFUSER PERFORMANCE - BUILD Ie vs. Ig

(CONFIGURATION NO.1)



LEGEND

SYMBOL	DATA PT.	f/A RATIO	P_3 "HgA	T_3, °R	BUILD
△	96	0.017	129.48	1610	Ie
◇	125	0.017	128.83	1610	Ig



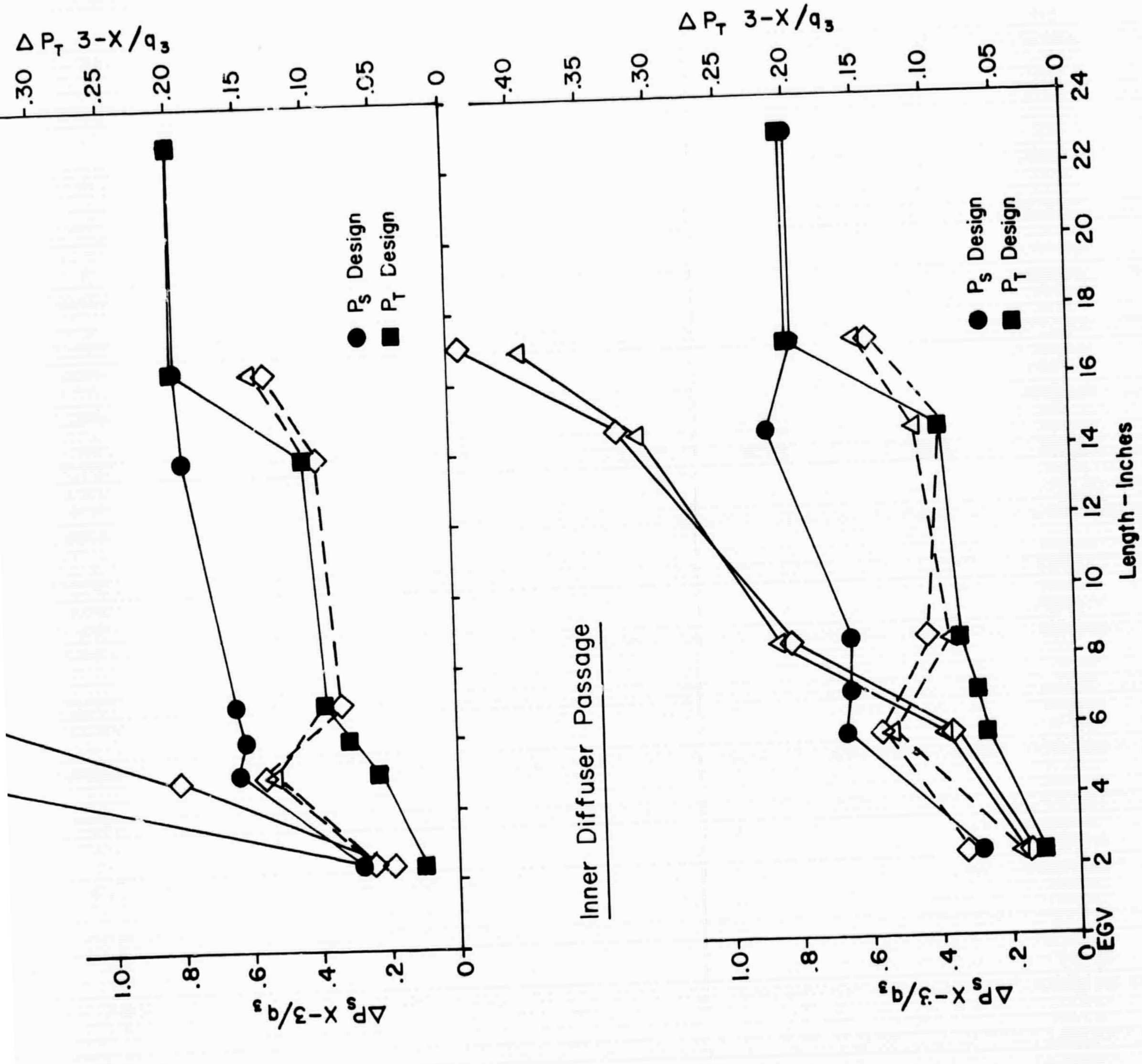


Figure 79

FOLDOUT FRAME 2

A review of Figures 78 and 79 shows that the total pressure loss factor was significantly lower for the inner flow path than for the outer flow path. For this reason, there was a preponderance of air, and resultant leaner fuel-air mixture, to the headplate I.D. The resultant higher exit temperature can be seen in Figure 80, and is reflected in the inverted temperature profiles shown in Figure 81.

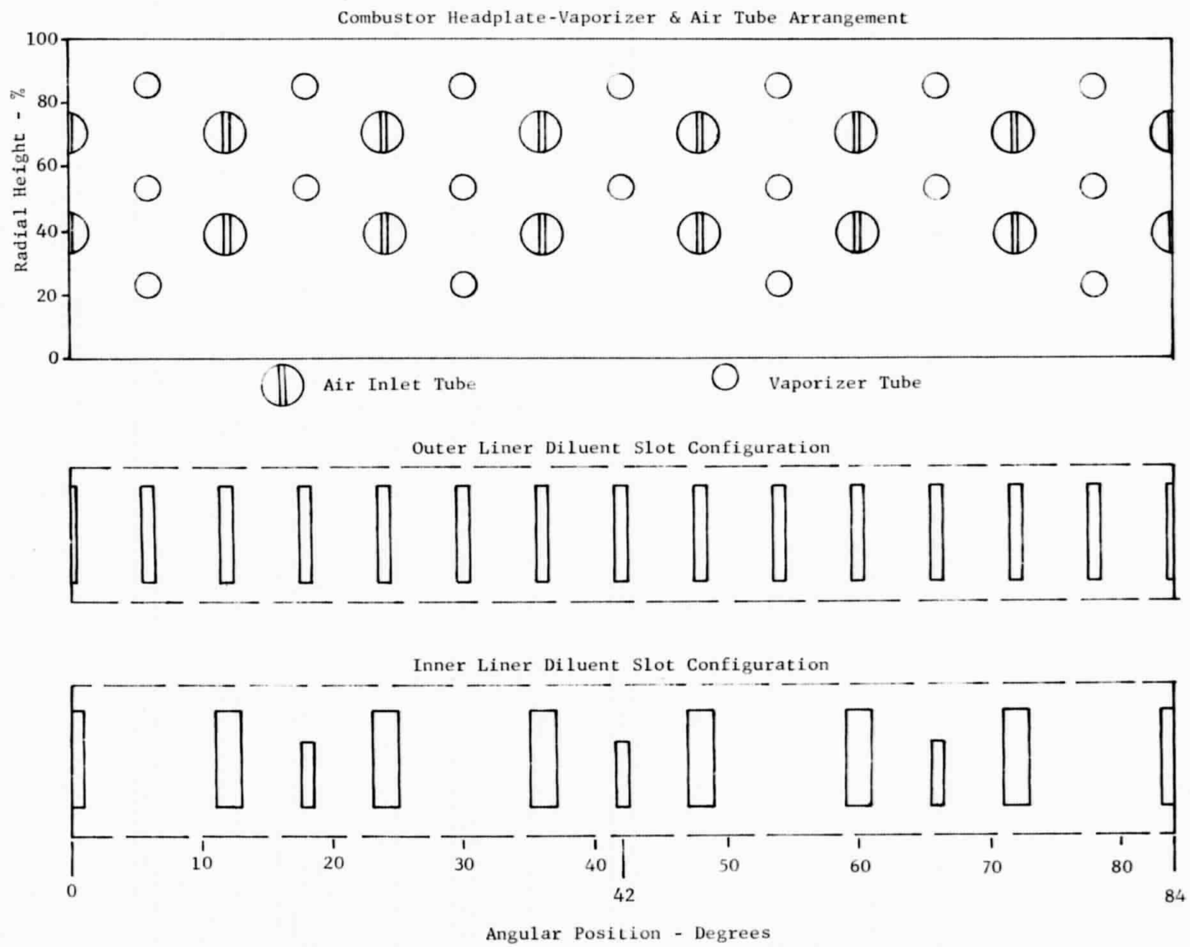
Studies were performed early in the program as to possible reworks or alternate courses. The studies indicated that the necessary modifications were too extensive, and that a new unit, shown in Figure 82, would be required. As the primary interest of the program was the liners, it was not considered feasible to expend large amounts of time and funding to correct an auxiliary piece of hardware.

The studies also indicated that modifications to the headplate would be an alternate method for modifying the air patterns. Though this would not be as effective, it was considered a more practical course for demonstrating the segmented liners. This course of action was therefore adopted, and was followed throughout the program. Development effort was then concentrated on the headplate.

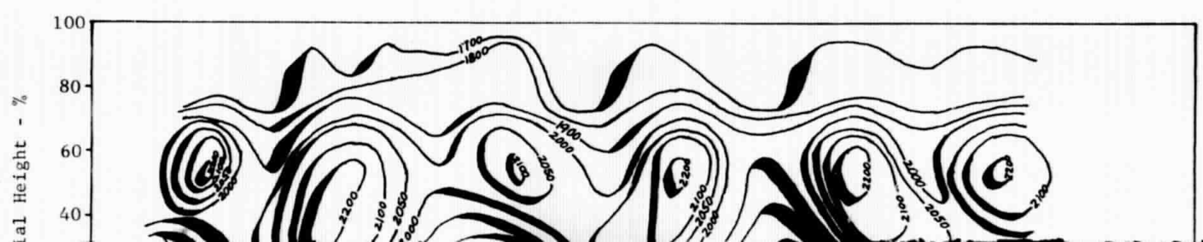
Testing revealed that there were three high-temperature zones, or "hot-spots", along the inner edge of the headplate. These were located where there were two vaporizers rather than three "in a line", as seen in Figure 53. These hot-spots persisted throughout the entire length of the combustor, and are noticeable in the exit temperature contours shown in Figure 80. They, in conjunction with the poor air distribution, were responsible for the obvious reversal of the mean temperature profiles plotted in Figure 81.

Though the program was directed toward the liner development, it was assumed that a modification which corrected the hot streaks in the combustion zone would also reflect in profile improvement. A headplate change was therefore incorporated into the rig. This change was a modification to the air cups to redirect the air and reduce the overall headplate air flow. This modification was first tried on build le by welding the side slots of the air cups closed with small plates. A further reduction in the air cup, embodied in a

