



Aerodynamics and Flight Dynamics

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The shuttle vehicle was uniquely winged so it could reenter Earth's atmosphere and fly to assigned nominal or abort landing strips. The wings allowed the spacecraft to glide and bank like an airplane during much of the return flight phase. This versatility, however, did not come without cost. The combined ascent and re-entry capabilities required a major government investment in new design, development, verification facilities, and analytical tools. The aerodynamic and flight control engineering disciplines needed new aerodynamic and aerothermodynamic physical and analytical models. The shuttle required new adaptive guidance and flight control techniques during ascent and re-entry. Engineers developed and verified complex analysis simulations that could predict flight environments and vehicle interactions. The shuttle design architectures were unprecedented and a significant challenge to government laboratories, academic centers, and the aerospace industry. These new technologies, facilities, and tools would also become a necessary foundation for all post-shuttle spacecraft developments. The following section describes a US legacy unmatched in capability and its contribution to future spaceflight endeavors.

Aeroscience Challenges

One of the first challenges in the development of the Space Shuttle was its aerodynamic design, which had to satisfy the conflicting requirements of a spacecraft-like re-entry into the Earth's atmosphere where blunt objects have certain advantages, but it needed wings that would allow it to achieve an aircraft-like runway landing. It was to be the first winged vehicle to fly through the hypersonic speed regime, providing the first real test of experimental and theoretical technology for high-speed flight. No design precedents existed to help establish necessary requirements. The decision that the first flight would carry a crew further complicated the challenge. Other than approach and landing testing conducted at Dryden Flight Research Center, California, in 1977, there would be no progressive "envelope" expansion as is typically done for winged aircraft. Nor would there be successful uncrewed launch demonstrations as had been done for all spacecraft preceding the shuttle. Ultimately, engineers responsible for characterizing the aeroscience environments for the shuttle would find out if their collective predictions were correct at the same moment as the rest of the world: during the launch and subsequent landing of Space Transportation System (STS)-1 (1981).

Aeroscience encompasses the engineering specialties of aerodynamics and aerothermodynamics. For the shuttle, each specialty was primarily associated with analysis of flight through the Earth's atmosphere.

Aerodynamics involves the study of local pressures generated over the vehicle while in flight and the resultant integrated forces and



Early conceptual designs for the Orbiter looked much like a traditional airplane with a fairly sharp nose, straight wings, and common horizontal and vertical stabilizers, as shown in this artist's rendering. As a result of subsequent aerodynamic and aerothermodynamic testing and analysis, NASA made the nose more spherical to reduce heating and used a double delta wing planform due to the severe heating encountered by straight wings and the horizontal stabilizer.

moments that, when coupled with forces such as gravity and engine thrust, determine how a spacecraft will fly. Aerothermodynamics focuses on heating to the spacecraft's surface during flight. This information is used in the design of the Thermal Protection System that shields the underlying structure from excessive temperatures. The design of the shuttle employed state-of-the-art aerodynamic and aerothermodynamic prediction techniques of the day and subsequently expanded them into previously uncharted territory.

The historical precedent of flight testing is that it is not possible to "validate"—or prove—that aerodynamic predictions are correct until vehicle performance is measured at actual flight conditions. In the case of the shuttle, preflight predictions needed to be accurate enough to establish sufficient confidence to conduct the first orbital

flight with a crew on board. This dictated that the aerodynamic test program had to be extremely thorough. Further complicating this goal was the fact that much of the expected flight regime involved breaking new ground, and thus very little experimental data were available for the early Space Shuttle studies.

Wind tunnel testing—an experimental technique used to obtain associated data—forces air past a scaled model and measures data of interest, such as local pressures, total forces, or heating rates. Accomplishing the testing necessary to cover the full shuttle flight profile required the cooperation of most of the major wind tunnels in North America. The Space Shuttle effort was the largest such program ever undertaken by the United States. It involved a traditional phased approach in the programmatic design evolution of the shuttle configuration.

The shuttle started on the launch pad composed of four primary aerodynamic elements: the Orbiter; External Tank; and two Solid Rocket Boosters (SRBs). It built speed as it rose through the atmosphere. Aeronautical and aerospace engineers often relate to speed in terms of Mach number—the ratio of the speed of an object relative to the speed of sound in the gas through which the object is flying. Anything traveling at less than Mach 1 is said to be subsonic and greater than Mach 1 is said to be supersonic. The flow regime between about Mach 0.8 and Mach 1.2 is referred to as being transonic.



This photo shows clouds enveloping portions of the vehicle (STS-34 [1987]) during ascent. When the launch vehicle was in the transonic regime, shocks formed at various positions along the vehicle to recompress the flow, which greatly impacted the structural loads and aerodynamics. Such shocks, which abruptly transition the flow from supersonic to subsonic flow, were positioned at the trailing edge of the condensation “clouds” that could be seen enveloping portions of the vehicle during ascent. These clouds were created in localized areas of the flow where the pressure and temperature conditions caused the ambient moisture to condense.

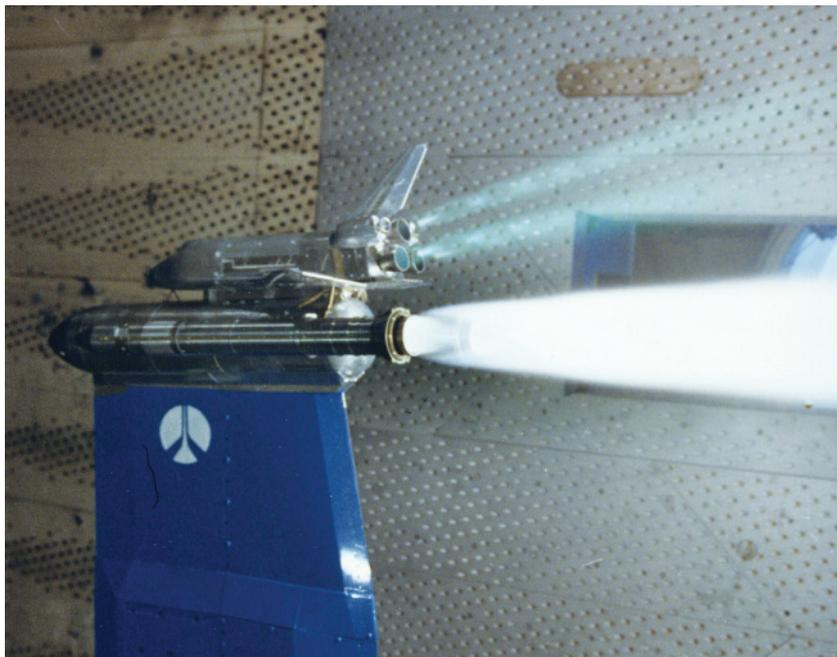
Aerodynamic loads decreased to fairly low levels as the shuttle accelerated past about Mach 5 and the atmospheric density decreased with altitude, thus the aerodynamic testing for the ascent configuration was focused on the subsonic through high supersonic regimes.

Other aspects of the shuttle design further complicated the task for engineers. Aerodynamic interference existed between the shuttle’s four elements and altered the resultant pressure loads and aerodynamics on neighboring elements. Also, since various shuttle elements were designed to separate at different points in the trajectory, engineers had to consider the various relative positions of the elements during separation. Yet another complication was the effect of plumes generated by SRBs and Space Shuttle

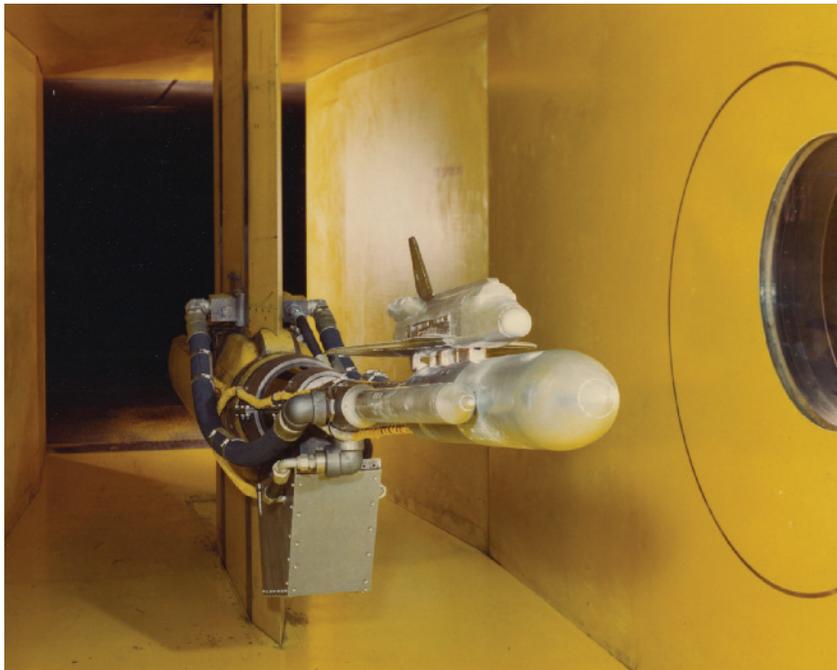
Main Engines (SSMEs). The plume flow fields blocked and diverted air moving around the spacecraft, thus influencing pressures on the aft surfaces and altering the vehicle’s aerodynamic characteristics.

