



**AIAA-81-2512
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Shuttle Orbiter as a
Research Vehicle**

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**AIAA/SETP/SFTE/SAE/ITEA/IEEE
1st Flight Testing Conference**

November 11-13, 1981/Las Vegas, Nevada

OEX--USE OF THE SHUTTLE ORBITER AS A RESEARCH VEHICLE

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Abstract

The Orbiter Experiments Program, referred to as OEX, is a NASA program to provide research instrumentation on the Shuttle Orbiter. The individual experiments currently under development are described as well as the specific research problems to be attacked. The research focuses on the entry phase of the flight. The experiments, combined with other instrumentation onboard the orbiter, will provide a wealth of benchmark flight data which is expected to make a significant impact on the design of future space transportation systems.

Introduction

One of the distinguishing marks of the 1980's for aerodynamicists and aerothermodynamicists will be periodic flights of the space shuttle, which will provide recurring opportunities to study flight problems of a winged vehicle from hypersonic entry conditions to touchdown. In order to capitalize on this opportunity, the National Aeronautics and Space Administration has instituted the Orbiter Experiments Program, familiarly known as OEX. The purpose of the OEX program is to provide the means by which researchers may design, develop, and mount on the shuttle instrumentation for specific flight research purposes.

For the initial shuttle flights, the instrumentation onboard may be categorized as either operational instrumentation for monitoring various operational functions, or developmental flight instrumentation for measuring parameters required to perform design verification. Most of this latter instrumentation is intended to be removed after the first four flights because its total weight is a significant fraction of the payload capability. Therefore, it is highly desirable to make maximum utility of this developmental flight instrumentation while it is onboard. The research plans and activities at Langley Research Center to make use of this flight data are described in Ref. 1. However, the OEX program hopes to retain that portion of the development flight instrumentation which is most important for research purposes. In addition, new OEX instruments will be added at appropriate times to provide measurements, of a research quality, specifically needed for the planned experiments.

This paper will discuss some of the aerothermodynamic problems of atmospheric entry which will benefit from full-scale flight data, and some of the OEX instruments being constructed for use on the orbiter during entry which are expected to provide flight data that will help find solutions to these problems.

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Nomenclature

C_p	pressure coefficient = $(p_w - p_\infty) / \frac{1}{2} \rho_\infty V^2$
H_0	stagnation enthalpy
M	Mach number
p_w	local wall pressure
p_∞	freestream pressure
R	gas constant
Re	Reynolds number based on body length
T_r	reference temperature = 273 K
V	freestream velocity
\bar{V}	viscous interaction parameter = M / \sqrt{Re}
λ	mean free path
ρ_∞	freestream gas density

Flight Aerothermodynamic Problems

The total data base available to researchers and designers who are concerned with future entry vehicles consists of ground test data, flowfield computations, and flight test data. From a combination of these three, correlation techniques have been derived to predict the performance and govern the design of candidate configurations. Because of deficiencies in this data base however, some such guideline correlations are very limited in scope, or untested, or even absent altogether. The data base deficiencies are the result of a combination of limitations of ground-test facilities and analytical methods in their ability to simulate the important parameters of full scale, hypervelocity flight, and a dearth of flight data in this regime.

Ground-Based Data Limitations

The most extensive portion of this base has been ground test data. However, wind tunnels are deficient in modeling of several aspects of entry environment. The most serious of these deficiencies are in the failure to duplicate flow chemistry and failure to predict reliably boundary-layer transition. Conventional wind tunnels are not designed to produce high flow enthalpy, and although they may be hypersonic, they are not hypervelocity. Various other devices, which include shock tunnels, shock tubes, arc tunnels, hot-shot tunnels, expansion tubes, and free piston compressors, have been built in attempts to model the high enthalpy aspects of entry. While such devices have made valuable contributions, each has encountered limitations which impaired its usefulness and restricted the type of problem to which it could contribute useful data.

Although innumerable studies of boundary-layer transition have been conducted in hypersonic wind tunnels, the results have been unreliable and inconsistent. One prominent cause of this lack of consistency is the noise of the tunnel wall boundary layer which radiates to the model boundary layer and thus perturbs its stability in a nonpredictable manner.