EXIT TEMPERATURE CONTOURS - RIG BUILD 1e



Pt. No. 76
F/A .017
P_{T_3} 128.68 "HgH
T_{T_3} 1030°R



7-3233

FOLDOUT FRAME

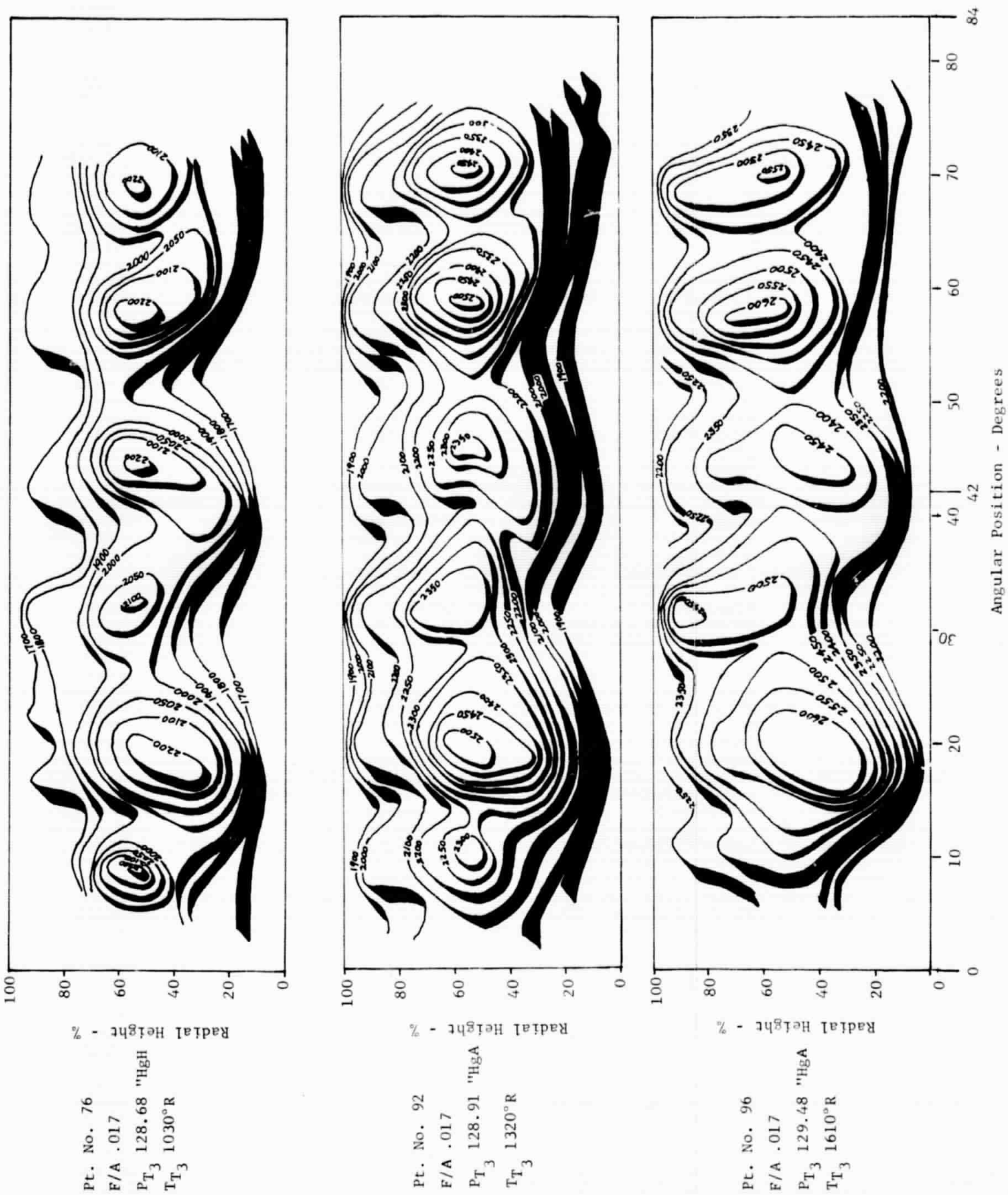
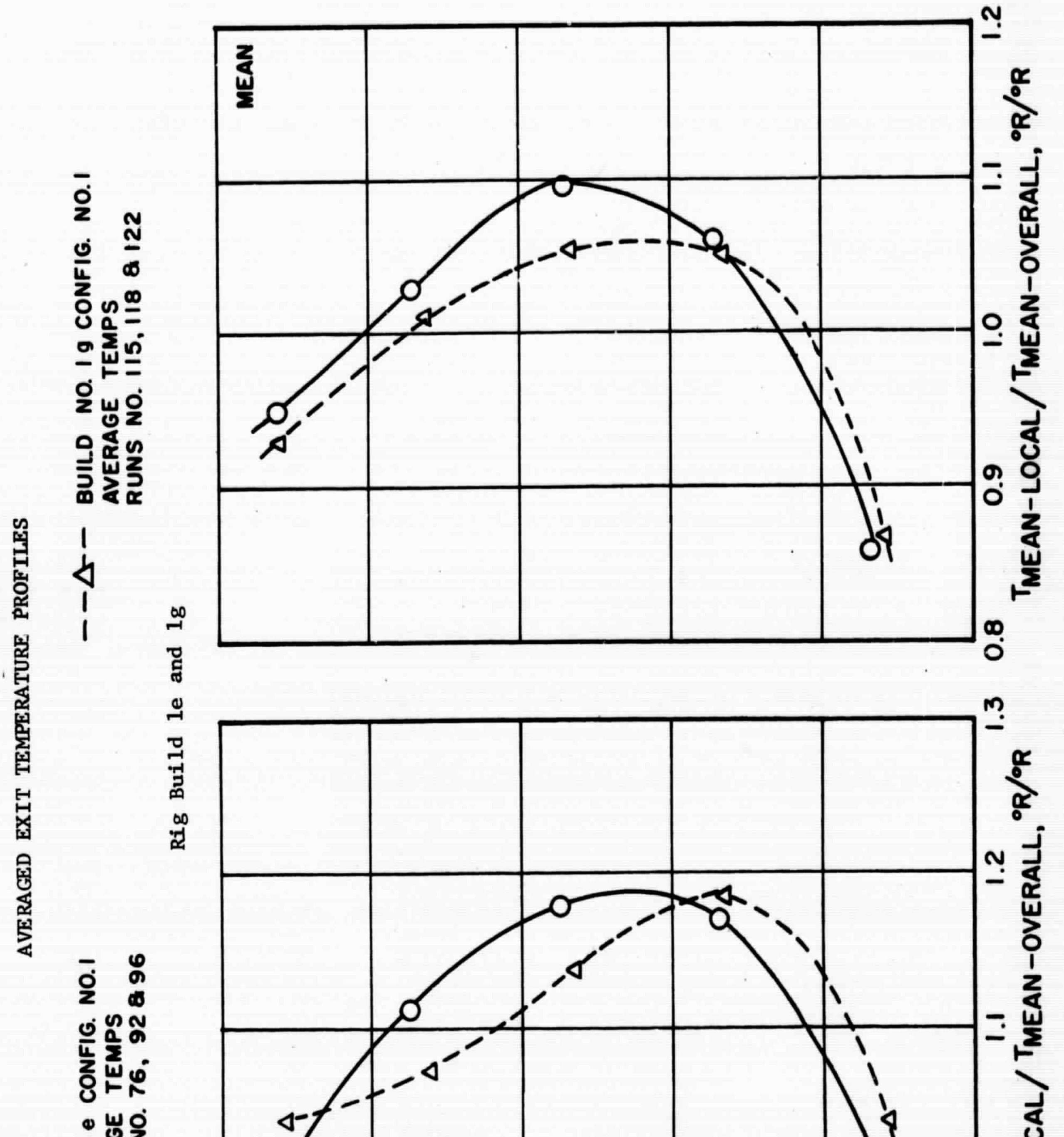


Figure 80

FOLDOUT FRAME 2



AVERAGED EXIT TEMPERATURE PROFILES
Rig Build 1e and 1g
BUILD 1e CONFIG. NO.1
AVERAGE TEMPS
RUNS NO. 76, 92 & 96
BUILD NO. 1g CONFIG. NO.1
AVERAGE TEMPS
RUNS NO. 115, 118 & 122
MAXIMUM
MEAN
PERCENT ANNULAR HEIGHT
TIP 100
80
60
40
20
HUB 0
0.9
1.0
1.1
1.2
1.3
0.8
0.9
1.0
1.1
1.2
$T_{MAX-LOCAL}/T_{MEAN-OVERALL}$, °R/°R
$T_{MEAN-LOCAL}/T_{MEAN-OVERALL}$, °R/°R

Figure 81

PROPOSED MODIFIED DIFFUSER CONTOURS

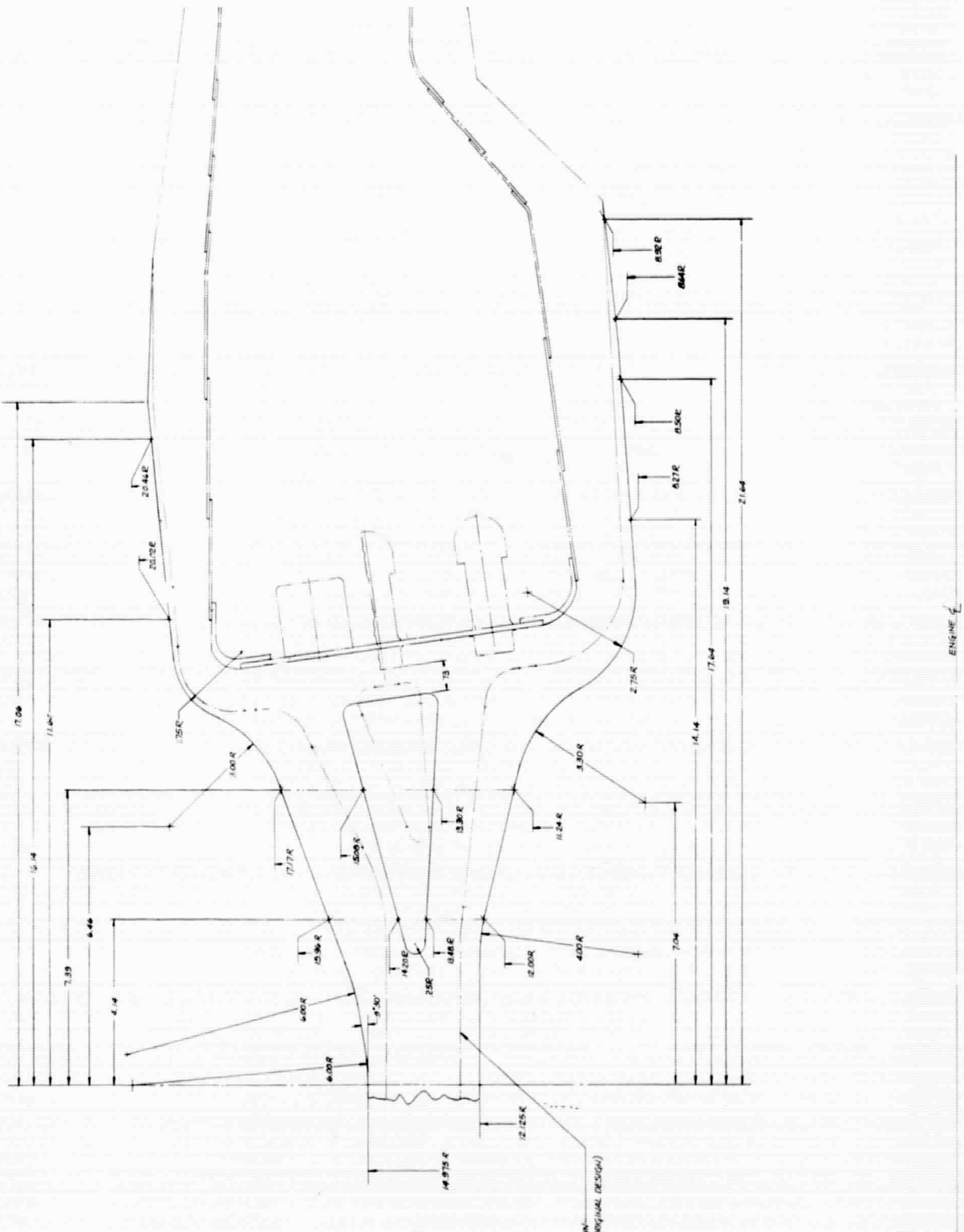


Figure 82

totally new aircup design, was later tested on build 1g. This reduction in headplate airflow produced a marked improvement in the profiles as contrasted to the earlier runs. This is shown in Figure 81. However, the profile improvement was obtained at the cost of a further total pressure loss, as can be seen in Figure 78. Further exit profile improvement would require recontouring of the air flow passages.

One other area where changes are recommended is the sector rig side plates. The original intent in using uncooled side plates was minimization of heat loss, to retain as realistic a temperature profile as possible over the entire width of the test section. It is apparent at this point that no uncooled side plate configuration will withstand the temperature environment in the primary zone of the combustor. Any long-duration tests would require cooling of the side plates.

5.0 CONCLUSIONS

Over the full course of the program, the segmented liner development effort, including design, development and test phases, has demonstrated the feasibility of the segmented liner concept. The following specific conclusions can be drawn from the results of work done.

