MSFC-474

Space Shuttle and Launch Pad Lift-Off Debris Transport Analysis – SRB Plume-Driven

by

Jeff West*, Louise Strutzenberg*, Sam Dougherty^ Jerry Radke[+], and Peter Liever[+]

18th Annual Thermal and Fluids Analysis Workshop (TFAWS 2007)

Abstract

This paper discusses the Space Shuttle Lift-Off model developed for potential Lift-Off Debris transport. A critical Lift-Off portion of the flight is defined from approximately 1.5 sec after SRB Ignition up to 'Tower Clear', where exhaust plume interactions with the Launch Pad occur. A CFD model containing the Space Shuttle and Launch Pad geometry has been constructed and executed. The CFD model works in conjunction with a debris particle transport model and a debris particle impact damage tolerance model. These models have been used to assess the effects of the Space Shuttle plumes, the wind environment, their interactions with the Launch Pad, and their ultimate effect on potential debris during Lift-Off. Emphasis in this paper is on potential debris that might be caught by the SRB plumes.

Introduction

The need to determine the possible size, speed, impact location, and impact energy of debris led NASA to use Computational Fluid Dynamics (CFD) techniques with debris trajectory tracking tools to analyze potential debris events [1-5]. The Space Shuttle Program undertook the effort of identification and control of every possible source of debris liberation for return-to-flight after the Columbia tragedy. The Loci - CHEM CFD program with an unstructured grid approach[5] has been in use at NASA/MSFC to simulate the Shuttle plume flow interactions of the integrated Space Shuttle Vehicle (SSV) with the Launch Facility at Lift-Off. Potential debris particles are liberated into CFD flowfield virtual engineering solutions at different times to determine (1) if they might impact the vehicle and (2) with what impact energy.

Trajectories of potential debris particles found that clearly miss the vehicle lend credence to a risk assessment that changes in nature from a single deterministic type particle trajectory analysis to a probabilistic type analysis based on a series of many particle trajectory runs. As long as the series of potential debris particle trajectory analyses covers the whole parametric space and treats each eligible variable within that space as a statistically independent variable, the virtual engineering simulations can help to (1) validate the risk mitigation strategy used for that potential debris source and (2) reduce the risk to the vehicle posed by that debris source. This analysis carries along with it whatever uncertainties there are. Confidence is built and risk is reduced when more and more of the uncertainty can be taken away.

* NASA/MSFC
^ ERC/Jacobs ESTS Group, MSFC
[+] CFDRC, Huntsville, AL

This paper discusses the Shuttle Lift-Off time line, the methodology being used in Lift-Off Debris Transport Analysis (DTA), and the 'design-of-experiment' aspects of the virtual engineering simulations being performed to reduce the risk to the SSV at Lift-Off. Emphasis in this paper is on Solid Rocket Booster (SRB) plume-driven debris potentials.

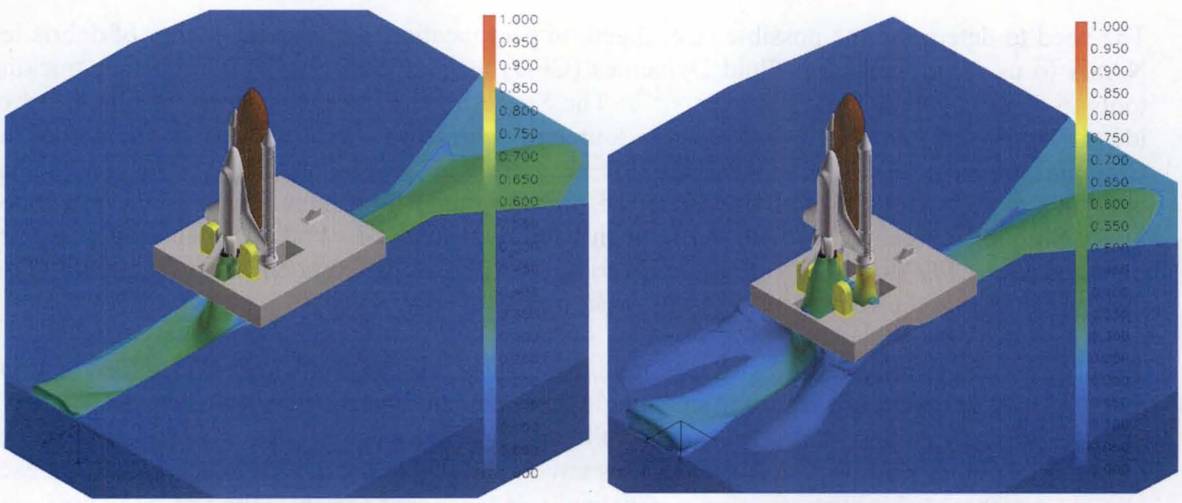
Time Line

Shuttle launch operations are simulated beginning with the tanking period when cryogenic propellants are on-board and dropped to the Space Shuttle Main Engines (SSMEs) for chill-down and recirculation. Ice formation, which depends on temperature, humidity and ground winds, presents the threat of falling ice debris from this time forward. Ice may come from the External Tank (ET), feedline bellows and brackets, aft fittings, and main engines. The Pre-Launch flowfield during this period of time with cryogenic hydrogen and oxygen aboard is governed by ground winds, is modeled, and is referred to as Cardinal Point 1.

At T0 - 6 sec, the Space Shuttle Main Engines (SSMEs) are started. By T0 - 2 sec, the SSMEs have reached 100 % rated power level and come to yaw parallel. The flowfield at SSME 100% power level time in the T0 - 2 sec to T0 time period is modeled and is called Cardinal Point 2.

SRB Ignition Command is issued at T0 at which time the SRB holddown explosive fasteners (holddown bolt frangible nuts) are fired and the T0 umbilicals are retracted. The T0 umbilicals consist of the LO2 and LH2 Tail Service Mast (TSM) umbilicals on the Mobile Launch Platform (MLP) and the GH2 Vent Line at the ET Intertank. CFD views of the Shuttle flowfield solutions at the moment of Lift-Off and at T0 + 1.9 sec are shown in Figure 1.

Note: 3,000 deg R Isotherm colored by Mach number



a. Lift-Off **b. T0 + 1.9 sec**

Figure 1. Shuttle SRB Exhaust Plumes Impinge on Holddown Posts/Haunches shortly after Lift-Off

The SRB chamber pressure reaches design pressure, about 900 psia, at approximately T0 + 0.5 sec. A typical chamber pressure profile is shown in Figure 2. SRBs are matched pairs per flight. The first 0.12 sec has chamber pressure rise up to about 50 psia at which time the SRB nozzle throat plug is burst and scatters as polyurethane foam and Room temperature Vulcanized (RTV)

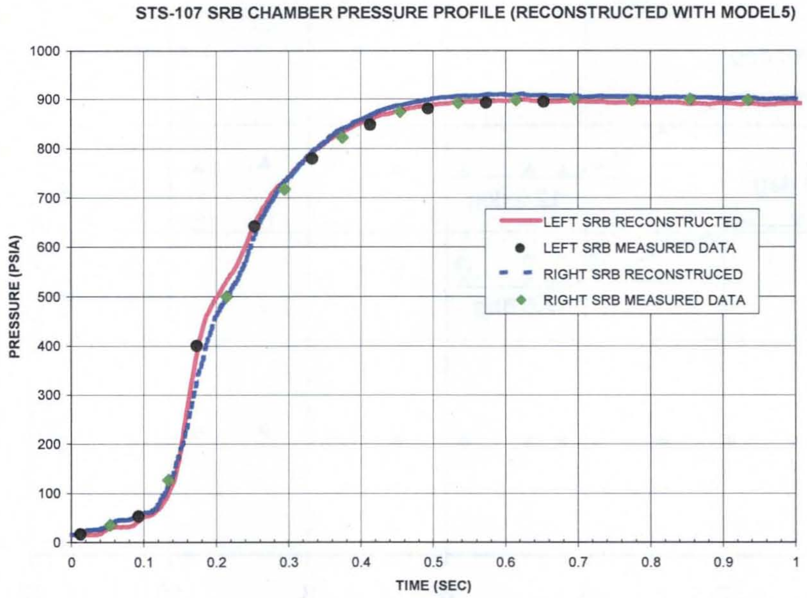


Figure 2. Typical SRB Chamber Pressure Ignition Transients (to T0 + 1 sec)