Advances in memory size and computation speed of large computers have been accompanied by advances in flowfield computational methods. Rapid strides

have been made in computing viscous flows over three-dimensional configurations. However, modern computer codes do not yet incorporate all the tools needed to provide benchmark solutions at entry speeds, particularly for winged configurations. The presence of embedded subsonic flow, for example, is inconsistent with the commonly used marching techniques. Such shortcomings are presently being removed however, and the current level of activity in this technology will undoubtedly bear much fruit in the coming years, and make more substantial contributions to the total data base.

Entry Flight Conditions

Figure 1 illustrates the ranges of some of the important parameters required to model Earth entry from low orbit. The trajectory shown for the orbiter is taken from its first flight, STS-1. Even the operational envelope of the X-15 research aircraft did not begin to include the high Mach numbers of interest. The deficiency of wind tunnels in terms of flow energy is indicated by the auxiliary abscissa showing the total enthalpy necessary to duplicate flow velocity. (This scale applies only to the lower altitude portion of the trajectory, below the Mach number peak.) As an example of the deficiency, it may be noted that the isentropic stagnation (reservoir) condition required in a steady flow wind tunnel to achieve the shuttle trajectory condition of 80-km altitude would be a pressure of 20,000 atmospheres and temperature of 12,500 K. Even if this condition could be achieved, the Reynolds number would be deficient by the scale of the model.

The ambient values of mean free path shown in Fig. 1 illustrate an additional complication for experimental and computational aerodynamics. At an altitude of 90 km, the mean free path is about 3 cm, while the shock standoff distance near the stagnation point of the orbiter is computed to be about 12 cm. Thus it is important that shock and body slip conditions, as well as finite-rate chemical reactions, be included in the computational method.

The foregoing discussion on limitations of ground-based data and methods is given to illustrate the great value of obtaining research grade data on the orbiter. Evaluation and analysis of orbiter flight data may be expected to increase our understanding of the basic flow phenomena in a number of problem areas. Some of these problems are described in the following paragraphs.

Aerodynamic Coefficients

The orbiter has been designed largely on the basis of tests run in perfect gas wind tunnels. Extraction of the aerodynamic coefficients from the flight data will provide the opportunity to assess the importance of gas chemistry on the static and dynamic aerodynamic coefficients and control effectiveness. Of particular importance is the separation of the response of the reaction control system from the overall coefficients. Reaction control response is particularly difficult to model in the wind tunnel, so flight data will be very valuable in this area. Windward surface pressures are notably insensitive to flow chemistry; however, lee-side pressures or other regions of flow expansion may be much more sensitive to the chemical state of the gas. Thus pitching moments may be critically affected by real-gas effects. Comparison of flight

pressure measurements to wind-tunnel measurements, such as discussed in Ref. 3, will be very helpful in defining the role of gas chemistry in affecting aerodynamic forces.

The difference in shock shape and standoff distance is very appreciable when real-gas cases are compared to perfect gas. Bow shock-wing shock interactions may be thus significantly shifted. In order to model more accurately the normal shock density ratio achieved in flight, wind-tunnel tests are sometimes conducted in a gas other than air. The Langley CF_4 tunnel⁴ is an example of a tunnel intended for Earth entry testing, but using a test medium which more closely models the normal shock density ratio of real air. Flight data are needed to verify this concept for complex configurations.

Rarefied Flow Effects

For entry trajectories such as flown by the orbiter, significant forces and heat transfer are sensed while the atmosphere is still quite rarefied. Figure 1 illustrates the range of values of mean free path and viscous interaction parameter, V , encountered. The author is not aware of any experimental data on the orbiter which model this rarefied portion of the entry. Interest in rarefied flows, particularly the transitional regime between continuum and free-molecule flow, has increased because of possible future missions utilizing aero-assist for trajectory control. For example, a future orbital transfer vehicle operating between geosynchronous orbit and low Earth orbit may accomplish its orbit change by a decelerating pass through the upper atmosphere. In such a maneuver the principal deceleration and heating would occur in the transitional flow regime. Thus, evaluation of rarefied flow effects on the orbiter would help assess performance of such aero-assist vehicles.

Body Flap and Control Surface Effectiveness

The effectiveness of control surfaces in hypersonic flows is frequently dominated by the extent of boundary-layer separation induced by the deflected surface. The separation pattern and resultant surface pressures are dependent on the state of the boundary layer, the three-dimensional aspects of the geometry, the roughness of the surface, and degree of chemical reactions occurring in the flow. Each of these aspects points to weaknesses in the ground data, thus creating uncertainties in flight performance.