1. The segmented liner designs approved for development were fabricated, with no serious difficulties encountered. It was necessary to form, machine and weld René 41 in the process of manufacturing the sections, with subsequent heat treating of the finished parts to obtain the required material strength. This was done. The tee welding procedure, which was selected in order to avoid lap joints, was a complete success, with full metal penetration and good strength. No stress cracks were encountered in the finished pieces, and structural integrity was proven with the manufacturing methods used.
2. The liner assemblies were subjected to many hot tests, without a single structural failure in any liner segment. In one instance the liners experienced temperatures more than 500° in excess of the design levels during a facility malfunction, and the worst damage incurred was local melting at the thin trailing edges of some segments. Even then, the general structural integrity of the liner assembly was maintained. This high structural reliability is due to the reduced liner thermal stress level inherent in the segmented concept. Another advantage of liner segmentation is the confinement of any stress crack that might occur to the segment in which it occurs.
3. The most liner damage incurred under ordinary operating conditions was warping of the slotted trailing edges of the segments in the regions of hottest combustor flow, with resultant degradation of the film cooling performance. This was found to be due to insufficient allowance for thermal growth of the liners in the area of the L-shaped brackets which maintain contact between segments in the area of the cooling slots, and insufficient support land surface in the same location. An increase in the number of support lands

and in the slot clearance for the brackets, coupled with shortening of the liner trailing edges, completely corrected this problem. The last test series demonstrated excellent liner dimensional stability, with no evidence of warping.

4. The test program demonstrated the effectiveness of the film cooling scheme, as applied to the segmented liner concept. Early testing showed overtemperature in some combustor liner areas, and undertemperature in others. Modifications to the design in the form of increased cooling slot height in one area, and increased diluent slot area in another, corrected the overtemperature problem in those areas. While the total cooling design was not optimized, and there were still regions of liner temperature in excess of the design values in the last test series, correction of the problem in those areas which were optimized demonstrated that the problem could be overcome in the liner assembly as a unit, and that the film cooling scheme used is a success.
5. One of the primary concerns in the segmented liner concept was ease of maintenance, and the potential for replacement of a single segment if necessary. This would produce considerable cost savings in combustor maintenance over the working lifetime of an engine. In the course of this program, the liner assemblies were disassembled, reworked and reassembled a number of times, with no problems. Thus, the concept of easy, inexpensive maintenance and repair of segmented liners was clearly demonstrated.

In sum, it is concluded that the segmented liner concept was proven to be feasible in every area of concern: Fabrication, structural strength, durability, thermal stability, induced stresses, maintenance and repair. In terms of liner durability, reliability, maintenance and repair factors, segmented liners are potentially very superior to the conventional hoop liner designs for both current and advanced gas turbine engines.

6.0 RECOMMENDATIONS

The results of the segmented liner program to date have verified the basic concept of the segmented liner. The segmented liner concept is considered to be valid for incorporation in an advanced demonstration or development engine. Further development of segmented liners should be done within the framework of an actual full-round combustor design which is related to a specific engine configuration.

It is recommended that the following work be included in any further segmented liner development program conducted by Curtiss-Wright.

1. Optimization of the entire segmented liner assembly in a full-round combustor, to reflect the latest design experience in sizing of coolant and diluent slots, and in liner dimensional control.
2. Performance of steady state demonstration tests in a full-round test rig for high pressure steady state and long duration cyclic testing. These tests should reflect all engine design operating parameters which affect combustor performance.
3. Performance of cyclic endurance tests to evaluate liner integrity over a duty cycle which reflects the full range of operating conditions which would be encountered in the actual engine.

7.0 APPENDICES

7.1 Stress Analysis Analytical Procedure

Each segmental element was analyzed for the thermal stress due to internal constraints and the mechanical stress due to the pressurized plate acting as a simple beam supported between support hangers. For the purpose of analysis, the segmental element was divided into five axial sub-elements. (See Figure A1).

Using the temperature data from the heat transfer analysis, average temperatures (T_1, T_2, T_3, T_4 and T_5) were obtained for each of the sub-elements. The free thermal growth of each element (δ_T) was determined as follows:

$$\delta_{T_n} = \alpha_n L \Delta T_n$$

where: α_n = Mean coefficient of linear expansion (in/in/°F).

ΔT_n = Average temperature of the element minus room temperature.

Since compatibility of deflections at the interfaces must be maintained, the deflection of each sub-element due to the thermal and mechanically induced growth (δ_n) can be expressed as follows:

$$\delta_1 = \delta_{T_1} + \frac{P_{1-2}\, L}{A_1 E_1}$$

$$\delta_2 = \delta_{T_2} + \frac{(-P_{2-1} + P_{2-3})\, L}{A_2 E_2}$$

$$\delta_3 = \delta_{T_3} + \frac{(-P_{3-2} + P_{3-4})\, L}{A_3 E_3}$$

$$\delta_4 = \delta_{T_4} + \frac{(-P_{4-3} + P_{4-5})\, L}{A_4 E_4}$$

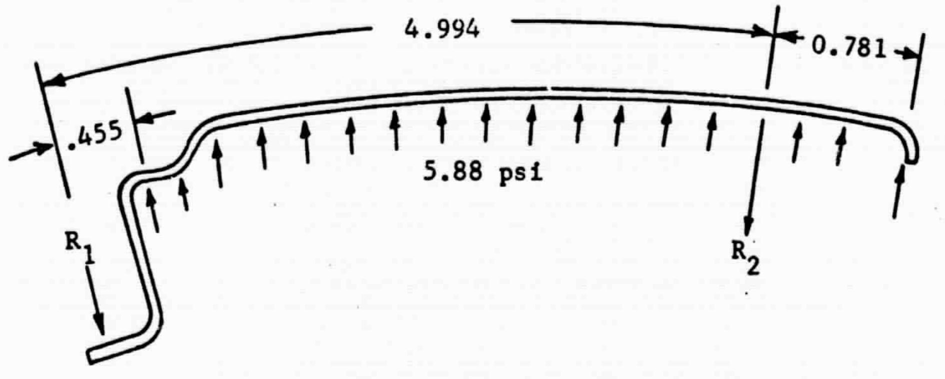
$$\delta_5 = \delta_{T_5} + \frac{-P_{5-4}\, L}{A_5 E_5}$$

The equations can then be solved simultaneously for the shear stress at the interfaces. The liner support structure analysis was based on simple beam support theory. The following is a typical stress calculation used for this portion of the analyses.

STRESS ANALYSIS SAMPLE CALCULATION

Liner Configuration No. 3

Segment Element No. 5



$$\Sigma M_{r_1} = 0$$

$$4.994\ R_2 = 5.88\ (5.32)\ (4.994 + 0.781 - 2.66)$$

(where the 5.32 is 4.994 + 0.781 -0.455)

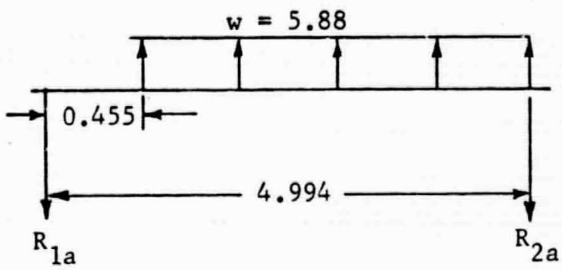
$$R_2 = 19.512\ \#/in$$

$$R_1 = 5.88\ (5.32) - 19.512$$

$$R_1 = 11.770\ \#/in$$

$$I = 17.16(10)^{-6}\ in^4$$

$$b_{tot.} = 1.65\ in$$



Ref. Roark 3rd Edition Table III Case 14

$M_{max.} = W \frac{d}{\ell} \left(a + \frac{cd}{2\ell}\right)$ at $X = a + \frac{cd}{\ell}$

$W = wc = 5.88\ (4.539) = 26.6893$

$a = 0.455$

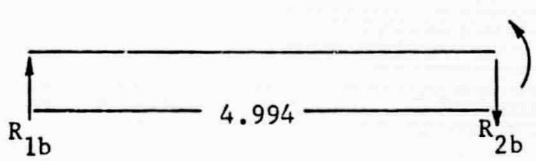
$b = 4.994 = \ell$

$c = 4.539$

$d = 2.2695$

$$M_{max.} = 26.6893\ \frac{2.2695}{4.994}\left[0.455 + \frac{4.539\ (2.2695)}{2\ (4.994)}\right] = 18.0279 \quad \frac{\text{in-\#}}{\text{in}}$$

$$X = 0.455 + \frac{4.539\ (2.2695)}{4.994} = 0.455 + 2.06273 = 2.51773 \text{ in}$$



$$M = \frac{5.88\ (0.781)^2}{2} = 1.79329 \quad \frac{\text{in-\#}}{\text{in}}$$

$$R_{1b} = R_{2b} = \pm \frac{1.79329}{4.994} = \pm 0.35909$$

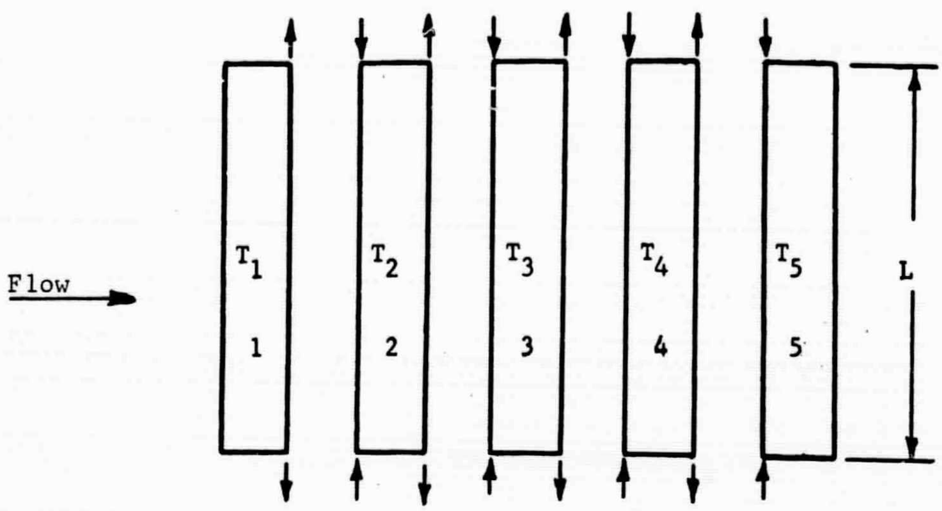
$$M_{bx = 2.51773} = 1.79329 - 0.35909\ (4.994 - 2.51773) = 0.9041 \quad \frac{\text{in-\#}}{\text{in}}$$

$$M_{tot.} = 18.0279 - 0.9041 = 17.124 \quad \frac{\text{in-\#}}{\text{in}}$$

$$f_b = \frac{17.124\ (1.63)\ (.028)}{17.16(10)^{-6}} = \pm 45{,}600 \text{ psi}$$

PRELIMINARY STRESS ANALYSIS ANALYTICAL PROCEDURE

Typical Segment



where: $T_1 \neq T_2 \neq T_3 \neq T_4 \neq T_5$

L = segment plate circumferential width

P_{1-2} = shear stress on element 1 at the interface of elements 1 and 2

P_{2-1} = shear stress on element 2 at the interface of elements 1 and 2

P_{2-3} = shear stress on element 2 at the interface of elements 2 and 3

etc.

Figure A1

7.2 Heat Transfer Analytical Procedure

In these analyses, the temperature distribution was determined by a balance between the various heat inputs and heat losses. Consideration was made for the following heat fluxes.

a. Luminous radiation from flame to liners.

b. Convective heat transfer from flame to liners associated with film cooling.

c. Conduction within liners.

d. Convective heat transfer to coolant flowing through the annuli formed by the liners and the casing.

e. Radiation from liners to casing.

f. Convective and radiative heat transfer within the film cooling slot.

These heat flows may conveniently be considered separately as follows:

Heat Transfer by Flame Radiation

At high pressures, radiation from the flame becomes the predominant factor influencing wall temperatures. Often it is necessary only to consider radiation from the primary zone, since the secondary zone temperatures will be substantially lowered by the dilution air and, consequently, secondary zone radiation may be negligible.

