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Space Shuttle Orbiter and Aerodynamic Testing

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The concept of utilizing the space shuttle orbiter as an aerodynamic flight research vehicle is discussed. The orbiter's planned flight frequency and its complex flight control system provide an unprecedented flight research potential. This paper defines the orbiter's flight environment and applicable baseline systems, their capabilities and limitations, as well as those instrument systems required to augment the baseline capability. These required systems, which are being developed under NASA's Orbiter Experiments Program (OEX), are the aerodynamic coefficient indentification package (ACIP), shuttle entry air data system (SEADS), and the shuttle upper atmosphere mass spectrometer (SUMS). Finally, the need for and capability of launching payloads from the orbiter to extend the research potential beyond the orbiter configuration and/or environment is defined.

Introduction

IT has long been recognized that in spite of the advantages of ground facility testing (i.e., known and controlled environment, ability to alter the relevant variables independently, extensive and detailed instrumentation, and modest cost), the shortcomings of ground-based facilities (i.e., incomplete simulation, interference from tunnel walls and support systems, flow nonuniformities, variations from facility to facility, short run times, small scale, and ideal test gases) result in uncertainties and necessitate conservatism in the design of flight systems. Because of this, the aerodynamics engineer has been forced to conduct flight test programs. The value of flight research to continued advances in aeronautics and space technology has long been recognized. The contributions of research airplanes from the X-1 through the X-15 in expanding the speed envelope from transonic to low hypersonic speeds are well documented. Suborbital rocket-launched probes, such as FIRE, RAM, Reentry F, ASSET, etc., have increased the knowledge of heating and boundary-layer phenomena. The feasibility of suborbital flight and landing of lifting entry systems has been demonstrated with the HL-10, M2-F2, and X-24 vehicles. In spite of these flight test programs and countless hours of supporting ground facility testing, many questions pertaining to vehicle aerodynamic flight performance, stability, handling qualities, control system effectiveness, etc., remain unanswered.

The space shuttle orbiter itself is an excellent example of the problems facing the aerodynamics-related design disciplines. Extensive ground facility testing and analyses have failed to remove many of the uncertainties related to the orbiter's aerodynamic performance during entry. As a result, complex control and avionics systems have been developed to maintain the control-configured aerodynamically unstable orbiter in a safe flight regime. In addition, strict control has had to be set on center-of-gravity location, payload distribution, and vehicle maneuver timeliness. When the shuttle becomes operational, however, it will provide the aerodynamics researchers an unprecedented opportunity to address many of these unanswered questions by providing full-scale free-flight data across the speed range. Such data will be of value not only for shuttle flight performance optimization, but for reducing uncertainties in the design and development of future flight systems.

Orbiter Experiments (OEX) Program

In recognition of this unprecedented opportunity, studies[1,2] were initiated to define the specific research that could and should be extended to the shuttle orbiter flights. These initial definition activities have continued and have been broadened within NASA as a result of the formation by the Office of Aeronautics and Space Technology of the Orbiter Experiments (OEX) Program.

The overall objective of the OEX Program as stated in the OEX Management Plan is "to utilize the space shuttle capabilities to obtain research and technology data with which to advance aerospace technology." Specific objectives are: 1) to augment the research and technology base for future aerospace vehicle design by utilizing the space shuttle as a research vehicle to collect data in all related technology disciplines; and 2) to maximize the total value of data collected in ground-based facilities by collecting flight data for verification of and correlation with these data and for development of procedures to accurately extrapolate ground-based facility results to flight conditions.

This paper defines the space shuttle orbiter's capabilities and limitations as an aerodynamics research facility, and discusses the instrumentation that has been proposed for incorporation into the vehicle to enhance its aerodynamic research capabilities. In addition, a proposed Space Shuttle Orbiter Aerodynamics Research Program is defined and discussed. Finally, the concept of launching entry payloads from the orbiter during normal orbital operations is introduced and discussed.

Flight Test Data Requirements

Aerodynamic flight data requirements were no more succinctly stated than by Click and Stern[3] in their discussion of data analysis difficulties for the flights of the PRIME

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vehicle:

> ...while the L/D is not a function of the free stream conditions [, the] individual aerodynamic coefficients (C_L, C_D, C_m, etc.), in addition to their dependence on the vehicle shape, are also directly affected by the free stream environment. Therefore, accurate knowledge of the free stream environment along the trajectory is of paramount importance.... It is important to note that even if the vehicle aerodynamics are known perfectly, the trajectory profile accuracy corresponds to the accuracy of the knowledge of the free stream conditions.

and finally when discussing data analysis,

> The significant conclusion to be drawn from these results is that reliable flight performance calculations can only be made when either the free stream environment is known with some certainty, or the instrumentation used to measure information leading to the calculation of the free stream condition is properly calibrated prior to flight.... The major uncertainties in the interpretation of the data arose from three sources, two of which are related. First, the reduction of the accurately measured acceleration to coefficient form required a free stream atmospheric density profile. The determination from available meteorological data and from onboard stagnation pressure measurements disagreed by as much as 20 percent, with the sources of the differences remaining unresolved...The third uncertainty arose from the lack of instrumentation in some areas, notably on the upper surface and ahead of the flaps.

From the above discussion and similar conclusions drawn from other recent flight programs, such as the Viking and X-15, it can be concluded that in order to conduct an accurate aerodynamics-related research program using the shuttle orbiter, three types of data are required: 1) state data, 2) freestream conditions, and 3) surface measurements.