Windward Surface Heat Transfer

Predictions of heat transfer to the windward surfaces of a three-dimensional configuration at high angle of attack, such as the orbiter, have been based on wind-tunnel data due to deficiencies of flowfield calculations up to the present. However, since the design of the orbiter, a number of improved prediction techniques based on flowfield calculations have been developed. Comparison of these predictions with flight data should prove quite useful. It has been shown (Ref. 5, for example) that inclusion of entropy-layer swallowing is quite important, and it is also necessary to account for the finite-rate catalytic recombination effects of the surface.⁶ These effects are not usually modeled in wind-tunnel tests, but can cause a factor of 2 difference in predicted heating for some cases.

Leeward Surface Heat Transfer

No accurate methods have been developed to characterize the leeside flow patterns over the orbiter. Our understanding of this region of complex flow is very poor, and consequently only very elementary approaches are available to estimate heat-transfer rates. Wind-tunnel tests tend to be influenced by interference effects, and may not model the pertinent parameters for regions of separated flow.

Boundary-Layer Transition

As discussed previously, flight values of the Reynolds number for boundary-layer transition sometimes differ significantly from wind-tunnel-based predictions. The degree to which nonequilibrium chemistry in the boundary layer influences transition is not well established. The particular form of surface roughness imposed by the RSI tiles adds additional uncertainty. For these reasons, the onset of turbulent boundary layers, and the accompanying increase in heat transfer, cannot be predicted with any degree of certainty.

The Orbiter Experiments Program

In order to obtain flight data which will help answer the technical questions discussed in the previous section, a number of research-dedicated experiments and instruments are being developed under the OEX program. The experiments currently approved for development in the OEX program are listed in Table 1. This table will also serve as a guide to the acronyms used for the experiment names. Each of these experiments will be described to show the type of data which will be obtained, the interdependence of the experiments, and how the expected results will apply to the previously discussed technical issues.

Shuttle Entry Air Data System

SEADS⁷ will provide researchers with vehicle attitude and freestream air data throughout the speed range of entry. This is accomplished by means of an array of flush orifices on the vehicle nose. Figure 2 shows the arrangement of the orifices. Two pressure transducers, a high range (0-20 psi) and a low range (0-1 psi) are connected to each of the 14 pressure taps. The pressure distribution in the vertical plane is primarily sensitive to angle of attack, while the horizontal distribution will indicate sideslip angle. An extensive matrix of wind-tunnel tests and flowfield calculations have been run to determine the effects of angle of attack and sideslip on the pressure distribution. Error analysis has indicated that the measured angles should have a 3σ accuracy of 0.5° for Mach numbers greater than 3. It is expected that the SEADS system will have sufficient pressure signal to begin providing usable data at an altitude of about 90 km.

The stagnation pressure can be determined from the nose pressure distribution, and the dynamic pressure $\frac{1}{2} \rho_{\infty} V^2$ is then obtained from a knowledge of the stagnation point pressure coefficient, which is shown in Fig. 3. In this figure, real-gas effects are considered by using real air properties along the shuttle entry trajectory.

Once the dynamic pressure is obtained, the freestream density may be calculated using the velocity obtained from trajectory analysis. Barostatic considerations will then permit calculation of pressure and temperature if the altitude descent rate is known accurately.

It may be seen that the primary intent of SEADS is to supply data needed by aerodynamic/aerothermodynamic researchers rather than to conduct a separate experiment. In addition, it will provide information on the performance of a flush air data system over a large speed range,⁸ and is expected to be an important step in the development of an advanced onboard air data system which is applicable over a wide speed range.

Shuttle Upper Atmosphere Mass Spectrometer

The SUMS system is likewise intended to provide freestream density, but this instrument is aimed at the rarefied regime, from an altitude of about 80-km upward. Use will be made of a backup flight mass spectrometer which remains from the Viking (Mars) project. The mass spectrometer and inlet system will be mounted in the nose wheel well of the orbiter as indicated in Fig. 4. Gas is sampled through an orifice located near the windward centerline just aft of the orbiter nose cap. Summation of the measured mass number densities,

$\sum_i n_i m_i$ with appropriate transfer functions for the inlet system response will determine the flow-field density at the orifice location. This local surface density will then be corrected to freestream density.

