Definition of an Entry Research Vehicle

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A study has been initiated to define a Shuttle-launched entry research vehicle experiment. Defining the experiment has required the development of a vehicle concept, the definition of candidate experiments, and the assessment of the experiment/vehicle integration. The results of the vehicle definition and experiment definition studies are presented herein.

Introduction

WITHIN the last year there has been a marked increase in the national interest to provide the technology to support the development of vehicles that can maneuver in the atmosphere while returning from orbit and that can fly in the atmosphere at hypersonic speeds for sustained periods of time. This rebirth of interest in hypersonics has resulted from both the success of the Space Shuttle and from a developing awareness of the potential benefits that can be derived from vehicles with the capability to operate between the limits of existing aircraft and spacecraft. Examples of the types of maneuvers that are projected for this new class of vehicles are presented in Fig. 1.[1-4] As can be seen from the figure, most of the projected requirements are dictated by either a need for flexibility offered by a large landing footprint or by a requirement for specific entry maneuvers such as a synergetic plane change. Maneuvers such as long downrange and high crossrange seem to be the key to operational flexibility for entry systems. For vehicles that operate in space or in the upper reaches of the atmosphere, orbital plane change offers significant flexibility for Earth overflight and space operations.

Addressing the technology problems for these future systems will provide a significant challenge for the aerospace community. One future vehicle requirement that provides a technical challenge is the synergetic or atmospheric plane change. Analyses to date have shown that the maneuver will require sustained flight at near entry Mach numbers for altitudes over 200,000 ft. This maneuver will be performed in the flight regime where the predicted aerodynamic trim of the Space Shuttle Orbiter was in error, and the body flap had to compensate by deflecting by as much as 9 deg.[5] The plane-change maneuver will dictate new requirements for vehicle thermal protection systems and thermostructures design.

The results from the Space Shuttle flights presented in Blanchard and Rutherford[6] have shown density variations as large as 60% in the altitude regime where the synergetic plane-change maneuver occurs. This large density variation is random and cannot be predicted and, therefore, must be treated as an uncertainty in the estimated aerodynamics and aeroheating used in the vehicle design. As seen in the projected mission requirements presented in Fig. 1, future entry vehicles will be required to perform atmospheric plane-change maneuvers and also to be able to fly both high crossrange and long downrange missions. The combination of these types of missions will dictate a need for high performance thermal-protection system and thermostructures designs.

The plane-change maneuver will require a TPS designed for a high heating rate much like the Space Shuttle; however, the high crossrange and downrange missions will result in a high heat load which would be similar to the case for a hypersonic cruise vehicle. These requirements significantly impact the vehicle thermostructures design. In order to accommodate the large density variations referred to earlier, the new vehicle systems will be required to have an adaptive guidance and navigation system. This system must be able to sense the atmospheric conditions and provide the necessary control inputs in real time. Much of the maneuvering that has been discussed will occur at speeds and altitudes where the vehicle will be flying in the continuum regime with large viscous effects and in the transitional flow regime with real-gas effects. Providing flight data to verify the estimation techniques used for design will definitely reduce the uncertainties in the predicted aerodynamics and aeroheating used for development of vehicle systems designed to fly in these flow regimes.

Synergetic Plane Change

Presented in Fig. 2 is a typical altitude-time profile for an entry research vehicle flight obtained from Ref. 3 where first a synergetic turn is performed and then the vehicle performs a normal entry. As shown in the figure, the entry vehicle is released from the Shuttle, performs a deorbit burn, and then descends into the atmosphere to an altitude of approximately 220,000 ft, where the engines are started and the vehicle cruises at a Mach number of 25 for 20 min or until the desired plane change is achieved. Once the desired plane change of 18 deg is achieved, the vehicle deorbits and performs a normal entry and landing.

