

# **Continuous Improvements to East Coast Abort Landings for Space Shuttle Aborts**

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Continuous Improvements to East Coast Abort Landings for Space Shuttle Aborts  
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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].

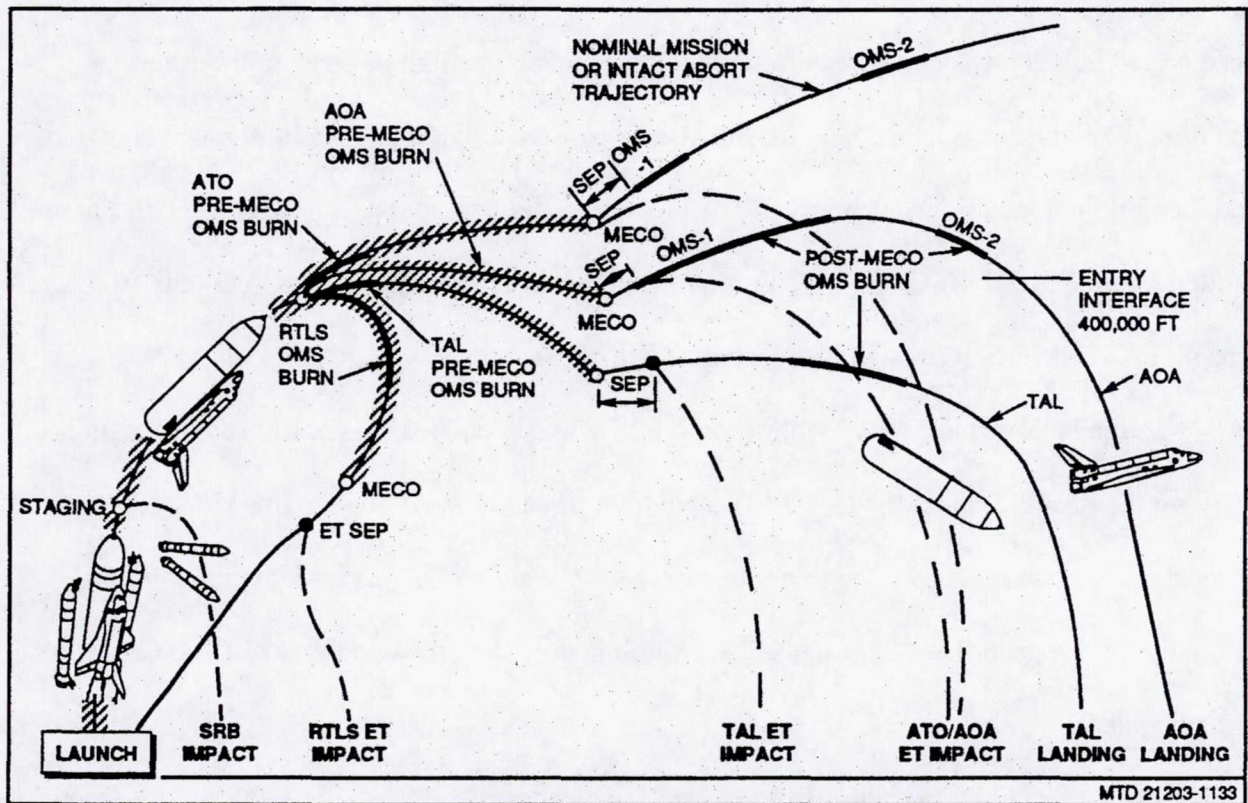


Figure 1 – Intact abort trajectory profiles.

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 tetroxide) 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.

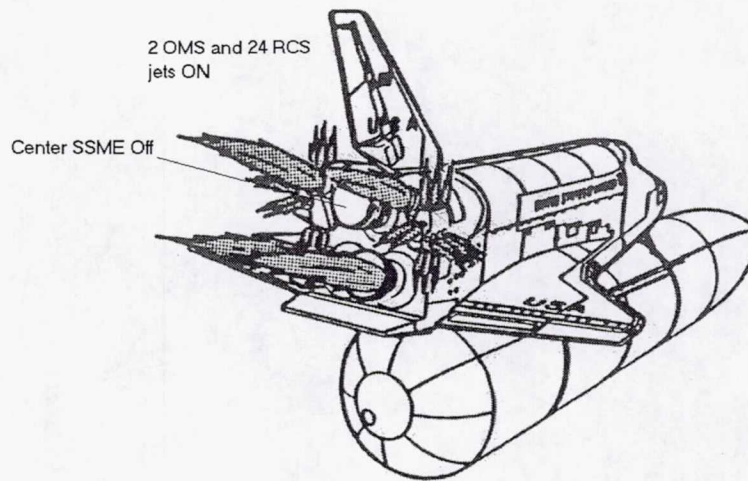


Figure 3 – OMS propellant dump.

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].