The correction factor which relates freestream density to surface density at the SUMS orifice must be determined by analysis, since ground facilities cannot duplicate the proper rarefied environment. The analysis makes use of viscous continuum flow-field calculations as well as the direct simulation Monte-Carlo method to model the flow and determine the density ratio ρ_w/ρ_{∞} as a function of the freestream state.

The altitude range of interest, for which SUMS measurements will be particularly valuable, encompasses the range from free-molecule flow, through the transitional regime, and into slip flow. For example, at an altitude of 80 km, the mean free path of the freestream molecules is only about four millimeters, but at 120-km altitude, the mean free path is over three meters. Through this range, the bow shock wave is expected to form, gas chemistry will become active in the shock layer, and a boundary layer with slip boundary conditions will emerge. Many questions remain about aerodynamic performance in this rarefied state, and the SUMS measurements combined with the following experiment, offer the hope of probing this regime in some detail.

Aerodynamic Coefficient Identification Package

The ACIP is comprised of three triads of instruments, one each of dual-range linear accelerometers, angular accelerometers, and rate gyros. The package is located below the cargo bay and the instruments are accurately aligned to the orbiter axes. The direct measurement of vehicle

accelerations and rates during entry at a high sampling frequency (~170/sec) will permit aerodynamic force determination, and when combined with the freestream dynamic pressure measurements of SEADS and SUMS, will allow direct determination of the static force coefficients.⁹ These data will be compared to the wind-tunnel data base in order to assess the accuracy with which the ground data were extrapolated to the flight condition. In addition, they will aid in removing flight restrictions so as to open the operational envelope of the orbiter during entry.

The current resolution capability of the ACIP accelerometers will not be sufficient to extract coefficients for the rarefied flow regime, where very low forces are incurred. Because of this limitation, a higher accuracy second generation instrument, known as HIRAP (High Resolution Accelerometer Package), is being constructed. HIRAP, combined with the freestream state definition provided by SUMS, is expected to contribute flight-based measurements of the aerodynamic coefficients through the transitional flow regime.

Technology Flight Instrumentation

As mentioned previously, TFI represents that portion of the Developmental Flight Instrumentation, particularly surface pressure and temperature measurements, which is to be retained past the orbital flight test period. In addition, plans are being made to include pressure and temperature measurements at new locations. The particular measurements to be included have been selected for their potential benefit in analyzing heat-transfer and pressure distributions at critical regions on the vehicle. These data are expected to be very important to the understanding of many of the problems noted in the preceding section.

Shuttle Infrared Leaside Temperature Sensing

The SILTS experiment will mount an infrared camera in a small pod on the top of the vertical tail (Fig. 5). From this vantage point, most of the upper fuselage and one wing can be viewed by the camera, as it alternately looks through each of two viewing windows which are transparent in the infrared. The camera will yield a continuous series of infrared pictures throughout the entry, from which surface temperature distributions may be obtained by means of camera calibration factors and a knowledge of the local surface emissivity. Heat-transfer rate distribution is then obtained from the temperature distributions through in-depth material response analysis. This heating rate may then be corrected to net aerodynamic heating by subtraction of solar heating and cross-radiation heat transfer.

The complex nature of the leaside flow at high angle of attack causes great uncertainty in heat-transfer prediction, thus incurring a large uncertainty in thermal protection system requirements. The SILTS data will be very valuable both to aerothermodynamics researchers and to those concerned with orbiter flight certification, since it greatly supplements the surface thermocouple and calorimeter data and gives a much more complete picture of temperature distribution.

Infrared Imagery of Shuttle

SILTS has an ideal vantage point from which to view the upper surface of the orbiter, but there is not an equivalent viewing point for the lower surface. The IRIS experiment will therefore utilize an underflying airplane to obtain windward and side surface infrared images of the orbiter.

This experiment involves no physical contact with the orbiter. A C-141 aircraft will have onboard an acquisition telescope, a primary telescope with a focal-plane array of infrared detectors, and the necessary data acquisition equipment. The instrument is thus able to obtain high resolution images of the orbiter windward surfaces. From these data, computer analysis will provide temperature distributions, and the inferred heat transfer may be compared to ground-based conditions. The heating effects of any boundary-layer separation ahead of the body flap, boundary-layer transition patterns, and bow-shock/winged-shock interaction may be delineated by these data.