Two kinds of radiation exist in the primary zone:

a. The non-luminous radiation due to the presence of carbon dioxide and water vapor in the combustion products.

b. The luminous radiation due to the presence of incandescent soot particles in the flame.

The non-luminous radiation in the primary zone can be analytically evaluated from a knowledge of the amount of carbon dioxide and water vapor present in the combustion products. However, radiation from luminous sources is much more important, and usually controls the rate of radiation to the combustor walls, especially at high pressures.

Unfortunately, it is not possible to predict the emissivity of a flame from theoretical considerations since soot density depends, not only upon combustor design and combustor inlet pressure, but also upon the degree of primary and secondary aeration and the type of fuel used. Therefore, the value of the flame emissivity used in any prediction of flame radiation must be based on data previously obtained from a system in which conditions of combustion simulate closely the flame under consideration.

Thermal radiation from the flame may be determined by use of the Stefan-Boltzman relation, provided that an appropriate value is used for the effective flame emissivity. Experimental values of emissivity which are applicable to typical aircraft combustion chamber operating conditions have been provided by J. Clarke and S. Jackson (Ref. 1). This information included data for high pressure operation.

An alternative independent method for assessing radiation effects takes into consideration the total radiation flux. Schirmer (Ref. 2) measured total radiant energy from flames under a wide range of operating conditions.

A third method of determining primary zone radiation was by use of the Northern Research (Ref. 3) equations for flame emissivity. Fuel properties used in the emissivity equation ($\lambda = 1.7$) were obtained from Reference 4.

The flame radiation flux for the NASA combustor was obtained using the three methods discussed above, and found to be 123,000 BTU/Hr/Ft^2 in the primary zone for the Mach 3 flight condition. The radiation heat flux in the secondary zone was evaluated based on the assumption that the flame front is terminated by the diluent air. The radiation in the secondary zone was estimated to be 20 to 60% of the value in the primary zone, depending on the view factor of a given surface with respect to the flame.

Heat Transfer by Flame Convection Associated with Film-Cooling

Film cooling of segmented liners consists of injecting cooling air through slots into the main gas stream along the surface of the liner. A cool film or insulating blanket is built up in the boundary layer which reduces the heat input from the hot gas by altering the velocity and temperature profiles in the boundary layer. The film remains intact for only a short distance downstream and is gradually destroyed by turbulent mixing with the hot gas flow. Thus, the cooling air must be renewed at intervals along the axial length of the liner. Uniform wall temperatures are not possible, and the liner surface is coolest nearest the slot.

Convection heat transfer in the presence of film-cooling may be represented by:

$$\dot{Q}/A = h(T_{ad}-T_w) \tag{1}$$

Adiabatic Wall Temperature - T_{ad}

The most suitable correlation applicable to film-cooling by injection through slots is that developed by Hatch and Pappel (Reference 5) using a simplified theoretical flow model in conjunction with experimental data. This correlation is expressed in the following form.

$$\frac{T_g - T_{ad}}{T_g - T_c} = \exp\left\{-\left[\frac{L_{xhg}}{WC_p} - 0.04\right]\left(\frac{SV_s}{\alpha_c}\right)^{.125} f\left(\frac{V_g}{V_c}\right)\right\} \tag{2}$$

$$\text{Where } f\left(\frac{V_g}{V_c}\right) = \left(\frac{V_c}{V_g}\right)^{1.5(V_c/V_g-1)} \text{ if } \frac{V_g}{V_c} \leq 1.0$$

$$\text{and } f\left(\frac{V_g}{V_c}\right) = 1 + 0.4\,\mathrm{Tan}^{-1}\left(\frac{V_g}{V_c} - 1\right), \text{ if } \frac{V_g}{V_c} \geq 1.0$$

T_{ad} is thus expressed as a function of distance downstream from the slot exit. Equation 2 is a valid correlation only for the case of coolant injection at one station. For the case of multiple slots, Sellars (Reference 6) has suggested a modification to this equation to take into account the influence of coolant injection at slots upstream from a given slot. This modification replaces T_g in the equation by the T_{ad} applicable to the previous slot. It will be noted that this correction is cumulative. For example, T_g used in the correlation applicable to locations downstream of the third slot will be replaced by T_{ad} evaluated for the second slot, which has already been corrected to allow for the influence of the first slot.

Heat Transfer Coefficient - h

Based on Reference 6, the heat transfer coefficient in the presence of film-cooling may be replaced, without serious error, by the conventional coefficient determined in the absence of film cooling. The coolant properties should be evaluated at a temperature given by $(T_c + T_g)/2$.

Conduction Within Liners

Steady state heat flow through the liner material and the supporting structure is evaluated by the relation

$$\frac{\dot{Q}}{A} = -k \nabla T \qquad (3)$$

Convection Inside the Annulus and Inside the Cooling Slot

The heat transfer coefficient is found from

$$Nu = .023\ Re^{.8}\ Pr^{.4} \qquad (4)$$

where the Nusselt and Reynolds numbers are based on the appropriate hydraulic diameter. Therefore, convection from the liner to the coolant and inside the slot is given by

$$\frac{\dot{Q}}{A} = 0.023 \frac{K}{D} Re^{0.8}\ Pr^{0.4}\ (T_w - T_c) \qquad (5)$$

Radiation from the Liners to the Casing and Inside the Cooling Slot

The radiation from the liners to the casing, and inside the cooling slot is evaluated using the following law of solid body radiation between two surfaces at different temperatures:

$$\frac{\dot{Q}}{A} = \left[\frac{\sigma E_w E_{ca}}{E_w + E_{ca} - E_w E_{ca}}\right] \left(T_w^4 - T_{ca}^4\right) \qquad (6)$$

NOMENCLATURE

M	Mach Number
Q/A	Heat Flux
h	Coolant Convective Heat Transfer Coefficient
T_{ad}	Adiabatic Wall Temperature
T_w	Wall Temperature
T_g	Gas Stream Temperature
T_c	Coolant Temperature
L	Slot Width
T_{ca}	Casing Temperature
x	Distance Along Cooled Wall in Direction of Flow
hg	Main Stream Convective Heat Transfer Coefficient
W	Flow Rate
C_p	Specific Heat
S	Coolant Slot Height
V_g	Main Stream Gas Velocity
α_c	Coolant Thermal Diffusivity
V_c	Coolant Velocity at Slot Exit
ρ	Coolant Air Density

REFERENCES

1. Clarke, J.S., and Jackson, S.R., "General Consideration in the Design of Combustion Chambers for Aircraft and Industrial Gas Turbines", presented at the 1962 SAE International Congress, Detroit, Michigan.

2. Schirmer, R.M., and Quigg, M.T., "High Pressure Combustor Studies of Flame Radiation as Related to Hydrocarbon Structure", Phillips Petroleum Company, Progress Report #3 for Navy BuWeps Contract NOw 64-0443-d.

3. "The Design and Performance Analysis of Gas Turbine Combustion Chambers - Vol. I", Northern Research and Engineering Corporation, 1964.

4. "The Design and Performance Analysis of Gas Turbine Combustion Chambers - Vol. II", Northern Research and Engineering Corporation, 1964.

5. Hatch, J.E., and Pappel, S.S., "Use of a Theoretical Flow Model to Correlate Data for Film Cooling or Heating an Adiabatic Wall by Tangential Injection of Gases of Different Fluid Properties", NASA TN D-130, November 1959.

6. Sellers, J.P. Jr., "Gaseous Film Cooling With Multiple Injection Stations", AIAA Journal, Vol. 1, Number 9, September 1960.

TABLE I

COMBUSTOR OPERATING CONDITIONS AT IGNITION AND MACH 3 DESIGN POINT

LOCATION A		
Conditions	Ignition	Mach No. = 3
P_T - "HgA (Total Gas Pressure)	35.0	183.0
T_T - °F (Total Gas Temp.)	2560	3240
W_G - lb/sec. (Gas Flow Rate)	5.50	60.80
Head Plate Fuel Air Ratio	.0236	.0320

Combustor Cond.		Ignition		Mach No. = 3	
Liner	Location	Wc - lb/sec. Coolant Flow Rate	Tc-°F Coolant Temperature	Wc - lb/sec. Coolant Flow Rate	Tc - °F Coolant Temperature
Inner	Slot # 1	0.0730	1150	0.875	1150
	Slot # 2	0.0795	1150	0.880	1150
	Slot # 3	0.0815	1150	0.905	1150
	Diluent	2.4400	1150	26.885	1150
	Slot # 4	0.0746	1150	0.830	1150
	Slot # 5	0.0875	1150	0.975	1150
	Slot # 6	0.1040	1150	1.150	1150
Outer	Slot # 7	0.1290	1150	1.420	1150
	Slot # 8	0.1300	1150	1.450	1150
	Slot # 9	0.1320	1150	1.460	1150
	Diluent	3.7100	1150	40.990	1150
	Slot #10	0.1270	1150	1.400	1150
	Slot #11	0.1340	1150	1.450	1150
	Slot #12	0.1380	1150	1.530	1150

TABLE II

THREE DIMENSIONAL TRANSIENT METAL TEMPERATURE DISTRIBUTION

CONFIGURATION 1 OUTER LINER

TEMPERATURES - °F

Node # \ Time sec.	2	4	6	10	16	30	50	100	Steady State
1	286	529	794	1308	1490	1502	1503	1503	1503
2	245	456	699	1237	1577	1622	1626	1629	1630
3	286	525	786	1295	1486	1501	1503	1506	1506
4	244	449	685	1195	1496	1542	1559	1576	1581
5	287	530	795	1311	1492	1503	1503	1503	1503
6	245	456	701	1243	1585	1631	1634	1636	1637
7	287	530	795	1310	1491	1503	1503	1503	1503
8	245	456	700	1241	1586	1634	1636	1636	1637
9	245	444	669	1164	1491	1541	1550	1558	1559
10	286	528	793	1305	1486	1498	1498	1499	1499
11	193	318	458	821	1141	1168	1174	1179	1180
12	195	326	473	850	1166	1184	1185	1185	1185
13	195	326	473	851	1166	1184	1184	1185	1185
14	194	323	467	835	1146	1168	1171	1176	1179
15	195	325	471	847	1163	1182	1182	1183	1184
16	225	388	567	970	1269	1308	1315	1321	1322
17	232	411	607	1037	1329	1356	1357	1358	1358
18	232	411	607	992	1330	1354	1355	1356	1357
19	225	394	579	992	1281	1313	1316	1322	1325
20	226	397	585	1008	1307	1338	1339	1341	1341
21	193	329	486	873	1252	1336	1348	1358	1361
22	193	335	498	898	1271	1343	1349	1356	1362
23	194	337	505	916	1308	1385	1388	1390	1392
24	178	299	439	798	1213	1338	1354	1368	1373
25	179	304	451	825	1237	1349	1357	1366	1373
26	180	307	458	845	1278	1400	1406	1409	1411
27	173	287	420	767	1199	1356	1378	1397	1407
28	174	294	434	799	1234	1373	1386	1395	1405
29	175	297	442	820	1279	1434	1444	1448	1451

TABLE II (Continued)

