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AEROTHERMAL ENVIRONMENT IN CONTROL SURFACE GAPS IN HYPERSONIC FLOW - AN OVERVIEW

ALLAN R. WIETING, JOANNE L. WALSH, AND
KIM S. BEY

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Langley Research Center
Hampton, Virginia 23665

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Allan R. Wieting , Joanne L. Walsh
and Kim S. Bey
NASA Langley Research Center
Hampton, Virginia

Abstract

Experimental and analytical research by the NASA Langley Research Center to develop an understanding of the fluid and thermal environment in control surface gaps such as the spanwise gap of the wing elevon and chordwise gap of a split elevon configuration typical of the Space Shuttle are summarized. Although the experimental and analytical studies were initiated too late to significantly impact the ~~basic~~ Shuttle design they do provide a fundamental understanding of the basic fluid/thermal environment in control surface gaps and help to establish a firm data base for future vehicle design.

Nomenclature

d,x,r	local coordinate
M	Mach number
$\dot{q}$	local cold wall convective heating rate
$\dot{q}_e$	heating rate on elevon windward surface
$\dot{q}_{ref}$, $\dot{q}_w$	reference heating rate on wing windward surface
T_g	local gas temperature
T_i	initial rub tube temperature
$T_{rub,max}$	maximum rub tube temperature
T_t	free stream total temperature
α	wing angle of attack
δ, σ	elevon deflection angle

Introduction

The ingestion of hot gas and the possible disastrous consequences of the flow of these gases in control surface gaps in hypersonic flow has been a continuing concern in the design of the current Space Shuttle Orbiter. Of specific concern was the flow in the spanwise gap or cove between the wing and the elevon and the flow in the chordwise gap between moveable surfaces such as the gap between the split elevons. The potential problem for the wing elevon cove is depicted in fig. 1 which shows a sketch of the current Space Shuttle Orbiter and a simplified cross-sectional view of its structure at the juncture between the wing and elevon. Without the spring-loaded polyimide rub seal, differential pressure between the windward and leeward surfaces of the wing would drive a portion of the boundary-layer flow into the cove where it would contact the unprotected aluminum load-bearing structure.

The concern for the split elevon centered about the unknown aerothermal environment which would be a changing mixture of wing and elevon flow dependent on wing and elevon attitude. The problem is compounded by the closeness of the sidewalls which reduces the radiation heat transfer to space; and hence increases the net structural heat transfer. Since the elevon net structural heat transfer is near the design limit there is a high probability that the elevon sidewall loads will exceed design limits and result in excessive surface and sub-structure temperatures.

To provide insight into these problems and provide a data base for future vehicles, essentially full scale models of the wing elevon cove gap and the split elevon gap were tested in the Mach 7 environment of the Langley Research Center 8-Foot High Temperature Tunnel (8' HTT). Supporting analytical studies of the wing elevon cove flow and heat transfer were also undertaken. Although the experimental and analytical studies were initiated too late to significantly impact the basic Shuttle design they do provide a fundamental understanding of the basic fluid/thermal environment in control surface gaps and help to establish a firm data base for future vehicle design.

The purpose of the present paper is to summarize these investigations and present some of the salient results of the experimental and analytical research. Brief descriptions of the 8' HTT and experimental and analytical models are included.

Facility

The Langley Research Center 8-Foot High Temperature Tunnel (8' HTT), schematically illustrated in fig. 2, is a hypersonic blowdown wind tunnel that operates at a nominal Mach number of 7, at dynamic pressures between 290 and 1450 psf, and at total temperatures between 2500°R and 4000°R for free-stream unit Reynolds numbers between 0.3×10^6 and 3.0×10^6 per foot. The test medium is the combustion products of methane and air which are produced in a high-pressure combustor, expanded through an axisymmetric contoured nozzle 8 ft. in diameter at its exit, and diffused and pumped from the test section to the atmosphere by means of a single-stage annular air ejector. In the test section, the stream is a free jet 12 ft. in length with a uniform test core approximately 4 ft. in diameter. During tunnel startup, models are stored in the pod below the test stream until the desired hypersonic flow conditions are established; the model is then inserted rapidly into the stream by means of a hydraulically actuated elevator and is withdrawn prior to termination of tunnel flow. The maximum test time for this facility is 2 minutes; the nominal aerothermal loads test is 10 seconds which is sufficient to obtain cold wall heating rates as presented herein. More detailed information on this facility is reported in reference 1.