Tile-Gap Heating

The TGH experiment is specifically aimed at increased understanding of the interference heating in tile gaps caused by the surface discontinuities of the gaps.¹⁰ The experiment will mount a removable panel carrying eleven tiles of the baseline thermal protection system material on the underside of the orbiter fuselage (Fig. 6). The gaps between the tiles on the panel will be controlled in an attempt to parametrically determine the effect on local heat-transfer rate. In addition, the depth of the gaps will be varied through the use of gap fillers fitted at the bottom of certain gaps. Temperature distributions of the tiles will be determined from thermocouple arrays as illustrated in Fig. 6. The objective of this experiment is to define improvements in the design of reusable surface insulation tiles through reduced interference heat transfer.

Catalytic Surface Effects

The CSE experiment examines another aspect of the orbiter's thermal protection system in a real-gas environment. At entry velocity, the boundary layer contains a significant number of oxygen and nitrogen atoms due to the dissociation which occurs in the shock layer. If these atoms recombine at the surface, much of the dissociation energy is yielded to the surface. If, however, the surface does not act as a catalyst in promoting recombination, it can be shown⁶ that substantially lower heating occurs. The glassy coating of the orbiter tiles is known¹¹ to be of low catalytic efficiency at low temperature, but the extent to which this surface reduces heat transfer under flight conditions as compared to a fully catalytic surface has not been determined.

In the CSE experiment, several instrumented tiles will be overcoated with a material of high catalytic efficiency. The overcoating material will not alter the thermal or mechanical properties of the tile, and may be nondestructively removed from the tile. Entry data will permit comparison of the surface temperature of the overcoated tiles to adjacent baseline tiles and thus provide a direct determination of the noncatalytic effectiveness of the baseline tile coating.

Figure 7, which is taken from Ref. 11, illustrates the location of the tiles to be overcoated. The lower surface tiles will be coated on early fuselage flights. The wing leading edge and upper wing surface will be coated in subsequent flights.

Dynamic, Acoustic, and Thermal Environment

The DATE experiment will provide data on a problem which was not discussed in the earlier section of this paper: definition of the environment in the orbiter's payload bay. The objective of the DATE experiment is to provide data on the payload bay so as to develop improved methods of predicting cargo bay environments.

In this experiment, sensors such as microphones, accelerometers, force gages, and thermal devices will be installed on the pallet and on cargo elements which do not leave the bay during flight. All three axes of the orbiter and various locations within the bay will be considered so as to determine parameters that can be used in environment prediction.

Present Status and Plans

As of the writing of this paper, only one flight, STS-1, has been made. The ACIP experiment was onboard, and obtained excellent data.¹² The IRIS experiment was also attempted, but the tracking equipment failed to lock onto the orbiter image, so no data were obtained. The TGH and CSE experiments will be flown on STS-2. Flight assignments are still uncertain for the SILTS, SEADS, and SUMS experiments, but in each case the experiments will be ready for installation early in 1982. Until the SILTS and SUMS data are available to provide the necessary freestream state data, this information must be inferred from meteorological data taken at flight time. The process used at Langley Research Center to accomplish this and the results for STS-1 are described in Ref. 13. These data are then presented along with the best estimated trajectory¹² for use by researchers.

Many experiments have been proposed for development under the OEX program; however, the present funding constraints will be more of a factor than just technical value in experiment selection for the future. This paper has attempted to show, however, that the present family of experiments will provide a very substantial addition to the body of entry flight data, and use of this data base will improve the design of future space transportation systems.

Concluding Remarks

This paper has attempted to show how the OEX program will take advantage of the repeated orbiter entries to provide a wealth of flight data, with a minimum impact on orbiter operations. Combining body accelerations as measured by ACIP with air data obtained by SEADS and SUMS, the aerodynamic performance of the vehicle can be verified. Such data may be compared to the great body of wind-tunnel data, most of which were obtained in a perfect gas, to improve the manner in which ground-based data are extrapolated to hypervelocity flight. IRIS and SILTS will yield full infrared pictures of the

lower and upper surface of the vehicle, providing a valuable addition to the surface thermocouple measurements of TFI. These data will be by far the most comprehensive ever obtained at Earth entry conditions and will serve as benchmarks in research studies on real-gas heat-transfer problems.

The experiments on tiles gaps (TGH) and wall catalytic effects (CSE) provide the opportunity to obtain data not available in ground facilities and apply the results to improvements in the orbiter's thermal protection system.

