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Martin Marietta Report No. MCR-73-116

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Final Report

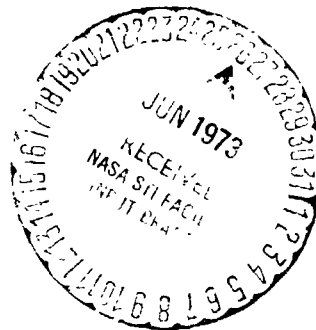
(NASA-7-128951) DESIGN, DEVELOP AND
TEST HIGH TEMPERATURE DYNAMIC SEALS FOR
THE SPACE SHUTTLE'S AERODYNAMIC CONTROL
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DESIGN, DEVELOP & TEST HIGH-TEMPERATURE DYNAMIC SEALS FOR THE SPACE SHUTTLE'S AERODYNAMIC CONTROL SURFACES

June 1973



MARTIN MARIETTA CORPORATION
DENVER DIVISION
Denver, Colorado 80201

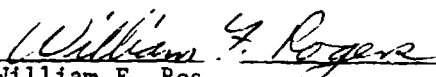
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AERODYNAMIC CONTROL SURFACES

June 1973

Approved



William F. Rogers
Program Technical Monitor, NASA-JSC

MARTIN MARIETTA CORPORATION
DENVER DIVISION
Denver, Colorado 80201

FOREWORD

This report is submitted by Martin Marietta Corporation in fulfillment of Contract NAS9-12883 and covers the period from July 6, 1972, through June 8, 1973.

The program was performed by Martin Marietta's Structures and Materials Research Organization with Mr. William F. Barrett as Department Manager and Mr. P. Paul Plank as Chief of Advanced Structural Concepts. The program manager, Mr. Ronald L. Kirlin, would like to especially thank the following individuals for their contributions to the success of this program: Mr. Ernest G. Littler, structural design and analysis; Mr. Durwin A. Schmitt, aerodynamic heating; Mr. Christopher C. Miller, thermal analysis; and Mr. Gerry J. Schmidt, plasma arc testing. Mr. William E. King, Jr, and Mr. Frank B. Click, Jr, also provided valuable advice and assistance in the areas of structural design and aerothermodynamics, respectively.

Special recognition and appreciation are also due to Mr. William F. Rogers, NASA-JSC Program Technical Monitor, for his administrative guidance and technical assistance throughout the program.

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ABSTRACT

The primary objective of this program was to design, develop, and test high-temperature dynamic seals for the gaps between the structure and aerodynamic control surfaces on the Space Shuttle. These aerodynamic seals are required to prevent high-temperature airflow from damaging thermally unprotected structures and components during entry.

Two seal concepts evolved from this program--a curtain seal for the spanwise elevon cove gap, and a labyrinth seal for the area above the elevon, at the gap between the end of the elevon and the fuselage. On the basis of development testing, both seal concepts were shown to be feasible for controlling internal temperatures to 350°F or less when exposed to a typical Space Shuttle entry environment. The curtain seal concept demonstrated excellent test results and merits strong consideration for application on the Space Shuttle Orbiter. The labyrinth seal concept, although demonstrating significant temperature-reduction characteristics, may or may not be required on the Orbiter, depending on the actual design configuration and flight environment.

SUMMARY

The Space Shuttle will require aerodynamic control surfaces for use during ascent, entry, cruise, and landing. During entry the windward surfaces will be subjected to high heating rates, making it necessary to protect the structure, control surfaces, and control surface actuators, as well as internal plumbing, wiring, and equipment. Aircraft seals, such as those used on the X-15 airplane, have successfully operated in the realm of 1200°F, and the single-use seal on the PRIME vehicle operated successfully up to 3000°F. However, the aerodynamic seals for the Space Shuttle must be reusable after operating in an environment where the surface temperatures may exceed 2000°F, and this requires the development of new, high-temperature dynamic seals.

During this contract, Martin Marietta conducted a Space Shuttle technology program to design, develop, and test high temperature dynamic seals for sealing off control surface gaps from high-temperature gas flow. A two-phase test program was initiated to define the cove gap heating environment and to evaluate the seal design concepts derived from the plasma arc environmental tests.

The environmental tests indicated that--

- 1) Heating levels are substantially lower in a sealed gap than in an unsealed gap;
- 2) Heating rates at the internal seal location (hinge line) are less than 2% of the rates at the external surface;
- 3) Pressure levels in sealed gaps approximate those at the external surface; and
- 4) Heating is higher as the gap width increases, as the elevon is lowered, and as the leakage increases.

The test data and resultant thermal analysis resulted in two seal concepts--a flexible curtain seal for the spanwise elevon cove gap, and a labyrinth seal for the elevon closeout gap. Three plasma arc models incorporating these concepts were then built and tested through a typical Space Shuttle entry heating environment. The first model used a curtain seal at the elevon cove gap; the second, a labyrinth seal at the elevon end closeout; and the third had no seal at the elevon end gap.

These seal evaluation tests revealed that

- 1) The curtain seal can survive the entry heat pulse and its use limits the unprotected structure to a maximum temperature of 325°F (for a 0.50-in. cove gap, 0.50-in. end gap, and the elevon 10° down);
- 2) The labyrinth seal reduces end gap effects on the curtain seal and lowers the temperature of the surrounding structure by more than 50%;
- 3) Resultant internal temperature effects can be tolerated without sealing the elevon end closeout gap;
- 4) The unsealed elevon end gap test identified a new design problem for end gap TPS surfaces: a radiation blockage effect, coupled with relatively high convective heating levels, produces temperatures exceeding 3000°F and causes the RSI coatings to deform.

INTRODUCTION

The overall purpose of this program was to recommend designs for sealing gaps between the structure and aerodynamic control surfaces for the Space Shuttle Orbiter. Specific end items were to include recommended seal designs, a development test plan, a development test report, an analysis report, and a final report, including a recommended qualification test program and a list of areas for further investigation and development.

Martin Marietta's approach for implementing these objectives consisted of a 9-month coordinated analytical and experimental program to develop dynamic seal concepts. The outline of the program is shown in Figure 1. The objectives of each task are summarized below:

- Task I - Review, evaluate, and select applicable seal concepts for further study
- Task II - Perform structural, environmental, and thermal analyses to support the design and development studies
- Task III - Conduct tests and analyses to determine the sensitivity of elevon cove gap environments and thermal responses to cove gap width, elevon position, end gap lateral flow effects, and leakage
- Task IV - Evaluate the results of Tasks I thru III and recommend seal designs for fabrication and testing
- Task V - Design and fabricate plasma arc test models for environmental testing and evaluation of the seal concepts
- Task VI - Perform a two-phase plasma arc test program to define the cove heating environment and evaluate the proposed designs.

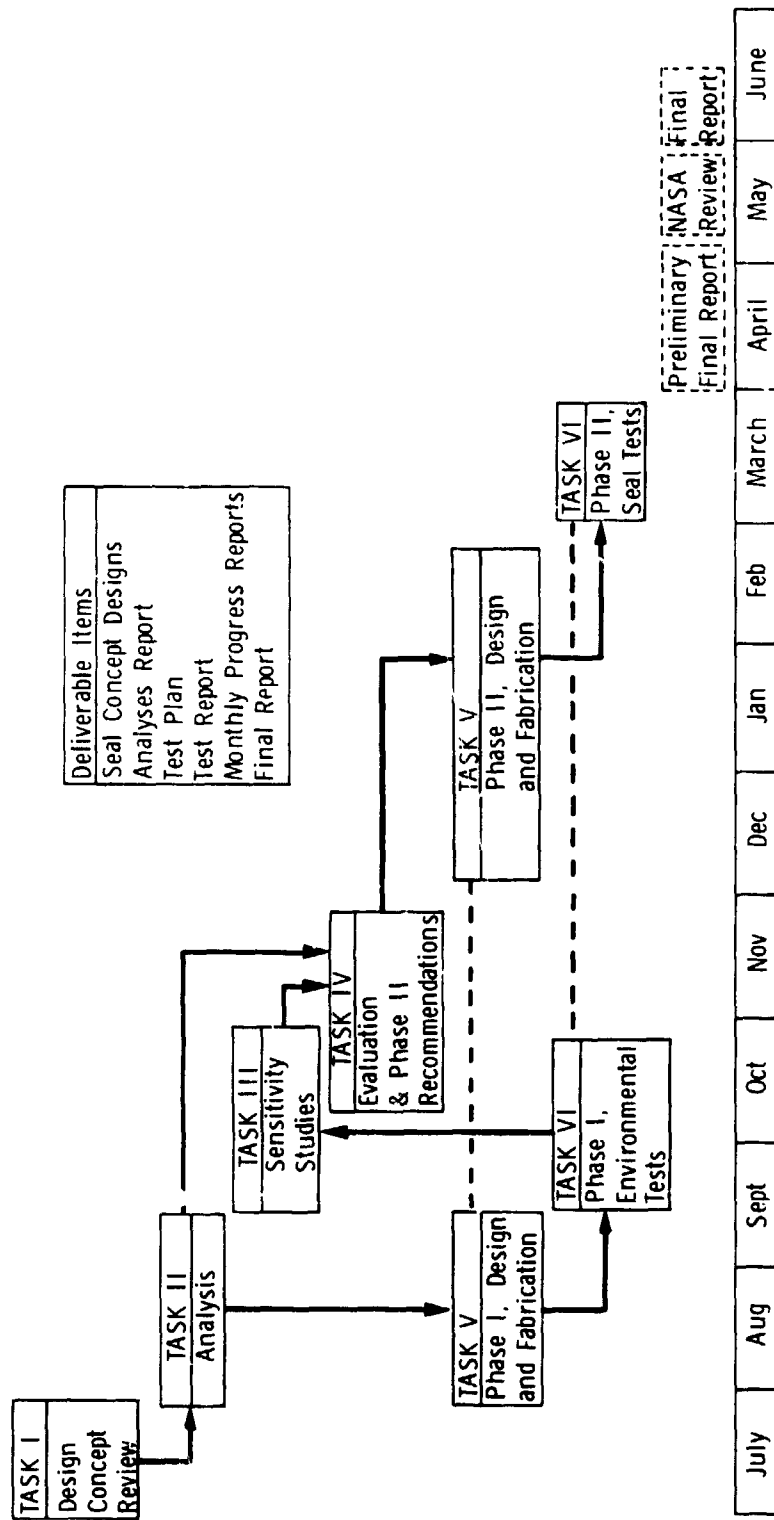


Fig. 1 Program Plan

TASK I - DESIGN CONCEPT REVIEW

The objective of Task I was to make a thorough survey of seal designs that have been successfully flown in high heating environments, as well as new conceptual design approaches developed for Space Shuttle application. Two test vehicles that have flown with seals are the Mach 6.7 X-15A-2 aircraft and the PRIME lifting body reentry vehicle.

SURVEY OF EXISTING FLIGHT-QUALIFIED SEALS

X-15A-2 Mach 6.7 Aircraft - The X-15A-2 aircraft was prepared by Martin Marietta for Mach 6.7 flight by making a number of modifications to the vehicle. The wing-flap area originally had a metallic wiping seal between the flap and fuselage; this seal was removed and the gap was reduced by bonding an insert of MA-25S-1 ablator against the fuselage. The next change affected the flap-to-wing joint which was a nested cove with no seal. The leading edge of the flap was sprayed with MA-25S ablator with the flap in the up position and the ablator was tailored to a gap of approximately 1/16 in. Finally, the gaps between the horizontal stabilizer and the fuselage and between the upper and lower vertical stabilizers and the fixed sections were reduced by building up ablator.

PRIME - The PRIME vehicle (shown in Fig. 2) was a maneuvering entry vehicle with actuated flaps. The gap around the upper surface of the hinged flap was sealed by using silica-phenolic and carbon-phenolic sliding seal blocks to prevent hot gas from passing through the gap. Figure 3 shows the recovered flap and the ablator char patterns and clearly shows that the seals were effective in stopping flow through the gap.

NEW CONCEPTUAL DESIGNS FOR SHUTTLE

Test data acquired during the Martin Marietta PRIME program (Ref 1 and 2) and in a later NASA study (Ref 3) have shown that the entry thermal environment in a control surface gap decreases from the entrance of the gap to the exit. The rate of decrease is a function of the gap width, control surface deflection, and whether the gap is sealed or not. In using these data to determine the environment within the Space Shuttle control surfaces we found that the heating levels decreased to 1% of the local surface value at distances more than 6 in. from the gap entrance. This suggested that control surface seals be placed in this lower heating region, rather than at the entrance to the gap where the heating environment is much more severe.



Fig. 2 PRIME Vehicle

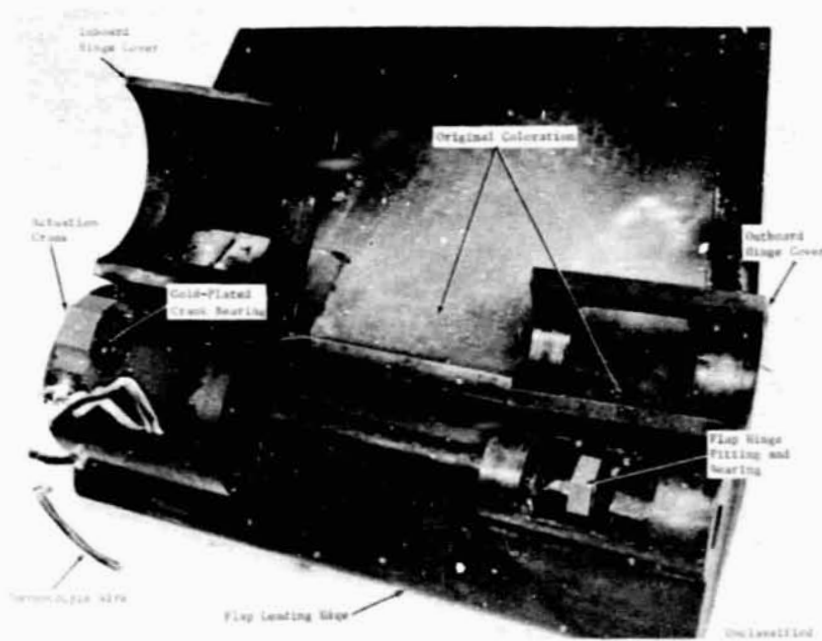


Fig. 3 Sealed Hinge Line, PRIME Vehicle

The two basic seal concepts proposed for Space Shuttle application are the flexible curtain seal and the rubbing seal. Both concepts involve buried seals and designs utilizing the results of previous analyses, plasma arc tests, and flight tests. Six design concepts, shown in Figures 4 thru 9, are variations of the two basic concepts.

Concept 1, Curtain Seal - Figure 4 depicts a curtain made of a silica cloth impregnated with silicone rubber and attached to both the wing and elevon. The curtain has enough slack to allow full elevon deflection, and the concept is forgiving of wing-elevon tolerance buildups and wing-elevon differential deflections.

Concept 2 Rubbing Seal - The rubbing seal design shown in Figure 5 consists of a spring-loaded silica-phenolic block. This concept maintains seal contact and is also forgiving of tolerance buildups and differential deflections. In addition, this type of seal is more resistant to temperature excursions than a silicone rubber seal.

Concept 3, Hinge-Supported Curtain Seal - The hinge-supported curtain seal shown in Figure 6 is a redundant seal that uses a metallic hinge to back up the silicone rubber curtain. This hinge serves as a positive guide for the silicone rubber curtain and acts as a hot gas baffle in case the curtain fails.

Concept 4, Dual Seal (Wire Brush/Rubbing) - Figure 7 shows a concept that uses two seals--a high-temperature wire brush (made from L-605 wires) in the cove gap area and a silicone rubber rubbing seal buried in the relatively low temperature area. In this concept the rubber seal would have to have a large deflection capability to handle tolerance buildups and differential deflections.

Concept 5, Dual Seal (Leaf Spring/Rubbing) - This dual seal design is shown in Figure 8 and is similar to Concept 4, except that a leaf spring is used as the high-temperature gas baffle. René 41 or L-605 material could be used for the leaf spring.

Concept 6, Rubbing Seal, Silicone Rubber - The simple rubbing seal shown in Figure 9 is probably the least reliable of all the concepts.

Table 1 compares seven candidate designs--the six concepts described above plus a hot seal concept proposed by North American Rockwell (Ref 4). The ratings are based on a gross cut comparison, and all items are compared relative to Concept 1. Based

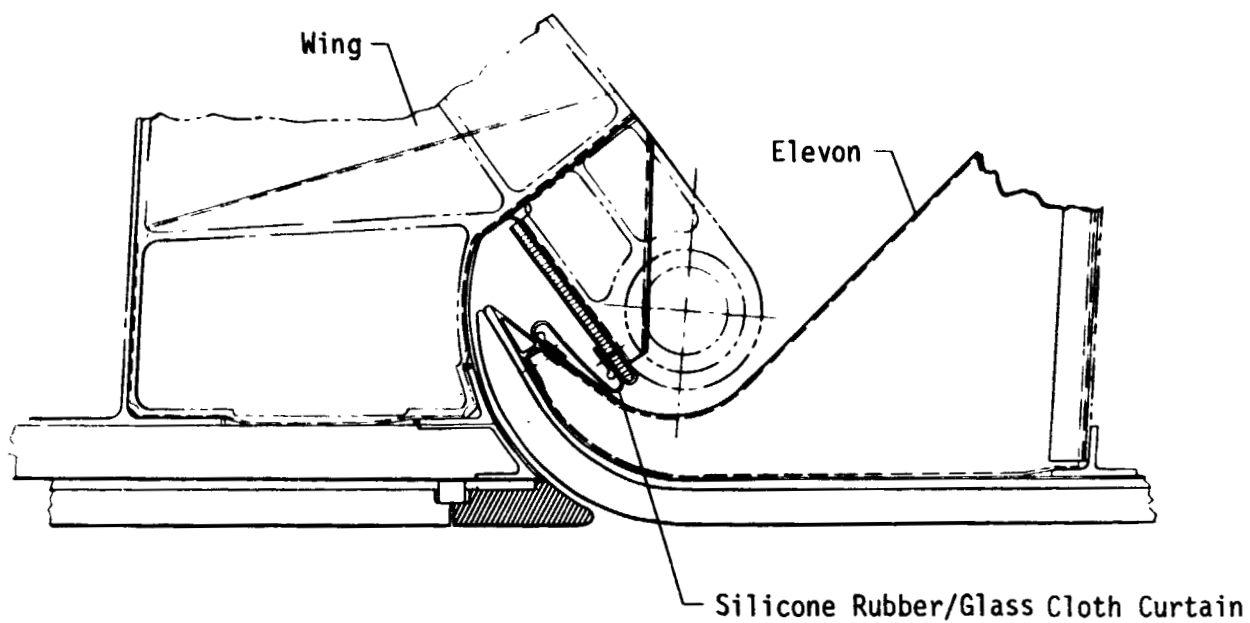


Fig. 4 Wing-Elevon Cove Seal: Concept 1 - Curtain Seal

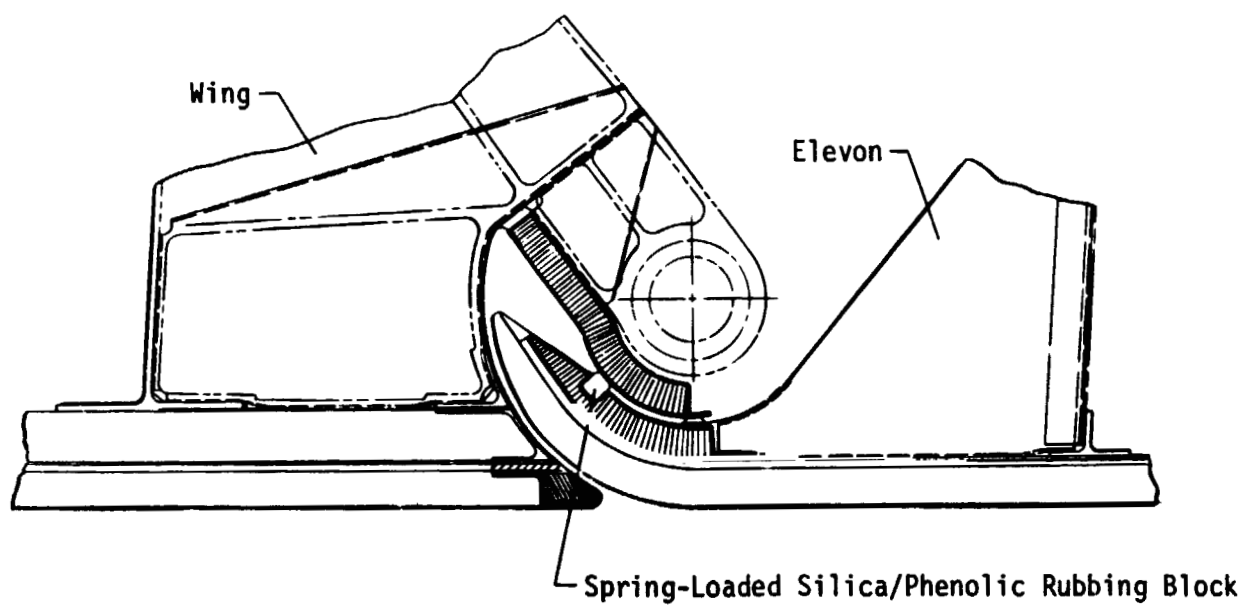


Fig. 5 Wing-Elevon Cove Seal: Concept 2 - Rubbing Seal

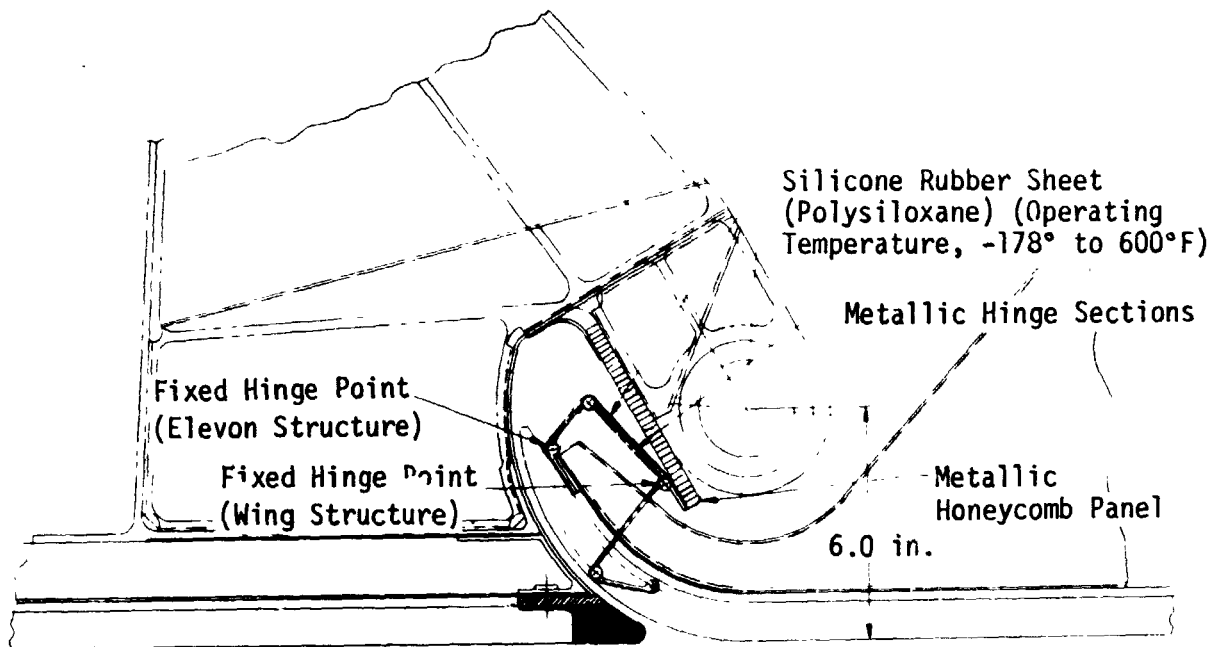


Fig. 6 Wing-Elevon Cove Seal: Concept 3 - Hinge-Supported Curtain Seal

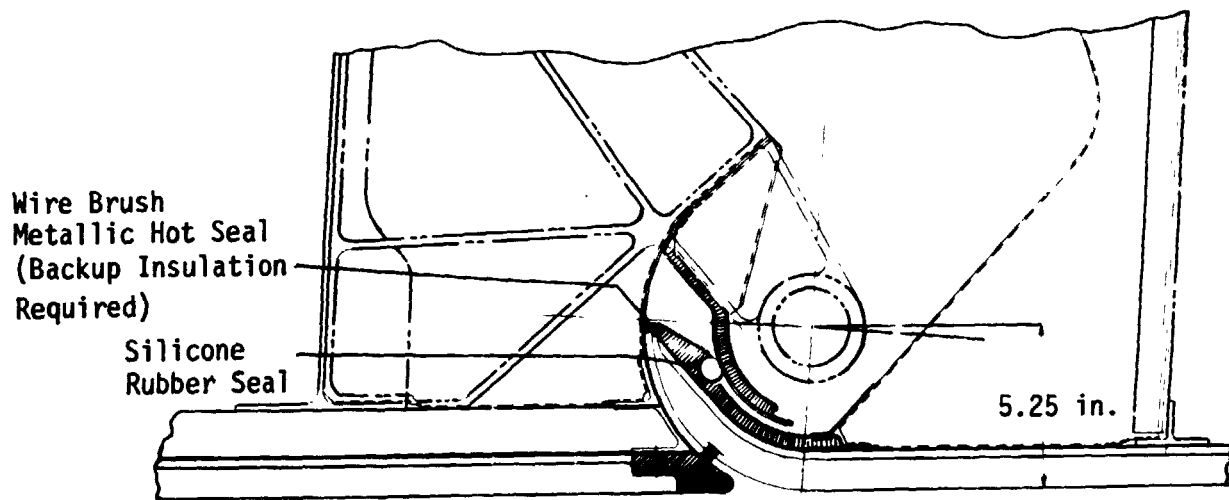


Fig. 7 Wing-Elevon Cove Seal: Concept 4 - Dual Seal (Wire Brush/Rubbing)

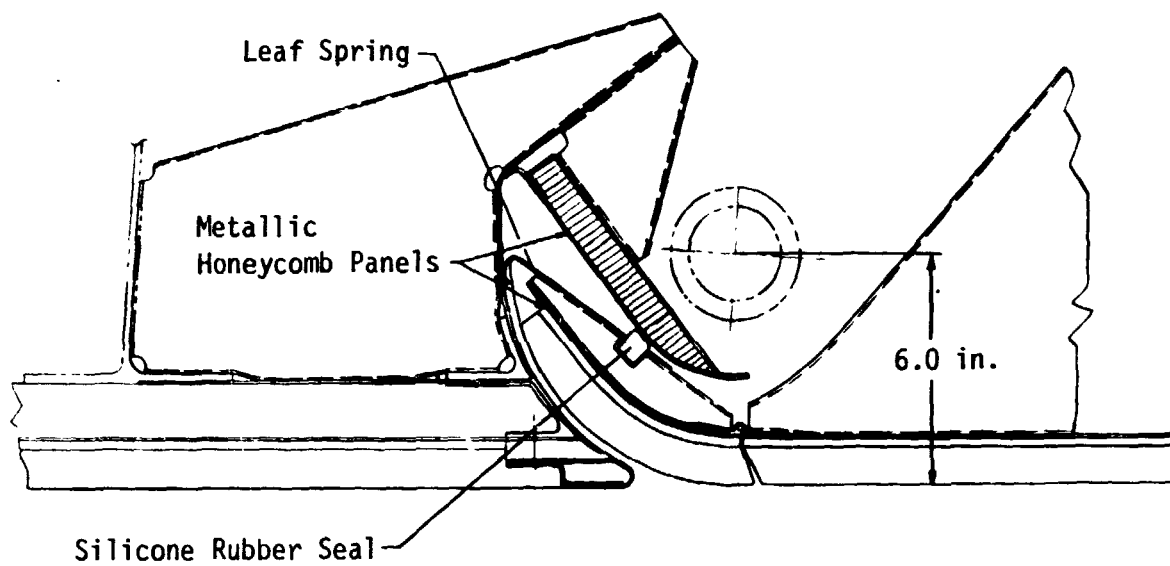


Fig. 8 Wing-Elevon Cove Seal: Concept 5 - Dual Seal (Leaf Spring/Rubbing)

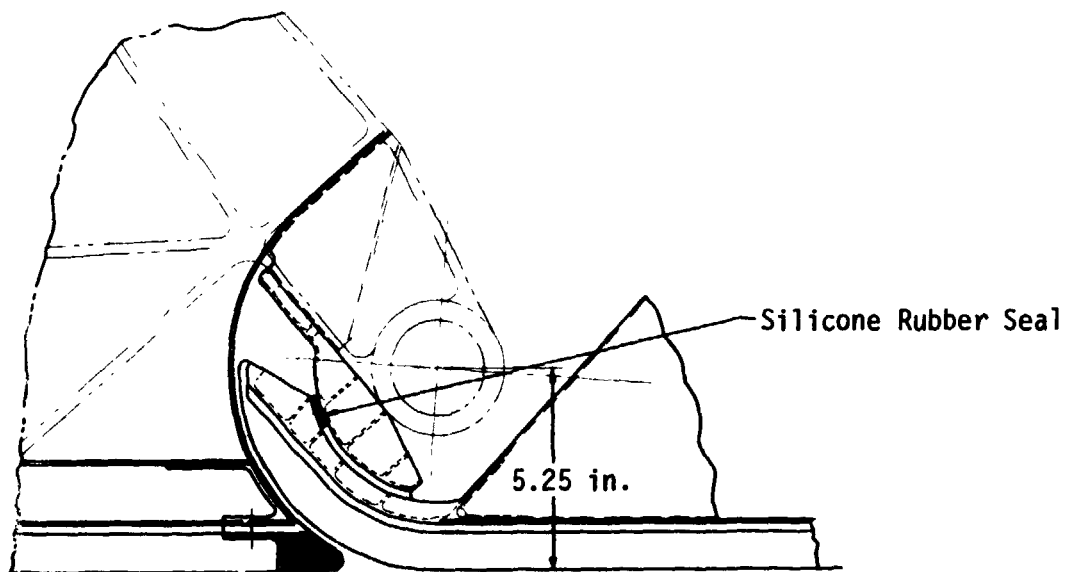


Fig. 9 Wing-Elevon Cove Seal: Concept 6 - Rubbing Seal

Table 1 Evaluation of Space Shuttle Wing-Eleven Cove Seal Concepts

Design	Name	Reuse*	Seal Operating Temperature, °F	Relative Installation Complexity	Tolerance & Deflection*	Mechanical Hangup*	Weight, lb	Relative Cost	Evaluation Rating
1†	Curtain Seal	7	-178 to 600	1.0	10	10	220	1.0	1st
2†	Rubbing Seal	9	-200 to 750	1.8	9	9	310	2.0	2nd
3†	Hinge-Supported Curtain Seal	7	-178 to 600	1.5	8	7	286	1.7	Low
4†	Dual Seal (Wire Brush/Rubbing)	9	-178 to 1200	2.0	6	7	320	4.0	Low
5†	Dual Seal (Leaf Spring/Rubbing)	9	-178 to 1200	2.0	6	6	305	3.5	Low
6†	Silicone Rubber Rubbing Seal	6	-178 to 600	0.8	6	5	210	1.0	Low
7§	NAR	9	-200 to 1200	1.7	5	9	No Data	3.0	§

*Ratings: 10 = Excellent
5 = Fair
0 = Unacceptable.

†Shuttle concepts.

§NAR concept.

on the results shown in the table, we selected the curtain seal as the baseline concept for further study and analysis, and chose the rubbing seal as the backup concept.

In addition to selecting candidate concepts, we reviewed several baseline assumptions and NASA-supplied criteria to establish the ground rules and guidelines for the remainder of the program. These basic assumptions and design criteria are as follows:

- 1) Structural Baseline - The structural subject of this program is the elevon, considered to be the control surface most sensitive to the entry environment. The baseline elevon configuration and hinge line locations are depicted in Figure 10. Additional criteria were:

Elevon Rotation Envelope: -50° to $+20^{\circ}$;

Nominal Elevon Cove Gap Width: 0.50 in.;

Nominal Elevon End Gap Width: 0.50 in.;

- 2) Entry Environment Baseline - Heating rate and pressure histories during entry were supplied by NASA and are shown in Figure 11;

- 3) Thermal Baseline - Maximum temperature limitations were assumed to be:

RSI: 2500°F ,

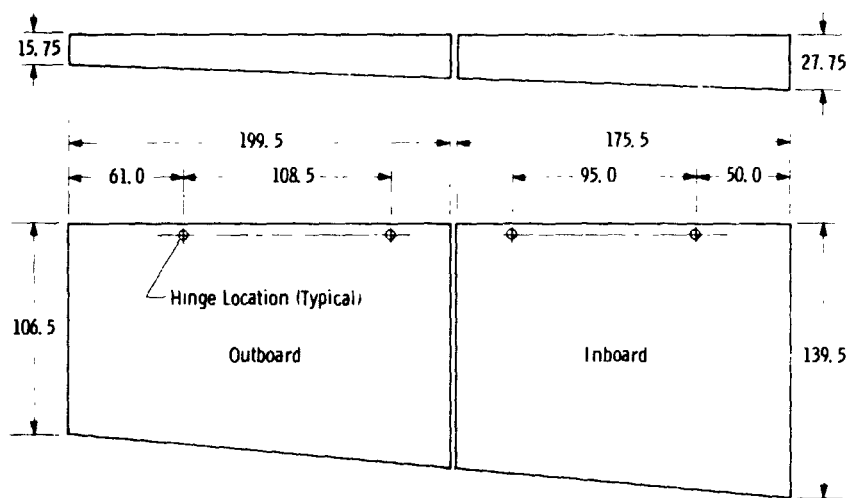
Seal: 500°F ,

Aluminum Structure: 350°F ;

- 4) Other criteria:

$$\dot{q}_{\max \text{ ref}} = 9.9 \text{ Btu/ft}^2\text{-sec},$$

$$Q_{\text{ref}} = 10,335 \text{ Btu/ft}^2.$$



Note: All dimensions are in inches.

Fig. 10 Elevon Configuration

Note: 1. Windward surface of the delta orbiter.
2. Entry at $\alpha = 30^\circ$
3. Numbers near asterisks denote flight surface pressure in psi.

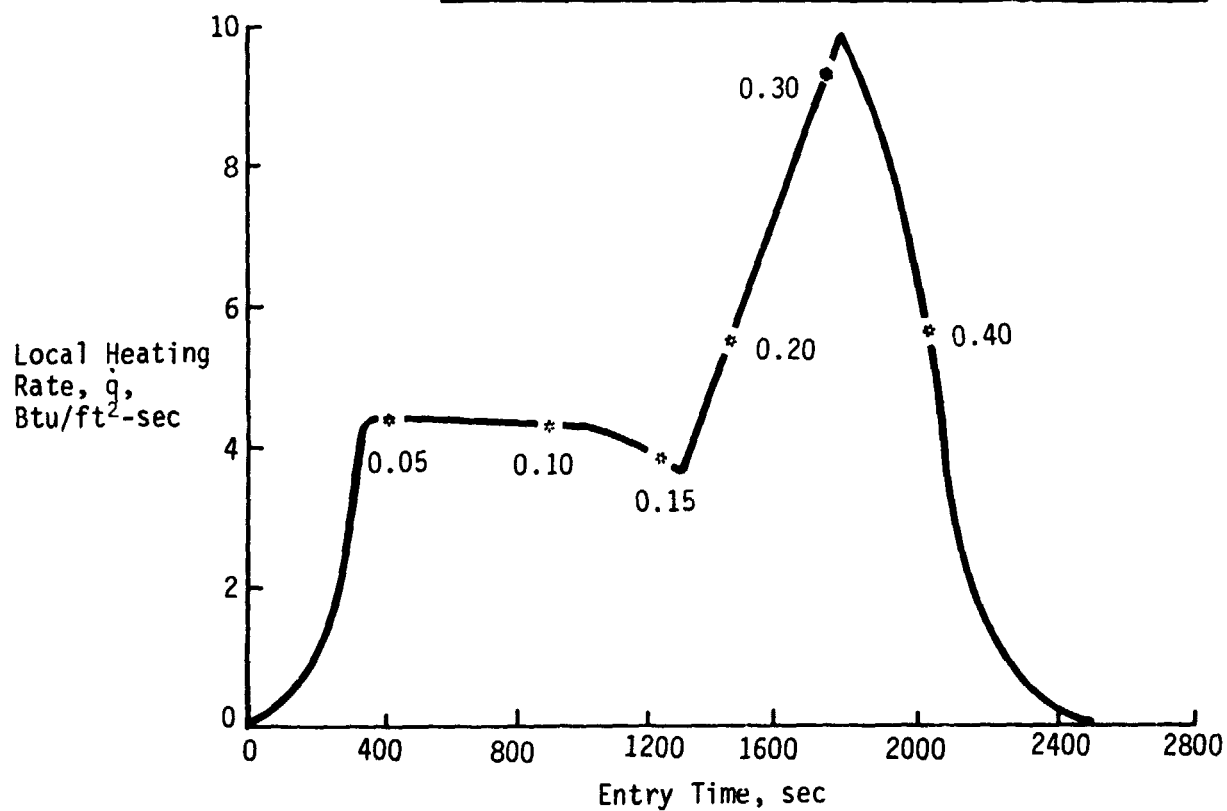


Fig. 11 Baseline Heating Environment

TASK II - ANALYSIS

WING-ELEVON GAP ANALYSIS

A wing-elevon gap analysis was conducted to determine the nominal cove gap width and end gap width. The baseline configuration used in this analysis was a Phase C Shuttle-proposal structure that employed a split elevon. The stiffness of the elevon was derived from a Martin Marietta structures drawing and used to calculate the elevon deflections. Results showed that the largest differential deflections between the wing and elevon occurred during ascent at the inboard end of the inboard elevon. The differential deflections between the wing and elevon at limit load were also calculated and a factor 1.15 was applied to obtain the design deflections. Figure 12 summarizes the manufacturing gap tolerances; Figures 13 and 14 summarize the inboard and outboard elevon deflections; and Figures 15 and 16 depict the results of the elevon cove gap and elevon end gap sizing studies. Detail of these analyses are included in a separate document that will be submitted with the final distribution of this report (Ref 7).

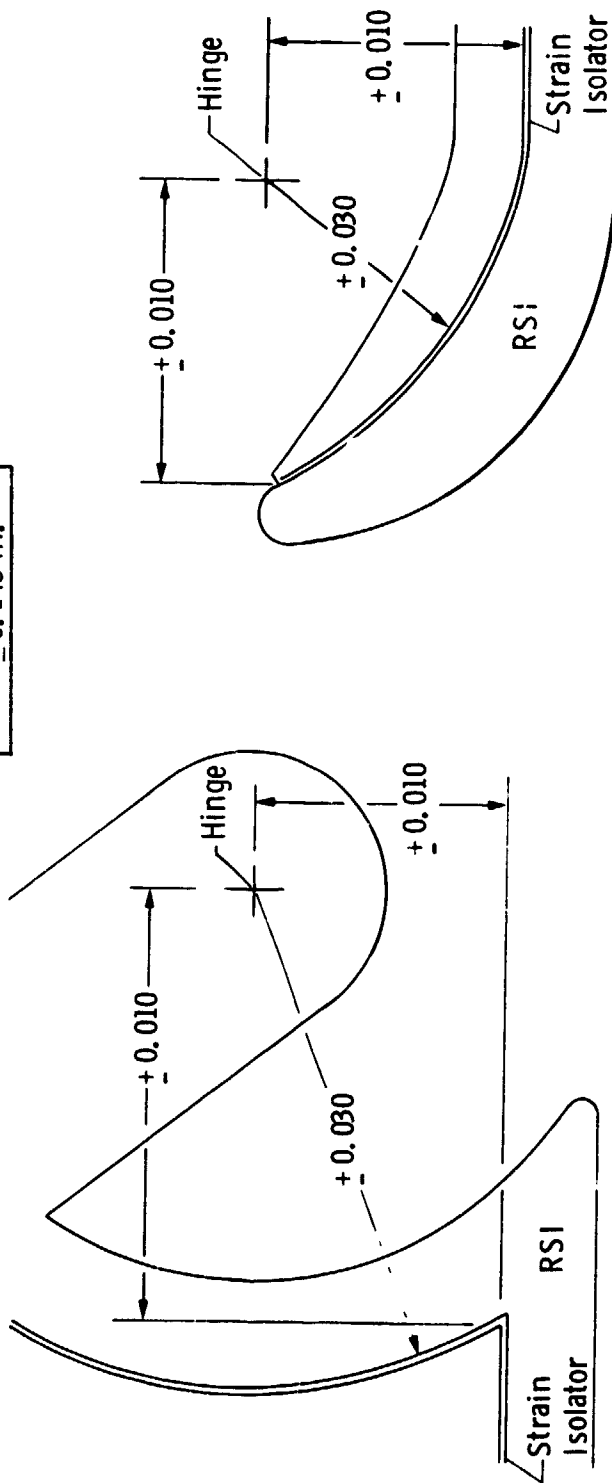
THERMAL ANALYSIS - ENVIRONMENTAL TEST

The second part of this task was a thermal analysis of the cove gap heating environment defined with Task VI Phase I tests. Our initial efforts enabled us to formulate a realistic thermal model and determinate the applicable internal radiation view factors, as shown in Figures 17 and 18, respectively. Figure 18 depicts the view factors for the three cove gap widths and three elevon positions used in the Phase I test program.

Figures 19 thru 21 analyze temperature responses to conclusions drawn from Phase I tests. These conclusions were:

- 1) The lowest curtain seal temperature occurs with no elevon deflection (Fig. 19);
- 2) Tripling the gap width doubles the seal temperature (Fig. 20);
- 3) The end gap effect resulting from the lateral flow in the cove gap increases the seal temperature by 165°F (Table 2);
- 4) Intolerable temperatures occur in an unsealed cove gap (Table 3);
- 5) Some leakage through the cove gap seal may be tolerable (Fig. 21).

Note: Gap dimension
tolerance =
 ± 0.148 in.



