Continuous Improvements to East Coast Abort Landings for Space Shuttle Aborts

By

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Improvement initiatives in the areas of guidance, flight control, and mission operations provide increased capability for successful East Coast Abort Landings (ECAL). Automating manual crew procedures in the Space Shuttle's onboard guidance allows faster and more precise commanding of flight control parameters needed for successful ECALs. Automation also provides additional capability in areas not possible with manual control. Operational changes in the mission concept allow for the addition of new landing sites and different ascent trajectories that increase the regions of a successful landing. The larger regions of ECAL capability increase the safety of the crew and Orbiter.

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Glossary of Terms and Abbreviations

AOA	Abort Once Around
ATO	Abort to Orbit
CA	Contingency Abort
DPSAC	Heading Error to the HAC tangency point
ECAL	East Coast Abort Landing
ELS	Emergency Landing Site
EO	Engine (SSME) Out
ET	External Tank
ETSEP	External Tank Separation
FPR	Flight Performance Reserve
fps	Feet per second
g	Gravitational acceleration
GPO	Guidance and Procedures Officer
GRTLS	Glide Return to Launch Site
I-load	Initialization Load
JSC	Johnson Space Center
KSC	Kennedy Space Center
MCC	Mission Control Center
MECO	Main Engine Cut Off
MET	Mission Elapsed Time
MPS	Main Propulsion System
NASA	National Aeronautics and Space Administration
Nz	Normal Load Factor (z-axis)
OI	Operational Increment
OMS	Orbital Maneuvering System
PPA	Powered Pitch Around
PPD	Powered Pitch Down
psi	Pounds per square inch
RCS	Reaction Control System
RPL	Rated Power Level
RTLS	Return to Launch Site
SERC	Single Engine Roll Control
SRB	Solid Rocket Booster
SRBSEP	Solid Rocket Booster Separation
SSME	Space Shuttle Main Engine
STS	Space Transportation System
TAEM	Terminal Area Energy Management
TAL	Transoceanic Abort Landing
USA	United Space Alliance
x-c.g.	Center of Gravity, x-axis location

I. Introduction

A Brief History

The Space Shuttle design requirements with respect to aborts were to design redundancy into each system such that aborts were not required. Intact aborts were the only failures considered in subsystems hardware design. Intact abort failures were specified as the loss of one Space Shuttle main engine (SSME) or the loss of one orbital maneuvering system (OMS) engine. All other failures were termed contingencies, and were to be accommodated with software and procedural changes only. Intact abort modes include, as illustrated in Figure 1, the abort to orbit (ATO), abort once around (AOA), transoceanic abort landing (TAL), and return to launch site (RTLS) [5].

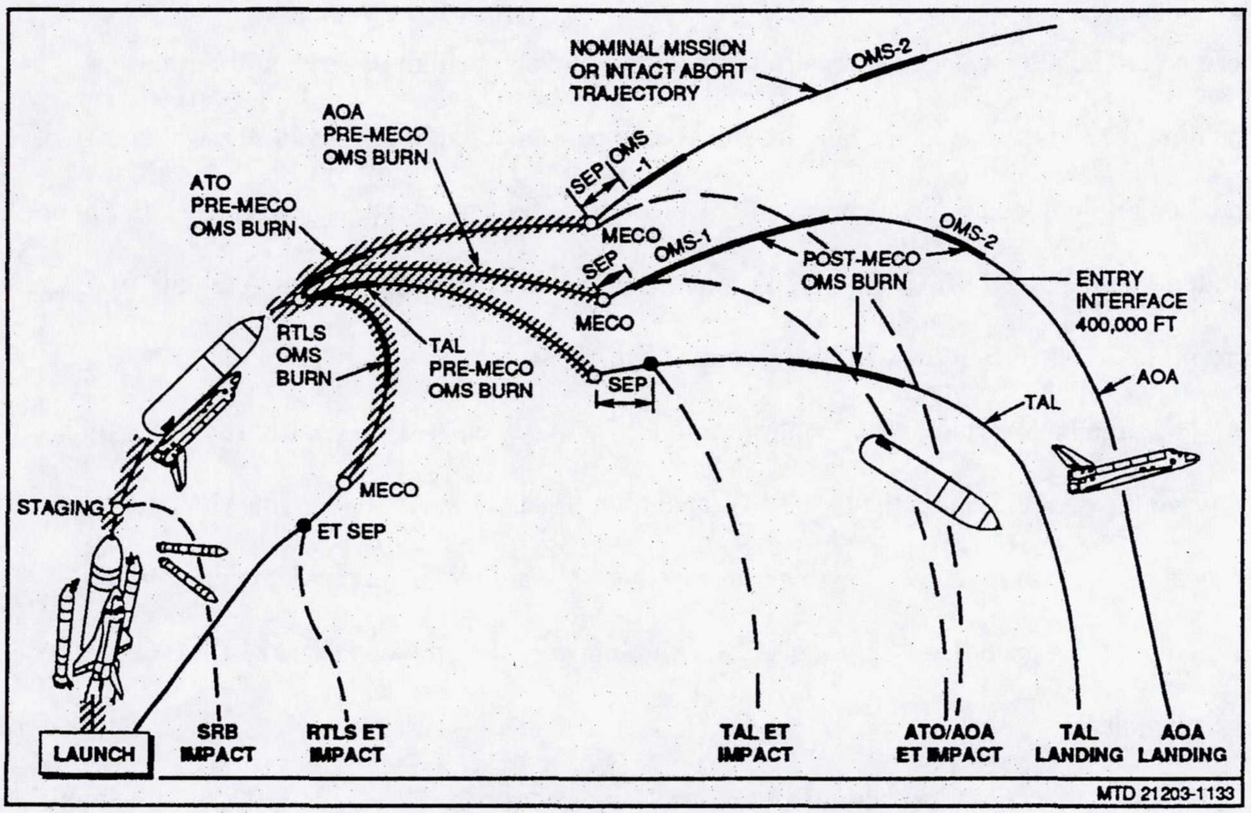

Figure 1 – Intact abort trajectory profiles.

A contingency abort (CA) analysis was originally intended for the first four test flights of the Space Shuttle to provide the crew with procedures needed to guide the orbiter to a safe ejection envelope. The ejection seats were removed from the Shuttle before STS-5 and the emphasis on CA flight analysis declined. This philosophy was reconsidered as a result of the STS-51L (Challenger) accident. The Rogers Commission recommended that NASA initiate a study to consider safely recovering the crew from failures outside the scope of intact abort modes. A comprehensive analysis of contingency abort procedures and software began to investigate the ability of the orbiter to achieve safe bailout conditions or, where possible, reach a landing site. [5]

A contingency abort is defined by the loss of 2 or 3 SSMEs during ascent when the Space Shuttle thrust-to-weight ratio is less than that needed to achieve orbit. CA procedures are designed to help the Orbiter maintain flight control and stay within its structural limitations, enabling the Orbiter to reach a landing site or safe bailout conditions. Due to the wide range of 2 and 3 engine-out situations, a variety of CA procedures are employed. These consist of, but not limited to, the guided MECO, Single Engine Limits, Droop, ELS, ECAL, and bailout. ECALs as a result of 2-SSME failures will be the center of this research.

Large bailout and loss of control regions previously existed for contingency scenarios between the last RTLS and the first TAL capability. East Coast Abort Landing (ECAL) procedures for contingency scenarios improve the probability of a successful landing within these regions. Appendices A through C show graphically the how window of ECAL capability has expanded.

In 1999, the NASA Administrator, Dan Goldin, proposed the Year 2000 Shuttle Safety Improvement Plan with the goal of increasing the Space Shuttle's safety for many more years of operation. Of the numerous initiatives cited in the plan, several were related to improving Shuttle abort modes and more specifically, contingency aborts like the ECAL. Abort Improvement No. 14 listed TAL Delay as a candidate to improving ECALs by making more landing sites available. Also, Abort Improvement No. 22 recommended adding more East coast landing sites to the list of approved airfields. This investigation will focus on how continuous improvements to ECAL methods have increased the probability of these landings.

Overview of Trajectories

At Liftoff, the three SSMEs are operating at 100% of their rated power level (RPL), each creating about 400,000 pounds of thrust. The solid rocket boosters (SRB) are also ignited and will continue to burn for the next 125 seconds of flight. First stage guidance is an open loop scheme where guidance commands are based on the vehicle's Earth relative velocity. First stage guidance uses an attitude versus velocity table to command the appropriate vehicle attitude needed to maximize performance within system constraints. The velocity value that triggers an event can be changed or "I-loaded" from mission to mission. The term I-load, which stands for Initialization Load, refers to a variable in the Shuttle's computer code that may be adjusted as mission design constraints change from flight to flight [1].

After the STS has cleared the launch tower, a roll maneuver aligns the vehicle with the desired azimuth and places it in a heads-down attitude that makes the horizon visible to the crew while maximizing the thrust vector. The SSMEs are throttled up to 104.5% RPL until the vehicle approaches Mach 1. Here the throttle levels are reduced to a typical value of 72% RPL to decrease the aerodynamic loads on the vehicle. Once it has passed the sound barrier, the throttle level is returned to 104.5%. When the solid rocket propellant is depleted and the internal chamber pressure has become less than 50 psi, the SRBs are jettisoned, concluding the first stage of flight. During the separation sequence, the vehicle is in a 3-axis attitude hold. The attitude hold is maintained until the second stage guidance solution converges. Once guidance converges, active steering and throttle settings are commanded.

Second stage continues with the SSMEs burning main propulsion system (MPS) propellants from the external tank (ET). Second stage guidance functions very differently from first stage guidance in that second stage guidance is closed loop. Second stage guidance computes the control variables and burn time-to-go in such a way that the vehicle flies from its current state to the prescribed target conditions within trajectory constraints. Ten seconds prior to MECO the three SSMEs are commanded to a minimum level of 67% RPL [1]. When guidance recognizes the Shuttle is at the correct inertial velocity, all SSMEs are commanded to shut down, which is where second stage, closed loop guidance is terminated. After main engine cutoff (MECO), the external tank separation (ETSEP) command is given by the computer when vehicle rates are within prescribed limits.

Nominally, the three SSMEs provide the necessary thrust throughout ascent to accelerate the vehicle to the desired MECO targets. If a main engine were to have a non-catastrophic failure, there may not be enough thrust to achieve orbit. Depending on the amount of total energy the vehicle has when the engine fails, a specific abort trajectory will be selected. The priority of abort modes for single failures from highest to lowest are: 1) the abort-to-orbit (ATO), 2) the abort-once-around (AOA), 3) transoceanic abort landing (TAL), and 4) return to launch site (RTLS). For secondary or tertiary failures, such as another SSME failure or a critical system failure, a multitude of contingency abort trajectories exist as previously mentioned.

ECAL procedures are largely employed from a TAL or nominal trajectory; however, a small window of opportunity exists for an ECAL from a RTLS trajectory.

TAL capability varies from mission to mission, but the average time in which the capability exists is from 140 seconds to 400 seconds MET. During a TAL, the vehicle continues on a trajectory across the Atlantic Ocean and lands at a predetermined runway. TAL landing sites and various inclination trajectories are shown in Figure 2. This figure also illustrates how the trajectories for higher inclination trajectories are closer to the East coast of the United States.

Figure 2 – TAL and ELS landing sites.

At abort selection, an OMS propellant dump begins. This dump is performed to reduce the vehicle's landing weight and improve its control by moving the x-c.g. forward. As illustrated in Figure 3, the OMS dump is actually burning the rocket propellants (monomethyl hydrazine and nitrogen tetraoxide) through the OMS and RCS engines because, unlike an aircraft dumping fuel, the hypergolic nature of the propellants does not allow for them to simply be released into the air stream. The dump is set to a predetermined, I-loaded time and is terminated when the timer expires, load factor exceeds a set limit, or when fine countdown begins 10 seconds prior to MECO. Also, at abort selection, TAL guidance begins steering the vehicle toward the plane of the landing site through reference guidance and navigation I-loads [1]. During TAL powered flight, a roll to the heads up position is performed to put the vehicle in the correct entry attitude at ETSEP.

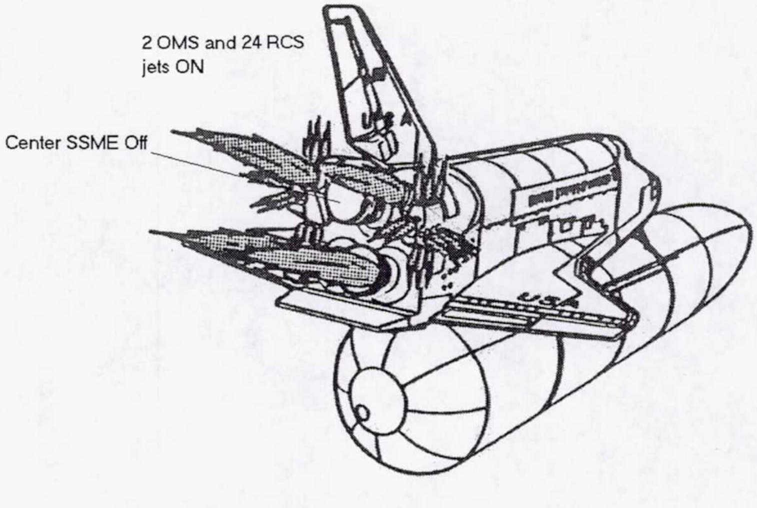

Figure 3 – OMS propellant dump.

The RTLS abort can be utilized for SSME failures within the first 230 seconds of flight. For SSME failures prior to SRB separation (SRBSEP), RTLS abort will not be initiated until second stage at 150 seconds MET. This allows the second stage guidance time to converge and transients to damp out after SRBSEP. For SSME failures after SRBSEP, RTLS is initiated approximately 15 seconds after the failure. Similar to the TAL, an OMS propellant dump begins at abort initiation.

Figure 4 depicts the typical RTLS profile, which consists of two distinct phases – powered flight and glided flight. Powered flight is composed of three sub-phases: fuel dissipation, flyback, and powered pitchdown (PPD) [1].