The schedule of when data from these experiments will be available is, in some cases, not clear because as of the present writing, specific flight manifests are uncertain for some of the experiments. Similarly, funding constraints create uncertainty as to which of the additional experiments that have been proposed will be developed. It can be stated with more certainty, however, that the technologies necessary to design improved space transportation systems will be greatly advanced by the data to be obtained in this program.

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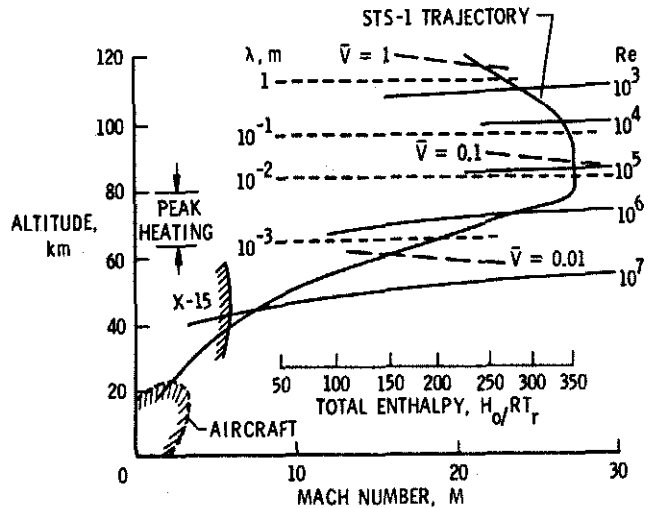


Fig. 1 Ranges of some important flight parameters encompassed by shuttle orbiter entry.

Table 1 Orbiter Experiments Program

Acronym	Title	Sponsoring Center
ACIP	Aerodynamic Coefficient Identification Package	Johnson
CSE	Catalytic Surface Effects	Ames
DATE	Dynamic Acoustic and Thermal Environment	Goddard
IRIS	Infrared Imagery of Shuttle	Ames
SEADS	Shuttle Entry Air Data System	Langley
SILTS	Shuttle Infrared Leaside Temperature Sensing	Langley
SUMS	Shuttle Upper Atmosphere Mass Spectrometer	Langley
TFI	Technology Flight Instrumentation	Langley
TGH	Tile-Gap Heating	Ames

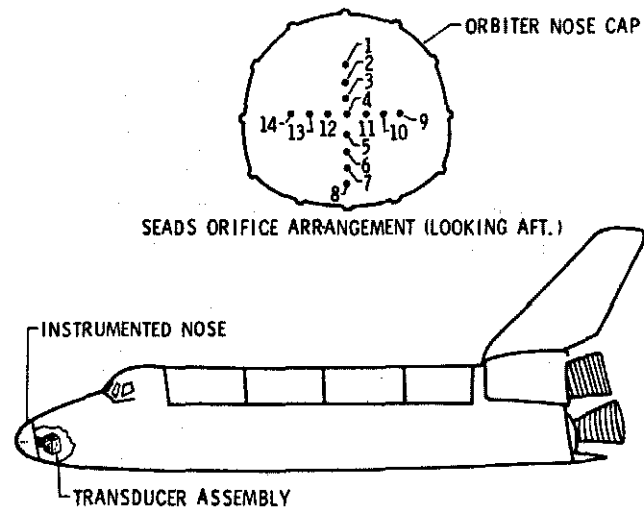


Fig. 2 Shuttle Entry Air Data System (SEADS) orifice arrangement and location.

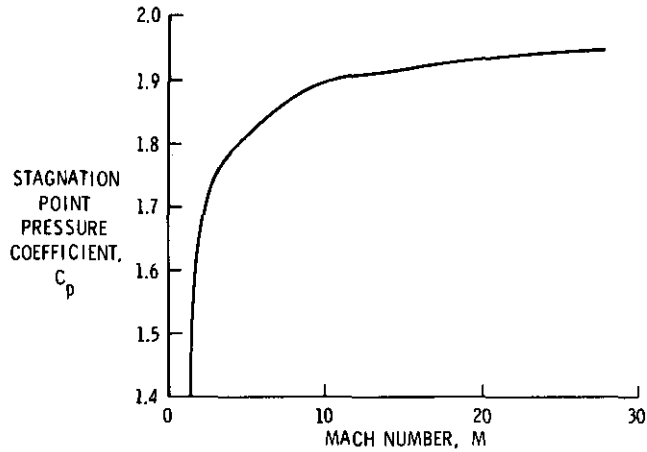


Fig. 3 Variation of the stagnation point pressure coefficient over the Mach number range of orbiter entry. Real-gas effects were considered at altitudes appropriate to the expected entry paths.