The entry profile presented in Fig. 2 shows that in performing the synergetic plane-change maneuver, the vehicle operates at altitudes near 220,000 ft. Presented in Fig. 3 is a plot of $\bar{V}_\infty$, a viscous interaction correlation parameter; Knudsen number; and the various hypersonic flow regimes as a function of altitude for the Space Shuttle Orbiter and the ERV obtained from Wilhite et al.[7] These data show that, at 220,000 ft where the plane-change maneuver is performed, the vehicle will be operating in the upper limit of the continuum flow regime where there are very large viscous effects or in the transitional flow regime where there are currently no reliable prediction techniques. To date, there has been no assessment of viscous effects (degraded aerodynamic performance) on the plane-change maneuver. Currently, in the study at Langley, the aerodynamic data base to be used in trajectory analyses of the plane-change maneuver is being formatted as shown in Fig. 3. At Mach numbers below 10, the aerodynamic coefficients are input as a function of Mach

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number; in the viscous flow regime, the coefficients are input as a function of V_∞; and in the transitional and free molecular regimes, the coefficients are input as a function of mean free path or altitude. To obtain the aerodynamic data, a combination of wind-tunnel data, hypersonic arbitrary body estimates, and a bridging function determined from Shuttle flight data are used.

Starting with the plane-change maneuver shown in Fig. 2, inviscid trajectory analyses have been made to determine the impact of increasing the allowable heating rate during the maneuver. The result of these analyses is presented in Figs. 4 and 5. Figure 4 shows the heating rate/time profile for an ERV design with allowable maximum heating rate cases of 80 and 125 BTU/ft^2-s. The rationale for performing the maneuver is to allow the vehicle to plunge into the atmosphere until the heating-rate limit is achieved, and at that point, start the engines and fly at a constant velocity and constant altitude until the desired plane change is achieved. As can be seen from Fig. 4, the lower heat limitation prevents the vehicle from entering as deep into the atmosphere and also requires the vehicle to cruise for much longer. These differences are the results of the higher heating rate allowing the vehicle to fly deeper into the atmosphere and generating higher lift to turn the vehicle quicker. The quicker the maneuver can be performed, allowing the vehicle to stay near the equator, the more efficient the maneuver. To further substantiate this result, the propellant required to perform these maneuvers is presented in Fig. 5. Data are presented showing the propellant required to perform a 20-deg plane change all propulsively with allowable heating rates of 80 and 125 BTU/ft^2-s. For the approximately 12,000-lb vehicle, to perform the 20-deg plane-change maneuver, all propulsively requires 7100 lb of propellant. To perform the maneuver with a heating rate limit of 80 BTU/ft^2-s requires 6400 lb of propellant; and to perform the maneuver with a heating-rate limit of 125 BTU/ft^2-s requires 5500 lb of propellant. In the analysis it was also determined that there is an optimum heating-rate limit for the amount of plane-change desired. An additional case was examined with a heating rate of 135 BTU/ft^2-s, resulting in an increase in the propellant required. Further analysis of the results showed that the 125 BTU/ft^2-s was the optimum heating rate for 20-deg plane change, and when the vehicle tried to fly the higher heating rate (135 BTU/ft^2-s), it actually flew an off-nominal trajectory to achieve the higher heating-rate limitation.

Maneuvering Entry

Figure 1 shows the typical missions that would be required for an operational maneuvering entry vehicle. Included in this sketch are maximum crossrange, maximum downrange, minimum time entries, and synergetic plane-change maneuvers. In addition to the synergetic plane-change studies, these maneuvers have also been analyzed. Presented in Fig. 6 is a comparison of the landing footprints (a plot of the maximum crossrange and maximum downrange for each vehicle) for the Space Shuttle Orbiter and the ERV. These results show that the Orbiter has flown a maximum crossrange to date of about 900 nautical miles and a maximum downrange of approximately 4000 nautical miles. Using the 125 BTU/ft^2-s ERV heating-rate limit for 20 deg of plane change discussed previously, the comparison shows the ERV to have a maximum crossrange of about 2200 nautical miles and a maximum downrange in excess of 8000 nautical miles with the heat load limited to that experienced for the maximum crossrange entry. The heat load profile for the maximum downrange, maximum crossrange, and the minimum downrange entries are presented in Fig. 7. The results of these analyses show a total heat load of 175,000 BTU/ft^2 for the maximum crossrange and maximum downrange missions. These results indicate that the design heat loads for this class of vehicle will double the heat load experienced by the Shuttle Orbiter and dictates a need for advanced technology thermostructures design. The minimum downrange case shown on the figures has a low heat load when compared to the other entries.