Experimental Models

Split Elevon. The 4.3 ft. wide, 8 ft. long model, shown installed in the 8' HTT in fig. 3, consisted of two elevon flaps (split elevons) attached to a forward body that had a sharp leading edge, a flat windward surface that simulated the lower surface of the Shuttle wing and a curved leeward surface. The split elevons were separated by a stub which interrupts flow in the spanwise gap between the wing and the control surface. Fences were attached at the top and bottom of the model to ensure two-dimensional flow on the wing portion of the model. Flow trips were attached near the leading edge of the model to produce a turbulent boundary layer on the windward surface. The model was mounted vertically on a wedge-shaped center support about which the model could rotate for angles of attack from 0 to 15°. The elevons could be rotated independently from 0 to 15° about a hinge line located 78 in. from the wing leading edge. The elevon/stub gap was varied from 0 to 0.5 in.; the corresponding variation in the elevon/elevon gap was 2.8 to 3.8 in. Based on a nominal elevon/elevon gap of 3.0 in. the model was approximately 1/2 scale; however, the elevons are truncated at approximately 50 percent chord to reduce model blockage effects on the tunnel flow. Further details can be found in reference 2.

Wing Elevon Cove. The model, shown installed in a sting-mounted 10 ft. long by 4.6 ft. wide flat test bed in fig. 4, consisted of a fixed wing-cove housing, a rotatable elevon, and aerodynamic fences at the sidewalls to channel the upstream surface flow across the cove entrance. The cove entrance located 49 in. downstream from the sharp leading edge, was unswept with respect to the tunnel flow. The model was used as shown for studies[3,4] (ref. 4 is an abbreviated version of ref. 3) in which the wing turbulent flow remained attached and was modified slightly for subsequent laminar studies[5] in which the wing flow was separated.

The cove channel gap height and radii duplicated that of the Shuttle Orbiter. Seal leakage was simulated by rectangular slots in a rub seal located at the end of the channel. Both the length and height of the slot were varied to simulate small localized seal failures as well as major seal failures over a range of 13 leak areas from 0 to 100 percent of cove entrance area. Details can be found in references 3-5.

Analytical Models

Brief descriptions of the one and two dimensional analytical models of the wing elevon cove flow and heat transfer follow. No analytical models of the split elevcn flow have been developed.

One dimensional heat transfer model. This model was developed to predict the thermal response of the Shuttle wing elevon cove during entry so that the various heat transfer modes could be evaluated and to estimate the maximum allowable cove leak area for the Shuttle. The ingested air was assumed to be a thermally perfect gas at the temperature of the wing surface. The flow was assumed to be a one dimensional, hydraulically and thermally developing flow between parallel straight plates. The model accounts for the effects of energy transport by the air mass flow, convection to the walls, and wall conduction, radiation, and thermal storage capability. Further details of the mathematical development and the relationship for the convective heat transfer coefficient are given in reference 6.

2D compressible Navier Stokes model. This analysis was undertaken to provide a fundamental understanding of the external and internal flow field at the wing elevon cove junction. In this analytical study a 2D mathematical model using the continuity, energy, and compressible Navier Stokes equations for laminar supersonic flow was developed. The explicit finite difference scheme reported in reference 7 was adapted to solve the governing equations. The computational domain was discretized into approximately 11,000 grid points and at each point two velocity vectors, density, and temperature were determined. This process required the solution of approximately 44,000 simultaneous equations for each time step. The numerical size of the problem and a small computational time step (10^{-6} s) restricted the model to a very small area which extended approximately 3 in. upstream and 5 in. downstream of the cove, 2 in. into the airstream and 2 in. into the cove.

2D incompressible Navier Stokes model. This analysis was undertaken to better understand the effects of cove geometry on flow field and cold wall convective heat transfer to the cove surfaces. The finite element procedure developed in reference 8 was used in this analysis as the thermal effects of the cove structure could be modeled along with the flow. The air flow was assumed to be a thermally perfect gas, incompressible, viscous, and laminar. To determine the effects of curvature, the 0.5 in. high by 12 in. long cove was first modeled as parallel straight plates and then as parallel curved plates. The straight plate model, which takes advantage of symmetry, consisted of 140 elements with approximately 1000 unknowns (velocity, pressure, and temperature). A high concentration of elements existed at the cove inlet, wall, and centerline to capture the gradients due to the developing boundary layer. The boundary conditions (inlet velocity and temperature, exit pressure) applied to this model were determined from experimental data from references 3 and 5.

Results and Discussion

Split Elevon

Oil flow studies provided an insight into the split elevon gap flow phenomena. Typical oil flow patterns on the windward wing and elevon surfaces, and stub and elevon sidewall surfaces are presented in fig. 5 for a wing angle of attack of 10° and elevon deflection of 10°. The patterns in fig. 5a indicate the gap flow consisted of flow from the windward surfaces of both the wing and the elevons. From fig. 5b the flow in the elevon/stub gap is shown to be primarily from the windward wing surface and apparently negligible; whereas, the flow in the elevon/elevon gap appears to be predominantly from the windward elevon surface with some effect of the wing flow. The oil streak, fig. 5b, parallel to the windward edge probably indicates the attachment of the windward elevon flow which expands around the elevon edge.