Unfortunately, wind tunnel testing with gas plumes was significantly more expensive and time consuming than “standard” aerodynamic testing. Thus, the approach implemented was to use the best available testing techniques to completely characterize the basic “power-off” (i.e., no plumes) database. “Power-on” (i.e., with plumes) effects were then measured from a limited number of exhaust plume tests and added to the power-off measurements for the final database.

The re-entry side of the design also posed unique analysis challenges. During ascent, the spacecraft continued



While it may be intuitive to include the major geometric elements of the launch vehicle (Orbiter, External Tank, and two Solid Rocket Boosters) in aerodynamic testing, it was also important to include the plumes emanating from the three main engines on the Orbiter as well as the boosters. The tests were conducted in the 4.9-m (16-ft) Transonic Wind Tunnel at the US Air Force Arnold Engineering and Development Center, Tennessee.



Every effort was made to accurately predict a vehicle's aerodynamic characteristics using wind tunnel testing. Engineers also had to be aware of anything that could adversely affect the results. This image is of the NASA Ames Research Center 2.4 x 2.1 m (8 x 7 ft) Unitary Wind Tunnel, California.

to accelerate past the aerodynamically relevant portion of the ascent trajectory. During re-entry, this speed was carried deep into the atmosphere until there was sufficient atmospheric density to measurably dissipate the related kinetic energy. Therefore, the aerodynamics of the Orbiter were critical to the design of the vehicle from speeds as high as Mach 25 down through the supersonic and subsonic regimes to landing, with the higher Mach numbers being characterized by complex physical gas dynamics that greatly influenced the aerodynamics and heating on the vehicle compared to lower supersonic Mach numbers.

Challenges associated with wind tunnel testing limited direct applicability to the actual flight environment that engineers were interested in simulating, such as: subscale modeling of the vehicle necessary to fit in the wind tunnel and

the effect on flow-field scaling; the support structure used to hold the aerodynamic model in the wind tunnel test section, which can affect the flow on the model itself; and any influence of the wind tunnel walls. To protect against any inaccuracies in the database, each aerodynamic coefficient was additionally characterized by an associated uncertainty. Great care had to be taken to not make the uncertainties too large due to the adverse effect an uncertainty would have on the design of the flight control system and the ultimate performance of the spacecraft.

In the end, given the 20,000 hours of wind tunnel test time consumed during the early design efforts and the 80,000 hours required during the final phases, a total of 100,000 hours of wind tunnel testing was conducted for aerodynamic, aerothermodynamic, and structural dynamic testing to characterize the various shuttle system elements.

Initial Flight Experience

Traditionally, a flight test program was used to validate and make any necessary updates to the preflight aerodynamic database. While flight test programs use an incremental expansion of the flight envelope to demonstrate the capabilities of an aircraft, this was not possible with the shuttle. Once launched, without initiation of an abort, the shuttle was committed to flight through ascent, orbital operations, re-entry, and landing. NASA placed a heavy emphasis on comparison of the predicted vehicle performance to the observed flight performance during the first few shuttle missions, and those results showed good agreement over a majority of flight regimes. Two prominent areas, however, were deficient: predictions of the launch vehicle's ascent performance, and the "trim" attitude of the Orbiter during the early phase of re-entry.

On STS-1, the trajectory was steeper than expected, resulting in an SRB separation altitude about 3 km (1.9 miles) higher than predicted. Postflight analysis revealed differences between preflight aerodynamic predictions and actual aerodynamics observed by the shuttle elements due to higher-than-predicted pressures on the shuttle's aft region. It was subsequently determined that wind tunnel predictions were somewhat inaccurate because SRB and SSME plumes were not adequately modeled. This issue also called into question the structural assessment of the wing, given the dependence on the preflight prediction of aerodynamic loads. After additional testing and cross checking with flight data, NASA was able to verify the structural assessment.



The Space Shuttle Enterprise was used to conduct approach and landing testing (1977) at the Dryden Flight Research Center, California. In the five free flights, the astronaut crew separated the spacecraft from the Shuttle Carrier Aircraft and maneuvered to a landing. These flights verified the Orbiter's pilot-guided approach and landing capability and verified the Orbiter's subsonic airworthiness in preparation for the first crewed orbital flight.

Another discrepancy occurred during the early re-entry phase of STS-1. Nominally, the Orbiter was designed to reenter in an attitude with the nose of the vehicle inclined 40 degrees to the oncoming air. In aeronautical terms, this is a 40-degree angle of attack. To aerodynamically control this attitude, the Orbiter had movable control surfaces on the trailing edge of its wings and a large “body flap.” To maintain the desired angle of attack, the Orbiter could adjust the position of the body flap up out of the flow or down into the flow, accordingly. During STS-1, the body flap deflection was twice the amount than had been predicted would be required and was uncomfortably close to the body flap’s deployment limit of 22.5 degrees. NASA determined that the cause was “real gas effects”—a phenomenon rooted in high-temperature gas dynamics.

During re-entry, the Orbiter compressed the air of the atmosphere as it smashed into the atmosphere at hypersonic speed, causing the temperature of the air to heat up thermodynamically. The temperature rise was so extreme that it broke the chemical bonds that hold air molecules together, fundamentally altering how the flow around the Orbiter compressed and expanded. These high-temperature gas dynamic effects influenced the pressure distribution on the aft portion of the heat shield, thus affecting its nominal trim condition. The extent to which this effect affected the Orbiter had not been observed before; thus, it was not replicated in the wind tunnel testing used during the design phase. NASA researchers developed an experimental technique to simulate this experience using a special test gas that mimicked the behavior of high-temperature air at the lower temperatures achieved during wind tunnel testing.

Advances in Computational Aeronautics

The use of computational fluid dynamics was eventually developed as a complementary means of obtaining aeronautics information. Engineers used computers to calculate flow-field properties around the shuttle vehicle for a given flight condition. This included pressure, shear stress, or heating on the vehicle surface, as well as density, velocity, temperature, and pressure of the air away from the vehicle. This was accomplished by numerically solving a complex set of nonlinear partial differential equations that described the motion of the fluid and satisfied a fundamental requirement for conservation of mass, momentum, and energy everywhere in the flow field.

Given its relative lack of sophistication and maturity, coupled with the modest computational power afforded by computers in the 1970s, computational fluid dynamics played almost no role in the development of the Space Shuttle aerodynamic database. In the following decades, bolstered by exponential increases in computer capabilities and continuing research, computational fluid dynamics took on a more prominent role. As with any tool, demonstrated validation of results with closely related experimental or flight data was an essential step prior to its use.