Vehicle Heating

The peak surface temperatures generated on the ERV during the synergetic plane change are presented in Fig. 8. These results show a stagnation temperature of 4180°F rankine decreasing to less than 3100°F 2 ft aft of the vehicle nose. Aft of the 2-ft station, the temperature decrease until at the end of the vehicle the temperature is 1720°F. The temperatures are low at the base of the vehicle because the plane-change maneuver is performed at high altitudes (above 200,000 ft) where the entire vehicle experiences laminar flow. The figure shows the upper wing surface and the upper part of the body to be at temperatures of approximately 600°F.

Table 1 Candidate aeroheating experiments

Objective
Provide data to define flowfield and boundary-layer character under entry flight conditions for developing techniques to reliably predict boundary-layer transition and flowfield/TPS interactions allowing more accurate surface temperature predictions and less conservative TPS designs.
Experiments
Wall catalysis and nonequilibrium chemistry
Boundary-layer transition
Viscous flow effects
Transition flow aerodynamics
Free-molecular flow

Table 2 Candidate aerodynamics experiments

Objective
Provide the data necessary to develop the tools that can accurately predict vehicle aerodynamic loads, the aerodynamic control effectiveness, and reaction control systems interactions in the free-molecular, transitional, slip and continuum flow regimes. Accurate prediction of these phenomena would reduce the aerodynamic uncertainties for both control system design and structural loads definition for future entry vehicle system designs.
Experiments
Continuum aerodynamics
RCS interactions
Free-molecular and transitional aerodynamics/control effectiveness
Viscous flow aerodynamics
Leeside flow

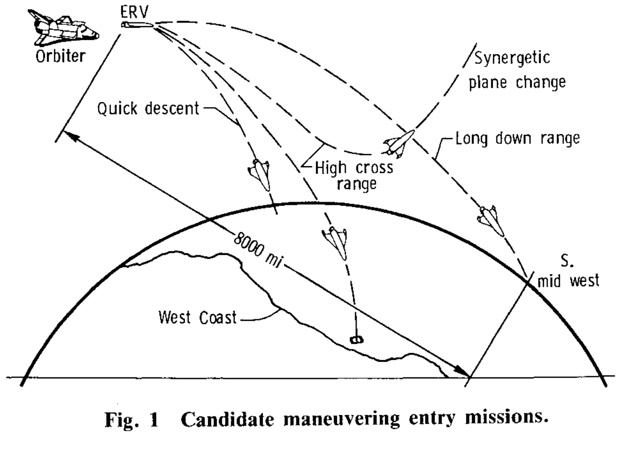

Fig. 1 Candidate maneuvering entry missions.

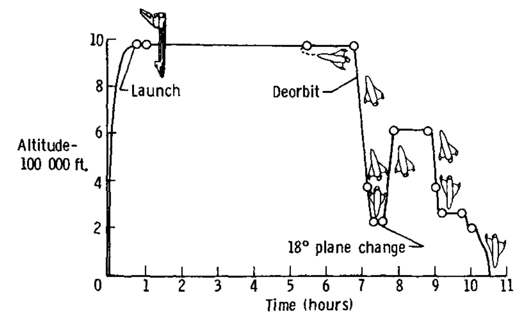

Fig. 2 Typical entry profile for an ERV synergetic plane change followed by reentry.

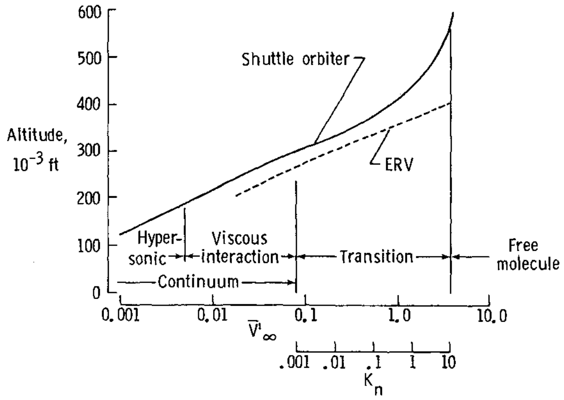

Fig. 3 ERV entry altitude and corresponding flow regimes.

