N84 10169 D5

AFFTC OVERVIEW OF ORBITER-REENTRY FLIGHT-TEST RESULTS

Robert G. Hoey
Air Force Flight Test Center
Edwards Air Force Base, California

INTRODUCTION

The Air Force Flight Test Center (AFFTC) has been participating in the flight esting of the Space Shuttle since 1976. We were tasked by Space Division to conuct an independent assessment of the reentry and landing capabilities of the rbiter with respect to Department of Defense (DOD) missions. This activity is n-going and reports have been published after each flight. AFFTC participation in his conference is not directly related to the DOD assessment activity, however, nd the views presented by myself and other AFFTC authors discuss the technical spects of testing and the technology emanating from these tests. Our views should ot be construed as representing official Air Force or Space Division position or olicy but rather the technical views of the "testers".

ABBREVIATIONS AND SYMBOLS

FFTC	Air Force Flight Test Center
SSET	Aerothermodynamic Structural Systems Environmental Test Program
m_o	basic pitching moment coefficient
OD	Department of Defense
/D	lift-to-drag ratio
MLE	~~Modified~~ Maximum Likelihood Estimator
ASA	National Aeronautics and Space Administration
MS	Orbital Maneuvering System
RIME	Precision Recovery Including Maneuvering Entry Program
TI	Programmed Test Input
TS-1,2,3,4,5	Space Transportation System flights 1, 2, 3, 4, and 5

BACKGROUND

The Air Force has been interested in hypersonic flight and maneuvering reentry or many years, primarily spearheaded by efforts of the Air Force Flight Dynamics aboratory (now Air Force Wright Aeronautical Laboratory) (Figure 1). In the late

1950's, the X-15 program was initiated by a joint DOD/NASA team, funded primarily by the Air Force. This program has been recognized as the most successful of all of the X-series research aircraft, breaking new ground in many areas of hypersonic flight and lifting reentry. The follow-on program, the X-20A DynaSoar, was cancelled before flight but resulted in many development activities which were technology advances: for example, a triply redundant, self-adaptive, fly-by-wire flight control system. The Air Force Aerothermodynamic Structural Systems Environmental Test (ASSET) and Precision Recovery Including Maneuvering Entry (PRIME) programs, both small, unmanned lifting reentry shapes, were flown in 1963 and 1966, respectively. These tests successfully demonstrated both radiative/metallic and ablative thermal protection system concepts. The lifting body programs (M-2, HL-10, X-24A) explored transonic aerodynamics and landing characteristics of low lift-to-drag ratio (L/D) reentry configurations. The Air Force X-24B, the last of the X-series rocket-powered research vehicles, was representative of high hypersonic L/D configurations and performed the first hard-surface runway landing for vehicles of this class.

The many years of preparation represented by these programs have produced prediction techniques for the design of lifting reentry vehicles. The Space Shuttle Orbiter represents the culmination of all of this activity combined with the technology from the "capsule" programs. During this conference you have heard how well these prediction techniques worked. Some were accurate, some too conservative, and some non-conservative.

This paper touches on flight test results from most of the technical disciplines and attempts to relate them to each other with regard to the design of future lifting reentry vehicles. Performance (i.e., aerodynamic lift and drag), stability and control, aerodynamic heating and thermal protection, and unpowered approach and landing are the technical areas where we think major technology advances are being made.

PERFORMANCE

The L/D of the Orbiter was predicted very well over most of the Mach range (Figure 2). Although all entries have followed a 40 degree angle of attack profile, transient pushover-pullup maneuvers have produced accurate trends with angle of attack. The subsonic L/D was underpredicted somewhat due to a conservative estimate of the effects of tile surface roughness on drag. Since aerodynamic L/D is the prime measure of reentry maneuvering capability, the Orbiter guidance and energy management control laws have worked well and entry trajectories have been very close to nominal. Although the ratio of lift to drag was well predicted, the magnitude of the normal force coefficient C_N, which is the prime contributor to both lift and drag at high angle of attack, was overpredicted as shown on the right side of Figure 3. The cause of this discrepancy is not well understood at this time and efforts to resolve the differences are hampered by a lack of accurate, onboard measurements of dynamic pressure at the high Mach numbers M. In addition, abrupt changes in measured accelerations (up to 19 percent over a one second time period) have been recorded which do not appear to correspond to flow changes over the vehicle. Changes in atmospheric density are currently considered the most likely cause for these anomalies and, if random in nature, could be an important design consideration for future vehicles and guidance concepts.