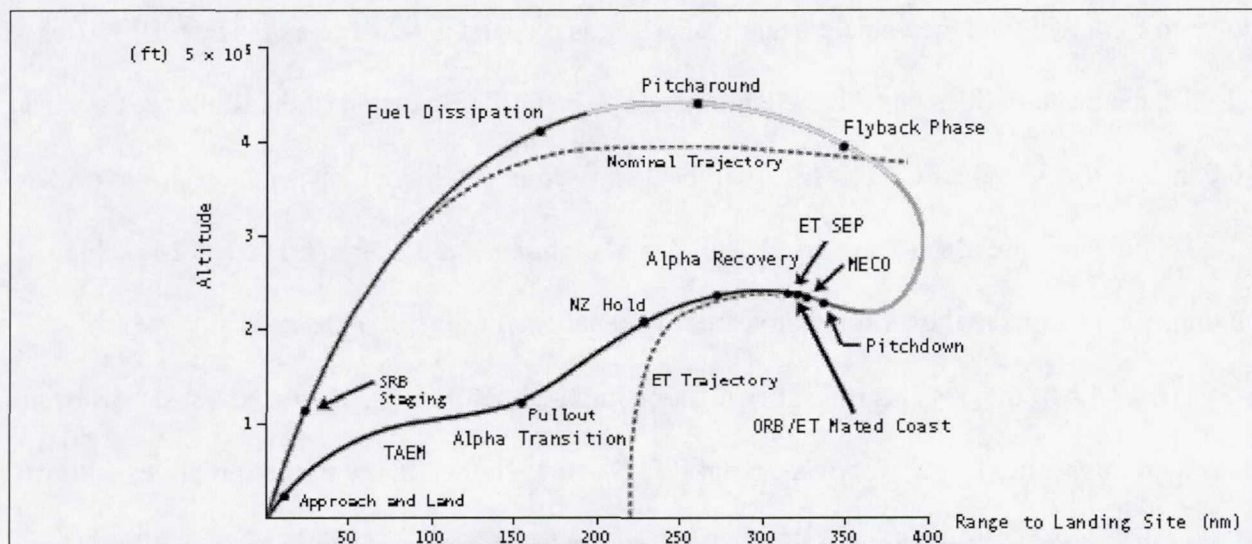


Figure 4 – RTLS trajectory profile with significant events.

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.

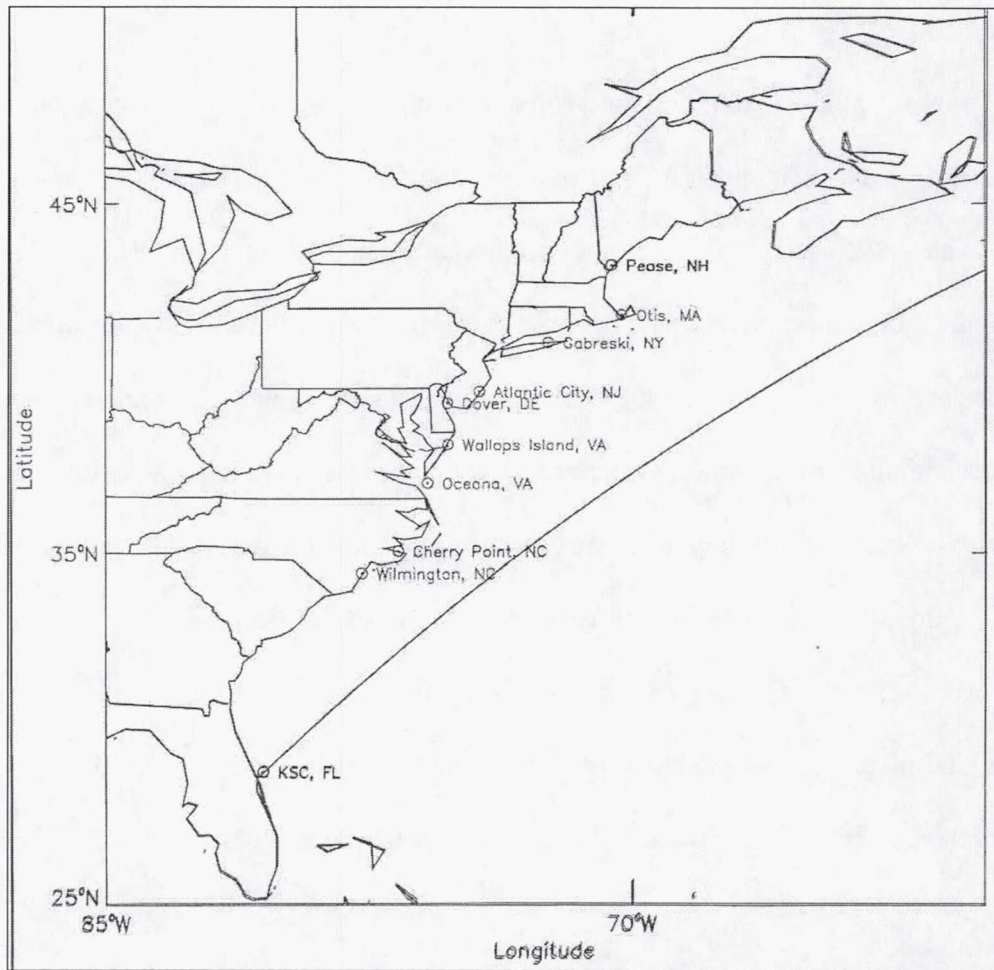


Figure 5 – East Coast Abort Landing Sites.