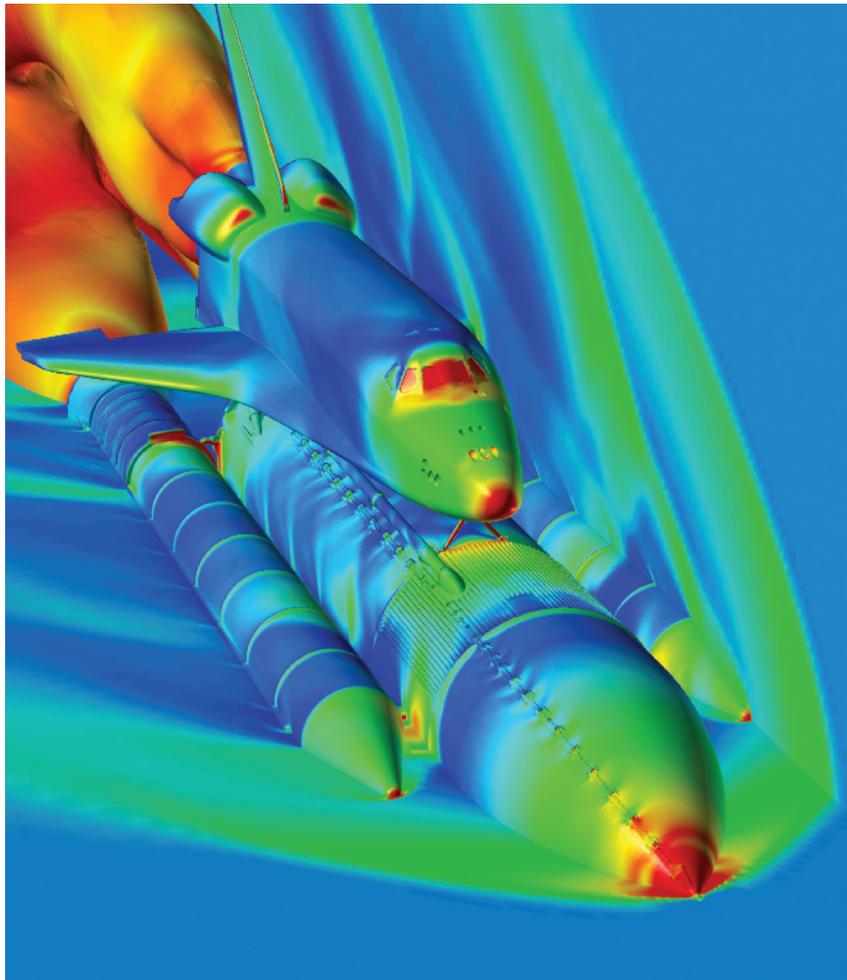
The most accurate approach for using wind tunnel data to validate computational fluid dynamics predictions was to directly model the wind tunnel as closely as possible, computationally. After results were validated at wind tunnel conditions, the computational fluid dynamics tool could be run at the flight conditions and used directly, or the difference between the computed flight and

wind tunnel predictions could be added to the baseline experimental wind tunnel measured result.

Because different flight regimes have unique modeling challenges, NASA developed separate computational fluid dynamics tools that were tuned to specific flight regimes. This allowed the computational algorithms employed to be optimized for each regime. Although not available during the preflight design of the Space Shuttle, several state-of-the-art computational tools were created that contributed significantly to the subsequent success of the shuttle, providing better understanding of control surface effectiveness, aerodynamic interference effects, and damage assessment. The examples of OVERFLOW and Langley Aerothermodynamic Upwind Relaxation Algorithm (LAURA) software packages were both based on traditional computational fluid dynamics methods while the digital to analog converter (DAC) software employed special-purpose algorithms that allowed it to simulate rarefied, low-density flows.

The OVERFLOW computational fluid dynamics tool was optimized for lower Mach number subsonic, transonic, and supersonic flows. It was thus most applicable for ascent and late re-entry simulations. Additionally, its underlying methodology was based on an innovative and extremely flexible approach for discretization of the domain around the vehicle. This was especially beneficial for analysis of a complex geometry like the shuttle.

The development of this computational fluid dynamics tool allowed engineers to effectively model the requisite geometric detail of the launch vehicle, as well as the plumes. OVERFLOW was subsequently used to investigate



This image depicts the geometric detail included in this high-fidelity modeling capability, as well as some representative results produced by the OVERFLOW tool. The OVERFLOW computational fluid dynamics tool was optimized for lower Mach number subsonic, transonic, and supersonic flows. The surface pressure is conveyed by a progressive color scale that corresponds to the pressure magnitude. A similar color scale with a different range is used to display Mach number in the flow field. OVERFLOW provided extremely accurate predictions for the launch vehicle aerodynamic environments. Color contouring depicts the nominal heating distribution on the Orbiter, where hotter colors represent higher values and cooler colors represent lower values.

the effect of design changes to the shuttle's aerodynamic performance. Some of these directly impacted shuttle operations, including all of the changes made to the tank after the Columbia accident in 2003 to help minimize the debris. Additionally, OVERFLOW solutions became a key element in the program's risk assessment for ascent debris, as the detailed flow-field

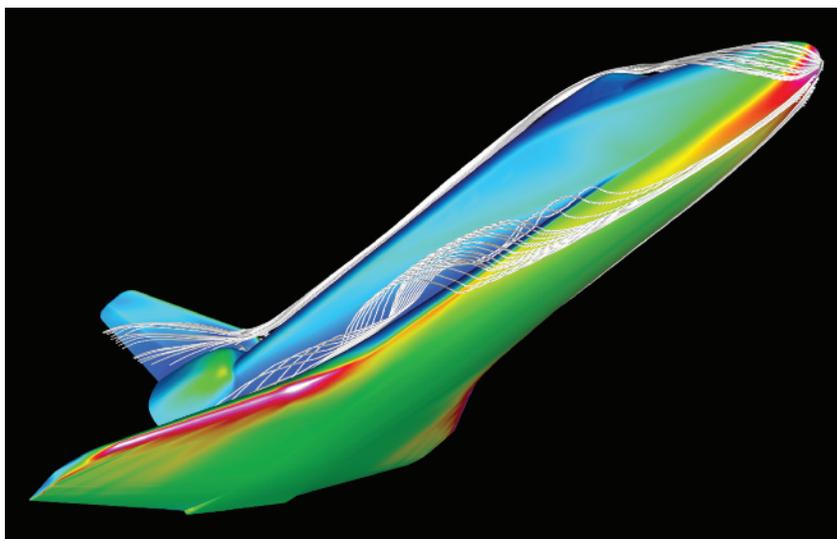
information it provided was used to predict trajectories of potential debris sources. OVERFLOW became a key tool for commercial and military transport analyses and was heavily used by industry as well as other NASA programs.

The LAURA package was another traditional computational fluid

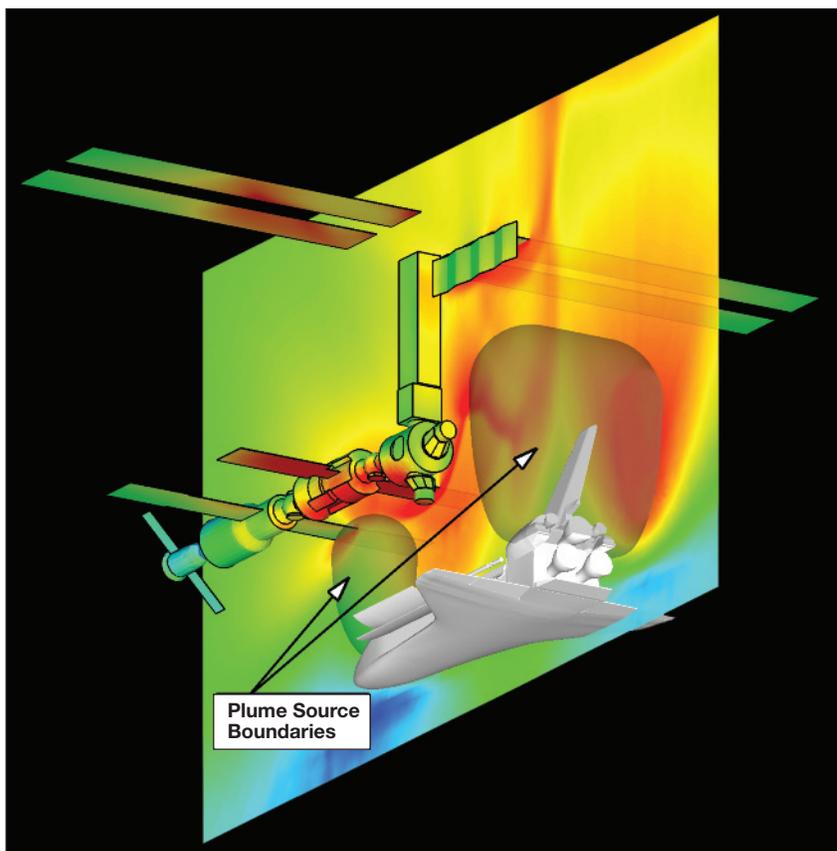
dynamics code, but designed specifically to predict hypersonic flows associated with re-entry vehicles. It incorporated physical models that account for chemical reactions that take place in air at the extremely high temperatures produced as a spacecraft reenters an atmosphere, as well as the temporal speed at which these reactions take place. This was essential, as the “resident” time a fluid element was in the vicinity of the Orbiter was extremely short given that the vehicle traveled more than 20 times the speed of sound and the chemical reactions taking place in the surrounding fluid occurred at a finite rate.