The effect of elevon deflection on the heating rate distribution along the aft edge of the elevon/stub gap is given in fig. 6 for a gap width of 0.5 in. and a 10° wing angle of attack. The heating rate which is shown normalized by the wing heating rate is independent of the elevon deflection angle and proportional to the wing heating rate. The maximum measured heating was 36 percent of the turbulent heating on the wing and occurred for an elevon/stub gap width of 0.07 in.

The effect of elevon deflection on the heating within the elevon/elevon gap is given in fig. 7 for a gap width of 3.8 in. and a 10° wing angle of attack. The local sidewall heating, which is shown normalized by the corresponding heating rate to the windward elevon surface, is essentially governed by the windward elevon flow as indicated by the near collapse of the data about a single line. Some influence of the leeward flow on gap heating near the leeward surface is apparent. Other results, not presented here, indicate that the maximum gap heating decreased with gap width. A peak heating of 30 percent of the turbulent heating on the elevon was obtained with an elevon/elevon gap width of 2.8 in.

This data, although limited, tended to indicate that the High Temperature Reusable Surface Insulation (HRSI) would provide adequate thermal protection during Shuttle entry. However unpublished results from subscale (0.03) tests at Ames Research Center with laminar flow indicated gap heating 136 percent of the corresponding laminar elevon heating. Consistent with the conservative Shuttle design philosophy, this ratio was assumed to apply also to turbulent flow for which the HRSI would not be adequate. Thus, the HRSI was removed from the elevon sidewalls and replaced with an ablator. During the first four Shuttle flights the ablation in the elevon/elevon gap was less than expected. On the fifth flight the ablation panels on one elevon sidewall were replaced with instrumented HRSI tiles (Air Force Flight Test Center Technical Letter Report, Dec. 1982). Sensors indicated a peak surface temperature of 2590°F (2700°F design limit) occurred during the first 500 s of entry with the elevons deflected down 5 degrees. The surface temperature decreased 100°F when the elevon was changed 4 degrees to a down deflection of 1 degree. This three percent temperature change reflects at least a corresponding 14 percent decrease in heat flux. Since the elevon heat flux would also decrease with the decrease in down deflection the trends appear to be consistent with the results presented in fig. 7. Post flight inspection of the HRSI tiles along the windward edge of the outboard elevon sidewall showed that they were glazed with some pitting and flowing outboard of the black coating on the tiles. This could be a result of flow attachment as discussed earlier with the oil flow patterns.

Even with flight results there is still some question about the elevon/elevon gap flow data obtained with truncated elevons. Consequently, the model used in the 8' HTT test is being modified to eliminate the truncation and simulate elevon/elevon gap and elevon chord at approximately one-third scale. The purpose of these tests will be to establish detailed aerothermal loads on the elevon sidewall surfaces for both laminar and turbulent flow.

Wing Elevon Cove

Attached flow. The experimental results[3,4] for attached flow indicated that the flow at the end of the fixed portion of the wing expanded prior to being compressed by the deflected elevon. The expansion resulted in cove pressures less than the windward wing pressure and hence a lower pressure differential to drive flow through the cove. Cove static pressures were essentially uniform and decreased as leak area (leakage) increased. Cove heating rates at maximum leakage were less than 30 percent of the wing heating rate and decreased by two orders of magnitude over the leakage range. Although the heating rates were relatively benign, the measured cove gas temperature at maximum leakage approached 50 percent of the free stream total temperature (T_t) at the cove entrance and 35 percent of T_t at the seal.

Three basic results emerged from these tests: (1) the cove environment is sufficiently hostile to require thermal protection of the cove surfaces and positive sealing to exclude hot gases from the unprotected interior aluminum structure is essential; (2) the cove aerothermal environment is dependent on the approaching wing boundary layer and leak area and not on elevon deflection as long as the wing flow is attached; and (3) the convective heat transfer in the cove increases with time. The latter occurs because, in contrast to the external flow where the energy source is essentially infinite, the cove flow consists of a relatively small portion of the wing boundary layer and hence has a finite energy content. Initially a substantial amount of the energy of the ingested mass is lost to the cool upstream cove surfaces, so that very little potential for transferring energy deep inside the cove remains. However, as the upstream cove walls approach thermal equilibrium (steady state), increasing amounts of energy are retained by the ingested mass. Consequently the potential for increased heat transfer to the cove interior exists.

Higher than expected cove heating was demonstrated on the first and second flight of the Space Shuttle (STS-1 and 2) when temperatures of approximately 2100°R were recorded at the outboard end of the elevons.[9] Post-flight inspection of STS-1 revealed thermally damaged insulation in the cove that required replacement by a material capable of withstanding higher temperatures. These high temperatures could be due to several factors not taken into account by these tests, such as the time dependency of the cove heating or three dimensional flow effects. The 3D flow effects will be studied in the 8' HTT in 1985 using a new general purpose lifting surface test apparatus which simulates a swept wing with a remotely controlled elevon.