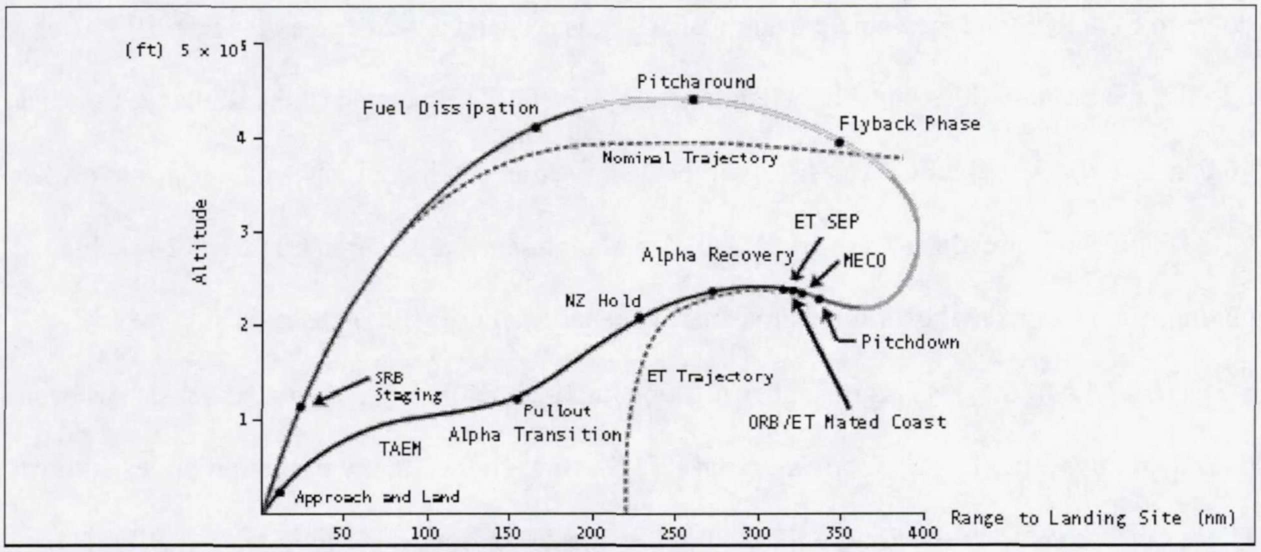

Figure 4 – RTLS trajectory profile with significant events.

The fuel dissipation phase lofts the vehicle to a higher altitude through an increased pitch command while the SSMEs continue to deplete the propellant in the ET. During fuel dissipation, guidance computations are performed to determine the PPD state if the turnaround were instantaneously initiated. The vehicle position, acceleration, and time are extrapolated to the estimated end of the turn. The velocity is added with the estimated velocity gained during the turn and is used in the ideal rocket equation to predict the final mass at PPD. [1] If the predicted final mass is less than or equal to the I-loaded desired final mass, then the turnaround is commanded at approximately 10 degrees per second and the flyback phase begins.

The flyback phase holds a pitch angle of approximately 45 degrees while the vehicle slows down and begins to fly back toward Kennedy Space Center. The SSMEs are throttled down to 100% RPL to reduce the heating on the ET. Guidance attempts to fly the vehicle to a specific target in the sky consisting of range, velocity, altitude, and flightpath angle. When these I-loaded targets are achieved, powered pitchdown (PPD) is commanded.

PPD is initiated about 20 seconds prior to MECO. The remaining SSMEs are throttled down to 67% RPL and the vehicle's angle of attack is reduced to –2 degrees for ETSEP. After ETSEP, the orbiter glides back to the landing site. The GRTLS portion of the flight uses similar guidance routines as the ECAL, which will be discussed in detail later. The major phases of the GRTLS guidance are alpha-recovery, Nz hold, and alpha transition. When Mach 3.2 is achieved, guidance transitions to the terminal area energy management (TAEM) phase.

ECALs from an RTLS trajectory must be initiated before PPA. Little emphasis has been placed on improving ECALs from an initial RTLS abort. In fact, many of the initiatives within Flight Operations from the Shuttle Safety Improvement Plan focus on minimizing the RTLS exposure as an intact abort mode by increasing the capability of other abort modes.

Initial design and development of the ECAL in 1988 was based off the nominal or TAL abort trajectory. The RTLS ECAL capability was not discovered until 1991 and revisited again in 1994. Little has been done to enhance this specific capability; however, RTLS-ECAL is seen as an improvement of ECAL capability because it eliminated a bailout region with the capability of a successful landing at Cherry Point, NC, as illustrated in the charts in Appendices B and C. Because of this, it bears mentioning as an improvement in ECAL capability; but the focus of this research is the improvements made to the initial design of ECAL aborts from 2-EO TAL and nominal trajectories.

Contingency Abort

The purpose of CA is to guide the vehicle to a safe gliding flight condition where an ECAL, a landing at a downrange TAL site or emergency landing site (ELS), or a bailout can be performed. The CA is a very dynamic flight mode that often takes the orbiter to the limits of its structural and flight control envelopes. In some cases, the orbiter is left without thrust at such high altitudes and low velocities that the entry may not be survivable. The regions where entry success is questionable are commonly referred to as black zones [3]. In some situations, there is enough energy to achieve a landing site after two or three SSME failures. On a due-east [28.5 degree] inclination, there is some capability to reach the island of Bermuda, and on a high-inclination mission, there is a large window of opportunity to reach an East coast landing site. The current landing sites available along the United States Eastern seaboard are marked in Figure 5 along with the nominal trajectory of a 51.6 degree inclination launch.

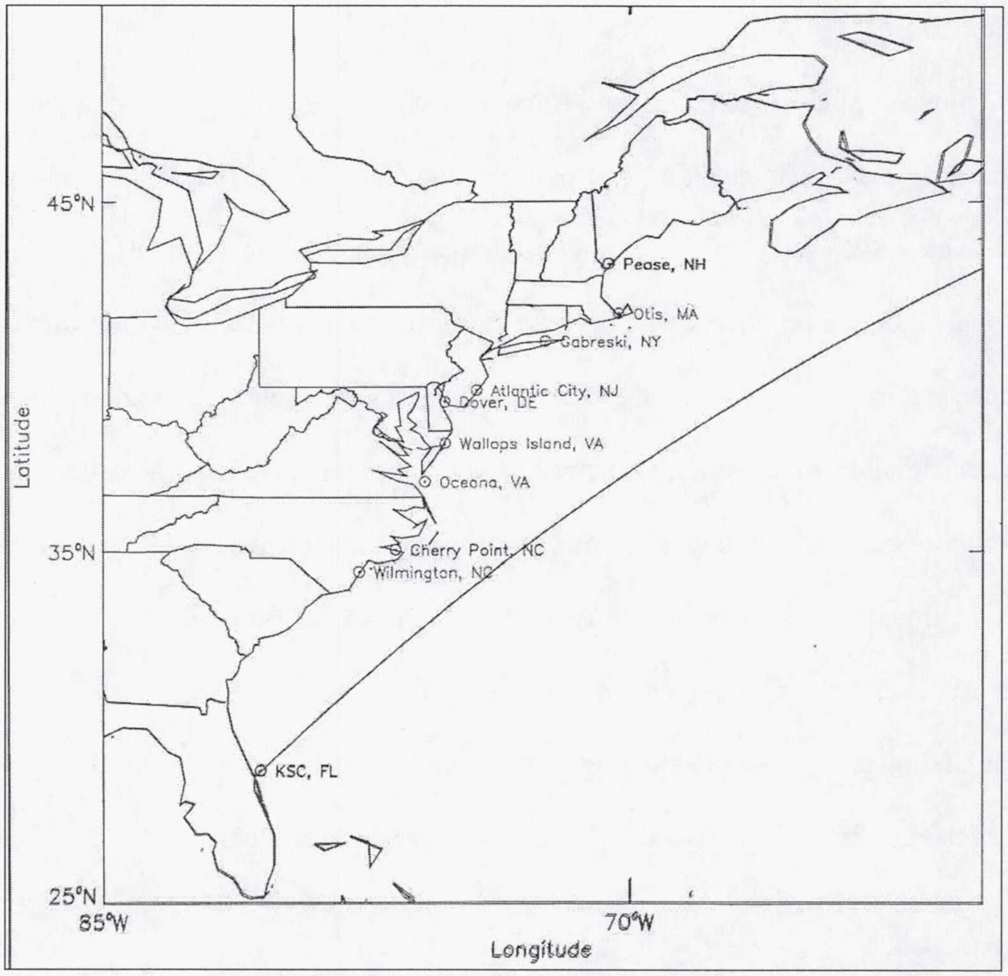

Figure 5 – East Coast Abort Landing Sites.

The specific capability boundaries to achieve a successful landing are defined by the United Space Alliance (USA) Flight Design and Dynamics Division Abort technical integration group. This group is part of the Space Shuttle Flight Operations and is responsible for designing and verifying all Shuttle abort related flight software I-loads, capability boundaries, and modifications/upgrades. The group creates data products that are utilized for flight software development, flight control team and astronaut training, and real-time operations support in the Mission Control Center (MCC). A sample of ECAL boundaries is shown in Figure 7.

II. Methodology

Boundary Definition

The actual site chosen for the ECAL landing depends on the energy of the vehicle at the time of the second engine failure. The longer the engines run, the more energy is attained and the further up the East coast the landing site will be located. In other words, the increased velocity due to a later engine failure and the range from the original trajectory to the selected landing site causes the Orbiter to fly past earlier sites, requiring a site further down range to be selected, as depicted in Figure 6.

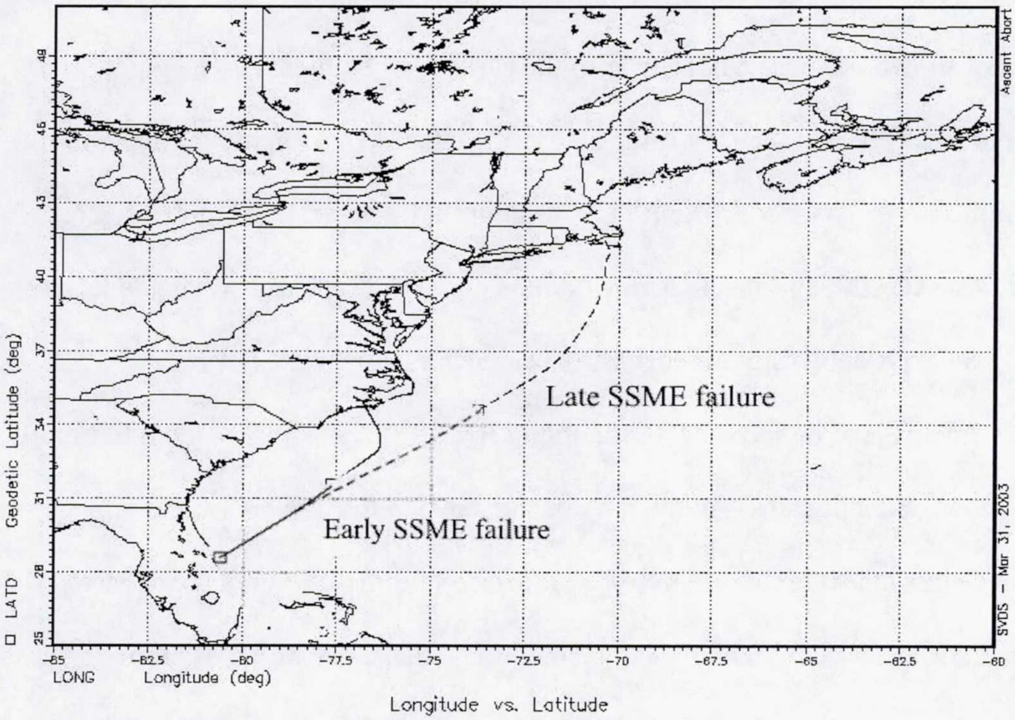

Figure 6 – ECAL groundtrack for early and late engine failures.

In the event of multiple engine failures during the launch of the Space Shuttle, the flight control team in the MCC needs to know precisely which ECAL sites are available at the time the engines shut down. The Flight Design and Dynamics personnel determine the ECAL capability charts for the operations support. ECAL boundary charts are the graphical representation of the vehicle's capability to reach a given landing site. The resulting window is defined in terms of the first SSME failure versus the second SSME failure.

The plot in Figure 7 illustrates the region or window of opportunity based on the inertial velocity at the moment the first and second SSMEs fail. The solid diagonal line represents a simultaneous failure of two SSMEs. The boundaries are actually symmetric about this line, but the sequential SSME failures are only shown to the left side of the diagonal line. The vertical, dashed line around 5800 fps represents the earliest velocity an intact TAL abort can be achieved. For a single SSME failure at a velocity slower (to the left) than this line, there is not enough performance to perform a successful TAL and an RTLS would initially be declared. ECAL capability is not shown on these charts prior to the early TAL boundary. The guidance sequence of initially aborting TAL and then aborting ECAL after the second engine failure would not occur prior to the TAL capability. The RTLS would initially be declared in this region. As stated earlier, a successful landing at Cherry Point is possible if the second engine failure is before PPA. The chart depicting this capability is shown in Appendix D.

Figure 7 shows the boundaries for the initial five ECAL sites. As shown in Figure 7, the capability to reach a landing site is defined by the area inside the curve. For example, a single SSME failure occurs at a velocity of 7000 fps. If a second SSME failure occurs between 7600 and 8500 fps, then a successful landing can be made at Oceana Naval Air Station. If the second SSME fails at 9000 fps, Figure 7 shows no capability to reach a landing site. In this scenario, the crew would be required to bailout and ditch the Orbiter. If the second SSME fails between 10,300 and 11,300 fps, there are two landing sites available – Otis or Pease. The Guidance and

Procedures Officer (GPO) in the MCC would make a real-time decision on the better site to land at given outside factors such as current wind and weather conditions.