Maximum Tolerance Buildup, in.	
0.014	Hinge Fitting Hole
0.030	Cove Sheet Metal
0.005	Rivet Head Protrusion
0.015	RSI Thickness
0.008	Strain Isolator Thickness
0.002	Bondline Thickness
0.074	For Wing and Elevon

(a) Wing

(b) Elevon

Fig. 12 Manufacturing Gap Tolerance

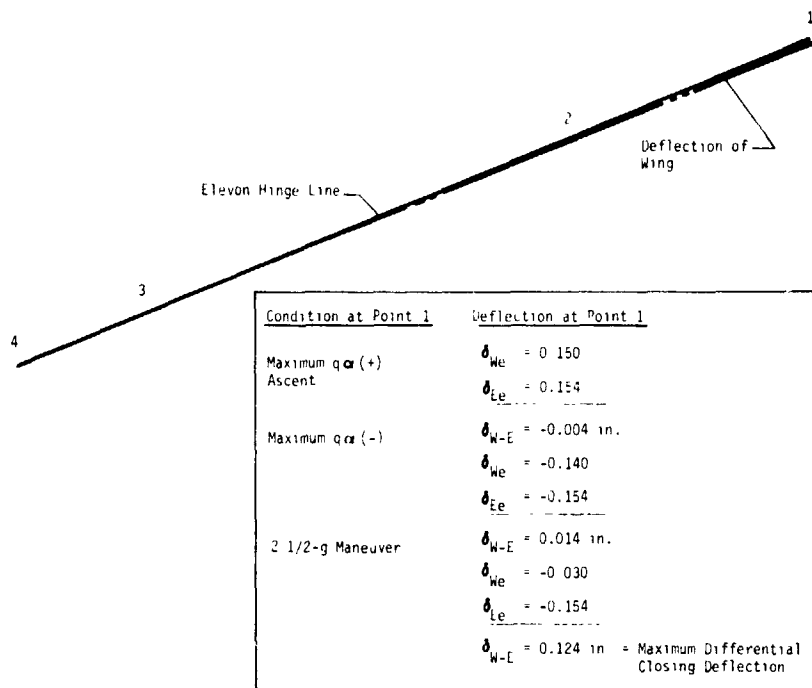


Fig. 13 Outboard Elevon Deflections

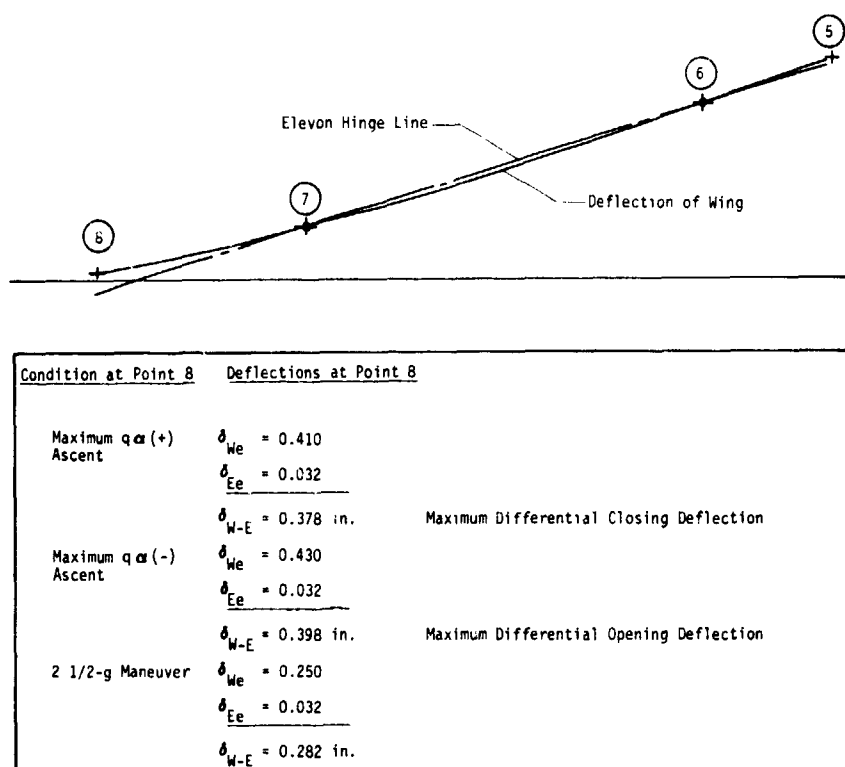


Fig. 14 Inboard Elevon Deflections

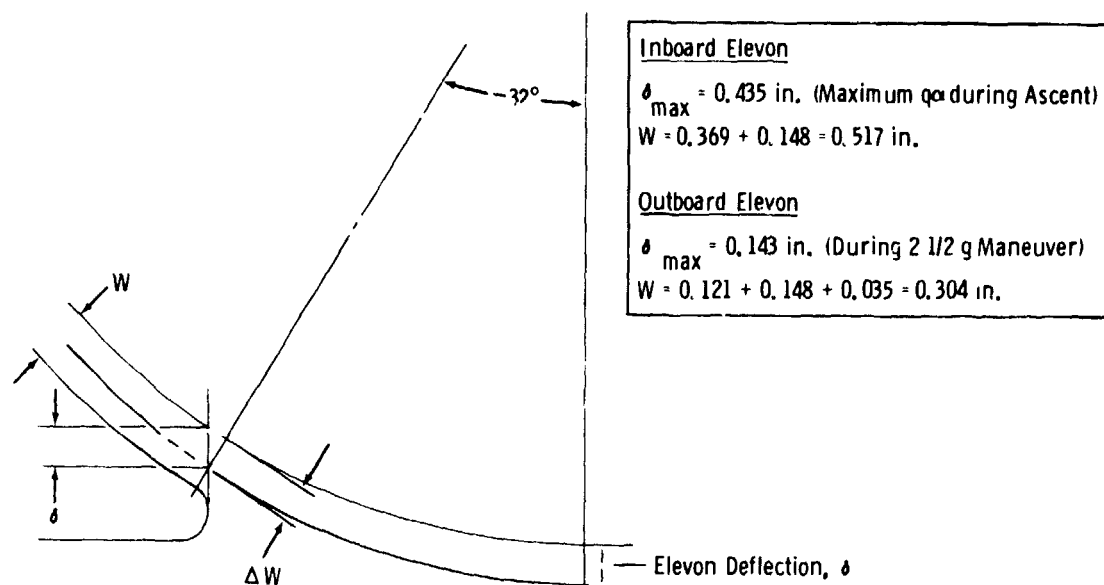


Fig. 15 Elevon Cove Gap Requirements

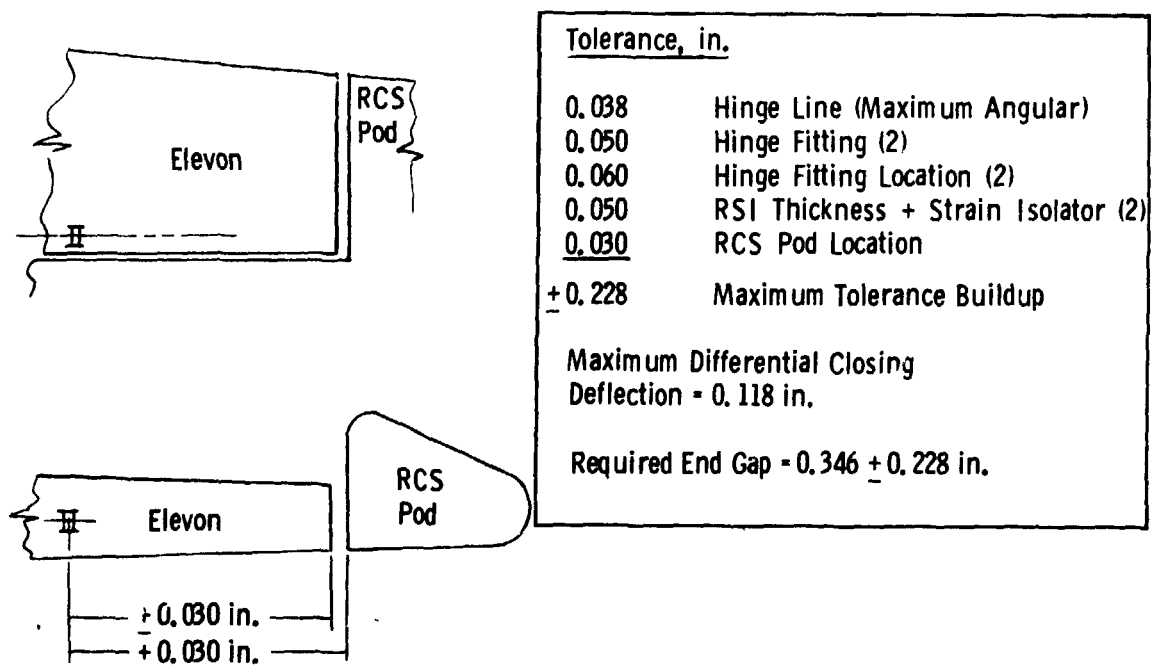


Fig. 16 Elevon End Gap Requirements

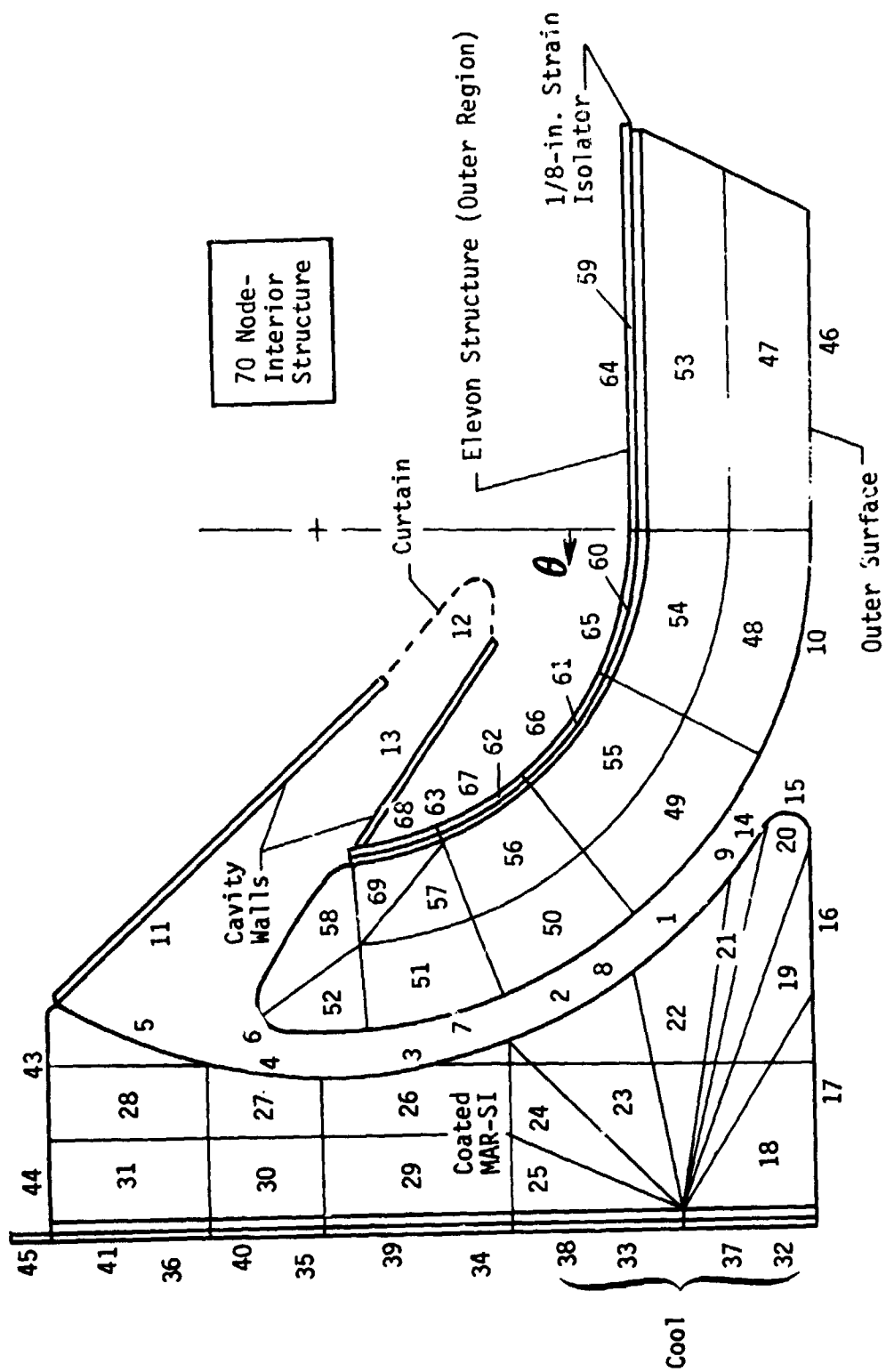


Fig. 17 Thermal Model

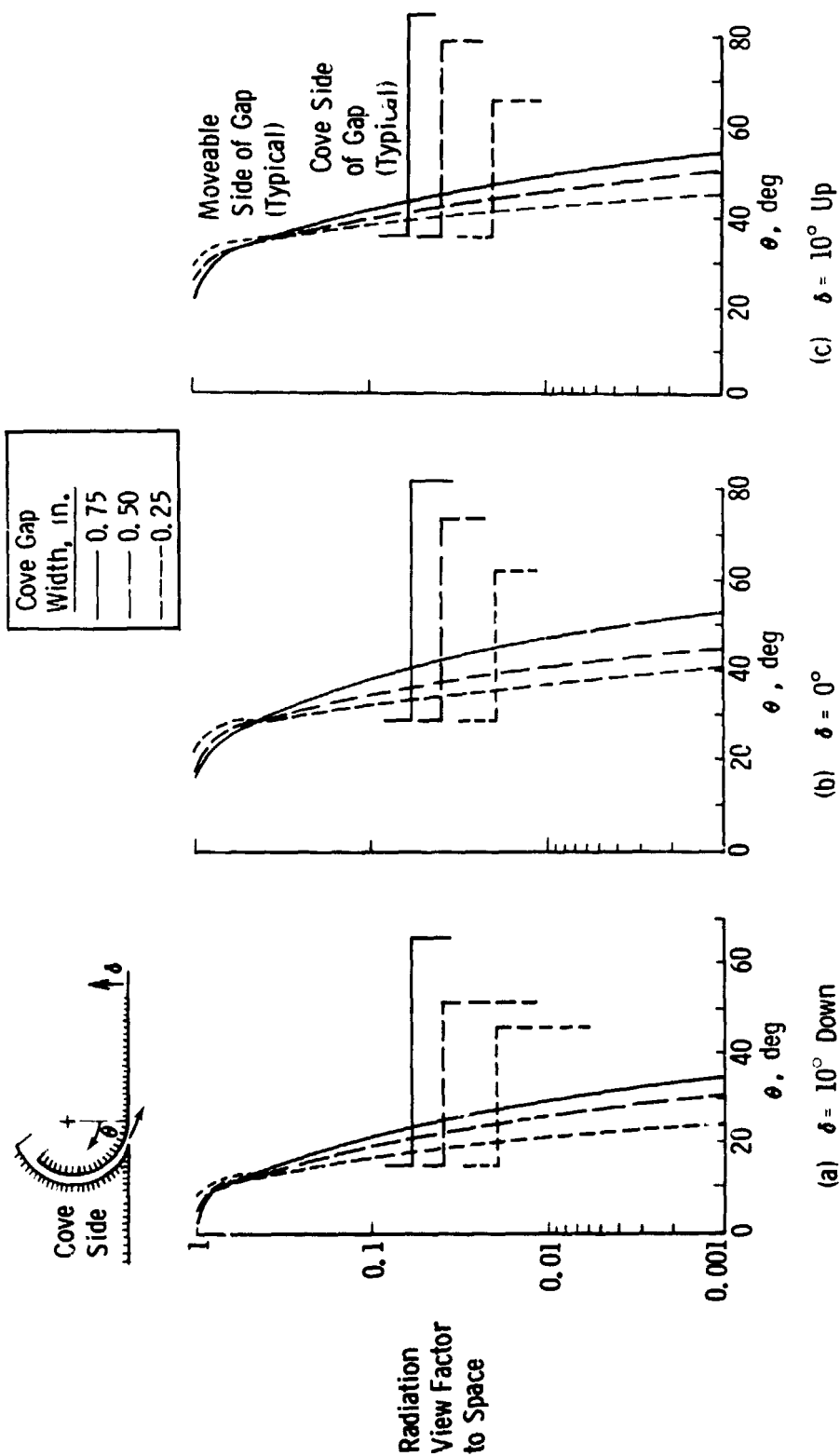


Fig. 18 Radiation View Factors

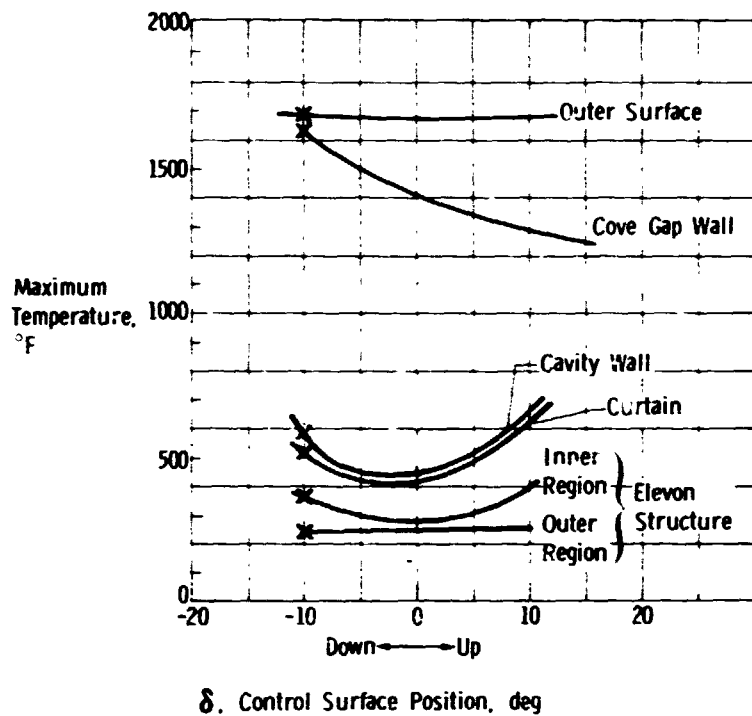


Fig. 19 Temperature Response to Variable Elevon Deflections

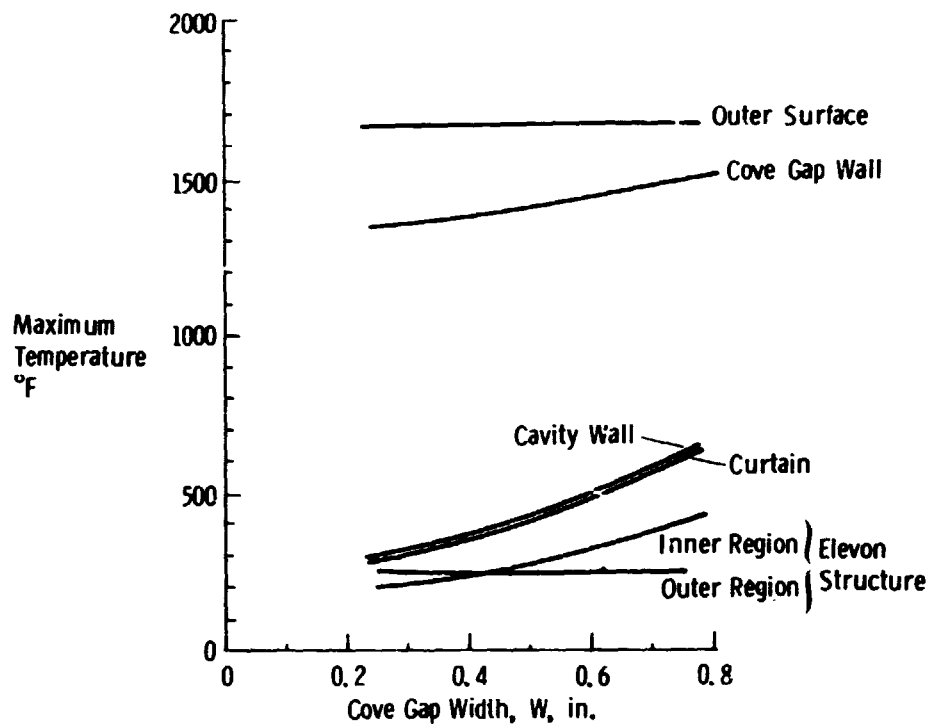


Fig. 20 Temperature Responses to Variable Gap Widths

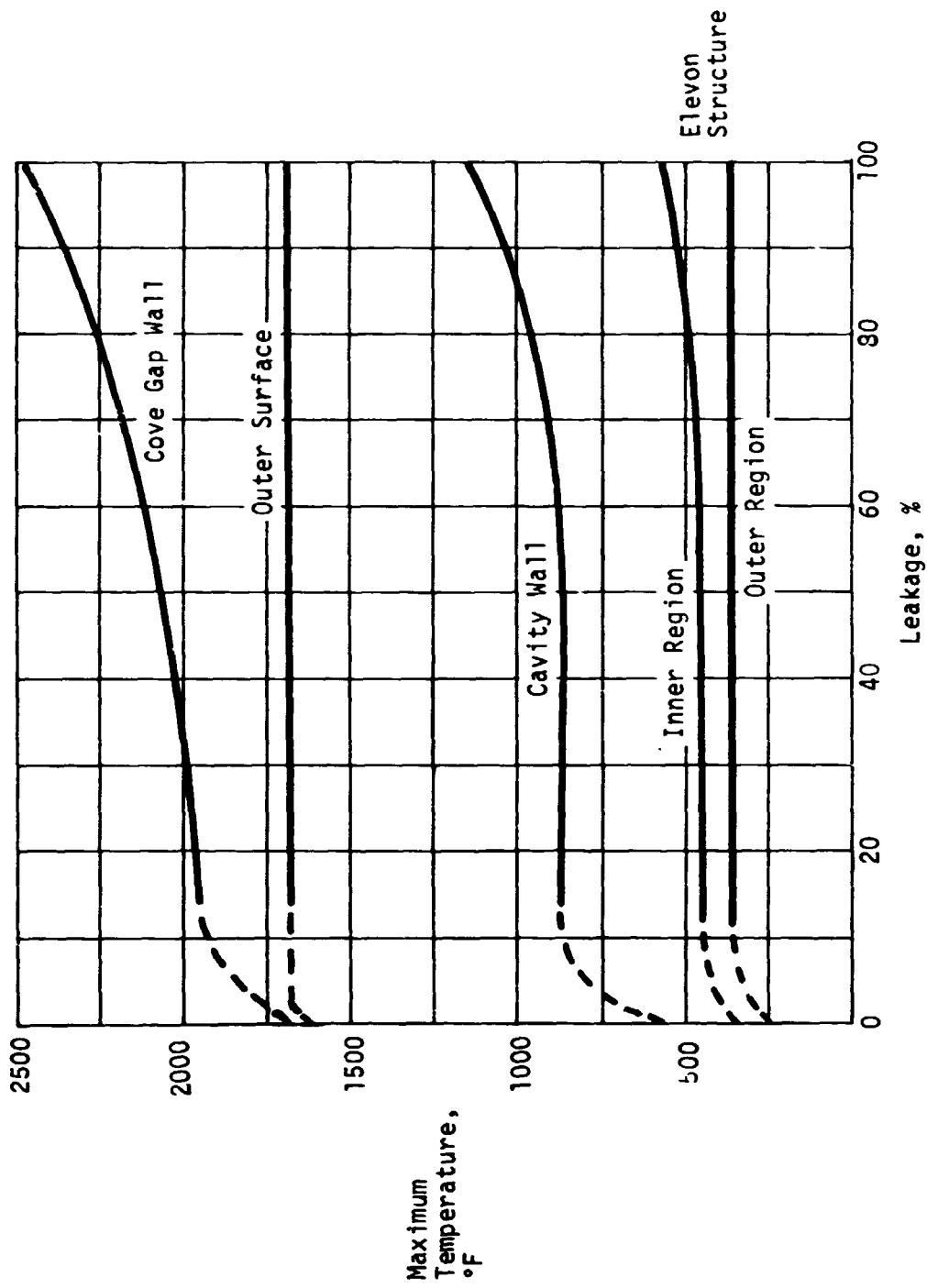


Fig. 21 Temperature Response to Cove Gap Seal Leakage

Table 2 Effect of End Gap on Temperatures

	Without End Gap	With End Gap	
Leakage, %	0	Some	
Maximum Outer Surface Temperature, °F	1680	1680	
Maximum Cove Gap Surface Temperature, °F	1632	1951	
Maximum Cavity Wall Temperature, °F	544	710	
Maximum Curtain Seal Temperature, °F	500	665	
Maximum Elevon Structure Temperature, °F	350	489	← Inner
	256	260	← Outer

Table 3 Temperature Response to Unsealed Cove Gap

	With Curtain	Without Curtain	
Leakage, %	0	100	
Maximum Outer Surface Temperature, °F	1680	1680	
Maximum Cove Gap Surface Temperature, °F	1632	2480	
Maximum Cavity Wall Temperature, °F	544	1160	
Maximum Curtain Seal Temperature, °F	500		
Maximum Elevon Structure Temperature, °F	350	574	← Inner
	256	263	← Outer

THERMAL ANALYSIS - PHASE II TEST MODELS

To assist us in designing the Task VI Phase II test models, we conducted a thermal analysis to predict typical flight entry temperatures on the curtain seals, the labyrinth seal in the end gap, the aluminum structure, and the RSI system. For this analysis we assumed a test configuration consisting of an installed curtain seal, a 0.50-in. cove gap, and a 10° down elevon position. Figure 22 depicts temperatures inside the cove gap and supports our design analysis of the RSI, Figure 23 relates the temperature responses to local heating data from the Phase I tests, and Figure 24 shows the temperatures on the labyrinth seal produced by predicted end gap heating rates on the test model.

The results of our thermal analysis are shown in Figure 25.

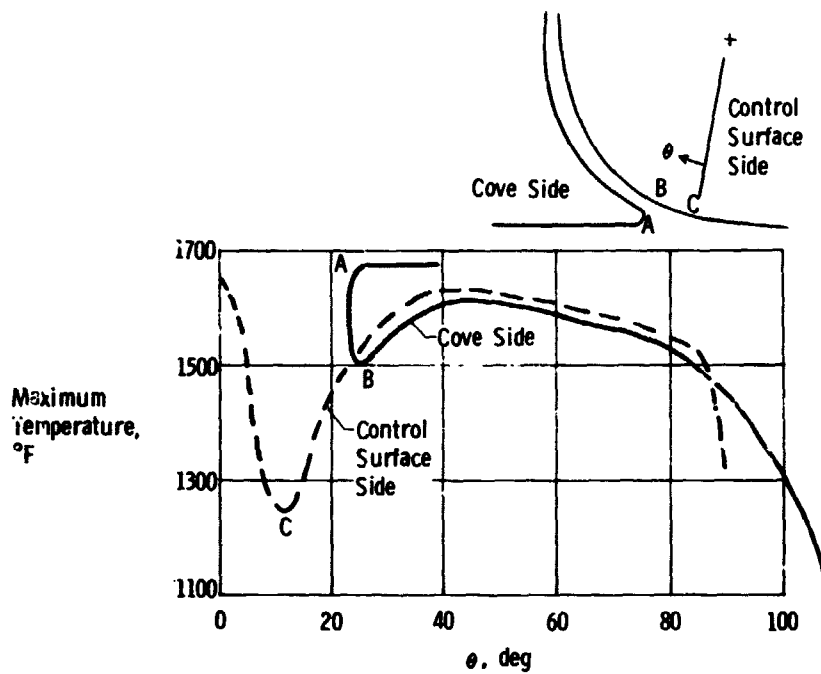


Fig. 22 Cove Gap-Wall Temperature Predictions

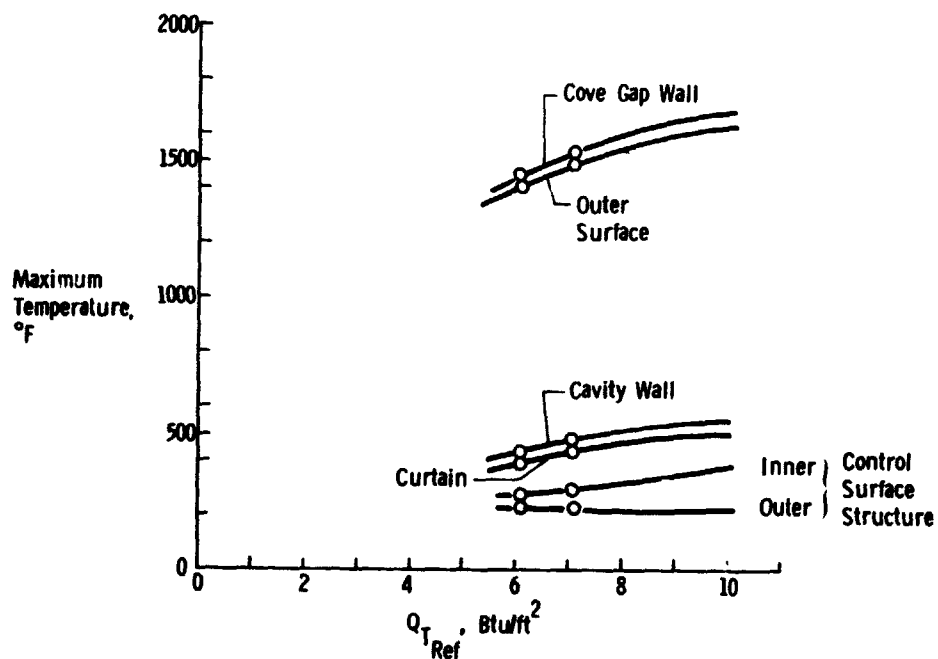


Fig. 23 Temperature Response to Local Heating Predictions

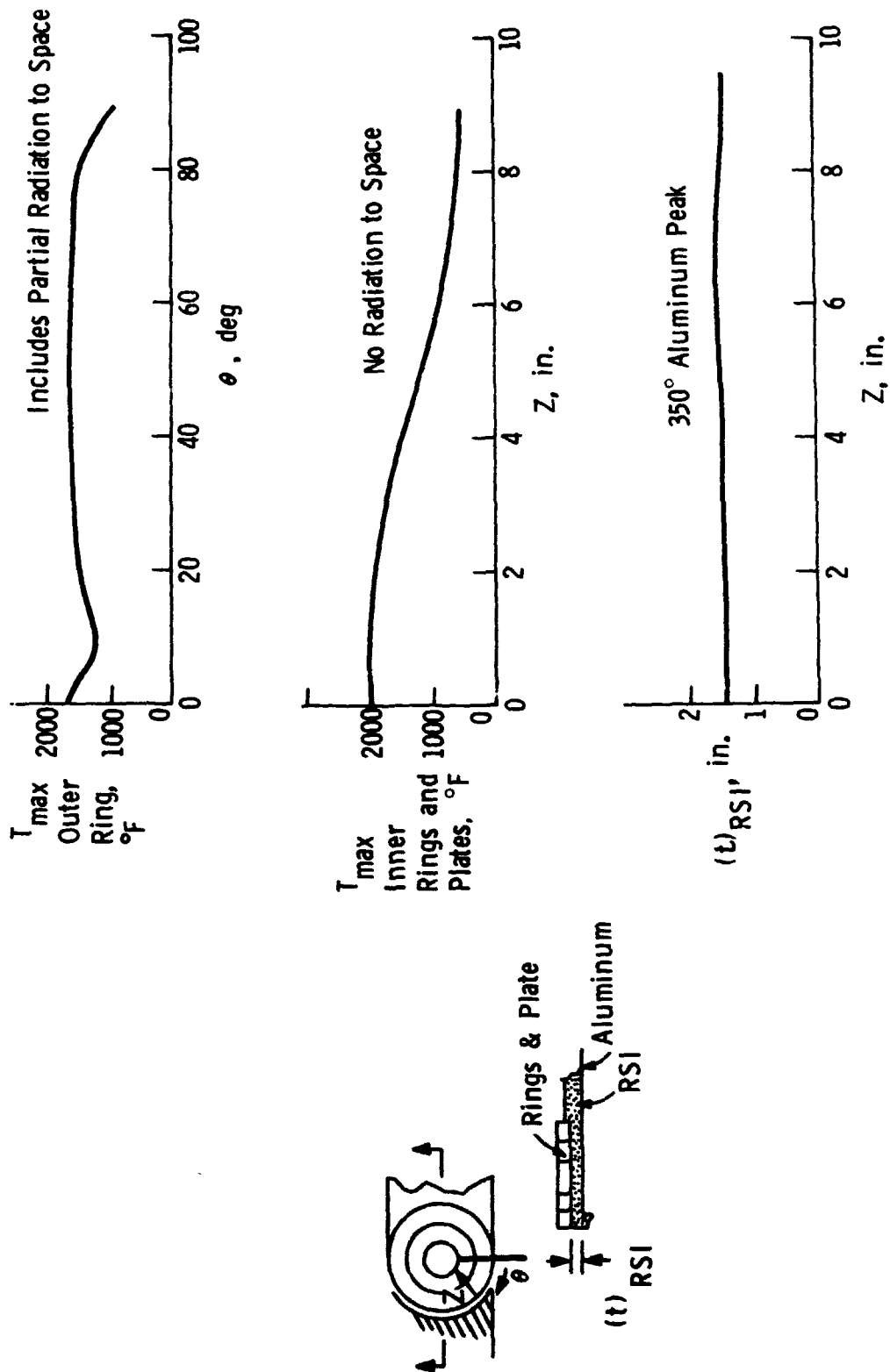


Fig. 24 Predicted Temperature Response for Labyrinth Seal Design

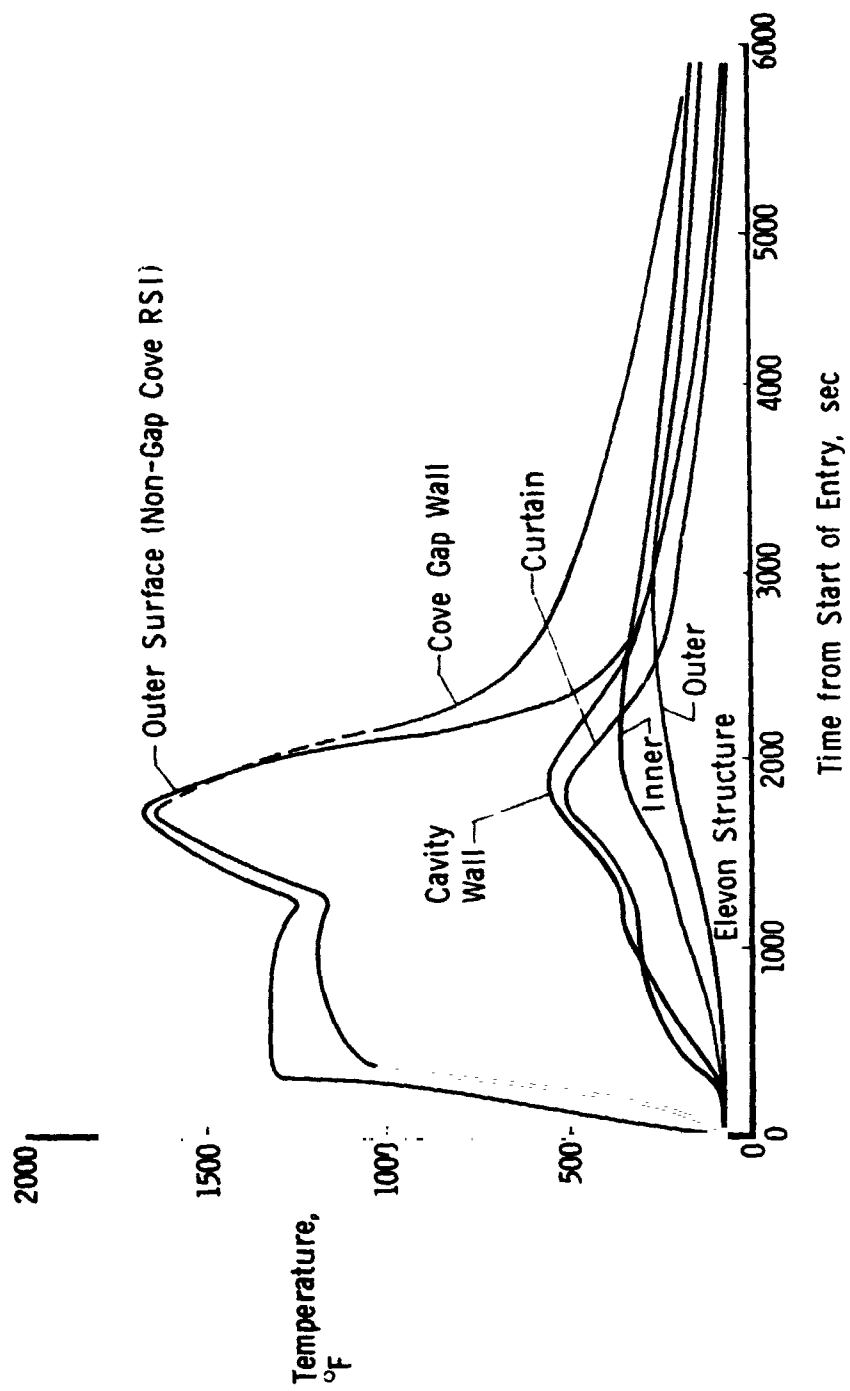


Fig. 25 Predicted Entry Temperature

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TASK III - SENSITIVITY STUDIES

ELEVON COVE AND END GAP SENSITIVITY STUDIES

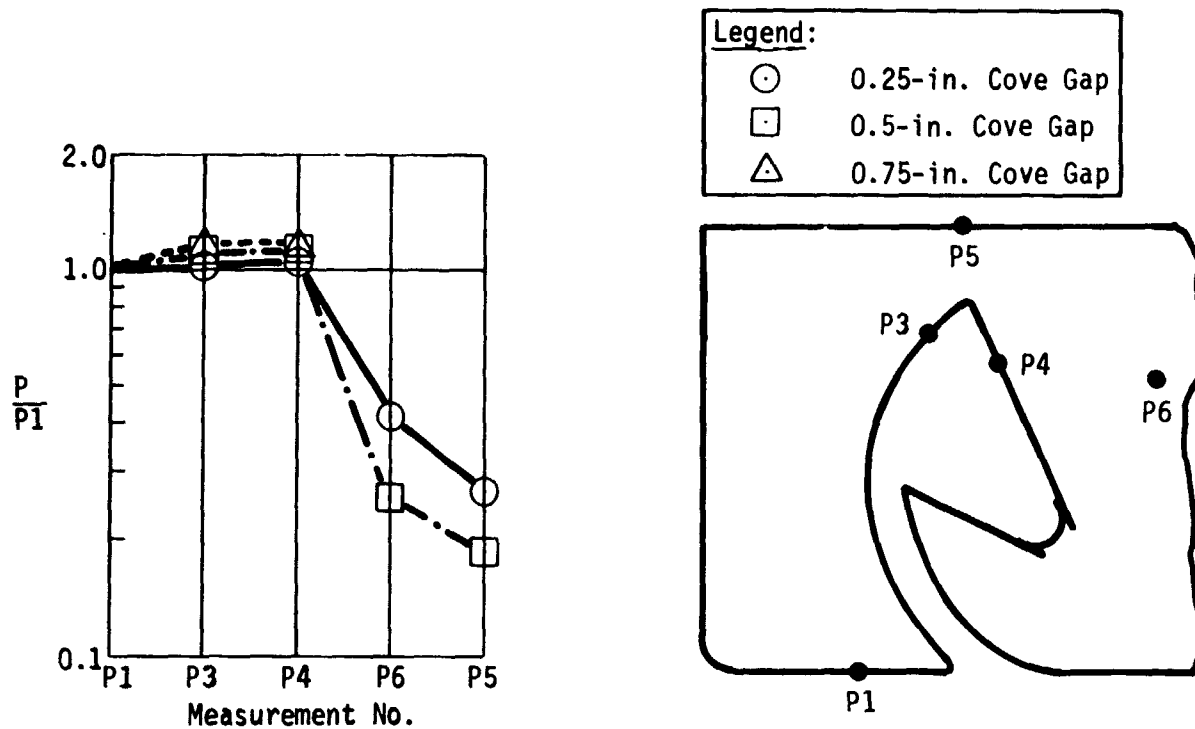
Wind tunnel tests have shown that the parameters affecting aerodynamic heating within a control surface gap are gap width, leakage through the gap, and the deflection angle of the control surface (Ref 1 thru 3). The studies also showed that sealing the hinge line gap can significantly reduce the convective environment within the gap. A successful seal design, however, requires an accurate knowledge of the local convective environment in the gap. Although the earlier studies have indicated the significant parameters and their effects, the larger dimensions and different geometry associated with the Space Shuttle introduced questions concerning the direct use and/or scaling of these data.

The objective of this task was to acquire aerodynamic heating data for a representative gap for a Space Shuttle control surface and to determine the effect of gap width, flow leakage through the gap, control surface deflection, and end effects on the convective heating environment within the gap. To implement these objectives we initiated a Phase I environmental definition test program, using an appropriately instrumented model to record the salient aerothermodynamic characteristics of the flows within a hinge line gap. Test conditions were selected to simulate portions of the expected full-scale Space Shuttle environment.

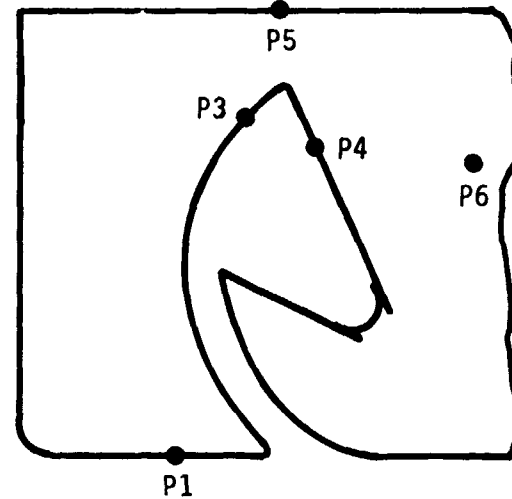
This section of the report will not attempt to describe the complete Phase I test program, but will summarize the test results and discuss the sensitivity of the gap environment to the previously discussed variables.

Sensitivity of Gap Environment to Cove Gap Width

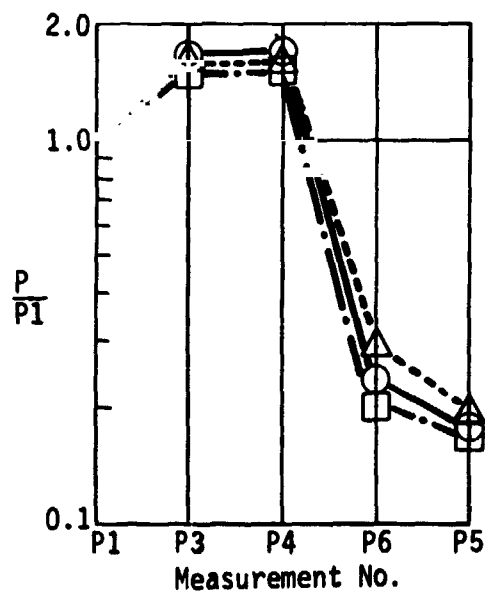
Figures 26 and 27 show the effect of cove gap width on the pressure and heating distributions within the cove gap for three different control surface positions. The pressure distributions shown in Figure 26 show that the pressure was constant up to the curtain seal, but dropped off rapidly behind the seal. The gap width had a relatively insignificant effect on the pressure distribution ahead of the seal. The biggest pressure change occurred when the control surface was deflected downwards and caused the increased pressure on the control surface to be fed into the cove gap region.