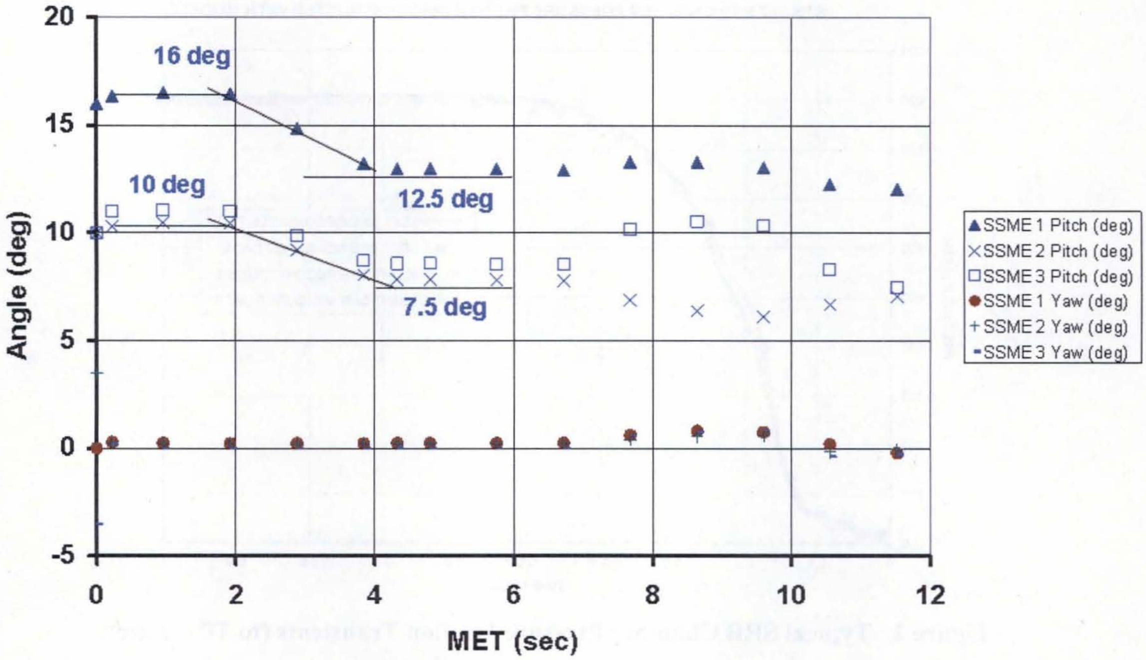
sealer debris. Then the profile rises and overshoots the asymptotic to the SRB design pressure. The SRB ignition overpressure (IOP) event reflects the chamber pressure rise rate.

The IOP wave occurs at approximately T0 + 0.19 seconds. Pressure waves persist until about T0 + 0.45 seconds with duct reverberations in the Exhaust Trench persisting after the initial IOP wave. Duct Overpressure (DOP) waves have a frequency of about 2.4 Hz and persist until about T0 + 0.75 seconds. The transient period of the IOP and DOP waves is Cardinal Point 3.

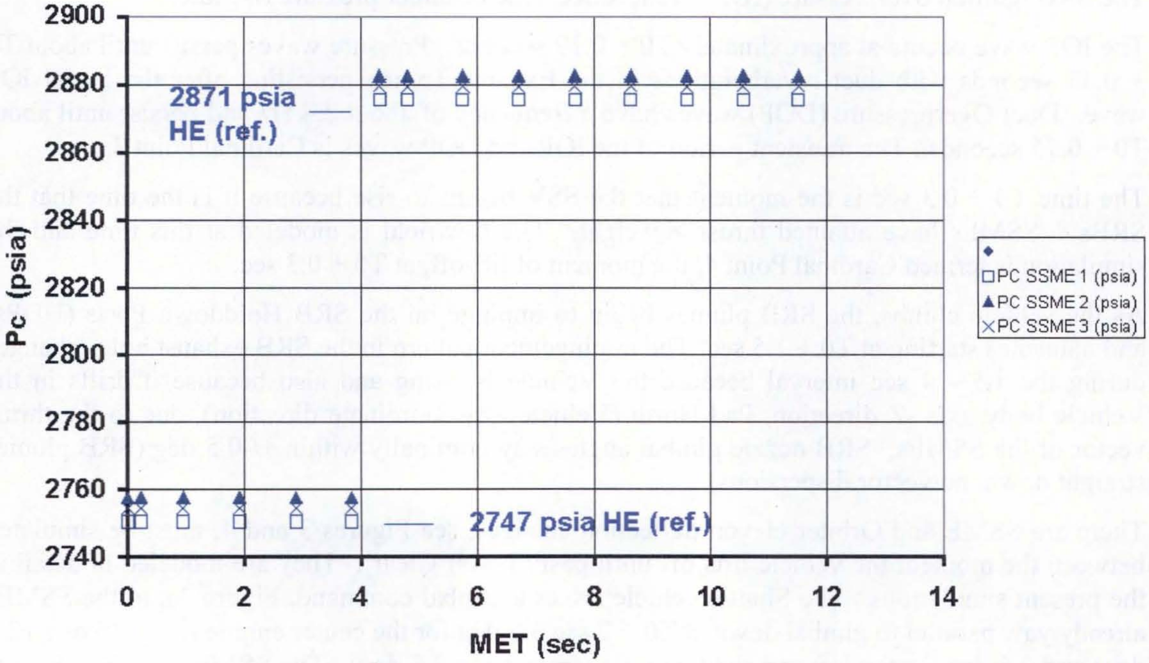
The time T0 + 0.3 sec is the moment that the SSV begins to rise because it is the time that the SRBs + SSMEs have attained thrust > weight. The flowfield is modeled at this time and the simulation is termed Cardinal Point 4, the moment of lift-off, at T0 + 0.3 sec.

As the vehicle climbs, the SRB plumes begin to impinge on the SRB Holddown Posts (HDPs) and haunches starting at T0 + 1.5 sec. The impingement pattern in the SRB exhaust holes changes during the 1.5 - 4 sec interval because the Vehicle is rising and also because it drifts in the Vehicle body axis -Z direction, Pad North (Vehicle $-Z_T$ coordinate direction), due to the thrust vector of the SSMEs. SRB nozzle gimbal angles stay nominally within +/-0.5 deg (SRB plumes straight down, no vector dispersions).

There are SSME and Orbiter elevon deflection changes, see Figures 3 and 4, must be simulated between the moment the vehicle lifts off until past 'Tower Clear'. They are modeled in detail in the present simulations. The Shuttle vehicle issues a gimbal command, Figure 3a, to the SSMEs already yaw parallel to gimbal down at T0 + 2 sec 3.5 deg for the center engine (from 16 deg 12.5 deg) and 2.5 deg for the left and right engines (from 10 to 7.5 deg). The SSMEs are throttled up, Figure 3b, from 100 % RPL to 104.5 % NPL at T0 + 4 sec. Additionally, an elevon deflection command is issued at T0 + 2 sec for the elevons to slew in the positive direction from 0 deg to 10 deg down for inboard elevons and 9 deg down for the outboard elevons at 1 deg/sec, Figure 3c. The SSMEs at 100 % Rated Power Level (RPL) are at ~ 2747 psia chamber pressure (Pc) measured at the head end (HE). The SSMEs at 104.5 % Normal Power Level (NPL) are at ~ 2871 psia. (Time is shown in Figure 3 as Mission Elasped Time (MET) measured from T0.)



a. **SSME Gimbals**



b. SSME Throttle-Up

Figure 3. SSME Gimbals and Throttle-Up are Modeled

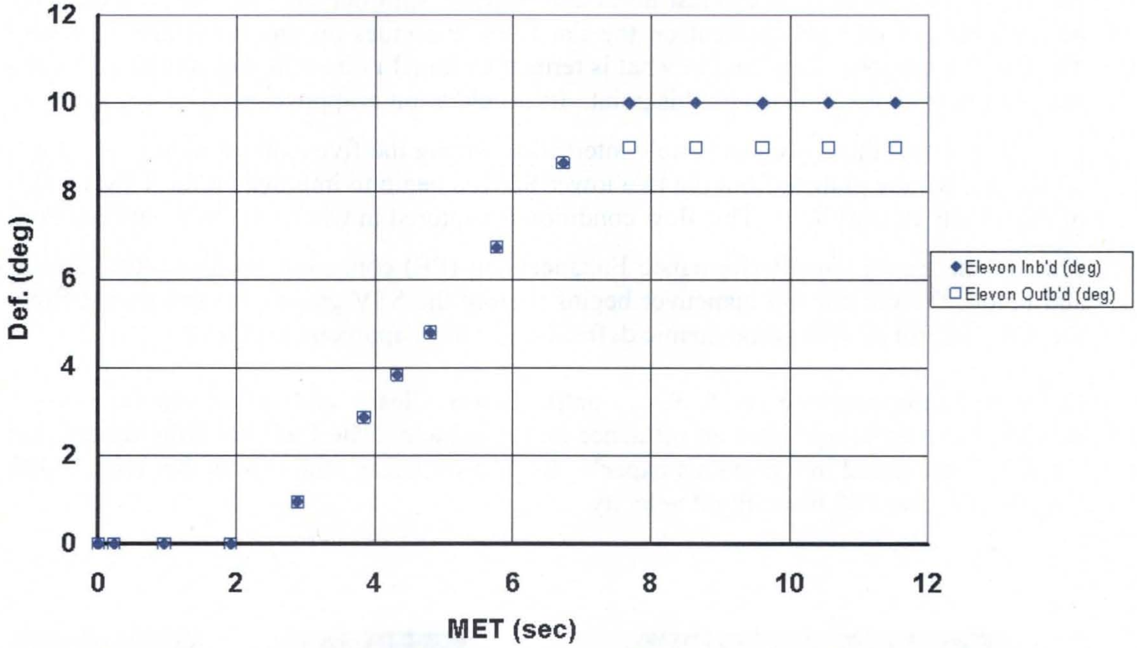


Figure 4. The Orbiter Elevon Deflection Schedule is Modeled (Slight Change in Wing Shape)