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.

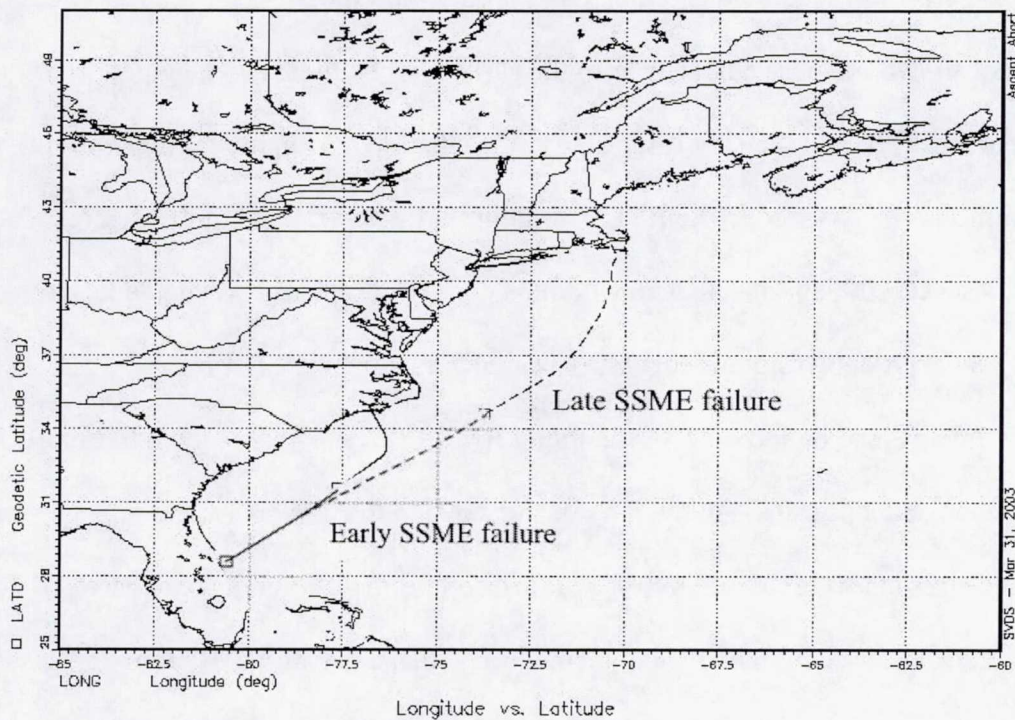


Figure 6 – ECAL groundtrack for early and late engine failures.

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.