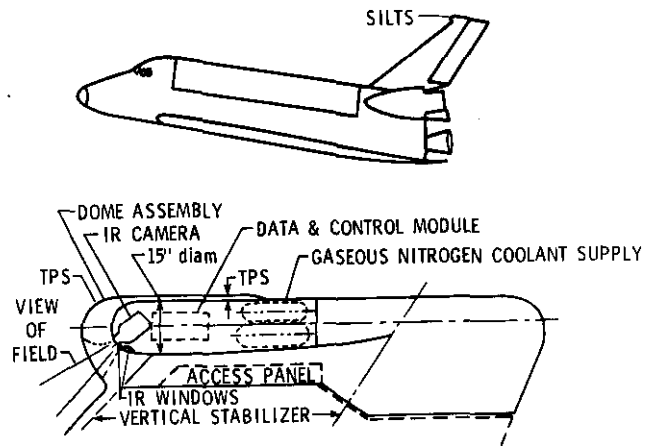


Fig. 5 Arrangement of SILTS (Shuttle Infrared Leeside Temperature Sensing) system in pod on top of orbiter vertical tail.

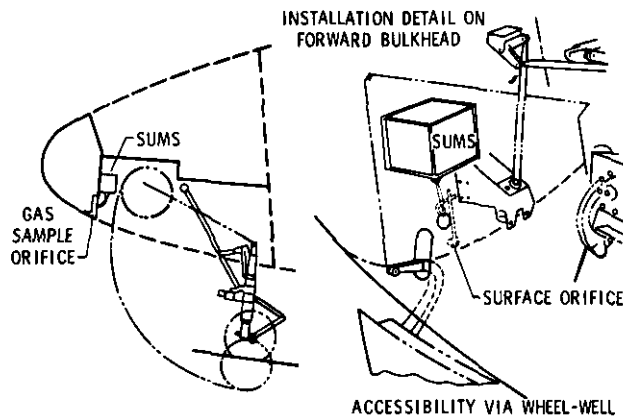


Fig. 4 Arrangement of SUMS (Shuttle Upper Atmosphere Mass Spectrometer) in the orbiter nose.

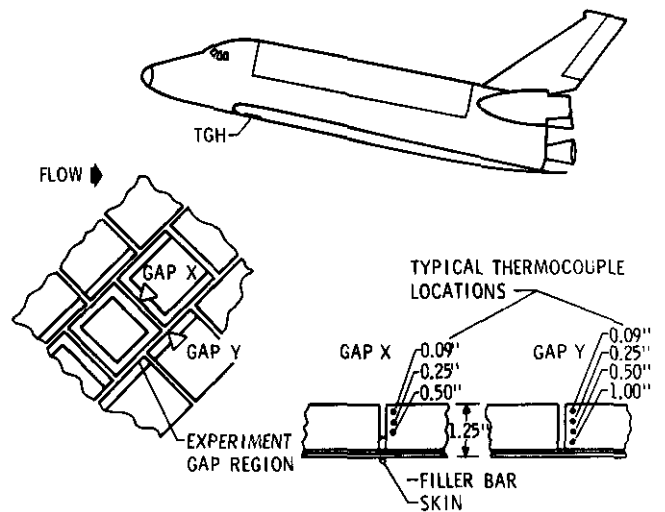


Fig. 6 Tile Gap Heating (TGH) experiment arrangement.

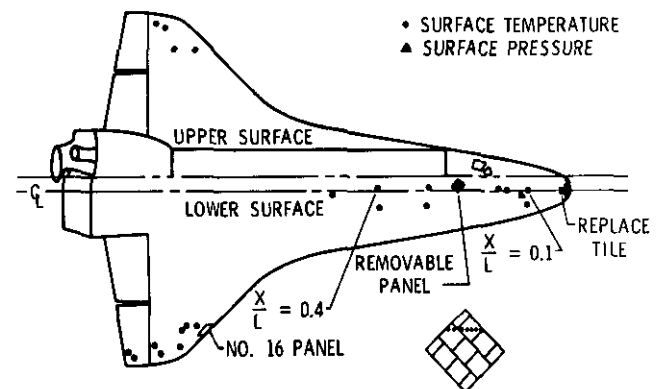


Fig. 7 Catalytic Surface Effects (CSC) locations on orbiter.