LAURA underwent extensive validation through comparisons to a wide body of experimental and flight data, and it was also used to investigate, reproduce, and answer questions associated with the Orbiter body flap trim anomaly. LAURA was used extensively during the post-Columbia accident investigation activities and played a prominent role in supporting subsequent shuttle operations. This included assessing damaged or repaired Orbiter Thermal Protection System elements, as well as providing detailed flow field characteristics. These characteristics were assessed to protect against dangerous early transitioning of the flow along the heat shield of the Orbiter from smooth laminar flow to turbulent conditions, and thus

NASA used the Direct Simulation Monte Carlo method to simulate low-density flows, such as those created by maneuvering thrusters during orbital rendezvous and docking of the shuttle to the space station. While the method made use of a distinctly different modeling technique to make its predictions, it produced the same detailed information about the flow field as would a traditional computational fluid dynamics technique.



Special computational fluid dynamics programs appropriately model the complex chemically reacting physics necessary to accurately predict a spacecraft's aerodynamic characteristics and the aerothermodynamic heating it will experience. Heating information was needed to determine the appropriate materials and thickness of the Thermal Protection System that insulated the underlying structure of the vehicle from hot gases encountered during re-entry into Earth's atmosphere. Color contouring depicts the nominal heating distribution on the Orbiter, where hotter colors represent higher values and cooler colors represent lower values.



greatly elevated heating that would have endangered the vehicle and crew.

While traditional computational fluid dynamics tools proved extremely useful, their applicability was limited to denser portions of the atmosphere. NASA recognized the need to also be able to perform accurate analysis of low-density flows. Subsequently, the agency invested in the development of a state-of-the-art computer program that would be applicable to low-density rarefied flows. This program was based on the Direct Simulation Monte Carlo (DSMC) method—which is a simulation of a gas at the molecular level that tracks molecules through physical space and their subsequent deterministic collisions with a surface and representative collisions with other molecules. The resulting software, named the DSMC Analysis Code, was used extensively in support of shuttle missions to the Russian space station Mir and the International Space Station, as well as Hubble Space Telescope servicing missions. It also played a critical role in the analysis of the Mars Global Surveyor (1996) and the Mars Odyssey (2001) missions.

Leveraging the Space Shuttle Experience

Never before in the history of flight had such a complex vehicle and challenging flight regime been characterized. As a result of this challenge, NASA developed new and improved understanding of the associated physics, and subsequently techniques and tools to more accurately simulate them. The aerospace techniques and technologies that successfully supported the Space Shuttle are useful for exploration of our solar system.

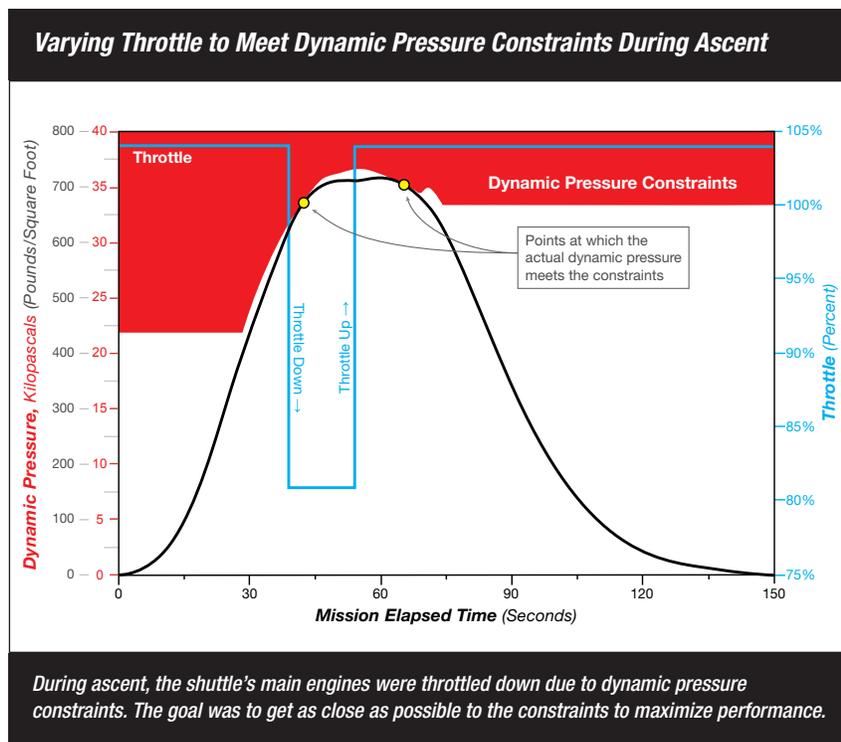
Ascent Flight Design

NASA's challenge was to put wings on a vehicle and have that vehicle survive the atmospheric heating that occurred during re-entry into Earth's atmosphere. The addition of wings resulted in a much-enhanced vehicle with a lift-to-drag ratio that allowed many abort options and a greater cross-range capability, affording more return-to-Earth opportunities. This Orbiter capability did, however, create a unique ascent flight design challenge. The launch configuration was no longer a smooth profiled rocket. The vehicle during ascent required new and complex aerodynamic and structural load relief capabilities.

The Space Shuttle ascent flight design optimized payload to orbit while operating in a constrained environment. The Orbiter trajectory needed to restrict wing and tail structural loading during maximum dynamic pressure

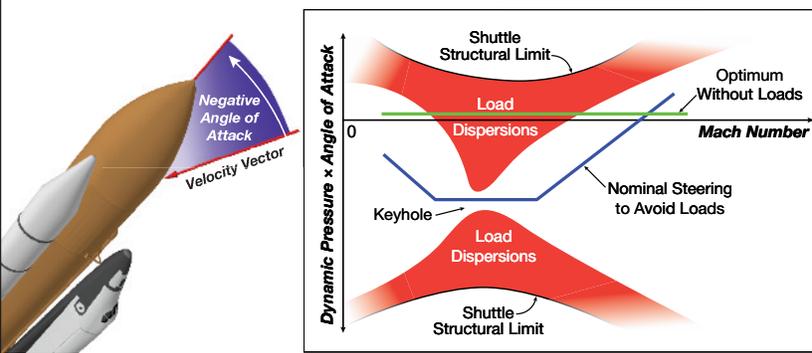
and provide acceptable first stage performance. This was achieved by flying a precise angle of attack and sideslip profile and by throttling the main engines to limit dynamic pressure to five-times-gravity loads. The Solid Rocket Boosters (SRBs) had a built-in throttle design that also minimized the maximum dynamic pressure the vehicle would encounter and still achieve orbital insertion.

During the first stage of ascent, the vehicle angle of attack and dynamic pressure produced a lift force from the wings and produced vehicle structural loading. First stage guidance and control algorithms ensured that the angle of attack and sideslip did not vary significantly and resulted in flying through a desired keyhole. The keyhole was defined by the product of dynamic pressure and angle of attack. The product of dynamic pressure and sideslip maintained the desired loading on the vehicle tail.





Flying Through a Keyhole



Load dispersions, which are mostly due to atmospheric and thrust variations, added further constraints to the shuttle's flight. To avoid the various load dispersions at certain Mach numbers, the shuttle had to deviate from its optimum angle of attack.

Because day-of-launch winds aloft significantly altered vehicle angle of attack and sideslip during ascent, balloon measurements were taken near liftoff and in proximity of the launch site. Based on these wind measurements, Orbiter guidance parameters were biased and updated via telemetry.

Also during first stage, a roll maneuver was initiated after the vehicle cleared the tower. This roll maneuver was required to achieve the desired orbital inclination and put the vehicle in a heads-down attitude during ascent.

Vehicle performance was maximized during second stage by a linear steering law called powered explicit guidance. This steering law guided the vehicle to orbital insertion and provided abort capability to downrange abort sites or return to launch site. Ascent performance was maintained. If one main engine failed, an intact abort could be achieved to a safe landing site. Such aborts allow the Orbiter and crew to either fly at a lower-than-planned orbit or land.

Ascent flight design was also constrained to dispose the External Tank (ET) in safe waters—either the Indian Ocean or the Pacific Ocean—or in a location where tank debris was not an issue.