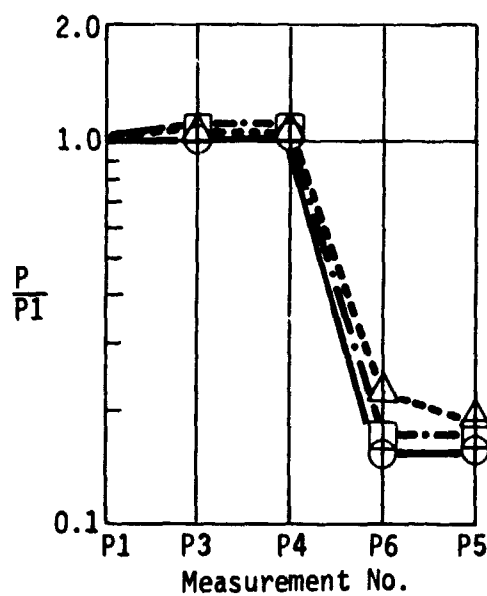
(a) $\delta = 0^\circ$



(b) Measurement Locations

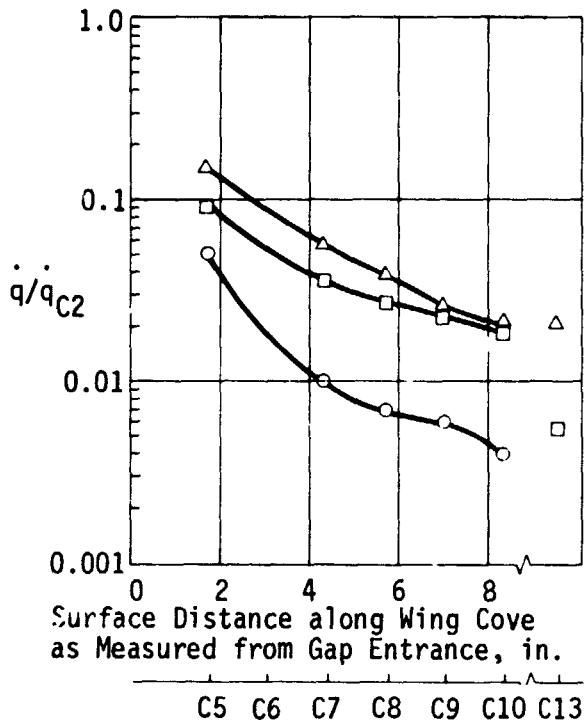


(c) $\delta = 10^\circ$ Down

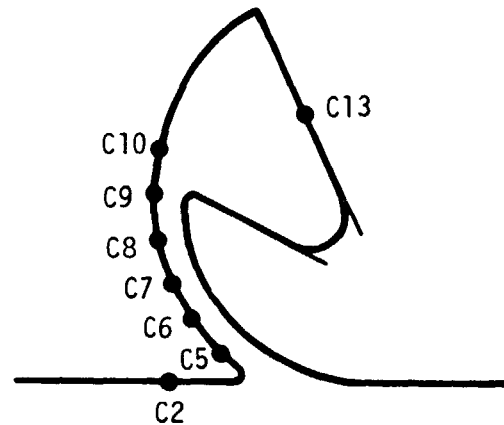
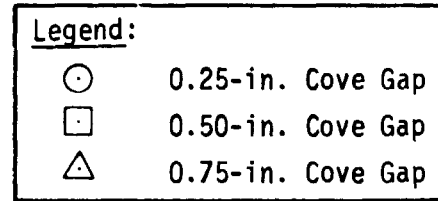


(d) $\delta = 10^\circ$ Up

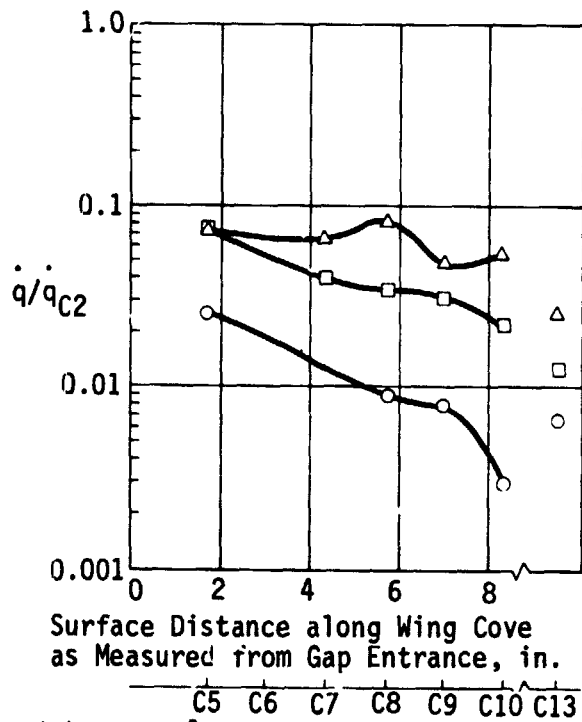
Fig. 28 Sensitivity of Pressure Measurements to Cove Gap Width and Control Surface Deflection with Curtain Seal in Place



(a) $\delta = 0^\circ$



(b) Measurement Locations



(c) $\delta = 10^\circ$ Up

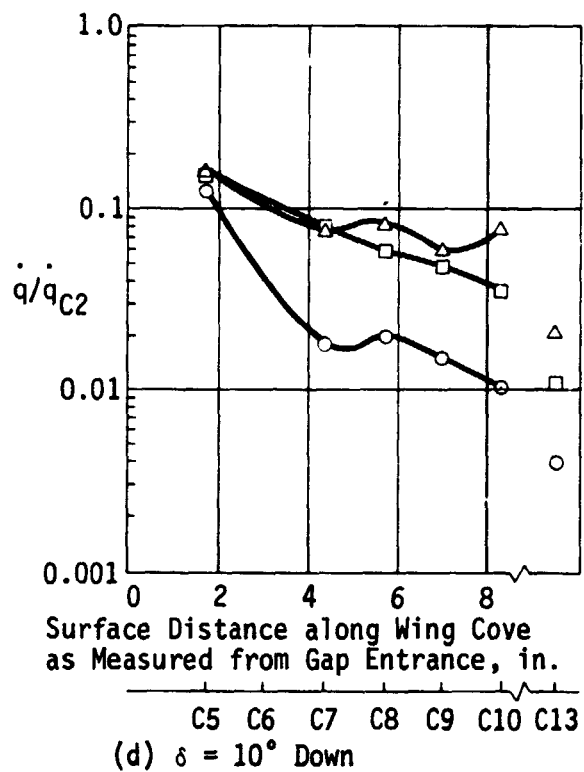


Fig. 27 Sensitivity of Cove Gap Heating Distribution to Cove Gap Width with Curtain Seal in Place

Changing the gap width had a much greater effect on the heating environment in the gap. Figure 27 shows that increasing the gap width from 0.25 to 0.5 in. increased the heating in the gap by factors ranging from 2 to 4 for each of the three control surface positions that were tested. Further increasing the gap width from 0.5 to 0.75 in. also increased the average heating level within the gap cavity, but to a lesser degree.

Sensitivity of Cove Gap Environment to Control Surface Deflection

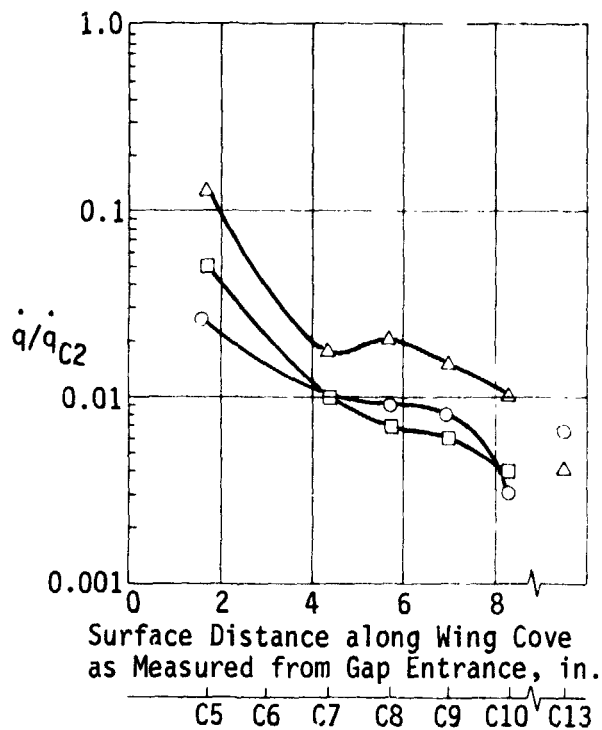
The calorimeter data shown in Figure 27 have been replotted in Figure 28 using control surface deflection as the parameter. The results of this analysis show that a downward deflection increased the heating within the gap over that recorded at the 0° position for all three gap widths. A comparable reduction with a 10° upward deflection did not occur--in fact the heating sometimes increased.

We suspect that the gap tends to act as an attenuator for flow into the cavity. As the control surface changes position from 0° to 10° upward, the gap length is decreased; but since the pressure level outside the gap does not change, higher energy flow is allowed into the cavity. Conversely, a downward deflection increases the gap length and, other things being equal, should reduce the heating environment in the cavity. However, the increased pressure felt by the deflected control surface propagates into the cavity and offsets the attenuating effect of the increased gap length.

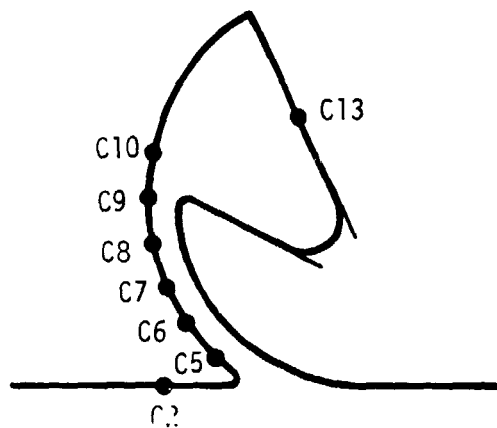
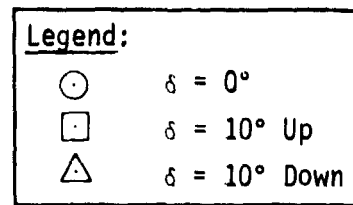
Effect of End Gap

Figure 29 compares the heat distributions in the sealed cove gap with and without a 0.5-in. end gap for a control surface tipped 10° down. Note that the end gap caused a substantial increase in cove gap heating levels for a 0.25-in. cove gap, but that there was only a slight increase for a 0.5-in. cove gap and no change (on the average) for a 0.75-in. cove gap. These differences are not reflected in the pressure distributions (see Fig. 30): each gap width produced basically the same pressure distribution both with and without the end gap. Yet in all cases, the end gap reduced the pressure gradient across the seal--lowering the pressures in the cove gap region and increasing the pressure behind the seal at location P6.

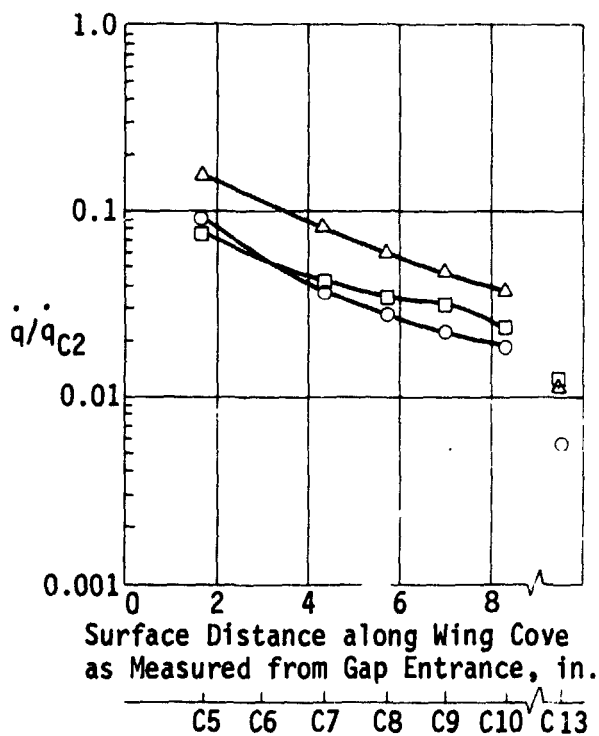
The reduced pressures in the cove gap of the end gap model would be expected to contribute to lower heating rates in this region.



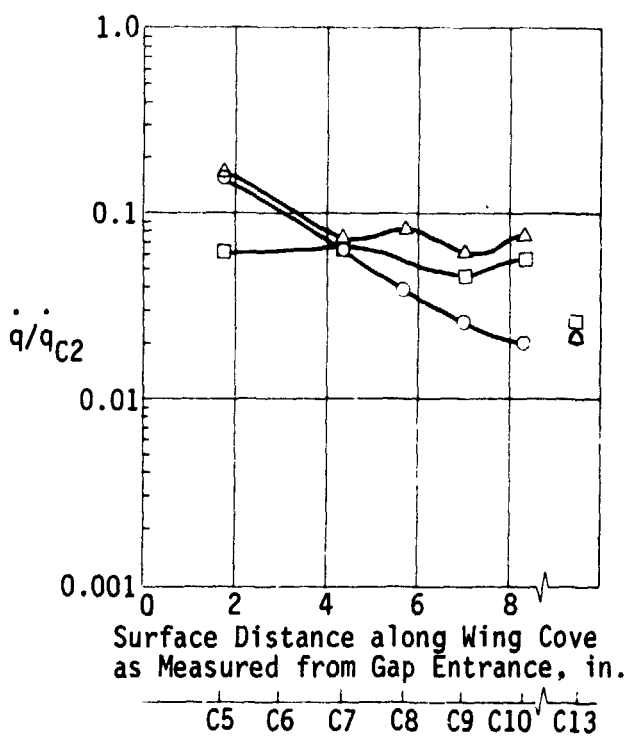
(a) 0.25-in. Cove Gap



(b) Measurement Locations

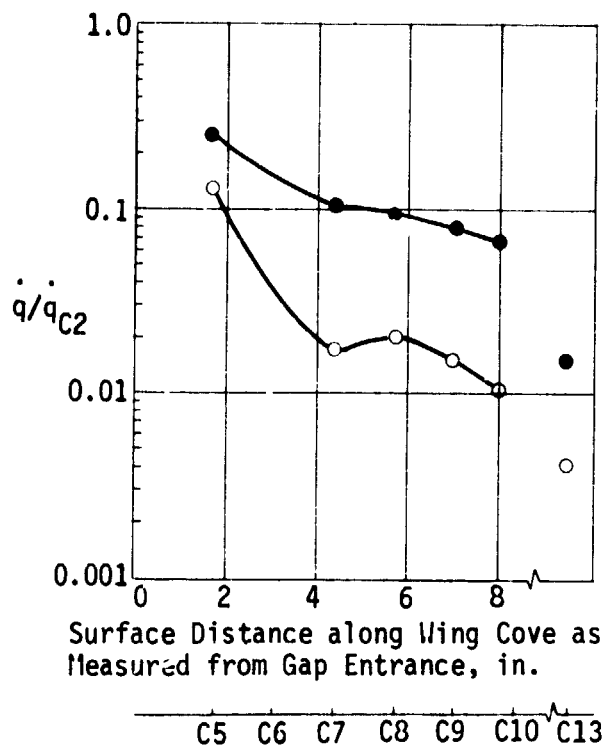


(c) 0.50-in. Cove Gap

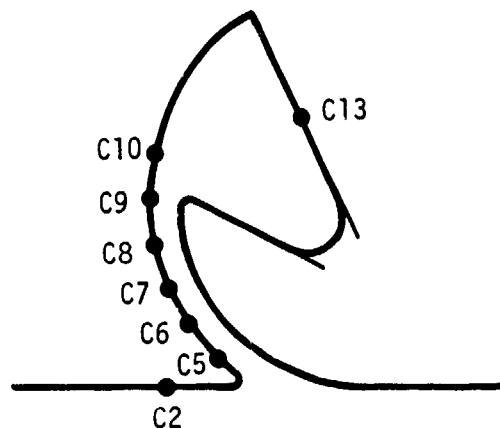
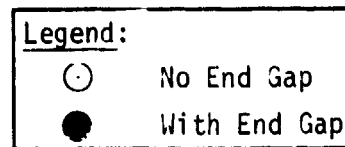


(d) 0.75-in. Cove Gap

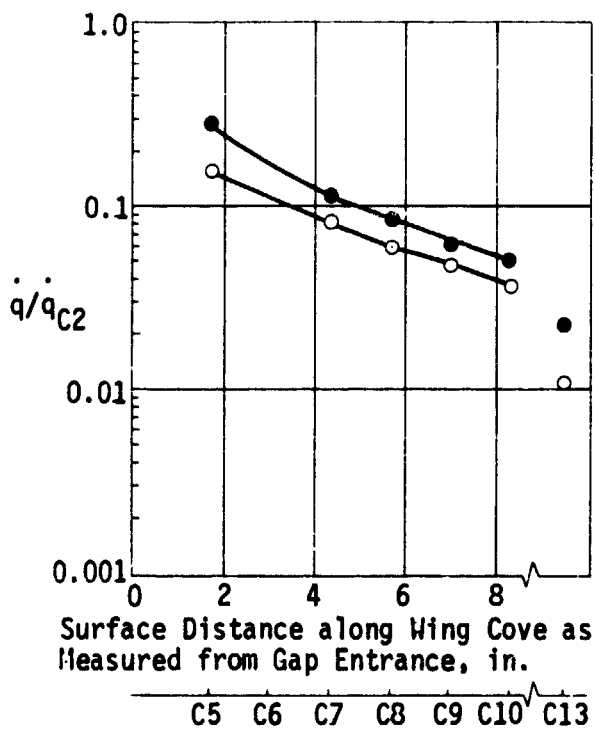
Fig. 28 Sensitivity of Cove Gap Heating Distribution to Control Surface Deflection with Curtain Seal in Place



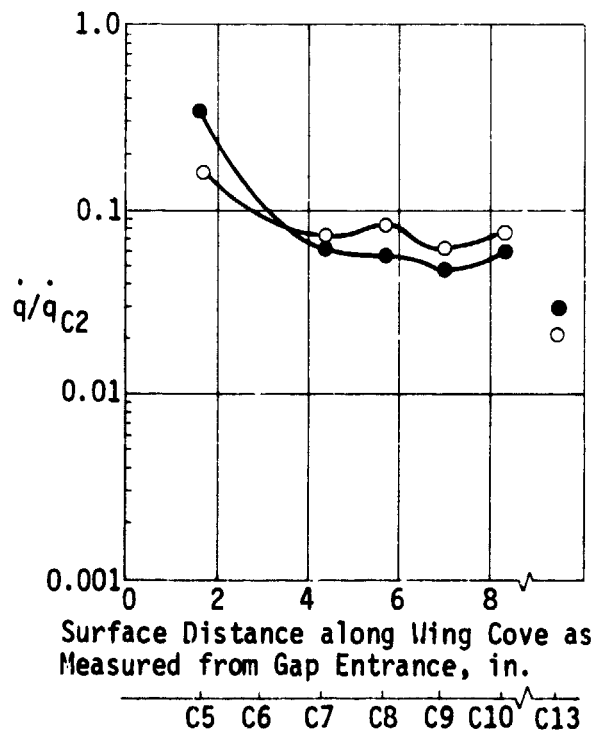
(a) 0.25-in. Cove Gap



(b) Measurement Locations

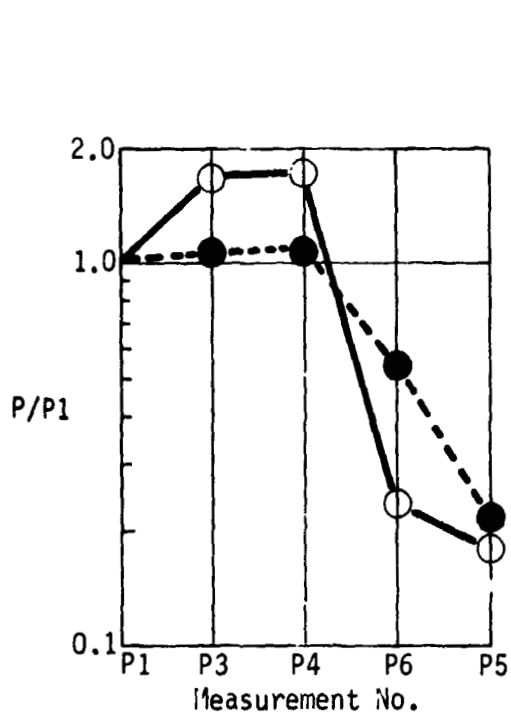


(c) 0.50-in. Cove Gap

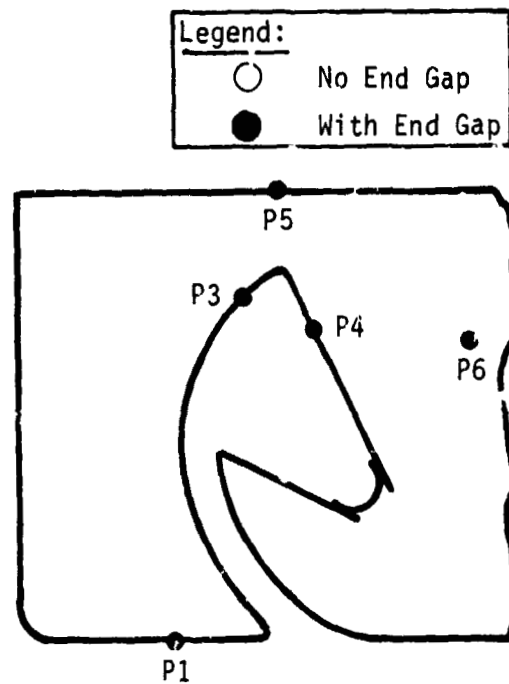


(d) 0.75-in. Cove Gap

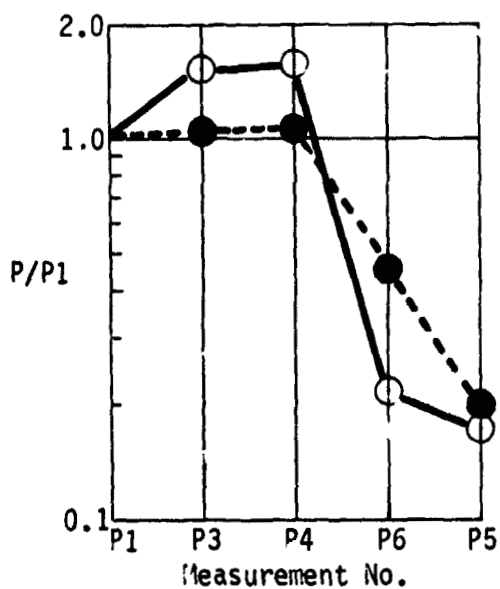
Fig. 29 Effect of 0.5-in. End Gap on Cool Gap Heating Distributions
(Curtain Seal in Place, $\delta = 10^\circ$ Down)



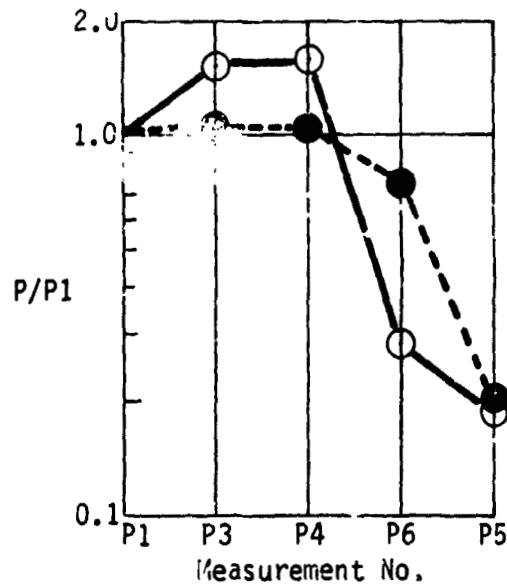
(a) 0.25-in. Cove Gap



(b) Measurement Locations



(c) 0.5-in. Cove Gap



(d) 0.75-in. Cove Gap

Fig. 30 Effect of 0.5-in. End Gap on Pressure Distribution across Model
($\delta = 10^\circ$ Down)

This pressure reduction, however, is apparently offset by the higher flow velocities that occur in the gap as a result of increased lateral flow.

Effect of Leakage

The effect of seal leakage on the cove environment within the cove gap and the cavity forward of the seal was determined by removing the curtain seal and using different-sized orifices to control the flow through the model. These ranged in size from a 7.5-in.² orifice, which allowed unrestricted flow through a 0.75-in. cove gap, to a 0.2-in.² orifice, which severely restricted the flow through a 0.5-in. cove gap. The amount of flow (leakage) observed through the gap was referenced to the maximum that could be achieved. For example, 50% leakage is defined as a leakage rate equal to one-half the maximum amount of flow that can be passed through the gap.

The sensitivity of the cove gap heating levels and pressure levels to different leakage rates is shown in Figures 31 and 32, respectively. The zero leakage curves show the results obtained with the curtain seal in place. The data shown were measured with a 0.5-in. cove gap and the control surface deflected 10° downward.

The results of this test show that leakage has a significant effect on both the pressure and heat transfer distributions within the gap. However, small amounts of leakage (on the order of 1 to 2%) may be tolerable.

Additional heating data for the 0.25-in. and 0.75-in gaps are shown in Figure 33. Only two leakage conditions--0% (a sealed gap) and 100% (an unsealed gap with no flow restrictions)--were measured for these models. Data for the 0.5-in. gap are included for comparison. In all cases, a sealed gap reduced the heating by a factor ranging from 3 to 6. The pressure distributions corresponding to these heating distributions are given in Figure 34.

CURTAIN SEAL MATERIAL TEMPERATURE SENSITIVITY STUDIES

Sensitivity tests were also conducted to determine the effect of temperature on candidate materials for the flexible curtain seal. Temperatures in the inner area of the wing-elevon cove, where the curtain seal would be installed, are expected to range from -200°F (during orbital cold soak) to 350°F, and local temperature excursions could increase the maximum temperature beyond 350°F.

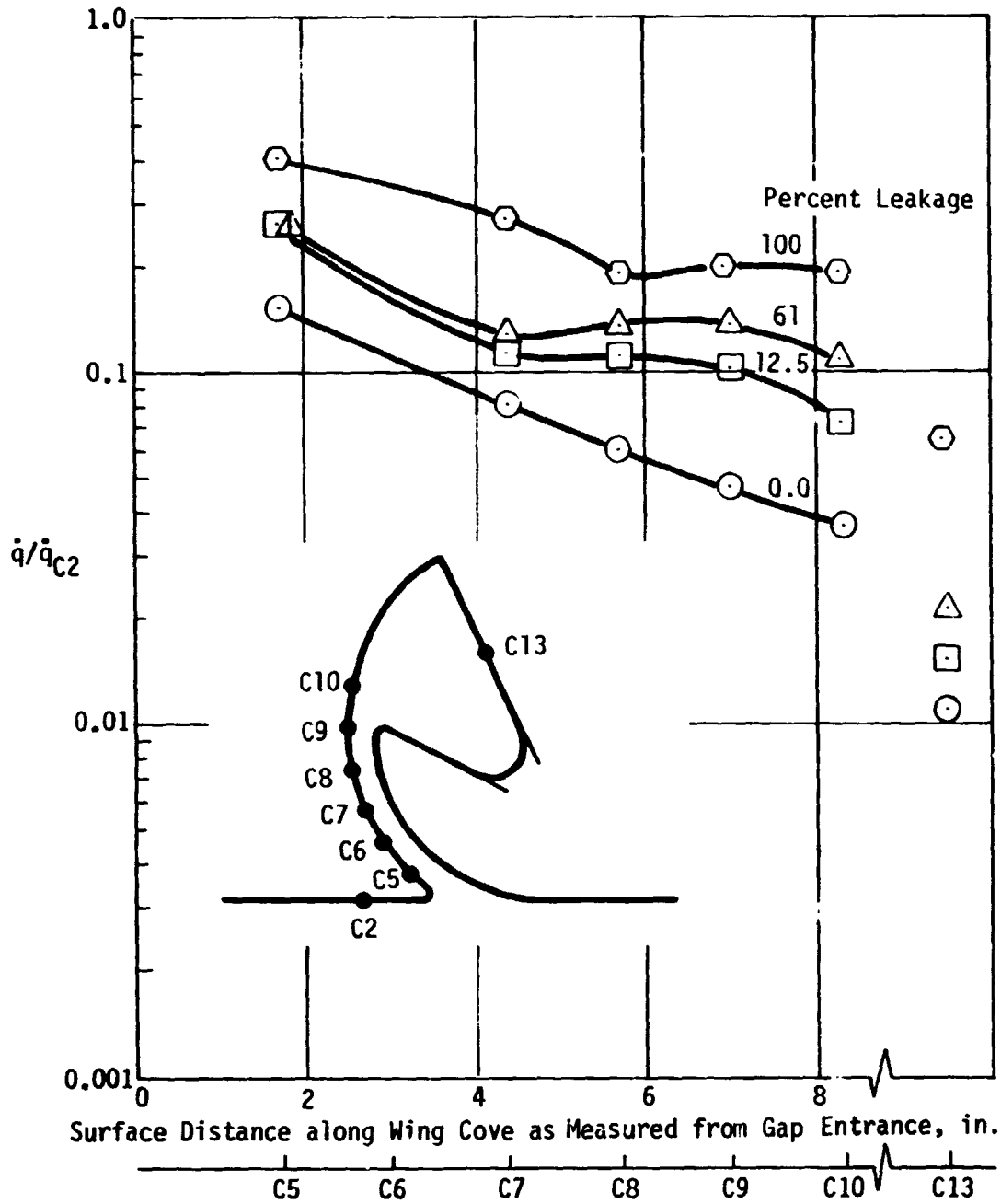
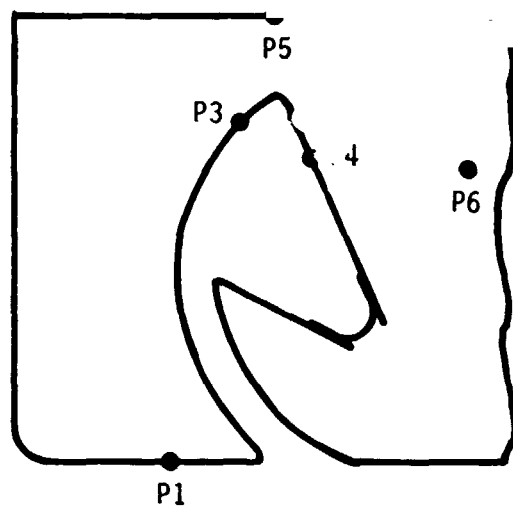


Fig. 31 Sensitivity of Cove Gap Heating Distributions to Leakage
(0.5-in. Cove Gap, $\delta = 10^\circ$ Down)



Measurement Locations

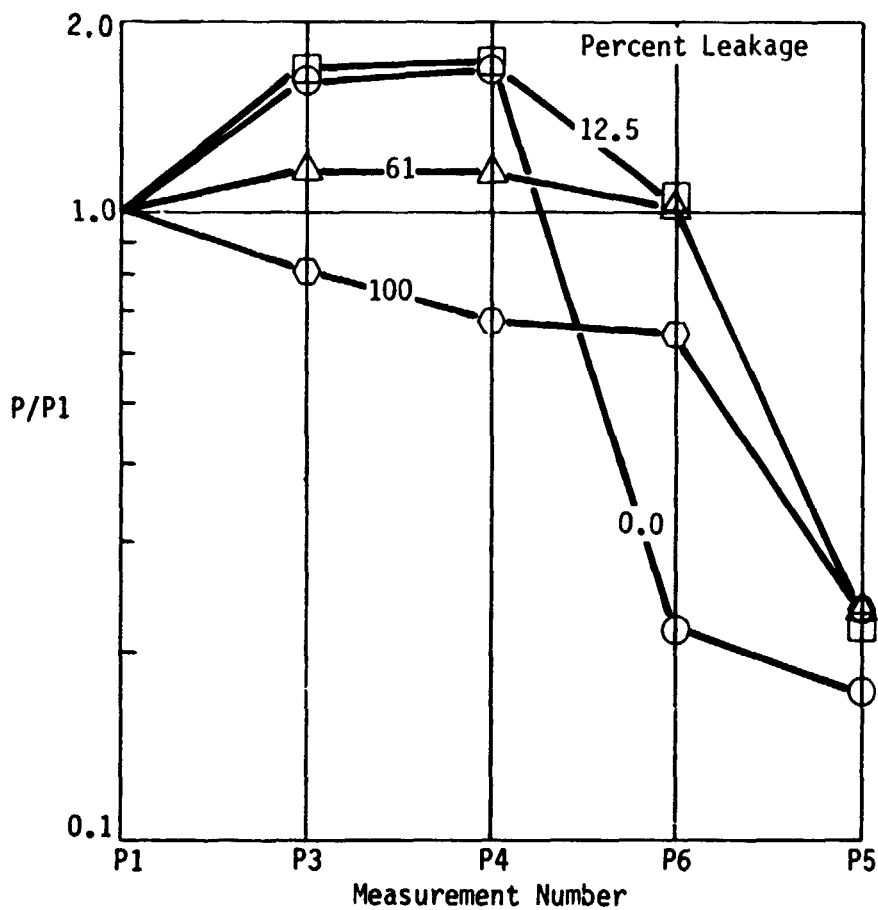
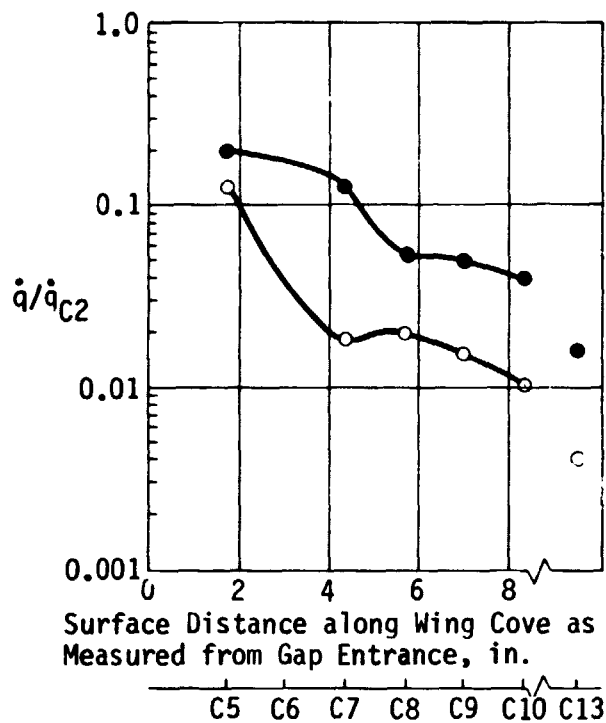
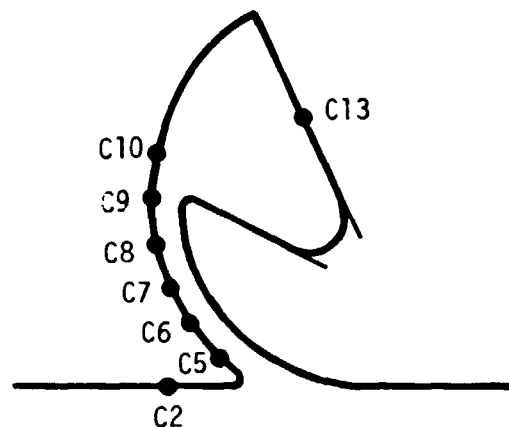
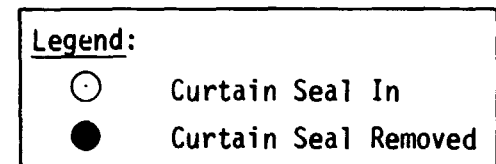


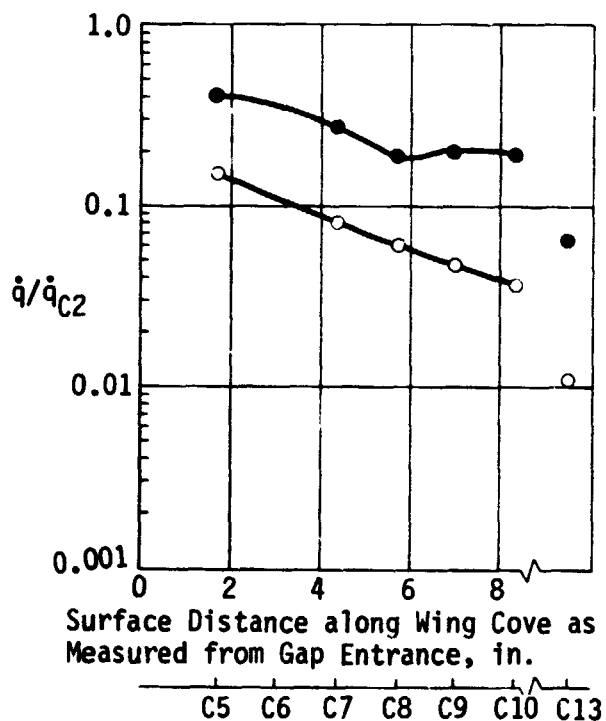
Fig. 32 Sensitivity of Model Pressure Measurements to Leakage
(0.5-in. Cove Gap, $\delta = 10^\circ$ Down)



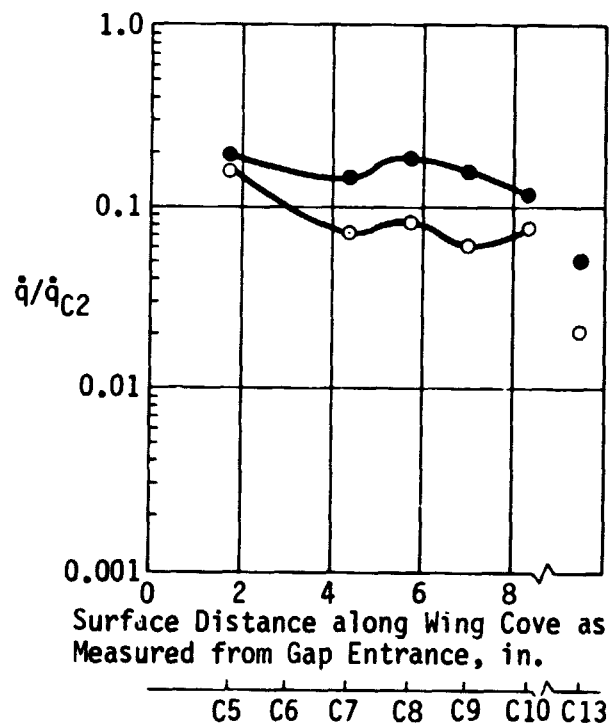
(a) 0.25-in. Cove Gap



(b) Measurement Locations

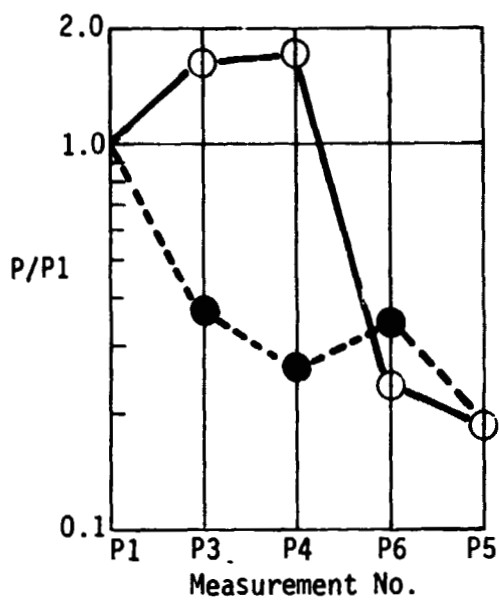


(c) 0.5-in. Cove Gap

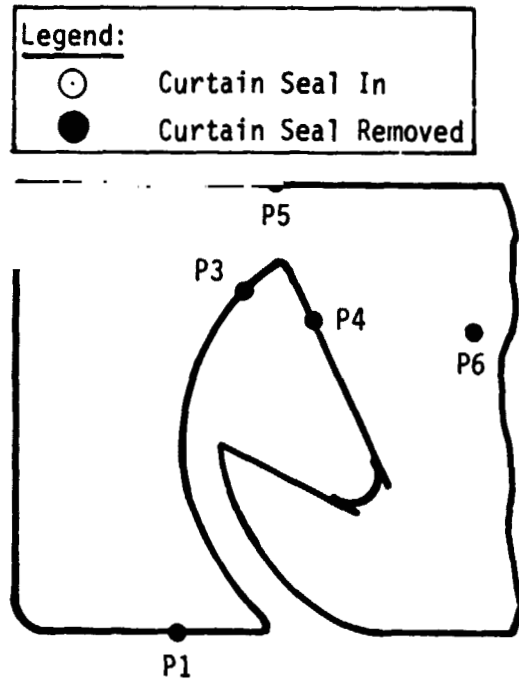


(d) 0.75-in. Cove Gap

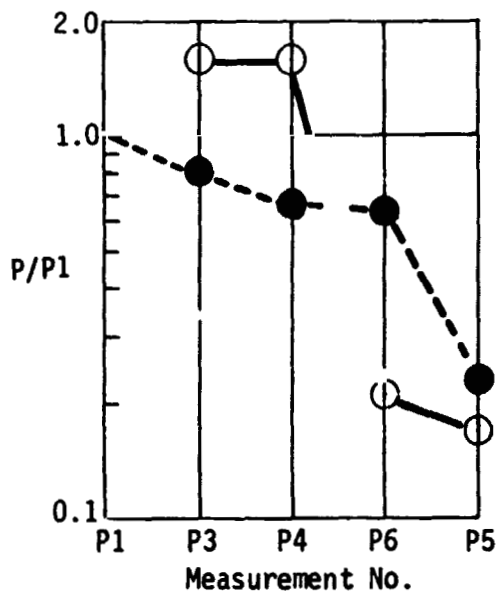
Fig. 33 Comparison of Cove Gap Heating Distribution with and without Curtain Seal ($\delta = 10^\circ$ Down)



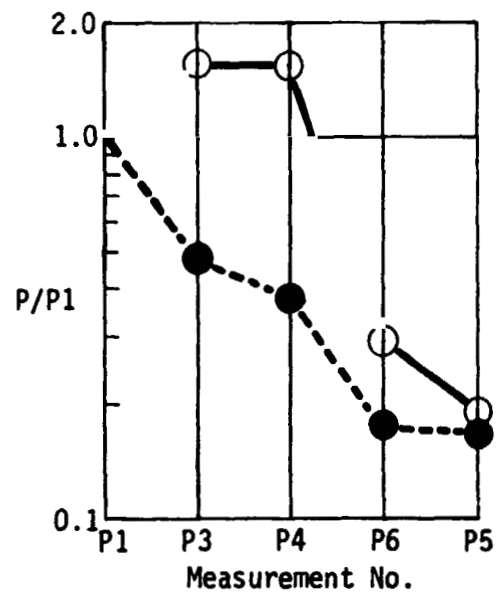
(a) 0.25-in. Cove Gap



(b) Measurement Locations



(c) 0.5-in. Cove Gap



(d) 0.75-in. Cove Gap

Fig. 34 Comparison of Model Pressure Measurements with and without Curtain Seal ($\delta = 10^\circ$ Down)

The development of a suitable curtain material was based on the use of an elastomer capable of operating within the Space Shuttle temperature range, reinforced with a fabric for strength. Methyl-phenyl silicone rubber compounds can withstand the temperature extremes for the inner wing-elevon core area (-200°F to over 350°F), and two such compounds, RTV 560 and RTV 511, were used to fabricate the curtain. Both materials have a quoted, low-temperature "brittle point" of below -150°F, whereas the maximum continuous operating temperature is 400°F for RTV 511 and 500°F for RTV 560.

Glass cloth was selected as the reinforcing fabric. Type 181 cloth was used for the first impregnation with RTV 560, and C1554-28 refrasil cloth was impregnated with RTV 560 for comparison. (These two specimens were labeled #2 and #1, respectively.)

The first impregnation was made by priming the 181 glass cloth and C1554-28 refrasil cloth with DC-1200. Mixed RTV was then poured on the center of the cloth and rolled to the edges. The RTV was worked between polyfilm sheets and rolled to approximately the thickness of the cloth. The overnight cure indicated that there was a need for constant pressure during the cure. The second impregnation was made in the same way, except that after the sample was initially rolled, it was vacuum-bagged and the final rolling was made under vacuum pump pressure (approximately 12 psi). The sample exhibited good, uniform impregnation with a few small voids.

During the material search, we found a roll of Teflon tape called Fluorolene Tape, made by Joclin Mfg. Co., Wallingford, Conn. This tape is a Teflon-impregnated 116 glass cloth. We stripped off the adhesive backing and identified this specimen as #5.

The RTV 560/181 glass and RTV 560/C1554-28 refrasil specimens were thought to be slightly stiff due to the composite thickness, so two more samples were fabricated. Type 116 glass was preferred for impregnation because of its tight weave and strength, but we used 108 cloth instead due to its availability. Curtain samples were constructed of RTV 560/108 glass and RTV 511/108 glass. The RTV 511 has a hardness of 45, compared to 60 for RTV 560.

Information about the composite curtain specimens is listed below.

Specimen	Material	Cloth Thickness, in.	Composite Thickness, in.
1	RTV560/Refrasil	0.014	0.018
2	RTV560/181 Glass	0.0085	0.015
3	Teflon/116 Glass	0.004	0.0063
4	RTV560/108 Glass	0.002	0.008 to 0.012
5	RTV511/108 Glass	0.002	0.005 to 0.006

The seal material test program was conducted in two phases. Phase I was conducted to determine the useful lower and upper temperature limits of the curtain materials. Low-temperature tests were run at -90°F , -150°F , -175°F , -185°F , -200°F , -225°F , and -250°F . Specimens 1-in.-wide were flexed at each temperature level by a tensile machine mounted within the environment chamber (see Fig. 35). In addition, a 41-hr cold soak test (at -200°F) was also run on the curtain specimens to determine the effect of a prolonged exposure at low temperature on the stiffness of the curtain seal.

Upper temperature tests began at 350°F and went up in 50°F increments to 600°F (the maximum capability of chamber).

The Phase I tests indicated that silicone rubber elastomeric materials (reinforced with glass cloth) and Teflon (reinforced with glass cloth) will successfully operate within the temperature extremes of -250°F to 600°F for short times. The 41-hr cold soak at -200°F had no effect on stiffening the curtains. Figure 36 shows that stiffening began at about -150°F and leveled off at -200°F .

In the Phase II tests we exposed the curtain specimens (#1, 3, 4, and 5) to 20 simulated orbit-entry temperature cycles with a total cold soak time of 91 hr at -200°F . All specimens apparently withstood the 20 temperature cycles combined with a total of 480 flex cycles (Fig. 37), and no flex cracking or other material deterioration was detected during posttest examination. Figure 38 shows four of the curtain seal materials in the -200°F cold soak chamber. Further details of these tests can be found in the separately submitted test report.