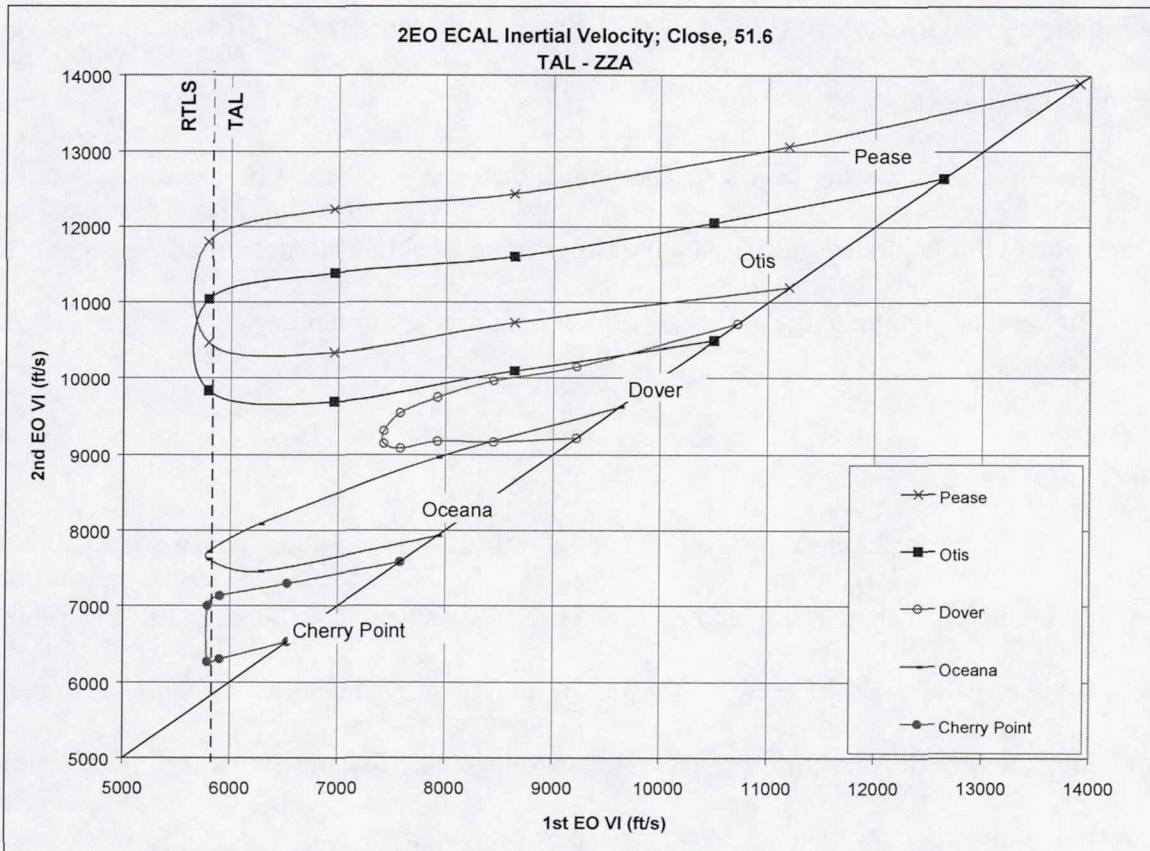


Figure 7 – ECAL boundary chart.

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 where 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,  $N_z$  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 ( $N_z$ ) on the Orbiter reaches a calculated mission and altitude rate dependant value, the  $N_z$  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  $N_z$ -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.

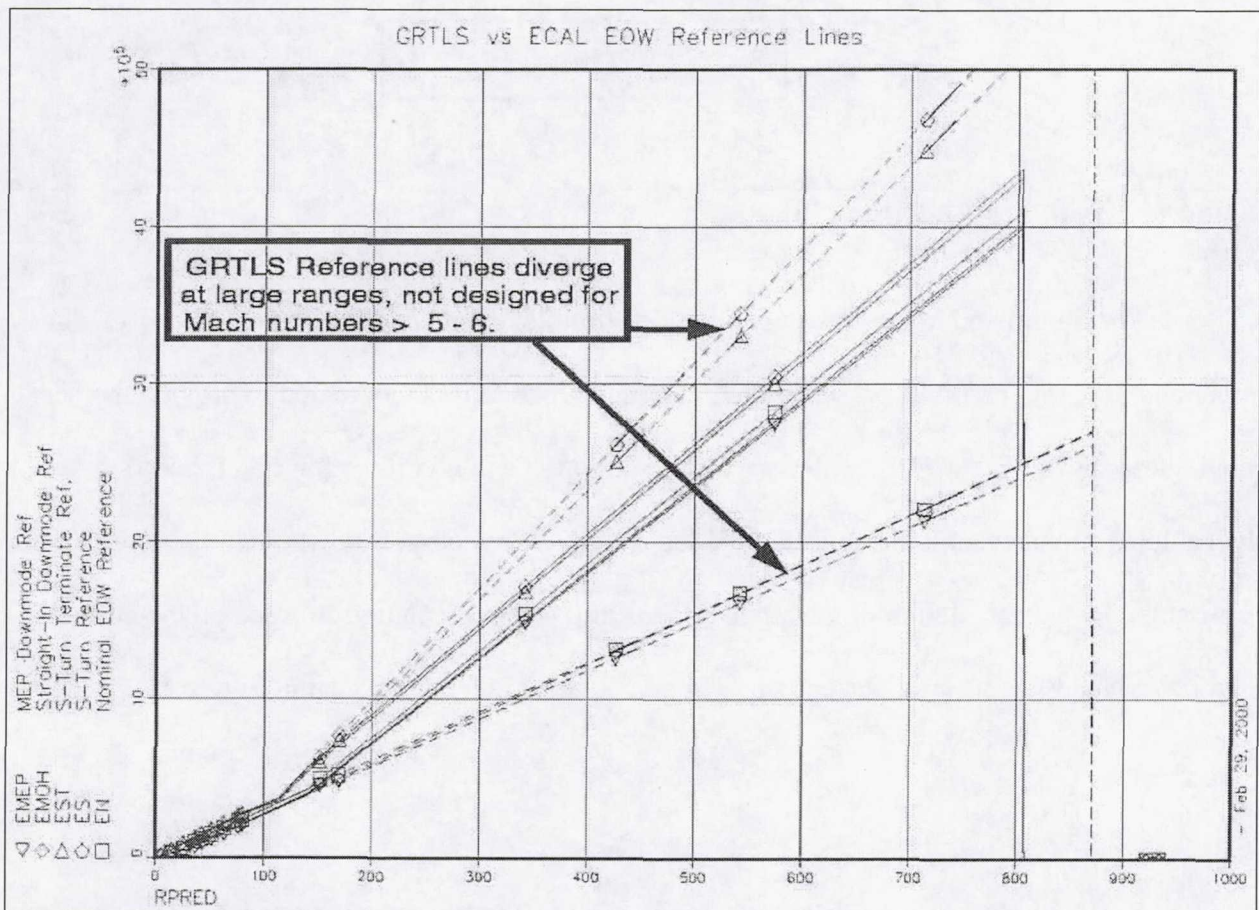


Figure 8 – Modified Energy Reference Lines for ECAL.[3]