A significant discrepancy in pitch trim predictions has been observed on all ghts (Figure 4). Elevon pulses, bodyflap sweeps, and pushover-pullup maneuvers re isolated the individual pitching moment contributions from the elevon, body- ip, and angle of attack and determined that they are all close to predictions. trim prediction error has thus been isolated to C_{m_0}. Recent theoretical compu- icns by personnel at the Arnold Engineering Development Center have attributed the screpancy to real gas effects. The magnitude of the correction is quite large and trays the heavy reliance that must be placed on theoretical and computational rodynamic models for the design of future reentry vehicles. Had this information en available sooner the nose ramp angle on the Orbiter could have been reduced ightly which would have brought the bodyflap and elevon back to the desired ired position. The result would have been lower temperatures in both the nose mp area and the control surfaces.

STABILITY AND CONTROL

Stability and control derivatives have been extracted from flight test maneuvers rformed over most of the current reentry flight envelope. For the most part the rivatives are close to predictions, although small discrepancies are seen in nearly l of the derivatives. A notable exception is the prediction of yaw jet interaction fects during the initial phase of reentry (Figure 5). The jet interaction effects roll were much smaller than predicted at the low dynamic pressures $\bar{q}$. The conse- ence of this prediction error is shown on Figure 6. A rather large, slow, lateral- rectional oscillation occurred on the first bank maneuver of the STS-1 entry. A mentary sideslip angle of over 4 degrees was reached during the oscillation com- red to a prediction of about 1 degree. This prediction discrepancy was again a sult of inadequate ground test facilities to accurately duplicate the simultaneous gh Mach number, low density, rocket-firing environment. Orbiter flight test data rrently being obtained should be invaluable in improving our ability to predict t interaction effects in the future.

The long dashed lines on Figure 5 also portray the use of derivative predicted ta uncertainties as used in the development of the Orbiter flight control system. considerable amount of effort was expended early in the program to establish appro- iate uncertainty bounds around each derivative prediction. These uncertainties re based on three factors: (1) differences between wind tunnels, (2) differences tween prediction and flight test results for a variety of aircraft, and (3) judg- nt regarding the validity of extrapolations in Mach number. The Orbiter control stem was designed to accommodate individual uncertainties in the derivatives as own by the dashed lines as well as certain logical combinations of uncertainties presenting worst-case conditions. The effort was well worth the time expended. l of the derivative prediction discrepancies have been within the variation bounds cept for the case shown in Figure 5. As a result, the flight control system has en adequate for safe reentry and landing approaches in either the automatic or nual modes in spite of prediction errors.

AEROTHERMODYNAMICS AND THERMAL PROTECTION

The lower surface or windward side of the Orbiter has experienced a less severe heating environment than expected (Figure 7). Three factors have combined to create this situation. The laminar heating during the early portion of the entry has been less than predicted, especially on the forward portion of the vehicle. The transition from laminar to turbulent flow has occurred later in the entry than expected which has also produced lower temperatures and a lower total heat load. After the vehicle passes through Mach 2.5, vent doors open on the side of the fuselage to equalize the pressure in the payload bay and other internal compartments. The flow of cold air into the vehicle as well as over the outside surface was not accounted for in the conservative heating models used in the design process. This atmospheric cooling effect is quite significant and causes internal structural temperatures to peak earlier and at lower values than anticipated. The combination of these three effects has alleviated concern over the overall adequacy of the lower surface design although several localized problems remain (tile gap heating, for example). The repeatability of these three effects needs to be considered. The reduced laminar heating appears to be repeatable. The transition from laminar to turbulent flow has been consistently later than expected but somewhat different for each flight. The mechanism for controlling flow transition needs to be better understood before a future design could confidently count on late transition in sizing the thermal protection. Carefully controlled testing of boundary layer transition phenomena on the Orbiter could be very beneficial to the design community. The atmospheric cooling effect has been, and should be, highly repeatable. The next generation of entry vehicles might well be equipped, not only with vent doors, but with air scoops and internal baffling to effectively utilize the three to five minutes of free cooling provided by the atmosphere while descending below 80,000 feet.