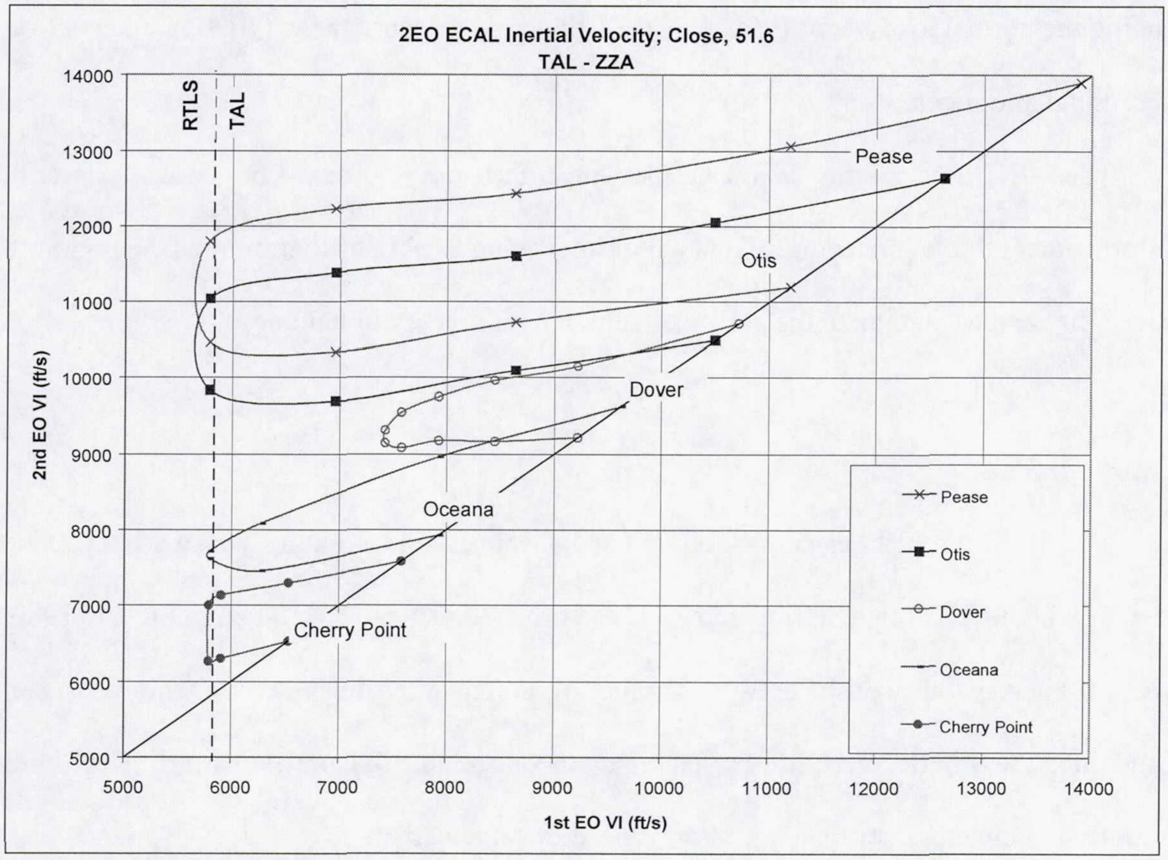

Figure 7 – ECAL boundary chart.

ECAL boundaries are determined by executing hundreds of computer simulations and noting which trajectories are within landing criteria. FORTRAN code mimics the Shuttle's onboard, ascent guidance routines. A JAVA based program models the entry procedures. The simulation output for each trajectory is analyzed for various limitations. These limitations include areas of structural, thermal, and vehicle controllability, but the biggest factor is simply distance to the runway. Typical output summaries from the ascent and entry simulations are provided in Appendices F and G. Appendix F is a summary of the ascent trajectory parameters at key points such as SSME failures and abort initiations. Appendix G summarizes the entry portion of the trajectory from ETSEP to landing interface. The important driver to determine a good versus bad trajectory is the type of landing interface. However, all factors are considered including the normal load factor (Max LFCGZ), dynamic pressure (Max QBAR), and control surface hinge moments.

These ECAL capability charts are the typical measure of effectiveness used to describe an improvement to the procedure. The goal of improving ECALs is to minimize the regions of no capability and to maximize the ability of achieving a successful landing.

ECAL Procedures

The ECAL procedures employ a pitch and yaw steering technique during ascent and a particular banking technique during entry. These procedures were developed in the late 1980s to increase the survivability of the crew and orbiter in regions were the crew was required to bail out and ditch the Shuttle, or both were lost in an uncontrollable dynamic situation. The Shuttle's pilot initially flew these contingency abort procedures manually.

Ascent procedures remain nominal until the first engine out (EO) occurs. If the EO occurs after the TAL boundary, TAL abort would be declared and the vehicle would start steering out of the nominal launch plane toward the TAL site. When the second engine fails, the ECAL procedures are employed and the crew presses the corresponding SSME shutdown push buttons so that guidance recognizes there are two failed engines. Single engine roll control (SERC) is enabled to use the RCS jets with roll controllability. Depressing the two Control Stick Steering (CSS) buttons activates commanding for pitch and roll/yaw. To improve the thrust to weight ratio, the remaining SSME is manually throttled up to 109% RPL. The pilot needs to push and twist the rotational hand controller to a pitch angle of 60 degrees and a yaw angle of 45 degrees. The pitch of 60 degrees is performed to increase the vertical thrust and reduce the negative altitude rate, while the yaw is performed to reduce the crossrange to the ECAL site. A contingency OMS dump is initiated to reduce the vehicles weight and move the center of gravity forward. This attitude is held through apogee. Because of the low thrust to weight ratio, the altitude decreases while the airspeed increases. When the equivalent airspeed is greater than 4 knots, the yaw angle is reduced until the sideslip angle is near zero degrees and then the vehicle is rolled to a wings level attitude. Prior to MECO and in preparation for ETSEP, the vehicle is pitched down at a rate of 3 degrees per second. After the ET is released, a burn of the –z RCS jets improves the clearance between the ET and orbiter. [7]

The entry procedures use a modified GRTLS guidance, which has three phases: alpha recovery, Nz hold, and alpha transition. After ETSEP, the Orbiter is pitched up to a recovery angle of attack (alpha) of 58 degrees to slow the large negative altitude rate. Arresting the altitude rate is called the pullout. The initial pullout experienced by the Orbiter is rather severe because ECALs exhibit fairly low velocities and large negative flight path angles at ETSEP [4]. Once the negative altitude rate has been arrested and the pullout controlled, loads on the vehicle begin to build. When the normal force (Nz) on the Orbiter reaches a calculated mission and altitude rate dependant value, the Nz hold phase begins. This phase reduces alpha in order to hold the normal force on the Orbiter constant to prevent the normal force from exceeding the Orbiter's structural limit. [4] A switch to the alpha transition phase occurs once the Orbiter's loads have started decreasing. The alpha transition phase is characterized by flying a specific alpha-Mach profile that is based on a reference alpha as a linear function of Mach number.

During the Nz-hold and alpha transition phases, a bank maneuver is performed to null any heading errors to the selected runway. A bank angle equivalent to twice the magnitude of the heading error, but to a maximum of 70 degrees, is commanded when the altitude rate is increasing and greater than –600 fps. [6]

ECAL Automation

After its initial development, the crew manually flew the ECAL procedure. To improve the probability of successful execution and remove the human interaction from the control, the procedures were automated for computer control. The Single Engine Auto Contingency Abort logic was added to the flight software in May 1992 with Operational Increment (OI) 21 to completely automate the powered flight portion of two engine out contingency aborts. An OI update is analogous to a software version update. When invoked, the auto CA logic commands the appropriate pitch and yaw attitude, starts SERC, and automatically initiates the OMS dump. Guidance achieves this through I-loads associated with this regime of flight. To initiate the Auto Contingency Abort logic, the only input needed from the pilot is to turn the abort switch to the correct position and press the abort pushbutton. Auto guidance commands the procedures previously discussed up to ETSEP.

For many years, the entry portion of the ECAL remained a manually flown procedure. The crew procedures were difficult to implement and it remained one of the last manually flown CA procedures. Integrated simulations have shown an automated technique is preferred. The entry ECAL automation significantly reduces concerns with loads in the pullout and improves capability to reach the runway, increasing survivability and reducing crew training [3].

The modifications to the Shuttle's guidance were incorporated with OI-28, which first flew in on STS-98 in February 2001. The major modifications were to the GRTLS and TAEM guidance. The pitch channel had been modified to manage energy as well as protect for load factor. The pitch channel continuously monitors the energy-over-weight ratio with respect to the nominal energy reference line and adjusts the angle of attack. Since the GRTLS energy-over-weight reference lines are not valid at the high Mach numbers flown by ECALs, new ECAL energy-over-weight reference lines were created as shown in Figure 8 [3]. The reference lines are calculated by the guidance routine using I-loaded constants. A corridor is created around the nominal energy reference with upper and lower energy limits. I-loads also define the amount of bias added to the alpha profile based on where the energy-over-weight is in relation to the corridor. If the energy is above the nominal energy line, guidance commands the vehicle to pitch up. Conversely, if the energy is below the nominal energy line, guidance will command the vehicle to pitch down. The energy corridor is shown in Figure 9.

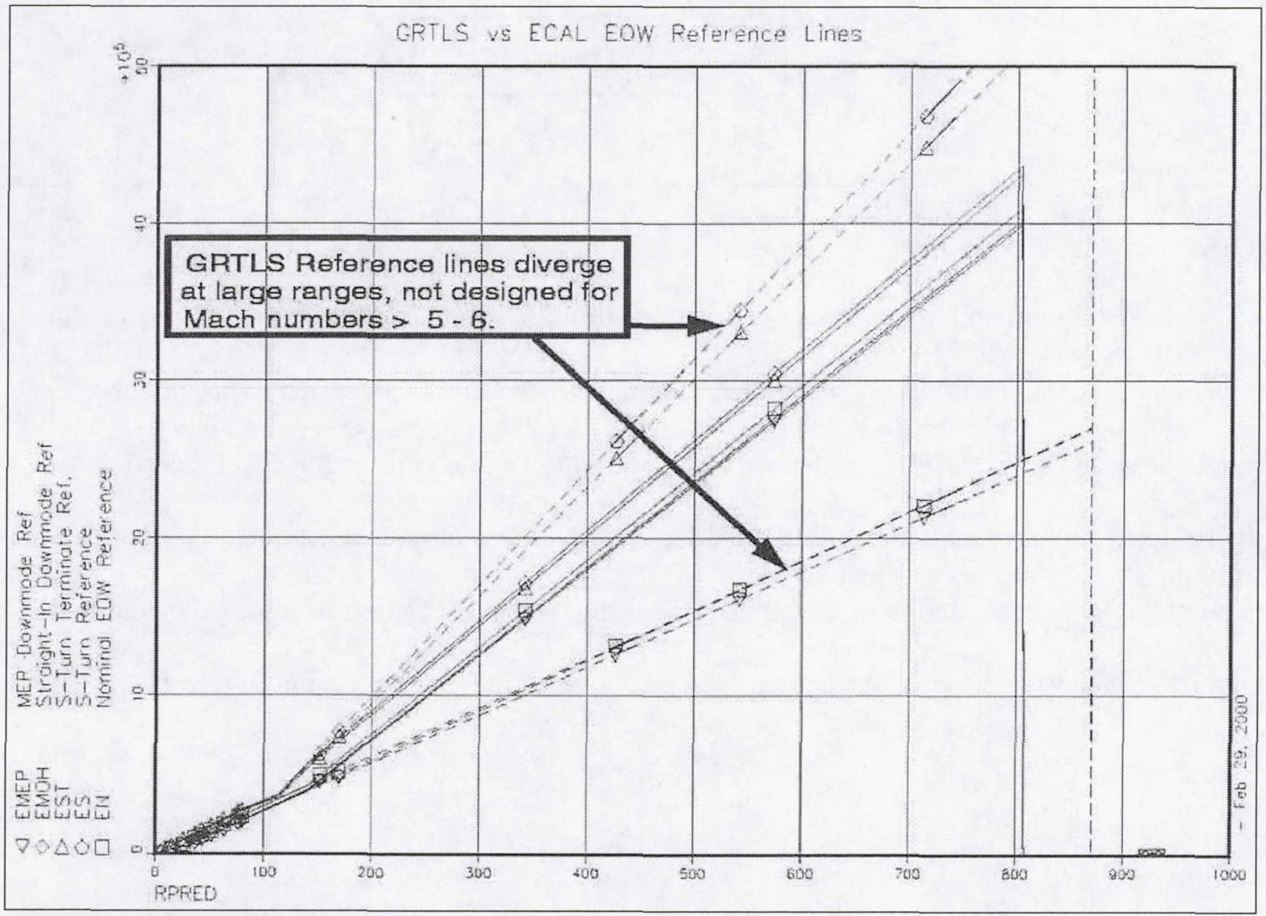

Figure 8 – Modified Energy Reference Lines for ECAL.[3]

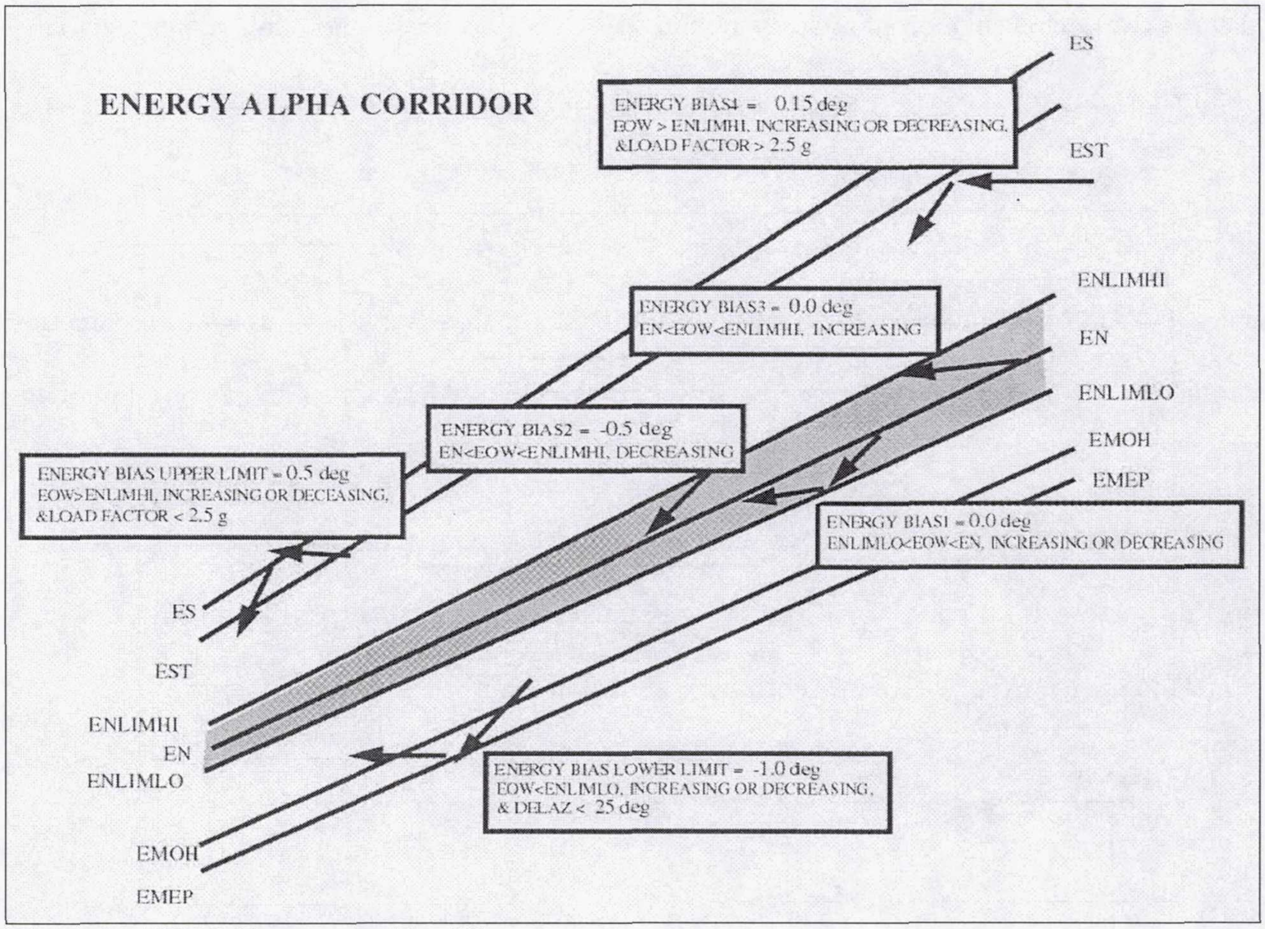

Figure 9 – ECAL Energy corridor [3].