A Shuttle Lift-Off sequence in the 2.5 - 3 sec MET timeframe is shown in Figure 5. T0 + 1.9 sec, see Figure 6, is at a critical time in the plume flow transient while the three SSME plumes are fully contained in the SSME exhaust hole in the Mobile Launch Platform (MLP), but the two SRB exhaust plumes begin to impinge on SRB holddown post structure at ~ T0 + 1.9 sec. The flowfield at this time is termed in the present simulation Cardinal Point 5. The SSV is rising only at about 30 ft/sec upward velocity by this point and is still vulnerable to debris that might rise up toward the vehicle from below. But the critical Lift-Off period is considered to remain in effect until the vehicle drift has taken the vehicle far enough to the North that the SRB plume impingement on the HDPs/haunches has subsided (until ~ T0 + 4 sec).

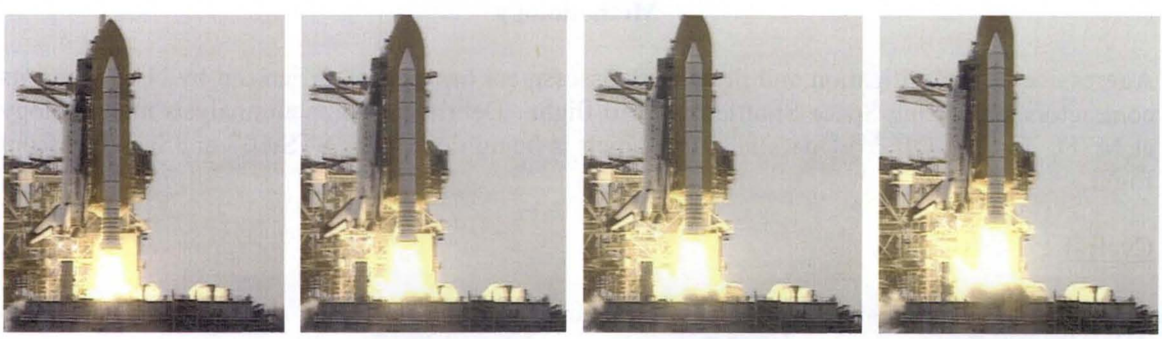


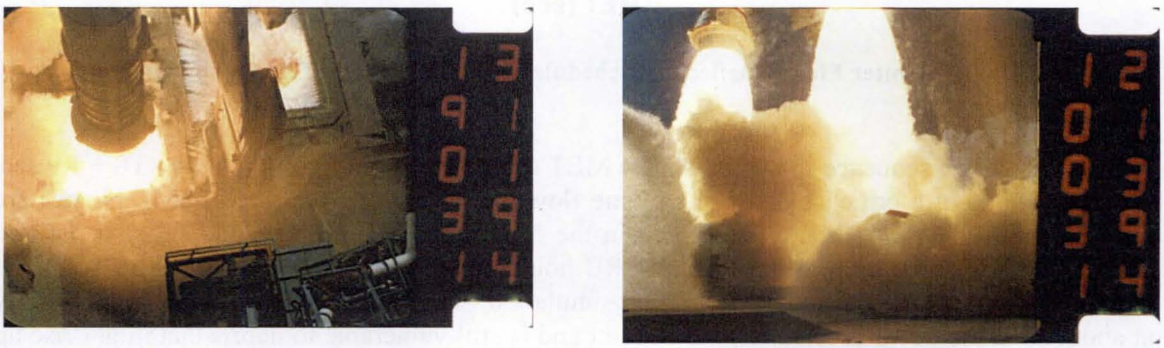
Figure 5. Shuttle Lift-Off Viewed from Perimeter Camera 7A (Looking West from ~ 2.5 to ~3 sec after Lift-Off)

A new flow phenomenon is initiated at ~ T0 + 3 sec, see Figure 5, as the SRB plumes are larger than the width of the SRB exhaust holes and begin to spill out onto the MLP Deck. Gross SRB plume spillage and impingement on the flat Deck continues on until well after 'Tower Clear'. This flow condition is captured in what is termed Cardinal Point 6 in the simulation. The vehicle is climbing at about 50 ft/sec by this point. Its acceleration is approximately 1.5 g's.

At ~ T0 + 4 sec, there is considerable interaction among the five exhaust plumes and the Facility structures, but the plumes from the two lower SSMEs begin to impinge on the TSMs and spill out of the SSME exhaust hole. This flow condition is captured in what is termed Cardinal Point 7.

The elevons reach their Performance Enhancement (PE) command settings after 'Tower Clear' and before the vehicle roll maneuver begins (before the SSV gains enough forward flight speed for wing control surface aerodynamic deflections to have appreciable effect).

Cardinal Points continue on 8, 9, ... until 'Tower Clear', and influences from the Facility structures can no longer have an influence on the vehicle. The Cardinal Point descriptions were given in some detail in a previous paper[4]. By 'Tower Clear', the vehicle has risen ~ 300 ft and has attained over 100 ft/sec flight velocity.



T0 + 1.9 sec **T0 + 3.0 sec**

Figure 6. Views of SRBs from Above (400 Frames/sec)

Methodology

Aggressive debris mitigation and debris risk assessment have been carried out by NASA and its contractors supporting Space Shuttle return-to-flight. Debris environment analysis methodology at MSFC for Lift-Off [4, 5, 6] parallels that which is being done after STS-107 at JSC[3] for ascent flight.

Cycle-1

The vehicle and critical launch facility structures are modeled using quasi steady-state CFD flowfield solutions at each Cardinal Point. The vehicle, engine, and SRB geometry features and power and gimbal settings mentioned above are modeled with great fidelity. The vehicle CFD model has articulating gimbals and elevon and rudder settings that are scripted to the time line. Various potential debris particles of specified size, density, and shape are released into the CFD flow solutions at given times (Cardinal Points), and a debris particle tracing program tracks their trajectories to hit or miss the vehicle. Thousands of potential debris trajectories are generated from varied points of origin and with varied initial conditions for each size (mass) and shape. If a debris hit is recorded, the debris particle impact location and relative kinetic energy, velocity, and angle of impact are computed. Hits are catalogued and damage tolerance models are run to predict remaining margins of safety in the Thermal Protection System (TPS) on the vehicle surface were that potential debris to cause that damage.

Cycle-2

It became apparent after the initial screening of Lift-Off debris sources for Shuttle's return-to-flight that better simulation of particle aerodynamics, a better particle rebound model if a debris particle should get caught by a plume and rebound from some Facility surface, better CFD definition of the exhaust plumes and their interactions with the Facility structures, and an increased amount of detail in the Facility CFD modeling was needed. The new simulation capability development and application has been on-going and is referred to as Cycle-2. The new simulation capability has database-driven 6 degree-of-freedom debris tracing in a set of higher-fidelity CFD flowfield simulations. The capability has been provided to be able to do Monte Carlo-type simulations of many possible debris particle trajectories in a CFD flowfield solution that represents a particular time during the Shuttle Lift-Off transient.

Aerodynamics of debris particle shapes and sizes are put into a look-up database so that the analysis of a given particle trajectory through each CFD solution is database-driven. Because of the wide range of flow field velocities a particle might be subjected to if it should be caught in an exhaust plume and accelerated in a supersonic flowfield and then expelled out of the plume in subsonic flight, the aerodynamic database needed to be 6 degree-of-freedom (6-DOF). Basic (simple) debris particle shapes – sphere, cylinder, box, plate, thin cone frustum (or disk) - are used, and any potential debris items are treated as which one of these is most like their potential shape.

Because a debris particle once accelerated in the plume flowfield interacting with the Launch Facility might rebound or ricochet from a hard Facility surface, a rebound model needed to be facilitated in the debris tracking tool. Gun testing of particles[6, 7] of simple size and shape was conducted at particle impact velocities up to 800 ft/sec to characterize potential debris particle rebound as a function of particle incidence velocity and angle and to develop the particle coefficient of restitution (COR) to be used in the model. This for various particle materials (metal, non-metal) and spherical (baseline) as well as irregular (cylinders, rectangular plates) shapes. The rebound model was added to the Lift-Off debris analysis methodology. The impact collision at higher particle velocities was found to involve appreciable plastic deformation of the particle, reducing the in-plane COR from values as high as ~ 0.5 down to an asymptotic value of ~ 0.2 at high particle velocities (> 300 ft/sec or more).