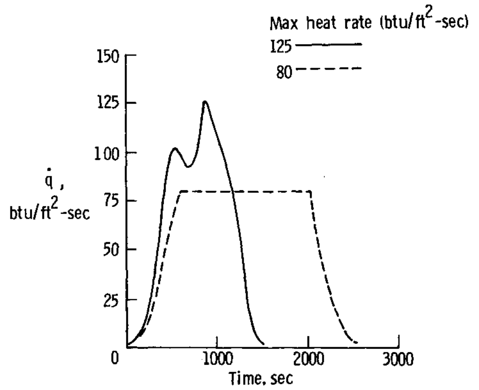

Fig. 4 Synergetic plane change heat-rate profiles for maximum heat rates of 80 and 125 BTU/ft^2-s.

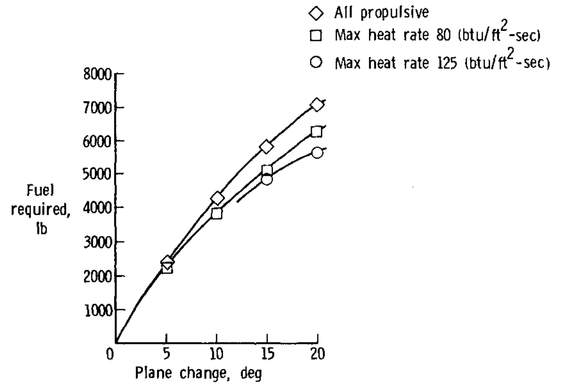

Fig. 5 Propellant required for the various ERV plane-change methods.

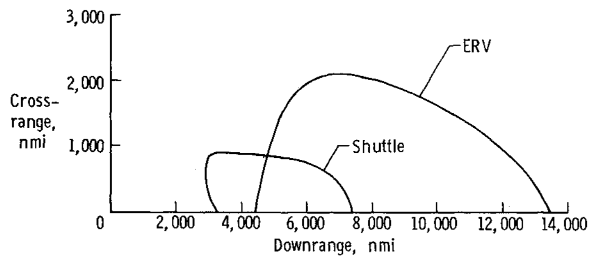

Fig. 6 Comparison of the ERV and Space Shuttle Orbiter landing footprints.

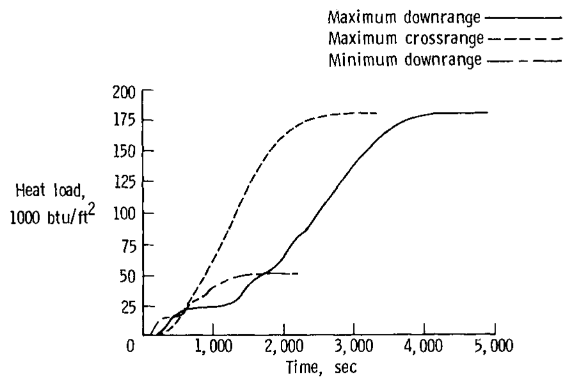

Fig. 7 Typical ERV entry heat loads.

The leading edges of the wing experience temperatures in excess of 3100°F and the leading edges of the tip fin controllers have a peak heating of 2210°F. Additional analyses with the body flap deflected 15 deg trailing edge down show an increase in the body-flap heating to about 2200°F.

Experiments and Instrumentation

A list of candidate aeroheating and aerodynamic flight experiments for the ERV is presented in Tables 1 and 2, respectively. The objective of the experiments is also presented in the tables. The list of aeroheating experiments includes wall catalysis, nonequilibrium chemistry, viscous flow effects, and determination of transitional and free-molecular flow character. The experiments included on this list are the same that have been proposed for a number of years, yet except for the Shuttle data, no new flight data have become available. The purpose of the current ERV activity is to assess the impact of using newly developed instrumentation techniques to provide insight into the flowfield character for high-altitude/hypervelocity flight. Preliminary results from the ERV assessment indicate that currently evolving nonintrusive laser measurement techniques offer a totally new approach for in-flight flowfield characterization. The significant technological challenge is to reduce the size and power requirements of these devices to make them compatible with flight test operations. The aerodynamic experiments presented in Table 2 include: continuum aerodynamics; reaction control systems interactions; aerodynamic control effectiveness in the transitional and free-molecular flow regimes; viscous flow aerodynamics; and leeside flow characterization. As with the aeroheating experiments, the list of aerodynamic experiments is not new; but like the aeroheating, there has been no new flight data generated.