After main engine cutoff and ET separation, the remaining main engine fuel and oxidizer were dumped. This event provided some additional performance capability.

After the shuttle became operational, additional ascent performance was added to provide safe orbit insertion for some heavy payloads. Many guidance and targeting algorithm additions provided more payload capability. For example, standard targets were replaced by direct targets, resulting in one Orbital Maneuvering System maneuver instead of two. This saved propellant and resulted in more payload to orbit.

The ascent flight design algorithms and techniques that were generated for the shuttle will be the foundation for ascent flight of any new US launch vehicle.

Ascent Abort

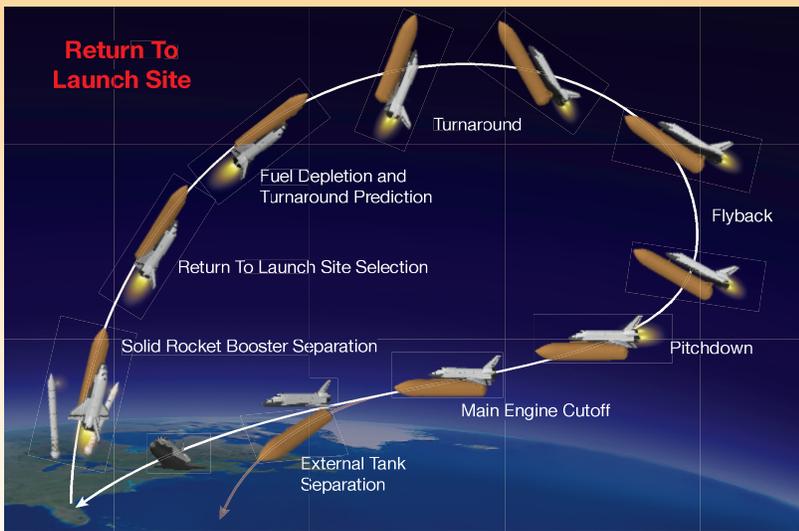
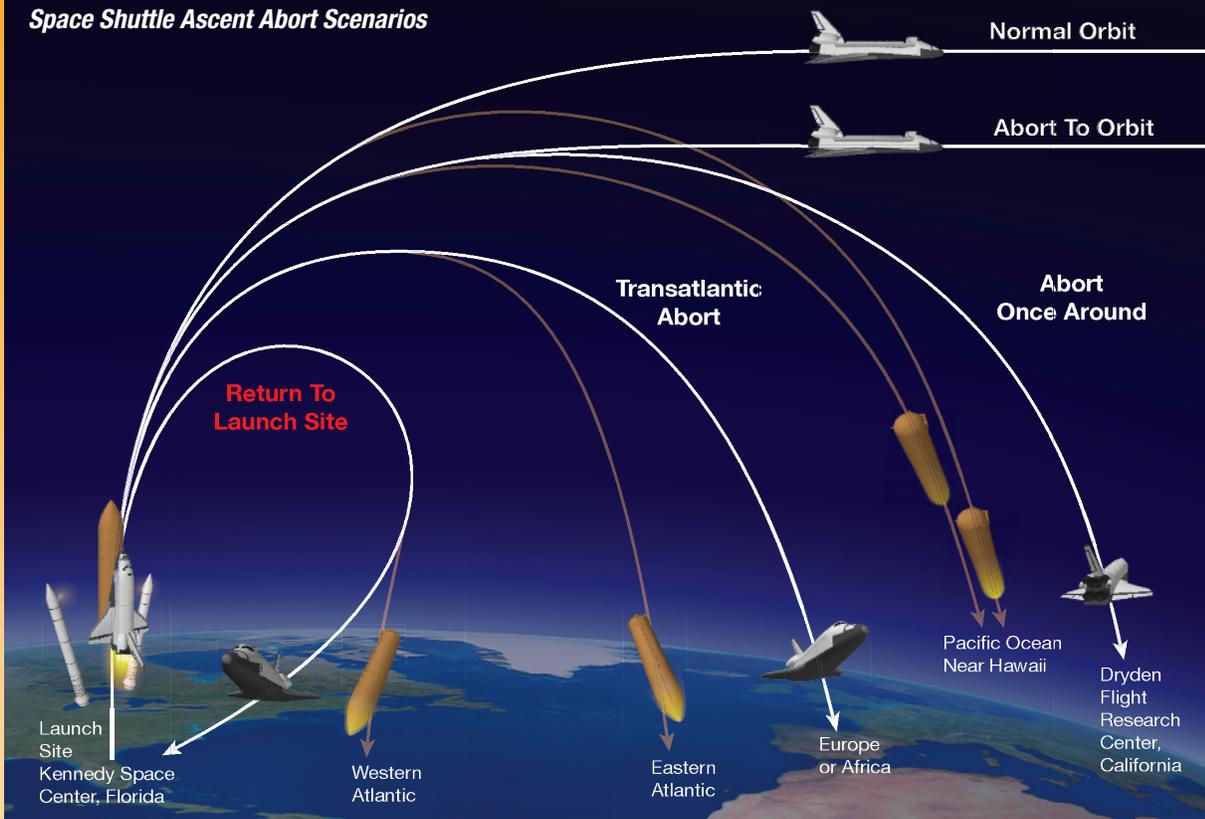
During ascent, a first stage Orbiter main engine out required the shuttle to return to the launch site. The on-board guidance adjusted the pitch profile to achieve SRB staging conditions while satisfying structural and heating constraints. For a side Orbiter main engine out, the vehicle was rolled several degrees so that the normal aerodynamic force canceled the side force induced by the remaining good side engine. Also, vehicle sideslip was maintained near zero to satisfy structural constraints.

After the SRBs were safely separated, second stage guidance commanded a fixed pitch attitude around 70 degrees to minimize vehicle heating and burn the fuel no longer required. This was called the fuel dissipation phase and lasted until approximately 2% of the fuel remained. At this point, guidance commanded the vehicle to turn around and fly back to the launch site using the powered explicit guidance algorithm. As the vehicle returned, it was pitched down so the ET could be safely separated. Dynamic pressure was also minimized so a safe re-entry could occur.

During second stage ascent, a main engine failure usually required the vehicle to abort to a transatlantic landing site. An abort to a downrange landing site was preferred to a return to launch site to reduce complex trajectory targeting and minimize the loads and heating environments, therefore increasing abort success. If a main engine failure occurred late during second stage, an abort to a safe orbit was possible. Abort to orbit was preferred over an abort to a transatlantic landing site. Once the shuttle was in a safe orbit, the vehicle could perform a near nominal re-entry and return to the planned US landing strip.



Space Shuttle Ascent Abort Scenarios



The shuttle had four types of intact aborts: Return to Launch Site; Transatlantic Abort Landing; Abort to Orbit; and Abort Once Around. The aborts are presented as they occurred in the mission timeline. The preferred order of selecting aborts based on performance and safety was: Abort to Orbit; Abort Once Around; Transatlantic Abort Landing; and Return to Launch Site.

If more than one main engine failed during ascent, a contingency abort was required. If a contingency abort was called during first stage, guidance would pitch the vehicle up to loft the trajectory, thereby minimizing dynamic pressure and allowing safe separation of the SRBs and ET. After these events, a pullout maneuver would be performed to bring the vehicle to a gliding flight so a crew bailout could occur.

Two engines out early during second stage allowed the crew to attempt a landing along the US East Coast at predefined landing strips. Two engines out late in second stage allowed an abort to a transatlantic site or abort to safe orbit, depending on the time of the second failure.

In general, Mission Control used vehicle telemetry and complex vehicle performance predictor algorithms to assist the crew in choosing the best abort guidance targets and a safe landing site. The Abort Region Determinator was the primary ground flight design tool that assisted Mission Control in making abort decisions. If communication with the ground was lost, the crew would use on-board computer data and cue cards to assist in selecting the abort mode.

Summary

The shuttle ascent and ascent flight design were complex. NASA developed and verified many innovative guidance algorithms to accomplish mission objectives and maintain vehicle and crew safety. This legacy of flight techniques and computer tools will prove invaluable to all new spacecraft developments.