The heating on the upper surface, or lee side, of the Orbiter has been poorly predicted (Figure 8). This was not entirely unexpected since theory is essentially non-existent for complex shapes and wind tunnels cannot simultanously duplicate the flow conditions of Mach and Reynolds number. Several localized areas have experienced higher heating than predicted, in particular the Orbital Maneuvering System (OMS) pod, side of the fuselage and payload bay door. Wind tunnel data predicted that a vortex impingement would occur on the OMS pod abruptly as the angle of attack decreased through 30 degrees. Flight test results to date indicate an increase in heating starting at about 37 degrees angle of attack and building to considerably higher levels at lower angles of attack. The heating patterns and trends are reasonably repeatable from flight to flight and aerothermodynamic math models for the OMS pod and several other upper surface locations are currently being revised using the available flight test data base. Here again, additional testing of the Orbiter is required to thoroughly understand the factors which influence upper surface heating and to establish better tools for predictions on future vehicles.

FLIGHT TESTING TECHNIQUES

Aerodynamic flight testing of the Orbiter during entry successfully utilized aircraft dynamic testing techniques. (See fig. 9.) Slow pushover-pullups were performed to sweep a range of angles of attack while the vehicle remained essentially in trimmed flight. This maneuver and the corresponding analysis program has been used successfully on rocket powered glide vehicles for many years producing lift, drag, and longitudinal trim data as a function of angle of attack for a particular Mach number.

Programmed Test Inputs (PTIs) were sharp control pulses designed to momentarily upset the trimmed equilibrium condition. The instrumentation then recorded the manner in which the inherent stability and the control system returned the vehicle to equilibrium flight. These maneuvers are similar to the stick pulses used in aircraft dynamic stability testing. The Modified Maximum Likelihood Estimator (MMLE) analysis program has been in use for several years. It produces a set of values for the vehicle stability and control derivatives for each PTI test maneuver. The bodyflap sweep was used to isolate the bodyflap effectiveness derivative and thus establish the overall pitch trim capability of the Orbiter.

The data from pushover-pullup and bodyflap sweep maneuvers were analyzed by an entirely new technique for the dynamic testing of the aerothermodynamic environment. Using the trajectory data and the angle of attack time history as inputs, the new program adjusts the heating model until the output temperature time history matches the thermocouple readings as shown on Figure 10(a). The flight-adjusted heating model is compared with the wind tunnel data in Figure 10(b). Excellent results of heating variation with angle of attack have been obtained for lower surface locations. Nonlinear heating variations, such as on the OMS pod, have also been successfully identified but with lower confidence. Thermal math models for various critical locations are being updated with these flight test results. It is hoped that the aerothermodynamic flight testing techniques which were developed for the Space Shuttle program will form the basis for a whole new flight test discipline which will be applicable to any hypersonic aircraft or reentry vehicle.

UNPOWERED LANDINGS

A piloting technique for landing a low L/D glide vehicle was developed in the late 1950's and early 1960's and was successfully applied to lakebed landings of the X-15 research aircraft. As confidence was gained in the ability to successfully control gliding energy, spot landings were attempted with a fair degree of success. In 1970 a short research program was conducted by AFFTC using an F-111A which successfully demonstrated a technique for accomplishing night and instrument approaches. Several [illegible] low L/D approaches were flown from Mach 2 down to 1500 feet altitude where a visual flare and landing were completed. Typical landing patterns for the X-15, X-24B, and Space Shuttle Orbiter are shown in Figure 11. The approach and landing technique were the same for each. An overhead, high altitude, circular pattern was flown followed by a high speed final approach (approximately 300 knots). A flare maneuver to essentially horizontal, decelerating flight was initiated at about 1500 feet altitude. The landing gear was extended during or after flare and touchdown occurred between 160 and 200 knots. Notice the similarity in the final approach glide slope between the three vehicles which is indicative of the similarity in subsonic L/D. Notice also that as the landing technique evolved toward improved landing accuracy, the geometry of the pattern was altered to include a longer final approach. This results from the necessity to establish a stabilized energy level at the flare point in order to properly control the touchdown point and stopping point.