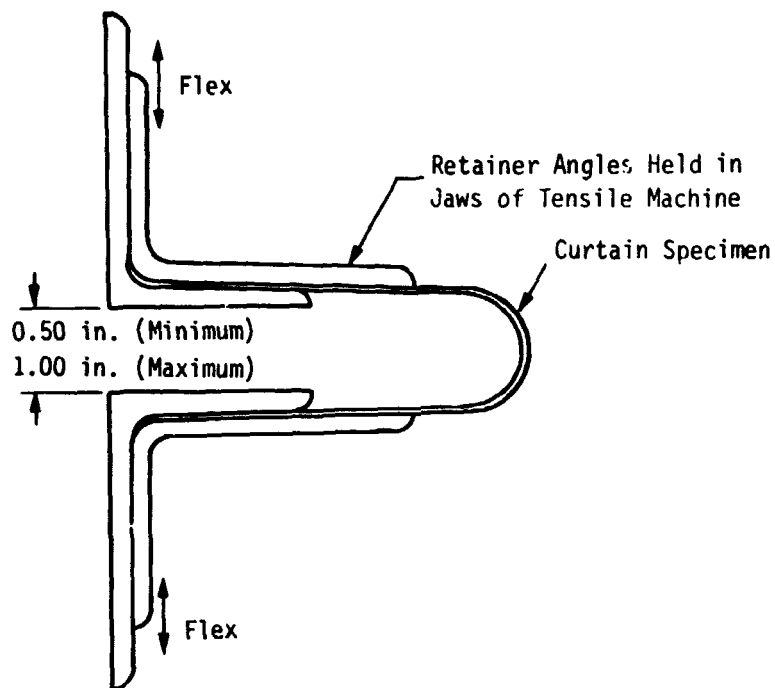


Fig. 35 Flexing Arrangement within Environmental Chamber

Phase I Results	
Composite Materials	Short-Time Temperature Exposure
Methyl-Phenyl Silicone Rubber/Glass Cloth	-250° to 600°F
Teflon/Glass Cloth	-250° to 600°F
Methyl-Phenyl Silicone Rubber/Irish Refrasil Cloth	Handling Failure

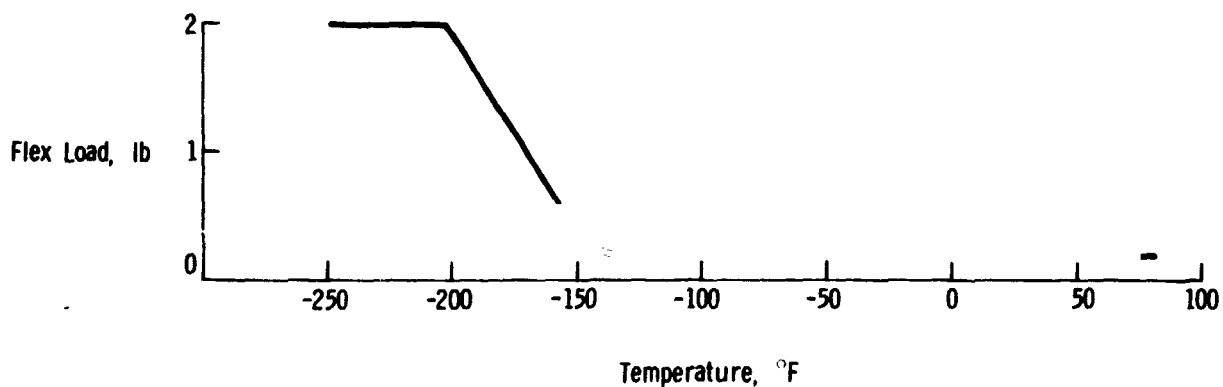


Fig. 36 Stiffening Effects of Low-Temperature Cycling

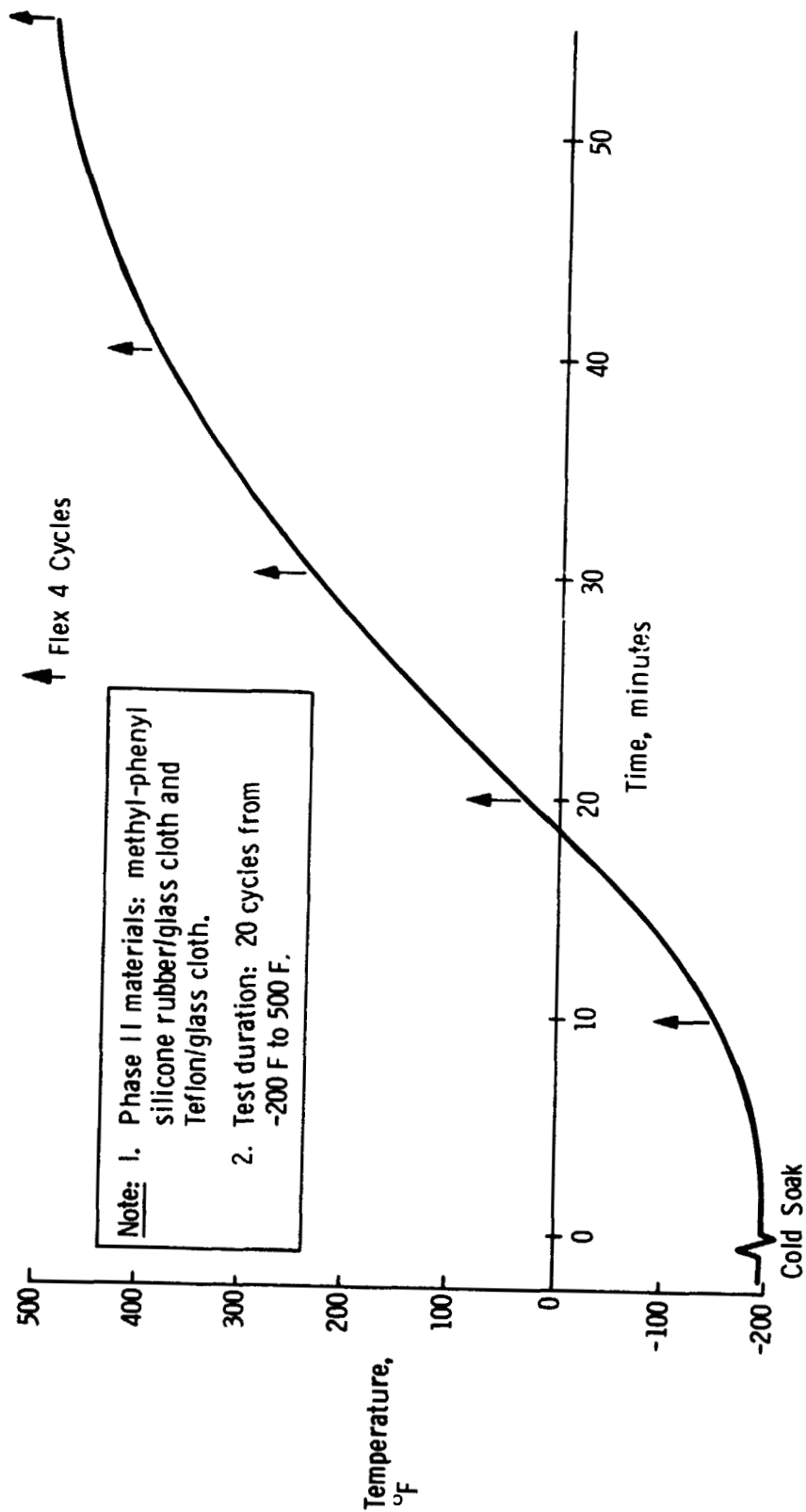


Fig. 37 Orbit-Entry Temperature Simulation Test



Fig. 38 Curtain Seal Materials in -200°F Cold Soak

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TASK IV - EVALUATION AND PHASE II RECOMMENDATIONS

The purpose of this task was to evaluate all progress made during the first three tasks and the Phase I test portion of Task VI, to recommend seal concepts for further testing, and to develop a comprehensive test approach to evaluate these designs during the Phase II testing portion of Task VI. These evaluations and recommendations were presented to NASA at the contract midterm review.

The objectives of the Phase II test program were to expose candidate dynamic seals to a simulated Space Shuttle entry environment, measure the temperature response of the seals and surrounding structure, reaffirm the environmental levels measured in the Phase I tests and determine the radiation contribution to the cavity area forward of hinge line seal and just inboard of the cove gap.

Three seal design concepts were considered for the Phase II tests. Figure 39 depicts a section of the elevon-to-wing cove gap with the curtain seal installed at the hinge line. This curtain seal spanned the complete width of the model. This concept enabled us to test a portion of the cove gap structure without including end gap effects. The second test model, shown in Figure 40, is the same as the first model except that here the curtain seal is replaced with a spring-loaded glass/phenolic rubbing block. The third test model (Fig. 41) shows a plan view of the spanwise elevon cove gap intersecting with the chordwise elevon end gap. This concept shows a high-temperature alloy labyrinth seal installed with one half mounted to the fuselage side of the end gap and the other side mounted to the end of the elevon. The labyrinth seal has a concentric shape and is installed on the centerline of the elevon hinge. The concentricity feature allows the elevon to rotate through the required deflection angles, and the concentric rings on each half of the labyrinth interlap to create a long torturous path for high-temperature flow to reach the open area above the elevon hinge line. Figure 42 is an artist's concept showing the labyrinth seal and the curtain seal installed on a typical Space Shuttle structure and showing how each concept is conceived to function.

After a considerable amount of discussion, it was mutually agreed at the midterm review that there was a great deal to be gained by testing an elevon end gap model with no seal to determine the

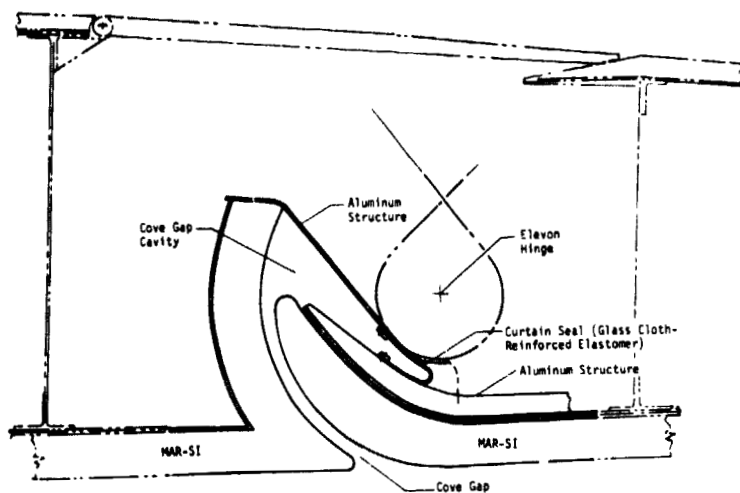


Fig. 39 Elevon Cove Gap Model - Curtain Seal

Fig. 40 Elevon Cove Gap Model - Rubbing Block Seal

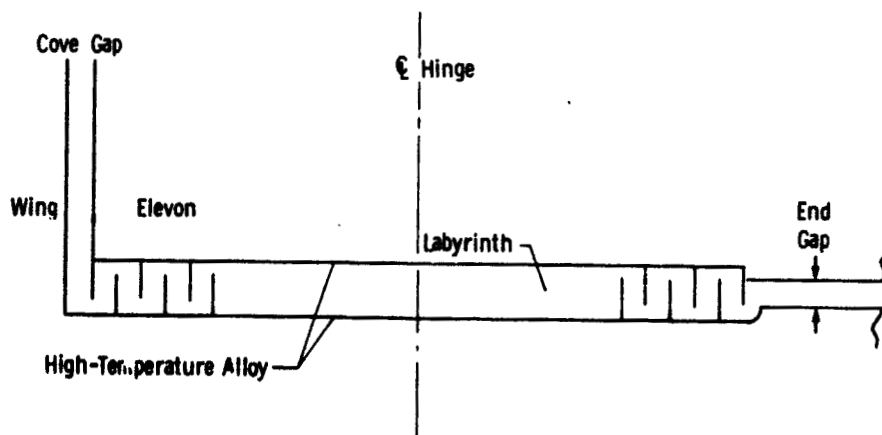
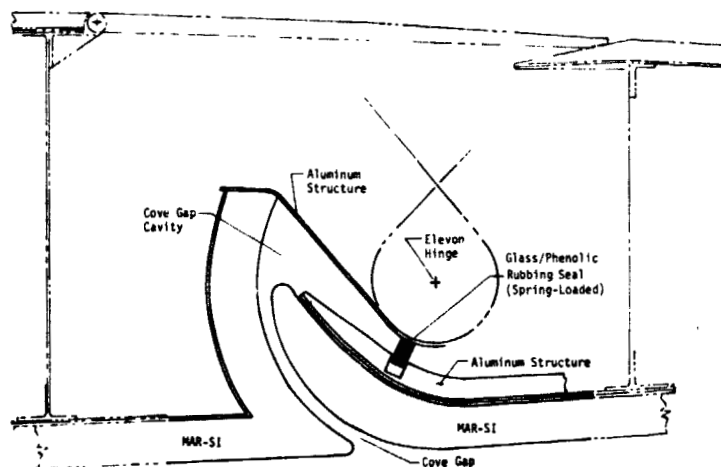


Fig. 41 Plan View of Labyrinth Seal

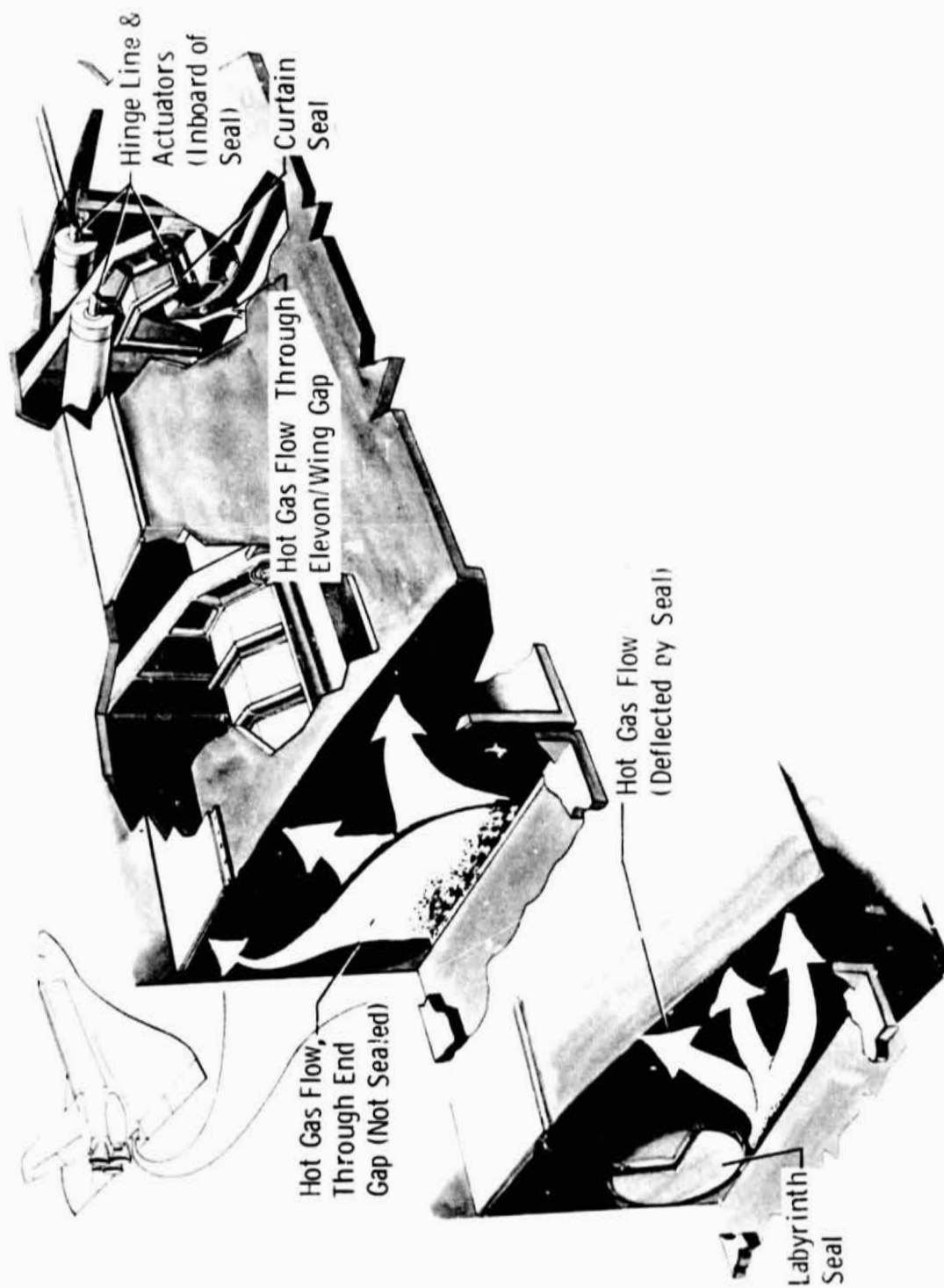


Fig. 42 Pictorial Concept of Elevation Gap Seals

effectiveness of the labyrinth seal concept and the feasibility of entry without an end gap seal. To minimize the impact on program cost and schedule, we proposed to eliminate the rubbing seal concept and test only three types of models:

- 1) A full-scale section of the elevon-to-wing cove gap with a curtain seal installed;
- 2) A full-scale section of the elevon end gap sealed with a labyrinth seal;
- 3) A full-scale section of the elevon end gap with no seal.

We also recommended that the curtain seal be a 0.17-in thick composite of methyl-phenyl silicone rubber and 181 glass cloth, that the gap widths be 0.50-in. for both the cove and end gap, and that the tests be conducted with elevon 10° down.

All models were to be instrumented to record complete responses to the plasma-arc-imposed environment (see Fig. 43), using thermocouples, pressure transducers, and calorimeters as required. In addition, radiation within the cove gap cavity was to be determined to evaluate the individual contributions of radiation and convection to the overall heating environment.

Based on the above evaluations, recommendations, and midterm review discussions, we began to work on the Phase II test plan and to design the three test-models in preparation for the test readiness review held prior to beginning the Phase II test program.

Note: Numbers near asterisks denote flight surface pressure in psi-

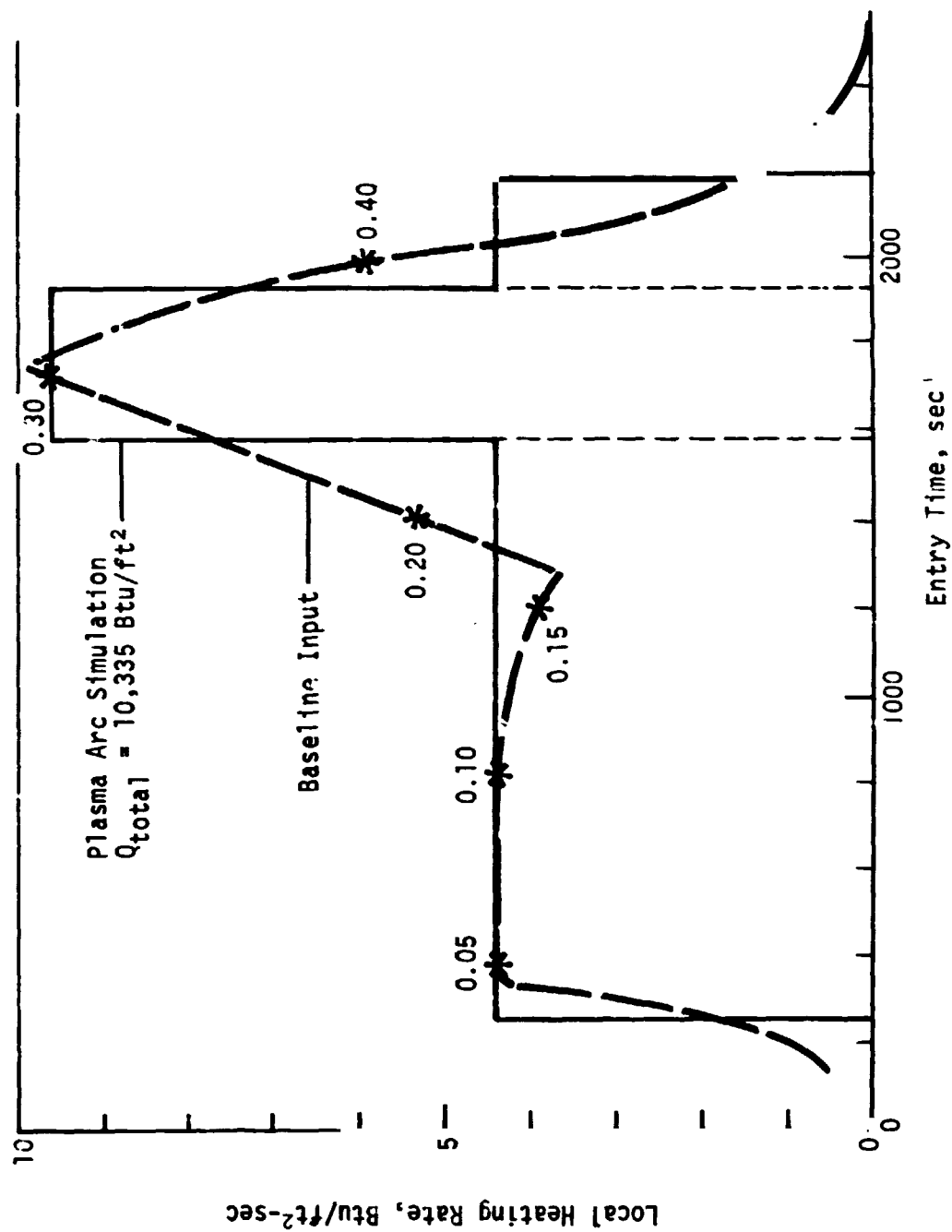


Fig. 43 Plasma Arc Simulation of Entry Heating Environment

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TASK V - DESIGN AND FABRICATION

The plasma arc models used for both the Phase I and Phase II tests were full-scale representations of the Space Shuttle wing-elevon cove area. These models were limited in depth and width by the geometry of the plasma arc test envelope and were approximately 8 by 15 by 20 in. The elevon cove radius was chosen as 6.0 in., and the models were designed for maximum elevon deflections of $+20^\circ$ (down) and -50° (up).

DESIGN & FABRICATION OF THE PHASE I ENVIRONMENTAL MODEL

The design requirements for the environmental test model were accommodated by providing:

- 1) A water-cooled structure for reusability;
- 2) A short (approximately 1-minute) exposure to the plasma arc;
- 3) Variable gap widths of 0.250, 0.500, and 0.750 in., respectively;
- 4) Variable elevon deflection angles of $\pm 10^\circ$ and 0° ;
- 5) The capability to change test configurations in 1 hr;
- 6) Thirteen calorimeters and 6 pressure transducers for monitoring heating rates and pressures.

The model shown in Figure 44 was designed as a water-cooled aluminum structure. The areas that required water cooling were the leading edge, the bottom surfaces, and the interior of the cove. Three-eighths-inch OD aluminum tubing was welded to the inside of these surfaces in three parallel circuits. The circuit to the elevon side had a flexible line connection for varying the deflection angle and gap width.

For simplicity, the model was designed for a $\frac{1}{4}$ -in. cove gap with an elevon radius of 6.0 in. and concentric wing cove radius of 6.25 in. The other gap widths were achieved by moving the elevon hinge point aft and measuring the 0.5 and 0.75 in. gap widths at the gap entrance. As a result, the gap corridor was not perfectly concentric for the 0.50- and 0.75-in. gaps.

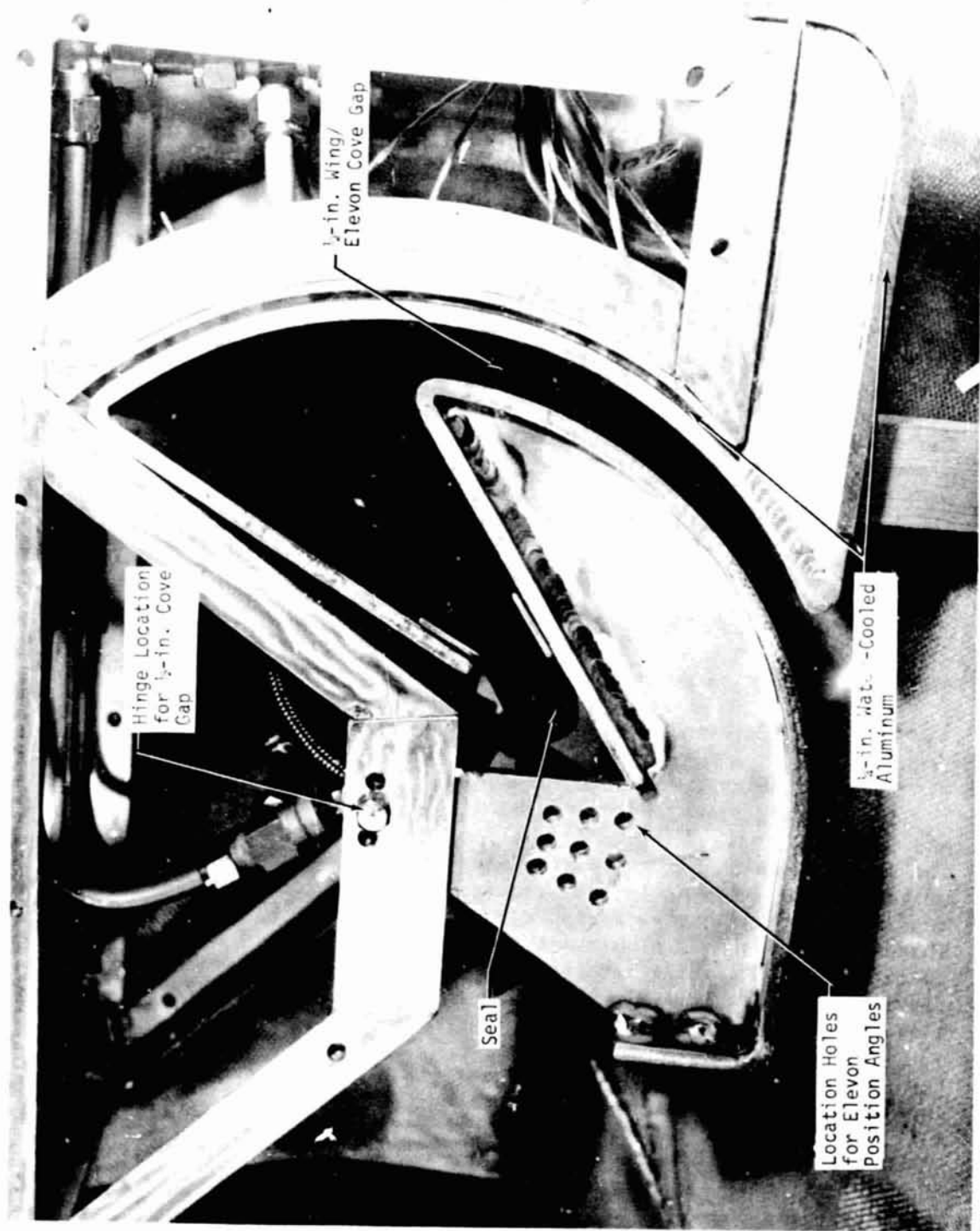


Fig. 44 Environmental Test Model

The two sides of the model were constructed of $\frac{1}{4}$ -in. aluminum plate sprayed with MA-25S ablator. The ablator was sprayed on the external surfaces and on the exposed lower surface of the interior. These ablator-covered plates are shown in Figure 45.

The front plate was a 0.040-in. aluminum sheet with a bonded-on SLA-561 ablator heat shield. After the plate was bolted to the model, plugs of SLA-561 were bonded in over the bolts.

The remaining sides of the model were closed with $\frac{1}{4}$ -in. aluminum plates. The only opening on the back of the model was the orifice hole shown in Figure 46. The model box was completely sealed with RTV so that the only possible leakage path was through the cove gap and seal, into the interior of the box, and out of the orifice hole.

Configuration changes were made by using predrilled locating holes to vary the gap width and deflection angle. The rear closure of the elevon had two different aluminum plates to accommodate these changes.

The elevon structure was fabricated with a $\frac{1}{2}$ -in.-thick aluminum side plate, as shown in Figure 45. Provisions were made to remove and replace it with a stainless steel angle for representing the $\frac{1}{2}$ -in. end gap condition.

The first 12 calorimeters were screwed into the $\frac{1}{4}$ -in.-thick, water-cooled aluminum plate of the wing and elevon parts. The 13th calorimeter was mounted on the wing's internal shelf. Pressure transducers were all shock-mounted on the top plate within the model. Tygon tubing was used between the pressure pickup and the pressure transducers.

DESIGN & FABRICATION OF THE PHASE II FLIGHTWEIGHT SEAL CONCEPT EVALUATION MODELS

Design requirements for the Phase II test model were as follows:

- 1) Reusability ----- Capable of demonstrating 3 simulated entry cycles;
- 2) Full entry heating environment -- $Q = 10,335 \text{ Btu/ft}^2$;
- 3) Gap width ----- 0.50 in.;
- 4) Elevon deflection angle ----- 10° down;

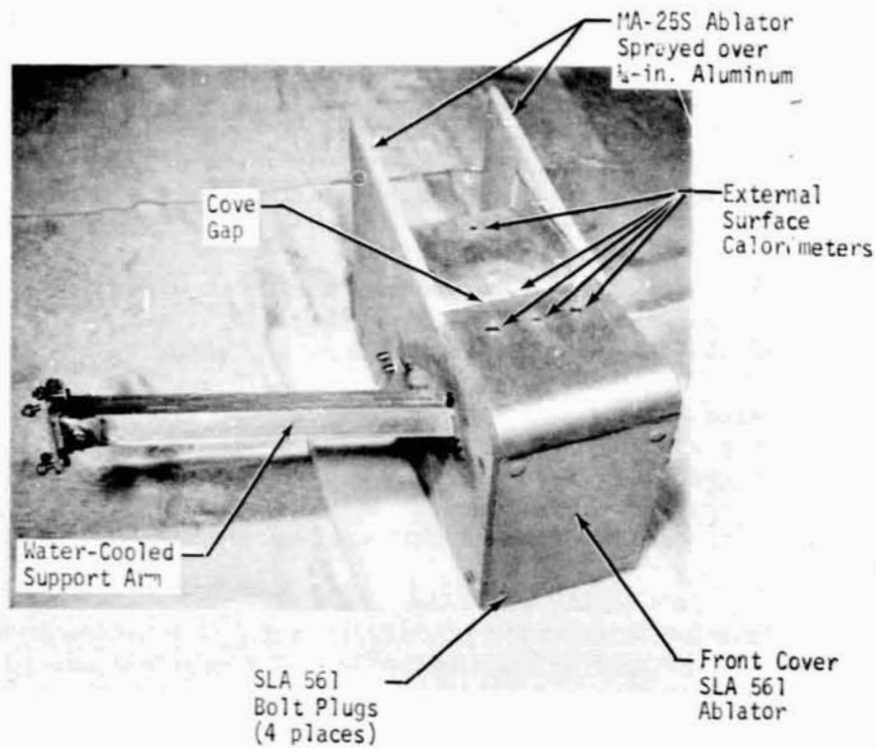


Fig. 45 Environmental Test Model after Assembly

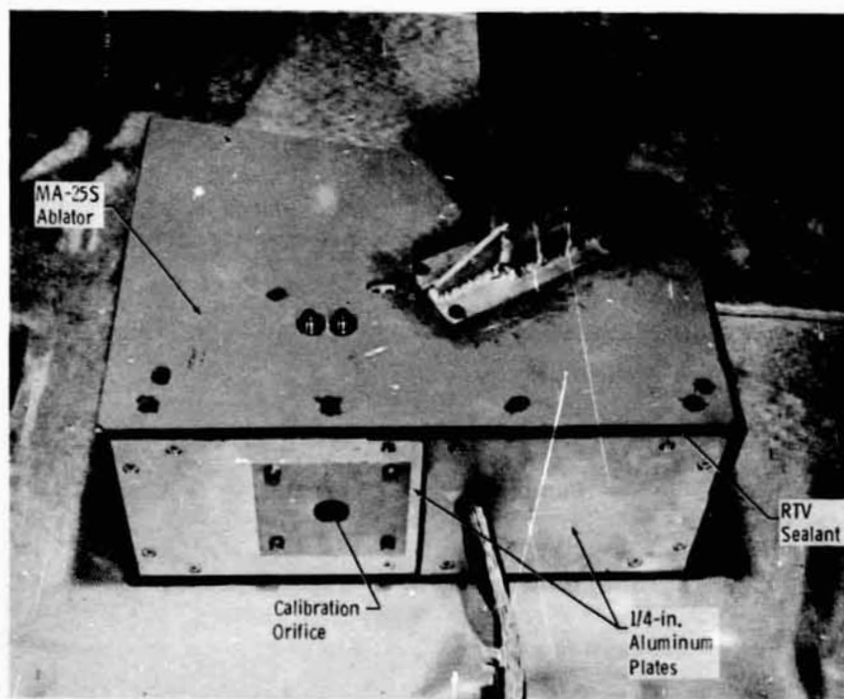


Fig. 46 Top View of Environmental Test Model

- 5) RSI insulation ----- MAR-SI;
- 6) Simulated flightweight system;
- 7) Three model configurations;
 - Full-width flexible cove gap curtain seal,
 - Combined labyrinth end gap seal and flexible cove gap curtain seal,
 - Combined open end gap with flexible cove gap curtain seal,
- 8) Cove gap curtain seal temperature range: -200° to 500°F;
- 9) End gap labyrinth seal temperature range: -250°F to 2000°F.

Curtain Seal

The curtain seal was a single-layer glass cloth impregnated with methyl-phenyl silicone rubber. The actual materials selected for the test curtains were 181 glass cloth and RTV 560 silicone rubber. The curtains were fabricated at Martin Marietta and used for both the Phase I and Phase II test models.

The fabrication procedure for the composite material curtain was as follows:

- 1) Both sides of the 181 glass cloth were primed with DC-1200 and allowed to cure for 8 hr;
- 2) Mixed-RTV 560 was then poured on the center of the cloth and rolled to the edges. The RTV was worked between two sheets of polyethylene film;
- 3) After the RTV 560 was worked well into the cloth, the sheet was turned over and more RTV was added to the other side. This was worked as in step 2 until all the RTV was uniformly impregnated to approximately the desired thickness;
- 4) The curtain was vacuum-cured overnight;
- 5) The polyethylene sheets were then stripped off both sides.

Labyrinth Seal

A preliminary heating analysis showed that the labyrinth could reach temperatures as high as 2000°F during the test. Rene' 41 alloy was used for fabricating the labyrinth because of its availability. One assembly of the labyrinth is shown in Figure 47. Note that the three rings were attached to the round disk by bent-over tabs that fit into slots in the disk. This allowed differential expansion of the rings and disk without restraint that would result in warping.

The rings were constructed with one closing butt weld. The disk and rings were made from 0.037-in.-thick material. The concentric rings were 0.82 in. apart on each assembly and 0.94 in. high. The assembled labyrinth provided 0.25 in. of clearance between rings and disk for deflection and expansion.

Thermal Protection System

The thermal protection system for the Phase II test models was fabricated from standard MAR-SI (15 lb/ft³) thermal insulation at our Denver Division's ceramic fabrication facility. Table 4 gives the composition of MAR-SI, and Figure 48 shows fabrication sequence.

Table 4 Composition of MAR-SI Insulation

Oxide	Form	Weight, %
Al ₂ O ₃ ·SiO ₂	2-micron-dia Fiber	65
Al ₂ O ₃	Colloidal Particles	11
SiO ₂	Microballoons	5
2Al ₂ O ₃ , 0.3 SiO ₂	-325 Mesh Grain	3
SiO ₂	Colloidal Particles	26

After the billets of MAR-SI (4 by 16 by 16 in.) were removed from the sintering furnace, we established which parts would be made from them and sectioned the billets into pieces slightly larger than the final parts. To machine the MAR-SI pieces in preparation for coating, we laid out a pair of matching aluminum templates to the final dimensions, allowing a small overage for shrinkage as the coating was fired. This overage amounted to an additional 0.035 in. parallel to the MAR-SI fibers and 0.090 in. perpendicular to the fibers. The width of the final part was then cut to the design dimension (allowing for shrinkage) and the templates were assembled to the parallel surfaces using bilateral film adhesive. Next, the MAR-SI was filed down to conform to the shape of the templates, the templates were removed, and the residual dust was blown from the part.

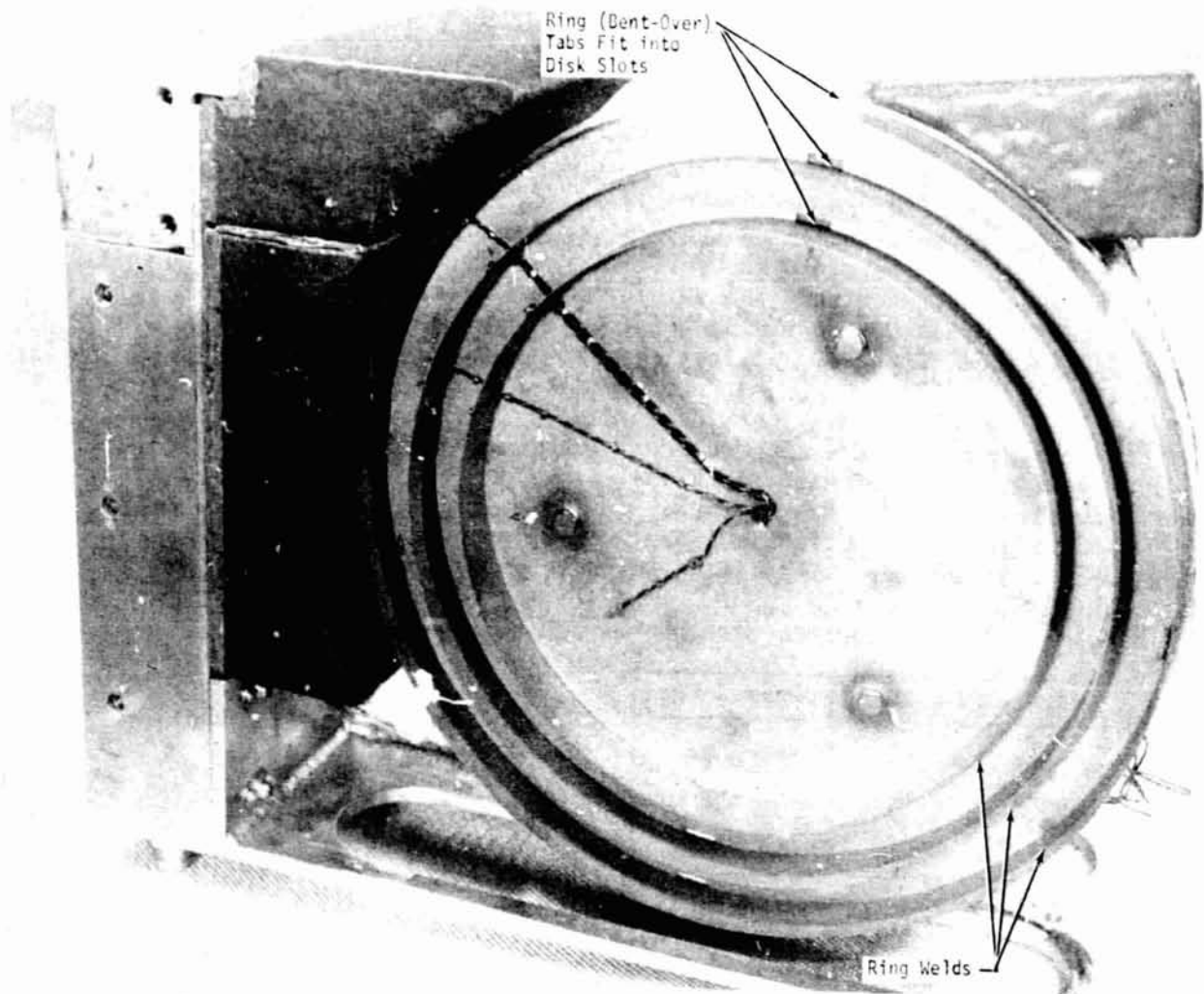


Fig. 47 René 41 Labyrinth Seal Assembly

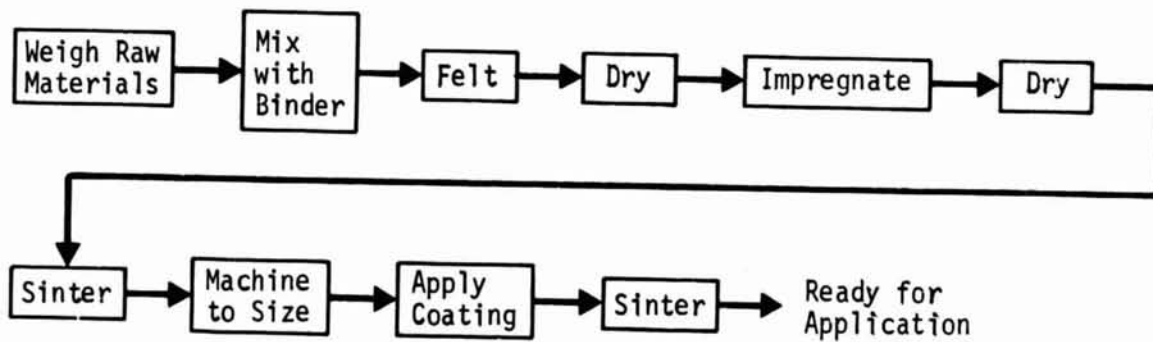


Fig. 48 Fabrication Sequence for MAR-SI Insulation

After being weighed and dimensionally checked, the parts were coated using Martin Marietta's 70-1 coating system. This procedure consisted of a paint-sprayed single application of coating slurry, followed by air drying at 250°F and firing at 2500°F. To ensure the accurate application of the coating for achieving uniform thickness, we determined the surface area for each contour of each part and calculated the weight of coating required for each contour. Areas not receiving the coating were masked off before spraying the surfaces. All coated parts were dried for a minimum of 16 hr at 250°F.

The coated parts were supported on blocks of MAR-SI shaped to match the bottom of each individual part and were fired in an electric resistance-heated furnace. These shaped blocks were used to provide a uniform support and prevent the parts from warping or sagging. The firing schedule used is shown in Table 5.

Table 5 Firing Schedule for Thermal Control Coatings

Temperature	Elapsed Time
Ambient to 2500°F	0 to 5 hr
2500°F	5 to 6 hr
2500°F to 375°F	6 to 21 hr

After the parts had cooled to 375°F they were removed from the furnace. When they were completely cool, their dimensions and weights were recorded and templates were used to check the curved surface for warpage. In cases where an allowance for shrinking had been made in the height dimension, we removed the excess uncoated material on the bottom of the part, bringing the height within the dimensional tolerance. Figure 49 shows some of the finished parts.

A total of thirteen 16 by 16 by 4-in. blocks of MAR-SI were required to fabricate the test specimens. In all, we prepared 19 billets, including parts rejected because of cracking, warping, or not meeting dimensional tolerances.

The MAR-SI parts were prepared for bonding by priming the uncoated lower surface with Dow Corning 1200 silicone primer and allowing it to dry for a minimum of 16 hr. The insulation was then bonded to the metal structure of the model in three stages: first the insulation was bonded to a 0.012-in.-thick strain arrestor plate; then the arrestor plate was bonded to the strain isolator; and finally, the strain isolator was bonded to the metal structure.