Node #	Time sec. 2	4	6	10	16	30	50	100	Steady State
30	165	269	390	717	1165	1368	1401	1425	1443
31	166	275	405	751	1210	1390	1412	1422	1435
32	166	278	412	771	1258	1464	1432	1458	1493
33	152	239	342	634	1069	1322	1383	1424	1463
34	155	261	392	747	1249	1468	1498	1511	1523
35	155	262	394	755	1265	1477	1500	1508	1515
36	154	252	371	699	1165	1374	1415	1436	1453
37	154	257	384	734	1247	1490	1518	1529	1557
38	220	380	556	967	1276	1314	1319	1322	1324
39	221	382	560	976	1286	1324	1327	1328	1329
40	221	382	560	977	1288	1325	1327	1328	1328
41	221	381	558	973	1283	1319	1323	1324	1325
42	221	381	558	973	1285	1324	1327	1328	1329
43	160	257	369	691	1088	1141	1142	1143	1150
44	160	257	370	692	1089	1141	1142	1143	1150
45	160	257	371	692	1089	1141	1142	1143	1150
46	160	257	370	691	1089	1141	1142	1143	1150
47	160	257	370	691	1089	1141	1142	1143	1150
48	188	317	463	824	1186	1245	1246	1247	1255
49	188	317	463	824	1185	1243	1244	1246	1254
50	188	317	463	824	1185	1243	1244	1246	1254
51	188	317	464	825	1186	1244	1245	1247	1255
52	188	317	464	825	1186	1244	1245	1247	1255
53	108	134	165	284	531	810	998	1121	1147
54	106	131	161	274	517	797	991	1121	1150
55	105	125	150	252	465	741	945	1092	1142
56	95	112	132	212	404	679	906	1095	1158
57	91	104	120	183	341	590	824	1062	1167
58	85	93	104	146	264	492	733	1017	1171
59	80	84	89	110	173	325	536	887	1165
60	148	227	316	584	979	1090	1125	1149	1153
61	144	219	307	574	973	1090	1130	1156	1162

TABLE II (Continued)

Node #	Time sec. 2	4	6	10	16	30	50	100	Steady State
62	130	190	261	489	895	1069	1122	1159	1171
63	120	170	232	435	836	1047	1113	1163	1178
64	110	150	199	367	735	993	1085	1162	1197
65	97	123	159	285	607	931	1054	1160	1211
66	86	99	118	191	408	747	931	1111	1252
67	152	249	364	682	1084	1148	1157	1164	1165
68	149	253	380	717	1115	1188	1199	1206	1207
69	134	216	322	623	1063	1201	1219	1232	1236
70	124	195	288	563	1016	1200	1224	1242	1249
71	115	176	257	503	950	1193	1235	1265	1279
72	101	150	218	427	863	1183	1248	1290	1315
73	90	123	173	329	697	1083	1208	1293	1365
74	153	266	409	789	1196	1274	1284	1292	1294
75	147	225	318	598	1002	1117	1156	1181	1186
76	108	136	169	291	548	830	1025	1154	1186
77	76	89	106	158	346	710	961	1122	1155
78	77	88	104	154	336	695	952	1122	1155
79	77	86	100	142	302	646	913	1106	1157
80	77	84	94	128	262	581	860	1095	1170
81	76	82	90	117	225	505	781	1062	1179
82	76	79	84	102	178	412	681	1007	1186
83	74	77	80	88	128	271	493	875	1177
84	77	87	103	153	338	720	994	1170	1197
85	80	84	89	110	176	333	548	908	1189
86	85	93	103	146	273	516	762	1050	1206
87	91	104	120	184	357	626	863	1090	1195
88	95	111	131	210	413	703	933	1124	1184
89	100	119	114	241	475	770	983	1135	1175
90	106	130	159	276	534	823	1016	1143	1170
91	108	134	164	284	546	829	1016	1133	1155
92	86	98	114	170	339	590	763	928	1087
93	97	122	154	261	544	830	952	1047	1121

TABLE II (Continued)

Node #	Time sec. 2	4	6	10	16	30	50	100	Steady State
94	111	151	199	358	716	966	1042	1100	1136
95	119	170	229	420	812	1028	1082	1121	1142
96	130	191	263	486	895	1067	1104	1133	1144
97	144	219	304	559	966	1091	1118	1139	1146
98	148	229	320	586	990	1099	1122	1140	1146
99	80	84	88	108	164	251	336	471	811
100	85	92	101	138	236	364	482	661	913
101	91	102	116	173	308	461	600	796	980
102	95	109	126	195	354	523	677	879	1018
103	99	117	138	221	403	584	744	937	1043
104	105	127	152	252	455	642	805	983	1061
105	108	131	157	262	471	662	825	997	1064
106	86	100	119	188	392	731	956	1085	1147
107	97	124	159	280	596	942	1071	1124	1154
108	111	154	206	380	768	1053	1117	1141	1155
109	120	173	237	444	864	1098	1133	1146	1155
110	130	194	272	511	943	1122	1140	1149	1154
111	144	222	314	586	1009	1132	1143	1150	1153
112	149	232	328	610	1029	1133	1141	1147	1149
113	108	135	168	297	582	879	1075	1199	1217
114	145	223	311	573	983	1101	1126	1146	1151
115	107	128	153	256	466	671	849	1031	1095
116	148	231	329	617	1040	1146	1153	1159	1161
117	82	90	101	141	270	510	730	959	1041
118	82	90	101	141	267	500	714	940	1028
119	81	89	99	136	253	475	683	915	1017
120	80	86	95	125	223	420	618	860	994
121	79	84	91	116	198	369	551	797	967
122	78	82	88	95	173	314	472	703	922
123	77	79	83	87	137	236	357	556	846
124	76	77	79	81	108	164	236	370	743
125	76	77	78	80	103	136	203	317	709

TABLE II (Continued)

Node #	Time sec.	2	4	6	10	16	30	50	100	Steady State
126		76	77	79	81	111	176	254	393	746
127		75	75	75	75	75	77	86	133	521
128		75	75	75	75	75	77	85	132	520
129		75	75	75	75	78	93	124	212	614
130		75	75	75	75	78	91	119	202	607

TABLE III

THREE DIMENSIONAL TRANSIENT METAL TEMPERATURE DISTRIBUTION

CONFIGURATION 3 OUTER LINER

TEMPERATURE - °F

Node #	Time sec. 2	4	6	10	16	30	50	100	Steady State
1	125	176	237	444	773	1030	1139	1175	1179
2	293	539	799	1284	1465	1483	1485	1487	1487
3	250	458	691	1178	1458	1509	1521	1534	1539
4	294	541	804	1291	1467	1483	1484	1484	1486
5	253	469	714	1223	1504	1545	1551	1563	1569
6	294	542	806	1294	1467	1482	1482	1483	1484
7	253	469	714	1225	1509	1549	1555	1567	1572
8	252	467	708	1212	1496	1537	1544	1555	1561
9	294	541	805	1292	1465	1481	1481	1482	1483
10	197	330	479	857	1140	1171	1174	1178	1183
11	197	330	478	858	1146	1173	1175	1180	1185
12	199	335	489	877	1156	1182	1185	1189	1194
13	197	330	478	856	1142	1178	1182	1186	1192
14	122	180	252	484	894	1119	1146	1152	1156
15	244	434	640	1073	1335	1374	1378	1382	1388
16	197	351	533	967	1339	1415	1419	1426	1434
17	243	427	626	1051	1319	1367	1371	1376	1382
18	242	425	620	1038	1306	1355	1361	1366	1371
19	121	180	252	484	899	1121	1148	1153	1158
20	197	340	503	895	1236	1322	1332	1338	1345
21	197	340	503	893	1234	1327	1338	1344	1349
22	109	152	208	395	776	1085	1152	1165	1171
23	184	314	465	842	1219	1331	1342	1348	1356
24	183	311	459	829	1200	1317	1332	1339	1347
25	107	150	205	389	772	1084	1152	1164	1171
26	186	316	465	840	1226	1350	1366	1374	1383
27	185	311	454	818	1194	1324	1347	1358	1367
28	96	122	158	284	584	954	1115	1169	1183
29	170	283	417	771	1198	1378	1403	1414	1424

TABLE III (Continued)

Node #	Time sec. 2	4	6	10	16	30	50	100	Steady State
30	170	282	414	761	1175	1347	1379	1393	1404
31	93	120	154	276	576	952	1115	1170	1184
32	158	264	393	746	1201	1405	1430	1444	1456
33	130	208	308	603	1070	1375	1412	1423	1435
34	118	193	294	584	1044	1314	1350	1370	1387
35	156	254	371	695	1126	1344	1392	1429	1446
36	83	94	109	166	327	631	890	1119	1198
37	225	390	569	982	1268	1312	1315	1316	1317
38	225	388	564	970	1252	1308	1314	1315	1316
39	226	391	571	987	1275	1317	1320	1321	1322
40	225	388	567	980	1265	1307	1310	1312	1313
41	163	261	375	703	1068	1140	1144	1146	1150
42	115	163	225	436	844	1112	1148	1151	1156
43	163	262	377	701	1046	1103	1108	1114	1124
44	162	257	367	682	1032	1104	1123	1139	1140
45	81	91	106	161	314	613	870	1102	1164
46	188	261	460	814	1152	1235	1240	1242	1248
47	126	190	268	502	894	1182	1228	1231	1238
48	189	319	465	824	1158	1228	1233	1237	1244
49	187	312	449	790	1113	1194	1215	1233	1243
50	82	94	111	174	337	641	895	1121	1182
51	205	336	476	827	1086	1145	1168	1176	1177
52	79	95	122	212	461	893	1096	1165	1171
53	94	112	135	224	416	665	861	1060	1127
54	112	153	203	374	717	984	1080	1135	1150
55	85	111	147	263	560	940	1110	1169	1174
56	87	113	123	191	379	637	844	1054	1125
57	141	210	289	537	898	1061	1117	1145	1152
58	124	182	255	491	896	1119	1145	1151	1156
59	110	153	209	398	777	1084	1150	1163	1170
60	95	122	157	283	581	952	1113	1168	1182
61	83	94	109	165	324	628	887	1116	1195

TABLE III (Continued)

Node #	Time sec.	2	4	6	10	16	30	50	100	Steady State
62		123	159	195	344	549	647	742	889	1025
63		112	141	170	291	480	607	714	854	975
64		105	128	151	250	412	517	617	769	916
65		99	118	138	222	378	512	618	751	912
66		81	90	101	144	274	530	773	1028	1114
67		76	80	86	105	167	309	462	699	921
68		76	78	81	93	133	251	405	654	888
69		77	81	87	109	180	336	487	690	867
70		76	78	82	95	141	259	395	602	799
71		75	77	79	86	114	202	325	533	750
72		76	79	83	97	149	273	397	563	774
73		76	77	79	85	104	148	208	318	627
74		76	77	78	84	102	143	192	288	606
75		75	75	75	75	75	77	83	116	421
76		75	75	75	75	75	76	82	115	420
77		75	75	75	76	78	88	112	181	509
78		75	75	75	76	77	87	109	174	503

TABLE IV

THREE DIMENSIONAL TRANSIENT METAL TEMPERATURE DISTRIBUTION

CONFIGURATION 1 INNER LINER

TEMPERATURES - °F

Node #	Time Sec. 2	4	6	10	16	30	50	100	Steady State
1	286	527	789	1291	1500	1516	1517	1517	1519
2	226	421	652	1177	1533	1583	1585	1589	1609
3	287	530	792	1304	1504	1519	1519	1520	1520
4	227	420	647	1162	1517	1576	1585	1590	1595
5	287	530	794	1306	1508	1523	1524	1524	1524
6	228	424	657	1203	1600	1668	1669	1669	1670
7	287	530	794	1306	1508	1524	1524	1524	1524
8	228	423	657	1200	1603	1674	1674	1674	1674
9	287	530	792	1304	1506	1522	1522	1522	1522
10	227	419	645	1169	1568	1638	1639	1639	1641
11	109	314	451	807	1149	1185	1185	1186	1188
12	191	318	461	826	1163	1190	1190	1190	1190
13	191	318	461	827	1162	1189	1190	1190	1190
14	193	319	458	813	1141	1177	1178	1179	1184
15	161	263	386	726	1117	1162	1165	1172	1201
16	225	392	574	984	1296	1337	1338	1339	1341
17	225	396	584	1003	1311	1344	1344	1344	1344
18	225	396	584	1003	1310	1342	1342	1342	1343
19	225	393	578	985	1280	1321	1322	1323	1328
20	224	393	577	985	1273	1304	1306	1309	1332
21	198	341	504	899	1278	1358	1361	1362	1367
22	197	341	504	891	1234	1310	1315	1317	1328
23	198	344	511	904	1232	1283	1287	1294	1342
24	178	301	444	809	1235	1363	1370	1372	1379
25	179	304	450	818	1213	1324	1333	1336	1349
26	179	306	453	823	1200	1282	1289	1298	1355
27	174	290	426	778	1222	1393	1410	1414	1424
28	174	292	431	784	1193	1332	1349	1354	1373
29	173	291	428	780	1181	1302	1316	1325	1392