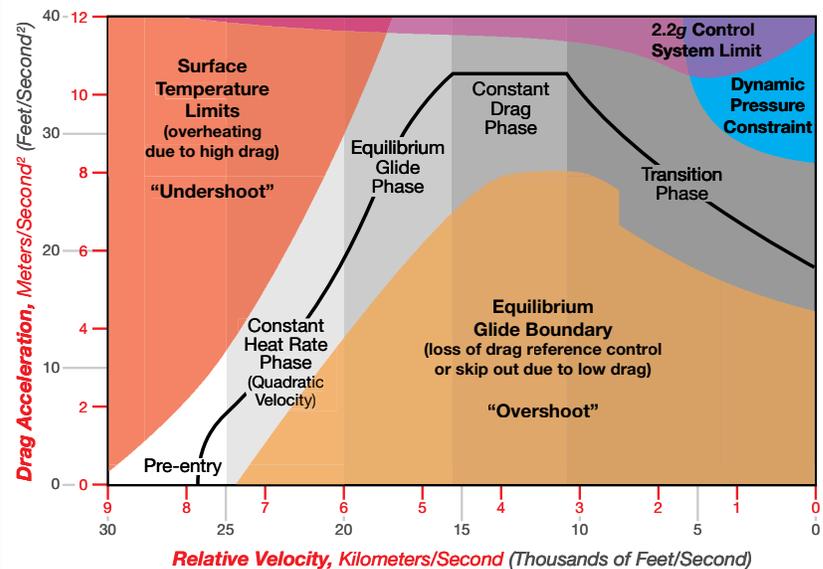
Re-entry Flight Design

The shuttle vehicle reentered the Earth's atmosphere at over 28,000 km per hour (kph) (17,400 mph)—about nine times faster than the muzzle speed of an M16 bullet. Designing a guidance system that safely decelerated this rapidly moving spacecraft to runway landing speeds while respecting vehicle and crew constraints was a daunting challenge, one that the shuttle re-entry guidance accomplished.

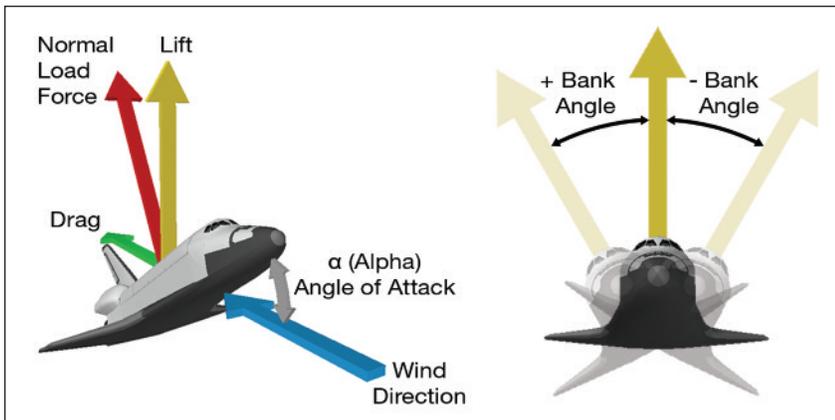
The shuttle re-entry guidance provided steering commands from

initial re-entry at a speed of 28,000 kph (17,400 mph), an altitude of 122 km (76 miles), and a distance of 7,600 km (4,722 miles) from the runway until activation of terminal area guidance (a distance of about 90 km [56 miles] and 24 km [15 miles] altitude from the runway). During this interval, a tremendous amount of kinetic energy was transferred into heat energy as the vehicle slowed down. This was all done while the crew experienced only about 1.5 times the acceleration of gravity (1.5g). As a comparison, 1g acceleration is what we feel while sitting on a chair at sea level.

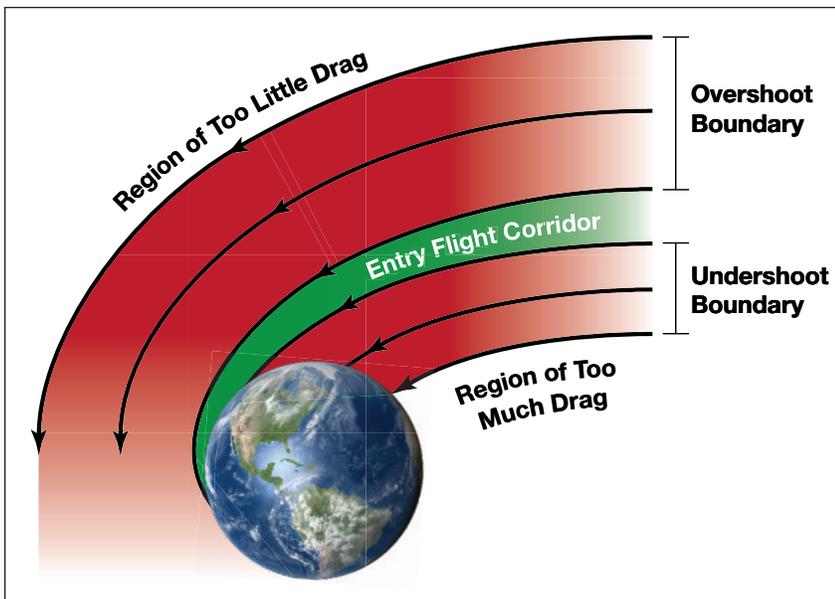
Entry Guidance Drag Velocity Profile



Shuttle re-entry guidance was segmented into several phases—each designed to satisfy unique constraints during flight. The narrow region of acceptable flight conditions was called the “flight corridor.” The surface temperature constraints resided at the lower altitude and high drag “undershoot” side of the flight corridor. In contrast, if the vehicle flew too close to the “overshoot” boundary, it would not have enough drag acceleration to reach the landing site and could possibly skip back into orbit. As the vehicle penetrated deeper into the atmosphere, the undershoot corridor was redefined by the vehicle control system and dynamic pressure constraints.



Shuttle re-entry guidance generated bank angle and angle-of-attack commands. The body flap was used to control the angle of attack by balancing the aerodynamic forces and moments about the vehicle center of gravity. The bank angle controlled the direction of the lift vector about the wind velocity vector at a fixed angle of attack. Drag, which was opposite to the wind-relative velocity, slowed the vehicle down. Lift was normal to the drag vector and was used to change the rate at which the vehicle reentered the atmosphere. The total normal load force was the sum of the lift acceleration and drag acceleration and resulted in the force felt by the crew.



The Entry Flight Corridor defined the atmospheric re-entry angles required for safe re-entry flight. Before any successful re-entry from low-Earth orbit could occur, the shuttle needed to fire engines to place the vehicle on a trajectory that intercepted the atmosphere. This deorbit maneuver had to be executed precisely. With too steep of a re-entry, the guidance could not compute steering commands that would stop the vehicle from overheating. With too shallow of a re-entry, the guidance could not adequately control the trajectory or, for very shallow trajectories, even stop the vehicle from skipping back out into space. The area between these two extremes was called the Entry Flight Corridor.

How did Space Shuttle Guidance Accomplish This Feat?

First, it's important to understand how the shuttle was controlled. Air molecules impacting the vehicle's surface imparted a pressure or force over the vehicle's surface. The shuttle used Reaction Control System jets initially to control the attitude of the vehicle; however, as the dynamic pressure increased on entering denser atmosphere, the position of the body flap was used to control the angle of attack and the ailerons were used to control bank.

Changing the angle of attack had an immediate effect on the drag acceleration of the vehicle, whereas changing the bank angle had a more gradual effect. It took time for the vehicle to decelerate into different portions of the atmosphere where density and speed affected drag. Controlling the direction of the vehicle lift vector by banking the vehicle was the primary control mechanism available to achieve the desired landing target. The vehicle banked about the relative velocity vector using a combination of aft yaw Reaction Control System jets and aileron deflection. The lift vector moved with the vehicle as it banked about the wind vector. The angle of attack was maintained constant during these maneuvers by the balanced aerodynamic forces at a given body flap trim position. The vehicle banked around this wind vector, keeping the blunt side of the shield facing against the flow of the atmosphere. Banking about the wind vector until the lift pointing down accelerated the vehicle into the atmosphere. Over time, this increased drag caused the vehicle to decelerate quickly. Banking about the wind vector until the lift vector pointed up accelerated the vehicle out of the

atmosphere. Over time, this decreased the drag acceleration and caused the vehicle to decelerate gradually. Control of the vehicle lift-and-drag acceleration by bank angle and angle-of-attack modulation were the two primary control parameters used to fly the desired range and cross range during re-entry. These concepts had to be clearly grasped before it was possible to understand the operation of the guidance algorithm.