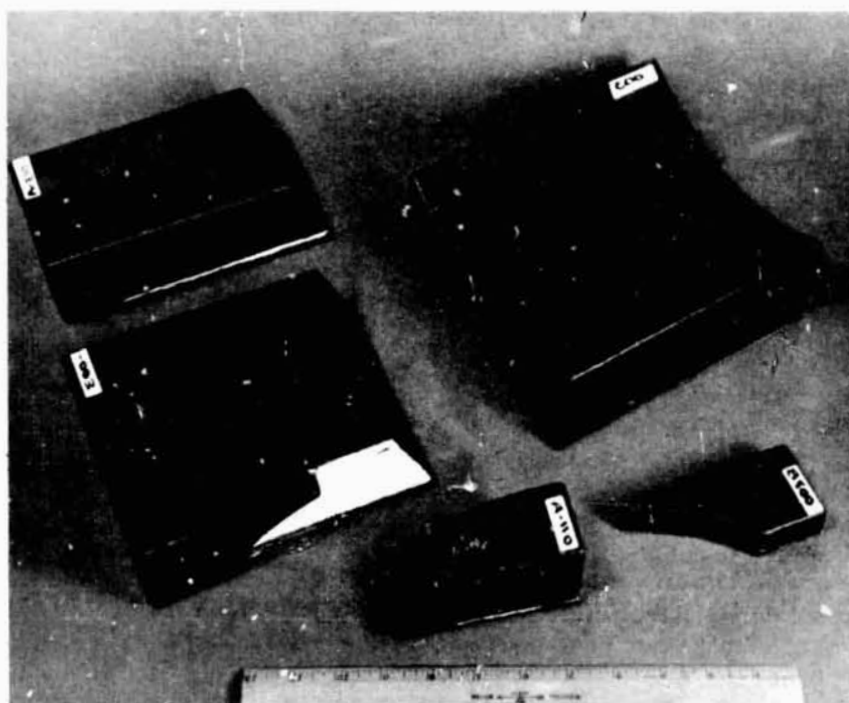
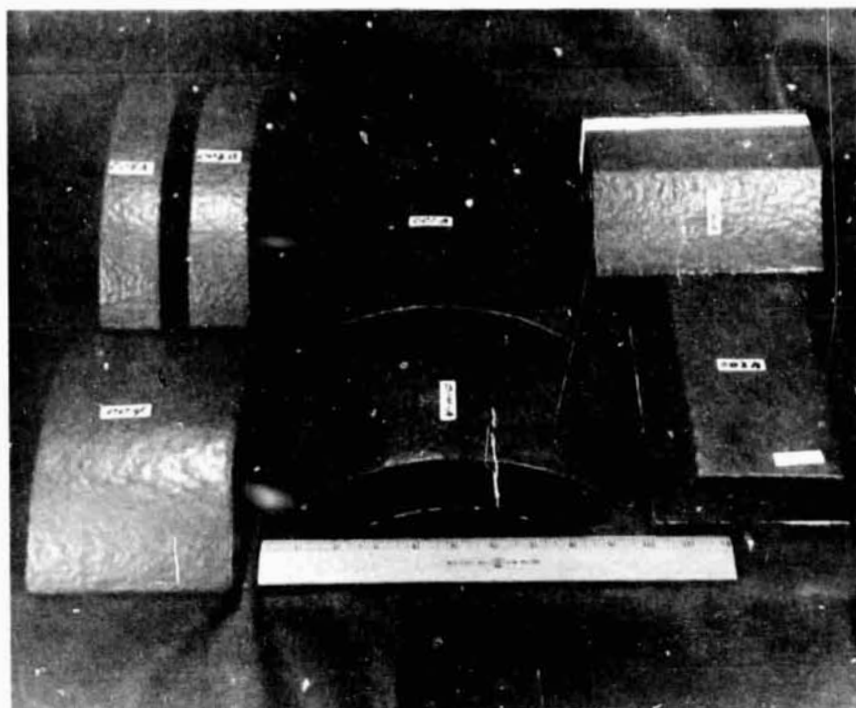


Fig. 49 Typical Coated MAR-SI Reusable Surface Insulation

The strain arrestor plate was made by vacuum-bag curing (2 hr at 150°F, followed by 2 hr at 300°F) three plies of style 120 glass cloth using 5868R resin. The strain isolator was a 0.12-in. piece of silicone sponge-type RL1973 (Raybesto Manhattan Inc.) with a density of approximately 22 lb/ft³. General Electric RTV 560 adhesive with a Thermolite 12 catalyst was used as the bonding agent. A bond line thickness of 0.015 in. was used in each bonding operation. All bond lines were cured for a minimum of 24 hr at room temperature.

Before bonding the MAR-SI parts to the model the surfaces were prepared as follows: the uncoated lower surface of the insulation was primed, both surfaces of the strain arrestor plate were primed, and the surfaces of the metal structure were then abraded with 200 grit sandpaper and primed.

All priming was done with Dow Corning 1200 primer that was allowed to cure for a minimum of 16 hr at room temperature.

The Phase II test models were designed as realistic flightweight configurations within the test envelope constraints of the plasma arc facility. A thermal analysis of the model indicated that 2 in. of MAR-SI would be required to protect the aluminum structure to a maximum temperature of 350°F. Fourteen different MAR-SI tiles were required for the three test models.

Fabrication Details

Full-Width Curtain Seal Model - The full-width curtain seal model is shown in Figure 50 with one side plate removed for clarity. This shows the main design features. Note that the leading edge, which is constructed of copper bar with water-cooling passages machined in, is assembled to the front frame member, which has two wing-side MAR-SI tiles bonded onto it. The gaps between the tiles (approximately 0.12 in. wide) are filled with folded Irish Refrasil cloth bonded to the structure. The front frame is mechanically attached to the upper frame, which has two hinge lugs. The aluminum shelf attaches to the two wing lugs and extends across the full width of the model.

The elevon structure is shown with two MAR-SI tiles bonded to its outside skin. One end of the curtain seal is fastened to the elevon and the other end is attached to the wing shelf. A simple loop compensates for elevon movement. The back plate of the elevon assembly fits against the rear bulkhead to seal the box. This back plate is protected from leeward heating by a 1/4-in. SLA 220 ablator sheet with honeycomb reinforcement and is bonded on with RTV 560.

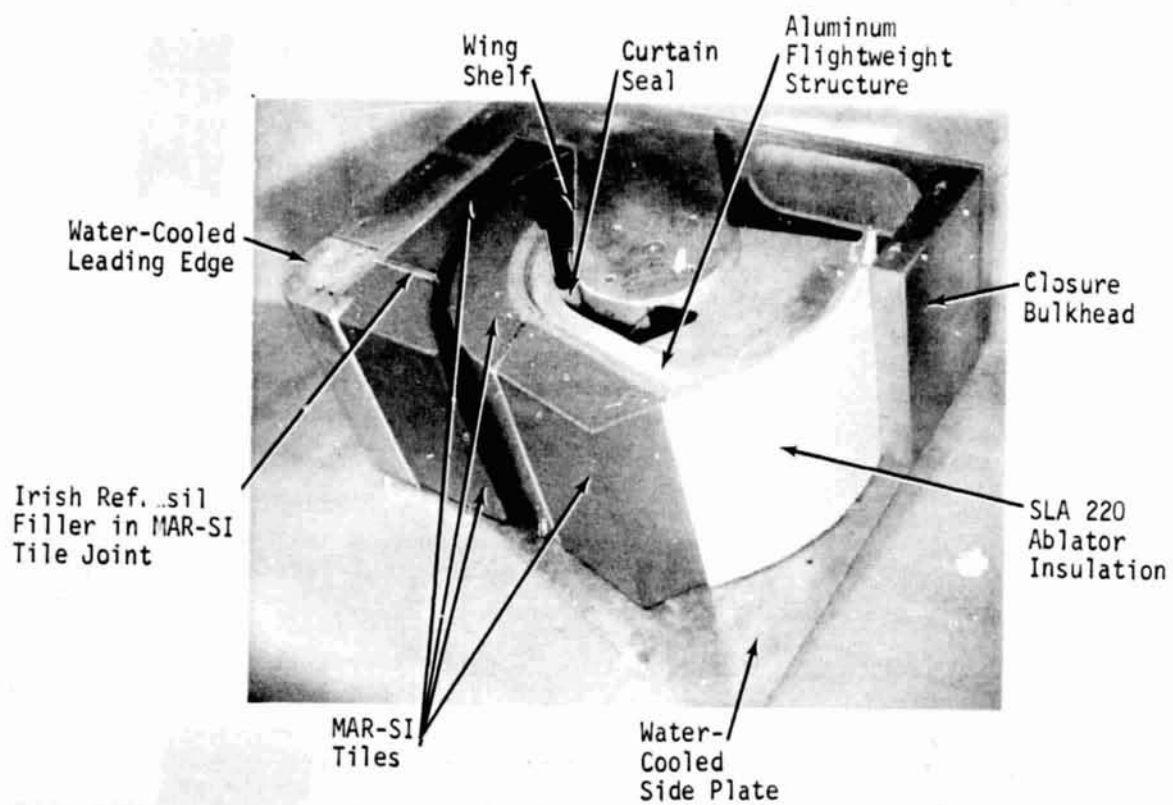


Fig. 50 Full-Width Cove Gap Model

The elevon skin and wing shelf are both made from 0.080-in. aluminum alloy. The side plates and front plate are constructed of 0.060-in. copper sheet. Copper tubing is brazed onto the side plates and front plate in order to water cool the structure. The tubes on the two side plates are externally brazed to the model assembly.

Labyrinth Seal Model - The labyrinth seal model shown in Figure 51 uses the same wing part as the full-width curtain seal model. The only difference is that the shelf width was changed to accommodate the 12-in.-diameter labyrinth. The labyrinth, with the insulation and standoff attachment, takes up about half of the width of the model.

Figure 52 shows the model with 1.5 in. of uncoated MAR-SI insulation and three mullite standoff attachments for the labyrinth-to-elevon closeout rib structure. One of the standoff fittings is removed to show its detail.

The following arrangement was used to hold the labyrinth seal in place. Two 3/8-in. holes were drilled in the 3/4-in. OD mullite tube and A-286 stainless steel barrel nuts were inserted and tacked in place with RTV. One A-286 steel bolt holds the labyrinth to the upper barrel nut and a second bolt holds the elevon rib to the lower barrel nut.

The two thermal isolator washers shown in Figure 52 are machined from asbestos/phenolic sheet stock and used to isolate the mullite tube and the bolt from the aluminum rib. In addition, the mullite standoff assembly is stuffed with fiberfax to minimize radiation heating within the tube. The labyrinth is padded from the MAR-SI using disks of Irish Refrasil cloth.

The labyrinth seal was designed with a 0.25-in. clearance between the rings of one assembly and the disk of the other assembly. A wiper seal--made of refrasil cloth, looped and stuffed with high resiliency fiberfax--was installed to close out the upper end of the assembly and seal the cove gap against the labyrinth and underlying MAR-SI surface (Fig. 53). Another rubbing seal of refrasil cloth runs along the end of the wing shelf and wipes against the inside surface of the elevon closeout rib.

The body side of the labyrinth seal is mounted to the water-cooled side plate and is insulated with 1/2-in. microquartz blanket. The blanket is protected from the direct blast of the plasma arc by a Rene' 41 flanged-pan, as shown in Figure 51. The microquartz blanket is covered with a refrasil cloth and retained in position by a perforated stainless steel screen.

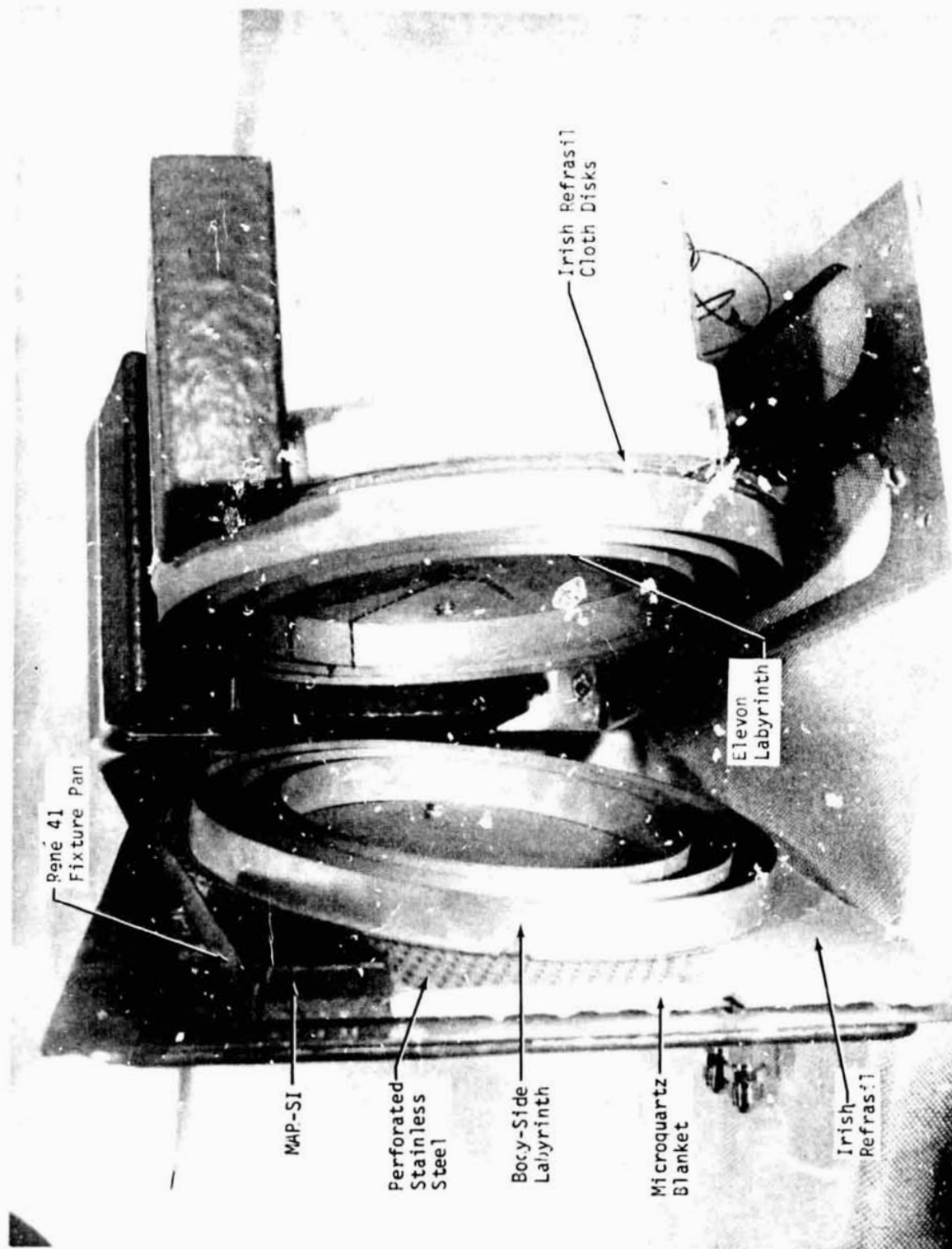


Fig. 51 Labyrinth-Sealed End Gap Model

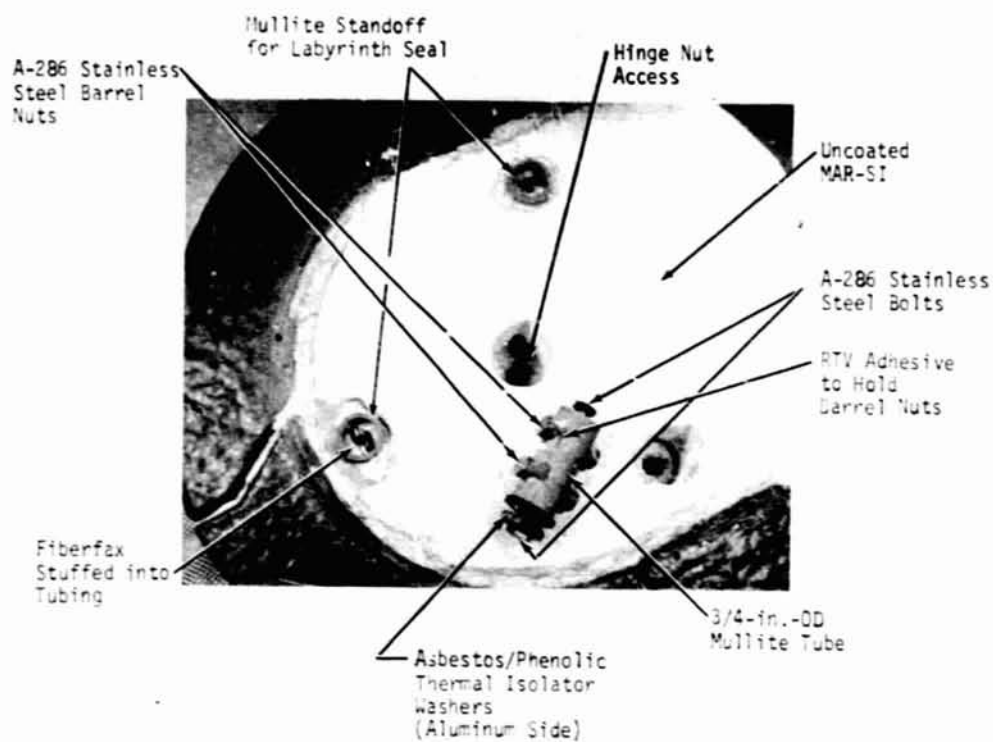


Fig. 52 Labyrinth Model Showing Standoff Hardware and Insulation



Fig. 53 Labyrinth Installation Showing Refrasil Wiper Seal

Figure 54 shows the assembled labyrinth-sealed test model. The rear closure has been modified because of the labyrinth. A threaded-steel rod inside a mullite tube holds the side plates together, and a local asbestos/phenolic bulkhead closes the opening above the tube. The backside of the elevon is protected with SLA 220 ablator, just as in the first model.

Unsealed End Gap Model - The unsealed end gap model is shown in Figure 55. The MAR-SI bonded to the elevon-end closure rib is made up of four pieces 2 in. thick. Note the SLA 220 on the backside of the elevon and the asbestos/phenolic closure bulkhead. The round MAR-SI plug shown at the centerline of the hinge is for access to the hinge nut.

The $\frac{1}{2}$ -in. MAR-SI disk, representing the body side of the model, is bonded to an aluminum plate that was attached to the water-cooled copper side plate by three studs and nuts. The strain isolator for the $\frac{1}{2}$ -in. MAR-SI disk stops approximately 2 in. from the edges, and the resultant gap was filled with Irish Refrasil cloth and fiberfax.

Figure 56 shows the configuration of the assembled model. The end gap is $\frac{1}{2}$ in. wide. Note the large slotted hole in the upper aluminum frame that allows unrestricted flow through the gap.

The three models were instrumented with thermocouples, calorimeters, and pressure transducers. The thermocouples in the aluminum structure were installed by peening; those in the Rene' 41 were welded in place. Probe-type thermocouples were installed in the MAR-SI, with the probe extending to within $\frac{1}{8}$ in. of the external surface.

Two calorimeters were installed on the wing shelf, directly opposite the cove gap opening.

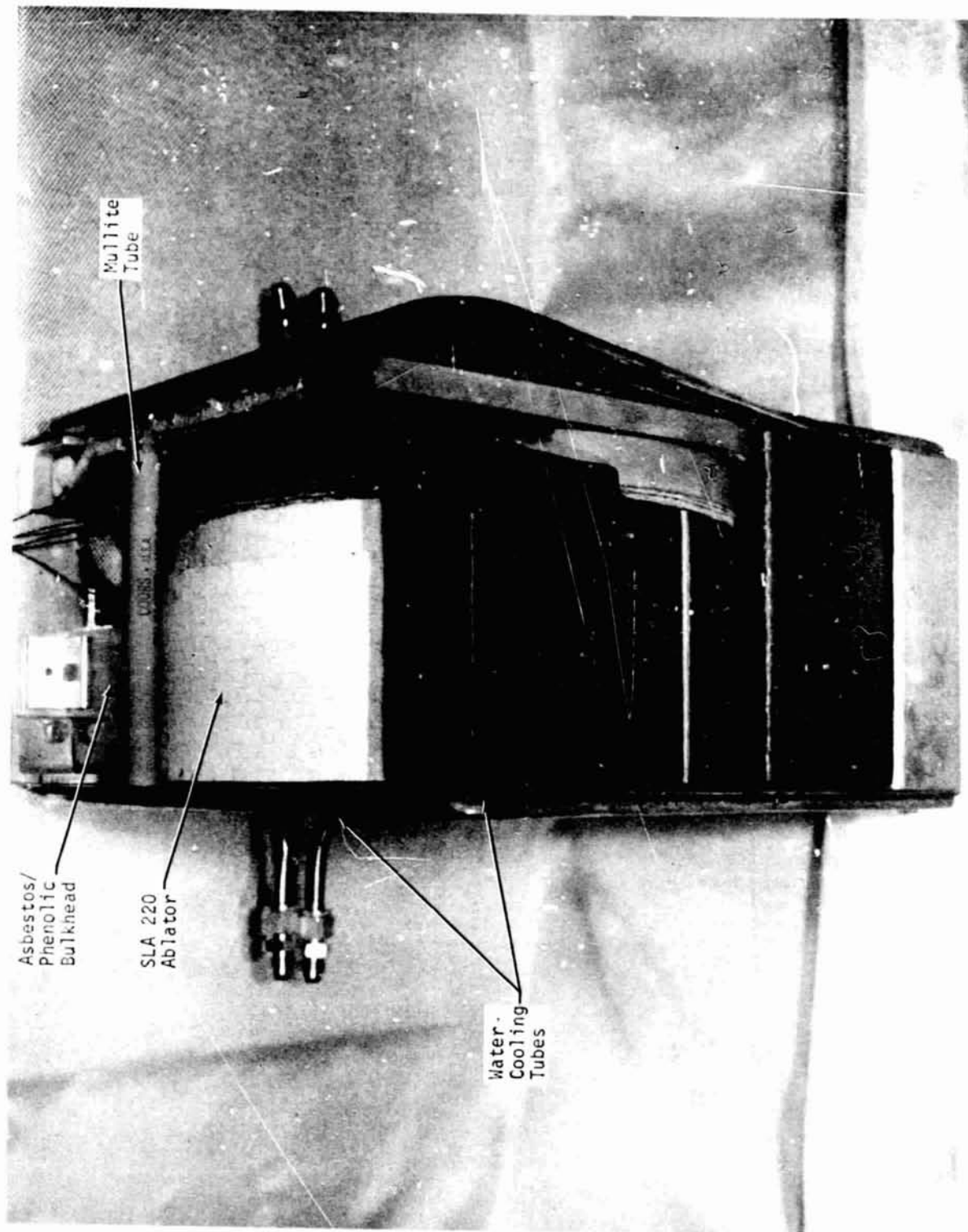


Fig. 54 Labyrinth Seal Model after Assembly

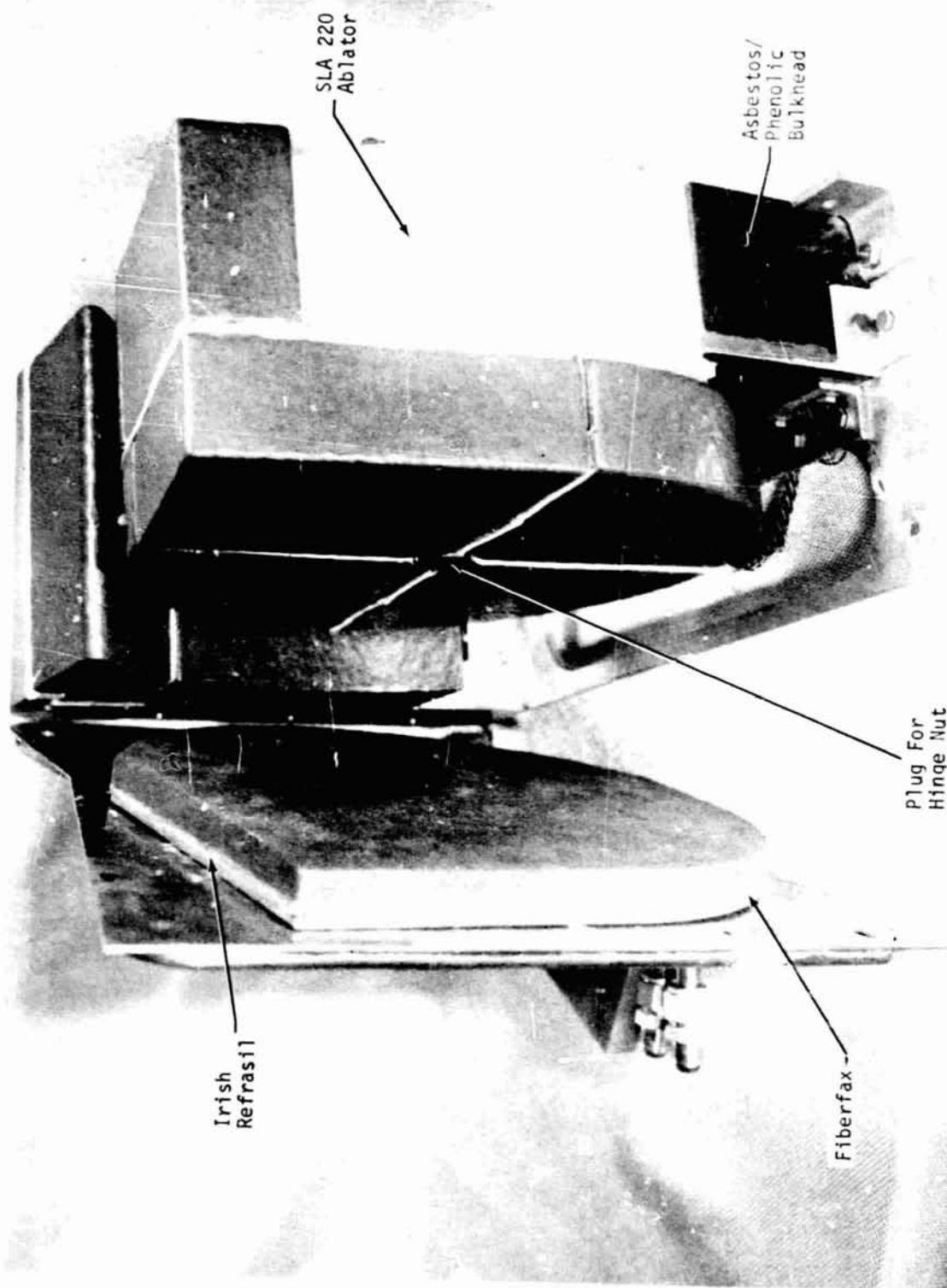


Fig. 55 Unsealed Gap Model Showing Interior Details

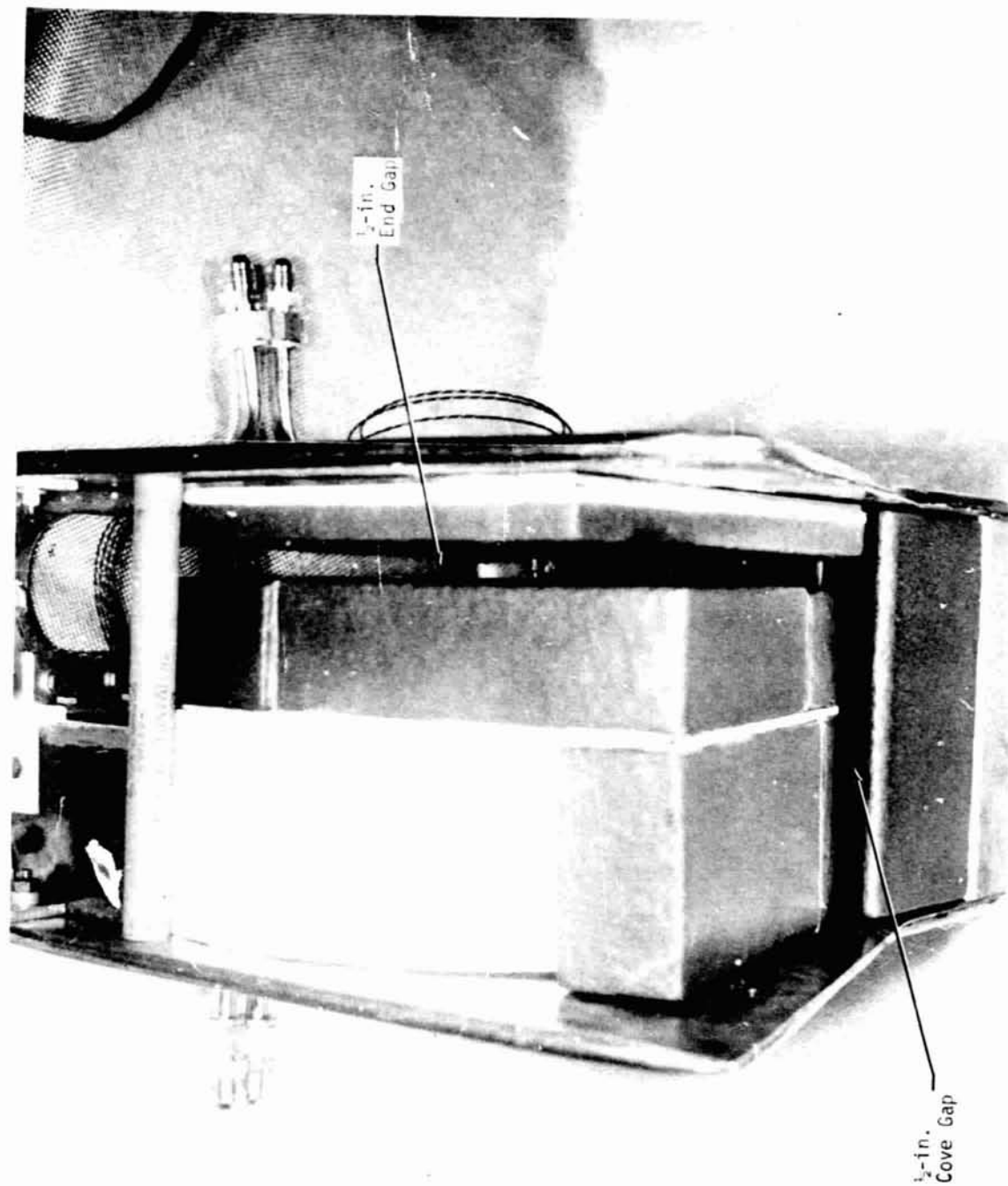


Fig. 56 End Gap Model after Assembly

TASK VI - TEST

PHASE I, "ENVIRONMENT DEFINITION" TEST (Ref 8)

The objective of the Phase I environmental test was to acquire aerodynamic heating data for a representative hinge line gap for a Space Shuttle control surface, and specifically, to determine the effects of width, leakage through the gap, control surface deflection, and end gap effects on the convective heating environment. Test conditions were selected to simulate portions of the expected full-scale Shuttle environment.

Test Description

All tests were conducted in Cell 1 of Martin Marietta's plasma arc facility. A Model F-5000 Thermal Dynamics gas and magnetically stabilized dc arc generator was used to provide the range of operating conditions shown in Figure 57. All tests were run using a conical 10-in exit diameter nozzle with a 50:1 area ratio. The test medium was a mixture of nitrogen and oxygen, simulating air. The arc was exhausted into a test chamber 48 in. in diameter and 12 ft long. A five-stage steam ejector system provided the necessary vacuum capability to operate the nozzle at its ideal expansion pressure.

The Phase I test model was a full-scale section of a typical structure/control surface concept (see Fig. 58). Tests were conducted for three control surface positions (10° down, 0°, and 10° up), as well as for gap widths of 0.25, 0.5, and 0.75 in. Figure 59 depicts a cross-section of the test model and shows adjustment points for accommodating the various gap widths and elevon positions.

The Phase I model was positioned in the plasma arc using a remote-controlled mechanism that allowed the model to be rapidly inserted into or retracted from the stream. A support arm was mounted on the side of the model and connected with the facility's remote-controlled arm. A side mounting was used to provide a vertical test position and to allow the test surface and gap to be viewed through a side window of the test chamber.

Sixteen calorimeters, 6 pressure transducers, and 3 thermocouples

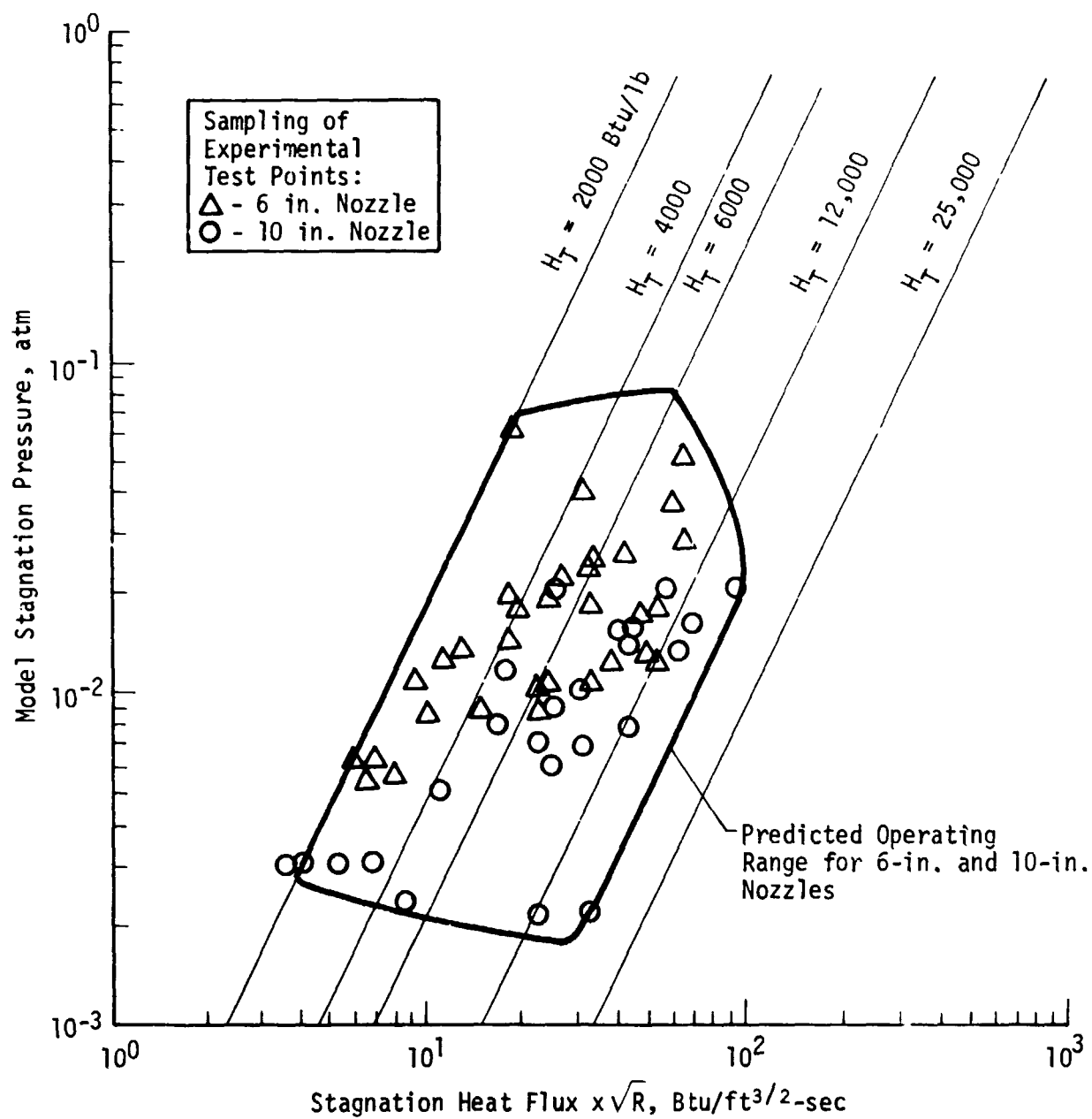


Fig. 57 Thermal Pressure Simulation Capability of Plasma-Arc F-5000 Arc Generator with 6-in. and 10-in. Nozzles (Cell 1)

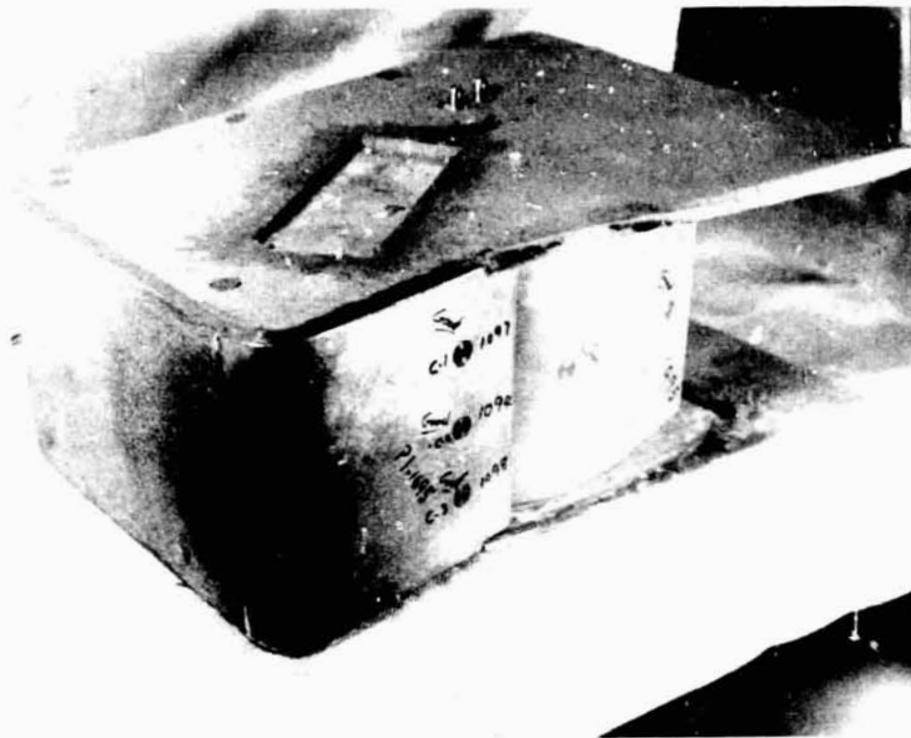


Fig. 58 Phase I Environmental Test Model

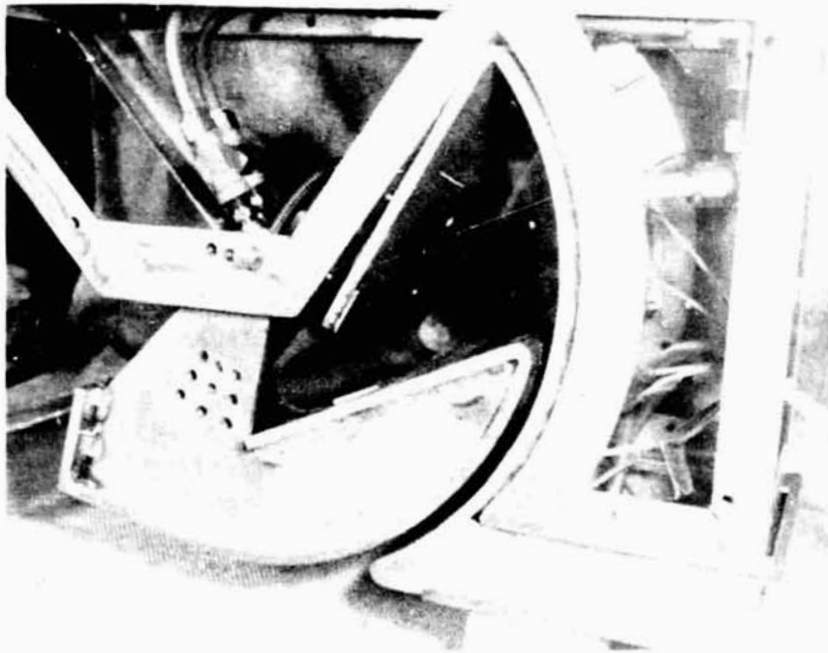


Fig. 59 Cross-Section of Phase I Environmental Test Model

were used to determine the external and internal aerothermal environment surrounding the model (see Fig. 60 and Table 6). Supplemental temperature measurements were made on the aluminum skin of the model to monitor the potential of overheating the structure.

The heat flux sensors were Thermogage, Inc., Gardon calorimeters mounted in interchangeable, miniature threaded modules that were screwed into the water-cooled shell of the model. Several different ranges were used to maximize measurement accuracy; namely, 0 to 20, 5, 1, and 0.1 Btu/ft²-sec. The highest range (0-20) was used on the external surface, where undeflected control surface heating rates of 5 to 10 Btu/ft²-sec were measured. The remaining ranges were used inside the gap and were selected on the basis of the expected environmental severity.

The calorimeters had an accuracy of $\pm 2\%$ of full scale, and each sensor was individually calibrated by the manufacturer in a resistance-heated black-body furnace. Calibration data are provided for each sensor as a continuous curve (generally linear) covering the full sensor range.

Static pressure measurements were made using absolute pressure transducers manufactured by Set Systems, Inc. Instruments with a 0-to-0.5-psia range were used for locations P1 and P2, whereas a 0-to-0.1-psia range was used at locations P3 to P6.

Chromel-alumel wire was used for all thermocouples. Compensating thermocouple extension wire led to a Research, Inc., constant-temperature-reference junction compensator box that maintained the thermocouple's cold junction at $150 \pm 0.5^\circ\text{F}$.