A maximum and minimum angle of attack limit is maintained for vehicle stability. The upper and lower alpha limits are calculated to bound alpha as it is modulated to provide the best ranging capability (Figure 10). After the initial pullout, the pitch protection flag is set to protect the vehicle from exceeding the normal load factor limit. Protection against pitching up too high is provided by the calculation of the alpha upper limit. This calculation is based on the current load factor, load factor limit, current angle of attack, and pitch rate as seen in Figure 11.

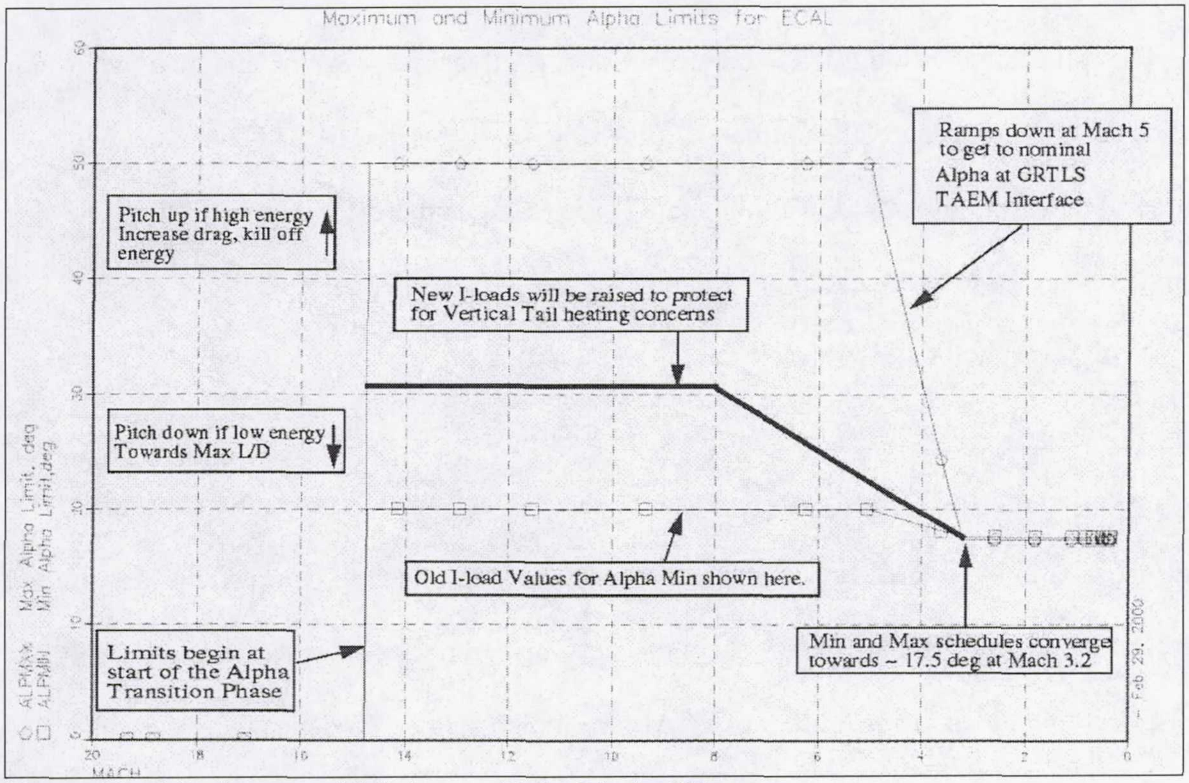

Figure 10 – Maximum and Minimum Alpha Limits [3].

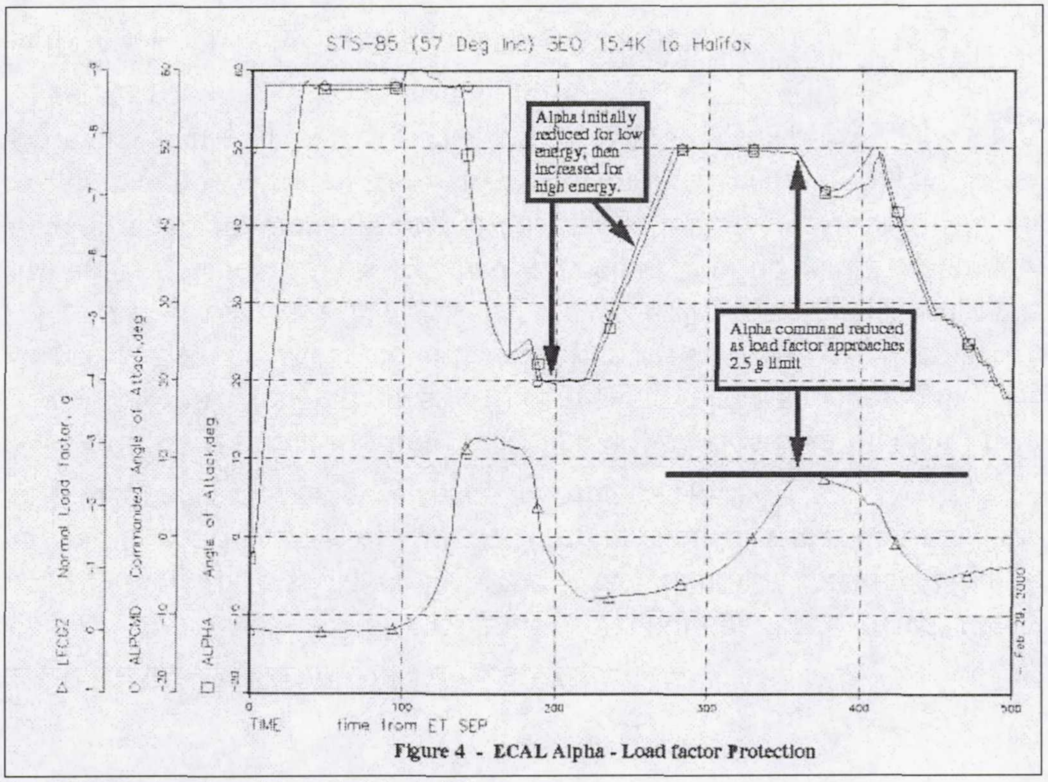

Figure 11 – ECAL Angle of Attack Limit [3].

The roll channel is modified to control crossrange, dynamic pressure, and load factor. Modeling the crew procedure, the normal 2.2 times the heading error (DPSAC) banking begins near the end of the pullout after the altitude rate is increasing and greater than –600 fps. The bank angle is limited to a maximum of 70 degrees.

A roll protection flag is set after the initial pullout is complete to protect dynamic pressure and load factor limits in subsequent oscillations. Figure 12 shows how the roll command during the alpha transition phase can be reduced as a function of altitude rate and altitude acceleration to indirectly protect for dynamic pressure. The roll command is also limited so that the total load factor plus the flight control nose-up compensation load factor does not exceed a maximum load factor limit. For ECALs with high energy, guidance logic basically models the current crew procedure of banking toward the site 70 degrees until the energy-over-weight drops below the calculated S-turn terminate (EST) line in Figure 9. If the heading error reaches 30 degrees past the site, the roll will be reversed. The roll command returns to the normal 2.2 times DPSAC when the energy-over-weight is less then the S-turn terminate line.

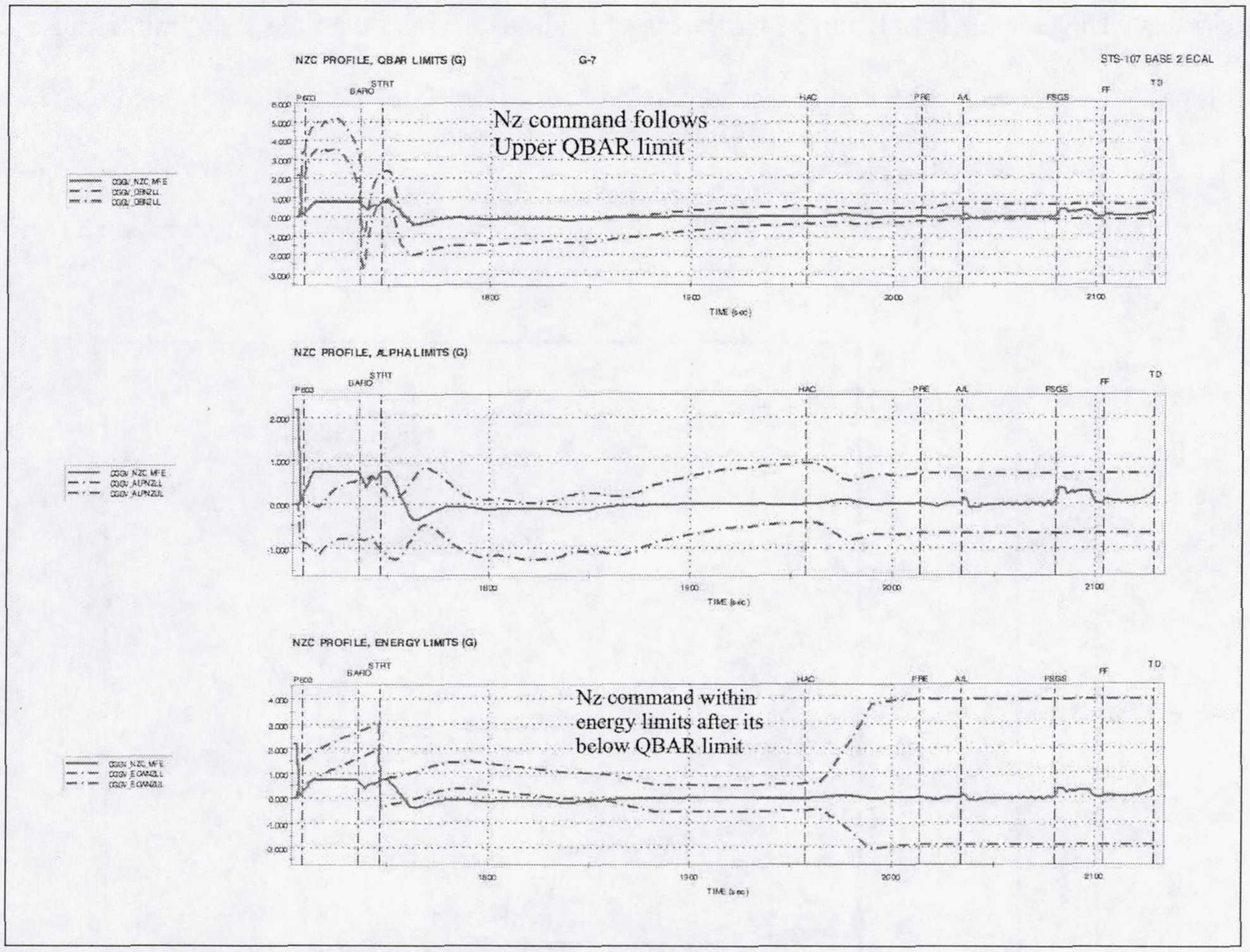

Figure 12 – Load limits protect the vehicle's structural limits.

An addition to the ECAL automation not present in the manual crew procedure is the introduction of a roll command during the initial pullout, commonly referred to as the "prebank". The prebank is a 20 degree roll toward the landing site commanded during the pullout when the maximum negative altitude rate is achieved. However, the prebank is only commanded when pullout loads are below specified limits and the heading error to the landing site is large. At the bottom of the initial pullout, guidance calculates a target load factor as a function of the maximum altitude rate. If the target load factor is less than 3.2g and the initial heading error to the landing site is greater than 20 degrees, then as seen in Figure 13 the prebank is initiated. When the altitude rate increases past –600 fps, the normal 2.2 times DPSAC roll command resumes. The prebank is only utilized if the target load factor is less than the 3.2g limit because rolling the vehicle induces a higher resultant load factor. Therefore, the target load factor is increased by 0.2g when the prebank is invoked.

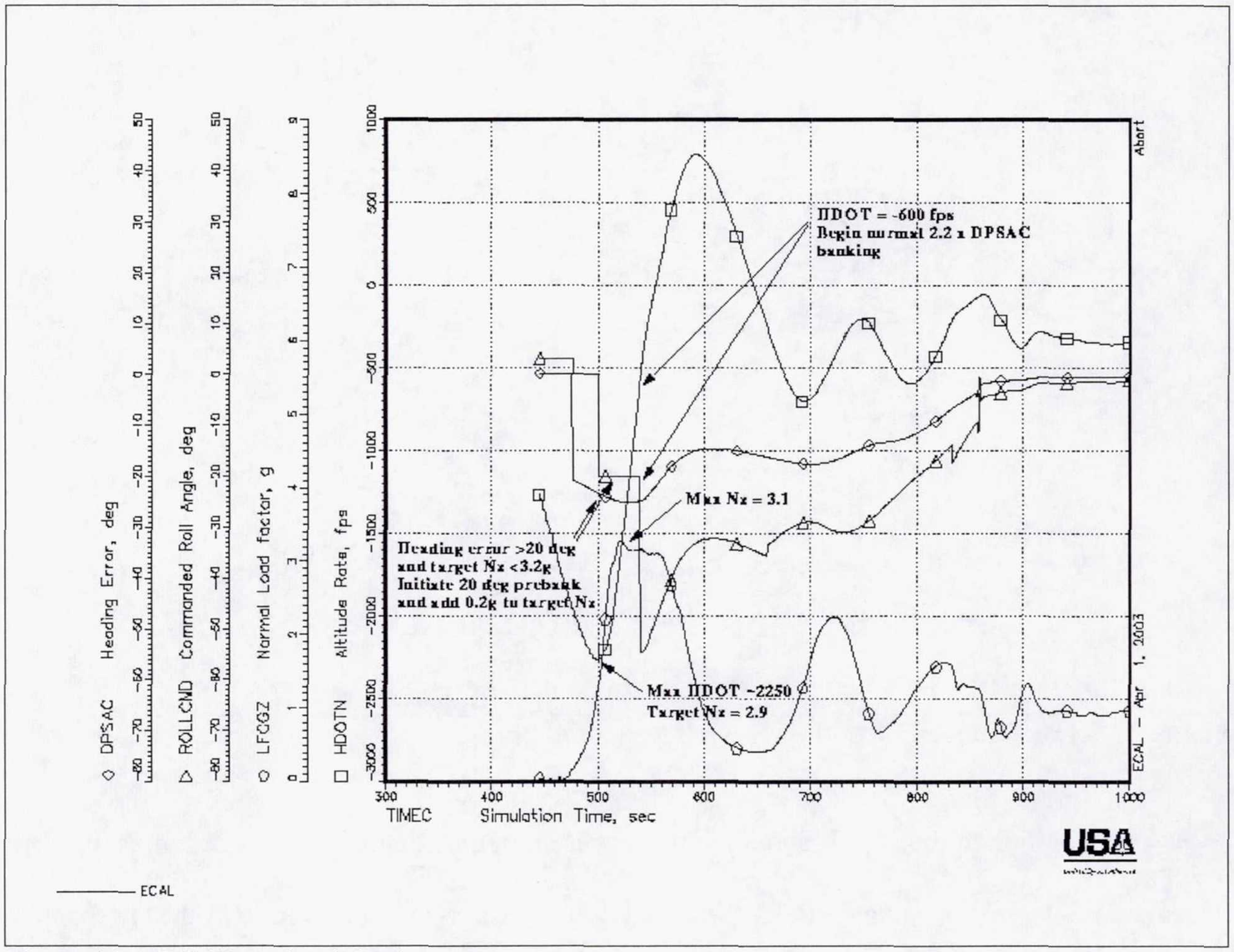

Figure 13 – ECAL prebank logic.