Table 1 Aerodynamic stability and control derivative research data requirements

	1σ (noise) accuracy	Overall accuracy	Sample rate, sps	Resolution	Units
Elevon (aileron) position	0.25	1	50	0.05	deg
Rudder position	0.25	1	50	0.05	deg
Speedbrake position	0.8	2	25	0.1	deg
Body flap position	0.34	1	12.5	0.05	deg
Bank angle	0.1	2	12.5	0.05	deg
Pitch angle	0.1	2	12.5	0.05	deg
Roll angular acceleration	0.2	1.0	50	0.5	deg/s^2
Pitch angular acceleration	0.1	0.5	50	0.2	deg
Yaw angular acceleration	0.1	0.5	50	0.2	deg
Roll rate	0.2	1.5		0.05	deg/s
Pitch rate	0.05	0.25	50	0.05	deg
Yaw rate	0.05	0.5		0.05	deg
Long accelerometer, c.g.	0.0001	0.005	50	0.0001	g
Normal accelerometer, c.g.	0.0002	0.002	50	0.0002	g
Lat. accelerometer, c.g.	0.0001	0.001	50	0.0001	g
Angle of attack, c.g.	0.05	0.5	25	0.05	deg
Angle of sideslip, c.g.	0.05	0.5	25	0.05	deg
Mach number			2	0.001	
Dynamic pressure		48 (1)	2	12 (0.25)	N/m^2 (lb$_f$/ft^2)
True velocity		7.6 (25)	2	0.61 (2)	m/s (ft/s)

Table 2 Research air data parameter requirements

Quantity	Altitude range, km (kft)	Desired accuracy	Minimum acceptable accuracy	Required resolution	Sample rate, sps
	0-15 (0-50)	1%	2%	0.01	10
Mach number	15-30 (50-100)	1%	2%	0.01	10
	>30 (>100)	5%	10%	0.1	10
	0-15 (0-50)	1%	5%	3 m/s (10 ft/s)	10
True velocity	15-30 (50-100)	1%	5%	3 m/s (10 ft/s)	10
	>30 (>100)	1%	5%	3 m/s (10 ft/s)	10
	0-15 (0-50)	1%	5%		10
Dynamic pressure	15-30 (50-100)	1%	5%		10
	>30 (>100)	1%	5%		10
	0-15 (0-50)	48 N/m^2 (1 lb$_f$/ft^2)	96 N/m^2 (2 lb$_f$/ft^2)		10
Static pressure	15-30 (50-100)	1%	5%		10
	>30 (>100)	1%	5%		10
	0-15 (0-50)	1%	1%	1 deg	10
Temperature	15-30 (50-100)	1%	1%	1 deg	10
	>30 (>100)	1%	1%	1 deg	10
	0-15 (0-50)	48 N/m^2 (1 lb$_f$/ft^2)	96 N/m^2 (2 lb$_f$/ft^2)		10
Pressure altitude	15-30 (50-100)	1%	5%		10
	>30 (>100)	1%	5%		10

On the basis of these experiences, data requirements for the proposed OEX aerodynamics investigations have been defined and are presented in Table 1, which presents the data requirements for determination of aerodynamic stability and control derivatives, and Table 2, which presents the air data requirements.

Characteristics of the Shuttle Orbiter as a Flight Test Vehicle

The aerodynamics program proposed herein is being defined to take advantage of the space shuttle orbiter, its flight control system, baseline instrumentation, and flight frequency. The orbiter is a double-delta-wing control-configured vehicle (Fig. 1), the re-entry atmospheric flight of which is controlled by an integrated flight control system. The re-entry is divided into three segments: entry, terminal area energy management (TAEM), and approach and landing. During the entry phase (as a result of a strict flight operating envelope to control heating, severe payload requirements, reduced aerodynamic control effectiveness, and large surface hinge moments), orbiter flight control is achieved by a blend of reaction control system jets and aerodynamic control surfaces. During the TAEM and approach and landing flight segments, flight control is achieved by the aerodynamic control surfaces alone.

Flight Control System

The control of the shuttle orbiter is accomplished by a digital, fly-by-wire flight control system.[4,5] Several components of the integrated flight control system (FCS) are discussed herein because of their direct relationships to the accuracy with which aerodynamic research can be accomplished. They are the aerodynamic surface control effectors, the reaction control system (RCS), the inertial measurement unit (IMU), rate gyro assembly (RGA), accelerometer assembly (AA), the air data system, the operational instrumentation (OI), and the development flight instrumentation (DFI).

Aerodynamic Control Surfaces

The aerodynamic control surfaces (Fig. 2) include the elevons, used in unison for pitch control and differentially for roll control; rudder panels, used in unison for rudder control and differentially as a speed brake; and a body flap, used to supplement the elevons for pitch trim.

Reaction Control System

The reaction control system (RCS) maneuver capability is used during entry to correct vehicle dispersions caused by guidance navigation and control system atmospheric and aerodynamic uncertainties. In addition, it provides rotational control of the vehicle.

The RCS consists of thirty-eight 4000-N (900-lb_f) primary thrusters and six 110-N (25-lb_f) vernier engines. The primary thrusters are distributed with fourteen in the forward nose region, three up-firing, four side-firing, four down-firing, and three forward-firing. The remaining twenty-four primary thrusters are located in the orbiter maneuvering system (OMS) pods, each pod housing four side-firing, three up-firing, three down-firing, and two aft-firing thrusters. The vernier thrusters are distributed with two down-firing in the nose, and one down-firing and one side-firing in each aft OMS pod. Each single-axis rotation is accomplished in two parts—the maneuver burn and the braking burn. The primary thrusters provide accelerations in the roll and pitch axes of ± 0.5 deg/s^2 and in the yaw axis of ± 0.65 deg/s^2. The vernier RCS thrusters provide an on-orbit pointing accuracy of ± 0.50 deg, an angular acceleration capability of up to 0.02 deg/s^2, and an angular velocity of up to 0.01 deg/s.