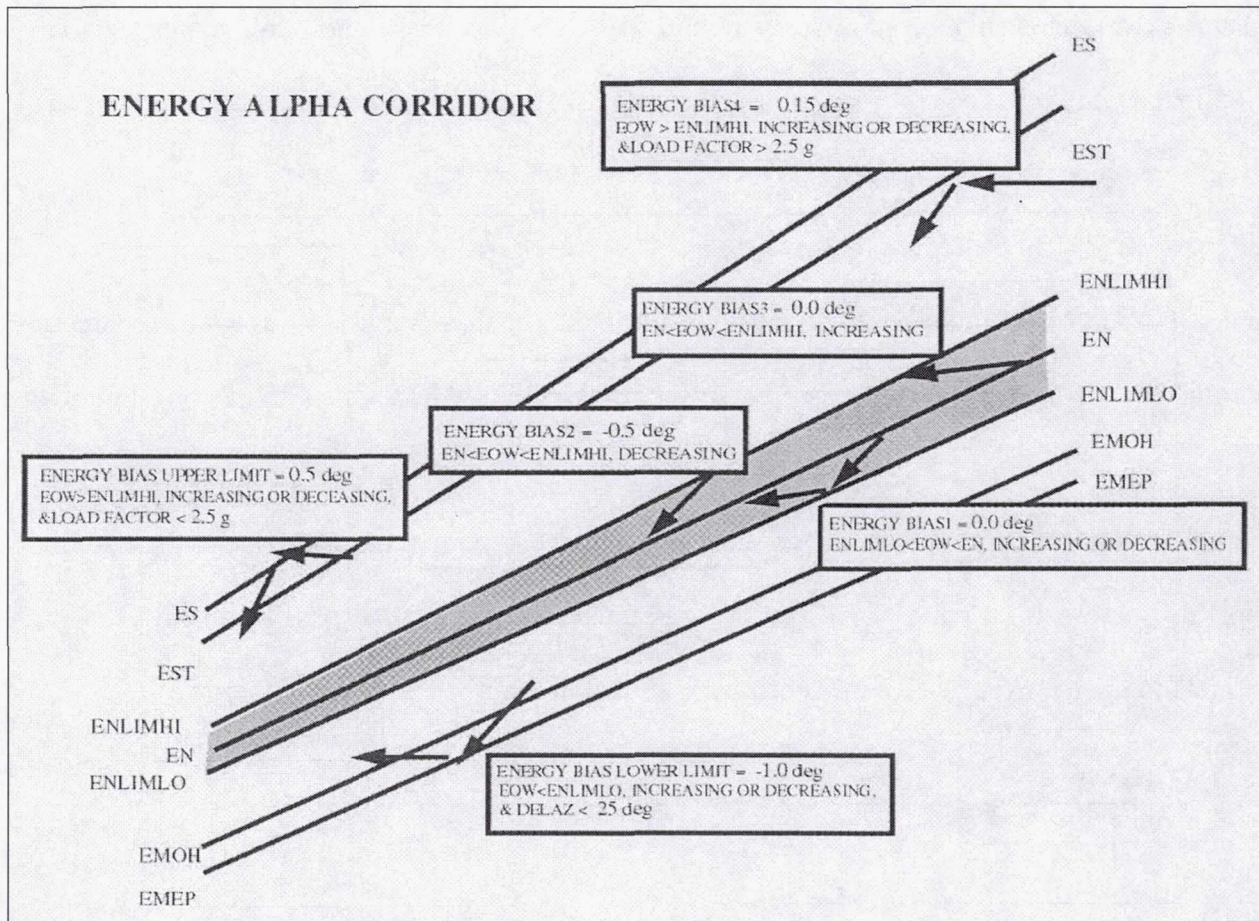


Figure 9 – ECAL Energy corridor [3].

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.