The 20 degree prebank increases the capability to a specific East coast landing site by reducing the crossrange to the landing site earlier in the trajectory. Reducing the crossrange is key to increasing the capability, as seen in Figure 14, to the landing site. By nulling out the heading error early, the vehicle can then fly a maximum lift-over-drag profile maximizing its range to the runway.

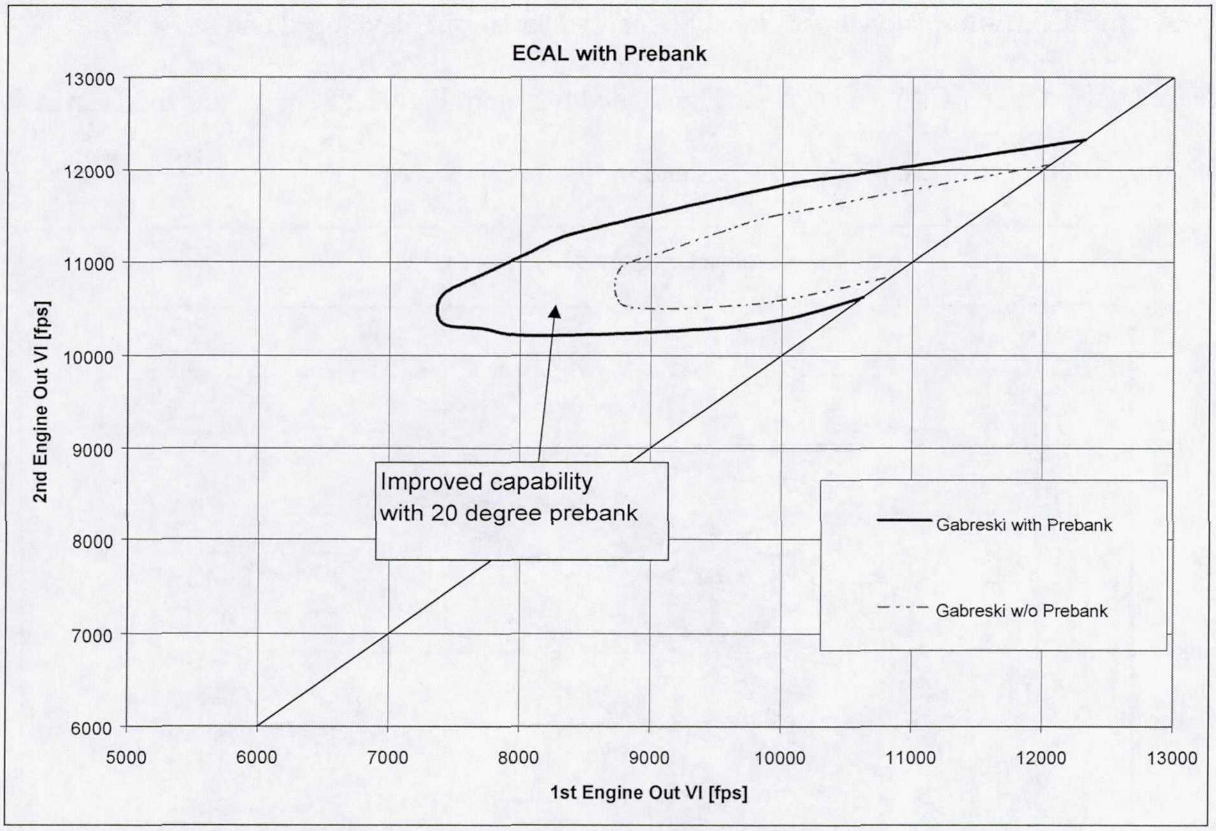

Figure 14 – ECAL capability improvement with prebank invoked.

Landing Site Table Expansion

The landing site table is a list of runway information utilized by the Shuttle's guidance. It contains the runway's name, latitude, longitude, altitude, and azimuth. In late 2000, the astronaut and GPO offices recommended that new sites be evaluated for use in the landing site table. The upgrade was developed in two parts. First the current table of 50 sites was reorganized and optimized prior to expanding the table to house data for 90 landing sites. The optimization included removing less desirable sites and adding some sites that provide better overall coverage for ECAL and other emergency landing sites. New ECAL sites added to the landing site table are Gabreski, NY; Atlantic City, NJ; Wallops Island, VA; and Wilmington, NC. These sites were specifically chosen to fill in the gaps and provide some overlap between the previous ECAL sites. New operational boundary charts were developed and show the increased coverage in ECAL capability. The shaded region in Figure 15 shows this increase in capability as compare to the original ECAL site in Figure 7.

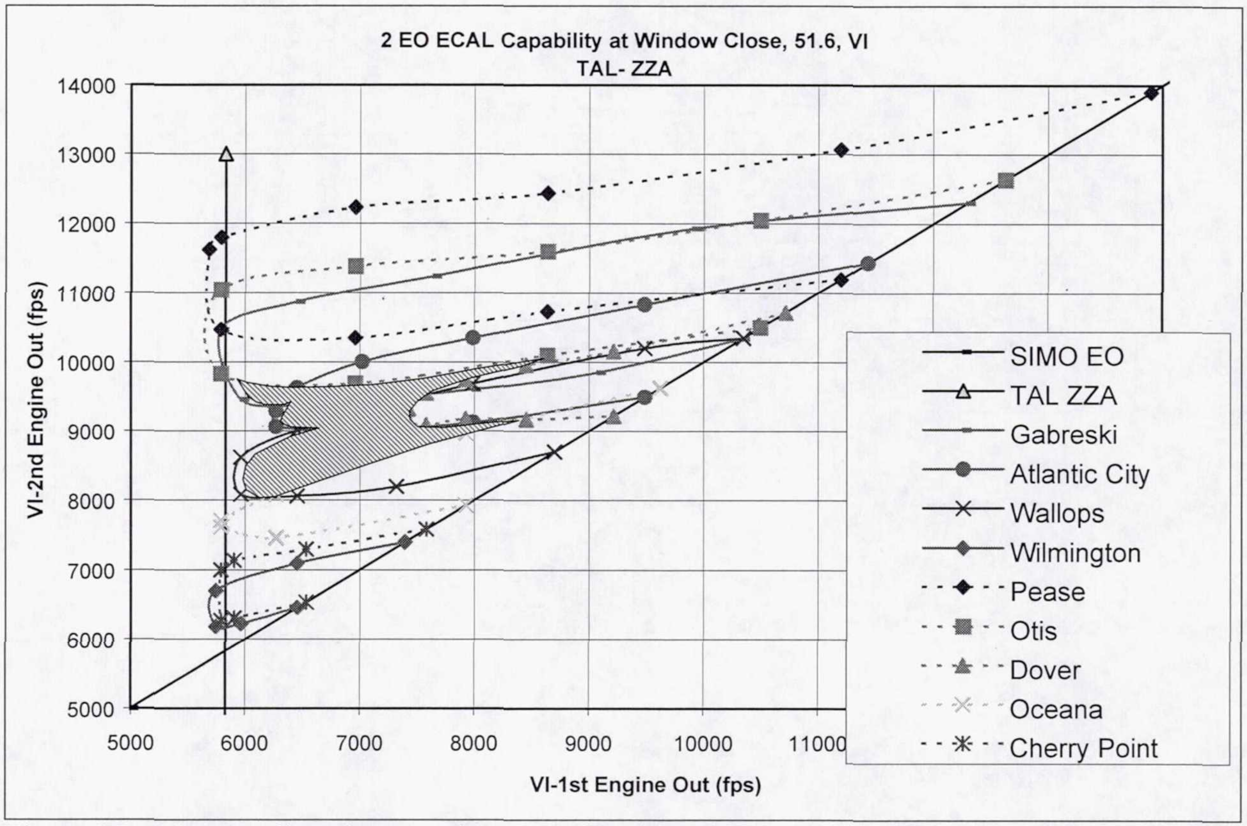

Figure 15 – New landing sites provide capability in previous gaps.

Delayed TAL Abort

Delayed TAL abort initiation increases the overall opportunity to reach a runway for ECAL availability. At TAL abort initiation, the guidance targets the intact abort TAL targets and begins steering toward the TAL site, away from the East coast. The delay in TAL abort initiation after a single engine failure allows the orbiter to stay on the nominal trajectory to protect for a possible second SSME failure and ECAL declaration. By delaying the selection of the TAL abort, the Orbiter stays closer to the East coast decreasing the range to many ECAL landing sites, in turn increasing the capability to land at the ECAL sites. Figure 16 displays the groundtrack of a standard TAL abort and a resulting ECAL to Otis as compared to an ECAL to Otis with a 200 second delay in TAL abort initiation. The trajectory without the delay falls short of the designated runway and crashes off of Cape Cod. However, the trajectory with the 200 second delay achieves a successful landing at the airfield.

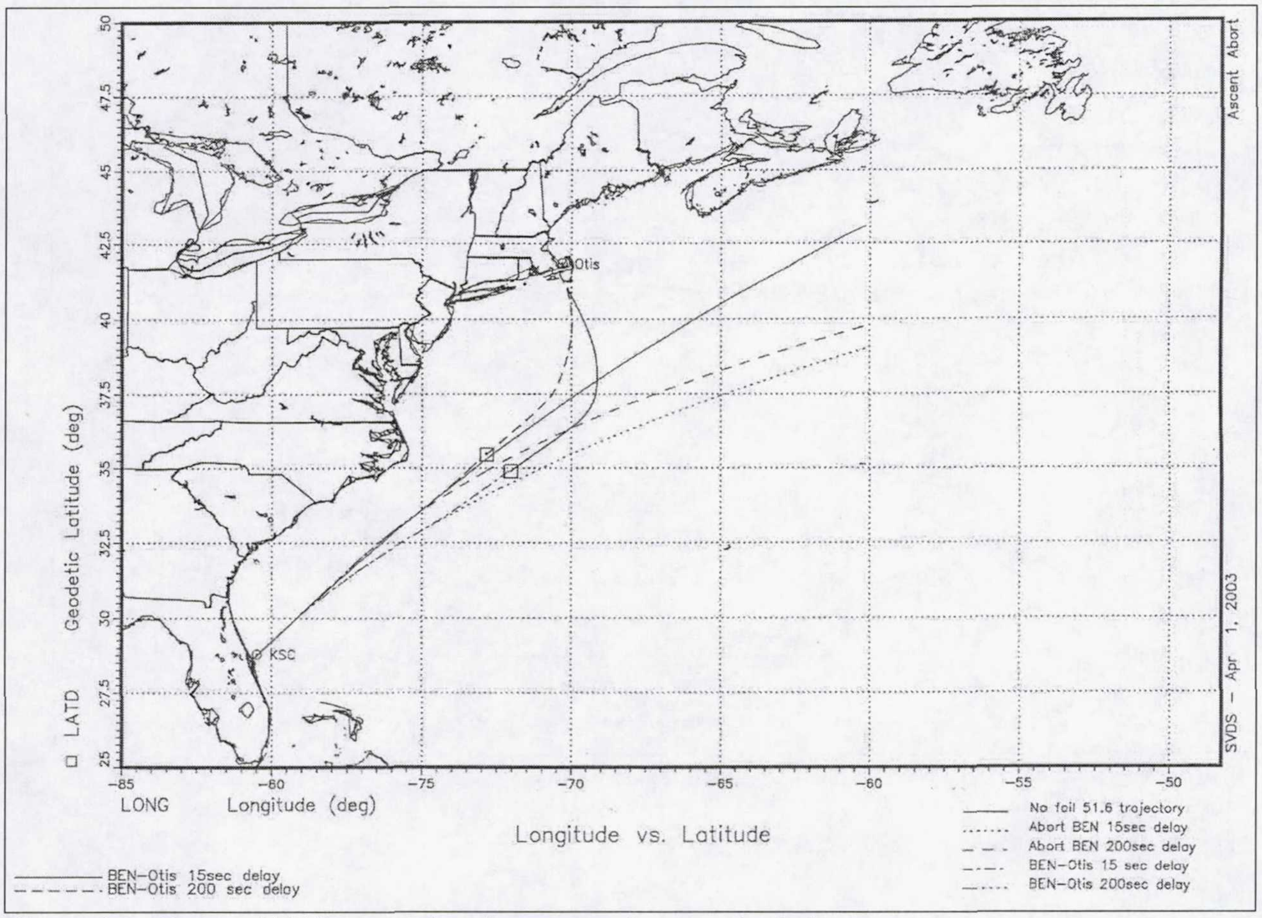

Figure 16 – Delayed TAL groundtrack compared to standard abort.

Delay in TAL abort initiation increases the capability to the ECAL site as compared to a TAL abort 15 seconds after the first engine failure (standard delay). This is most notable for first engine failures around 170 to 200 seconds MET where the longest TAL delay time can occur. The capability drops off significantly once past the MPS FPR line due to the operational flight rule of not delaying TAL beyond the MPS FPR line. Figure 17 shows in the chart format the increased capability to two of the landing sites. The chart in Appendix E shows the increase for all of the ECAL sites. With TAL delay implementation at the close of the launch window, almost complete ECAL coverage is attainable. This includes overlap between all ECAL sites as the trajectory advances up the East coast.