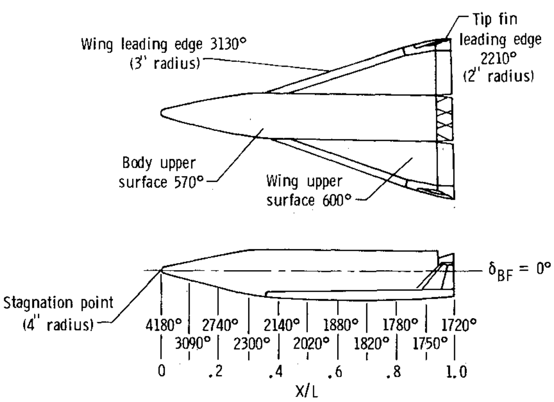

Fig. 8 ERV peak surface temperatures for the synergetic plane change maneuver (°R).

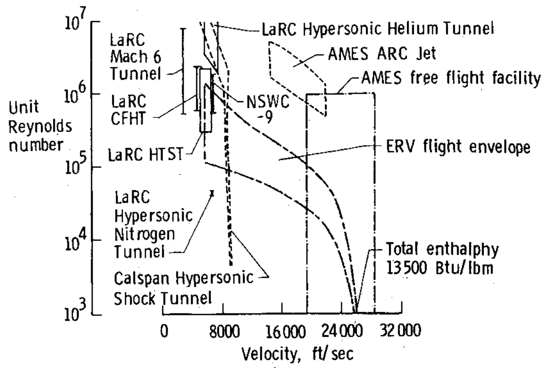

Fig. 10 Comparison of the ERV flight Reynolds number and velocity with existing ground test capability.

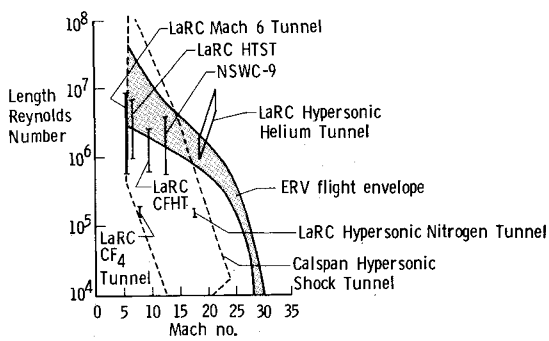

Fig. 9 Comparison of the ERV entry profile with existing ground test capability.

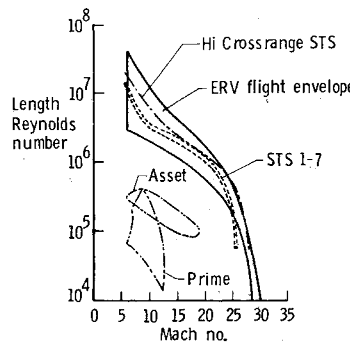

Fig. 11 Comparison of the ERV flight profile with existing flight data.

Table 3 ERV instrument requirements

Instrumentation	Measurements	Purposes
Pressure transducers	Nose cap	Determine freestream α, β, Q
	Pressure distributions	Provide data for computational methods verifications
Thermocouples	TPS surface temperatures	Provide surface heating rates and TPS operating temperatures
	Bond line temperatures	Measure TPS insulation qualities and provide back face structure operating temperatures
	Instrument compartment temperature	Temperature compensation for instrument measurements
Accelerometer	Vehicle motion (forces and moments)	Extract aerodynamics and atmospheric uncertainties
	High rate accelerometer package	Upper atmospheric measurements experiment
Mass spectrometer	Species concentration in boundary layer	Define boundary layer for catalysis and transition experiments
Thermal emission	Temperature and species identity in boundary layer	Define boundary layer for catalysis and transition experiments
Rayleigh scattering	Temperature density and velocity	Define surface flowfield beyond boundary layer
Accelerometers	Dynamic responses	TPS and structural component dynamic response

However, a vehicle capable of atmospheric plane change must operate in the contiuum flow regime with large viscous effects and in the transitional flow regime. A vehicle designed for this mission using existing aeroheating and aerodynamic prediction techniques would be penalized with large design margins to accommodate uncertainties in the predicted flight environment.