Additional refinements to this landing technique are still being made, such as improvements in the ability to compensate for upper altitude winds; however, the basic technique for accomplishing unpowered, low L/D landings has proven to be effective and practical.

CONCLUDING REMARKS

The Space Shuttle test program has been highly successful by any standard of measure. The vehicle was designed to fly in an environment which was largely uncharted. Many design prediction tools were verified (see fig. 12), including a general verification of lifting entry design methods and confirmation of reusable thermal protection system technology. Aircraft flight testing techniques were successfully applied and new aerothermodynamic flight testing techniques were successfully demonstrated.

Many of the design prediction tools were found wanting, as shown in figure 13, but the application of a conservative design philosophy allowed the test program to proceed safely. For example, hypersonic pitch trim and normal force coefficients were not well predicted. Jet interaction effects at low dynamic pressure were also mispredicted. Aerodynamic heating on the lower (windward) surface was generally lower than predictions while heating on local areas of the upper (leeward) surface was higher than expected. It appears that future designers will have to rely more heavily on theory and computational aerodynamics (or even empirical methods based on flight test) to supplement the wind tunnels for the hypersonic environment. (See fig. 14.)

The five-flight test program of the Orbiter has opened the door to several technological advances which could significantly impact the design of future hypersonic vehicles. It is essential that the necessary test data be gathered on future Space Shuttle Orbiter reentries to insure that this new technology is properly developed.

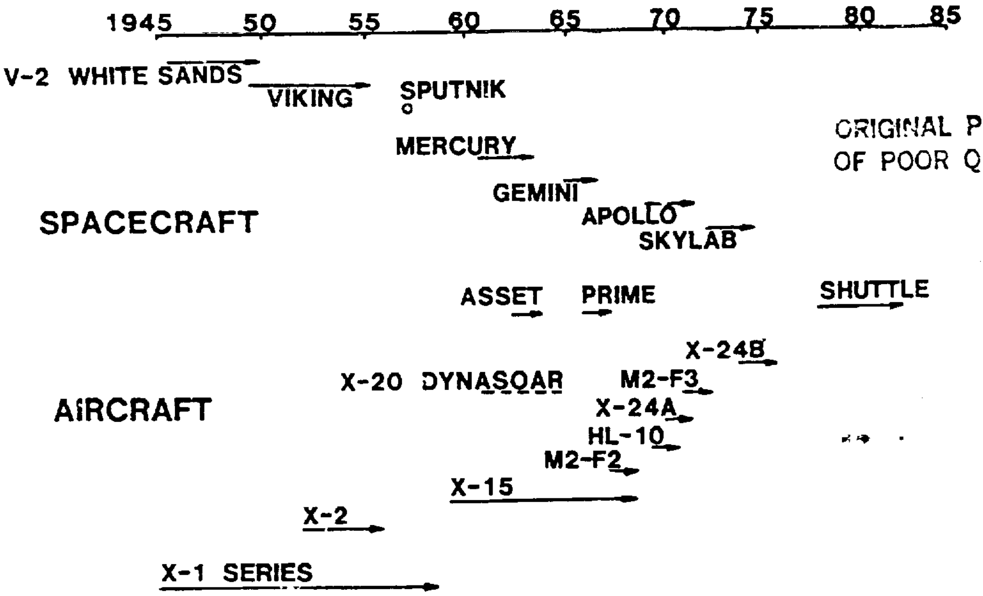


Figure 1.- Chronology of spacecraft/aircraft development.