Separated flow. Although not anticipated for Shuttle flight conditions, the potential exists for ingestion of more fluid mass into the cove and attendent higher heating when the wing flow is separated than when the flow is attached. For example, as illustrated in fig. 8 for a leaking seal, a separation bubble forms on the wing upstream of the cove entrance. The wing boundary layer flows over the bubble and reattaches on the deflected elevon producing a pressure plateau over the cove entrance which drives the boundary layer mass between the separating streamline and the dividing streamline into the cove. Consequently, a follow-on investigation[5] was initiated to define cove response to flow separation as a function of cove seal leak area, elevon deflection angle, and free-stream unit Reynolds number. The bulk of the investigation was conducted for separation from an initially attached laminar boundary layer, although a few tests were also conducted to induce separation from an initially attached turbulent boundary layer.

Similar to the attached flow results, the level of heating within the cove is highly dependent upon flow conditions on the wing at the cove entrance, as shown in fig. 9. In these plots the local heating rates ($\dot{q}$) normalized to the laminar attached flow wing value at the cove entrance ($\dot{q}_{REF}$) are compared with theoretical predictions. The theoretical laminar and turbulent heating rates were predicted by Eckert's reference temperature method and the cove heating rates were obtained with the one dimensional (channel) heat transfer analysis. With laminar-flow separation near the cove entrance (left graph) wing heating rates (open symbols) under the separated boundary layer decrease sharply from equivalent attached-flow values, and cove heating rates (filled symbols) diminish along the cove length by an order of magnitude. Increased elevon deflection angle (σ) moves the flow separation point upstream and, as shown by the rising wing heating rates (center graph), the separated laminar boundary layer transitions to turbulent flow ahead of the cove entrance. Consequently, cove heating rates are an order of magnitude greater than for purely laminar flow separation at the same cove seal leak area. However, as shown in the right graph, for the same elevon deflection, if the leak area is sufficiently large boundary layer suction can force the separated boundary layer to reattach, thereby reducing cove heating rates. Comparison of results[3-5] indicated that the cove heating rates for attached flow were lower than those for separated flow but consistent with the concept that the heating would be the same for the same mass flow and ingested gas temperature.

<u>One dimensional heat transfer analysis</u>. The validity of the mathematical model was established by comparison with the experimental results of references 3-5 as shown in fig. 9. The parametric study[6] to determine the effects of various transport, thermal and geometric parameters indicated the following: Although convection is the predominant factor controlling the cove wall temperature, energy penetration deep into the cove interior can be retarded by low wall thermal conductivity, low internal radiation (low emittance), and high wall thermal capacitance. Although low radiation heat transfer retards the initial cove wall temperature rise, increased radiation reduces the interior wall temperature during the latter part of the entry exposure when cove temperatures are highest. The model was also used to predict the maximum rub tube (fig. 1) temperature as a function of leak area and initial tube temperature at entry as shown in fig. 10. Predicted thermal response of the elevon cove subjected to Shuttle-entry conditions indicated that the allowable leak area at the cove seal could not exceed 0.035 times the cove entrance area. This result was 20 percent less than that previously indicated by the experimental results reported in reference 10. This small allowable leak area and the unlikelihood that the rub seal would provide a leak tight seal resulted in a decision to install a redundant membrane seal (fig. 1). The membrane seal provides a leak tight seal except at the spanwise extremities.

<u>2D compressible Navier Stokes analysis</u>. Sealed and unsealed cove configurations were analyzed using boundary conditions from laminar attached flow results reported in references 3 and 5. Although a converged solution was not obtained, the analysis provided qualitative insight into the interaction between the laminar external boundary layer flow and the flow in the cove. The basic flow phenomena for a nominal leak rate is illustrated in fig. 11. The external flow expands off the fixed portion of the wing and is compressed by the deflected elevon forming a compression shock. The small portion of external boundary layer between the wing and separating streamline is ingested into the cove and a recirculating eddy develops at the entrance of the cove. The basic flow in the cove is characteristic of incompressible developing flow between parallel plates. The mass and energy of the boundary layer flow ingested into the cove depends on the cove inlet to outlet pressure differential and the seal leak area. The flow field for a sealed cove consists primarily of a single recirculating eddy at the cove entrance with the remainder of the cove media essentially stagnant. This analysis effort is continuing through the use of alternate numerical techniques and grid mapping procedures to eliminate the problems of the initial effort. The exact problems are not known, however the two boundary mapping technique and the excessive smoothing required by the solution algorithm to handle flow (i.e., shock) and geometry (i.e., wing elevon junction) discontinuities are felt to be the main factors. Even with these problems unresolved, the insight provided by the analysis gave credence to simplifying assumptions used in the other math models of the cove flow and to conclusions drawn from experimental results.

<u>2D incompressible Navier Stokes analysis</u>. Only results from the parallel straight plate model analysis are currently available. Results from the flow analysis indicate that fully developed flow does not exist in the cove. The flow Mach number is less than 0.2 which is within the limits of the incompressible flow assumption provided the effect of temperature dependent properties is negligible.