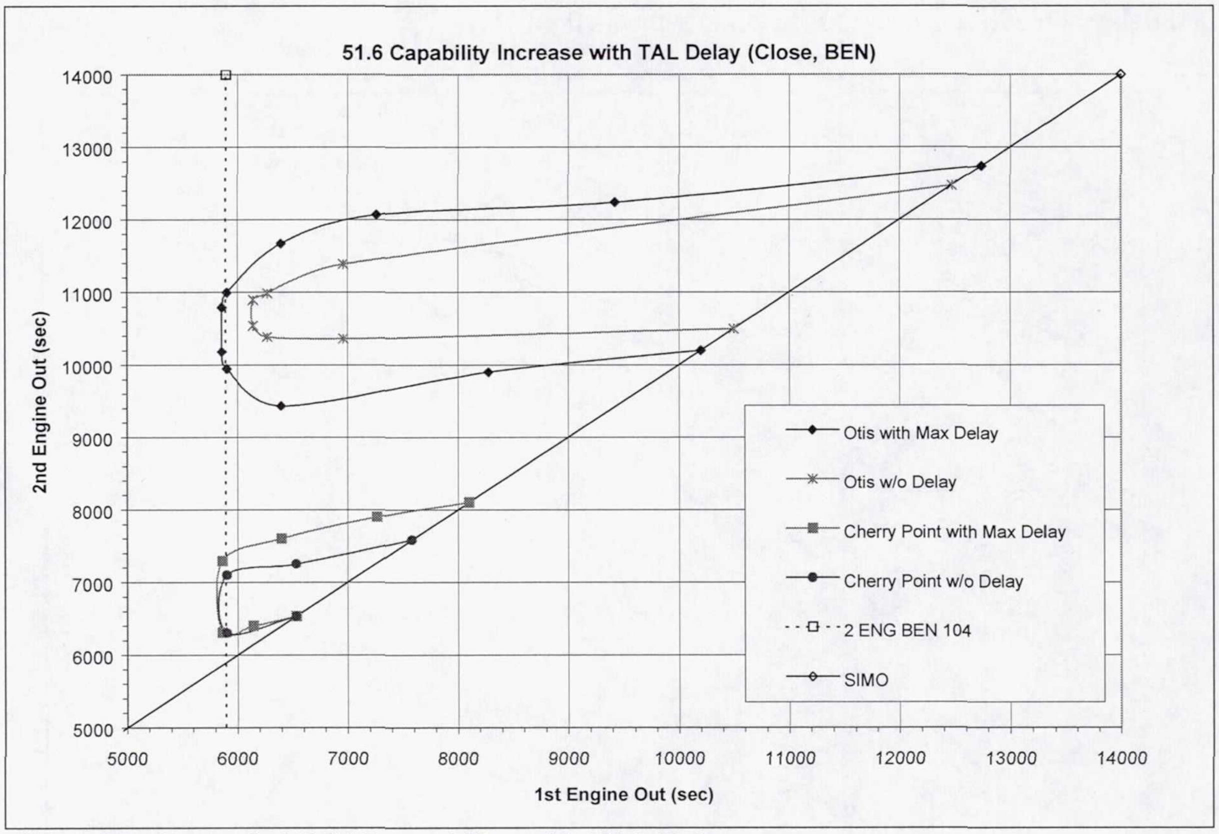

Figure 17 – Expanded ECAL capability with TAL Delay.

III. Conclusion

After STS-51L, a study began to provide a means of both Shuttle and crew survivability in the event of a contingency failure. A result of the study was the creation of the East Coast Abort Landing. Analysis was conducted, and crew flight procedures were developed to determine the capability of the Shuttle completing a successful ECAL. Nearly a decade after its initial development, improvement initiatives began to increase the ECAL capability. These initiatives were rooted in the areas of guidance and flight control automation and mission, operational philosophy.

Automation of the Shuttle's flight control through the addition of onboard guidance routines for ECAL improved the probability of a successful landing. With the Shuttle's computer commanding the flight control, faster reaction rates to control feedback and tighter tolerances in control limits can be achieved as compared to human control. This allows the shuttle to fly closer to the nominal energy reference while staying within the structural and thermal limitations. Automated guidance also improved the manual crew procedures by initiating a roll command earlier in the pullout, which decreases the range to the landing, site more rapidly, increasing the capability.

Changes in the mission operations allowed the introduction of new landing sites and the philosophy of delaying the TAL abort to increase the ECAL capability. Four new landing sites strategically selected between the previous five landing sites provided new capability for ECAL. The new sites also provided overlap of coverage in the event another nearby site was unavailable. Delaying the TAL abort allows the vehicle to fly closer to the East coast before turning toward Europe, protecting for the possibility of a second engine failure. Keeping the trajectory closer to the coastline naturally reduces the range to the ECAL site and in turn increasing the capability of a successful landing.

The compilation of these improvements provides almost complete coverage of ECAL capability for the later half of the launch window, as illustrated in Appendix E. The increase in coverage is an improvement in regions that previously required the crew to bailout and ditch the Space Shuttle in the ocean. East Coast Abort Landing capability provides an increase in safety for the crew and Orbiter.

Bibliography

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[2] Johnson, Yusef A. *Contingency Abort Training Guide. Guidance Primer*. Presentation. March 2001.

[3] Jones, Joe *OI-28 Entry ECAL Automation*, Mission Operations Directorate Presentation. May 18, 2000.

[4] Jones, Joseph. *Continental U.S. Abort Landings Feasibility Study*. STF No. FDD-DFA-89-540-039. Rockwell Space Operations Co. July 1989.

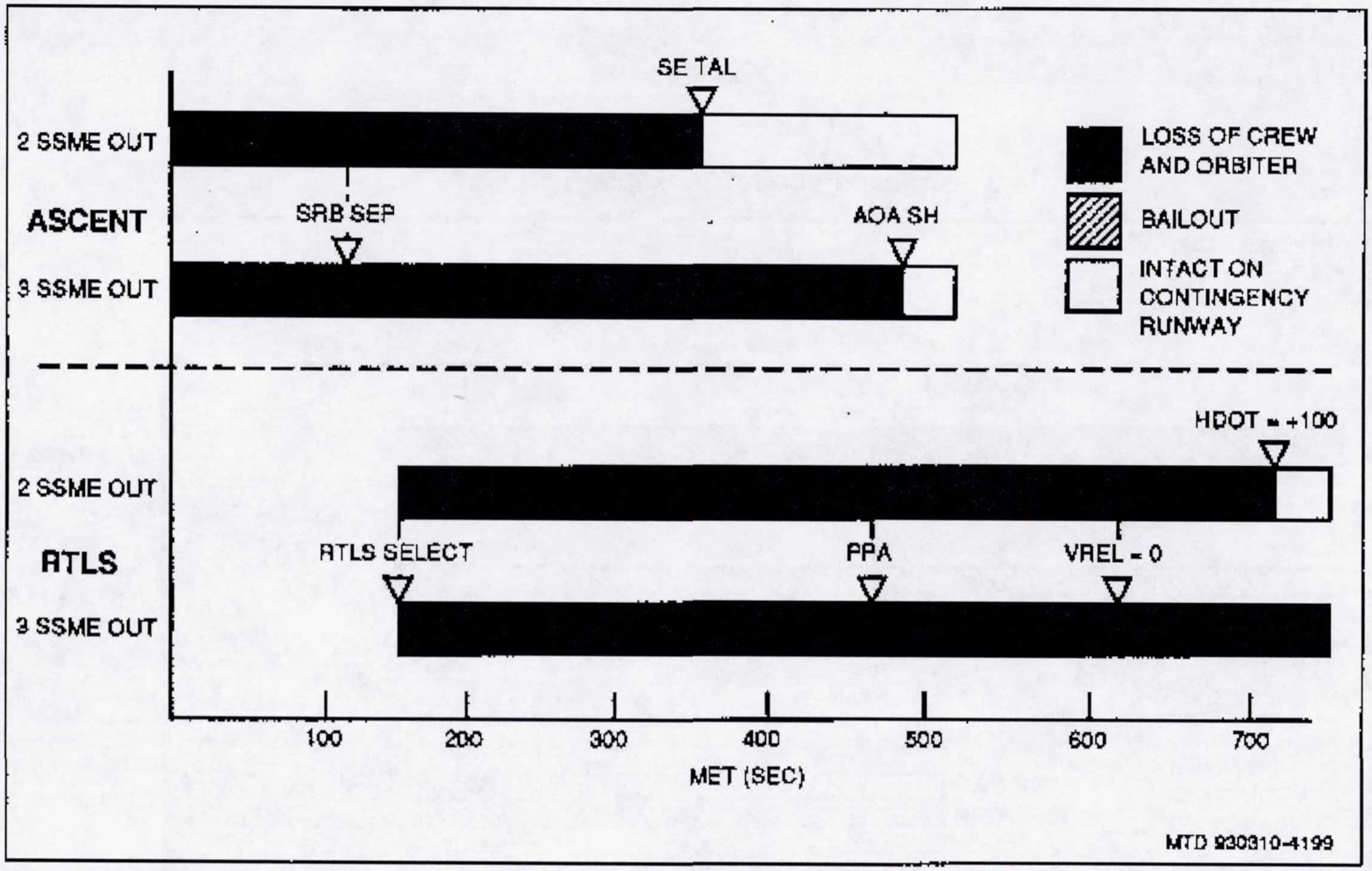
[5] *Space Shuttle Contingency Abort Data Book*. NSTS-08347. NASA Johnson Space Center. September 1990.

[6] *Space Shuttle Operational Level C Functional Software Systems Requirements Guidance, Navigation, and Control, Part A. Entry through Landing Guidance*. STS 83-0001-28. June 1998.

[7] *STSOC Contingency Abort Training Manual*. Rockwell. 1990.