TABLE IV (Continued)

Node #	Time Sec.	2	4	6	10	16	30	50	100	Steady State
30		167	273	395	718	1165	1397	1446	1461	1483
31		168	278	407	746	1190	1390	1426	1434	1454
32		109	170	256	516	1012	1437	1498	1512	1596
33		155	253	372	697	1183	1444	1490	1503	1521
34		155	256	380	718	1208	1426	1443	1446	1458
35		161	269	399	749	1235	1428	1440	1442	1453
36		155	256	379	715	1202	1429	1460	1467	1485
37		155	256	379	714	1193	1414	1439	1447	1503
38		212	367	539	955	1297	1345	1349	1350	1352
39		213	367	539	955	1299	1344	1346	1346	1348
40		190	324	479	877	1279	1344	1346	1346	1348
41		213	367	539	954	1298	1345	1348	1348	1351
42		234	405	590	1013	1313	1353	1356	1357	1361
43		156	246	348	642	1045	1138	1141	1144	1155
44		152	242	347	655	1069	1138	1140	1142	1153
45		152	242	347	654	1069	1142	1143	1146	1155
46		156	247	352	649	1052	1139	1142	1144	1155
47		106	255	224	446	908	1128	1138	1142	1159
48		186	312	453	801	1163	1234	1237	1239	1251
49		186	312	454	803	1168	1234	1236	1239	1251
50		186	312	454	802	1165	1230	1232	1235	1248
51		186	312	453	801	1165	1234	1236	1239	1251
52		186	309	446	785	1147	1233	1236	1239	1252
53		116	156	200	339	602	694	736	819	1148
54		116	156	199	337	600	692	734	817	1159
55		111	146	184	308	556	657	701	789	1163
56		107	138	173	286	523	631	677	766	1166
57		100	125	152	249	476	590	638	729	1170
58		94	113	134	211	406	529	582	681	1175
59		81	87	95	122	204	299	377	513	1196
60		150	234	332	613	1024	1129	1133	1137	1153
61		149	236	337	626	1038	1143	1147	1151	1167

TABLE IV (Continued)

Node #	Time Sec.	2	4	6	10	16	30	50	100	Steady State
62		141	217	306	570	991	1133	1141	1146	1166
63		133	201	283	530	956	1133	1146	1152	1176
64		122	179	249	474	918	1129	1148	1154	1182
65		107	147	197	368	767	1073	1130	1153	1188
66		87	105	130	219	476	864	1065	1150	1274
67		148	233	336	638	1072	1165	1169	1173	1186
68		115	154	197	341	627	718	763	855	1171
69		75	76	78	83	103	168	255	435	1168
70		75	76	77	83	101	164	250	429	1170
71		75	76	78	82	100	161	245	421	1174
72		75	76	77	81	97	155	236	408	1178
73		75	76	77	80	95	149	225	391	1183
74		75	75	76	79	89	135	207	368	1187
75		75	75	76	77	84	118	182	341	1196
76		75	76	78	83	105	178	277	484	1195
77		87	100	115	169	334	523	608	716	1254
78		93	112	134	213	427	584	644	740	1207
79		101	127	157	267	548	701	760	844	1219
80		107	138	174	296	574	715	761	844	1203
81		111	146	186	318	596	717	760	843	1186
82		116	156	200	344	628	731	772	851	1176
83		116	157	201	344	627	735	774	851	1162
84		86	98	114	170	339	590	763	928	1087
85		97	122	154	261	544	830	952	1047	1121
86		111	151	199	358	716	966	1042	1100	1136
87		119	170	229	420	812	1028	1082	1121	1142
88		130	191	263	486	895	1069	1104	1132	1144
89		144	219	304	559	966	1091	1118	1139	1146
90		148	[illegible]	320	586	990	1099	1122	1140	1146
91		80	84	88	108	164	251	336	471	811
92		85	92	101	138	236	364	482	661	913
93		91	102	116	173	308	461	600	706	980

TABLE IV (Continued)

Node #	Time Sec. 2	4	6	10	16	30	50	100	Steady State
94	95	109	126	195	354	523	677	879	1018
95	99	117	138	221	403	584	744	937	1043
96	105	127	152	252	455	642	805	983	1061
97	108	131	157	262	471	662	825	997	1064
98	95	118	147	252	546	918	1083	1131	1155
99	104	138	180	325	688	1020	1112	1133	1149
100	115	161	216	401	809	1085	1130	1139	1150
101	125	180	246	454	862	1104	1136	1141	1150
102	131	193	267	495	911	1117	1138	1141	1149
103	140	209	292	539	956	1127	1140	1143	1149
104	140	210	293	542	960	1127	1138	1141	1148
105	107	132	263	284	551	852	1042	1150	1177
106	145	223	311	573	983	1101	1126	1146	1151
107	107	128	153	256	466	671	849	1031	1095
108	83	98	118	188	409	776	1011	1147	1179
109	82	90	101	141	270	510	730	959	1041
110	82	90	101	141	267	500	714	940	1028
111	81	89	99	136	253	475	683	915	1017
112	80	86	95	125	223	420	618	860	994
113	79	84	91	116	198	369	551	797	967
114	78	82	88	95	173	314	472	703	922
115	77	79	83	87	137	236	357	556	846
116	76	77	79	81	108	164	236	370	745
117	77	77	78	80	103	136	203	317	709
118	76	77	79	81	111	176	254	393	746
119	75	75	75	75	75	77	86	133	521
120	75	75	75	75	75	77	85	132	520
121	75	75	75	75	78	93	124	212	614
122	75	75	75	75	78	91	119	202	607

TABLE V

THREE DIMENSIONAL TRANSIENT METAL TEMPERATURE DISTRIBUTIONS

CONFIGURATION 3 INNER LINER

TEMPERATURES - °F

Node #	Time Sec.	2	4	6	10	16	30	50	100	Steady State
1		154	246	354	660	1040	1161	1169	1172	1172
2		295	547	817	1315	1491	1506	1506	1507	1508
3		273	501	748	1231	1450	1478	1482	1491	1503
4		294	543	809	1308	1491	1506	1506	1507	1508
5		275	509	763	1256	1461	1480	1484	1493	1506
6		294	544	811	1310	1494	1512	1513	1514	1515
7		237	440	676	1198	1544	1610	1616	1628	1636
8		240	445	681	1196	1525	1599	1613	1622	1625
9		298	550	810	1304	1500	1511	1512	1513	1513
10		192	319	462	834	1131	1165	1168	1173	1177
11		192	322	469	843	1139	1169	1171	1176	1182
12		192	321	467	841	1140	1171	1173	1178	1183
13		190	315	453	816	1122	1161	1164	1169	1174
14		128	193	272	514	914	1119	1141	1147	1151
15		230	404	593	1005	1277	1317	1320	1325	1331
16		253	452	666	1101	1343	1371	1375	1385	1396
17		230	405	594	1007	1276	1309	1312	1317	1323
18		230	402	588	995	1266	1311	1315	1320	1326
19		128	194	273	515	915	1120	1143	1148	1152
20		203	351	518	915	1252	1331	1338	1344	1351
21		173	290	426	779	1161	1286	1297	1302	1308
22		118	172	237	446	833	1100	1145	1153	1158
23		186	317	470	850	1229	1344	1353	1359	1368
24		176	294	430	777	1154	1285	1297	1303	1309
25		116	169	234	439	829	1099	1145	1153	1158
26		187	318	466	837	1218	1351	1368	1378	1387
27		163	267	389	714	1117	1303	1331	1344	1353
28		94	120	154	272	551	932	1124	1199	1207
29		173	290	429	791	1221	1407	1429	1441	1452

TABLE V (Continued)

Node # / Time Sec.	2	4	6	10	16	30	50	100	Steady State
30	148	240	348	632	1130	1390	1425	1444	1456
31	88	107	134	232	477	885	1123	1221	1232
32	161	266	392	732	1176	1406	1450	1471	1476
33	161	270	403	760	1209	1397	1419	1432	1439
34	163	268	390	713	1132	1350	1420	1453	1458
35	153	234	326	584	1070	1388	1440	1443	1452
36	92	126	172	309	611	1012	1236	1345	1357
37	217	375	549	964	1284	1342	1346	1348	1349
38	218	367	552	970	1289	1344	1347	1348	1349
39	184	311	457	845	1250	1343	1344	1345	1345
40	198	336	492	888	1251	1319	1321	1322	1322
41	157	251	361	682	1062	1149	1153	1157	1160
42	157	251	361	682	1063	1151	1154	1157	1160
43	160	250	370	730	1121	1151	1153	1156	1158
44	158	255	370	676	1040	1121	1147	1152	1156
45	89	106	129	213	427	770	1003	1140	1156
46	191	321	467	825	1171	1255	1259	1261	1263
47	190	321	466	824	1172	1256	1259	1261	1263
48	192	328	481	849	1185	1255	1258	1261	1263
49	190	319	462	812	1148	1237	1251	1260	1262
50	91	111	137	231	460	800	1021	1149	1163
51	84	98	118	190	373	717	997	1214	1255
52	115	163	222	423	822	1130	1196	1225	1231
53	100	124	153	264	477	662	800	1004	1164
54	153	236	331	605	962	1077	1104	1138	1154
55	116	166	230	445	867	1167	1225	1247	1253
56	94	115	140	237	441	631	778	995	1166
57	153	237	332	607	966	1084	1109	1134	1154
58	133	198	278	526	918	1119	1141	1147	1151
59	121	175	240	454	836	1098	1144	1152	1157
60	100	130	168	300	597	942	1091	1145	1159
61	87	105	131	224	449	848	1101	1236	1250

TABLE V (Continued)

Node #	Time Sec. 2	4	6	10	16	30	50	100	Steady State
62	97	109	125	203	324	457	601	822	996
63	99	117	138	222	379	527	660	845	996
64	87	97	109	161	285	451	602	810	987
65	81	87	96	133	251	446	603	792	983
66	77	78	82	99	160	342	549	852	1098
67	76	78	82	95	143	285	464	739	967
68	78	83	90	115	195	347	506	748	947
69	75	77	79	88	122	245	411	671	887
70	77	81	87	107	177	340	503	727	924
71	75	76	78	84	101	209	361	617	845
72	76	76	77	82	104	193	333	584	803
73	77	80	84	98	138	225	323	484	682
74	77	80	83	97	136	220	307	454	661
75	75	75	76	79	92	146	219	323	403
76	75	75	76	79	92	146	219	323	403
77	75	75	79	88	115	195	288	421	523
78	75	75	79	88	115	195	288	421	523

TABLE VI

SEGMENTED LINER CONFIGURATION NO. 1 TEST SUMMARY

Rebuild No.	Total Time	Cumulative Total Time	Burn Time	Cumulative Burning Time	Objective	Results
1	25:25	-	-	-	To determine airflow split and aerodynamic characteristics.	Airflow distribution conforms with design intent.
1a	19:10	44:35	4:55	4:55	To evaluate exit temperature profile at 2 atmos. press. and 570°F inlet.	Inner vaporizer burned due to low velocity and lean operation.
1b	7:00	51:35	3:40	8:35	To determine effect of reducing number of liner vaporizers.	Mean exit gas temperature profile high near inner liner. Local cooling air leakage affecting temperature distribution.
1c	2:50	54:25	0:35	9:10	Evaluate exit temperature profile with 25% increase of inner diluent and improved exit sealing.	Limited data indicated exit temperature profile improvement. One vaporizer failed.
1d	6:45	61:10	4:05	13:15	Continue to evaluate exit temperature profile with 25% increase of inner diluent.	Slight exit temperature profile improvement. A number of inner and outer liner film cooling slots warped and partially closed shut. Maximum exit gas temperature is high at all radial positions. One vaporizer tube failed.
1e	35:00	96:10	15:40	28:55	Determine the effect of 35% reduction of headplate aircup flow area, liner rework for thermal growth and improved exit sealing.	Ran up to 130" HgA pressure and 1150°F inlet at design F/A of .017. Completed testing of Liner Config. #1. No vaporizer tube failures. Side walls damaged. General condition of liners was good. Some film slots warped and slight burning of a few edges occurred. Maximum exit temperature is high.
1g	16:00	112:10	5:00	33:55	Determine effect of new aircup and vaporizer designs, shortened liner segments, widened liner hanger slots, and increased number of cooling slot support lands.	Ran up to 130" HgA pressure and 1150°F inlet at design F/A of .017. No vaporizer tube failures. Side walls damaged. Headplate i.d. damaged in location of removed vaporizer tubes. Liners in very good condition.