Inertial Measurement Unit (IMU)

The IMU consists of an all-attitude, four-gimbal, inertially stabilized platform and platform electronics, power supply, interface electronics, built-in test equipment, and thermal control circuitry. The IMU outputs are proportional to vehicle attitude and accumulated velocity. There will be three IMU's on the orbiter.

Rate Gyro Assembly (RGA)

The RGA consists of three single-degree-of-freedom integrating gyros mounted orthogonally and operated in a caged mode to provide angular rate output information. The RGA senses angular rate about the vehicle pitch, yaw, and roll axes. There will be four RGA's on each orbiter.

Accelerometer Assembly (AA)

The AA consists of two mutually perpendicular single-axis body accelerometers, which provide outputs proportional to translation acceleration along the normal and lateral axes. There will be four AA's on the orbiter.

The comparison of the capabilities of the IMU, RGA, and AA[4] and the requirements put forth in Table 1 reveal that the baseline systems will not satisfy the aerodynamic research data accuracy, resolution, or rate requirements.

Instrumentation

The space shuttle orbiter baseline instrumentation system[6] considered here is instrumentation that will provide data pertaining to the state, performance, or condition of hardware elements, software computations, or expendables. This instrumentation system is at a maximum during the Orbiter Flight Test (OFT) Program and is referred to as the development flight instrumentation (DFI) and operational instrument (OI). Of the thousands of measurements to be made, those of interest for aerodynamic research are those

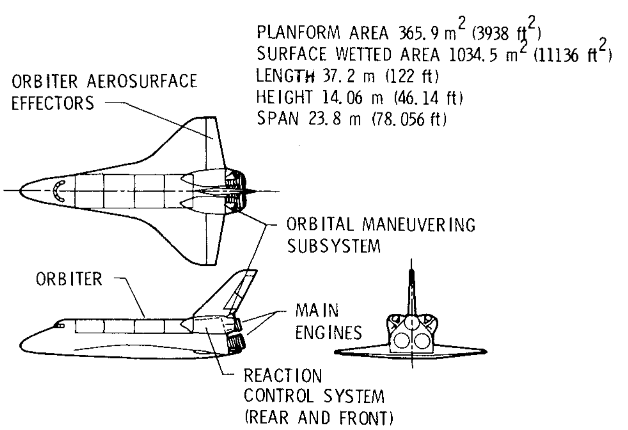

Fig. 1 Space shuttle orbiter.

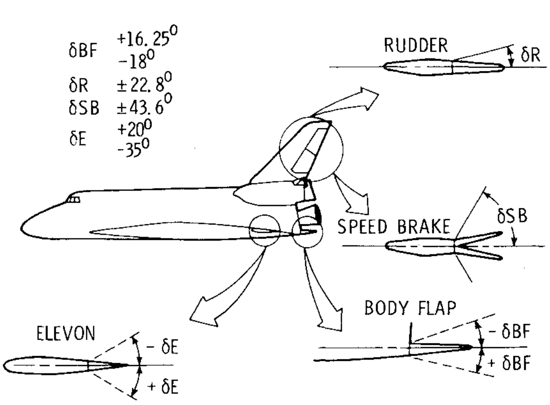

Fig. 2 Orbiter aerosurface configuration.

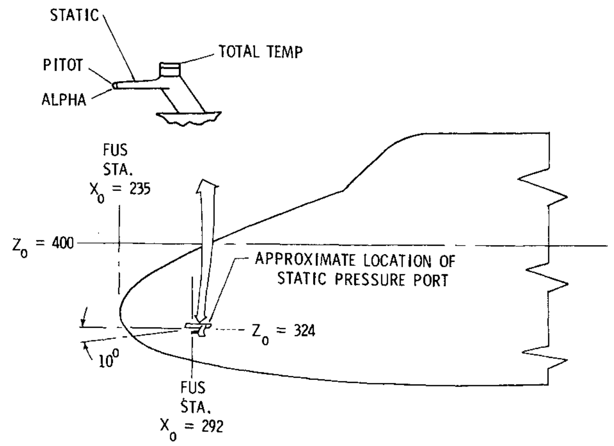

Fig. 3 Orbiter operational air data system.

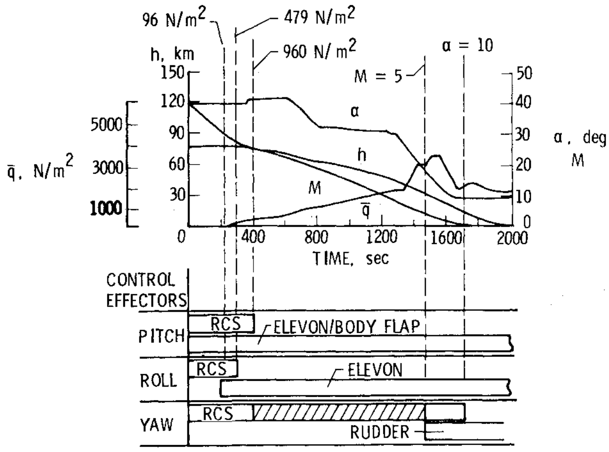

Fig. 4 Space shuttle orbiter re-entry profile and control system utilization.

associated with the thermo-aerodynamic (DFI), aerosurface control (OI), flight control (OI), and guidance and navigation (OI) subsystems, as well as the software subsystem reserved for navigation, guidance, flight control, and the inertial measurement unit (OI).