Because of the critical Lift-Off period for potential plume-driven debris spanning the whole time period of significant plume impingement on the SRB holddown posts and haunches (1.5 – 4 sec) and the need for refinement in the LODTA methodology, intermediate CFD points were added in between Cardinal Points 4 and 7, denoted Points 4.5, 5.5, and 6.5.

The new matrix of CFD analysis points, Cardinal Points plus intermediate points for Cycle 2, are shown in Table I. They are at 0.5 - sec intervals from 1.5 – 4.0 sec. The emphasis here is on SRB plume-driven.

Table I. Matrix of CFD Points for Cycle 2 Lift-Off Debris Transport Analysis

North Drift Matrix
Half SRB

Time (sec)	CardPt		Min		Mid		Max	
< 0	1,2	Drift W (ft)	Drift (ft)	Height (ft)	Drift (ft)	Height (ft)	Drift (ft)	Height (ft)
0.3	4	0	0	0				
1.5	4.5	0	0.8	14			2.3	12.0
2.0	5	0	1.1	28.9	3.2	28.9	4.6	23.7
2.5	5.5	0	2.9	48.2	5.4	48.2	7.6	37.0
3.0	6a	0	5.3	71.9	7.7	71.9	11.0	50.0
3.5	6.5	0	8.5	99.9	10.8	99.9	15.2	70.0
4.0	7	0	11.5	132.8	13.9	132.8	19.5	91.0
5.0	8a	0	18.0	201.2				
6.0	9a	0	24.0	297.9				

'Worst Case' 6.4 % Acoustic Tests West Drift Case

Time (sec)	CardPt	Drift N (ft)	Drift W (ft)	Height (ft)
0.0	4	0	0	0
1.5	4.5	2.3	1.5	13.9
2.0	5	5.2	2.1	28.7
2.5	5.5	9.1	2.65	48.1
3.0	6a	12.9	3.3	71.9
3.5	6.5	17.6	4.1	99.9
4.0	7	22.9	5.0	132.8
5	8a	33.8	6.8	201.2

The table of CFD solution points contains 'nominal' plus 'dispersion' solution points. They are based on discrete positions of the SSV above the Pad corresponding to time after Lift-Off. 'Dispersions' were necessary to cover sensitivities to vehicle drift of plume interactions that may occur in other than nominal PE vehicle Lift-Off trajectories.

Each CFD solution was allowed to go to convergence with the vehicle positioned at the fixed Height H and Drift S coordinates shown relative to the ground. These are half-second intervals in this numerical simulation approach, but do not fully represent the actual transient. This may produce results somewhat different from reality, owing to the analysis not being a true time-accurate transient solution for the moving vehicle, but are considered to be reasonable approximations because they show significant flow features that are seen in the launch imagery.

The simulation includes SSV East-West lateral drift. For a given height H, there may be a lateral drift component as well as North drift, but for most Shuttle Lift-Off trajectories, the lateral drift has been very small. The sensitivities of potential debris transport to lateral as well as North drift should be investigated and understood.

'Design of Experiment' Considerations

The most significant influence parameter in the critical time period for SRB exhaust plume interactions with the Launch Facility is the SSV climb-out trajectory. The Performance Enhancement[8-10] trajectory was introduced with the STS-87 flight and has been used thereafter. PE involves getting the vehicle's climb-out as near vertical as possible. The SSMEs have pitched down with respect to the vehicle's longitudinal axis and therefore produce more thrust upward and less drift to the North than had been in Shuttle launches prior to STS-87. But prior to STS-87, vehicle drift while it climbs caused a different impingement history of SRB plume impingement on the holddown posts and haunches below.

A vehicle Lift-Off trajectory of lower performance is one where the vehicle does not climb as quickly but stays lower and maybe drifts farther North or even laterally to the East or West. The SSV guidance, navigation, and control (G, N, and C) system holds the vehicle very nearly vertical as it rises with almost no wing roll until the vehicle clears the Tower, initiates the roll maneuver, and heads out over the ocean. Strong ground winds at Lift-Off may have a secondary influence of making the vehicle go more nearly straight up (a wind from the North) or have more drift (a wind from the South). There were missions prior to introducing the PE requirements where the vehicle had even more Northerly drift that should there ever be a malfunction of SSME pitch gimbal commands or a deficit of SSME or SRB combined thrust at Lift-Off.

There are possible, but highly unlikely, trajectories where the vehicle has a lateral drift due to some other malfunction in guidance or propulsion. One of these trajectories was used prior to STS-1 as the 'worst-case' lateral drift design trajectory [11-13] for Launch Facility design environments.

Ground winds may have an effect on the vehicle's climb-out trajectory interacting with the vehicle's G, N, and C system and an additional effect on the SRB plume outer mixing layers of deforming the plume mixing layer shape and altering the plume interactions slightly with the Facility structures near the top of the MLP. Hence, there may be some ground wind influences on potential debris particle trajectories.

Variations in Shuttle Vehicle Climb-out Trajectories

The 'design of experiment' therefore requires as matrix of vehicle lift-Off trajectory points with varied vehicle drift (SRB plume footprint) plus varied ground winds. The matrix of analysis points shown in Table I places focus on what is considered to be the most critical time interval (from T0 + 1.5 sec to T0 + 4 sec) for what is the expected case. These are the Min (Minimum Drift) points in Table I. The Min points follow the mean of PE nominal trajectories of Shuttle launches since STS-87. The latest launch trajectory, STS-117, had the highest climb-out rate of the 'family'. The Mid (Middle of the Drift) bound the slower climb rate PE trajectories. A number of recent Shuttle Lift-Off trajectories are shown in Figure 7. This is post-flight reconstructed Best Estimated Trajectory (BET) data from radar and flight acceleration measurements.

The STS-5 BET is shown for reference in Figure 7. STS-5 was the first operational Shuttle mission and carried a light payload. Recent Shuttle missions have all carried heavy payloads to the International Space Station (ISS) as will most remaining Shuttle flights until retirement.