TABLE VII

SEGMENTED LINER CONFIGURATION NO. 3 - TEST SUMMARY

Rebuild No.	Total Time	Cumulative Total Time	Burn Time	Cumulative Burn Time	Objective	Results
1.f	29:30	29:30	12:15	12:15	To evaluate exit temperature profile, efficiency, pressure drop and liner operating temperatures and integrity.	Liner temperatures and combustor performance comparable to Configuration No. 1. Testing interrupted due to rig damage resulting from facility valve malfunction.

TABLE VIII

SEGMENTED LINER COMBUSTOR TEST LOG

Data Point	Build No.	Type of Run	Air Flow Parameters: Total Pressure (psig)	Air Flow Parameters: Total Temperature (°F)	Air Flow Parameters: Flow Rate (lb/sec)	Fuel Flow Parameters: Flow Rate (lb/hr)	Fuel Flow Parameters: Fuel-Air Ratio	Purpose
1	1	Cold Flow	0.8	51	.685	-	-	Flow check film cooling slots
2	1	" "	1.3	52	.826	-	-	" " " " "
3	1	" "	2.1	52	1.13	-	-	" " " " "
4	1	" "	3.0	53	1.398	-	-	" " " " "
5	1	" "	4.9	53	1.855	-	-	" " " " "
6	1	" "	0.7	50	.964	-	-	Flow check vaporizer tubes
7	1	" "	0.7	50	.964	-	-	" " " "
8	1	" "	1.2	50	1.53	-	-	" " " "
9	1	" "	2.5	50	1.918	-	-	" " " "
10	1	" "	3.4	50	2.20	-	-	" " " "
11	1	" "	5.0	51	2.61	-	-	" " " "
12	1	" "	3.2	50	2.70		-	" " " "
13	1	" "	5.0	50	3.72	-	-	" " " "
14	1	" "	6.7	50	4.24	-	-	" " " "
15	1	" "	0.7	51	1.262	-	-	Flow check aircups
16	1	" "	1.2	50	1.573	-	-	" " "
17	1	" "	2.7	50	2.47	-	-	" " "
18	1	" "	4.7	50	3.49	-	-	" " "
19	1	" "	6.6	49	4.38	-	-	" " "
20	1	" "	3.3	49		-	-	" " "
21	1	" "	6.5	39	4.45	-	-	" " "
22	1	" "	3.5	38	4.42	-	-	" " "
23	1	" "	4.7	38	5.44	-	-	" " "
24	1	" "	7.2	40	6.54	-	-	" " "
25	1	" "	0.8	40	1.39	-	-	Flow check outer diluent slots
26	1	" "	1.3	35	1.79	-	-	" " " " "
27	1	" "	2.5	36	2.60	-	-	" " " " "
28	1	" "	5.0	34	4.03	-	-	" " " " "
29	1	" "	5.0	33	5.72	-	-	" " " " "
30	1	" "	7.2	33	6.84	-	-	" " " " "
31	1	" "	8.6	35	7.64	-	-	" " " " "

TABLE VIII (cont'd.)

SEGMENTED LINER COMBUSTOR TEST LOG

Data Point	Build No.	Type of Run	Air Flow Parameters: Total Pressure (psig)	Air Flow Parameters: Total Temperature (°F)	Air Flow Parameters: Flow Rate (lb/sec)	Fuel Flow Parameters: Flow Rate (lb/hr)	Fuel Flow Parameters: Fuel-Air Ratio	Purpose
32	1	Cold Flow	0.7	34	1.142	-	-	Flow check inner diluent slots
33	1	" "	1.1	33	1.58	-	-	" " " " "
34	1	" "	2.5	32	2.58	-	-	" " " " "
35	1	" "	4.7	32	4.04	-	-	" " " " "
36	1	" "	7.1	33	7.04	-	-	" " " " "
37	1	" "	8.7	37	7.59	-	-	" " " " "
38	1	" "	10.3	43	8.29	-	-	" " " " "
39	1	" "	12.1	33	9.21	-	-	" " " " "
40	1	" "	17.6	33	11.29	-	-	" " " " "
41	1	" "	22.5	36	12.93	-	-	" " " " "
42	1	" "	30.9	45	13.02	-	-	" " " " "
43	1	Preheater	67.8	728	-	-	-	Calibrate exit probe
45	1a	Cold Flow	19.8	40	12.7	-	-	Facility checkout
46	1a	" "	49.6	55	22.8	-	-	" "
47	1a	" "	50.2	55	24.4	-	-	" "
48	1a	" "	60.7	58	28.8	-	-	" "
49	1a	Preheat	15.2	570		-	-	System check
50	1a	Hot	19.6	572	5.8	268	.0129	First burn
51	1a	"	19.6	572		473		Data
52	1a	"	20.0	565	12.9	514	.011	"
53	1b	"	17.5	579	13.45	700	.0145	"
54	1b	"	17.4	577	13.1	795	.0169	"
55	1b	"	17.3	573	13.3	707	.0147	"
56	1b	"	17.6	578	12.9	795	.0170	"
57	1b	"	17.6	579	13.0	930	.0199	"
61	1c	Hot	17.7	568	13.7	708	.0144	Data
62	1c	Preheat	49.0	578	24.1	-	-	Air flow checks
63	1c	"	65.1	575	31.5	-	-	" " "

TABLE VIII (cont'd.)

SEGMENTED LINER COMBUSTOR TEST LOG

Data Point	Build No.	Type of Run	Air Flow Parameters: Total Pressure (psig)	Air Flow Parameters: Total Temperature (°F)	Air Flow Parameters: Flow Rate (lb/sec)	Fuel Flow Parameters: Flow Rate (lb/hr)	Fuel Flow Parameters: Fuel-Air Ratio	Purpose
64	1d	Hot	17.7	573	13.6	702	.0144	Data
65	1d	"	17.7	576	13.6	832	.017	"
66	1d	"	17.7	577	13.6	983	.020	"
67	1d	"	48.9	580	24.2	1300	.015	"
68	1d	"	48.8	585	24.2	1470	.017	"
69	1d	"	48.7	565	24.2	1730	.020	"
70	1e	"	19.6	570	13.0	702	.015	"
71	1e	"	19.3	570	13.0	795	.017	"
72	1e	"	19.6	586	13.0	935	.020	"
73	1e	"	49.1	585	24.0	1300	.015	"
74	1e	"	49.1	580	24.0	1475	.017	"
75	1e	"	49.1	570	24.0	1470	.017	"
76	1e	"	47.9	568	24.0	1470	.017	"
77	1e	"	49.1	565	24.0	1730	.020	"
78	1e	"	19.7	858	13.0	795	.017	"
79	1e	"	19.8	865	13.0	935	.020	"
80	1e	"	19.4	864	13.0	760	.0163	"
81	1e	"	19.4	864	13.0	702	.015	"
82	1e	"	-	864	24.0	1470	.017	"
83	1e	"	44.2	858	22.4	1370	.017	"
84	1e	"	19.9	858	13.0	795	.017	"
85	1e	"	19.8	985	13.0	795	.017	"
86	1e	"	19.5	1022	13.0	795	.017	"
87	1e	"	19.9	1075	13.0	795	.017	"
88	1e	"	19.6	1132	13.0	795	.017	"
89	1e	"	19.9	1161	13.0	795	.017	"
90	1e	"	49.3	864	24.0	1470	.017	"
91	1e	"	49.1	967	24.0	1470	.017	"
92	1e	"	48.8	877	24.0	1470	.017	"
93	1e	"	49.1	972	24.0	1470	.017	"
94	1e	"	49.1	1065	24.0	1470	.017	"
95	1e	"	49.1	1118	24.0	1470	.017	"
96	1e	"	49.1	1150	24.0	1470	.017	"

TABLE VIII (cont'd.)

SEGMENTED LINER COMBUSTOR TEST LOG

Data Point	Build No.	Type of Run	Air Flow Parameters: Total Pressure (psig)	Air Flow Parameters: Total Temperature (°F)	Air Flow Parameters: Flow Rate (lb/sec)	Fuel Flow Parameters: Flow Rate (lb/hr)	Fuel Flow Parameters: Fuel-Air Ratio	Purpose
97	1f	Hot	19.8	585	13.0	702	.015	Data
98	1f	"	20.0	588	13.0	795	.017	"
99	1f	"	19.6	590	13.0	935	.020	"
100	1f	"	50.0	588	24.2	1299	.015	"
101	1f	"	49.1	572	24.2	1470	.017	"
102	1f	"	49.1	572	24.6	1730	.020	"
103	1f	"	19.7	870	13.12	702	.015	"
104	1f	"	19.8	868	13.0	795	.017	"
105	1f	"	19.7	865	13.0	935	.020	"
106	1g	Cold Flow	19.4	50	13.0	-	-	Isothermal System evaluation
107	1g	" "	48.9	58	23.2	-	-	" " " "
108	1g	Preheater	20.2	548	13.06	-	-	" " " "
109	1g	"	19.8	870	13.0	-	-	" " " "
110	1g	"	48.9	590	24.2	-	-	" " " "
111	1g	"	50.6	775	23.0	-	-	" " " "
112	1g	"	20.6	588	12.8	-	-	System checkout
113	1g	"	49.1	580	23.65	-	-	" "
114	1g	Hot	19.6	578	13.1	701	.0149	Data
115	1g	"	19.4	575	13.0	793	.01695	"
116	1g	"	19.1	578	13.1	931	.01975	"
117	1g	"	19.9	565	13.4	931	.0193	"
118	1g	"	19.6	863	13.14	797	.01685	"
119	1g	"	19.6	870	12.92	933	.020	"
120	1g	Preheater	20.1	573	13.0	-	-	System checkout
121	1g	Hot	19.8	1092	12.7	700	.0153	Data
122	1g	"	19.4	1158	13.1	791	.0168	"
123	1g	"	49.1	870	24.0	1472	.0171	"
124	1g	"	48.6	868	23.8	1739	.0203	"
125	1g	"	48.6	1122	23.7	1470	.01725	"
126	1g	"	49.7	1148	23.6	1293	.0152	"

TABLE VIII (cont'd.)