An operational air data system (OI) is provided which is intended to fulfill the operational data requirements. This sytem, which becomes operation for $M<3.5$ [($h<30.5$ km (100,000 ft)] consists of two fuselage-mounted deployable sensor assemblies, as shown in Fig. 3.

The air data parameter requirements that this system is designed to satisfy are presented in Table 3. A comparison of the operational air data requirements and the air data requirements presented in Table 2 reveals that the operational ADS will not meet the requirements of the proposed aerodynamic research program.

Flight Profile

The space shuttle entry profile will be flown with the orbiter pitched up to a fairly high angle of attack and with roll modulation. The resultant zero sideslip flight attitude will result in reduced pitch change requirements to control vertical descent velocity during entry. Typical re-entry profiles (time histories) of Mach number, angle of attack, altitude, and dynamic pressure are shown in Fig. 4, which also shows the blended RCS/aerodynamic control surface utilization.

The control of the orbiter through the blending of the flight control system components is depicted in Fig. 4 and described as follows:

During early entry, all RCS control is used. When a dynamic pressure of 96 N/m² (2 lb_f/ft^2) is reached (sensed

Table 3 Operational air data parameter requirements

				Measured air data requirement		
Air data parameter	Symbol	Units	Flight phase utilization	Range	Accuracy (% of reading unless noted) (3σ)	Resolution
Pressure altitude	h	Geopotential km	Entry	20 to 30	±3%	30 m
			TAEM	3 to 20	±3%	15 m
			A/L	0 to 3	±10 m or ±2% W/E is greater	3 m
Dynamic pressure	$\bar{q}$	kN_f/m^2 (lb_f/ft^2)	Entry	...	...	...
			TAEM	3.8 to 16.8 (80 to 350)	±7%	0.10 (2)
			A/L	2.4 to 16.8 (50 to 350)	±10%	0.25 (5)
True air speed	V_t	m/s (ft/s)	Entry	...	...	...
			TAEM	120 to 600 (400 to 2000)	±5%	0.6 (2)
			A/L	30 to 180 (100 to 600)	±5%	0.6 (2)
Mach number	M		Entry	1.5 to 3.5	±10%	0.02
			TAEM	0.6 to 1.5	±7%	0.02
			A/L	0.25 to 0.6	±10%	0.01
Angle of attack	α	deg	Entry	+5 to +25	±2 deg	0.2
			TAEM	−5 to +15	±2 deg	0.2
			A/L	−5 to +20	±2 deg	0.2
Air density	ρ	kg/m^3 (lb_m/ft^3)	A/L	0.01672 (0.0010438) to 1.26125 (0.078737)	±4%	0.00013) (0.000008)

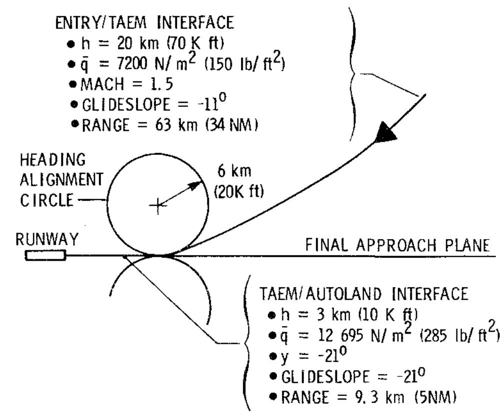

Fig. 5 Terminal area energy management (TAEM) geometry.

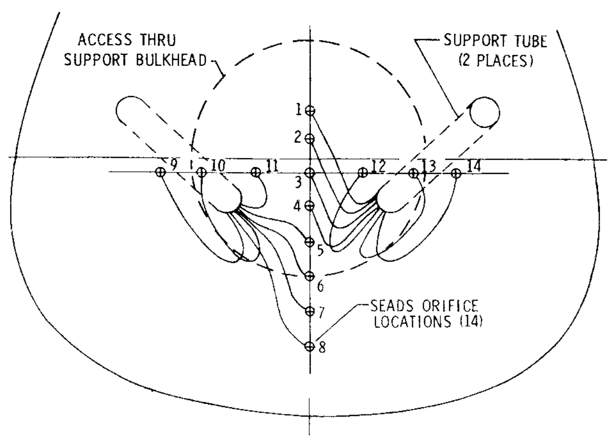

Fig. 6 Shuttle entry air data system configuration and array.

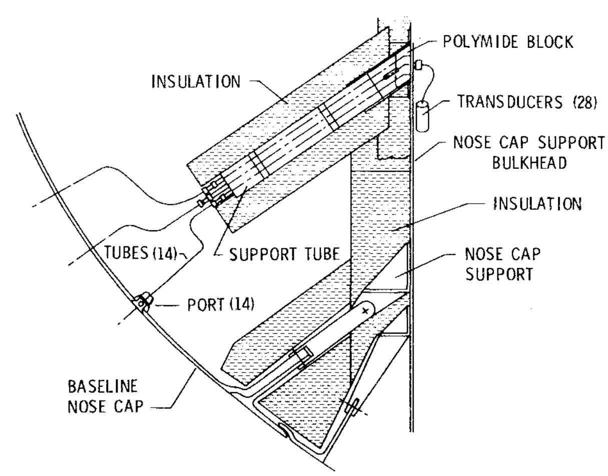

Fig. 7 Shuttle entry air data system nose cap assembly.

from vehicle accelerations), the elevons are activated to provide pitch and roll trim supplement to the RCS system. When a dynamic pressure of 479 N/m^2 (10 lb_f/ft^2) is reached, the elevons provide sufficient roll control and the roll jets are inhibited. When a dynamic pressure of 960 N/m^2 (20 lb_f/ft^2) is reached, the pitch jets are inhibited. The yaw jets are retained, however, for yaw stabilization and control until the vehicle reaches an angle of attack of 10 deg and a velocity of 457 m/s (1500 ft/s), which corresponds to the TAEM interface, Fig. 5. Just prior to TAEM or at approximately Mach 5, $\alpha = 18$ deg, the rudder control is activated. At the TAEM interface the FCS is switched to a conventional aircraft control mode for the remainder of the flight.