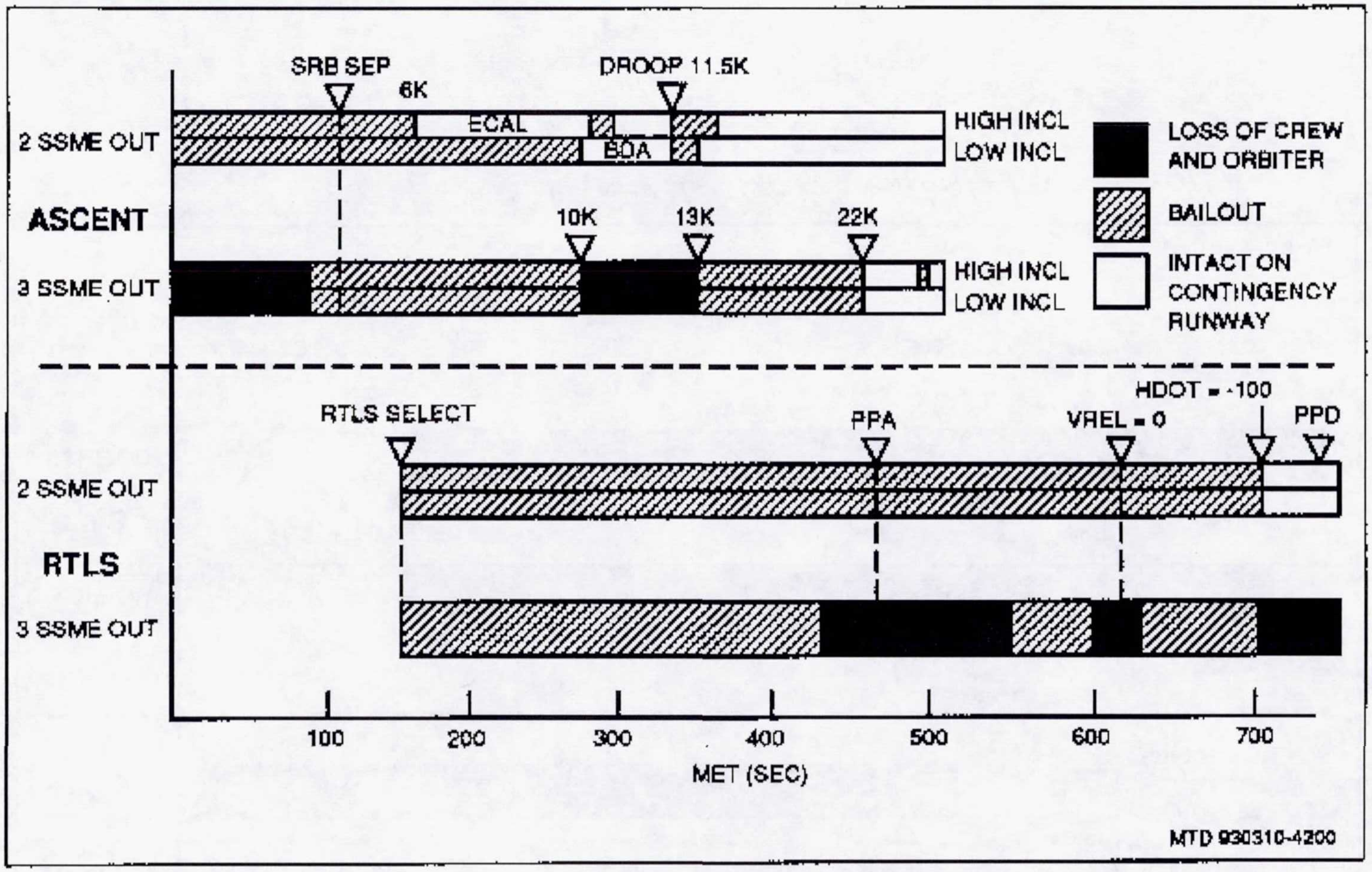
Appendices

Appendix A: Contingency Abort Capability in 1986



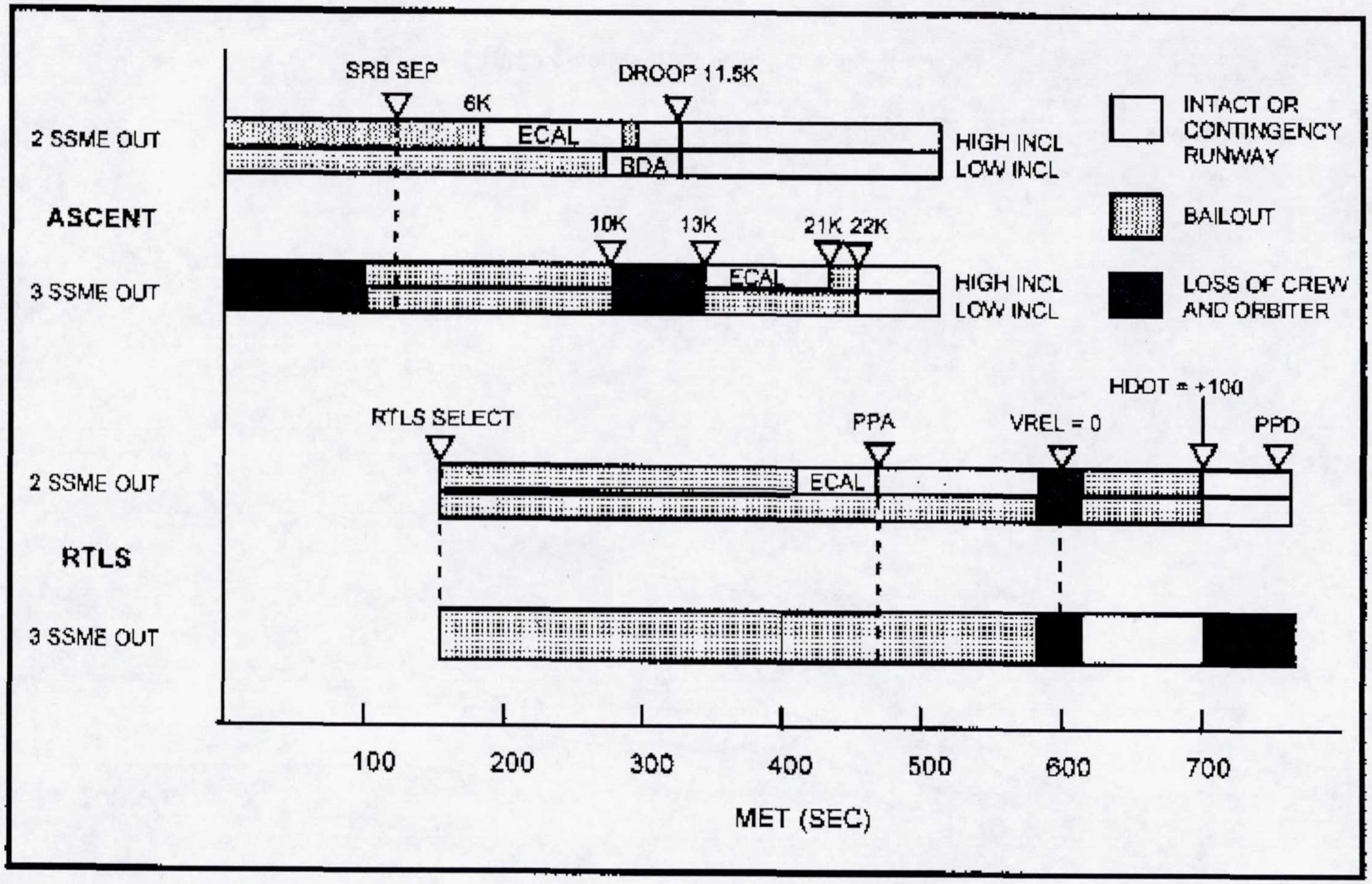
Contingency Abort Capability–STS-51L

Appendix B: Contingency Abort Capability in 1991



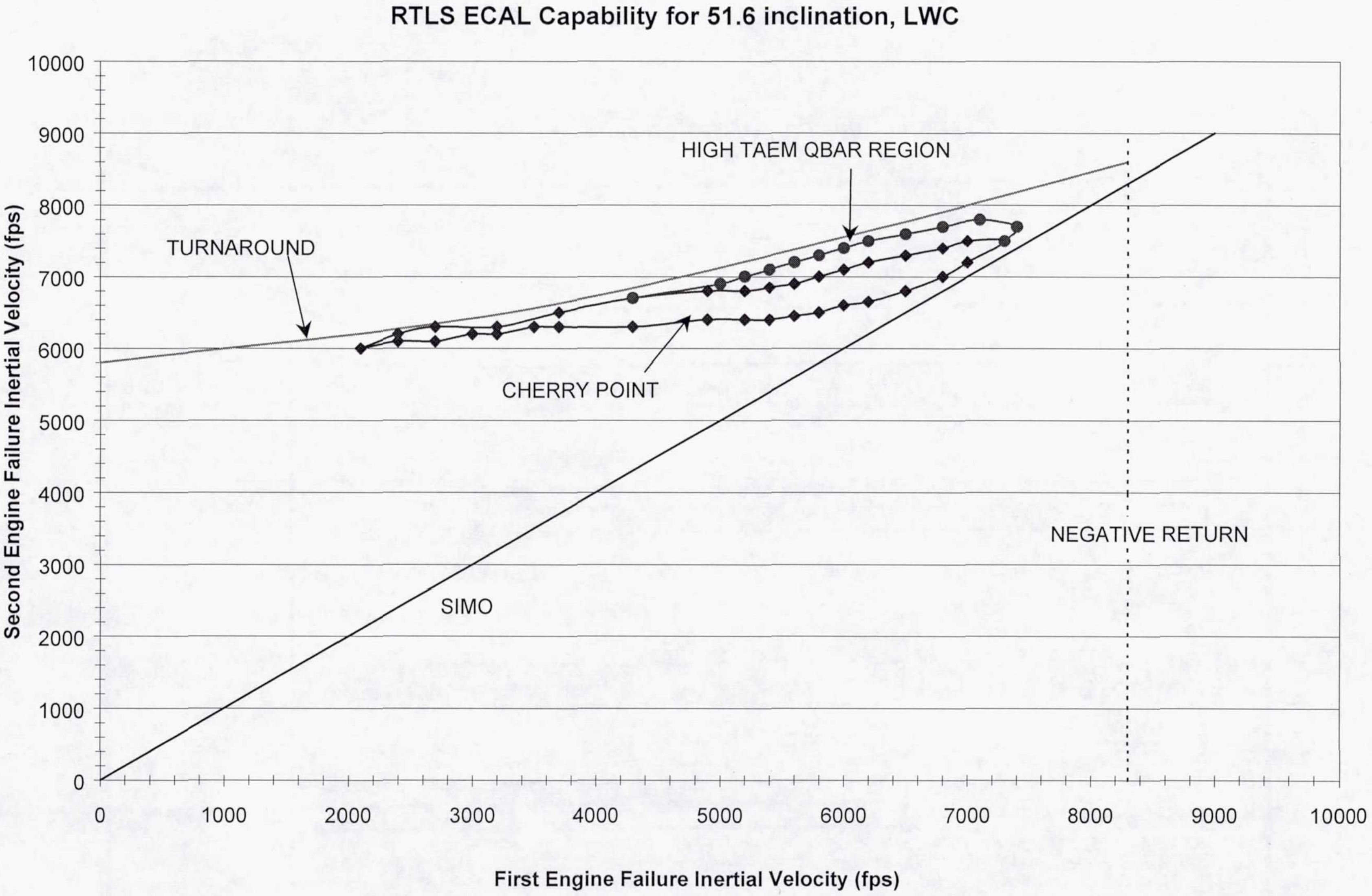
Contingency Abort Capability–1991

Appendix C: Contingency Abort Capability in 1998

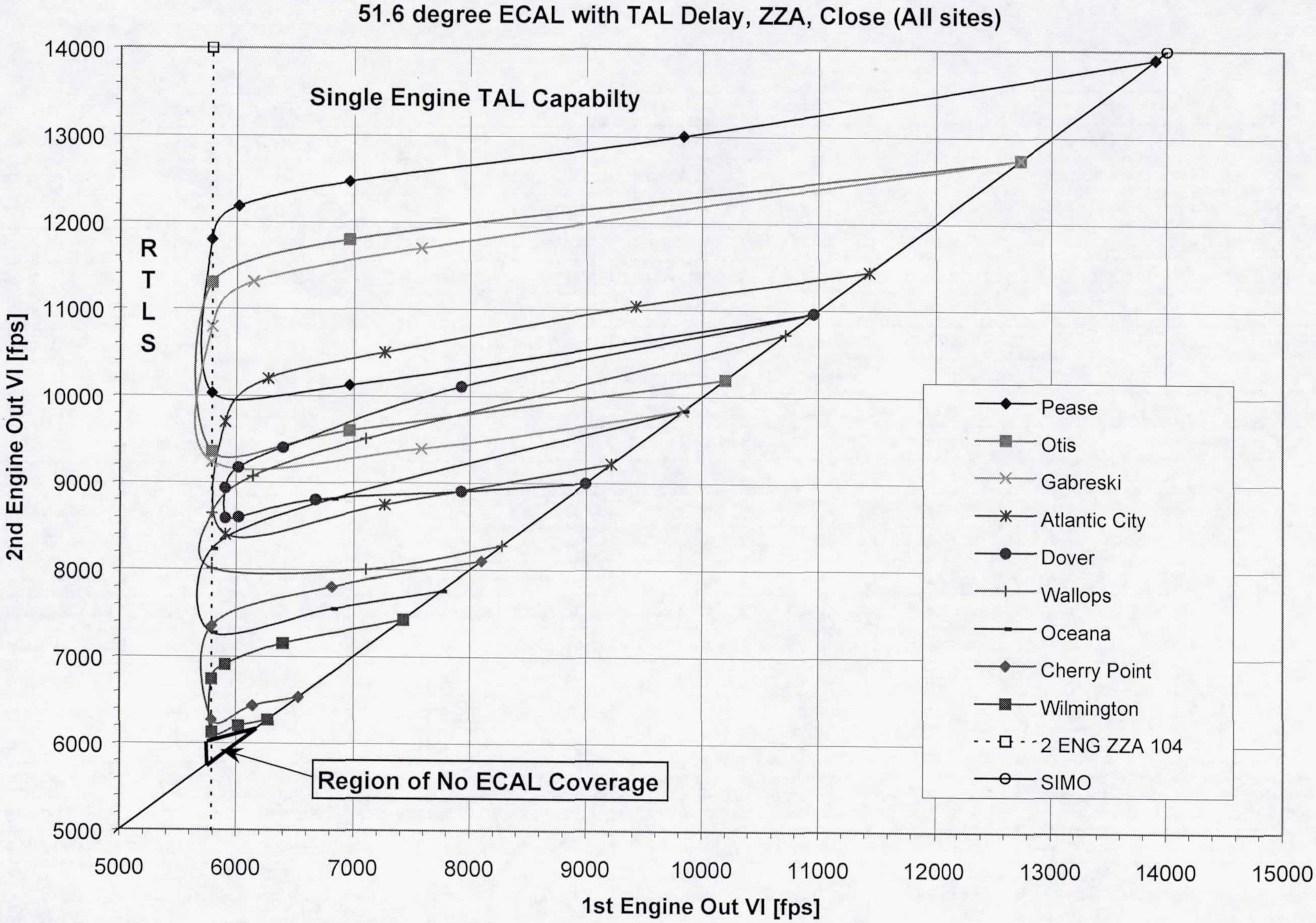


Contingency Abort Capability - 1998

Appendix D: ECAL Capability from RTLS Abort.



Appendix E: ECAL Capability with all improvements.



Appendix F: Ascent Simulation Summary Page

EVENT	MET (SEC)	ALT (FT)	HDOT (FT/SEC)	VI (FT/SEC)	VDR (FT/SEC)	EAS (FT/SEC)	ALPHA (DEG)	BETA (DEG)	BANK (DEG)	QBAR (PSF)
SRB Staging	124.5	155477.	2117.2	5289.29	0.00	159.25	3.6	0.1	-179.1	28.1
OMS Dump	134.7	176465.	1997.5	5469.38	0.00	108.61	3.2	-0.4	-178.5	13.7
Engine 2 Out	160.3	223517.	1688.2	6009.26	0.00	48.08	0.3	-0.4	-180.0	2.9
OMS Complete	265.6	344104.	725.9	7212.83	0.00	2.59	-32.1	-5.4	179.7	0.0
Abort TAL	360.0	383798.	158.6	8973.63	0.00	1.08	-28.8	-3.1	179.4	0.0
RCS Dump	363.5	384328.	146.2	9056.26	0.00	1.08	-28.3	-3.0	179.5	0.0
Engine 1 Out	420.2	386720.	-39.8	10522.48	0.00	1.18	-23.5	19.0	179.5	0.0
RCS Complete	421.8	386641.	-50.8	10555.31	0.00	1.19	-23.4	19.4	178.9	0.0
SERC Init	422.4	386600.	-64.1	10565.57	0.00	1.19	-23.5	19.5	178.2	0.0
AutoCA Armed	432.0	385314.	-184.3	10699.69	0.00	1.25	-54.3	20.4	176.6	0.0
Abort RTLS	435.1	384698.	-205.1	10717.11	-8956.94	1.28	-63.3	19.5	176.6	0.0
AutoCA Init	435.8	384542.	-213.4	10720.82	-8956.94	1.29	-63.8	19.5	176.7	0.0
MODE 21	435.8	384542.	-213.4	10720.82	-8956.94	1.29	-63.8	19.5	176.7	0.0
YAW Init	435.8	384542.	-213.4	10720.82	-8956.94	1.29	-63.8	19.5	176.7	0.0
MODE 22	457.0	378678.	-367.0	10817.22	-9000.88	1.53	-66.4	1.6	131.9	0.0
Roll Init	457.0	378678.	-367.0	10817.22	-9000.88	1.53	-66.4	1.6	131.9	0.0
Roll End	478.1	368064.	-661.0	10976.46	-9006.95	2.10	66.2	16.2	-38.8	0.0
MODE 23	480.0	366769.	-689.0	11000.42	-9016.89	2.18	66.6	14.7	-39.6	0.0
MODE 24	550.9	284920.	-1534.7	11908.07	-9312.04	22.62	67.6	-1.0	2.9	0.7
Pitchdown	550.9	284920.	-1534.7	11908.07	-9312.04	22.62	67.6	-1.0	2.9	0.7
MECO	554.2	279714.	-1557.8	11965.26	-9361.71	26.85	65.1	-1.0	0.3	0.9
Engine 3 Out	554.4	279464.	-1561.0	11968.03	-9367.99	27.44	64.8	-1.0	0.2	0.9
ET SEP	559.9	270609.	-1677.2	12001.30	-9379.39	34.90	48.5	0.1	-1.9	1.4