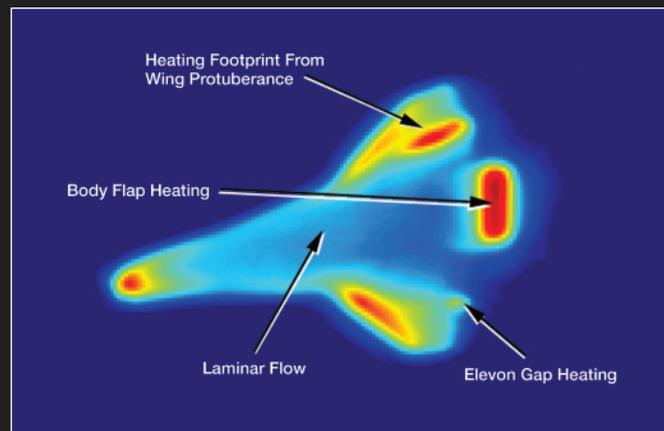
Within each guidance phase, it was possible to use simple equations to analytically compute how much range was flown. As long as the shuttle trajectory stayed “close” to reference profiles, the guidance algorithm could analytically predict how far the vehicle would fly.

By piecing together all of the guidance segments, the total range flown from the current vehicle position all the way to the last guidance phase could be predicted and compared to the actual range required to reach the target. Any difference between the analytically computed range and the required range would trigger an adjustment in the drag-velocity/energy references to remove that range error. The analytic reference profiles were computed every guidance step (1.92 seconds) during flight. In this manner, any range error caused by variations in the environment, navigated state, aerodynamics, or mass properties was sensed and compensated for with adjustments to the real-time computed drag-velocity or drag-energy reference profiles.

In fact, the entire shuttle re-entry guidance system could be described as a set of interlocked drag-velocity or drag-energy pieces that would fly the required range to target and maintain the constraints of flight.

Boundary Layer Transition

Accurate characterization of the aerothermodynamic heating experienced by a spacecraft as it enters an atmosphere is of critical importance to the design of a Thermal Protection System. More intense heating typically requires a thicker Thermal Protection System, which increases a vehicle's weight. During the early phase of entry, the flow near the surface of the spacecraft—referred to as the boundary layer—has a smooth laminar profile. Later in the trajectory, instabilities develop in the boundary layer that cause it to transition to a turbulent condition that can increase the heating to the spacecraft by up to a factor of 4 over the laminar state. Subsequently, a Boundary Layer Transition Flight Experiment was conceived and implemented on Space Shuttle Discovery's later flights. This experiment employed a fixed-height protuberance (speed bump) on the underside of the wing to perturb and destabilize the boundary layer. NASA used instrumentation to measure both the elevated heating on the protuberance as well as the downstream effect so that the progression of the transition could be captured. The experiment provided foundational flight data that will be essential for the validation of future ground-based testing techniques or computational predictions of this flow phenomenon, thus helping improve the design of all future spacecraft.



A NASA team—via a US Navy aircraft—captured high-resolution, calibrated infrared imagery of Space Shuttle Discovery's lower surface in addition to discrete instrumentation on the wing, downstream, and on the Boundary Layer Transition Flight Experiment protuberance. In the image, the red regions represent higher surface temperatures.

Constant Heat-rate Phase

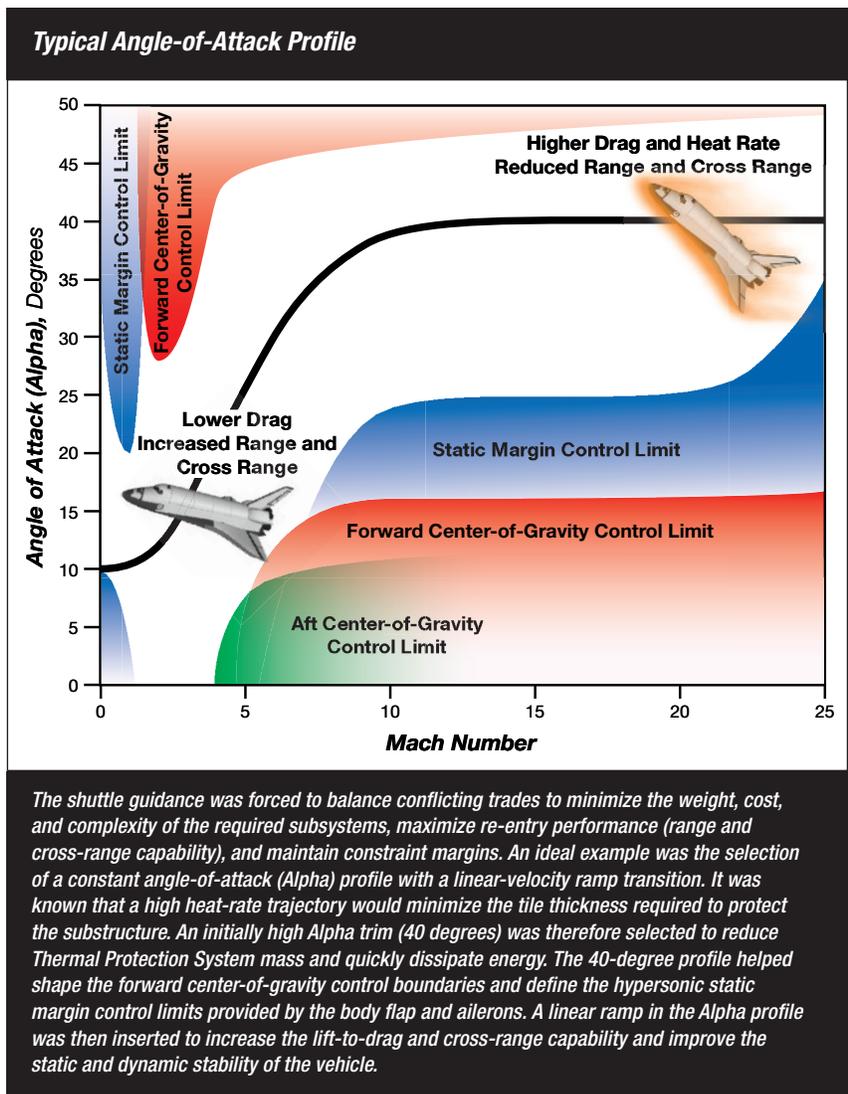
The guidance phase was required to protect the structure and interior from the blast furnace of plasma building

up outside of the vehicle. That blast furnace was due to the high-velocity impact of the vehicle with the air in the atmosphere.

The Thermal Protection System surface was designed to withstand extremely high temperatures before the temperature limits of the material were exceeded. Even after a successful landing, structural damage from heating could make the vehicle un-reusable; therefore, it was essential that the surface remain within those limits. To accomplish this, different parts of the vehicle were covered with different types of protective material, depending on local heating.

The objective of the re-entry guidance design during this phase was to ensure that the heat-rate constraints of the Thermal Protection System were not compromised. That is why the constant heat-rate phase used quadratic drag-velocity segments. A vehicle following a drag acceleration profile that was quadratic in velocity experienced a constant rate of heating on the Thermal Protection System. Because the shuttle tile system was designed to radiate heat, the quadratic profiles in shuttle guidance were designed to provide an equilibrium heating environment where the amount of heat transferred by the tiles and to the substructure was balanced by the amount of heat radiated. This meant that there was a temperature at which the radiant heat flux away from the surface matched the rate of atmospheric heating. Once the vehicle Thermal Protection System reached this equilibrium temperature, there would no longer be a net heat flow into the vehicle.