SEGMENTED LINER COMBUSTOR TEST LOG

Data Point	Build No.	Type of Run	Air Flow Parameters			Fuel Flow Parameters		Purpose
			Total Pressure (psig)	Total Temperature (°F)	Flow Rate (lb/sec)	Flow Rate (lb/hr)	Fuel-Air Ratio	
SG 1	le	Preheater	15.2	620	13.5	-	-	Vibration measurement
SG 2	le	"	51.6	620	14.0	-	-	" "
SG 3	le	"	19.4	620	16.3	-	-	" "
SG 4	le	"	50.6	615	23.9	-	-	" "
SG 5	le	"	72.7	610	25.7	-	-	" "
SG 6	le	Hot	-	560	13.6	940	.020	" "
SG 7	le	"	19.6	570	13.4	795	.017	" "
SG 8	le	"	18.7	585	13.5	701	.015	" "
P 1	lf	"	20.1	583	13.0	702	.015	Radiation measurement
P 2	lf	"	19.8	588	13.0	795	.017	" "
P 3	lf	"	-	585	13.0	935	.020	" "
P 4	lf	"	19.5	572	13.0	702	.015	" "
P 5	lf	"	19.7	578	13.0	795	.017	" "
P 6	lf	"	19.6	580	13.0	935	.020	" "
P 7	lf	"	19.6	582	13.0	702	.015	" "
P 8	lf	"	19.6	585	13.0	795	.017	" "
P 9	lf	"	19.6	588	13.0	935	.020	" "
P 10	lf	"	19.6	578	13.0	702	.015	" "
P 11	lf	"	19.6	582	13.1	795	.017	" "
P 12	lf	"	19.6	588	13.0	935	.020	" "
P 13	lf	"	19.6	580	13.0	702	.015	" "
P 14	lf	"	19.6	585	13.0	795	.017	" "
P 15	lf	"	19.6	590	13.05	935	.020	" "
P 16	lf	"	49.9	588	24.0	1299	.015	" "
P 17	lf	"	48.9	592	24.0	1470	.017	" "

TABLE IX

LINER THERMOCOUPLE TEMPERATURE READINGS

Configuration No. 1 - Build 1e

Burner Inlet Condition	570°F @ 2 Atm.			570°F @ 4 Atm.			860°F @ 2 Atm.			860°F @ 4 Atm.	1015°F @ 2 Atm.	1065°F @ 2 Atm.	1065°F @ 2 Atm.	1150°F @ 2 Atm.	1150°F @ 4 Atm.
F/A	.015	.017	.020	.015	.017	.020	.015	.017	.020	.017	.017	.017	.017	.017	.017
Data Point No.	70	71	72	73	76	77	81	78	79	92	86	87	94	89	96
Thermocouple #1	970	955	855	955	-	-	-	-	-	-	-	-	-	-	-
2	735	705	650	760	725	670	1065	1010	960	1100	1230	1305	1325	1420	1445
3	475	480	390	435	610	610	875	880	890	915	1050	1090	1090	1175	1190
4	585	610	680	555	900	945	1225	1265	1315	-	-	-	-	-	-
5	770	790	790	820	-	-	-	-	-	-	-	-	-	-	-
6	905	970	1000	900	945	975	1210	1275	1335	1255	1425	1455	1395	1515	1495
7	1040	1160	1255	1100	1165	1295	1235	1365	1445	1205	1425	1445	1475	1520	1600
8	745	780	810	730	765	800	1055	1095	1135	1075	1265	1295	1270	1375	1370
9	645	660	670	630	655	675	970	985	1005	985	1165	1210	1180	1300	1285
10	765	795	843	808	885	905	1132	1135	1165	1180	1028	1360	1358	1440	1440
11	800	840	940	795	835	885	1110	1145	1195	1155	1310	1345	1330	1425	1435
12	890	950	1010	915	990	1060	1195	1250	1315	1275	1425	1460	1445	1535	1550
13	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
14	685	710	730	675	710	730	1020	1040	1070	1050	1225	1265	1240	1350	1350
15	735	765	805	740	775	795	1075	1095	1120	1105	1290	1325	1280	1405	1380
16	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
17	970	1030	1085	1015	1105	1185	1275	1350	1415	1390	1495	1520	1545	1585	1640
18	1135	1065	965	1065	775	735	1425	1415	1410	1375	1600	1640	1665	1710	1750
19	830	850	857	860	915	920	1165	1170	1190	1248	1410	1450	1400	1522	1470
20	860	885	885	890	865	885	1145	1180	1195	1180	1355	1395	1375	1470	1485
21	905	945	950	960	870	875	1255	1295	1340	1340	1485	1505	1490	1575	1620
22	1025	1060	1075	1105	1180	1205	1350	1400	1435	1620	1665	1685	1715	1710	1730
23	1090	1140	1185	925	930	965	1215	1245	1260	1225	1420	1455	1400	1525	1515
24	1110	1175	1245	1150	1095	1125	1380	1445	1520	1550	1595	1615	1655	1660	1725
25	1025	1080	1115	1035	1140	1230	1305	1355	1380	1350	1515	1540	1505	1605	1595
26	1120	1150	1190	1165	1225	1235	1395	1405	1445	1425	1555	1580	1565	1650	1640
27	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
28	800	820	850	790	830	845	1133	1150	1182	1190	1335	1375	1355	1450	1430
29	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
30	810	840	860	815	840	865	1130	1155	1165	1180	1335	1370	1355	1450	1460
31	720	740	760	720	745	760	1040	1055	1065	1075	1235	1275	1255	1365	1365
32	665	685	695	670	695	705	990	1005	1010	1025	1185	1225	1205	1315	1320
33	705	725	735	700	720	735	1035	1050	1055	1060	1230	1275	1240	1360	1350
34	860	900	945	855	900	945	1155	1185	1235	1200	1335	1365	1365	1435	1440

TABLE X

LINER THERMOCOUPLE TEMPERATURE READINGS

CONFIGURATION NO. 3 BUILD 1.f

BURNER INLET CONDITION		570°F @ 2 Atm.			570°F @ 4 Atm.			860°F @ 2 Atm.		
F/A Ratio		.015	.017	.020	.015	.017	.020	.015	.017	.020
DATA POINT NO.		97	98	99	100	101	102	103	104	105
THERMOCOUPLE #	1	775	735	675	1065	1060	1045	1110	1091	1011
(°F)	2	940	935	945	1030	1065	1090	1302	1320	1372
	3	610	615	625	610	615	620	838	848	854
	4	850	855	895	865	890	910	1168	1186	1222
	5	805	805	840	815	835	855	1119	1140	1169
	6	925	965	1065	925	980	1050	1172	1217	1280
	7	1015	1080	1195	955	995	1060	1246	1295	1381
	8	775	790	840	765	790	820	1040	1068	1110
	9	700	715	745	720	745	770	1000	1022	1060
	10	735	755	795	725	745	780	1032	1060	1100
	11	735	755	795	715	735	770	1022	1050	1087
	12	730	745	775	725	750	780	1010	1030	1060
	13	855	885	955	855	890	935	1119	1159	1212
	14	790	815	860	825	860	905	1038	1125	1172
	15	785	805	845	780	805	840	1080	1107	1149
	16	880	915	990	900	935	980	1139	1180	1237
	17	810	835	885	825	860	905	1082	1112	1155
	18	1240	1165	1015	885	865	920	1468	1458	1414
	19	685	690	705	705	725	745	986	999	1010
	20	1035	1075	1070	1045	1005	1050	1288	1336	1407
	21	1015	1050	1135	1015	965	1005	1255	1306	1362
	22	865	890	925	1000	1035	1080	1192	1222	1259
	23	1135	1190	1335	1180	1305	1340	1352	1418	1480
	24	1165	1220	1340	1200	1225	1300	1369	1442	1525
	25	1235	1310	1335	1330	1285	1360	1420	1490	1590
	26	995	1020	1045	965	965	970	1260	1265	1310
	27	1205	1315	1430	1290	1355	1425	1420	1505	1590
	28	1175	1240	1335	1060	1095	1155	1385	1450	1515
	29	965	1010	1060	1000	1030	1090	1280	1325	1375
	30	1085	1160	1265	1185	1250	1340	1340	1400	1480
	31	765	800	835	825	845	870	1080	1105	1150
	32	745	765	795	760	775	800	1045	1070	1105
	33	715	735	755	720	730	755	1025	1050	1075
	34	415	420	440	430	430	435	500	500	505

TABLE XI

LINER THERMOCOUPLE TEMPERATURE READINGS

CONFIGURATION NO. 1 - BUILD 1g

BURNER INLET CONDITION	570°F @ 2 Atm.				860°F @ 2 Atm.		860°F @ 4 Atm.		1050°F @ 2 Atm.	1150°F @ 2 Atm.	1150°F @ 4 Atm.	
F/A Ratio	.015	.017	.020	.020	.017	.020	.017	.020	.015	.017	.015	.017
DATA PT. NO.	114	115	116	117	118	119	123	124	121	122	126	125
THERMOCOUPLE #1 (°F)	800	745	660	680	1120	1040	1320	1110	1600	1540	1670	1630
2	850	830	740	770	1210	1180	1320	1360	1520	1550	1570	1610
3	620	605	510	605	900	900	900	910	1170	1180	1150	1150
4	790	780	780	780	1110	1120	1110	1150	1430	1430	1380	1410
5	1000	1010	1030	1010	1320	1360	1290	1350	1550	1570	1510	1560
6	930	940	980	970	1220	1250	1200	1250	1480	1480	1430	1460
7	920	925	960	950	1210	1240	1230	1270	1480	1470	1460	1480
8	680	675	685	680	980	995	990	1010	1280	1290	1260	1260
9	680	675	695	680	990	1000	1010	1030	1290	1300	1270	1280
10	850	850	905	890	1140	1180	1190	1250	1430	1430	1420	1450
11	860	870	900	900	1180	1210	1180	1240	1440	1440	1420	1450
12	840	840	860	850	1140	1170	1140	1180	1410	1420	1380	1420
13	855	860	880	880	1160	1190	1200	1240	1440	1440	1430	1460
14	800	790	810	800	1110	1140	1150	1190	1390	1400	1390	1430
15	775	760	780	780	1070	1090	1080	1110	1360	1360	1320	1360
16	1000	995	1030	1030	1280	1320	1330	1400	1500	1540	1550	1590
17	920	930	960	960	1220	1260	1260	1320	1480	1480	1470	1520
18	1160	1090	930	960	1350	1360	1200	1210	1490	1450	1730	1430
19	940	935	870	870	1290	1310	1320	1360	1510	1510	1540	1570
20	770	750	730	730	1140	1130	1220	1240	1440	1450	1330	1450
21	840	820	790	790	1220	1220	1270	1300	1460	1460	1510	1540
22	975	975	960	960	1310	1340	1370	1410	1580	1600	1780	1770
23	860	840	820	810	1290	1290	1410	1420	1570	1570	1430	1610
24	870	880	850	850	1300	1300	1350	1390	1540	1530	1570	1620
25	1060	1075	1060	1055	1480	1525	1625	1685	1660	1735	1825	1860
26	-	-	-	-	-	-	-	-	-	-	-	-
27	1020	1040	1030	1015	1420	1460	1430	-	1605	1645	-	-
28	885	925	950	935	1275	1340	1305	1375	1455	1520	1540	1570
29	980	1025	1065	1060	1335	1415	1405	1445	1570	1590	1615	1660
30	1170	1255	1350	1355	1500	1585	1715	-	1610	1695	-	-
31	1135	1225	1315	1310	1480	1520	1600	1770	1545	1625	1695	1785
32	725	740	750	750	1070	1110	1115	1150	1290	1355	1320	1355
33	815	850	865	850	1180	1225	1290	1345	1365	1435	1405	1500
34	1120	1180	1250	1235	1410	1480	1505	1595	1530	1605	1635	1690

TABLE XII

SEGMENTED LINER COOLANT FLOW - COMPARISON OF MEASURED VALUES WITH DESIGN

Liner	Slot #	Design $\frac{P_t}{P_{sg}}$	Test $\frac{P_t}{P_{sg}}$	% $\dot{\omega}_3$ Design	% $\dot{\omega}_3$ Test*	Deviation From Design
Inner	1	1.074	1.056	.67%	.60	-10%
	2	1.074	1.053	.67%	.58	-13%
	3	1.077	1.050	.67%	.56	-16%
	4	1.064	1.052	.67%	.61	-10%
	5	1.073	1.054	.67%	.59	-12%
	6	1.080	1.057	.67%	.58	-13%
Outer	7	1.070	1.041	1.00%	.80	-20%
	8	1.072	1.044	1.00%	.81	-19%
	9	1.074	1.049	1.00%	.83	-17%
	10	1.062	1.047	1.00%	.88	-12%
	11	1.072	1.054	1.00%	.88	-12%
	12	1.082	1.061	1.00%	.88	-12%

* Calculated on the basis of design slot areas.