Appendix G: Entry Simulation Summary

```
==================================================================================================================================
| Data Set:  /fads/fd8d/dsc/analysis/ecal/2EO_JAVASET.txt          Atmos File: N/A                                               |
| Traj File: raj/BEN36_FMH32_inplane_2_160_1_420_200.entry.mgdf  Wind File:  N/A                                                 |
|================================================================================================================================|
|   ||   FLAGS & I-LOADS     |          MASS PROPERTIES          |        ENVIRONMENTAL MODEL FLAGS       |    LANDING SITE DATA     |
|   ||   ---------------     |          ---------------          |        -------------------------       |    -----------------     |
|   || FSW    = OI28         | ETSEP WT = 247181 lb              | ATMOS    = 62Standard                  | RWY-ID  =      FMH32     |
|   || HAC    = Auto-select  | ETSEP CG = 1090.2,   0.0, 370.0 in| DESC     = 1962 Standard Reference     | RWY-AZ  =        308 deg |
| I || APPCH  = Auto-select  | M3.5 Iyy = 7500000 slug-ft^2      | ALT_BIAS=  -83.4 ft                    | RWY-HD  =        -83 ft  |
| N || AIMPT  = Nominal      |===================================|                                        | RWY-LATD=   41.6516 deg  |
| P || NAV    = Off          |          PROPELLANT DUMPS         | WIND     = None                        | RWY-LONG=  -70.5109 deg  |
| U ||                       |          ----------------         |                                        |==========================|
| T || GAMSGS=    -18 deg    | Fwd RCS Duration         =   0 sec|                                        |                          |
|   || WRTLS =   7397 slugs  | Aft RCS Duration         = 130 sec|                                        |  INITIAL RANGE TO RUNWAY |
|   || DNZMAX=  3.90 g       | MPS LO2 8" F&D Delay     =  20 sec|                                        | ------------------------ |
|   || ALPRCU=  58.0 deg     | MPS LH2 8" F&D Delay     =   0 sec|                                        | Flat-Earth Range= 435.5 nm|
|   || CASTRT= EO2           | OMS Dump Mode            =   1    | VEHICLE =     103                      | Geocentric Range= 408.1 nm|
|================================================================================================================================|
|                                                                                                                                |
|IPH  TIME   RPRED     VE       HD     QBAR  LFCGZ     HDOT GAMMAE  ALPHA  ROLLC  DPSAC   PSIE      LATD      LONG PSHA S S M    |
|(nd) (sec)   (nm)  (fps)     (ft)    (psf)    (g)    (fps)  (deg)  (deg)  (deg)  (deg)  (deg)     (deg)     (deg)(deg) T I P   |
|--------------------------------------------------------------------------------------------------------------------------------|
|      0.00   435.5  11130   270609      1.5  0.025  -1681.4   -8.8   48.5    0.0  -25.4   42.0   35.4504  -72.8410  290 R        |
| 6    5.28   430.7  11151   261405      2.5  0.035  -1805.4   -9.5   34.3    0.0  -26.0   42.1   35.5674  -72.7118  291 R        |
| 6   30.00   429.0  11183   209914     22.8  0.444  -2324.2  -12.1   57.6    0.0  -29.2   42.7   36.1126  -72.1009  294 R        |
| 5   51.36   426.5  10587   159050    134.5  2.621  -2283.5  -12.6   57.9  -20.0  -32.4   42.7   36.5705  -71.5771  297 R        |
| 5   60.00   394.1   9951   140917    250.5  3.409  -1867.3  -11.0   41.7  -20.0  -33.1   41.9   36.7456  -71.3793  299 R        |
| 4   84.96   324.6   8632   114555    617.3  3.249   -295.8   -2.1   22.5  -70.0  -32.8   37.2   37.2249  -70.8786  303 R        |
| 4   90.00   308.1   8404   113418    617.4  3.100   -179.2   -1.4   21.9  -68.7  -31.2   34.7   37.3197  -70.7924  304 R        |
| 4  120.00   249.7   6999   115320    391.6  1.894    355.2    2.7   20.7  -42.6  -19.3   19.2   37.8801  -70.4387  308 R        |
| 4  150.00   217.4   6394   126473    195.5  0.914    306.5    2.6   19.8  -35.7  -16.2   13.6   38.4036  -70.2480  310 R        |
| 4  180.00   187.1   6031   130714    143.8  0.683    -47.6   -0.6   19.8  -34.3  -15.6   10.5   38.9000  -70.1139  313 R        |
| 4  210.00   159.2   5593   124652    162.4  1.490   -250.0   -2.7   30.5  -28.9  -14.5    6.6   39.3731  -70.0200  316 R        |
| 4  240.00   134.6   4424   122188    113.7  1.696     86.8    0.9   41.5  -25.0  -11.3    0.7   39.7859  -69.9857  319 R        |
| 4  270.00   115.0   3780   123420     78.5  0.733    -90.0   -1.6   28.6  -21.2   -9.8   -2.9   40.1165  -69.9947  321 R        |
| 4  300.00    96.9   3507   115005     99.7  0.716   -463.4   -7.8   23.4  -17.2   -9.2   -5.5   40.4120  -70.0228  323 R        |
| 4  330.00    80.6   3250    97780    193.7  1.057   -626.9  -11.3   18.9  -14.0   -8.2   -8.8   40.6833  -70.0665  325 R        |
| 1  334.56    78.1   3200    94933    214.6  1.107   -620.3  -11.4   18.0  -19.8   -7.9   -9.4   40.7222  -70.0747  325 R        |
| 1  335.52    77.6   3189    94339    219.2  1.125   -618.3  -11.4   17.9  -19.6   -7.9   -9.5   40.7303  -70.0765  325 R        |
| 1  360.00    66.0   2777    81459    306.8  1.318   -352.5   -7.5   14.8  -10.9   -4.4  -14.7   40.9241  -70.1306  327 R        |
| 1  390.00    53.7   2225    74872    270.6  1.071   -111.6   -3.1   12.1   -4.8   -1.9  -18.2   41.1201  -70.2075  328 R        |
| 1  420.00    43.5   1810    70157    225.5  0.935   -210.9   -6.9   11.0   -2.7   -1.1  -19.6   41.2755  -70.2780  329 R        |
| 1  450.00    35.6   1455    63039    205.8  0.914   -263.9  -10.6    9.7   -1.4   -0.6  -20.6   41.3995  -70.3383  329 R        |
| 1  480.00    29.4   1180    54360    204.9  0.964   -301.3  -15.0    8.4   -0.8   -0.3  -21.2   41.4976  -70.3881  329 R        |
| 2  501.60    25.5   1011    48010    203.6  0.972   -284.5  -16.5    7.8    7.1   -0.4  -21.6   41.5556  -70.4184  330 R        |
| 2  510.00    24.3    957    45610    204.6  1.053   -290.7  -17.9    8.5   32.7  -12.2  -17.0   41.5759  -70.4283  338 R        |
| 2  540.00    20.2    783    37320    203.7  1.349   -252.4  -19.0   11.0   38.6   -7.9   41.7   41.6386  -70.4138  274 R        |
| 2  570.00    16.7    716    30371    224.6  1.275   -217.9  -17.7    9.4   38.5   -7.0  103.8   41.6557  -70.3434  212 R        |
| 2  600.00    13.4    673    23970    249.5  1.266   -210.2  -18.0    8.4   38.8   -5.5  169.8   41.6188  -70.2960  145 R        |
| 2  630.00    10.3    634    17831    273.1  1.241   -199.6  -18.3    7.6   38.0   -3.2 -121.3   41.5749  -70.3217   74 R        |
| 3  651.36     8.2    608    13638    287.8  1.222   -192.3  -18.5    7.1   31.5   -1.0  -71.8   41.5710  -70.3659   21 R        |
| 3  660.00     7.3    599    12023    294.2  1.041   -183.5  -18.0    6.0   15.8    1.1  -57.3   41.5770  -70.3821    9 R        |
| 3  671.52     6.3    591     9894    306.4  0.987   -185.3  -18.4    5.4    1.2    1.1  -51.9   41.5876  -70.4013    9 R        |
|                                    ***** Nominal Approach & Landing Interface *****                                            |
====================================================== Page 1 of 2 ==============================================================
```

```
=====================================================================================================================================
|                                                  ETSEP & MM602 STATE VECTORS                                                      |
|                                          --------------------------------------------                                             |
|   EVENT        TIME    RPRED    LATD       LONG       HD      VE     PSIE    GAMME   ALPHA  ROLL   BETA     P       Q       R     |
|               (sec)    (nm)     (deg)      (deg)     (ft)    (fps)   (deg)    (deg)   (deg) (deg)  (deg) (deg/s) (deg/s) (deg/s)  |
|-----------------------------------------------------------------------------------------------------------------------------------|
| ETSEP Init      0.00   435.5    35.4504  -72.8410   270609  11130      42.0    -8.8   48.5  -2.4    0.1     0.0    -3.1    0.0    |
| MM602 Init      5.28   430.7    35.5674  -72.7118   261405  11151      42.1    -9.5   34.3  -0.8    0.3     0.1    -1.1    0.0    |
|===================================================================================================================================|
|                            PERFORMANCE SUMMARY                             |                  MASS PROPERTIES                     |
|                           ---------------------                            |                 -----------------                    |
|                                  VALUE  IPHASE TIME   RPRED   VE    HEG    |                                  WT (lb) CGX (in)    |
|                                          (nd)  (sec)  (nm)   (fps)  (ft)   | ETSEP Initiation                 247181   1090.2     |
|OVERALL---------------------------------------------------------------------| MM602 Initiation                 247043   1090.3     |
|  Max |HDOT|  (1st peak)    -fps  -2419     6    41.04  438.8 11032  183661   | TAEM Interface (Mach=3.2)       240993   1081.8     |
|  Max |HDOT|  (2nd peak)    -fps   -269     4   203.76  165.3  5734  126376   | A&L Interface                    240993   1081.8     |
|  Max QBAR    (1st peak)    -psf    619     4    87.36  317.9  8522  114026   |======================================================|
|  Max QBAR    (2nd peak)    -psf    163     4   212.88  156.6  5513  124044   |              PROPELLANT DUMP SUMMARY                 |
|  Max |LFCGZ| (1st peak)    -g    -3.42     5    60.96  390.8  9885  139237   |             -------------------------                |
|  Max |LFCGZ| (2nd peak)    -g    -3.32     4   103.20  274.1  7772  112194   |DUMP TYPE    START TIME   END HD   END VE   DUMP WT   |
|DURING ETSEP & PULLOUT PHASES-----------------------------------------------|                (sec)      (ft)     (fps)     (lb)    |
|  Max ALPHA                 -deg   58.0     6    21.12  425.1 11203  229961   |Fwd RCS           5.28   261405     11151    -9999    |
|  Max NZC                   -g     2.29     5    84.00  327.9  8677  114942   |Aft RCS          25.44   128025      6317     1618    |
|  Max |DPSAC|               -deg  -33.5     5    76.32  348.3  9041  119222   |MPS LH2           0.00   233995     11202      304    |
|  Max |ROLL|                -deg    -66     4    93.60  296.5  8241  112932   |MPS LO2           5.28   131591      9599     3870    |
|DURING TAEM PHASES----------------------------------------------------------|OMS OME           5.28   261405     11151        0    |
|  Max |HDOT|                -fps   -618     1   335.52   77.6  3189   94422   |======================================================|
|  Max QBAR                  -psf    313     1   367.20   62.5  2651   79211   |               NOMINAL A&L INTERFACE                  |
|  Max |LFCGZ|               -g    -1.80     1   353.28   69.1  2914   84216   |              -----------------------                 |
|  Min HAC RF                -ft           <<<<<<<<< No HAC shrink >>>>>>>>>>|                 VALUE       ERROR       |LIMIT|      |
|============================================================================|  HEG     -ft     9964    -58 (high)        993       |
|       BALLISTIC MAX HD        |           MAXIMUM HINGE MOMENTS            |  Y       -ft      -62    -62 (left)        993       |
|      ------------------       |          ------------------------          |  GAMMAE -deg    -18.3   -0.3 (shallow)     4.0       |
|   Time         -sec  -53.05   |  CONTROL SURFACE   DEF    HM      LIMIT    |  QBARF  -psf      306     -1 (high)         24       |
|   HD           -ft   315887   |                   (deg) (in-lbf) (in-lbf)  |======================================================|
|   VE           -fps   10998   |  Inboard Elevon    -4.3 -762357  1260000   |                  ENERGY SUMMARY                      |
|===============================|  Outboard Elevon    0.7 -358128   600000   |                 ----------------                     |
|      LOAD FACTOR LIMITS       |  Bodyflap           7.1 -960120  1560000   |  Minimum Delta RPRED To:   S-Turn  =       5.2 nm    |
|      ------------------       |  Speedbrake        64.8  950641  1230000   |                         MEP Alert  =     -56.4 nm    |
|   @ Max LF (1st) -g    2.19   |                                            |                       St-In Alert  =     -59.0 nm    |
|   @ Max LF (2nd) -g    2.20   |                                            |  Integrated EOW Error During TAEM  =       1.2 nm    |
=========================================================== Page 2 of 2 =============================================================
```

```
=======================================================================================
|                       ECAL TRAJECTORY PERFORMANCE EVALUATION                        |
|-------------------------------------------------------------------------------------|
| Condition                                                                           |
| VI                       12.0 kfps                                                  |
| Runway                   FMH32                                                      |
| Status                   GO                                                         |
| Sim Termination          Nominal A&L Interface                                      |
| S-Turn                   No                                                         |
| Straight-In Downmode     No                                                         |
|-------------------------------------------------------------------------------------|
|                           VALUE  CAUTION LIMIT  WARNING LIMIT  UNITS       STATUS   |
| ETSEP Weight             247181                210000/270000  lbm                  |
| ETSEP CGx                1090.2                1076.0/1124.0  in                   |
| Range at HD 70k            43.3    30.0/  50.0    28.0/  54.0  nm                   |
| QBAR at HD 70k              225     100/   800            850  psf                  |
| Max ALPHA                    58             65             70  deg                  |
| Max |ROLL|                  -66             80             90  deg                  |
| Max |DPSAC|                 -12            100            120  deg                  |
| Max |LFCGZ| (1st peak)      3.4            3.5            3.9  g                    |
| Max |LFCGZ| (2nd peak)      3.3            3.5            3.9  g                    |
| Max |LFCGZ| (TAEM)          1.8            3.5            3.9  g                    |
| Max QBAR    (1st peak)      619            800            850  psf                  |
| Max QBAR    (2nd peak)      163            800            850  psf                  |
| Max QBAR    (TAEM)          313            800            850  psf                  |
| Max |HM Bodyflap|         -0.96           1.56           1.72  10^6 in-lb           |
| Max |HM Elevon Inbd|      -0.76           1.26           1.39  10^6 in-lb           |
| Max |HM Elevon Outbd|     -0.36           0.60           0.70  10^6 in-lb           |
=======================================================================================
```