In addition to the integrated flight control system, the orbiter flight is aided by a TACAN (tactical air navigation) navigation aid, which is acquired by the communication system for navigation update after the vehicle exits blackout at approximately 46 km (150,000 ft). Finally, as the vehicle rounds the heading alignment circle, it is aided by a microwave scan beam landing system (MSBLS) navigation aid. This corresponds to the TAEM approach and landing interface.

Research Instrumentation

A comparison of the research data requirements (Tables 1 and 2) and the capabilities of the orbiter baseline systems[4] reveals that although the orbiter vehicle flight control system (including the IMU, rate gyros, accelerometer assembly, air data system, and surface instrumentation) will accomplish the control and guidance of the vehicle during launch, orbital flight, and entry, they will not satisfy the OEX aerodynamic flight research program data requirements.

To remedy this, several instrumentation systems have been defined and proposed for incorporation into the orbiter through the OEX program. These systems, which will provide the necessary air data, attitude, and accelerations across the speed range at the required rate and accuracy for aerodynamic research, are the shuttle entry air data system (SEADS), shuttle upper atmosphere mass spectrometer (SUMS), and the aerodynamic coefficient identification package (ACIP). In addition, studies relative to the incorporation of a radar altimeter have recently been initiated.

Shuttle Entry Air Data System (SEADS)

The purpose of SEADS is to make those measurements necessary to fulfill the air data requirements specified in Table 2, with emphasis on providing freestream conditions across the entry speed regime. As a result of the orbiter's large angle-of-attack range (10-40 deg), the orbiter nose cap's non-spherical geometry, and the required system accuracy, preliminary design analyses indicated that basic heimispherical air data probe technology was not applicable to the SEADS concept. These analyses indicated that a crossed array consisting of at least 10 orifices was required to meet data requirements.[7,8]

The SEADS[9] concept, therefore, consists of an array of 14 orifices (4 for redundancy), nose cap orifice plugs, instrumentation tubing and associated supporting members, bulkhead feedthrough, and dual pressure transducers (Figs. 6 and 7). The dual pressure transducer configuration will provide accurate pressure measurements from 80 km to touchdown. On the basis of preliminary (precalibration) analysis[7,9] of Mach-10 test data, the accuracy of the SEADS data across the speed range is estimated to be 5% for freestream atmospheric density and < 1 deg in vehicle attitude. Although the SEADS was designed to be a hypersonic system, recent tests have indicated that the use of SEADS measurements in conjunction with existing DFI pressure measurements can provide air-data-related parameters to a greater accuracy without correction than can the side probes without corrections.[10] SEADS design and integration studies are presently underway. It is expected that the SEADS will be available for flight in mid-1981.

Shuttle Upper Atmosphere Mass Spectrometer (SUMS)

The SUMS system is being proposed to provide freestream environmental data at pressure levels (altitudes > 80 km) beyond the lower range of the SEADS. The SUMS will provide a measurement of atmospheric mass density via a mass spectrometer, the inlet of which will be located just aft of the orbiter nose cap on the vehicle longitudinal centerline at

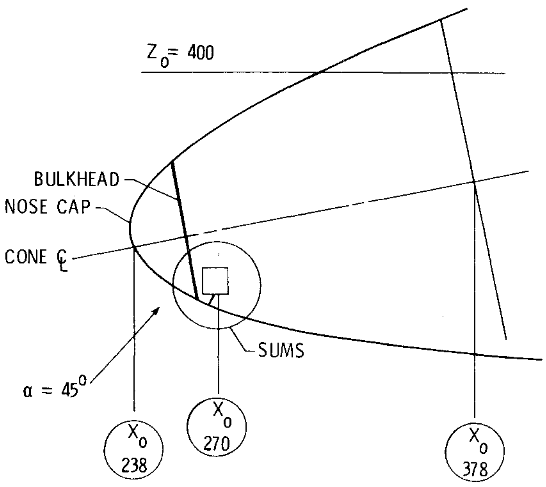

Fig. 8 Shuttle upper atmosphere mass spectrometer location – proposed.

$X_0 = 270$ (Fig. 8). The system's operating characteristics are presented in Table 4. The concept of utilizing the mass spectrometer for such measurements has been defined by Compton et al.[11]

The mass spectrometer[12] is a double-focusing magnetic deflection device that uses the Mattauch-Herzog geometry. The instrument is under vacuum until the time of usage, when the cap is removed exposing the ion source to the gas stream. SUMS design and integration studies are presently underway. It is expected that the SUMS will be available for flight in early 1981.

Aerodynamic Coefficient Instrument Package (ACIP)

The ACIP is designed to provide the high-resolution state data required for postflight research quality aerodynamic analyses.