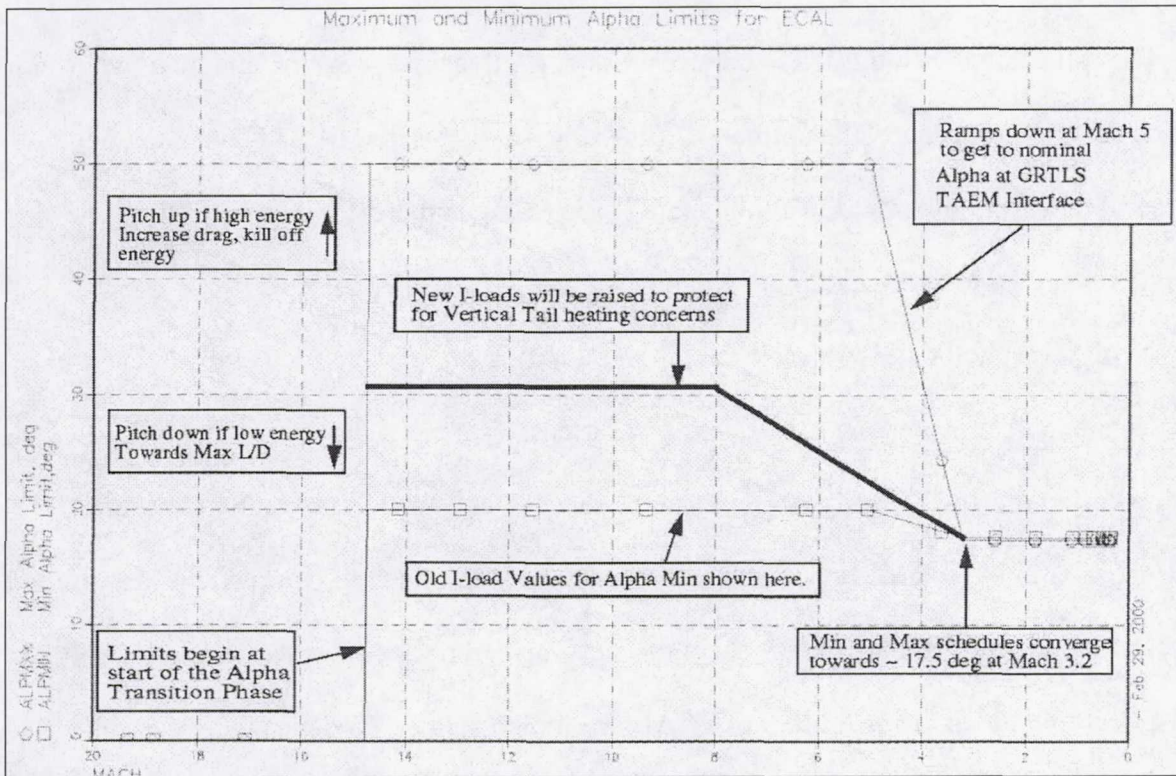


Figure 10 – Maximum and Minimum Alpha Limits [3].

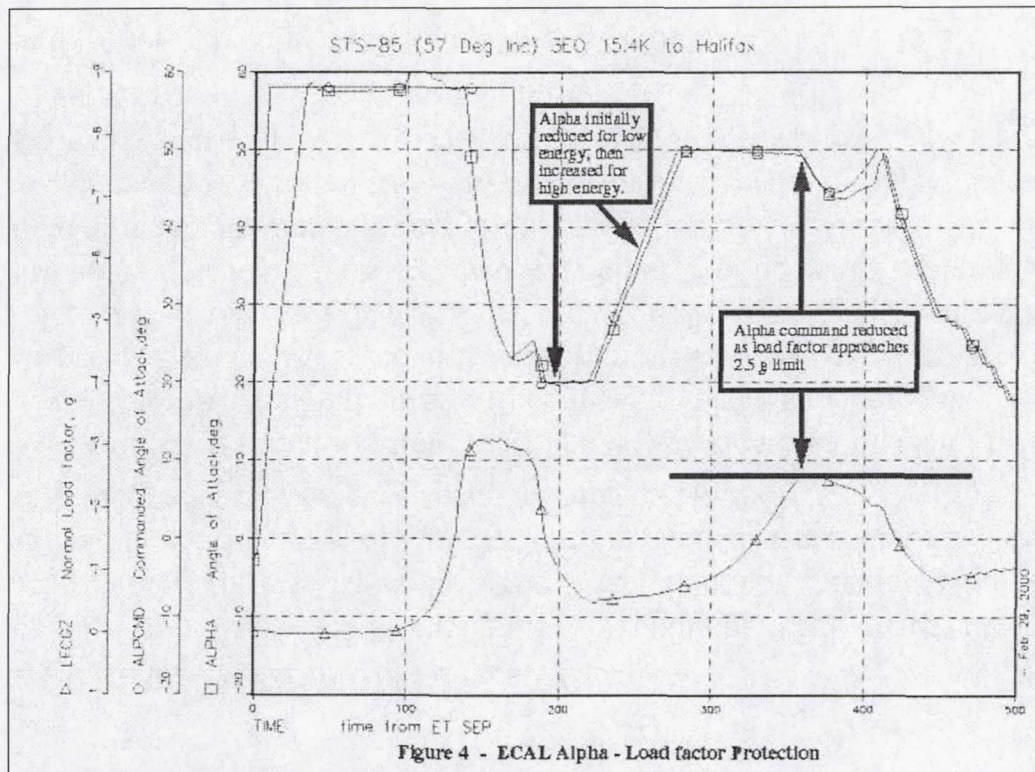


Figure 11 – ECAL Angle of Attack Limit [3].

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 than the S-turn terminate line.