Results from the analysis are compared with experimental data in figs. 12 and 13. The gas temperature along the centerline of the cove normalized to the free stream total temperature is shown in fig. 12. The predicted temperatures are higher than the experimental temperatures by approximately 15 percent. The corresponding cold wall heating rate distribution along the length of the cove is shown in fig. 13. The analysis and the experimental data agree well over the first 30 percent of the cove length. Downstream there is some scatter in the experimental data that is not predicted by the parallel straight plate model. These discrepancies could be due to normal experimental data scatter, due to the curvature of the cove, or due to the change in area and shape at the downstream end of the cove. The effects of curvature on cove flow and hence the gas temperature and cold wall heating rate distributions are currently being investigated by modelling the parallel curved section of the cove.

Concluding Remarks

Experimental and analytical research by the NASA Langley Research Center to develop an understanding of the fluid and thermal environment in control surface gaps such as the spanwise gap of the wing elevon and chordwise gap of a split elevon configuration typical of the Space Shuttle have been summarized. This data generally became available too late in the Shuttle design and fabrication phase and consequently several components underwent modifications. To assure an adequate and timely data base for future vehicles, continued research is required to include more realistic 3D flow and geometric effects.

Generally the results indicate that the gap environments are dependent on the flow immediately upstream and the pressure differential forcing the flow through the gap. Experimental gap heating rates are substantially less than local windward heating rates, however measured gas temperatures (wing elevon cove only) are sufficiently high to warrant thermal protection of the structure. Analytical studies have provided insight into the fluid flow and heat transfer mechanism for the wing elevon cove.

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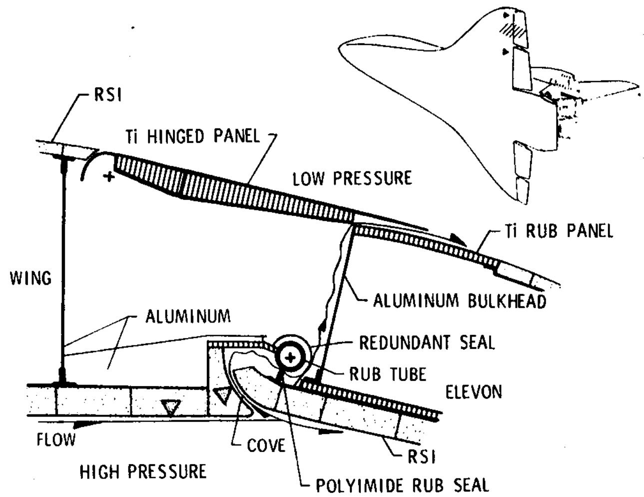


Fig. 1 Cross section of a Space Shuttle Orbiter type structure at wing-elevon juncture.

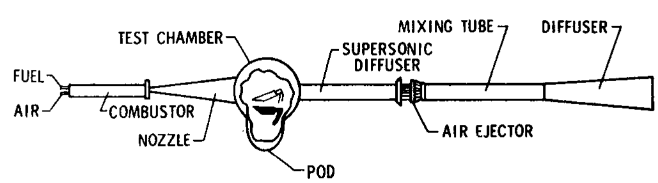


Fig. 2 Schematic of LaRC 8-Foot High Temperature Tunnel.