Table 4 Shuttle upper atmosphere mass spectrometer parameters

Data	800 bits/s
Mass range	1-50 AMU
Dynamic range	10^5
Scan time	5 s
Accuracy	Absolute ±10%, relative ±3%

To accomplish this task, the ACIP will consist of linear and angular accelerometers and rate gyros forming an orthogonal three-axis system that is mounted on an aligned baseplate in the rear quarter of the payload bay of the orbiter on the longitudinal centerline at the forward end of the midbody wing box. The ACIP sensor complement, range, and resolution are shown in Table 5. Detail design and integration studies are presently underway, and it is anticipated that the ACIP will be available for the orbiter's first flight in 1979.

OEX Aerodynamic Research Program

The proposed OEX aerodynamic research will provide full-scale across-the-speed-range flight data relative to many aerodynamic phenomena. The postflight analysis of these data will result in significant advancement in aerodynamic design technology, which will provide for the optimization of future flight systems through an understanding of the implications of the various flight parameters (Mach number, Reynolds number, dynamic pressure, etc.) and of wind-tunnel-to-wind-tunnel and wind-tunnel-to-flight variations and uncertainties.

Aerodynamic investigations that have application to OEX aerodynamic research were first identified for the OAST Space Technology Workshop[2] in August 1975. They were defined in more detail at the OAST Entry Technology Mini-Workshop in March 1976. The emphasis of the aerodynamic investigations defined at these workshops was on the definition of vehicle aerodynamics in the hypersonic ($M > 5$) flight regime.

It is during the hypersonic flight regime that low-density, viscous, and real-gas flows are experienced and ground-to-flight comparison data are extremely sparse. Because of these data voids, a lack of knowledge relative to the combined viscous-interaction and real-gas effects exists. Furthermore, no practical means, either experimental or analytical, are available to study these combined effects on complex shapes at high angle of attack.

In addition, the problem of high-altitude low-density aerodynamics in the free molecular-transitional flight regime cannot be satisfactorily simulated or modeled by existing experimental or analytical techniques. Yet the aerodynamics in this regime may be the governing factor in maximizing vehicle performance, particularly in terms of lateral offset (or range) capability.

These proposed investigations will make use of the data provided by the baseline orbiter and OEX systems already defined. Other investigations, such as body flap flow separation/effectiveness and base pressure/drag, require not

Table 5 ACIP parameters

		Range	Resolution
Linear accelerometer	*X*-axis (longitudinal)	±1.5	0.00016
	Y-axis (lateral)	±0.5 *g*	0.00005 *g*
	Z-axis (normal)	±3 *g*	0.00189 *g*
Angular accelerometer	*X*-axis (roll, *p*)	±29 deg/s²	0.137 deg/s²
	Y-axis (pitch, *q*)	±12 deg/s²	0.0408 deg/s²
	Z-axis (yaw, *r*)	±12 deg/s²	0.0288 deg/s²
Rate gyro	*X*-axis (Roll, *p*)	±20 deg/s	0.020 deg/s
	Y-axis (Pitch, *q*)	±10 deg/s	0.005 deg/s
	Z-axis (Yaw, *r*)	±10 deg/s	0.005 deg/s

Table 6 Typical OEX aerodynamic research program

Experiment	Objective	Instrumentation
Aerodynamic data extraction (continuum)	Provide across-the-speed-range correlation of preflight predictions and flight stability and control performance Evaluate applicability of prediction techniques. Develop extrapolation capabilities	OI (FCS, RCS), DFI, ACIP, SEADS
Aerodynamic data extraction (upper atmosphere	Identification of vehicle upper atmosphere flight performance Correlate with preflight predictions; evaluate prediction, test requirements, and capabilities	OI (FCS, RCS) DFI, ACIP, SUMS
Real-gas effects	Definition of real-gas/viscous effects on orbiter performance Establishment of design/ground test techniques, requirements, and ground-to-flight extrapolations	OI (FCS, RCS), DFI
Hypersonic boundary layer	Definition of boundary layer in flight environment; definition of transition occurrence/extent, and its effect on performance Establishment of design/test techniques and extrapolations to flight	OI (FCS, RCS), DFI augmented (surface pressure), ACIP, SEADS
Body flap flow separation/ effectiveness	Definition of flow separation forward of control surfaces and its impact of control effectiveness Establishment of design/test techniques and flight extrapolations criteria.	OI (FCS, RCS), DFI augmented (surface pressures), ACIP, SEADS
RCS/aerosurface interaction	Definition of the performance of the RCS and aerosurfaces in a flight environment and their interactions Establishment of design and test techniques and flight extrapolation criteria	OI (FCS, RCS), DFI, ACIP, SEADS, SUMS
Base pressure/drag	Determination of base pressure and drag in a flight environment Establishment of ground test and analysis techniques and flight extrapolations criteria.	OI (RCS, FCS), DFI augmented (differential press gages), SEADS, ACIP
Entry gust loads/air loads	Definition of statistical model of high-altitude gusts Development of gust and air load design criteria	OI (FCS), SEADS, ACIP

only these systems, but additional surface pressure measurements to those provided by the DFI system.

The total potential of the space shuttle orbiter flight relative to aerodynamics extends from the hypersonic regime through the supersonic, transonic, and subsonic flight regimes to touchdown. Investigations that will exploit each of these regimes have not been identified to date, and a conscientious effort is required to develop investigations that will take full advantage of the orbiter's aerodynamic flight testing potential. Those investigations that have been identified and are being defined for implementation are summarized in Table 6.