Conditions for the environment definition test were selected to simulate the aerothermal environment expected over the elevon hinge region during flight. Representative time-histories of several of these flight environmental parameters are shown in Figure 61. The shear Reynolds number plotted in this figure was suggested by Donaldson (Ref 5) to be the most significant parameter defining the gap flow characteristics, and is defined as

$$\text{Re}_\tau = \frac{V_\tau \rho_w b}{\mu_w},$$

where

$$V_\tau = \sqrt{\tau/\rho_w}$$

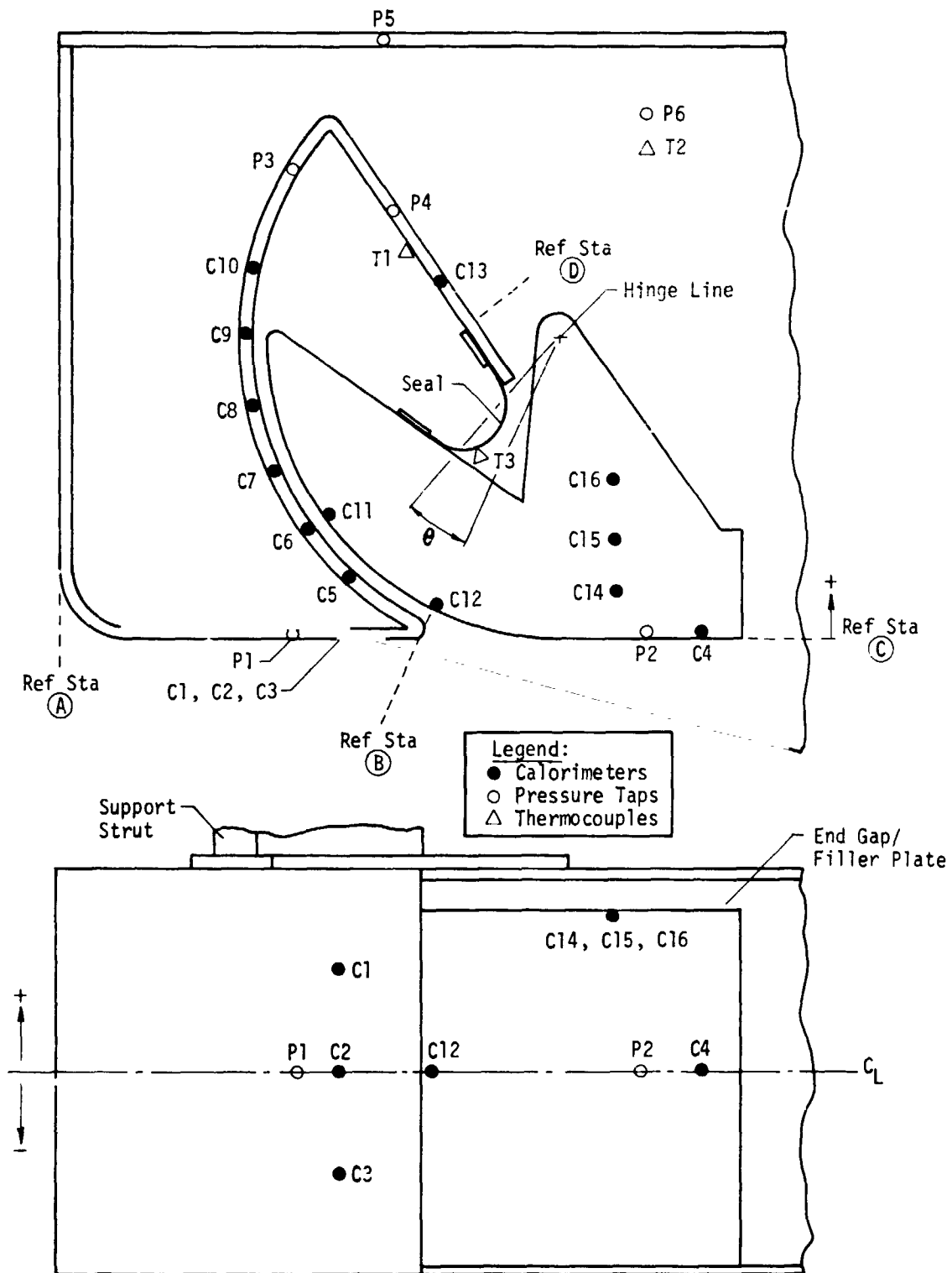


Fig. 60 Instrumentation Locations for the Phase I Environmental Test Model

Table 6 Instrumentation Locations for the Phase I Environmental Test Model

Measurement		Location (For 0.25-in. Gap Width, 0° Control Surface Position)			
No.	Type	Description	Reference Station	Distance from Ref Station	Lateral Location
C1 C2 C3	Calorimeter	Windward Portion of Wing Section ↓	Front Face (A) ↓	5.75 in. ↓	2.0 in. Centerline -2.0 in.
C4		Windward Portion of Control Surface	Front Face (A)	12.85 in.	Centerline
C5 C6 C7 C8 C9 C10		Wing Face of Hinge Line Gap ↓	Gap Entrance (E) ↓	16° (1.74 in.) 28° (3.05 in.) 40° (4.36 in.) 52° (5.67 in.) 64° (6.98 in.) 76° (8.29 in.)	Centerline ↓
C11 C12		Control Surface Face of Hinge Line Gap ↓	Gap Entrance (B) ↓	-3° (-0.31 in.) 28° (2.93 in.)	Centerline ↓
C13 C14 C15		End Face of Control Surface ↓	Windward Side of Control Surface (C) ↓	1.0 in. 2.0 in. 3.0 in.	3.25 in. ↓
C16		Forward of Wing/Seal Attachment	(D)	1.15 in.	Centerline
P1 P2	Pressure	Windward Portion of Wing Section Windward Portion of Control Surface	Front Face (A) ↓	4.55 in. 11.85 in.	Centerline ↓
P3 P4		Wing Face of Hinge Line Gap Forward of Wing/Seal Attachment	Gap Entrance (B) (D)	95° (10.4 in.) 2.70 in.	Centerline ↓
P5 P6		Inside Box Behind Seal Leeside Surface of Box	Front Face (A)	6.60 in.	-2.60 in.
T1 T2 T3	Thermocouple ↓	Forward of Wing/Seal Attachment inside Box Behind Seal On Back-side of Curtain Seal	(D) Front Face (A)	1.90 in. 13.0 in.	Centerline 3.0 in. Centerline

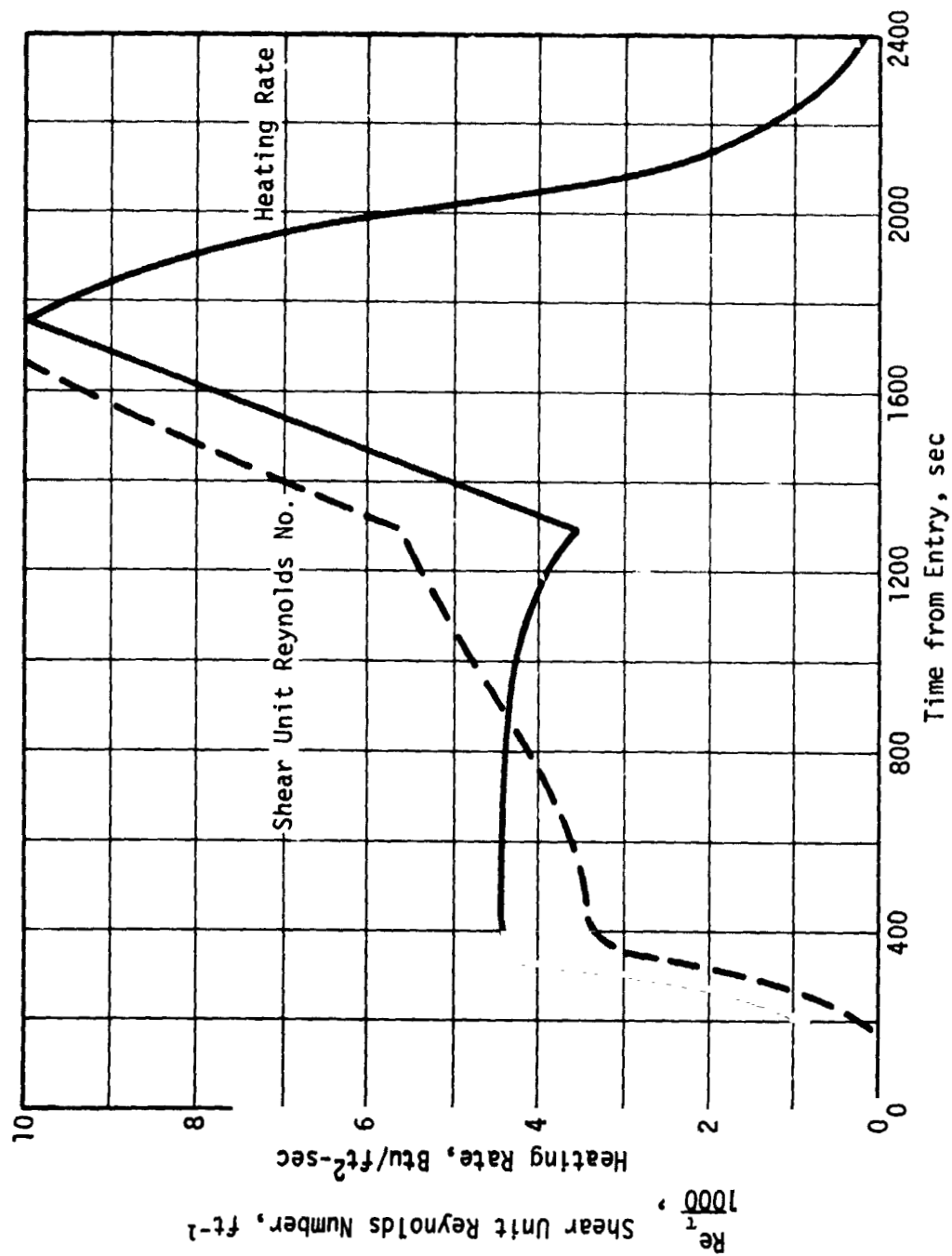


Fig. 61 Environmental History at Elevon Hinge Line for Full-Scale Shuttle

τ = Shear stress at the wall,

ρ_w = Air density at the wall,

b = Gap width,

μ_w = Dynamic viscosity at the wall.

The variation of Re_τ and q with the mass flowrate and stagnation enthalpy of the plasma arc is shown in Figure 62. Note that this figure was prepared using one-dimensional real gas nozzle flow relations to determine the exit conditions. Local flow properties on the surface of the model were determined by processing the flow through a normal shock and then expanding the flow isentropically to the pressure on an equivalent wedge. Heating rates were determined from Eckert's reference enthalpy relation, and the local shear stress was calculated using Reynolds' analogy.

Comparing Figures 61 and 62, it is seen that the plasma arc can simulate both the shear Reynolds number and the heating rate during the first 1000 sec of flight. Therefore, Test Condition 1 was selected as a representative point simulating this portion of the trajectory. Test Condition 2 was chosen to simulate the peak heating rate of 10 Btu/ft²-sec while maintaining the same unit shear Reynolds number of 4000/ft used in Test Condition 1. These two test conditions are summarized below.

Re_τ /ft	$\dot{q}$, Btu/ft ² -sec	Test Condition	Mass Flowrate, lb/sec	Stagnation Enthalpy, Btu/lb
4000	5	1	0.060	2800
4000	10	2	0.035	5850

These test conditions result in the following properties of the plasma arc stream.

Test Condition	Mach No. at Nozzle Exit	Mach No. at Model Surface	Plenum Pressure, atm	Pitot Pressure, atm	Total Arc Temperature, °F
1	4.17	1.30	0.445	0.0163	5900
2	4.33	1.29	0.357	0.0124	9560

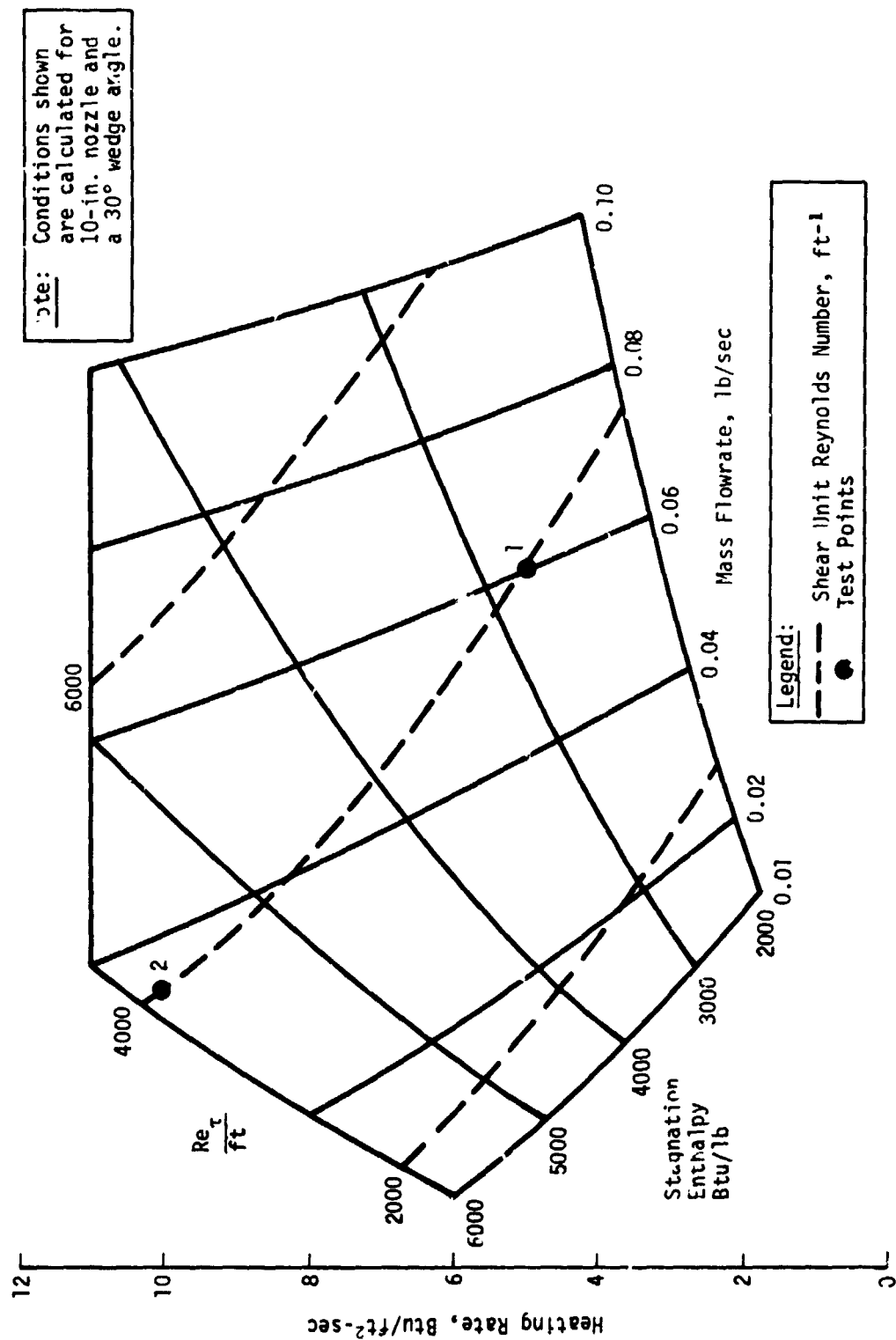


Fig. 62 Plas ϵ Simulation of Heating Rate and Shear Unit Reynolds Number

The plasma arc facility was calibrated to determine the input power and gas flowrate needed to produce the two test conditions specified above. The total enthalpy was determined by the energy balance method, where the measured power input, system losses, and total gas mass flow are used to solve the equation:

$$H_t = \frac{\text{Power in} - \text{Losses}}{\text{Gas Mass Flow}}$$

Test conditions were calibrated using an 8-in. by 12-in. wedge holder with an aluminum plate mounted at an angle of attack of 30°. Side plates were incorporated on the wedge so that it duplicated the external geometry of the gap model. Three Gardon calorimeters were installed in a lateral line at the location of the control surface gap and the input power was then varied to give the required heat fluxes for the two test conditions. The center calorimeter was used as the control instrument for this procedure.

Once the test points were established, several runs were made to establish the repeatability of the data. Following this calibration procedure, the phase I gap seal model was installed in the cell. Test runs were then made for each of the various model configurations. Each test run lasted approximately 30 sec. Data were recorded on strip chart recorders, and data reduction was accomplished using the strip chart millivolt values and the appropriate calibration constants.

A total of 24 runs were made during the Phase I test. A summary of the configuration variables for these runs is given in Table 7. Note that a curtain seal was installed in 17 of these runs, and that three runs were made for the model with a 1/2-in. end gap. Most of the tests were run with a 1-in.² orifice on the leeward side of the model. Only those models without the curtain seal utilized different-sized orifice plates.

The initial tests were conducted with the ends of the curtain sealed with an RTV compound to eliminate all leakage paths across the seal. The results of these tests were then compared with those of subsequent tests in which the ends of the curtain simply butted against the side plates of the model. The differences noted were judged to be within the data scatter of the test so all of the remaining tests were performed without the curtain ends sealed, since this allowed much easier and faster model changes.

Table 7 Run Summary for Phase I Environmental Tests

Facility Run No.	Gap Width, in.	Control Surface Position	Curtain Seal	Curtain Seal with Ends Sealed	End Gap	Test Condition	Orifice Area, in. ²
17058	0.25	0°	Yes	No	No	1	1
17047	0.25	10° Up	Yes	No	No	1	1
17048	0.25	10° Down	Yes	No	No	1	1
17060	0.25	10° Down	Yes	No	Yes	1	1
17063	0.25	10° Down	No	No	No	1	2.5
17064	0.25	0°	No	No	No	1	2.5
17065	0.25	10° Up	No	No	No	1	2.5
17039	0.50	0°	Yes	Yes	No	1	1
17040	0.50	0°	Yes	Yes	No	2	1
17043	0.50	0°	Yes	No	No	1	1
17059	0.50	0°	Yes	No	No	1	1
17049	0.50	10° Up	Yes	No	No	1	1
17050	0.50	10° Down	Yes	No	No	1	1
17056	0.50	10° Down	No	No	No	1	5
17069	0.50	10° Down	No	No	No	1	1.0
17070	0.50	10° Down	No	No	No	1	0.20
17061	0.50	10° Down	Yes	No	Yes	1	1
17044	0.75	0°	Yes	No	No	1	1
17045	0.75	0°	Yes	No	No	1	1
17046	0.75	0°	Yes	No	No	2	1
17051	0.75	10° Up	Yes	No	No	1	1
17052	0.75	10° Down	Yes	No	No	1	1
17062	0.75	10° Down	Yes	No	Yes	1	1
17072	0.75	10° Down	No	No	No	1	7.5

A similar assessment was made to determine the effect of the test condition on the test results. Based on this analysis, Test Condition 1 was selected for the majority of the testing.

Test Results

Table 8 summarized the pressures recorded during the Phase I test. Note that the values shown are the absolute levels recorded at each gage.

As can be seen in the table, the nominal cell pressure during the test was 0.011 psia. One of the trends noted in the data was that the pressure at P2 was consistently higher than the value recorded at P1, even for a control surface deflection angle of 0°. This was unexpected for the null position and was initially thought to be an erroneous reading. Further evaluation, however, has led us to conclude that the P2 reading is correct and was apparently caused by a shock reflection from within the jet impinging on the downstream edge of the model.

All the calorimeter readings within the control surface gap have been normalized with respect to the external heating level recorded at location C2. Table 9 presents gap calorimeter data normalized in this manner for measurements C5, and C7 to C13. Calorimeter C6 was damaged during installation and had to be replaced with a high-range instrument that was not sensitive enough to record the low heating levels in the gap. As a result, the heating data for C6 have been deleted from this table.

Table 8 Pressure Data for Phase I Environmental Tests

Facility Run No.	P1, psia	P2, psia	P3, psia	P4, psia	P5, psia	P6, psia
17058	0.051	0.114	0.053	0.056	0.0135	0.021
17047	0.048	0.059	0.050	0.049	0.0076	0.0076
17048	0.043	0.096	0.072	0.074	0.0081	0.0102
17060	0.041	0.109	0.044	0.045	0.0090	0.023
17063	0.041	0.101	0.016	0.011	0.0076	0.015
17064	0.042	0.097	0.011	0.009	0.0088	0.0117
17065	0.04	0.075	0.0133	0.0122	0.0103	0.0146
17059	0.046	0.085	0.050	0.052	0.0085	0.0117
17039	0.048	0.051	0.051	0.052	0.0072	0.0087
17040	0.036	0.052	0.034	0.035	0.0048	0.0041
17043	0.046	0.083	0.051	0.054	0.0075	0.0094
17049	0.046	0.054	0.049	0.050	0.0075	0.0076
17050	0.046	0.096	0.072	0.073	0.0079	0.010
17066	0.046	0.150	0.037	0.032	0.0109	0.030
17069	0.041	0.120	0.047	0.047	0.0098	0.042
17070	0.044	0.101	0.075	0.076	0.0098	0.046
17061	0.046	0.109	0.049	0.049	0.0086	0.021
17044	0.047	0.078	0.056	0.055	0.0081	0.0097
17045	0.043	0.080	0.054	0.056	0.0069	0.0061
17046	0.031	0.062	0.035	0.040	0.0085	0.0103
17051	0.046	0.049	0.054	0.056	0.0091	0.0133
17052	0.046	0.101	0.070	0.072	0.0094	0.036
17062	0.046	0.119	0.049	0.049	0.0081	0.008
17072	0.046	0.119	0.022	0.018	0.0081	0.008

Table 9 Cove Gap Calorimeter Data for Phase I Environmental Tests

Facility Run No.	C2, Btu/ft ² -sec	C5/C2	C7/C2	C8/C2	C9/C2	C10/C2	C11/C2	C12/C2	C13/C2
17058	5.05	0.050	0.010	0.0070	0.0060	0.0040	0.030	0.228	
17047	5.23	0.0258		0.0090	0.0080	0.0030	0.010	0.330	0.0067
17048	4.86	0.128	0.018	0.020	0.015	0.0103	0.0216	0.178	0.0040
17060	4.77	0.252	0.105	0.094	0.079	0.058	0.252	0.161	0.015
17063	5.24	0.199	0.128	0.053	0.050	0.040	0.027	0.181	0.016
17064	5.05	0.103	0.111	0.032	0.038	0.029	0.019	0.380	0.004
17065	5.01	0.100	0.100	0.032	0.035	0.026	0.040	1.04	0.008
17059	5.14	0.091	0.037	0.028	0.023	0.0186	0.0372	0.224	0.0055
17039	4.77	0.067	0.026	0.0117	0.0123	0.0082	0.0319	0.161	0.0096
17040	10.3	0.025	0.014	0.0073	0.0105	0.0058	0.015	0.092	0.010
17043	5.61	0.072	0.018	0.009	0.009	0.006	0.028	0.205	0.0065
17049	5.42	0.076	0.041	0.035	0.032	0.023	0.089	0.354	0.0124
17050	5.42	0.153	0.083	0.060	0.048	0.037	0.053	0.071	0.011
17066	4.68	0.406	0.278	0.193	0.203	0.197	0.225	0.206	0.065
17069	4.86	0.258	0.124	0.138	0.140	0.111	0.114	0.198	0.021
17070	4.86	0.268	0.114	0.116	0.103	0.074	0.062	0.075	0.015
17061	4.86	0.288	0.113	0.086	0.062	0.051	0.051	0.158	0.0226
17044	4.86	0.150	0.057	0.039	0.026	0.020	0.037	0.197	0.022
17045	5.52	0.122	0.040	0.0366	0.0312	0.0226	0.0243	0.208	0.0217
17046	10.4	0.070	0.024	0.018	0.018	0.018	0.033	0.277	0.016
17051	5.14	0.061	0.065	0.084	0.047	0.057	0.031	0.261	0.026
17052	5.14	0.161	0.074	0.084	0.061	0.078	0.028	0.75	0.021
17062	4.86	0.34	0.062	0.057	0.048	0.060	0.041	0.156	0.029
17072	5.05	0.198	0.149	0.190	0.156	0.119	0.129	0.265	0.051

PHASE II, "SEAL CONCEPTS EVALUATION" TESTS (Ref 8)

The Phase II tests had two primary objectives. The first objective was to expose candidate seal concepts and flightweight structures to a simulated Space Shuttle entry environment and monitor the temperature response during the test pulse in order to demonstrate the ability of the seals to limit the internal cavity temperatures to their design values. Several ancillary environmental measurements were also included in the test to reaffirm the results from the Phase I tests and to determine the radiation contribution of the hot gap surfaces to the overall heating environment within the cavity. The structure and insulation were sized to withstand the thermal environment established during the Phase I tests, and thermocouples were installed on the seal and surrounding structure.

The second objective of the Phase II test was to evaluate the effect of an end gap in raising the temperature of the curtain seal and surrounding structure. This was accomplished by testing three different models. The first model represented a full-scale section of the wing/elevon cove gap with a curtain seal, and was used to obtain baseline data. The second model depicted a portion of a wing/elevon cove gap with a curtain seal installed, and also had an open, $\frac{1}{4}$ -in. end gap. The third model was identical to the second model except that a labyrinth seal was installed in the end gap to reduce the flow into the area on the backside of the seal and to the unprotected internal structure.

Test Description

The Phase II tests were also conducted in Cell 1 of Martin Marietta's plasma arc facility. The torch, nozzle, test medium, and steam ejector system were identical to those used for the Phase I tests.

The test models were full-scale sections of typical structure control surface concepts. The basic model was 8 by 15 by 20 in. and was designed to house a different kit for each design concept.

This model was the same size as the model used in the Phase I test fixture. The sides, front, and leading edge of the model were made of copper and had copper tubes for water-cooling the structure. The configuration kits for the simulated elevon and end gap structure were constructed of flightweight (0.08 gage) aluminum that was thermally protected by a Martin-developed HRSI material referred to as MAR-SI.

All models were tested with the control surface in the 10° down position and with a 0.50-in. cove gap. The end gap model, both with and without the labyrinth seal, provided a 0.50-in. end gap.

A flexible curtain seal was installed in the cove gap for all tests. The curtain seal was a composite of glass cloth-reinforced, methyl-phenyl silicone rubber fabric, and the "labyrinth seal" was constructed from René 41. Photographs of each of the three models are shown in Figures 63 to 65, and additional details are shown in Figure 66.

A support arm was mounted on the side of the basic Phase II test model to connect it with the facility's remote-controlled arm. As in the Phase I tests, the side mounting provided a vertical test position and allowed the test surface and gap to be viewed through the side window of the test chamber.

Figure 67 shows the unsealed end gap model installed in the test facility. This photograph was taken after the test, and the model shows some of the effects of the test exposure; namely, small cracks in the MAR-SI coating and a slight displacement of the glass cloth filler that was placed in the MAR-SI tile gaps.

The following figures and tables define the types of instrumentation and the locations used for each of the Phase II test models:

Wing/Elevon Gap Model - Table 10 and Figure 68;
Unsealed Elevon End Gap Model - Table 11 and Figure 69;
Sealed Elevon End Gap Model - Table 12 and Figure 70.

Eleven thermocouples (chromel-alumel devices with type "K" wire), two static pressure transducers (Setra Systems, Inc., absolute pressure transducers), and two heat flux sensors (Thermogage, Inc., Gardon calorimeters) were used on the wing/elevon gap model. On both end gap models, additional instrumentation was used to determine temperatures in and around the end gap: besides having two pressure transducers and two heat flux sensors on each model, there were 18 thermocouples on the sealed end gap model and 16 thermocouples on the unsealed end gap model. Table 13 provides a cross reference showing the thermocouple locations that were common to the various models.

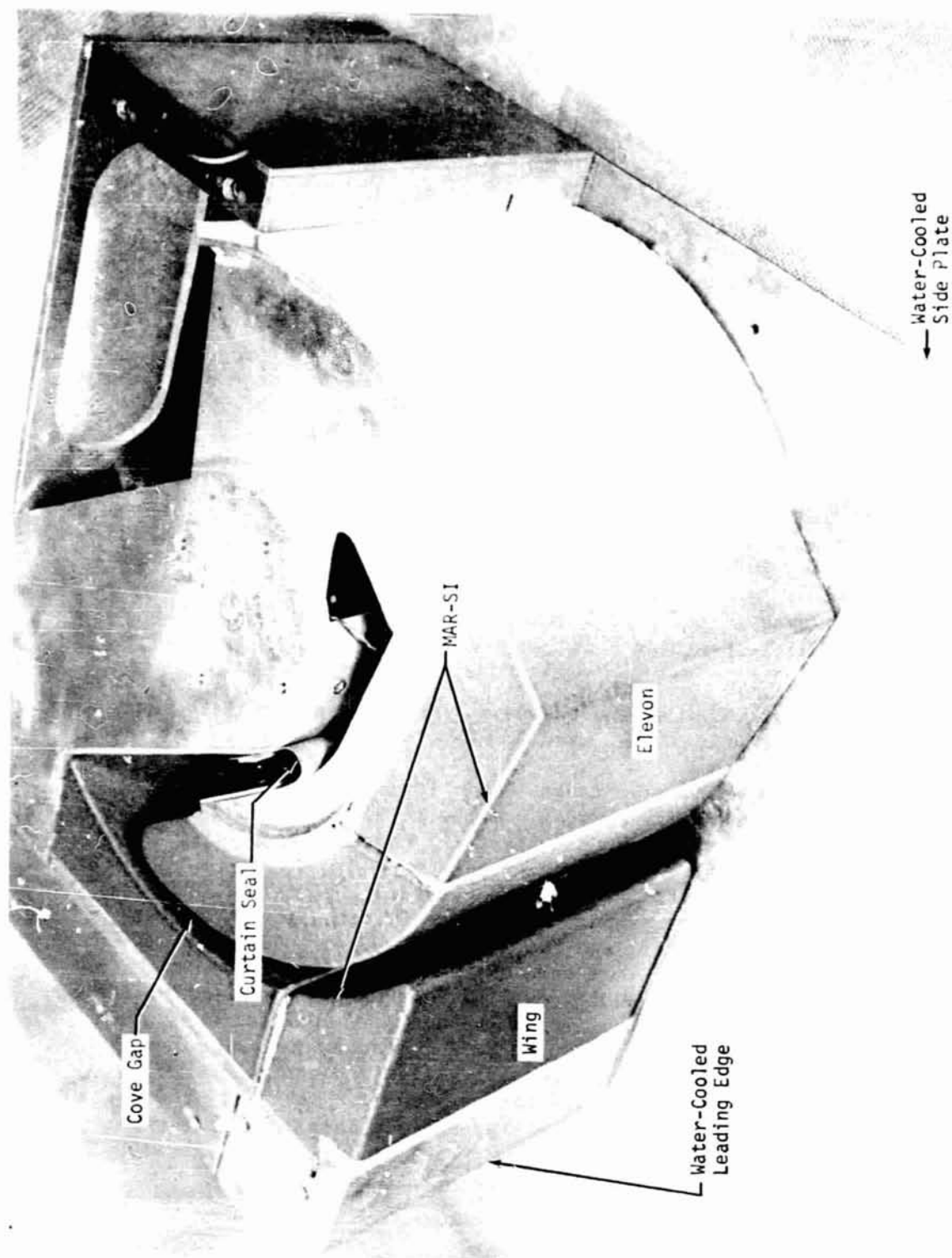


Fig. 63 Elevon/Wing Cove Gap Model

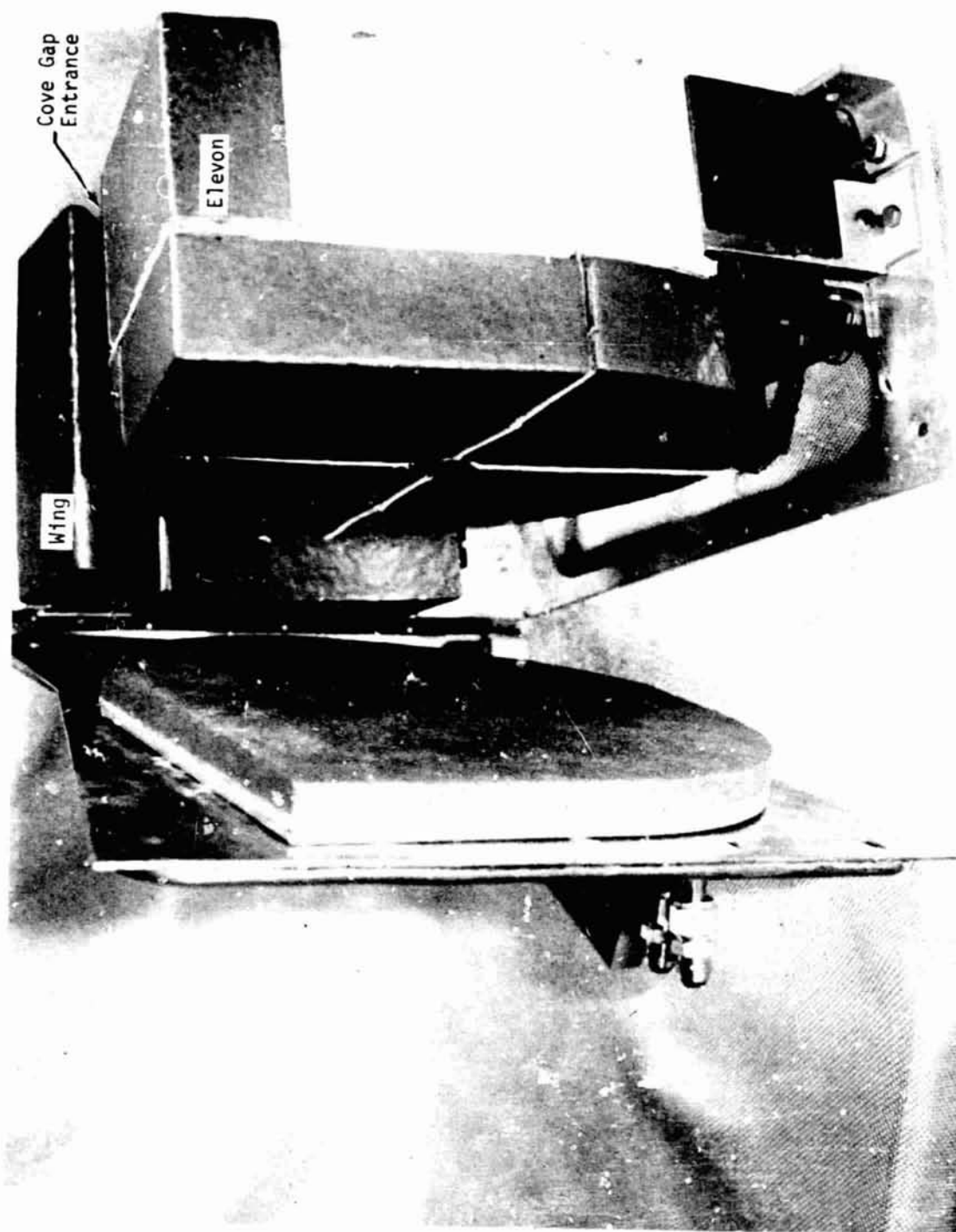


Fig. 64 End Gap Model with No End Seal

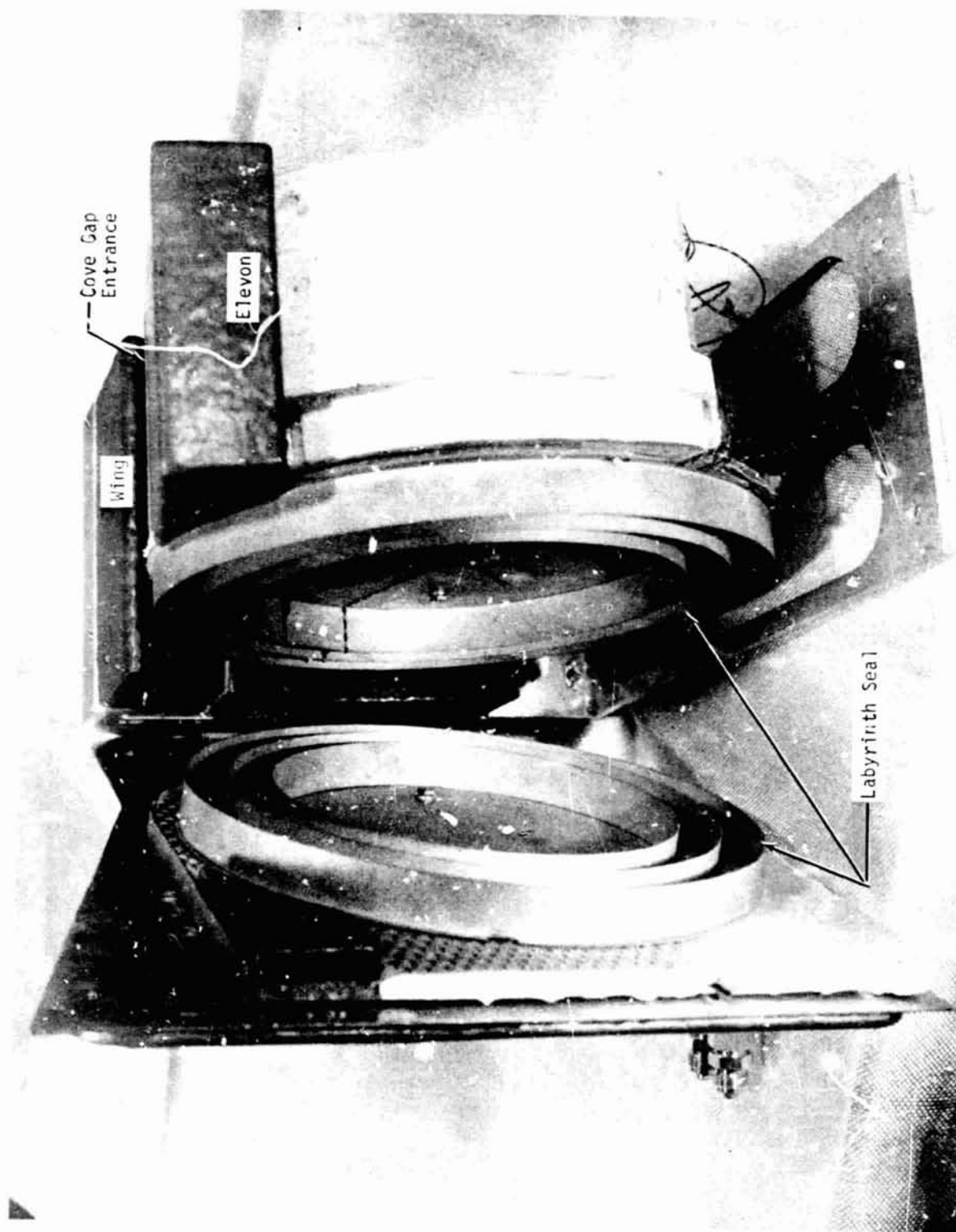
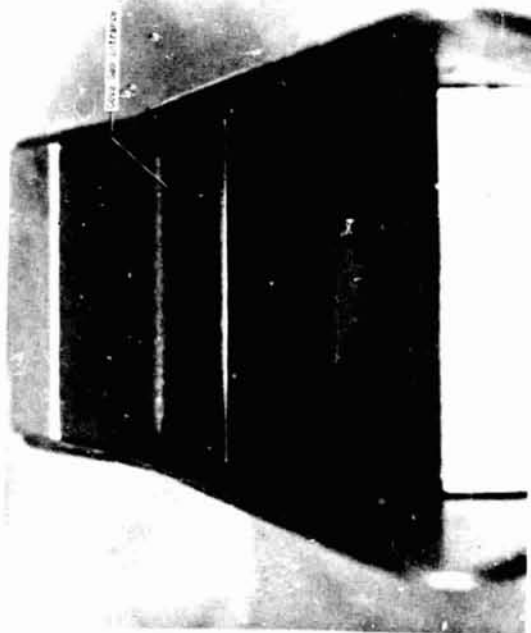
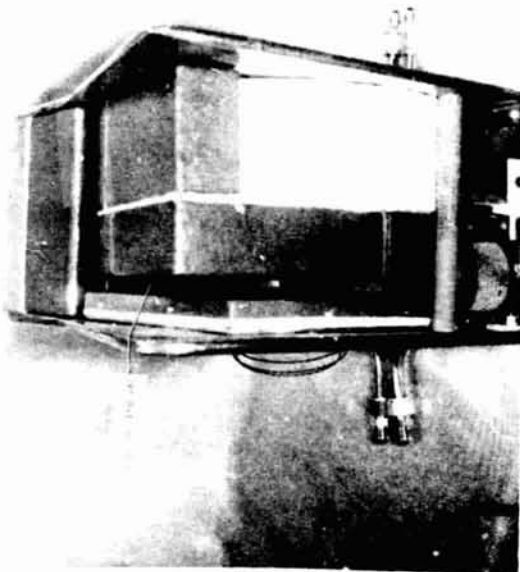


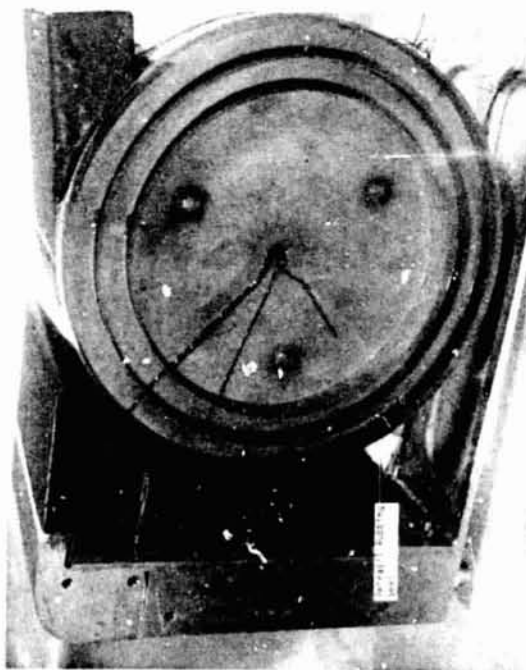
Fig. 65 End Gap Model with Labyrinth Seal



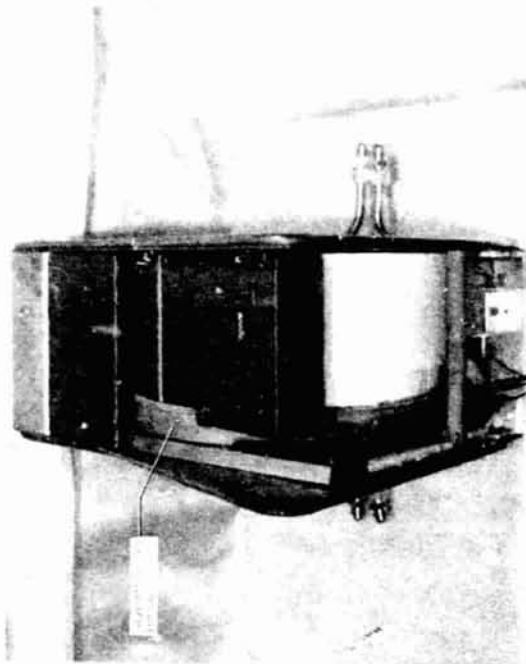
(a) Cove Gap Entrance - Wing/
Elevon Model



(b) View of End Gap - End Gap Model
with No End Seal



(c) Elevon Portion of Labyrinth Seal



(d) Assembled Labyrinth Seal Model

Fig. 66 Photographs of Various Phase II Test Models

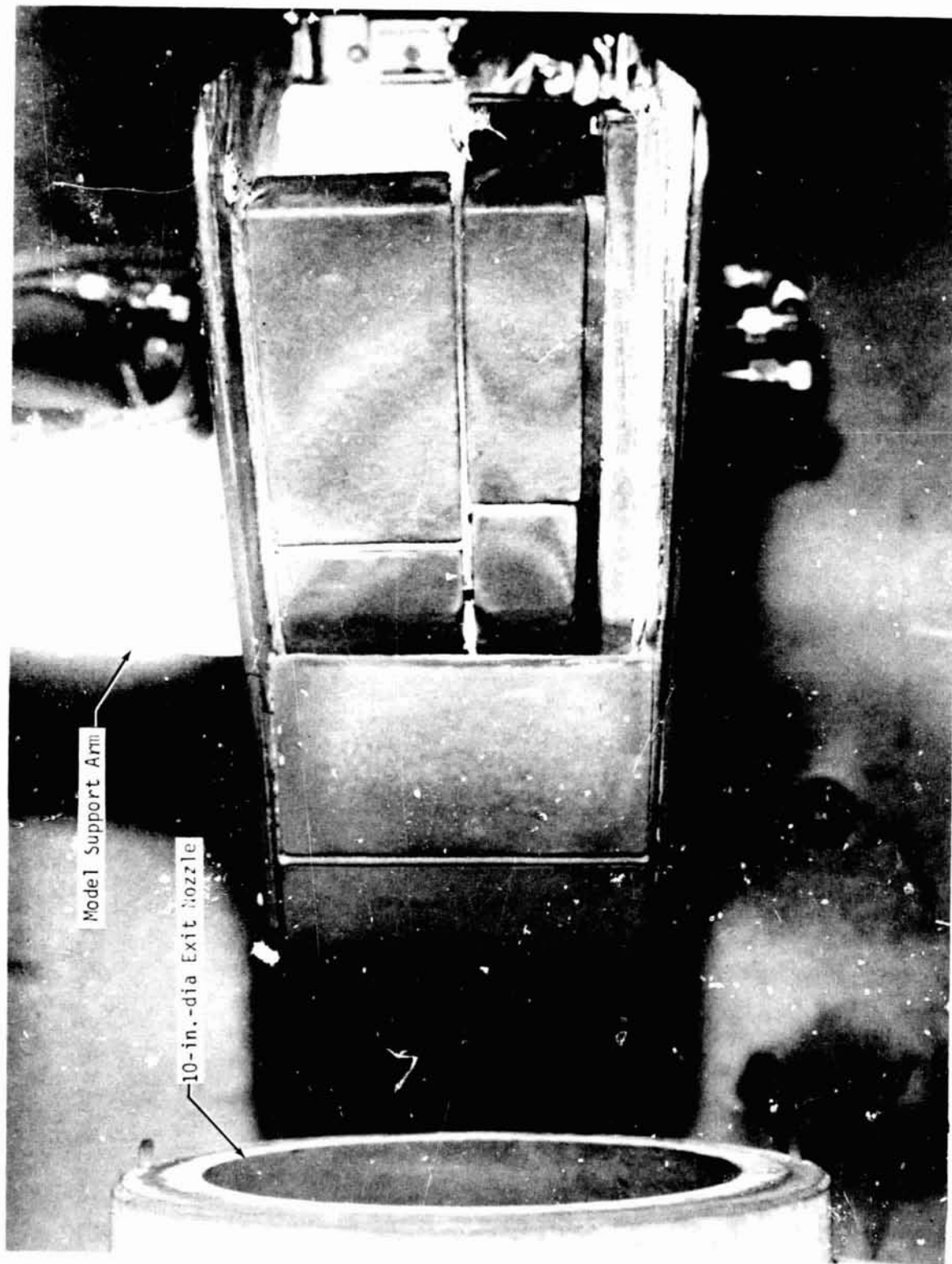


Fig. 67 Phase II End Cap Model Installed in Test Facility

Table 10 Instrumentation Locations for the Phase II Wing/Elevon Gap Model Shown in Figure 68

Measurement		Location*	
No.	Type	Description	Inboard Location from Near-Side Edge of Model, in.
T1	Thermocouple	Inside Gap Cavity on Wing Structure	1.4
T2	Thermocouple	Inside Gap Cavity on Wing Structure	5.0
T3	Thermocouple	Inside Gap Cavity on Elevon Structure	1.4
T4	Thermocouple	Insulated Elevon Structure (in gap area)	1.4
T5	Thermocouple	Near Surface of Insulation on Elevon (in gap area)	1.4
T6	Thermocouple	Insulated Elevon Structure (windward area)	1.4
T7	Thermocouple	Aft Surface of Curtain Seal	1.4
T9	Thermocouple	Near Surface of Insulation on Elevon (windward area)	1.4
T39	Thermocouple	Near Surface of Insulation on Wing Side of Cove Gap	1.4
T40	Thermocouple	Near Surface of Insulation on Wing Side of Cove Gap	1.4
P1	Pressure Port	Inside Gap Cavity on Wing Structure	1.4
P2	Pressure Port	Inside Model behind Curtain Seal	-
C1	Calorimeter	Inside Gap Cavity on Wing Structure	1.0
C2	Calorimeter	Inside Gap Cavity on Wing Structure	1.8

*Instrumentation locations are shown approximately to scale below.