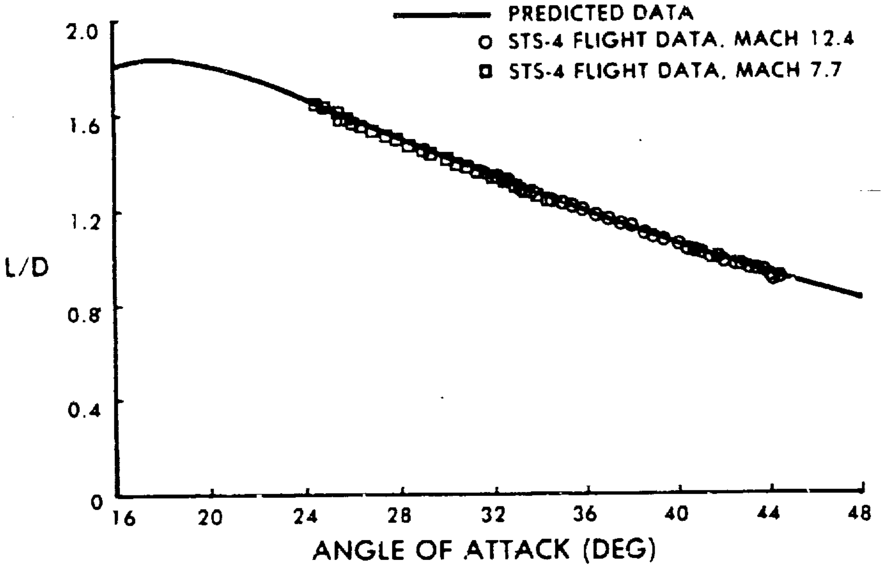


Figure 2.- Hypersonic lift-to-drag ratio data.

C-8

ORIGINAL PAGE IS
OF POOR QUALITY

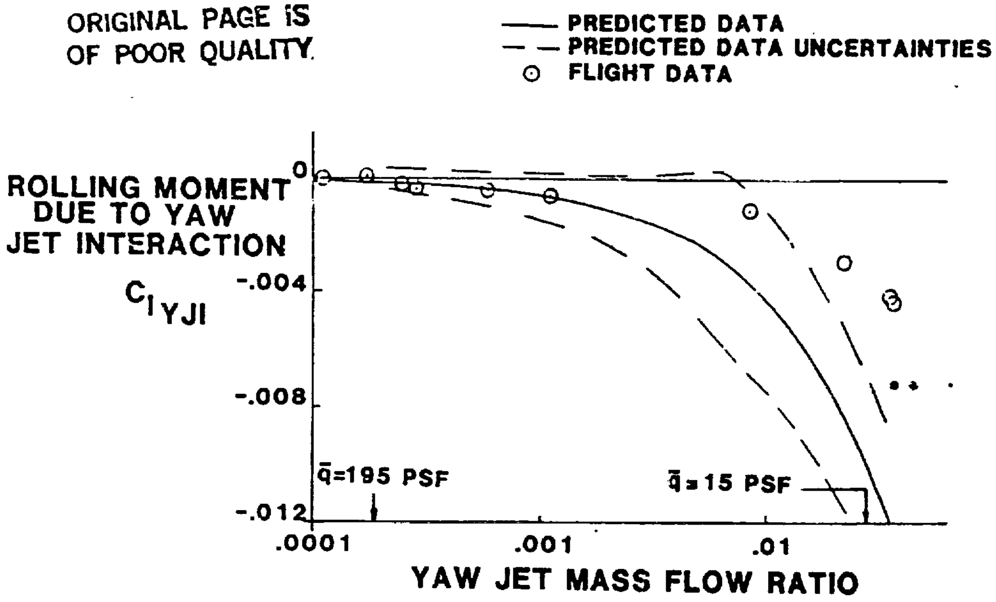


Figure 5.- Yaw jet/aerodynamic interaction.