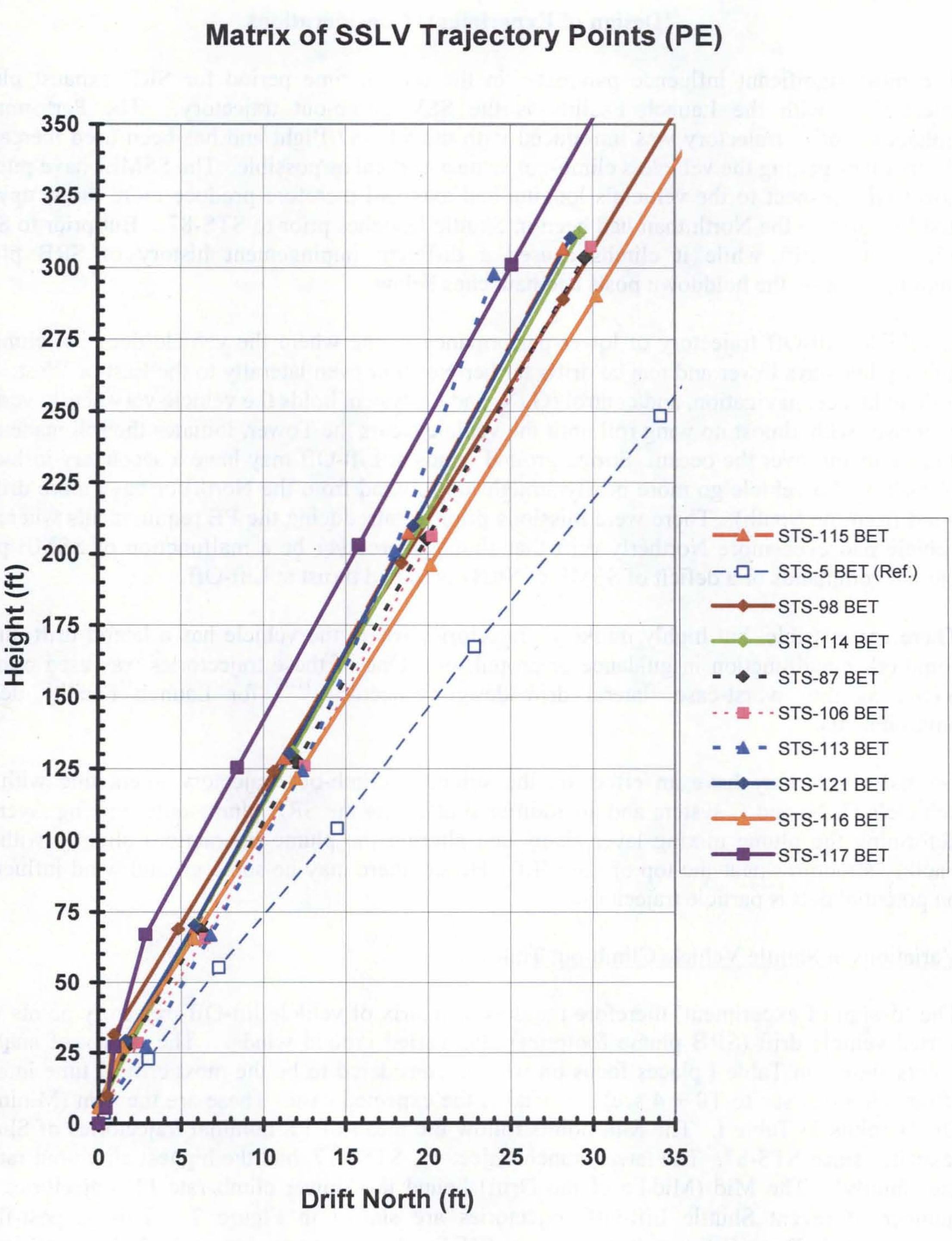


Figure 7. Recent Shuttle Lift-Off Best Estimated Trajectory Data

The Max (Maximum Drift) points follow the Pre-STS-1 design-to 'worst case' drift cases. They were the reference mission 'design to' cases for Lift-Off environments – thermal, acoustic, … The 6.4 % Scale Model Shuttle tests performed in the 1970's and '80 were performed using the 'worst case Northerly drift' and 'worst case Lateral drift' expected from all of the possible tolerance buildups that had been analyzed prior to STS-1. This was with all three SSMEs and both SRBs operating. Another 'near worst case' lateral drift trajectory was one with a bottom engine out at Lift-Off (a Return-to-Launch-Site abort situation). The matrix of trajectory points from Table I is shown versus the recent PE Lift-Off trajectories, the STS-5 trajectory, and the 'worst case' trajectories in Figure 8. The 'worst case lateral drift' reference trajectory is included in Figure 8 and is shown in Figure 9.

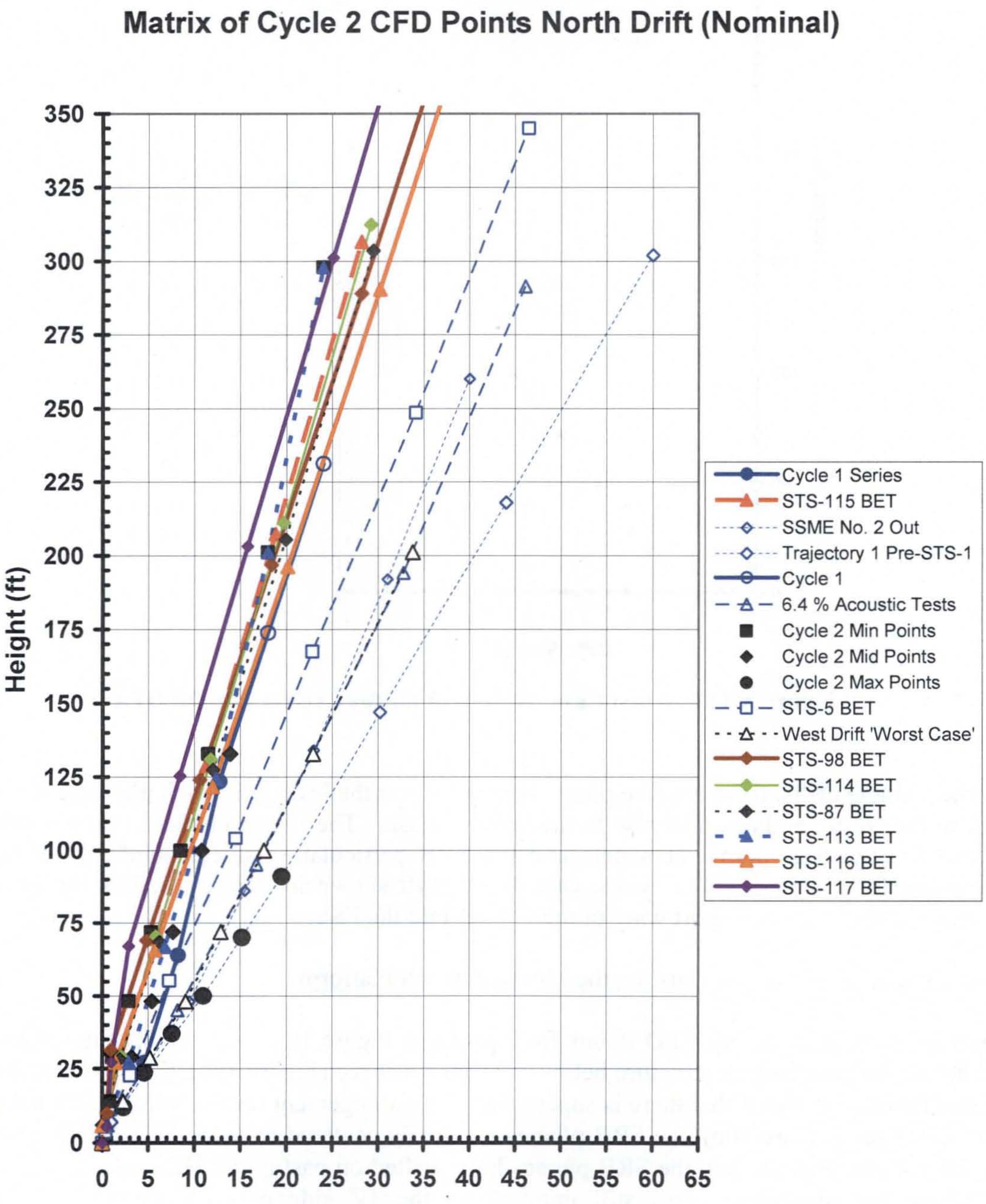


Figure 8. Mid-Mid-Max Matrix of CFD Points versus Flight and Reference North Drift