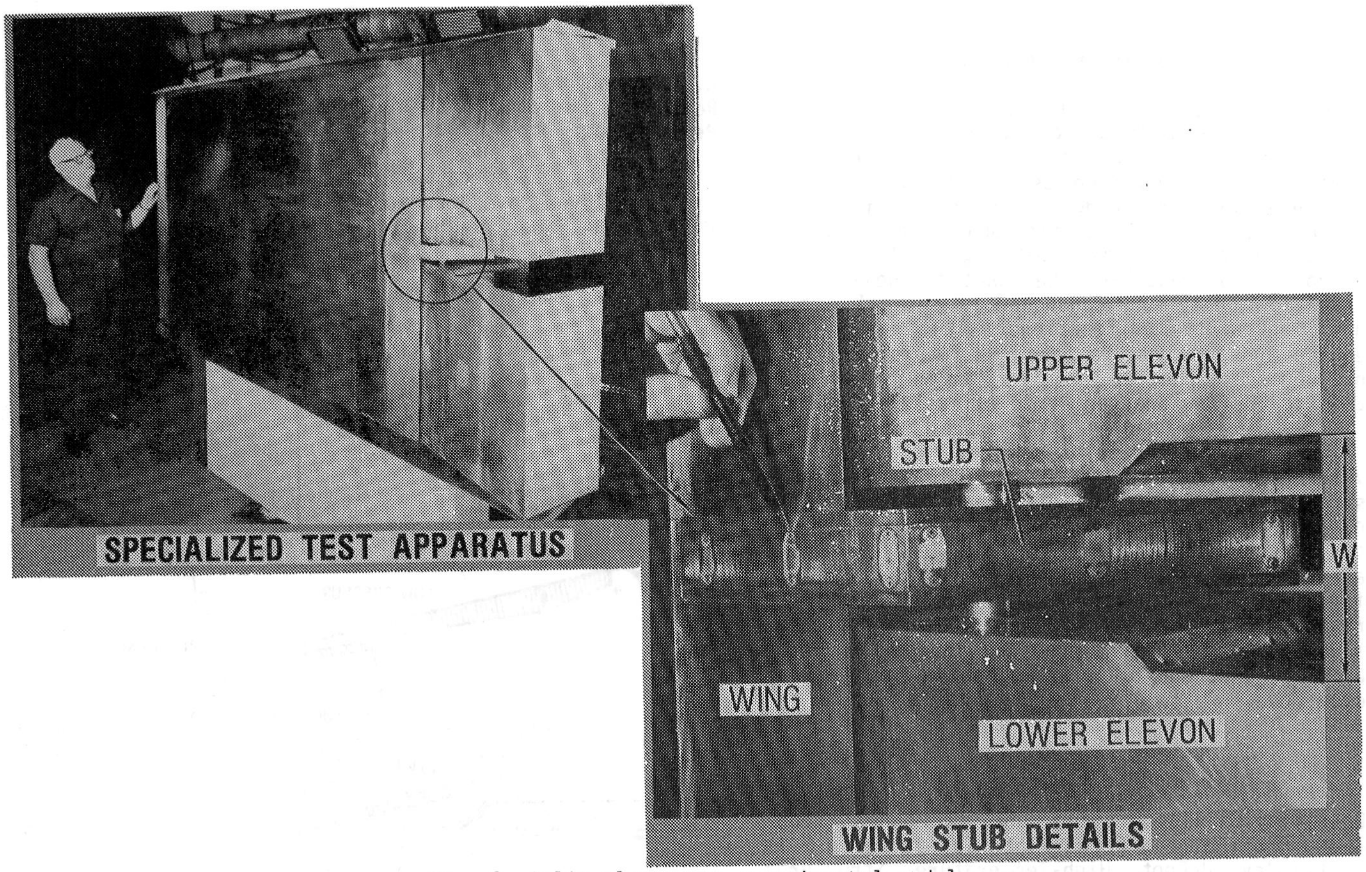


Fig. 3 Split-elevon gap experimental model.

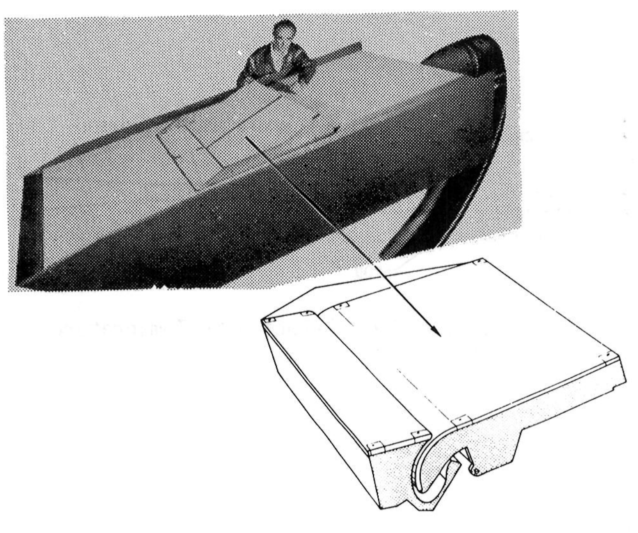
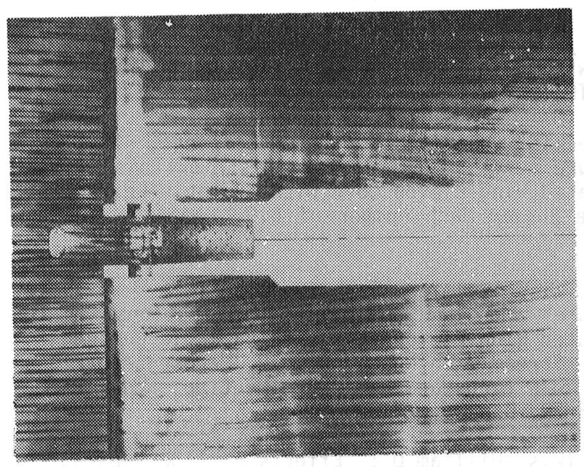
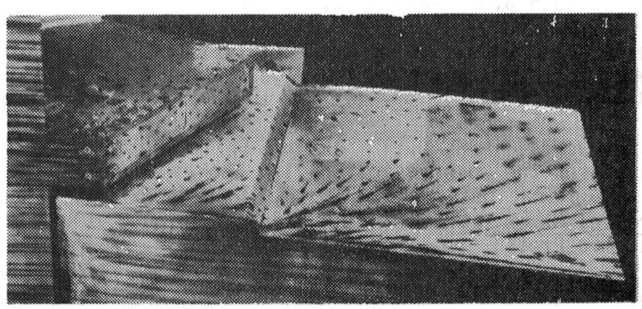


Fig. 4 Wing elevon cove experimental model.



a) Wing-elevon windward surface



b) Stub and elevon sidewalls

Fig. 5 Oil-flow pattern on wing and elevon surfaces. $\delta = 10°$; $\alpha = 10°$.