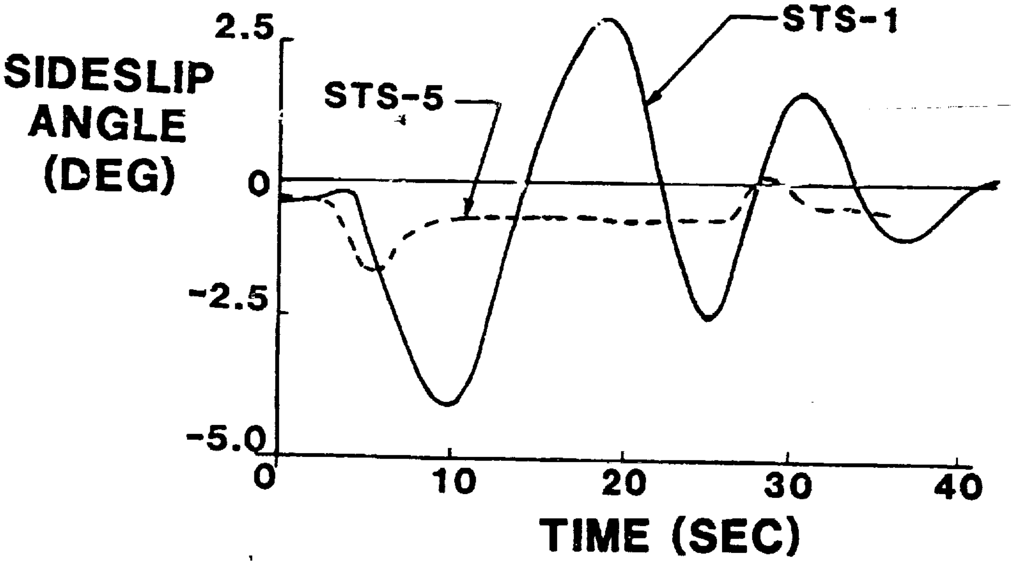


Figure 6.- First bank maneuver (auto).

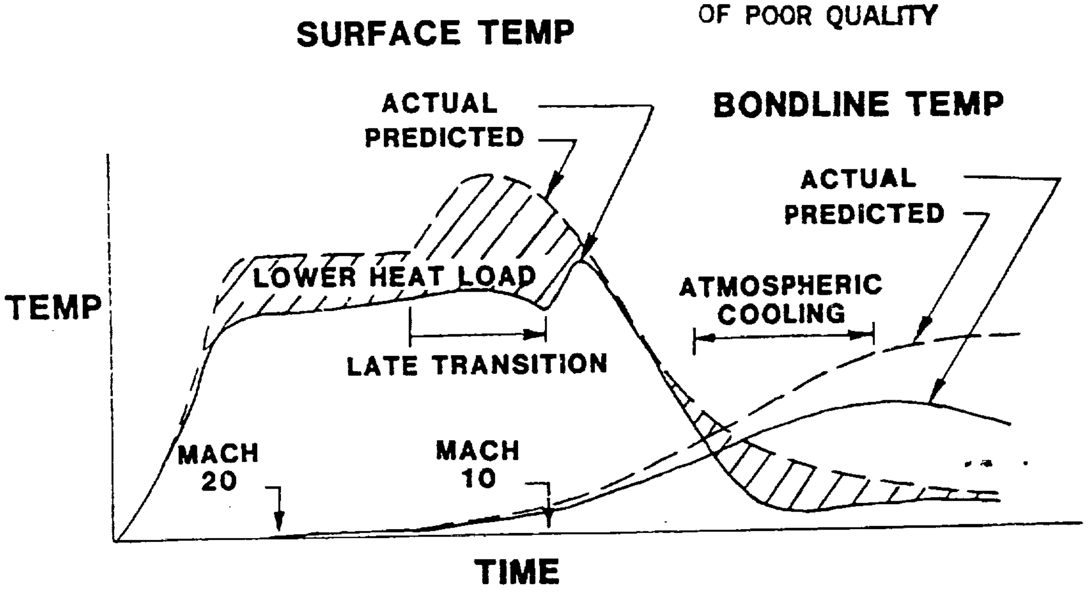


Figure 7.- Generalized lower surface heating results.