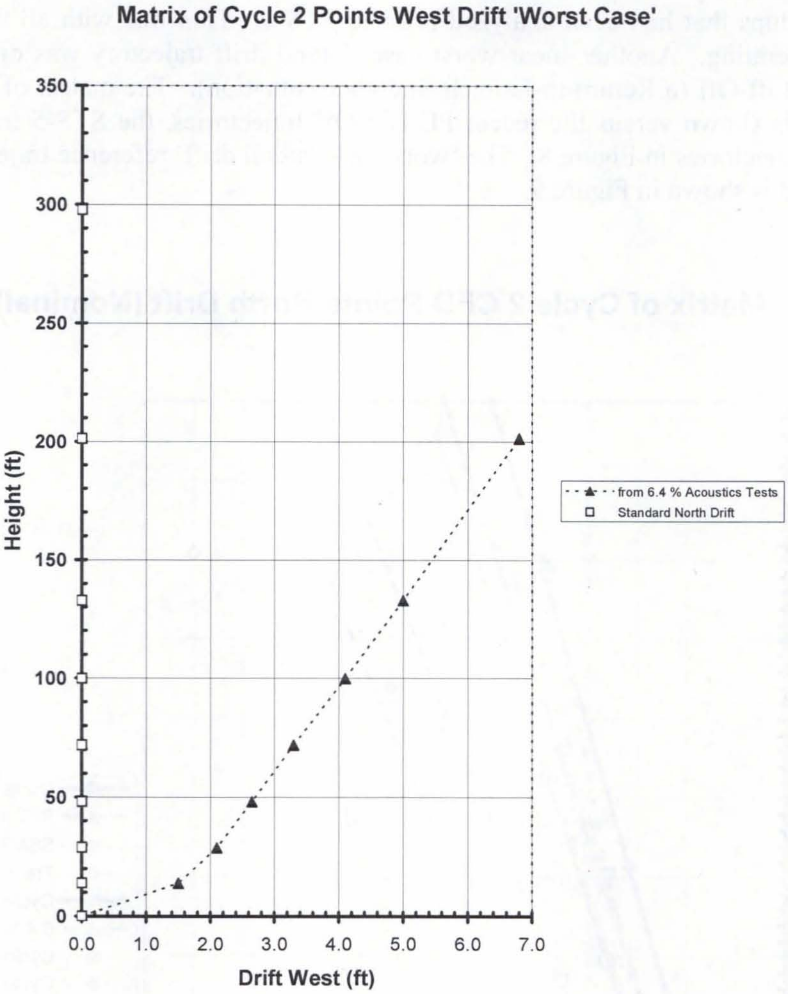


Figure 9. The 'Worst Case' West Drift for the Cycle-2 Lift-Off DTA

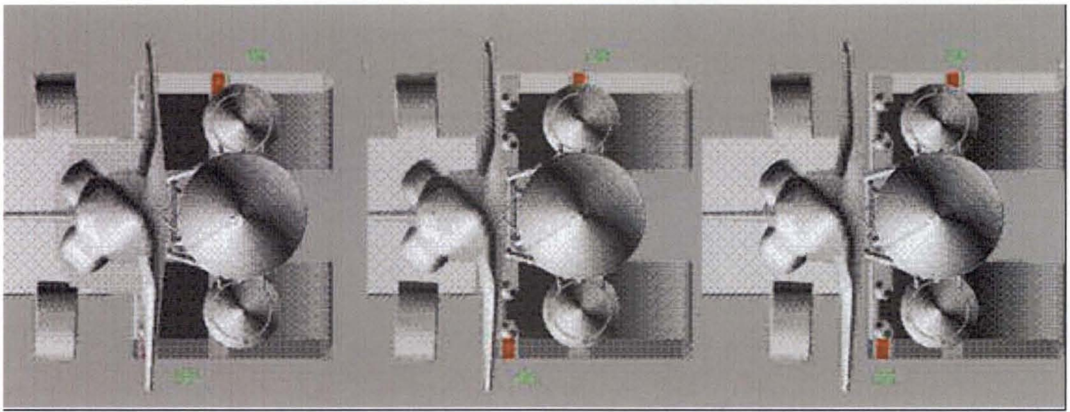
As the Vehicle drifts, there are five plume 'footprints' on the Mobile Launch platform below that drift to the North, and can drift also to the West or East. The 'footprint' locations are indicated by the five gaseous plume diameters and the SRB particulate diameter at the MLP Deck 0 Elevation, for reference. The 'worst case West' drift shown in Figure 9 incurs the danger of coming close to flying the port wing of the Orbiter into the FSS.

Plume Impingement 'Footprints' on the Mobile Launch Platform

The view of Mid trajectory CFD Points from above in Figure 10 shows the Shuttle vehicle over the holddown post/haunch structure below. At T0 + 1.9 sec (Figure 10c), the SRB plumes have drifted far enough North that there is supersonic core impingement on the North HDPs/haunches. By T0 + 3 sec (Figure 10b), the SRB plumes are nearly centered over the North HDP/haunches. By T0 + 4 sec (Figure 10a), the SRB plumes have drifted on past North HDP/haunch centerlines to where the supersonic cores still impinge on the +Z side of each plume. The plume impingement flow has lateral flow components toward the North before T0 + 3 sec and then to South after T0 + 3 sec. Red areas marked in Figure 10 are haunch flat surface areas. The plume cores stay mostly contained in the drift portion of the SRB exhaust holes until approximately

'Tower Clear'. The illustration of 'worst case North' drift (Trajectory 1 Pre-STS-1) in Figure 8 is given in Figure 11, and the plume gaseous boundaries and SRB plume condensed species particulate boundaries are drawn in Figure 11 at the MLP Deck 0 elevation.

Note: Visible flat haunch surface areas denoted in Red (those underneath the ET the same but not visible in these views). See the relative motion of the Vehicle with respect to the Red markers in these views.



North →

a. T0 + 4 sec **b. T0 + 3 sec** **c. T0 + 1.9 sec**

Figure 10. Shuttle Vehicle Lift-Off Geometry Views (Mid - North Drift case seen from above)

The plume 'footprints shown in Figure 11 for the hypothetical 'worst case North' drift case provide the illustration of plume impingement effects, first from the SRBs, then from the SSMEs, and containment of the most of the SRB gaseous plume flow in the drift portion of the SRB exhaust holes until about T0 + 5sec. Then there is impingement of the SRB plume cores onto Deck 0, now North of the SRB exhaust holes. For a nominal PE trajectory, there will still be SRB plume impingement on the MLP Deck 0 surface North of the SRB exhaust holes but it will occur later and when the vehicle has risen higher. There are Post-Lift-Off sound suppression water sprays on this portion of MLP Deck 0 North of the SRB exhaust holes as this makes a 'worst case' Lift-Off acoustic environment of plume impingement on large a flat plate surface area. These Post-Lift-Off water sprays (not simulated in the present CFD analysis) are called the 'Rainbird' water system sprays.

A Three-Tiered Analysis Approach

To 'design' the analytical experiment in a way to conserve computer memory and cpu resources and gain a maximum from the most significant eligible variable (the vehicle Lift-Off trajectories), a three-tiered analytical approach was selected. The three tiers are as follows:

1. Symmetric Half-SRB Model
2. Full SRB Model
3. Full 3-D Shuttle and Launch Pad Model

The first tier has all the detail features of the SRB exhaust hole and HDP/haunch structures modeled with great fidelity. Potential debris caught in a SRB plume has all the potential opportunities for rebound, ricochet, and be caught in recirculating or upward flow regions.

Note: Taken from NASA KSC GP-1059

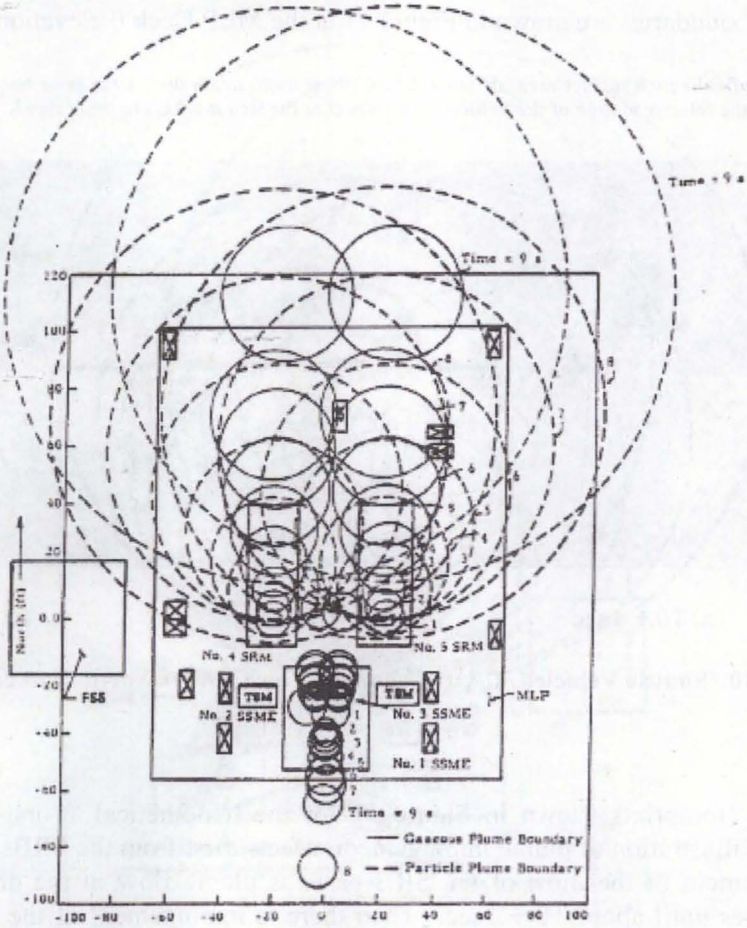
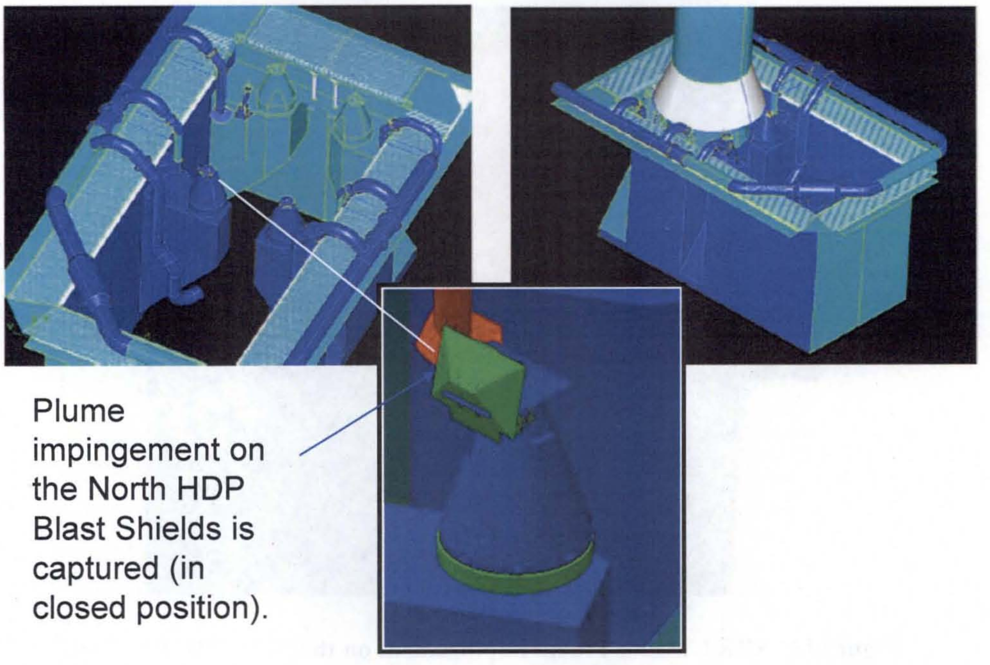