Shuttle Launched Payloads

In spite of the space shuttle orbiter's capability to provide flight aerodynamic data, the orbiter is inherently limited in application because of 1) geometry and 2) flight envelope. To expand the aerodynamic testing capability, it has been proposed[1,13-16] to develop the systems and operational capability to launch entry payloads during normal orbital operations. These payloads would be of both lifting and ballistic geometries to support the broad range of vehicle configurations presently being considered by NASA and the DOD for future flight systems. The payloads would range from small "piggyback" configurations, which would make use of excess payload bay weight and volume, to large-scale dedicated payload configurations. The original launched entry payload study[13] emphasized planetary entry simulation, with special emphasis on the design of short-length velocity package to allow more latitude in payload bay sharing. This study established the feasibility of 1) launching payloads from the orbiter in a "piggyback" or shared operational mode, as well as in a dedicated mode; 2) developing a ballistic entry technology test (BETT) vehicle consisting of a standardized entry test bed and capable of accommodating a wide range of experiments; and 3) developing a short-length modular design

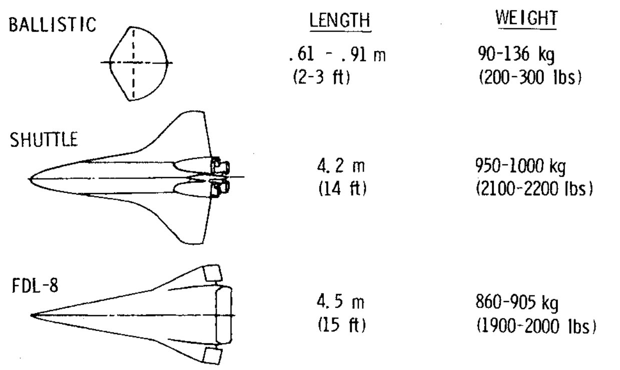

Fig. 9 Typical shuttle launched entry payload configurations.

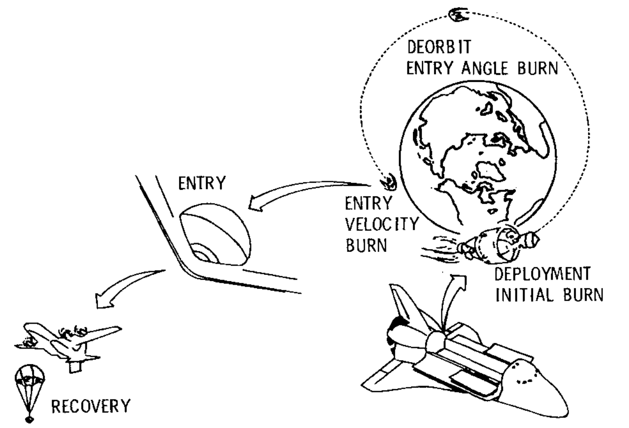

Fig. 10 Typical shuttle launched ballistic entry payload mission profile.

velocity package composed of shuttle reaction control system (RCS) components to provide shared mission entry technology flights.

Candidate orbiter-launched vehicle configurations that evolved from this study are shown in Fig. 9, while a typical mission profile for a planetary probe simulation is shown in Fig. 10.

Subsequent studies expanded the BETT/velocity package concept and defined the specific mission requirements and operational constraints related to the conduct of an Earth entry experiment that would simulate many of the significant aspects of an entry into the atmospheres of the outer planets, where heating rates of up to 30 kW/cm^2 are expected.[14,15] Such a simulation, even after the successful entry of a probe (Project Galileo) into a planetary atmosphere (Jupiter), will provide a calibration of probe performance in a known environment that will benefit the interpretation and reduction of scientific data. While this will not influence the Jupiter probe design, a more detailed knowledge of the associated flowfield, heating, and heat shield response would result in the minimization of heat shield and structural mass fraction and thereby a maximization of scientific payloads of future probes. In addition, this study addressed military flight test requirements and the potential use of the shuttle to satisfy these requirements. The conclusions of this phase of the study were that the shuttle can benefit the DOD program by providing 1) a unique capability not available in ground launch systems; 2) targeting flexibility for investigating reentry into nontraditional impact areas and adverse atmospheric environments (rain, ice, and snow); and 3) conducting numerous experiments with a single launch. A typical mission profile for a military experiment is shown in Fig. 11.

More recently, a study relative to the launching of a highly maneuverable lifting research vehicle from the shuttle orbiter[15] was conducted and concluded that "flight testing now,

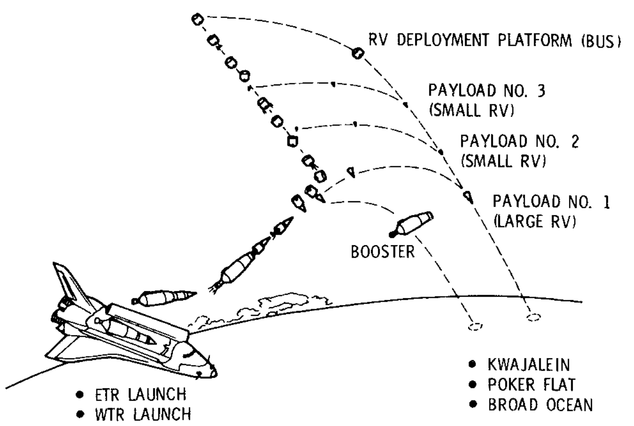

Fig. 11 Typical DOD re-entry vehicle mission.

as in the past, is an integral part of the progress in technology demonstration leading to the definition and development of new application and systems concepts." Also shown were "the capabilities inherent in a maneuverable reentry research vehicle which can be transported to orbit by the shuttle and perform a wide spectrum of operational and technological experiments."