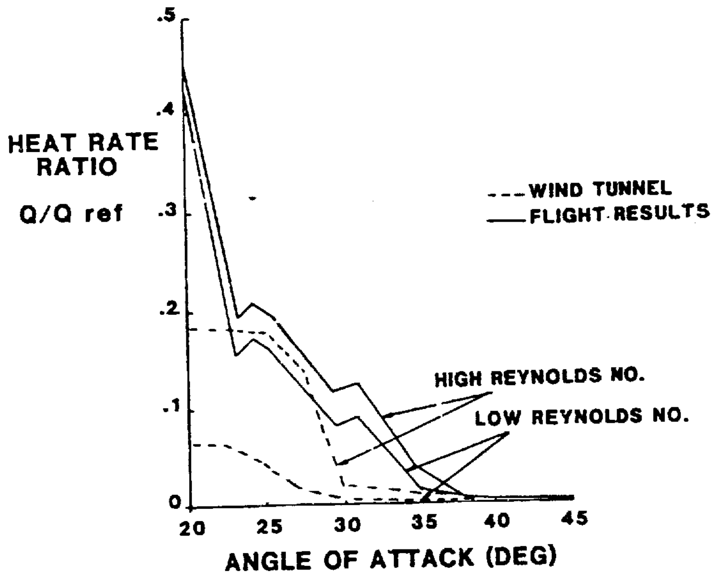
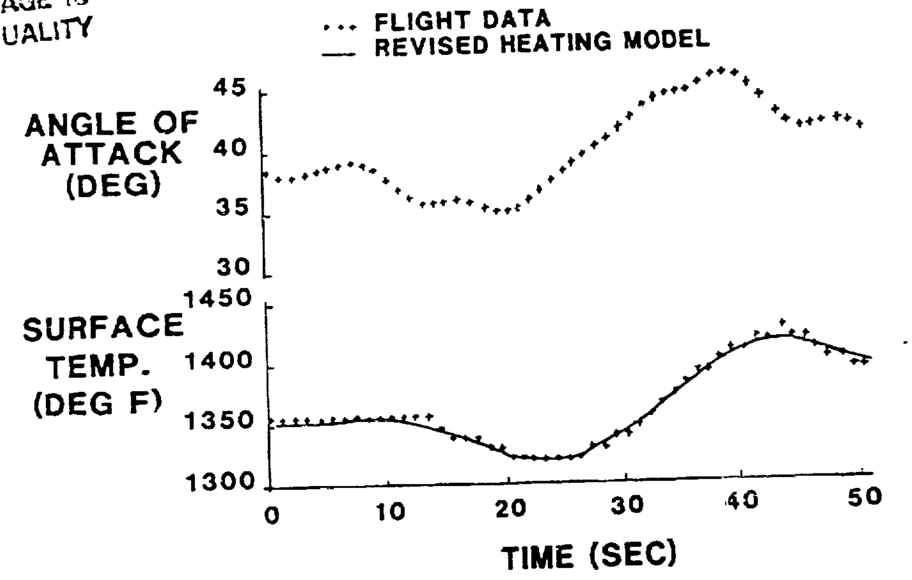


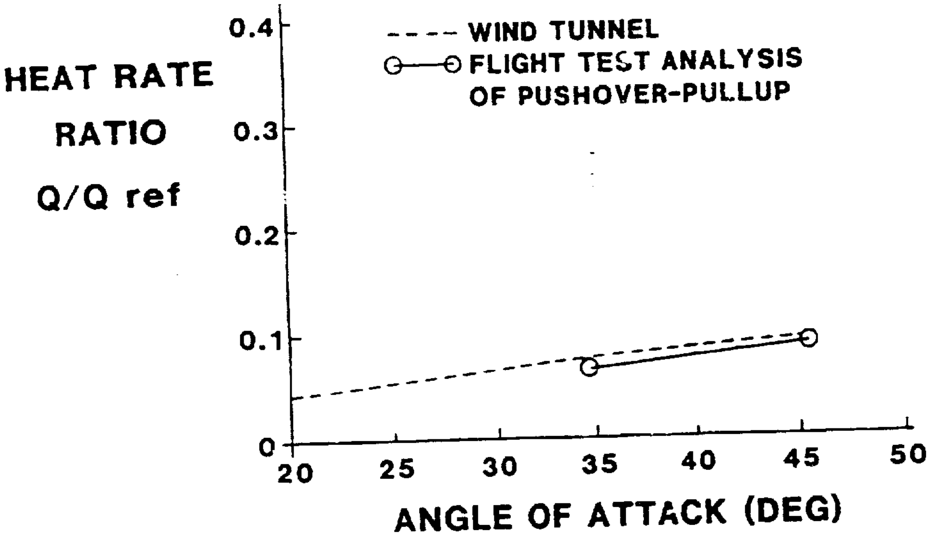
Figure 8.- OMS pod heating.