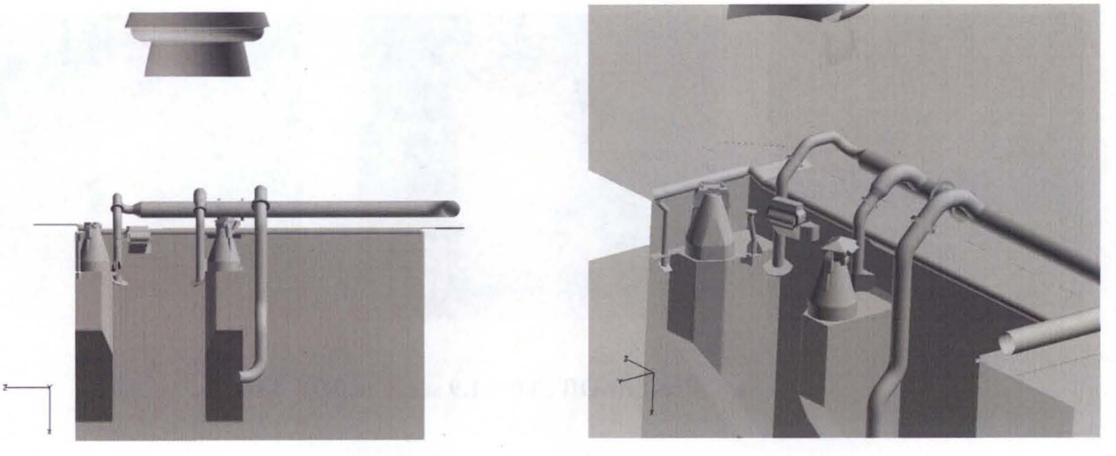
Figure 11. 'Worst Case' Northerly Drift Shuttle Vehicle Trajectory (Hypothetical Case Max Drift Up to Roll Maneuver) – Trajectory 1 Pre-STS-1 Reference

Geometry for the Symmetric Half-SRB and Full SRB detailed models is shown in Figure 12. The Symmetric Half-SRB model is used for all the North drift CFD Points in Table I. Potential debris particles are released into these CFD flowfields simulating the different times and North drift variation during climb-out. Sensitivities to SRB plume impingement effects are identified using the Symmetric Half-Model. Debris particle trajectories which have the potential to go upward, clear the MLP top deck (Deck 0) and be heading toward the vehicle are identified in this analysis tier. The Symmetric Half SRB has great Facility feature detail and 50-60 million grid cells.

Potential debris trajectories so identified as posing a potential threat to the vehicle are investigated further using the Full SRB Model. The Full SRB Model has more grid cells owing toward the larger grid volume. It has all the Facility detail and is about 120 M grid cells. Possible lateral drift cases are investigated using the Full SRB Model. The Full 3-D CFD Model of the Shuttle and Launch Pad is on the order of 100 M grid cells and has the ground winds and the full CFD flowfield for possible upward-bound debris to travel.



a. Full SRB Model



b. Symmetric Half-SRB Model

Figure 12. Full SRB and Symmetric Half-SRB CFD Models

Potential debris trajectories that obviously will not impact the vehicle and pose no threat are catalogued to build statistical evidence for risk evaluation. Those that pose potential risk are thus evaluated further to attempt to quantify that risk. Information will be gained for possible steps to be taken that may mitigate that debris risk. It is the 1 out of 10,000 or so (if that turns out to be the case) that poses a real threat that is traced to impact in the full 3-D model.

Some SRB gaseous plume flow solutions are shown in Figures 13 and 14. The CFD modeling uses a variable γ curve fit for SRB plume gas modeling, another variable γ for SSME plumes mixing in air with a $\gamma = 1.4$. Screening of potential debris of various sizes, shapes, and materials is in progress for SRB plume-driven threat assessment using these CFD flowfield solutions.

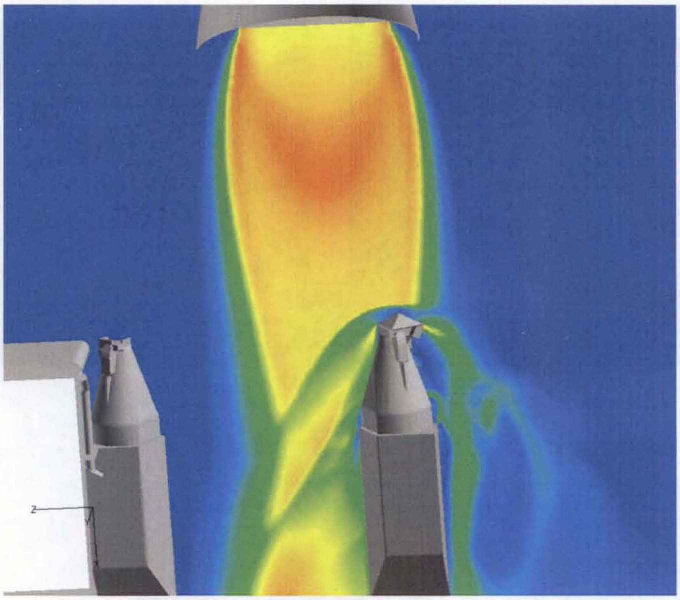
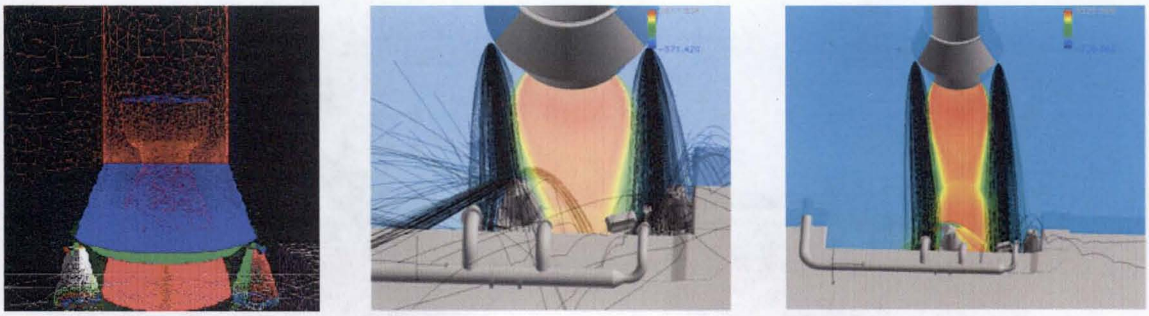
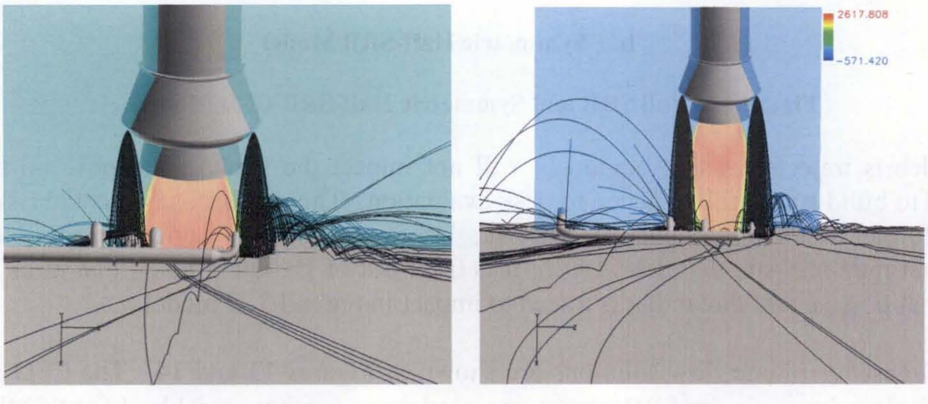


Figure 13. SRB Gaseous Plume Impingement on the North HDP/Haunch



a. Pre-Lift-Off , T0 + 1.9 sec, and T0 + 3 sec



b. T0 + 1.5 sec and T0 + 1.9 sec

Figure 14. Min Drift Debris Particle Traces Example (Released from the SRB Aft Skirt Base)

These are being done first with the gaseous SRB plume definition and then with the condensed-species particulate added. The shock wave on the HDP protective blast shield is evident in Figure 13. Some example debris particles that might be released at two locations at the base of the SRB aft skirt are shown in Figure 14 for illustration. One potential debris particle is being analyzed here. But there are tens of thousands of potential particle trajectories. None of these particular trajectories in Figure 14 rises high enough above Deck 0 to be considered a threat to the vehicle.