Concluding Remarks

The development of the technology required to establish optimized aerodynamic designs for future space vehicles is a task that can best be accomplished through a combination of analysis, ground facility experimentation, and flight research. The space shuttle orbiter, because of its configuration (control configured), control system (dual mode), baseline instrumentation, and planned flight frequency, provides an unprecedented opportunity to conduct full-scale flight research across the speed range. This research, which can be conducted as an adjunct to normal orbital missions, can make significant contributions to an understanding of flight aerodynamics.

The orbiter's potential to accomplish flight aerodynamics research is compromised, however, by the lack of research quality instrumentation systems. The baseline orbiter system must, therefore, be augmented by systems that will meet the stringent research accuracy, resolution, and frequency requirements. Systems that will satisfy these requirements have been defined. They are the aerodynamic coefficient instrumentation package (ACIP), shuttle entry air data system (SEADS), and the shuttle upper atmosphere mass spectrometer (SUMS).

With the addition of the ACIP, SEADS, and SUMS systems, the full flight research potential of the orbiter can be realized. Since the shuttle provides access to flight environments and conditions never before available to aerodynamics researchers, the proposed research program will contribute to a greatly improved understanding of the capabilities of existing test and analysis techniques. Data obtained from the operational instrumentation (OI) and the development flight instrumentation (DFI) systems, augmented by that obtained from the ACIP, SEADS, and SUMS systems, will provide new insight into such important areas as vehicle stability and control across the entire entry speed range, real-gas and viscous interaction phenomena at hypersonic speeds, and ground-to-flight data extrapolation techniques. The incorporation of additional surface instrumentation (beyond that already in the DFI) will permit investigations of such important phenomena as flow separation ahead of control surfaces (such as the orbiter body flap) and base flow (as it affects vehicle drag). The use of shuttle-launched entry vehicles will extend the OEX aerodynamic flight research program to configurations different from the present orbiter and to a greatly expanded range of flight conditions and associated phenomena.

The data obtained from these proposed flight investigations will allow increases in the capabilities of the present shuttle orbiter, will allow the resolution of important aerodynamic questions that have plagued researchers for years, and will contribute significantly to the data base needed to provide more efficient, lower cost advanced space transportation vehicles.

References

[1] Siemers, P.M. III, "Shuttle Entry Technology Payloads," *21st Annual Meeting of the AAS "Space Shuttle Missions of the 80's,"* Denver, Colo., Aug. 26-28, 1975, pp. 75-251.

[2] OAST/ODU, "Entry Technology," *OAST Summer Workshop,* Vol. 9, NASA TM X-73969, 1975.

[3] Click, F. and Stern, I., "PRIME Aerodynamic and Thermodynamic Data Analysis," *PRIME Lifting Body Spacecraft* (a collection of papers), Vol. 2, AF SAMSO TR 68-111, May 1968.

[4] "Shuttle Operational Data Book," Vol. 1, Rev. C, NASA/JSC, JSC-89934, July 1977.

[5] Minott, G.M., Peller, J.B., and Cox, K.J., "Space Shuttle Digital Flight Control System," *Advanced Control Technology and Its Potential for Future Transport Aircraft,* NASA TM X-3409, Aug. 1976, pp. 271-294.

[6] "Space Shuttle Program Master Measurements List for Orbital Flight Test," *Orbiter and Payload Interface Measurements/Stimuli,* Vol. 1, Rev. C., NASA/JSC, JSC-08220, July 1, 1977.

[7] Wolf, H. and Eades, J.B., Jr., "Analysis of the Shuttle Air Data System," NASA CR-145279, Oct. 1977.

[8] Wolf, H., "Analytical Techniques for the Reduction of Measurement from the Shuttle Entry Air Data System," AIAA Paper 78-791, AIAA 10th Aerodynamic Testing Conference, San Diego, Calif., April 1978.

[9] Siemers, P.M. III, "Shuttle Entry Air Data System," Paper No. 17, 1978 Air Data System Conference, Colorado Springs, Colo., May 1978.

[10] Larson, T.J., "Extending Use of Shuttle Entry Air Data System to Subsonic Speeds," Paper No. 18, 1978 Air Data System Conference, Colorado Springs, Colo., May 1978.

[11] Compton, H.R., Blanchard, R.C., and Walberg, G.D., "An Experiment for Shuttle Aerodynamic Force Coefficient Determination from Inflight Dynamical and Atmospheric Measurements," AIAA Paper 78-795, April 1978.

[12] Nier, A.O., Hanson, W.B., McElroy, M.B., Seiff, A., and Spencer, N.W., "Entry Science Experiment of Viking 1975," *ICARUS,* Vol. 16, Feb. 1972, pp. 74-91.

[13] McNeilly, W.R., "Advanced Shuttle Payloads Sizing Study," NASA CR-132714, 1975.

[14] Christensen, H.E., Krieger, R.J., McNeilly, W.R., and Vetter, H.C., "Planetary/DOD Entry Technology Flight Experiments," NASA CR-137842, Feb. 1975.

[15] Vetter, H.C., McNeilly, W.R., Siemers, P.M. III, and Nachtsheim, P.R., "Shuttle Launched Flight Tests: Supporting Technology for Planetary Entry Missions," AIAA Paper 75-1152, AIAA/AGU Conference on the Exploration of the Outer Planets, St. Louis, Mo., Sept. 1975.

[16] Draper, A.C., Lane, P., Jr., and Zima, W.P., "A Flight Research Vehicle to Bridge Shuttle Hypersonic Aircraft Technology," AIAA Paper 77-1165, AIAA Atmospheric Flight Mechanics Conference, Hollywood, Fla., Aug. 1977.