MANEUVER	DATA OUTPUT
● SLOW PUSHOVER-PULLUP	LIFT, DRAG VARIATION WITH ANGLE OF ATTACK NEW AEROTHERMODYNAMIC ANALYSIS
● PROGRAMMED TEST INPUTS (CONTROL PULSES)	STABILITY AND CONTROL DERIVATIVES
● BODY FLAP SWEEPS	BODY FLAP/ELEVON EFFECTIVENESS NEW AEROTHERMODYNAMIC ANALYSIS

Figure 9.- Successful application of aircraft dynamic testing techniques.



(a) Dynamic test maneuver for aerothermodynamics.



(b) Aerothermodynamic results from dynamic maneuver analysis.

Figure 10.- Dynamic testing of aerothermodynamic environment.
Aft lower centerline.

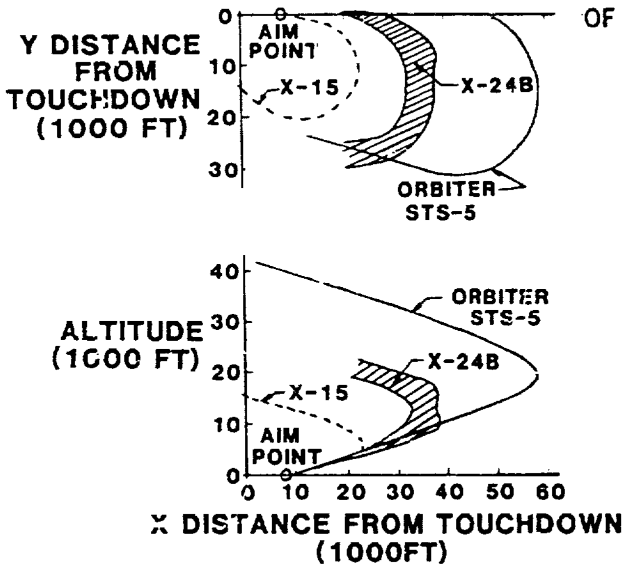


Figure 11.- Low L/D landing patterns.

- OVERALL LIFTING ENTRY DESIGN METHODOLOGY
- REUSABLE THERMAL PROTECTION SYSTEM TECHNOLOGY
- APPLICATION OF AIRCRAFT TEST TECHNIQUES
- AEROTHERMODYNAMIC FLIGHT TEST METHODS
- UNPOWERED, LOW L/D LANDING TECHNIQUES

Figure 12.- Lessons learned. Design prediction methods verified.

- HYPERSONIC PITCH TRIM AND NORMAL FORCE COEFFICIENTS
- JET INTERACTION EFFECTS
- LOWER SURFACE HEATING (OVERPREDICTED)
- UPPER SURFACE HEATING (LOCALLY UNDERPREDICTED)
- SUBSONIC LIFT-DRAG RATIO

Figure 13.- Lessons learned. Design prediction discrepancies.

- FUTURE HEAVIER RELIANCE ON

  THEORY
  COMPUTATIONAL AERODYNAMICS
  EMPIRICAL FLIGHT TEST RESULTS

  TO SUPPLEMENT WIND TUNNEL PREDICTIONS

- SIGNIFICANT TECHNOLOGY BENEFIT TO BE DERIVED FROM CONTINUED ORBITER REENTRY TESTING

Figure 14.- Concluding remarks.