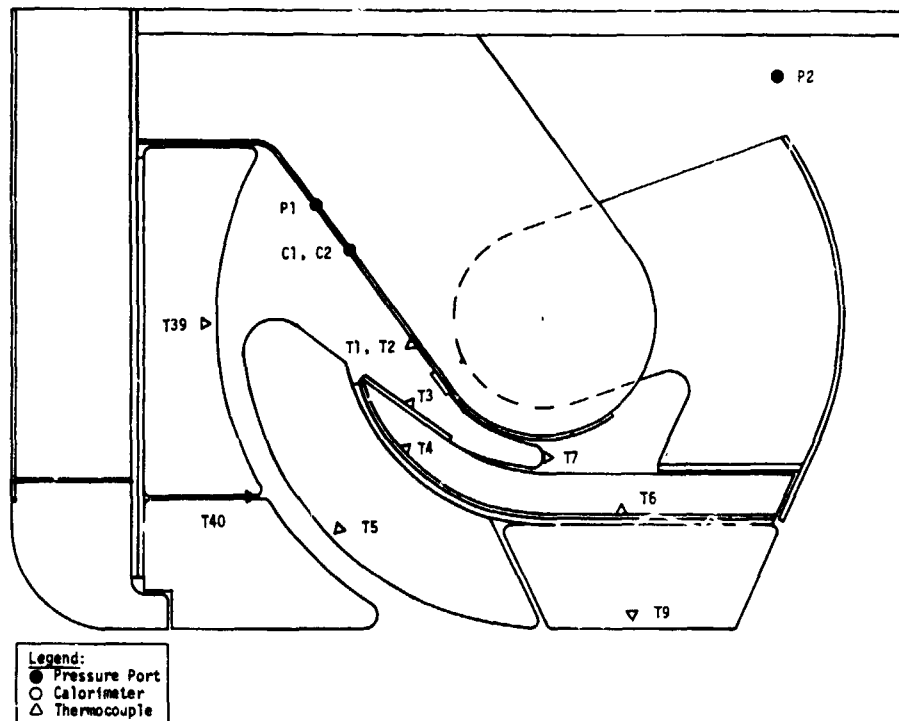


Fig. 68 Instrumentation Locations for the Phase II Wing/Elevon Cove Gap Model

Table 11 Instrumentation Locations for the Phase II Unsealed Elevon End Gap Model Shown in Figure 69

Measurement		Location*	
No.	Type	Description	Inboard Location from N. r Side Edge of Model, in
T11	Thermocouple	Inside Gap Cavity of Wing Structure	1.4
T26	Thermocouple	Aft Surface of Curtain Seal	1.4
T27	Thermocouple	Inside Gap Cavity of Elevon Structure	1.4
T28	Thermocouple	Insulated Elevon Structure (in gap area)	1.4
T29	Thermocouple	Near Surface of Insulation on Elevon (in gap area)	1.4
T30	Thermocouple	Insulated Elevon Structure (windward area)	1.4
T31	Thermocouple	Near Surface of Insulation on Elevon (windward area)	1.4
T32	Thermocouple	Near Surface of Insulation in End Gap	5.6
T33	Thermocouple	Backface Surface of Insulated Elevon Closeout Rib	3.4
T34	Thermocouple	Backface Surface of Insulated Elevon Closeout Rib	3.4
T35	Thermocouple	Backface Surface of Insulated Elevon Closeout Rib	3.4
T36	Thermocouple	Near Surface of Insulation in End Gap	5.6
T37	Thermocouple	Near Surface of Insulation in End Gap	5.6
T38	Thermocouple	Backface Surface of Insulated Elevon Closeout Rib	3.4
T39	Thermocouple	Near Surface of Insulation on Wing Side of Cove Gap	1.4
T40	Thermocouple	Near Surface of Insulation on Wing Side of Cove Gap	1.4
P2	Pressure Port	Inside Model Behind Curtain Seal	
P1	Pressure Port	Inside Gap Cavity of Wing Structure	1.4
C1	Calorimeter	Inside Gap Cavity of Wing Structure	1.0
C2	Calorimeter	Inside Gap Cavity of Wing Structure	1.8

*Instrumentation locations are shown approximately to scale below.

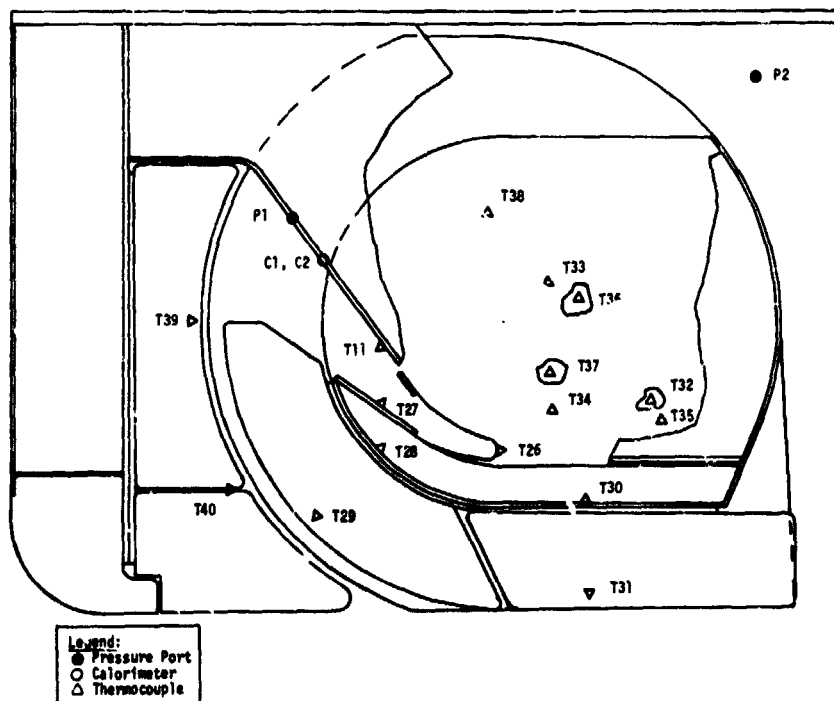
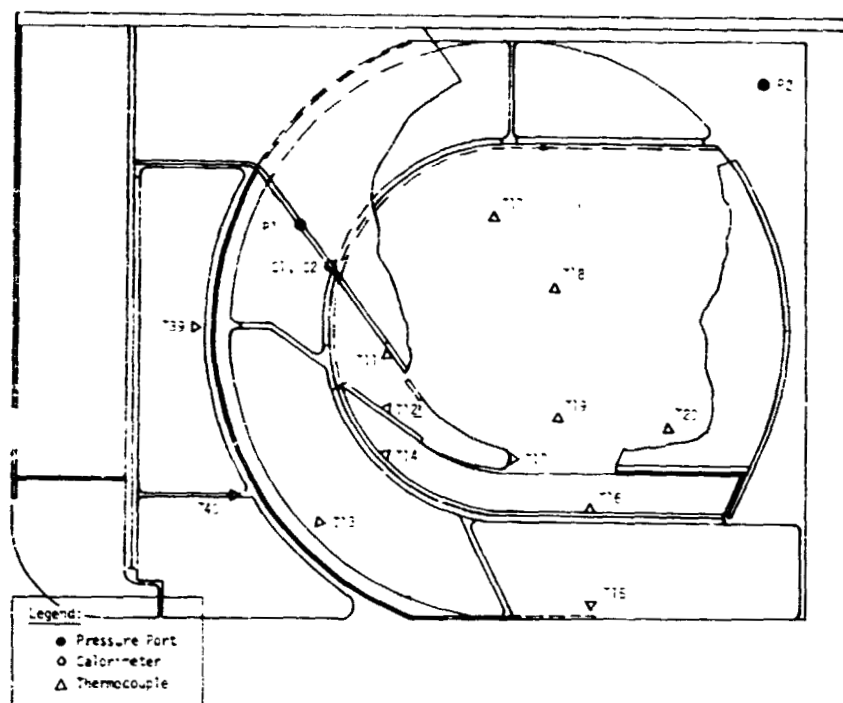


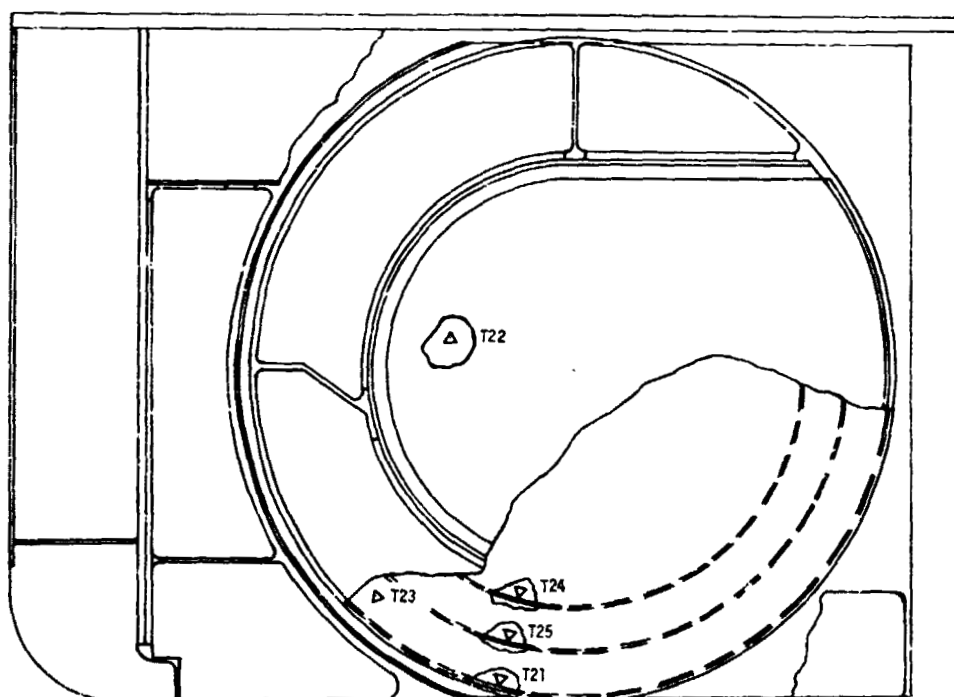
Fig. 69 Instrumentation Locations for the Phase II Unsealed Elevon End Gap Model

Table 12 Instrumentation Locations for the Phase II Sealed Elevon End Cap Model Shown in Figure 70

Measurement		Location*	Inboard Location from Near-Side Edge of Model, in.
No.	Type	Description	
T10	Thermocouple	Aft Surface at Curtain Seal	1.4
T11	Thermocouple	Inside Gap Cavity on Wing Structure	1.4
T12	Thermocouple	Inside Gap Cavity on Elevon Structure	1.4
T13	Thermocouple	Near Surface of Insulation on Elevon (in gap area)	1.4
T14	Thermocouple	Insulated Elevon Structure (in gap area)	1.4
T15	Thermocouple	Near Surface of Insulation on Elevon (windward area)	1.4
T16	Thermocouple	Insulated Elevon Structure (windward area)	1.4
T17	Thermocouple	Backface Surface of Insulated Elevon Closeout Rib	3.4
T18	Thermocouple	Backface Surface of Insulated Elevon Closeout Rib	3.4
T19	Thermocouple	Backface Surface of Insulated Elevon Closeout Rib	3.4
T20	Thermocouple	Backface Surface of Insulated Elevon Closeout Rib	3.4
T21	Thermocouple	Surface of External Ring on Labyrinth Seal	5.8
T22	Thermocouple	Surface of Labyrinth Seal (elevator side)	5.0
T23	Thermocouple	Surface of Labyrinth Seal (elevator side)	5.0
T24	Thermocouple	Surface of Internal Ring on Labyrinth Seal	5.8
T25	Thermocouple	Surface of Middle Ring on Labyrinth Seal	5.8
T39	Thermocouple	Near Surface of Insulation on Wing Side of Cove Gap	1.4
T40	Thermocouple	Near Surface of Insulation on Wing Side of Cove Gap	1.4
P2	Pressure Port	Inside Model Behind Curtain Seal	
P1	Pressure Port	Inside Gap Cavity on Wing Structure	1.4
C1	Calorimeter	Inside Gap Cavity on Wing Structure	1.0
C2	Calorimeter	Inside Gap Cavity on Wing Structure	1.8
*Instrumentation locations are shown approximately to scale on opposite page.			



(a) Basic Model Instrumentation Locations



(b) Labyrinth Seal Thermocouple Locations

Fig. 70 Instrumentation Locations for the Phase II Sealed Elexon End Gap Model

Table 13 Thermocouple Comparison Chart

	1st Test Series, Wing/Elevon Gap Model	2nd Test Series, Sealed Elevon End Gap Model	3rd Test Series, Unsealed Elevon End Gap Model
Thermocouples That Are Commonly Located on All Test Models	T1 T3 T4 T5 T6 T7 T9 T39 T40	T11 T12 T14 T13 T16 T10 T15 T39 T40	T11 T27 T28 T29 T30 T26 T31 T39 T40
Thermocouples That Are Commonly Located on the Sealed and Unsealed End Gap Models		T17 T18 T19 T20	T38 T33 T34 T35
Thermocouples on the Labyrinth Seal Struc- ture Only			T21 T22 T23 T24 T25
Thermocouples on the Surface of the MAR-SI in the Unsealed End Gap		T32 T36 T37	

The radiation environment within the gap cavity was measured using two Thermogage Model 2000 asymptotic calorimeters. These sensors were mounted side-by-side and were positioned so that they viewed the gap entrance to the cavity, as well as the cavity in which the curtain seal was installed. One sensor was coated with black paint that provided a surface emissivity of 0.95; the other was given an aluminized coating that had a measured emissivity of 0.12. The reflectivity curve for this low-emissivity surface was furnished by the manufacturer. The radiation and convective environments within the cavity were determined from these two gages.

Since the Phase I environmental data indicated that the heating environment in a transverse gap was relatively insensitive to the shear Reynolds number, the primary parameters we simulated in the Phase II tests were the external heating rate and the heat load. For these tests we selected two test conditions that gave heating levels of 4.5 and 9.5 Btu/ft²-sec, respectively. These levels were maintained for the times shown in Figure 71 to simulate the entry heat pulse at a windward elevon hingeline location.

The surface pressures on the model for these two test conditions are noted in the cross-hatched portions of the figure. The flight variation of the local surface history is indicated by the asterisks on the flight heating rate curve, which is designated as the baseline input.

Note that the surface pressure expected during the first 21.5 minutes of the test approximates the average flight pressure during this interval. However, the surface pressure expected during the second heating pulse of 9.5 Btu/ft²-sec is lower than the average flight pressure during this period by approximately a factor of 2. Using the 3.5-Mw facility, as originally planned, would have allowed us to produce a test surface pressure of 0.35 psia, matching the flight value during peak heating. However, the unavailability of this facility necessitated that the tests be conducted using the 1.5-Mw torch.

This did not seriously compromise the test results since the flow into and through the cove and end gaps is controlled by the *pressure ratio* across the gaps rather than by the *absolute pressure levels*. As long as this ratio is greater than two, the flow will be choked and there will be a potential for leakage. Since the pressure ratio across the seal simulated the flight values, and since the flight heat pulse is being applied, the test should

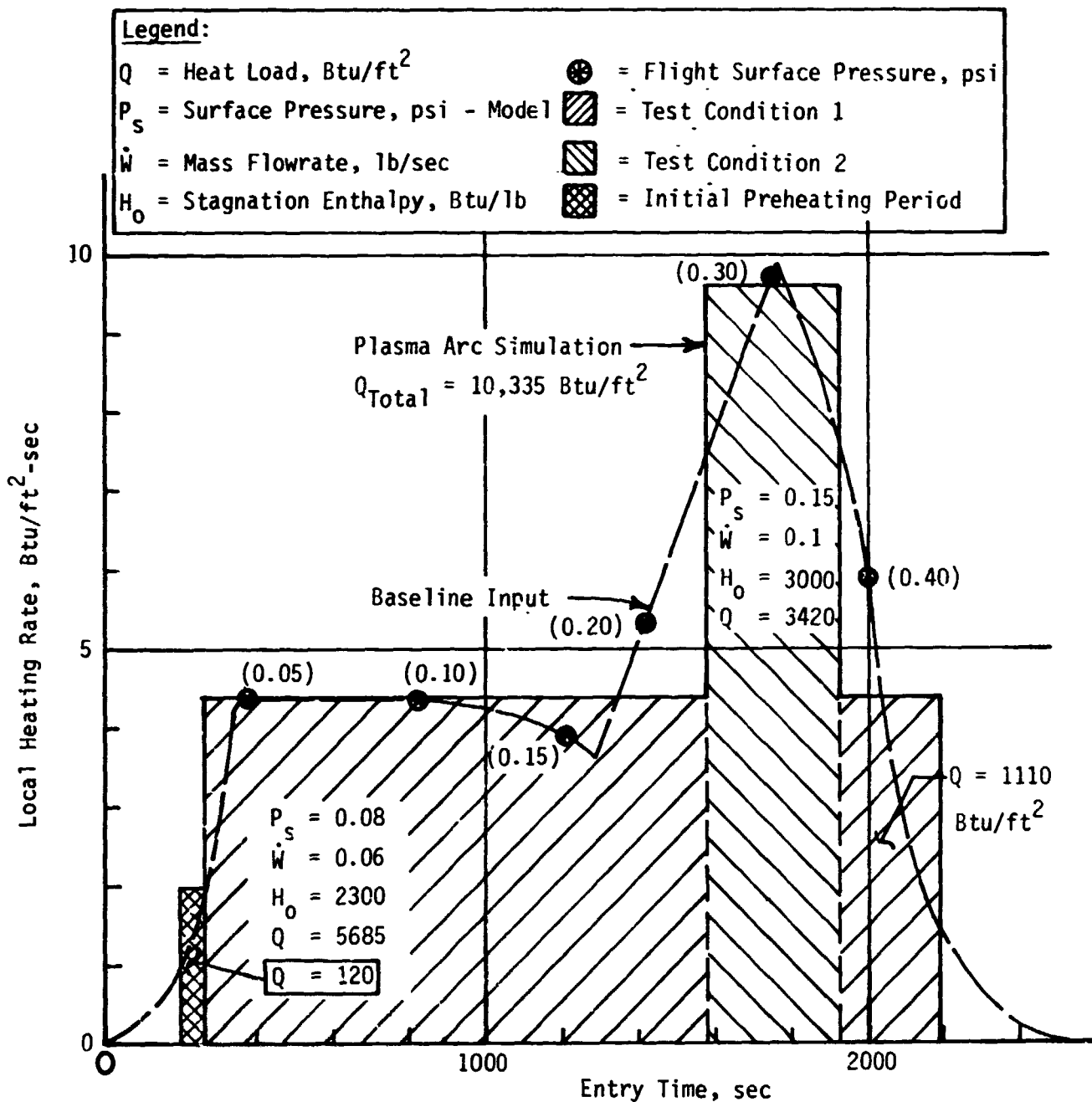


Fig. 71 Plasma Arc Simulation of Space Shuttle Reentry Heating Environment

have reproduced the flight heating environment within the gap regions.

The plasma arc facility was calibrated by determining the optimum input power level and gas flowrate needed to produce the two test conditions specified. Total enthalpy was determined by the energy balance method, in which measurements of power input, system losses, and total gas mass flow were used to solve the following equation:

$$H_t = \frac{\text{Power In} - \text{Losses}}{\text{Gas Mass Flow}}$$

Conditions within the test chamber were calibrated using an 8-in. by 12-in. wedge holder with an aluminum plate mounted at a 30° angle of attack. Five Thermogage Gardon calorimeters were installed to measure variation in the lateral and longitudinal heating rate across the surface of the wedge. The input power was then varied to give the required heat fluxes for the two test conditions.

Three of the calorimeters were installed in a lateral line at the location of the cove gap on the test models (8 in. from the leading edge of the wedge model). The center calorimeter was used as the control measurement during this procedure. Once the test points were established, several runs were made to establish the repeatability of the data.

In addition to establishing the two test conditions, we also took arc settings and calorimeter readings for the initial preheating period shown in Figure 71. This preheating period was required for two reasons. First, the weight of the model precluded the use of the model insertion arm after the test conditions had been established. Consequently, the model was positioned before we started the torch. Using a low initial heating level also provided the necessary time to reach the torch settings for Test Condition 1, provided a preheating period for the RSI material, and minimized the thermal shock that would have existed if the model had been inserted directly into the test stream, which was already at Condition 1.

Following this calibration procedure, we installed the test model in the cell. The total run time was approximately 32 minutes. After the test, all instrumentation was left on for a period of from 5 to 10 additional minutes to record any maximum temperatures that might have occurred as a result of heat soakback.

These data were recorded on strip chart recorders and reduced using the appropriate calibration constants.

A total of seven tests were conducted during the Phase II test period. Table 14 summarizes the configurations used for these runs. As seen in the table, three test exposures were made with the elevon/wing cove gap model, and two runs were made on each of the end gap models.

The second run on the unsealed end gap model was made using a modification of the original model. A $\frac{1}{2}$ -in. aluminum plate was used to replace the $\frac{1}{2}$ -in. MAR-SI slab used on the fixed portion of the end gap. Figure 72 shows the model modified to accommodate the aluminum plate. This plate was instrumented with seven Thermo-gage Gardon calorimeters, which were located as shown in Figure 73.

Test Results

Both of the objectives of the test were accomplished during the Phase II test period. All of the models were exposed to a simulated Space Shuttle entry heating pulse, and the dynamic seal concepts successfully limited the structure within a representative control surface cove gap to temperatures below the design limit of 350°F. Each of the models exhibited a unique temperature response to the entry environment, and repeat runs resulted in good data reproducibility.

Table 15 summarizes the data obtained during the Phase II test. All the thermocouples provided output during the test with the single exception of T17, which did not record during Run 4.

Recording difficulties on the elevon/wing cove gap model resulted in a loss of the calorimeter data during the first two runs. This problem was resolved after the second run, and data were obtained for the last run on this model and for all subsequent runs on the end gap models.

Surface pressure measurements were not obtained during any of the runs. We did not consider the lack of model pressure data serious, however, since we were able to reliably estimate the actual surface pressures on the model using the pitot pressures that had been recorded during the calibration runs and the ratios of the surface-to-pitot pressure that had been recorded during the Phase I environmental tests. This technique resulted in the surface pressures listed below.

Table 14 Phase II Run Schedule

Run No.	Model	Curtain Seal Installed	Labyrinth Seal Installed	End Gap Open (0.5 in.)	Test Duration, Minutes
1	Elevon/Wing Cove Gap	Yes	No	No	32
2		Yes	No	No	32
3		Yes	No	No	32
4	Elevon End Gap Model with Labyrinth Seal	Yes	Yes	Yes	32
5		Yes	Yes	Yes	32
6	Unsealed Elevon End Gap Model	Yes	No	Yes	32
7*		Yes	No	Yes	0.5

* Calorimeter plate installed on one side of end gap.

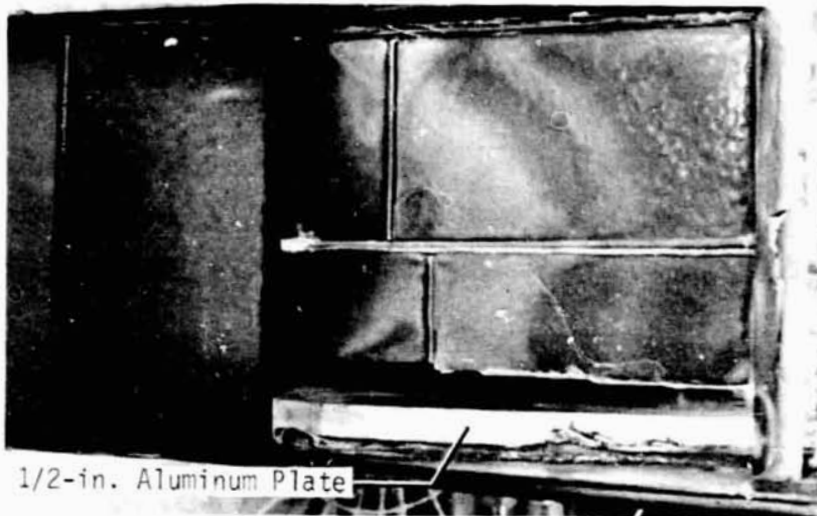


Fig. 72 End Gap Model with Aluminum Calorimeter Plate Installed

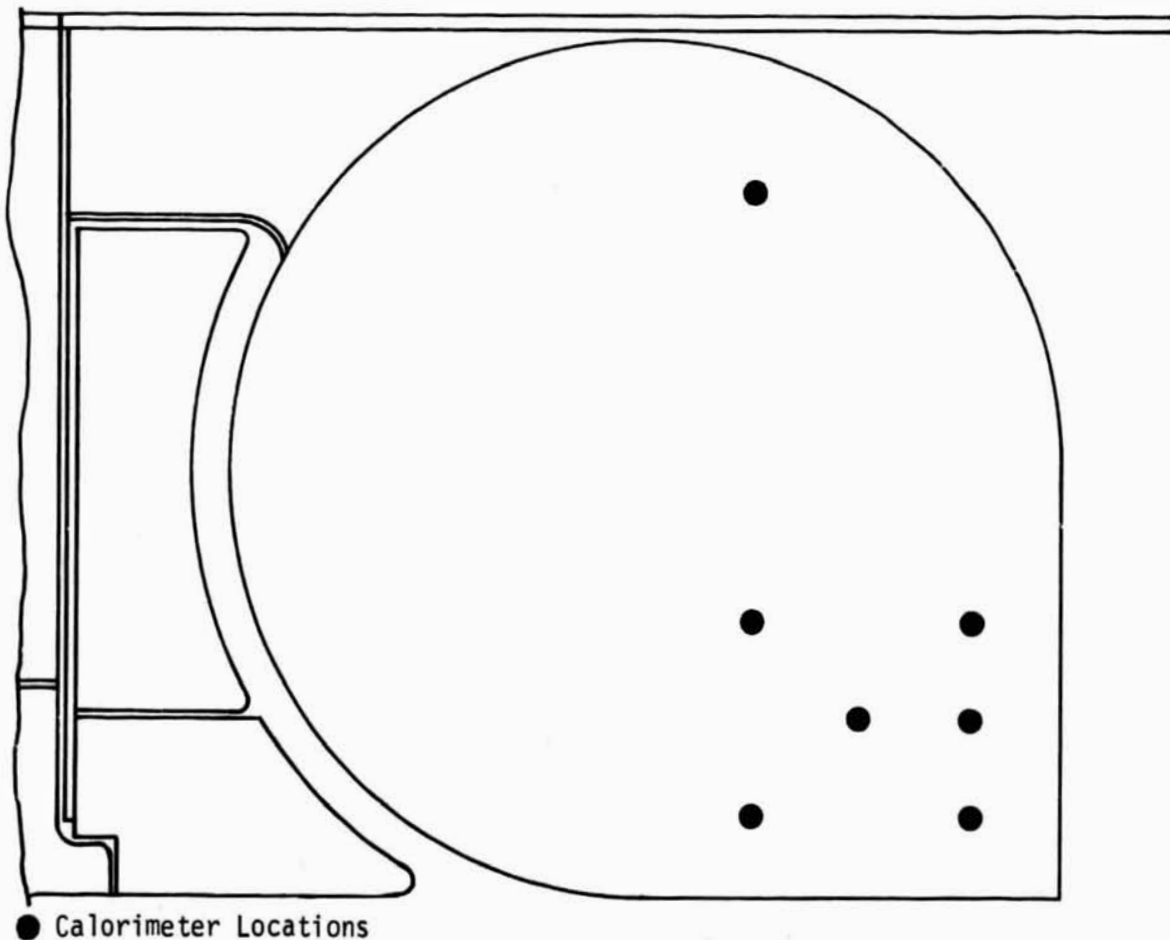


Fig. 73 End Gap Calorimeter Locations - Modified End Gap Model

Table 15 Data Summary for Phase II Seal Concepts Test

(a) Run 1 Results

Measurement	Units	Time from Start of Test, minutes									
		5	10	15	20	22.5	25	27.5	30	32	35
T1	*F	*	115	136	150	167	201	223	219	214	191
T2		*	126	150	171	201	238	258	256	254	212
T3		*	*	115	143	171	201	223	234	240	232
T4		*	*	106	132	145	169	193	210	221	230
T5		115	184	267	357	424	504	557	591	621	578
T6		*	*	119	143	156	176	199	214	225	231
T7		*	117	143	167	193	234	258	260	262	241
T9		294	465	591	669	762	878	927	890	878	775
T39		93	128	163	205	245	303	334	348	371	334
T40		526	742	827	1138	1280	1357	1387	1420	1295	1101

* Below 100°F.

Arc Exposure Period

Soak-back

(b) Run 2 Results

Measurement	Units	Time from Start of Test, minutes									
		5	10	15	20	22.5	25	27.5	30	32	35
T1	*F	*	*	125	138	155	180	197	197	195	176
T2		*	117	142	163	194	223	239	228	225	194
T3		*	106	128	156	180	203	221	221	225	219
T4		*	104	115	140	154	173	197	205	214	220
T5		*	223	303	393	469	526	570	582	587	539
T6		*	*	119	143	199	171	197	205	216	222
T7		*	117	141	166	189	219	241	240	238	222
T9		289	460	578	665	762	869	920	911	907	792
T39		106	137	180	223	262	312	334	348	357	325
T40		677	806	1017	1203	1345	1409	1380	1174	1122	963

* Below 100°F

Arc Exposure Period

Soak-back

(c) Run 3 Results

Measurement	Units	Time from Start of Test, minutes									
		5	10	15	20	22.5	25	27.5	30	32	35
T1	*F	82	109	128	147	159	189	206	203	201	184
T2		91	121	150	167	193	227	249	236	232	198
T3		73	91	113	139	158	189	210	216	214	210
T4		66	82	102	128	137	158	180	194	201	210
T5		111	194	267	335	380	438	504	526	535	483
T6		66	93	111	134	150	165	184	201	210	214
T7		84	111	136	158	178	210	236	236	236	224
T9		281	438	570	665	765	890	932	910	910	785
T39		88	128	167	201	223	271	312	316	326	289
T40		617	805	890	932	1187	1357	1335	1145	1102	932
C1	Stu/ft ² -sec	0.045	0.075	0.10	0.12	0.20	0.25	0.22	0.22	0.22	
C2		0.045	0.065	0.08	0.09	0.16	0.17	0.12	0.13	0.13	

Arc Exposure Period

Soak-back

Table 15 (concl)

(d) Run 4 Results

Measurement	Units	Time from Start of Test, minutes									
		5	10	15	20	22.5	25	27.5	30	32	35
T10	°F	128	160	190	195	227	262	285	271	269	240
T11		97	126	144	163	180	208	232	234	232	206
T12		85	106	125	145	167	196	212	226	228	219
T13		140	281	402	495	547	625	705	750	760	420
T14		74	87	114	135	146	167	190	199	207	220
T15		228	389	510	605	695	800	865	860	852	776
T16		73	83	99	120	139	144	167	183	193	212
T17		*	*	*	*	*	*	*	*	*	*
T18		67	81	95	117	124	141	159	177	180	206
T19		65	78	97	116	129	150	163	190	195	207
T20		71	84	99	120	131	150	168	177	193	201
T21		1303	1396	1315	1297	1405	1532	1567	1462	1419	1195
T22		180	413	608	716	762	861	983	1042	1051	1030
T23		985	1172	1182	1177	1263	1405	1470	1375	1336	1101
T24		898	1140	1182	1165	1195	1332	1427	1392	1340	1220
T25		1169	1322	1080	1276	1327	1466	1541	1453	1405	1242
T39		150	276	353	407	445	496	535	555	535	502
T40		1350	1427	1400	1405	1687	1815	1605	1540	1483	1220
C1	Btu/ft ² -sec	0.39	0.54	0.61	0.63	0.92	1.10	1.16	0.96	0.72	
C2		0.15	0.17	0.18	0.18	0.29	0.33	0.24	0.23	0.21	

* Open thermocouple junction.

Arc Exposure Period

Soak-back

(e) Run 5 Results

Measurement	Units	Time from Start of Test, minutes									
		5	10	15	20	22.5	25	27.5	30	32	35
T10	°F	99	176	201	203	236	274	294	283	278	251
T11		86	130	157	167	184	214	242	240	236	206
T12		73	108	134	154	178	206	227	234	231	232
T13		62	232	425	525	582	682	755	793	805	755
T14		63	88	113	140	150	172	203	212	230	229
T15		96	366	492	595	695	818	890	877	869	780
T16		62	80	101	122	137	154	174	197	210	223
T17		67	72	137	119	127	143	171	184	193	211
T18		60	76	96	118	131	148	167	195	202	214
T19		62	77	102	123	139	157	179	208	210	227
T20		65	92	102	123	138	160	186	201	214	227
T21		1060	1536	1531	1545	1620	1802	1755	1585	1555	1310
T22		106	351	652	793	823	940	1114	1185	1203	1173
T23		742	1349	1400	1315	1445	1616	1656	1466	1445	1298
T24		521	1147	1310	1259	1302	1510	1616	1527	1492	1315
T25		826	992	1462	1400	1466	1680	1639	1602	1550	1349
T39		124	274	393	438	487	555	605	609	613	591
T40		1169	1715	1665	1514	1780	1974	1866	1585	1563	1276
C1	Btu/ft ² -sec	0.20	0.67	0.81	0.74	1.00	1.20	1.20	1.05	0.95	
C2		0.12	0.27	0.27	0.24	0.36	0.40	0.33	0.26	0.25	

Arc Exposure Period

Soak-back

(f) Run 6 Results

Measurement	Units	Time from Start of Test, minutes									
		5	10	15	20	22.5	25	27.5	30	32	35
T11	°F	97	145	176	195	212	236	256	249	245	203
T26		132	208	241	268	300	325	349	331	327	287
T27		97	143	180	217	249	281	305	312	321	307
T28		75	106	143	180	201	232	262	281	294	305
T29		233	53	742	890	987	1089	1190	1199	1190	1080
T30		64	91	122	160	173	201	232	249	277	285
T31		315	526	665	767	941	1064	1177	1101	1101	912
T32		299	712	957	1140	1220	1332	1490	1444	1435	1275
T33		63	88	117	150	165	184	186	236	265	279
T34		76	93	137	157	182	202	223	267	277	292
T35		65	101	119	160	174	199	225	258	276	281
T36		119	376	585	742	817	886	963	920	907	882
T37		498	1017	1237	1445	1497	1545	1635	1496	1487	1349
T38		67	84	124	160	178	185	203	246	259	278
T39		136	300	402	473	514	570	613	617	617	547
T40		1445	1790	1802	1792	2007	2040	2075	1747	1701	1319
C1	Btu/ft ² -sec	0.33	0.74	0.92	1.01	1.35	1.56	1.66	1.21	1.13	
C2		0.30	0.36	0.46	0.37	0.55	0.57	0.55	0.36	0.34	

Arc Exposure Period

Soak-back

Test Condition	Measured Pitot Pressure, psia	Predicted Surface Pressure, psia
1	0.15	0.075
2	0.28	0.14

Comparison of Maximum Temperatures - Figure 74 compares the maximum temperatures recorded for each of the three models. Note that these temperatures are for locations that were common to all three models. The MAR-SI temperature measurements were corrected for conduction losses and extrapolated to represent the values at the surface by using theoretical predictions of the temperature gradient through the basic MAR-SI material.

Figure 74 also includes optical pyrometer readings taken during runs 4 to 7 on the end gap models. These pyrometer readings were corrected to a surface emissivity value of 0.8.

The first point to note from this compilation is that the baseline cove gap model had temperatures much lower than the design limits of 500°F for the curtain seal and 350°F for the aluminum structure. The maximum temperature that was recorded was 236°F on the curtain seal. In contrast, the maximum temperatures on the structure ranged from 203°F to 216°F. These low temperatures are particularly noteworthy when compared with the temperatures in the gap (> 1500°F) and on the external surfaces (~2100°F).

Most of the internal temperatures were higher for the end gap model with the labyrinth seal. The maximum temperature of the seal increased by 50°F, and the maximum increase for the structure was 31°F at the curtain support shelf (location B in Fig. 74). Gap temperatures also increased significantly by over 200°F.

The only places where the temperature decreased were at locations D and E (the structure underneath the MAR-SI) and on the MAR-SI at point I. These locations should not have been as sensitive to the model configuration change since the latter measurement (at point I) is an external measurement that would be expected to be independent of any end gap effects, and since the other two are insulated from the gap environment. We attribute the small reduction in these temperatures to the fact that a slightly different heating environment occurs at the trailing edge of the elevon. (As indicated earlier, this portion of the model was subject to shock reflections from within the test

Location *	Temperature, °F		
	Cove Gap Model	E..d Gap Model with Labyrinth Seal	Unsealed End Gap Model
A	236	285	349
B	203	234	256
C	216	228	321
D	210	207	305
E	214	193	285
F†	1461	1689	1751
G†	1590	1920	2308
H†	1610	1835	2249
I†	2095	2050	2062
J§		1770	1760
K§		2150	2080
L§		2080	2100
* Locations common to all models.			
† Corrected for conduction losses and extrapolated to surface levels.			
§ Pyrometer readings.			

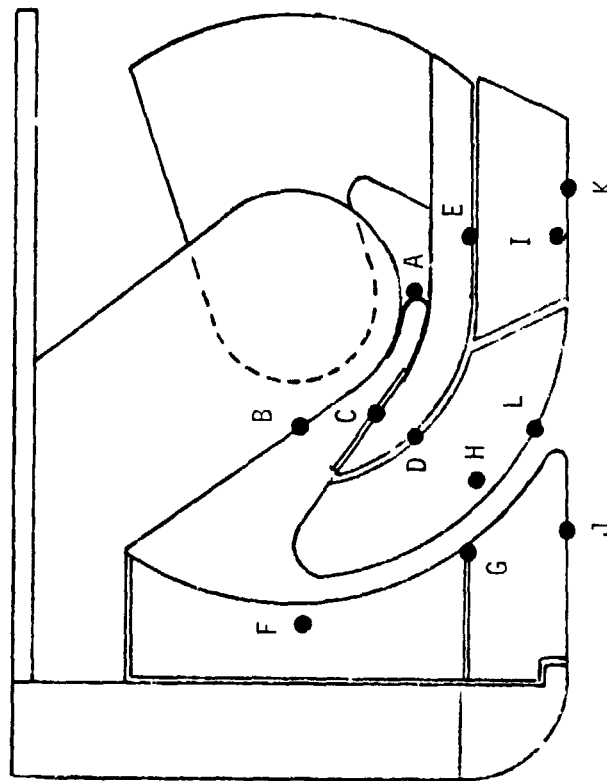


Fig. 74 Summary of Maximum Temperature Recorded during Tests

jet and experienced some variations in heating rate that were apparently dependent on the balance between the jet exit pressure and the cell pressure.)

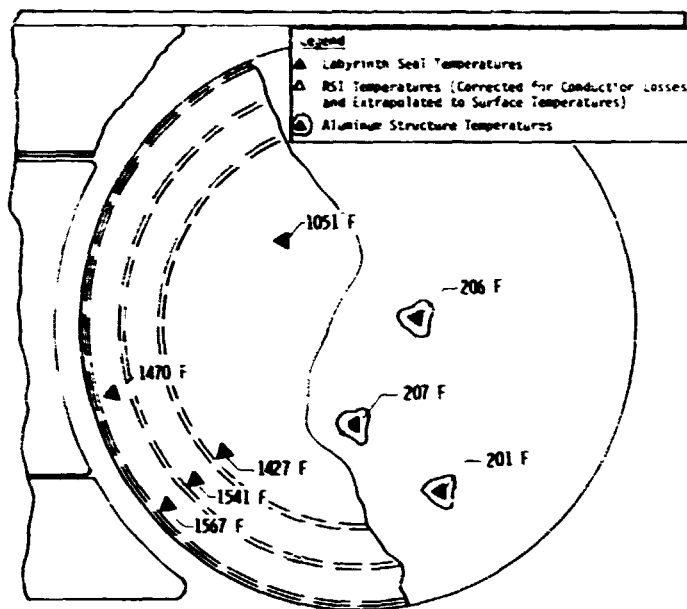
A comparison of temperatures for the unsealed end gap model with temperatures for the other two models results in the following observations:

- 1) The labyrinth seal has a significant effect on the temperature increases caused by an end gap and decreases the temperature rise resulting from an unsealed end gap by more than 50%. Temperature reductions of this order were observed at all of the internal locations [A to E (Fig. 74)] and along the surfaces of the cove gap.
- 2) Despite the higher temperatures recorded in the unsealed end gap model, the observed values are still below the design limits, suggesting that a labyrinth seal may not be required to maintain suitable temperatures within a wing/elevon cove gap.

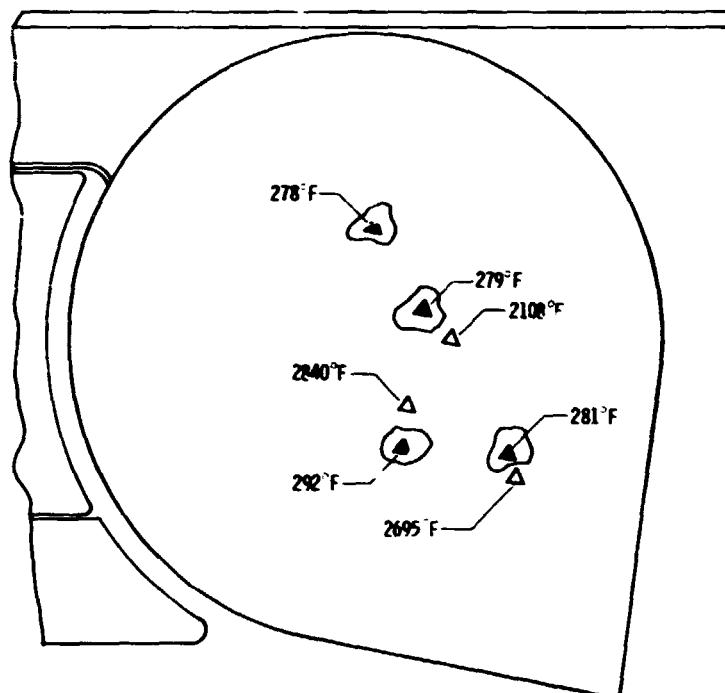
The maximum temperatures recorded in the end gap region of the end gap models are summarized in Figure 75. Again, the beneficial effects of the labyrinth seal can be seen by comparing the surface temperatures recorded underneath the MAR-SI end gap insulation. Measurements on the labyrinth seal model showed that the aluminum structure had a maximum temperature of 207°F, compared with a value of 292°F for the open end gap model--a difference of 85°F.

The MAR-SI temperatures recorded in this region show the potential TPS design problem that exists along the end gap surfaces; namely, that extremely high temperatures can be expected along these surfaces because of radiation blockage effects. This is graphically illustrated in Figure 76, which shows the damage to the MAR-SI coating that occurred during the first run with the unsealed end gap model. Note that the coating actually melted in some spots, which would have required temperatures on the order of 3000°F.

Even the labyrinth seal experienced relatively high temperatures, as shown by the discoloration patterns in Figure 77. Here again, although the labyrinth seal model did not experience the same extremely high temperatures recorded in the end gap of the unsealed end gap model, this was only because size limitations did not allow a full-length simulation of the elevon end gap: similar high temperatures would be expected further downstream in a labyrinth-sealed end gap. The primary function of the labyrinth seal is to limit the amount of flow entering the area on the backside of the curtain seal, not to seal the elevon end gap.