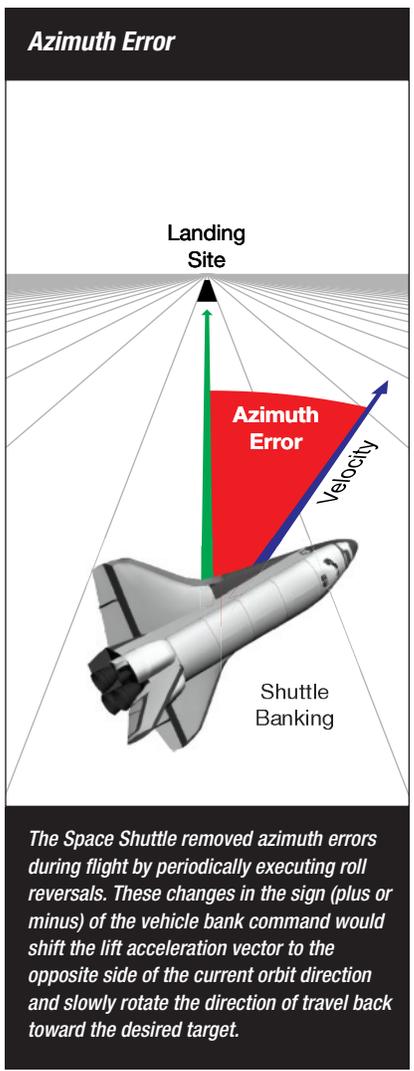
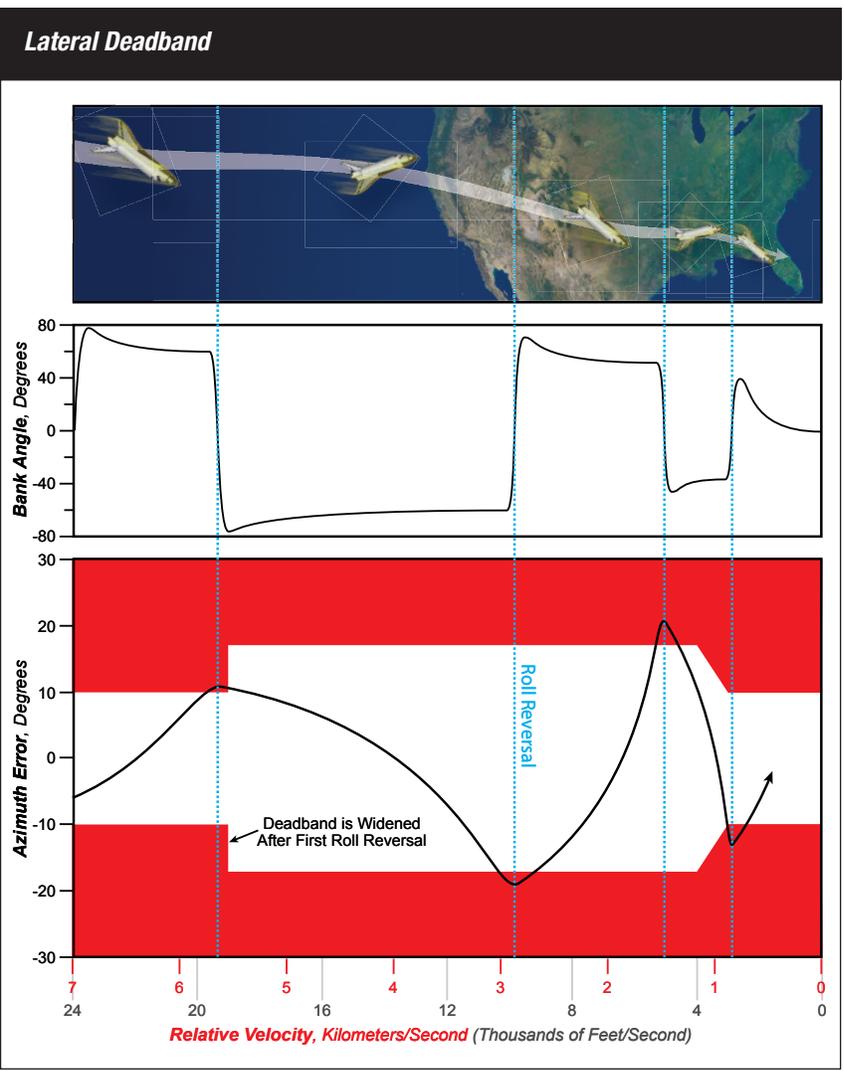
The existence of a temperature limit on the Thermal Protection System material implied the existence of a maximum heat rate the vehicle could withstand. As long as guidance commanded the vehicle to achieve a quadratic velocity reference that was at or below the surface temperature



constraint boundaries, the vehicle substructure was maintained at a safe temperature. The Thermal Protection System would be undamaged and reusable, and the crew would be comfortable.

During flight, if the vehicle was too close to the landing site target, the velocity and reference drag profiles were automatically shifted upward, causing an increase in the rate energy

is dissipated. The vehicle would, as a result, fly a shorter range. If the vehicle was too far away from the landing site, the combined velocity and reference drag profiles were automatically shifted downward, causing a reduction in the rate at which energy was dissipated. The vehicle would, as a result, fly a longer range.



Equilibrium Glide Phase

As the speed of the shuttle dropped below about 6,200 m/s (20,500 ft/s), the constant heat-rate phase ended and the equilibrium glide phase began. This was an intermediate phase between high heating and the rapidly increasing deceleration that occurred as the vehicle penetrated deeper into the atmosphere. This phase determined the drag-velocity reference required to

balance gravitational and centrifugal forces on the vehicle. During this phase, only the reference drag profile in the equilibrium glide phase was modified to correct range errors. All future phases were left at their nominal setting. This ranging approach was designed into the shuttle re-entry guidance to reserve ranging capability. This enabled the vehicle to accommodate large navigation errors post ionization blackout (ground

communication and tracking loss due to plasma shield interference) and also change runway landing direction due to landing wind changes.

Constant Drag Phase

The constant drag phase began and the equilibrium glide phase ended when either the desired constant drag acceleration target of 10 m/s² (33 ft/s²)



occurred or the transition phase velocity of about 3,200 m/s (10,500 ft/s) was achieved.

During the constant drag phase, the drag-velocity reference was computed to maintain constant drag acceleration on the vehicle. This constrained the accelerations on the vehicle structure and crew. It also constrained maximum load accelerations for crew members confined to a sitting position during re-entry with normal accelerations directed along their spine. For the shuttle, the normal force constraint was set at 2.5g maximum; however, typical normal force operational design was set at 1.5g. The form of the drag-velocity reference during this phase was particularly simple since the drag accelerations were held constant. Operationally, shuttle guidance continued to command a high 40-degree angle of attack during this phase while the velocity was rapidly reduced and kinetic energy was rapidly removed from the vehicle. Guidance commanded higher drag levels to remove extra energy from the vehicle and to attain a target site that was closer than the nominal prediction. Guidance commanded lower drag levels to reduce the rate energy removed from the vehicle and to attain a target site that was farther away than the nominal prediction.

Transition Phase

When the velocity dropped below approximately 3,200 m/s (10,500 ft/s), the transition phase of guidance was entered and the constant drag phase was terminated. It was during this phase that the guidance system finally began to modulate the energy-vs.-drag reference to remove final

trajectory-range errors and issued a command to begin reducing the angle of attack. This pitch-down maneuver prepared the vehicle for transonic and subsonic flight. During the transition phase, the angle of attack was reduced and the vehicle transitioned from flying on the “back side” to the “front side” of the lift-to-drag (lift acceleration divided by drag acceleration) vs. angle-of-attack curve. A vehicle flying on the back side (at a higher angle of attack) was in an aerodynamic posture where increasing the angle of attack decreased the lift-to-drag. In this orientation, the drag on the vehicle was maximized and the vehicle dissipated a great deal of energy, which was highly desirable in the early phases of re-entry flight. A vehicle flying on the front side of the lift-to-drag curve (or at a lower angle of attack) was in an aerodynamic posture where increasing the angle of attack increased the lift-to-drag. In this front-side orientation, the drag was reduced and the vehicle sliced through the air more efficiently. Most airplanes fly on the front side of the lift-to-drag curve, and it was during the transition phase that shuttle guidance began commanding the vehicle to a flying orientation that mimicked the flight characteristics of an airplane.

It was also during the transition phase that the flight-path angle became significantly steeper. This happened naturally as the vehicle began to dig deeper into the atmosphere. A steeper angle was what influenced the formulation of the shuttle guidance to switch from velocity to energy as the independent variable in the reference drag formulation. The linear drag-energy reference acceleration did not use a shallow flight-path angle approximation as was done in the

previous guidance phases, and a concise closed-form solution for the range flown at higher flight-path angles was obtained. At the end of transition phase, the vehicle was about 90 km (56 miles) from the runway, flying at an altitude of 24 km (15 miles) and a speed of 750 m/s (2,460 ft/s).

Summary

At this point, the “unique” phase of re-entry required to direct the shuttle from low-Earth orbit was complete. Although other phases of guidance were initiated following the transition phase, these flight regimes were well understood and the guidance formulation was tailored directly for airplane flight.