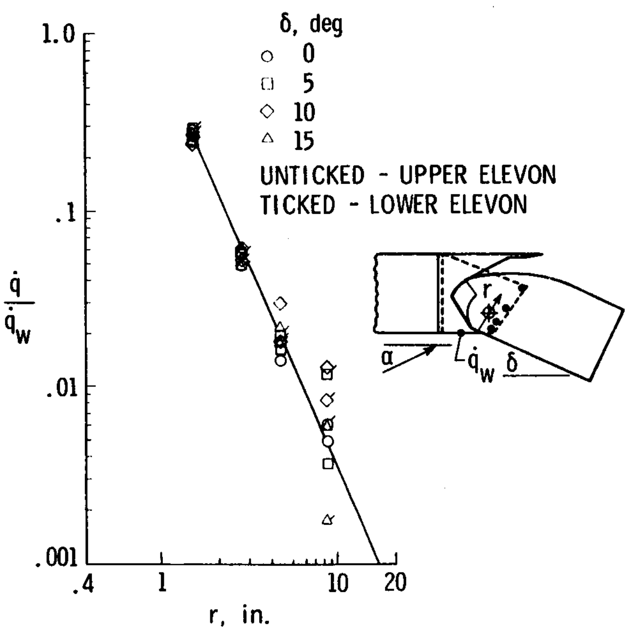


Fig. 6 Elevon/stub gap heating distribution for various elevon deflections for a elevon/stub gap of 0.5 in. α = 10°.

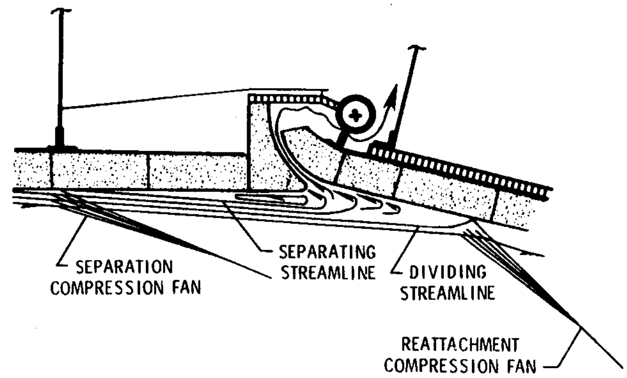


Fig. 8 Simplified flow details across cove entrance for separated flow.

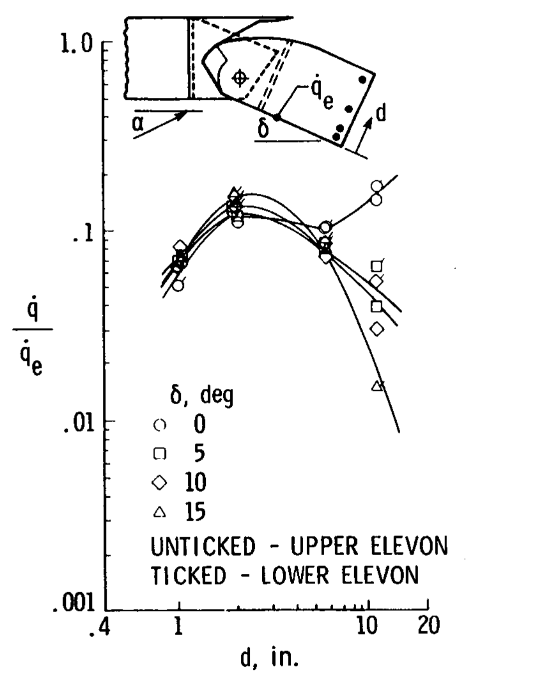


Fig. 7 Elevon gap heating distribution for various elevon deflection angles for an elevon/elevon gap width of 3.8 in. α = 10°.

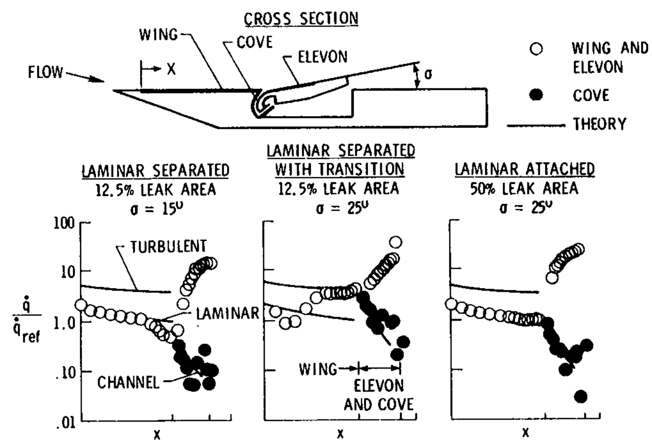


Fig. 9 Typical heating rate distribution for a wing elevon cove with leakage.