The Ground Winds Model

The ground winds model will be utilized in the Full 3-D Shuttle and Launch Pad model. The Full 3-D is used covering the full Cardinal Point range for PE trajectory simulation Min Points at the least and trajectory dispersion cases only as needed. The extent of the Full 3-D Shuttle and Launch Pad Model is a half mile (square) in all compass directions North, East, South, and West, and a half-mile up. It includes the primary wind blockage features of the FSS for winds from the West and debris might come from the West and it includes the 'Hill' and berm effect of the crawler way ramp, side ramps, and exhaust trench openings out to the grade level of Launch Complex 39 Pads A and B (they are the same).

The ground wind model in the far field approaching the Launch Pad has a velocity profile of increasing velocity as height h increases from the Grade level surface (Earth's boundary layer profile). Winds are measured in knots at the 60-Ft Elevation Level on Camera Towers around the Launch Pad periphery. The velocity profiles are inferred from a large amount of statistical data that has been gathered over the years as mean, 3σ, and 2σ, and 1σ.

The Cycle-2 CFD model uses the Ground Winds Model accepted by the Shuttle Program:

- Peak Wind Profile Model (NASA-NSTS-07700 Vol. X Book 2), stated in meters/sec.
- Exponential value (1.6) associated with a 3σ profile shape (determined through statistical analysis)
- Capability to model 1σ and 2σ profiles as needed
- This boundary profile is imposed on the boundaries of the CFD Computational Domain.

$$u(h) = u_{18.3}\left(\frac{h}{18.3}\right)^{1.6(u_{18.3})^{-3/4}}$$

h = altitude AGL (m)
$u_{18.3}$ = wind speed (m/s) at 18.3 m
u(h) = wind speed (m/s) at h

The number of wind cases analyzed per CFD Point using the Full 3-D Shuttle and Launch Pad and Full SRB Models will be limited to those needed to conserve the total computer resource requirements. Debris-sensitive results will guide how many total wind cases will be needed.

Memory and CPU Requirements

The Symmetric Half-SRB CFD Model consists of approximately 50 (up to 60) million grid cells. Convergence requires about six days using 128 cpu's of the Columbia supercomputer at NASA/Ames and 4 days using 100 cpu's of NASA/MSFC Linux cluster. Memory usage measured just under 200 gigabytes for 55 million volume cells.

These debris tracing results were executed serially under Redhat Linux on an AMD Opteron (tm) Processor 250 with approximately 32 gigabytes RAM, and g95/g++ compilers.

Concluding Remarks

The three-tiered analysis approach using Symmetric Half-SRB, Full SRB, and Full 3-D integrated Shuttle and Launch Pad CFD models for assessing potential debris threats and developing the Lift-Off debris threat environment has been described. Key 'design-of experiment' considerations for potential SRB plume-driven debris analyses have been related. Lift-Off Debris Transport Analysis is in progress to support Shuttle launch and flight operations and to continue to understand and reduce the Lift-Off debris environment threat to the Shuttle vehicle.

References

1. "Space Shuttle Expected Debris Generation and Impact Tolerance Requirements, Groundrules, and Assumptions," NSTS 60559, Rev A, June 30, 2006.

2. Murman, S., Aftosmis, M.J., and Rogers, S.E., "Characterization of Space Shuttle Aerodynamic Debris Aerodynamics using CFD Methods," AIAA 2005-1223, January 2005.

3. Gomez, R.J., Vicker, D., Rogers, S.E., Aftosmis, M.J., Chan, W.M., Meakin, R., and Murman, S., "STS-107 Investigation Ascent CFD Support," AIAA 2004-2226, July 2004.

4. Dougherty, N.S., West, J.S., Droege, A., Wilson, J., Liever, P.A., and Slaby, M., "Space Shuttle and Launch Pad Computational Fluid Dynamics Model for Lift-off Debris Transport Analysis," presented at the 17th Annual Thermal and Fluids Analysis Workshop (TFAWS 2006), University of Maryland, College Park, MD, August 2006.

5. Liever, P.A., Slaby, M., and Habchi, S., "Development of Cycle-2 Lift-Off Debris Transport Analysis Tool Definition," CFDRC Final Report, Jacobs ESTS Group Task Order: 23-040301-00, Huntsville, AL, October 2006.

6. West, J.S., Dougherty, N.S., Strutzenberg, L.L., Liever, P.A., and Smith, S.D., "Space Shuttle Propulsion Systems Plume Modeling and Simulation for the Lift-Off Computational Fluid Dynamics Model," presented at the 54th JANNAF Propulsion Meeting, 5th Modeling and Simulation Subcommittee Meeting, Denver, CO, May, 2007.

7. Stellingwerf, R. F., Robinson, J., Stallworth, R., "SPHC Analysis of Launch Pad Debris Rebounds," Stellingwerf Consulting Technical Memo 060930, Jacobs ESTS Group Task Order: 32-030201-00, (October 2006).

8. "Shuttle Systems Design Criteria: Volume I Shuttle Performance Assessment Databook," NSTS 08209, Vol. I, Rev. B, March 14, 1999.

9. "Shuttle Systems Design Criteria: Volume IV Generic Ascent Flight Design Requirements," NSTS 08209, Vol. IV, Rev. C, July 27, 1999.

10. "Performance Enhancement Operational Aerodynamic Design Data Book, Launch Vehicle Aerodynamic Data," Boeing Reusable Space Systems RSS98D0313, January 1999.

11. Sulyma, P.R., Carter, R.C., Audeh, B., and Smith, S.D., "Prediction of Launch Induced Thermal and Pressure Environments to Launch Complex 39, Lockheed Missiles and Space Report LMSC-HREC TR D496999, September 1976.

12. Donald, E.G., "6.4 % Scale Model Test Requirements for ETR," MSFC Pre-Test Report 1977.

13. Sulyma, Peter, Carter, Robert E., Audeh, Beverly, and Smith, Sheldon D., "Environment and Test Specification Levels Ground Support Equipment for Space Shuttle System Launch Complex 39: Volume II of II Thermal and Pressure, Part 1 of 2 Heating Rates, Pressure Loads, and Plume Flow Fields," NASA KSC Design Engineering Directorate GP-1089, Revision A, June 1982.

Nomenclature

BC	Boundary Condition
BET	Best estimated Trajectory (Shuttle Vehicle Climb-out)
CAD	Computer-Aided Design
CardPt	Cardinal Point
CFD	Computational Fluid Dynamics
CFDRC	Computational Fluid Dynamics Research Corporation
COR	Coefficient of Restitution (of a Debris Particle rebound)
cpu	Central Processing Unit
DOF	Degrees of Freedom (3-DOF, 6-DOF)
DOP	Duct Overpressure
DTA	Debris Transport Analysis
ERC	Engineering Research Corporation
ESTS	Engineering, Science, and Technology Support Contract, MSFC (Jacobs)
ET	External Tank
ETR	Eastern Test Range
FSS	Fixed Service Structure
γ	Ratio of Specific Heats (of the Gas Mixture)
G, N, and C	Guidance, Navigation, and Control
h	Altitude (above Ground Level)
H	Height of Vehicle (above the Launch Pad)
HE	Head End (SSME Chamber Pressure)
HDP	Holddown Post
IOP	Ignition Overpressure
JANNAF	Joint Army Navy NASA Air Force
LH2	Liquid Hydrogen
LO2	Liquid Oxygen
LODTA	Lift-Off Debris Transport Analysis
MLP	Mobile Launch Platform
MSFC	Marshall Space Flight Center
NASA	National Aeronautics and Space Administration
NSTS	National Space Transportation System
NPL	Normal Power Level (SSMEs)
Pc	Chamber Pressure (SRB or SSME)
PE	Performance Enhancement
PSE&I	Propulsion Systems Engineering and Integration

RAM	Random Access Memory
RANS	Reynolds-Averaged Navier-Stokes
RPL	Rated Power Level (SSMEs)
RTF	Return to Flight
S	Range (of Vehicle downrange, North drift during climb-out)
SPHC	Smooth Particle Hydrodynamics Code
SRB	Solid Rocket Booster
SSME	Space Shuttle Main Engine
SSV	Space Shuttle Vehicle
σ	Standard Deviation
T0	Time of SRB Ignition Command, sec
TPS	Thermal Protective System
TSM	Tail Service Mast
u(h)	Wind Velocity (at a given h)
$u_{18.3}$	Wind Velocity at the 18.3 m (60 Ft) measuring location
Z_T	Shuttle Tank Coordinate System coordinate (+ toward the Orbiter Vertical Tail)