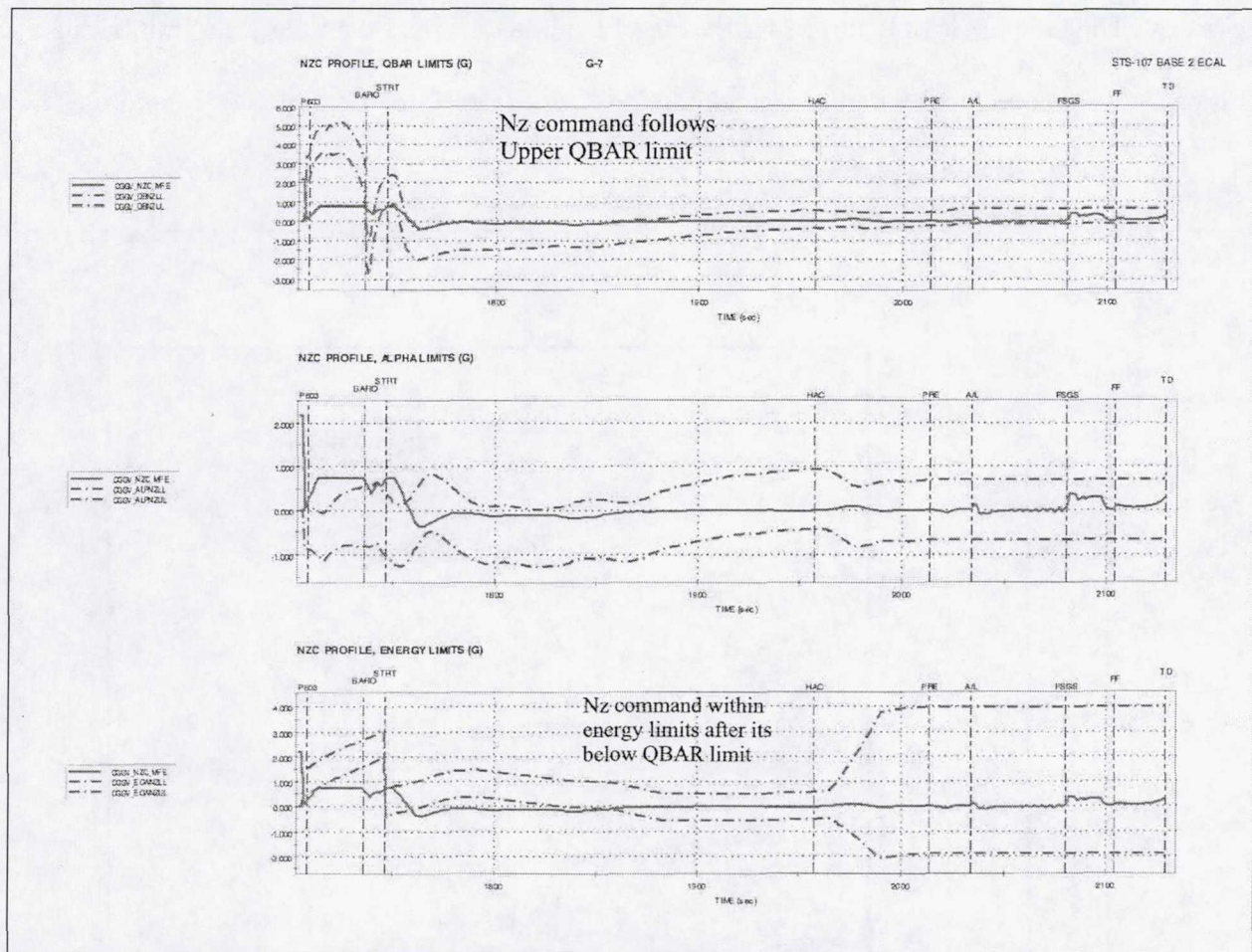


Figure 12 – Load limits protect the vehicle’s structural limits.

An addition to the ECAL automation not present in the manual crew procedure is the introduction of a roll Nzc 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.