Presented in Figs. 9 and 10 are comparisons of Reynolds number/Mach number and unit Reynolds number/velocity profiles for STS-7, the ERV, and existing ground-test capability. Presented in Fig. 10 is a comparison of the capability of existing ground-test facilities to duplicate vehicle aerodynamics for maneuvering entry. These comparisons show that gound-test facilities exist to simulate aerodynamic phenomena up to Mach numbers of 20. However, the unit Reynolds number/velocity comparison presented in Fig. 11 shows that ground-test facilities can simulate only a small part of the reentry flight experiment envelope. For aerodynamic heating, the enthalpy (a function of velocity) is the important parameter in simulating proper heat rates with the proper flow conditions. Figure 11 indicates that an ERV program would significantly extend the flight data base for aeroheating prediction.

Presented in Fig. 11 is a comparison of the proposed ERV flight envelope, the envelope of the Space Shuttle Orbiter, and the envelope for two previous flight programs, ASSET and PRIME. This comparison shows that the projected ERV flight profile will provide data over a much larger entry flight envelope than the Shuttle and at much higher altitudes and velocities than ASSET and PRIME, since these were suborbital flight tests.

The ERV instrumentation requirements are presented in Table 3. Instrumentation to provide pressure, temperature, and motion measurements currently exist. Flight data to determine freestream conditions, surface pressure distributions, surface bond line and backface temperatures, and vehicle forces and moments can be obtained with state-of-the-art instrumentation. Unfortunately, these data, without detailed flowfield measurements, contribute very little to the understanding of basic flowfield character required to define the physics of nonequilibrium chemistry, boundary-layer transition, and catalytic wall effects. In-flight measurements of boundary-layer species concentration, temperature and velocity gradients, and transition are requird to fully understand these phenomena. Instrumentation utilizing newly developed mass spectrometers and laser techniques offers the possibility of obtaining these kinds of measurements. Development of these nonintrusive measurement techniques will provide an understanding of the flow physics required to generate confidence in the ability to use ground test data and computational fluids techniques to accurately predict entry aeodynamics and heating.

Summary

The ERV definition study has identified a complement of flight experiments that makes a flight test worthwhile. This complement of experiments includes, in addition to the more routine measurements, investigations of basic flowfield phenomena for high-altitude/hypervelocity flight. The study has also shown that the development of nonintrusive measurement techniques are required to support this complement of candidate flight experiments. The results of trajectory analyses have shown that synergetic plane change maneuvers could be performed more efficiently with improved thermostructures design and with better prediction of aerodynamic heating.

References

[1]Martin, J.A. et al., "Orbit on Demand: In This Century If Pushed," *Aerospace America*, Vol. 23, Feb. 1985, pp. 46-61.

[2]Gabris, E.A., Freeman, D.C., and Martin, J.A., "Concepts, Technology, and Operations For a Quick Response, Highly Maneuverable Launch Vehicle," Twenty-First Space Congress, Cocoa Beach, FL, April 1984.

[3]Rockwell International Corporation, "Development of Military Flight Test Experiments," AFFDL-TR-79-3125, Jan. 1980.

[4]Rockwell International Corporation, "Concept Evaluation of a Maneuverable Reentry Research Vehicle (MRRV) and Related Experiments," AFWAL-TR-81-3125, Nov. 1981.

[5]Griffith, B.J., Maus, J.R., and Best, J.T., "Explanation of the Hypersonic Longitudinal Stability Problem—Lessons Learned," Shuttle Performance/Lessons Learned Conference, NASA CP-2283, March 1983.

[6]Blanchard, R.C. and Rutherford, J.F., "Shuttle Orbiter High Resolution Accelerometer Package (HIRAP): Preliminary Flight Results," *Journal of Spacecraft and Rockets*, Vol. 22, No. 4, July-Aug. 1985, pp. 474-480.

[7]Wilhite, A.W., Arrington, J.P., and McCandless, R.S., "Performance Aerodynamics of Aeroassisted Orbital Transfer Vehicles," AIAA Paper 84-0406, Jan. 1984.