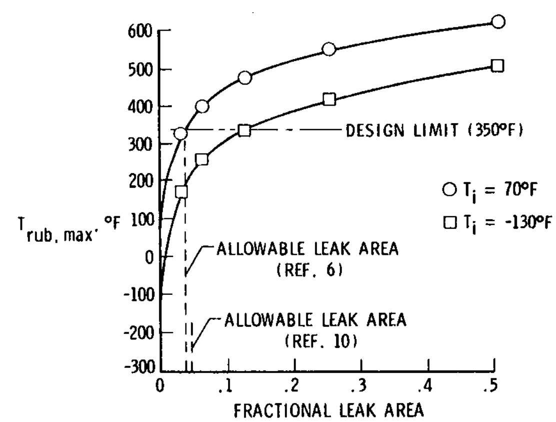


Fig. 10 Variation of maximum rub-tube temperature with fractional leak area.

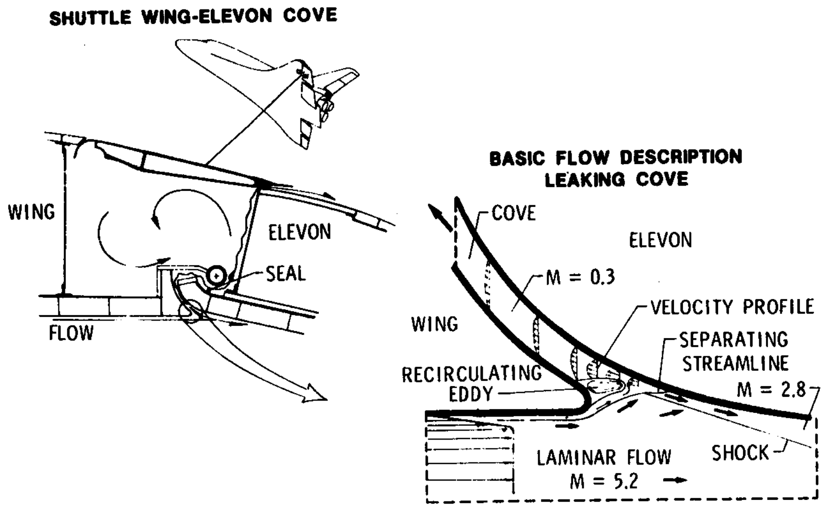


Fig. 11 Basic flow description of leaking cove as predicted by 2D compressible Navier Stokes analysis.

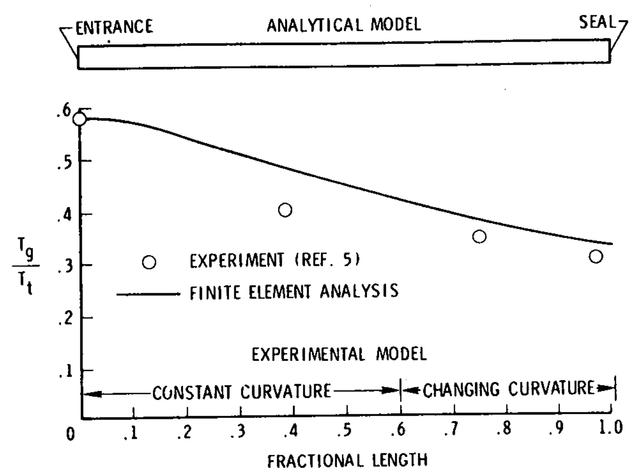


Fig. 12 Cove centerline gas temperature distribution.

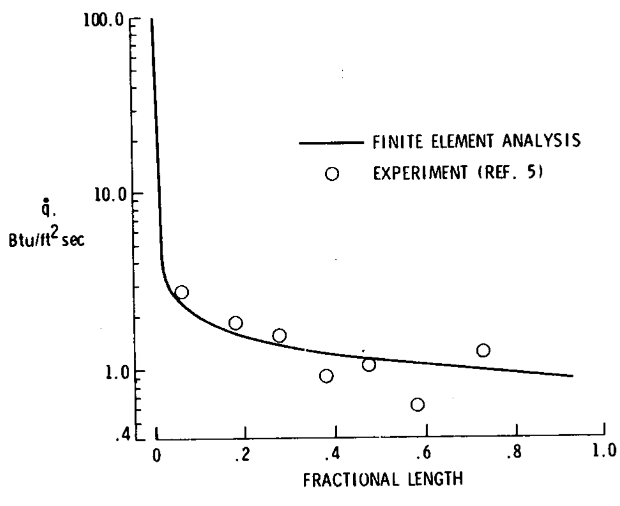


Fig. 13 Cove cold wall heating rate distribution.

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15. Supplementary Notes

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16. Abstract

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