(a) End Gap with Labyrinth Seal



(b) Unsealed End Gap

Fig. 75 Summary of Maximum Temperatures Recorded in the End Gap Region during the Phase II Tests

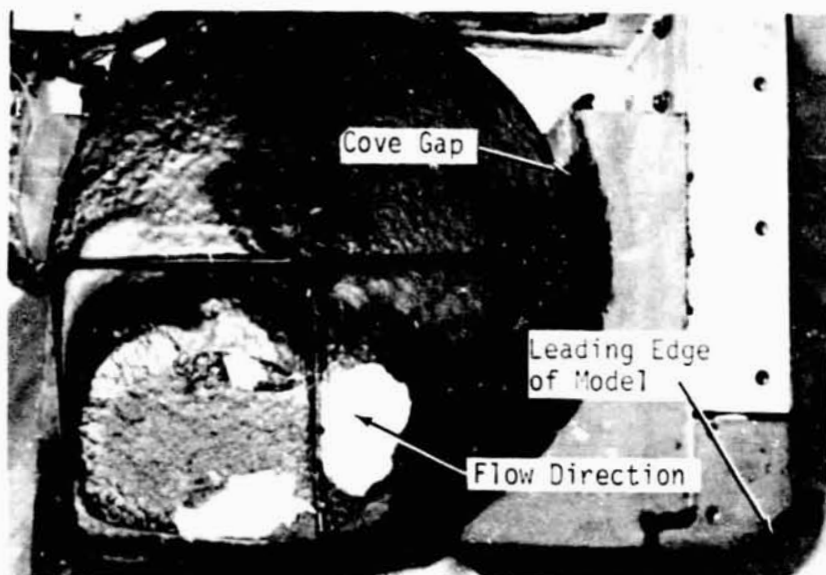


Fig. 76 Damaged MAR-SI Surface at End Gap in Unsealed End Gap Model

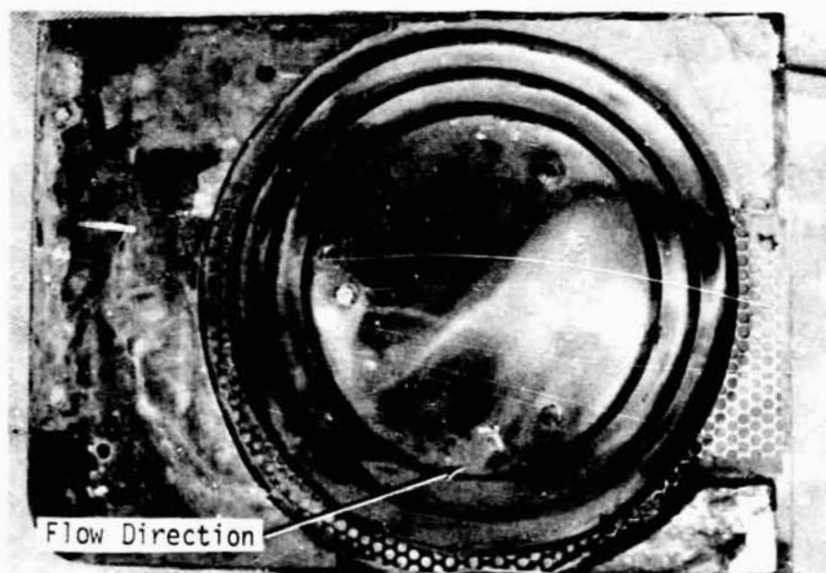


Fig. 77 Discoloration Pattern on Labyrinth Seal after Phase II Tests

Transient Temperature Response - Figure 78 indicates the transient response of the thermocouples located on and near the curtain seal. Data are shown for each model. The times corresponding to the two different test conditions are noted on the figure.

Predictably, the thermocouples located on the thermally unprotected curtain seal and on the support shelf (locations A and B, respectively) reacted immediately to the change in test conditions, as noted by the change in slope at this time. Conversely, the thermocouple located on the structure underneath the MAR-SI was not immediately affected by the abrupt change in environment. Similarly, the temperatures at A and B peaked just after the end of Test Condition 2, whereas the temperatures recorded at C continued to increase during the entire test duration and did not peak until 3 minutes after shutdown.

Figure 78 also shows that the maximum temperature differences noted earlier between the models existed throughout the entire test. Again, it can be seen that the end gap model with a labyrinth seal reduced end gap temperature effects by 50% from those measured in the unsealed end gap model.

Knowing the transient temperature history during soakback allowed us to assess the effect of the water-cooled end plates on the temperatures of the flightweight aluminum structure surrounding the seal. These data were taken at the end of runs 1 and 2 on the wing/elevon cove gap model. In the first run, the water cooling was continued during the cooldown period that followed torch shut-down, and all model temperatures were recorded for 5 minutes during this interval. After the second run the cooling water to the side plates was shut off and the temperatures were again monitored for 5 minutes. A comparison of the temperature-time slopes during this period showed that there were no apparent differences and substantiated the use of the refrasil cloth gaskets between the end plates and the internal model structure to minimize conduction losses.

Further evidence suggesting that the conduction losses to the water-cooled end plates were negligible was obtained by noting the temperature differences between the curtain seal and the aluminum structure. As seen earlier in Figure 74, the curtain was no more than 50°F hotter than the highest structure temperature recorded. Thermal analyses supported the fact that the curtain should have a higher temperature because of its lower thermal

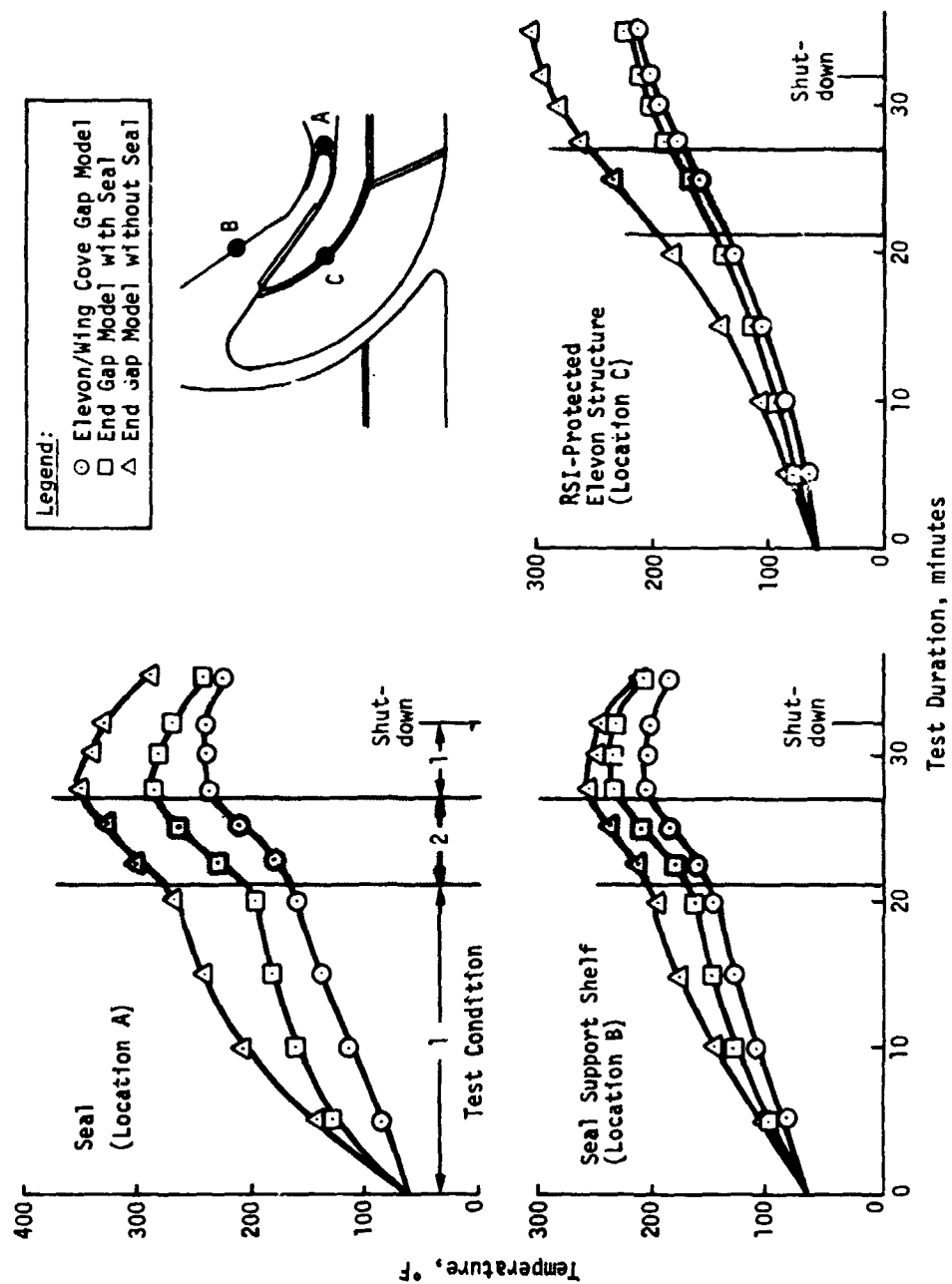


Fig. 78 Temperature Response of Curtain Seal and Surrounding Structure during Phase II Tests

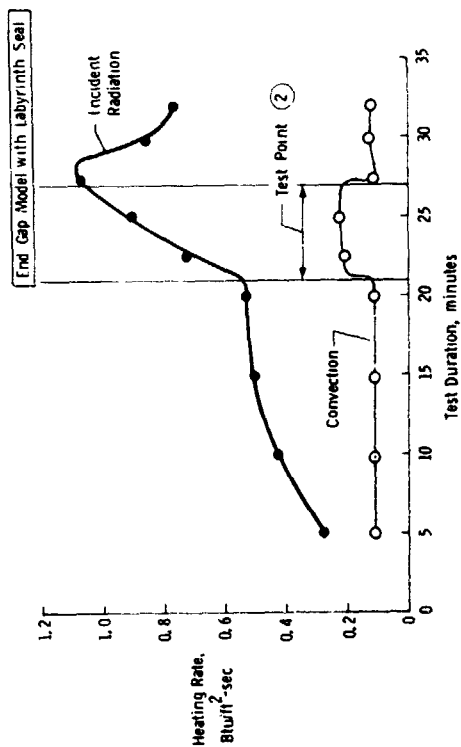
capacitance and because the low lateral thermal conductance of the curtain seal ensures that there will be virtually no conduction losses between the seal and end plate. Since the maximum temperature differences between the curtain and structure were no more than 50°F, this suggests that there are negligible conduction losses between the end plates and the aluminum structure.

Cove Gap Heating Measurements - The results of the Phase II cove gap calorimeter measurements are shown in Figure 79.

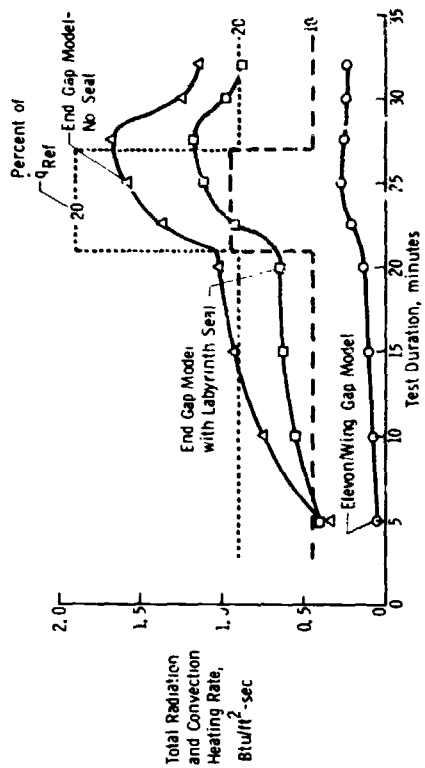
Figure 79(a) compares the radiation and convection heating rates measured in the labyrinth-sealed end gap model and shows the significance of the thermal radiation emanating from the hot surfaces of the gap. This thermal radiation was five times greater than the level of the convective environment. Note that the actual radiation environment during flight will be slightly higher than that measured in the test since the test calorimeters also viewed the side walls of the model. During flight, a calorimeter placed at the midspan of the hinge line gap would not "see" a side wall, and would effectively "see" a hot gap of infinite span. The difference between the test view factor of a finite gap span and the flight view factor for an infinite gap span is estimated to be on the order of 10%.

It is also interesting to note that the maximum radiation heating rates measured during the plasma arc test are equivalent to a source temperature of 840°F (assuming an emissivity of 0.8). This value represents the average temperature of all the surfaces surrounding the calorimeter (including the cooler aluminum structure, and implies that the actual gap temperatures would be much higher than this -- qualitatively reinforcing the thermocouple measurements obtained in the gap.

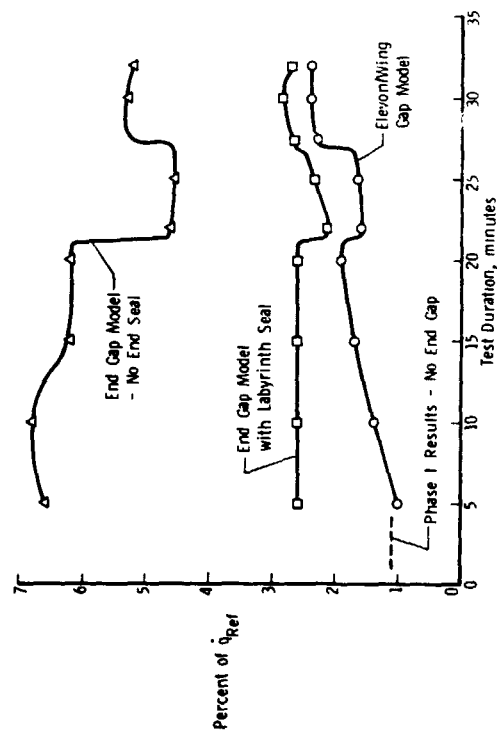
The combined radiation and convection environment for all three models is compared in Figure 79(b). This figure also substantiates the thermocouple data, which indicated that the heating environment increased as the test configurations were varied from the baseline wing/elevon gap model, to the labyrinth sealed end gap model, and finally to the unsealed end gap model. The figure also shows the percentage of the external environment at the cove gap entrance during the test. The total heating level in the cavity is about 20% of the external level.



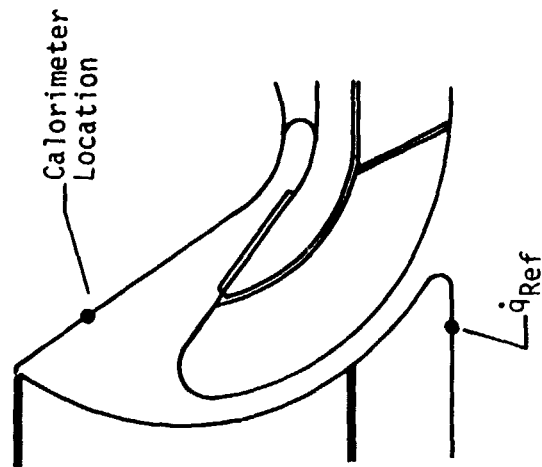
(a) Comparison of Radiation and Convection Heating Rates



(b) Combined Radiation and Convection Heating Rates



(c) Comparison of Convective Heating Rates



(d) Calorimeter Locations

Fig. 79 Results of Phase II Cove Gap Calorimeter Measurements

The convective heating environment in the cavity is shown in Figure 79(c), again for the three configurations that were tested. The results are presented in terms of the percentage of the reference external heating rate at the gap entrance. For comparison, the Phase I environmental results are given for a 0.5-in. cove gap and 10° down control surface position.

The same trend with configuration is evident; that is, the lowest heating rates occurred in the elevon/wing gap model and the highest rates were measured in the open end gap model.

Figure 79(c) also shows that the Phase I and Phase II measurements agree during the initial portion of the test, but the Phase II readings for the elevon/wing gap model gradually increase over time to a level approximately twice the initial value. This increase could be due to a gradual increase in the cove gap surface temperatures during the test. As these temperatures increase, the amount of heat taken from the incoming air decreases, resulting in a higher heating rate being measured by the calorimeters. The relatively constant heating rate curve shown for the second model could have occurred because the higher heating rates drove the wall temperatures to higher values sooner, thus minimizing this effect.

Unfortunately, this would not explain the decreasing convective history observed for the unsealed end gap model. The only explanation offered for this phenomenon is based on the following observations: First, the convective heating in the sealed cove gap is a strong function of the presence of an end gap; and secondly, in testing the unsealed end gap model, the high temperatures in the end gap caused the MAR-SI coating to melt and close off portions of the end gap. This blockage of the end gap during the test may have contributed to the different convective heating levels noticed in the cove gap.

It is also interesting to speculate on which portions of a full-scale cove gap would be influenced by end gap effects. Certainly those regions near the end gap that are as close as the test configuration (4 in.) would be expected to see the same increase in heating noted between the baseline model (without an end gap) and the end gap models. However, it seems reasonable to expect these effects to diminish as the spanwise distance from the end gap is increased, much the same as the heating in the cove gap decreased with distance from the gap entrance. It is therefore possible that

the environmental measurements obtained on the baseline model could apply to a large portion of the cove gap near the midspan of the wing. Unfortunately, we were unable to assess this possibility with the current models because of their limited spanwise dimension. Resolving this question will require further testing on a model with a greater spanwise simulation capability.

End Gap Heating Measurements - The data obtained when the aluminum plate containing the calorimeters was installed in the unsealed end gap are presented in Figure 80. The measured heating rates have been normalized with respect to the external heating rate at the cove gap entrance.

As shown in the figure, the heating in the gap exceeded the reference value near the entrance to the end gap and then fell below the reference value as the distance into the gap increased. The top calorimeter recorded a very low heating rate -- only 4.1% of the reference level. This value, however, may not be representative of the heating rate at the same distance from the gap entrance further downstream since it could have been outside the primary flow path through the gap.

Figure 81 is a plot of the heating rate distribution along a path aligned with the external flow direction. Here the measured heating rates are given as a function of the distance from the gap entrance divided by the gap width.

Flow through two parallel plates may be considered analogous to pipe flow if the flow is considered choked (subsonic). For this reason, a theoretical pipe flow curve is also shown in Figure 81. Kays theory (Ref 6) of pipe flow, which includes entrance effects, was evaluated using the following two assumptions:

- 1) The average pressure in the gap is 75% of the pressure at the reference location;
- 2) The effective pipe diameter can be defined by the hydraulic radius for two parallel plates (i.e., $D_e = 2W$).

Thermodynamic properties in the gap were determined by assuming that the total temperature in the gap was equal to the local external static temperature.

A comparison of the data with the theory is inconclusive since the model did not simulate the 36-in. depth that occurs at the elevon/body end gap. The figure does emphasize, however, the large degree of uncertainty that exists for S/W values greater than 15.

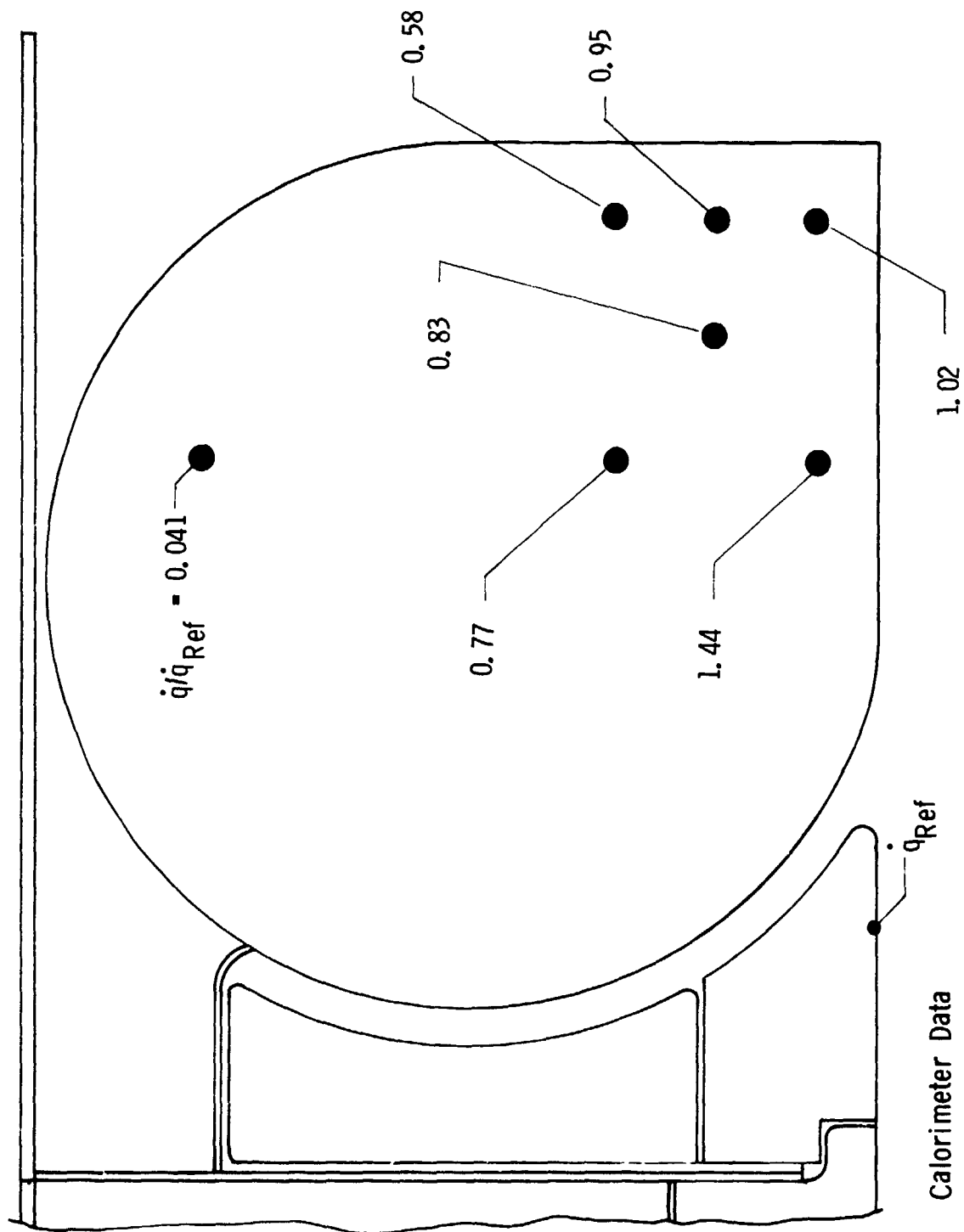


Fig. 80 Results of Phase II End Gap Calorimeter Measurements

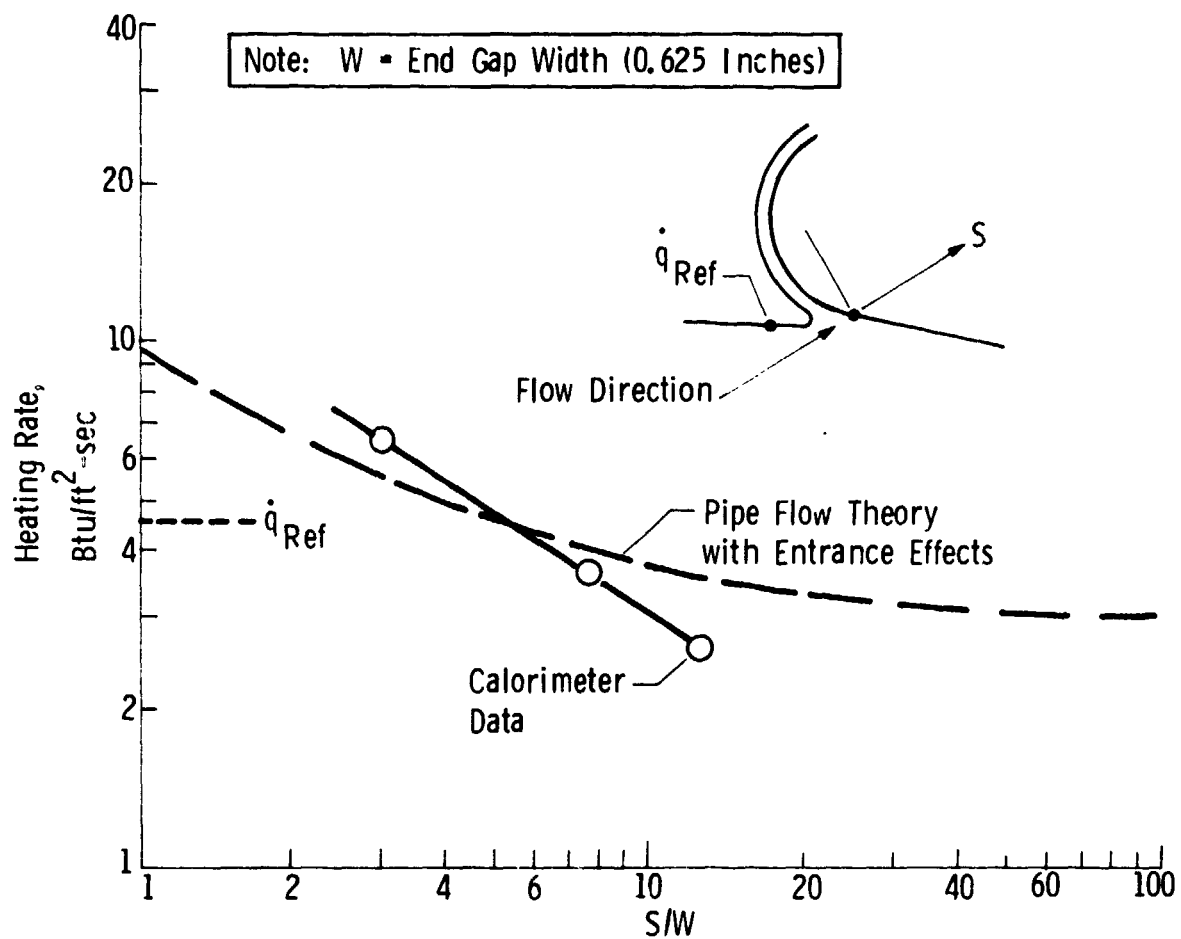


Fig. 81 Comparison of Phase II End Gap Calorimeter Data with Pipe Flow Theory

CONCLUDING DISCUSSION

GENERAL REMARKS

The primary objective of this contract was to design, develop, and test dynamic seal concepts for use on the Space Shuttle. Two seal design concepts were investigated -- the flexible curtain seal and the labyrinth seal. The curtain seal concept must be considered a strong candidate for Shuttle application on the basis of its evaluation in this program. Our tests show that a spanwise seal must be installed to control the high-temperature environment and that the curtain seal does that job. The labyrinth seal, however, though demonstrating that it too can do the job, may not really be required. Tests conducted without a labyrinth seal indicated that the temperatures in the gap did not surpass the design maximum of 350°F.

This latter observation tends to present some concern about pushing the margin of safety and seems to say that additional experimental testing is probably required to support a "no-seal" approach. Nevertheless, the labyrinth seal concept should be considered if actual entry environments surpass the baseline test criteria used in this contract. For example, the entry environment at the wing tip, as presently understood, produces external surface temperatures exceeding 2000°F, whereas this program's surface temperature was baselined at between 1700°F and 1800°F. In the face of higher surface temperatures a labyrinth seal built of a temperature-insensitive material in the 2000°F range (like carbon-carbon) may be the answer.

During the course of testing the two seal design concepts, a serious problem of high radiation blockage was found within the elevon end gap and along its entire length to the trailing edge. This problem, although not contributing to the temperature effect on the unprotected structure within the elevon, does contribute to the high temperatures on the external surfaces of the elevon-end TPS and the TPS on the side of the Shuttle body and is, therefore, a "must" for further study, development, and testing.

DEVELOPMENT TEST DISCUSSION

On the basis of our development tests, we can make the following observations relative to the design of dynamic seals for Space Shuttle control surfaces.

Gap Environment

Convection - The convective environment within a sealed hinge line gap aligned normal to the flow decreases rapidly as the distance into the gap increases. Heating rates measured in the vicinity of an internal seal are 2% of the external level for a $\frac{1}{2}$ -in.-wide gap. Increasing the gap width by a factor of two can quadruple the gap convective environment. Similarly, a control surface deflection angle of 10° downward produces twice the heating measured for a 0° angle. Lateral flow effects created by an end gap can also double the convection levels in the cove gap. Sealing the gap reduces the environment within a given gap configuration by factors ranging from 4 to 6. A comparison of the convective data obtained in the present test with other transverse gap investigations suggests that the convective heating can be correlated with the ratio of the gap distance divided by gap width.

An initial assessment of the convective heating in the end gap of a control surface indicates that heating levels will decrease as the distance from the gap entrance increases. In our tests, however, the model was too shallow to determine whether the heating reaches a constant level (as would occur in pipe flow) or continues to decrease. Additional tests should be considered to define the environment along the entire depth of representative end gaps for Space Shuttle control surfaces.

Radiation - Although the convective heating rates in control surface gaps are not excessive, the radiation interchange to space can cause very high temperatures within these gaps. Radiation from high-temperature regions in the cove gap to the internal portions of the cavity was measured to be 5 times greater than the convection level.

Seal Performance

The curtain seal design concept recommended for the elevon/wing cove gap of the Space Shuttle can survive a typical Shuttle entry heat pulse. This concept limits the unprotected structure to temperatures below 350°F. The labyrinth seal, which had been developed as an end closeout for the curtain seal, reduces end gap effects by 50%, but may or may not be required, depending on the actual design configuration and environment.

SPECIFIC CONCLUSIONS

1. The hinge line seal technique (as opposed to external seal) is definitely feasible for the Space Shuttle.
2. The curtain seal concept has excellent test credentials, is cost effective and reusable, and demonstrates an excellent capability for accommodating deflections and tolerance buildups.
3. The 70-node thermal model developed under this contract is well suited for working thermal design problems in cove gaps.
4. The sizing of cove and end gap widths is dependent on the strategic placement of hinge points, which in turn, govern the deflection and expansion allowances.
5. A plasma arc simulation of the Space Shuttle entry environment is an effective test method for screening design concepts with respect to aerodynamic heating in gaps.
6. Mullite standoffs and refracil rubbing seals have potential for helping resolve design problems related to localized heating.

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RECOMMENDATIONS

ELEVON END GAP STUDIES

As shown in the Phase II tests, the radiation blockage effect--coupled with relatively high convective heating levels--caused severe damage to the RSI coating in the 0.50-in. unsealed end gap. Temperature predictions based on calorimeter data for the open-gap test models show that these temperatures may be well above 3000°F during flight. This suggests that additional design efforts are needed to reconfigure these gaps so as to increase the radiation relief to space and minimize the radiation interchange by using baffles, by optimizing the radiative characteristics of the surfaces, etc.

There are essentially two basic approaches for resolving this problem. The first of these involves determining the temperature reduction that can be achieved by reconfiguring the gap to reduce the convective environment within the gap and to increase the radiation view factors to space. The basic objective of this approach would be to obtain an end gap geometry that allows the use of HRSI or carbon/carbon materials, thus ensuring TPS reusability in this region.

The temperature reductions that can be realized from this type of approach are shown in the top band of Figure 82, which gives the predicted temperature distribution across a 36-in. deep end gap at the elevon/body juncture. The top curve is for a 1-in. parallel gap between two HRSI surfaces. The dashed curve shows the temperature distribution across a 1-in.-wide gap at the windward surface with a 10° divergence angle to the leeward surface. It can be seen that this simple change in geometry reduces the temperature in the end gap by 500°F and provides end gap temperatures approaching the maximum re-use temperature of HRSI.

The second approach would be to investigate the various methods that could be used to maintain one side of the gap at a temperature low enough to remove heat from the opposing surface by radiation. Preliminary studies have shown that the most promising approach (from a weight standpoint) appears to be to use a low-temperature-subliming material such as Teflon.

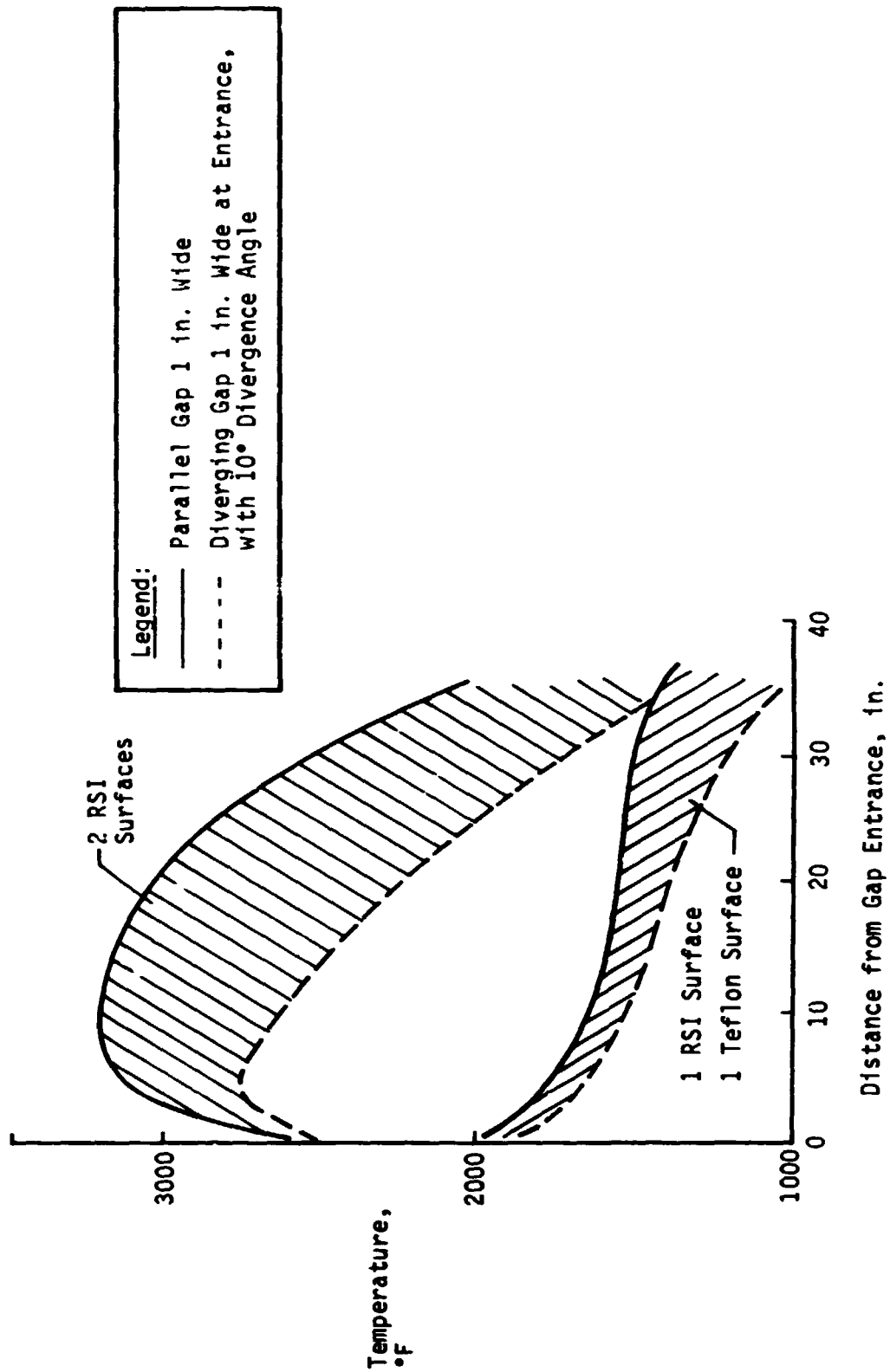


Fig. 82 Predicted Maximum Flight Temperatures at the End Gap

The lower band of Figure 82 shows the predicted temperature distributions in an elevon/body end gap using Teflon on the elevon side of the gap and HRSI on the body side. The temperatures plotted in the figure are the maximum surface temperatures on the HRSI material. It can also be seen that using a sublimator on one side of the gap can lower the HRSI temperatures to acceptable levels, but does so at the expense of additional weight and refurbishment costs.

ADDITIONAL PLASMA ARC TESTS ON EXISTING TEST MODELS

Although the present program provided a great deal of experimental test data and analysis toward resolving gap heating problems, there is a much more complete understanding of the problem to be realized by conducting additional plasma arc tests. For example, the existing Phase I environmental test model provided heating trends for seal designs with the elevon deflected 10° up, 0° , and 10° down. The Phase II "seal concept evaluation" gap model tested the curtain seal concept utilizing the worst heating condition experienced during the Phase I tests -- namely, with the elevon 10° down. However, the Orbiter elevon control envelope allows elevon deflections from 40° up through 20° down. An evaluation of the gap heating effect of these elevon deflections should be pursued to fill in the missing design data.

Several other investigations should be considered to provide additional benefits in the area of design criteria and guidelines. The results of testing controlled leakage through a typical curtain seal would demonstrate limit conditions of seal damage such as tears, etc. And knowing the effects of higher total heat loads could also be valuable backup data if entry trajectory histories are revised. Another question that could be answered with a simple modification to the Phase II "elevon cove" test model concerns the effects on internal elevon temperatures from testing a 0.75-in. spanwise gap.

Because of the sensitivity of the gap environment to lateral flow effects, further testing is recommended to determine the lateral heating variation within an elevon/wing cove gap. The effects of lateral pressure gradients and hinge lines aligned at angles other than 90° should also be examined. This line of testing, however, would require new test models and different test facilities.

ADDITIONAL TEST RECOMMENDATION - CURTAIN SEAL MATERIALS

The preliminary evaluation testing of Space Shuttle wing-elevon cove seal materials should be backed up by additional testing to justify our recommendation of the flexible seal design.

Additional tests that should be performed are:

- 1) Tensile tests:
 - Tests at temperatures from -250°F through 600°F,
 - Room-temperature tests of cycled specimens;
- 2) Shear tests at temperatures of -250°F, -200°F, -150°F, and -100°F;
- 3) Thermal conductivity tests;
- 4) Thermal expansion tests;
- 5) Compatibility tests with hydraulic fluid, salt spray, and fungi;
- 6) Vacuum testing.

"SECOND GENERATION" TEST RECOMMENDATIONS

The next consideration for developing high-temperature gap design technology must be focused on resolving the elevon end gap problem. However, some future planning beyond this step is necessary. Very briefly, the following ideas represent some of our thinking on "second generation" tests.

- 1) Configuration Goals
 - Full-scale depth & length - Elevon/Wing
 - Latest TPS system, including curtain seal & labyrinth (if required)
- 2) Test Conditions - Latest Shuttle entry environment
- 3) Test Objective - Qualification of elevon TPS and seals
- 4) Test Facility - Langley High-Temperature Structure Wind Tunnel or suitable equivalent.

REFERENCES

1. W. H. Rowe, Jr.: *PRIME Project Hypersonic Heat Transfer and Pressure Test Results on Variable-Gap Cove Models in Tunnel of Arnold Center*. ER 13881. Martin Marietta Corporation, Baltimore, Maryland, September 1965.
2. I. Stern and W. H. Rowe, Jr.: "Effect of Gap Size on Pressure and Heating over the Flap of a Blunt Delta Wing in Hypersonic Flow." *J. Spacecraft and Rockets*, Vol 4, No. 1, January 1967.
3. J. D. Dearing and H. H. Hamilton: *Heat Transfer and Pressure Distributions Inside the Hinge Line Gap of a Wedge/Flap Combination at Mach No. 10.4*. NASA TN D-4911. November 1968.
4. W. D. McKaig: *Structural Test Program Test and Evaluation Report: Task 3.0 - Dynamic Seals*. North American Rockwell, December 7, 1971.
5. Coleman DuP Donaldson and J. Dunn: *Preliminary Investigation of Methods for Calculating Substructure Heating on Cracked Reentry Vehicles (U)*. Contract DA-49-146-xz-430. June 1969. (Secret) - page referenced is unclassified.
6. W. M. Kays: *Transactions of the ASME*, Vol 77, 1955, p. 1265.
7. R. L. Kirlin, E. G. Littler and C. C. Miller: *High-Temperature Dynamic Seals for Aerodynamic Control Surfaces on the Space Shuttle*. MCR-73-138. Martin Marietta Corporation, Denver, Colorado, June 1973.
8. R. L. Kirlin and D.A. Schmitt: *High-Temperature Dynamic Seals for Aerodynamic Control Surfaces on the Space Shuttle*. MCR-73-117. Martin Marietta Corporation, Denver, Colorado, June 1973.

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APPENDIX

RECOMMENDATIONS FOR
QUALIFICATION TEST PROGRAM
FOR SPACE SHUTTLE ORBITER
AERODYNAMIC CONTROL SURFACE
SEALS

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Developing a qualification program to test dynamic seals for Space Shuttle aerodynamic control surfaces requires more data and information than is presently available. Some of the data that are not fully defined are as follows:

- 1) End gap heating;
- 2) Structural configuration;
- 3) Thermal protection system;
- 4) Final vehicle geometry;
- 5) Aerodynamic control surface deflection history;
- 6) Structural deflections.

We recommend that the seal qualification test program include, as the major component, a full-scale wind tunnel test bed. The full-scale refers only to the elevon cross-section; the length and width of the test bed would be limited by the constraints of the test facility.

The Langley Research Center's Mach 7, 8-ft-diameter High-Temperature Structures Tunnel and the AFF DL 50-megawatt Hypersonic Facility are two candidate facilities for testing the full-scale test bed. The full-scale test article would be similar to that shown in Figure A-1, which is a model of the Space Shuttle Orbiter wing-elevon-body area. This model is approximately 30 in. deep by 50 in. wide by 80 in. long (not counting the leading edge fixture). The model is in the inverted position with the flow angle of attack 30° off the centerline of the vehicle. The elevon is shown with its full deflection capability of -40° to 20° , actuated by means of a screw jack or a hydraulic cylinder.

The orbiter body is represented on one side of the model as shown. The model support sting is in a low position and the rear frame of the fixture is out of the way, allowing unblocked airflow through the elevon end gap. Note that the hinged seal panel at the upper surface wing/elevon juncture is also a part of the model.

The mounting arrangement for the model should include the capability of varying the yaw angles to test the effectiveness of seals in tolerating the lateral flow component. The model must include the orbiter thermal protection system for the surfaces.

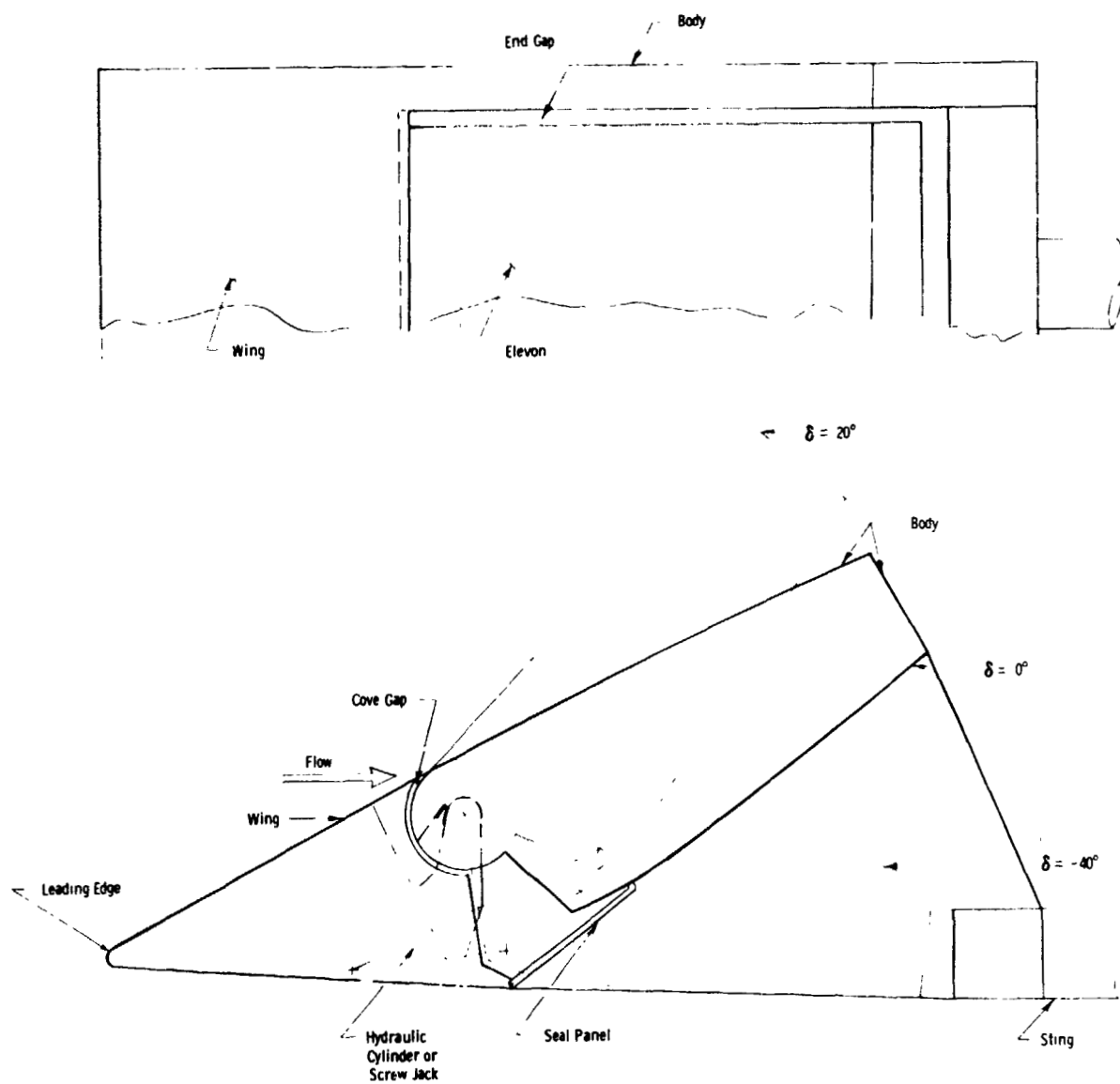


Fig. A-1 Test Bed for Aerodynamic Control Surface Seals

The leading edge and forward 40 in. (wing) of the model can be part of the model fixture and do not have to be flightweight structure with a flight TPS. Since the model is a test bed for aerodynamic control surface seals, the seals should be readily replaceable.