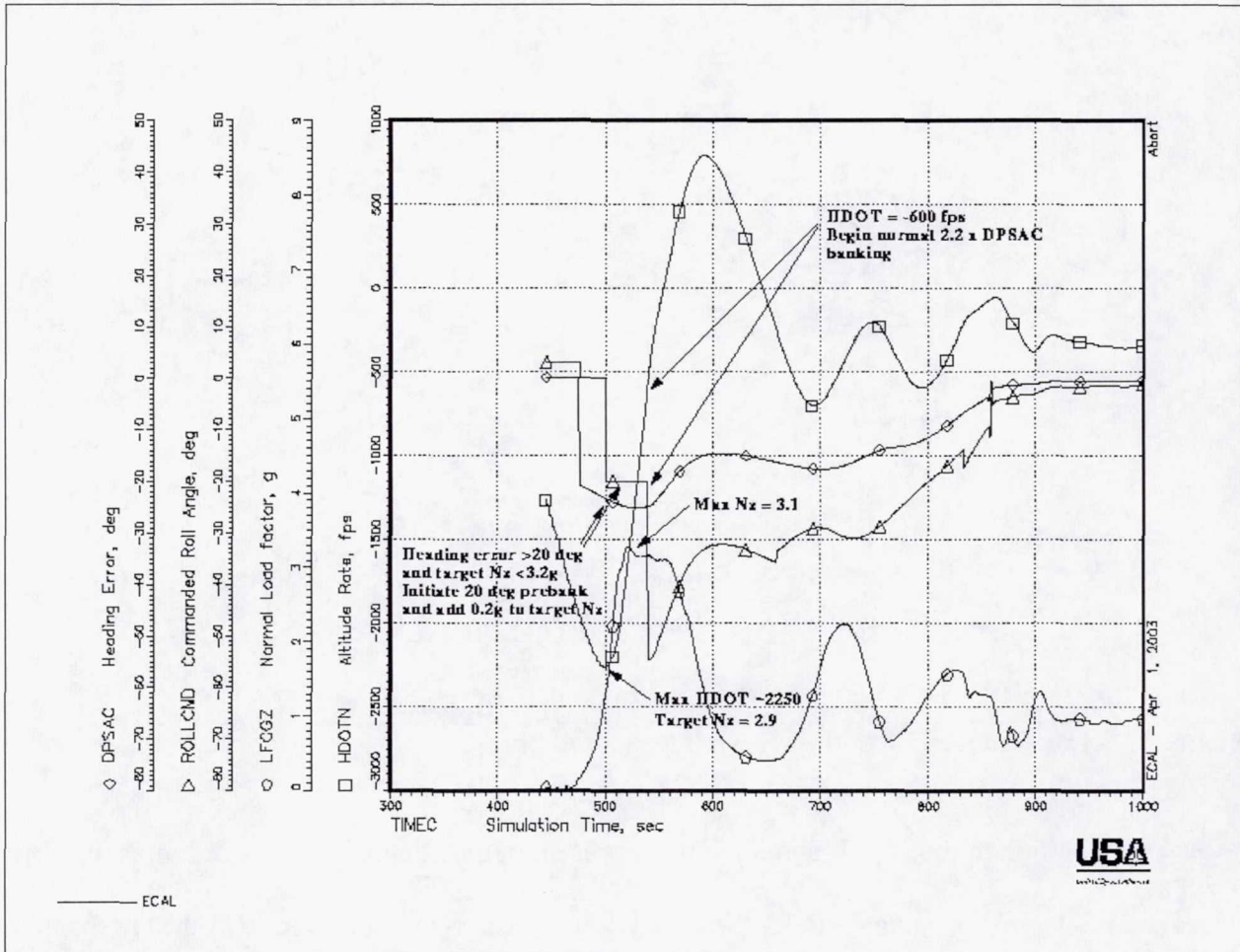


Figure 13 – ECAL prebank logic.

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.

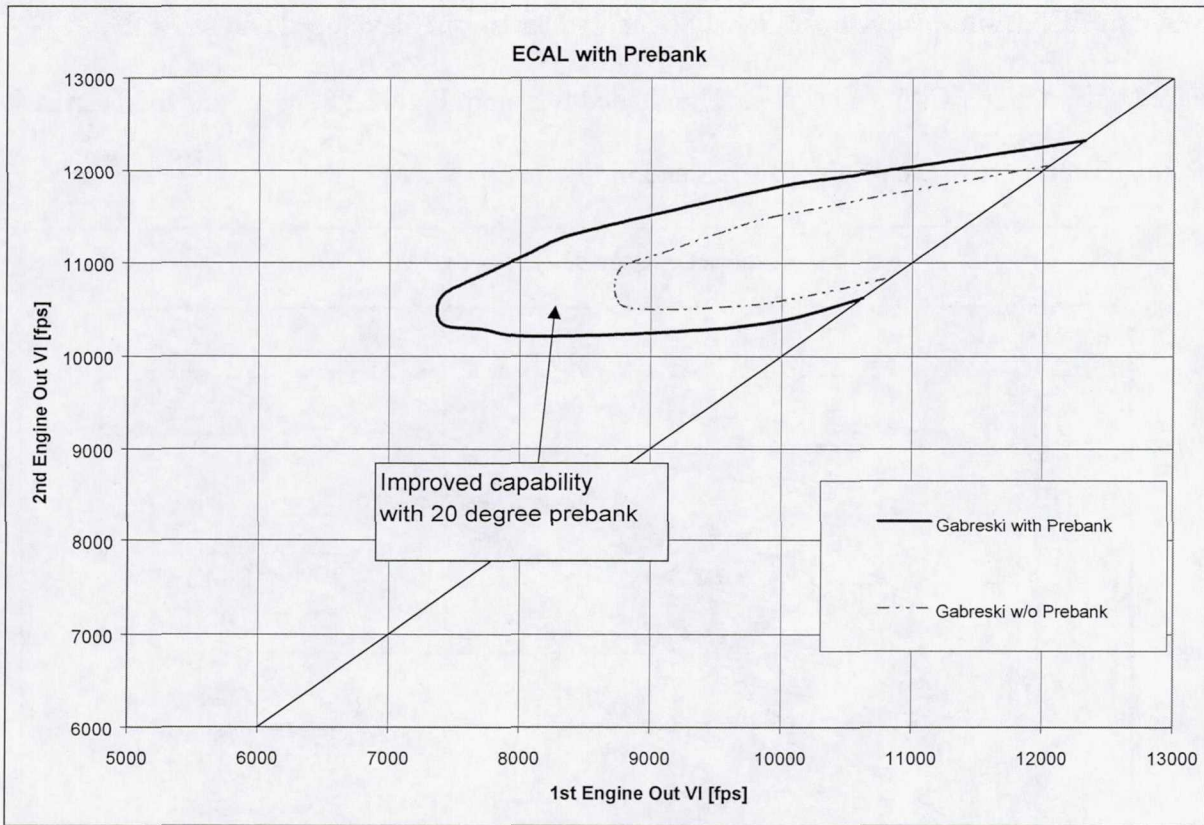


Figure 14 – ECAL capability improvement with prebank invoked.

### *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.

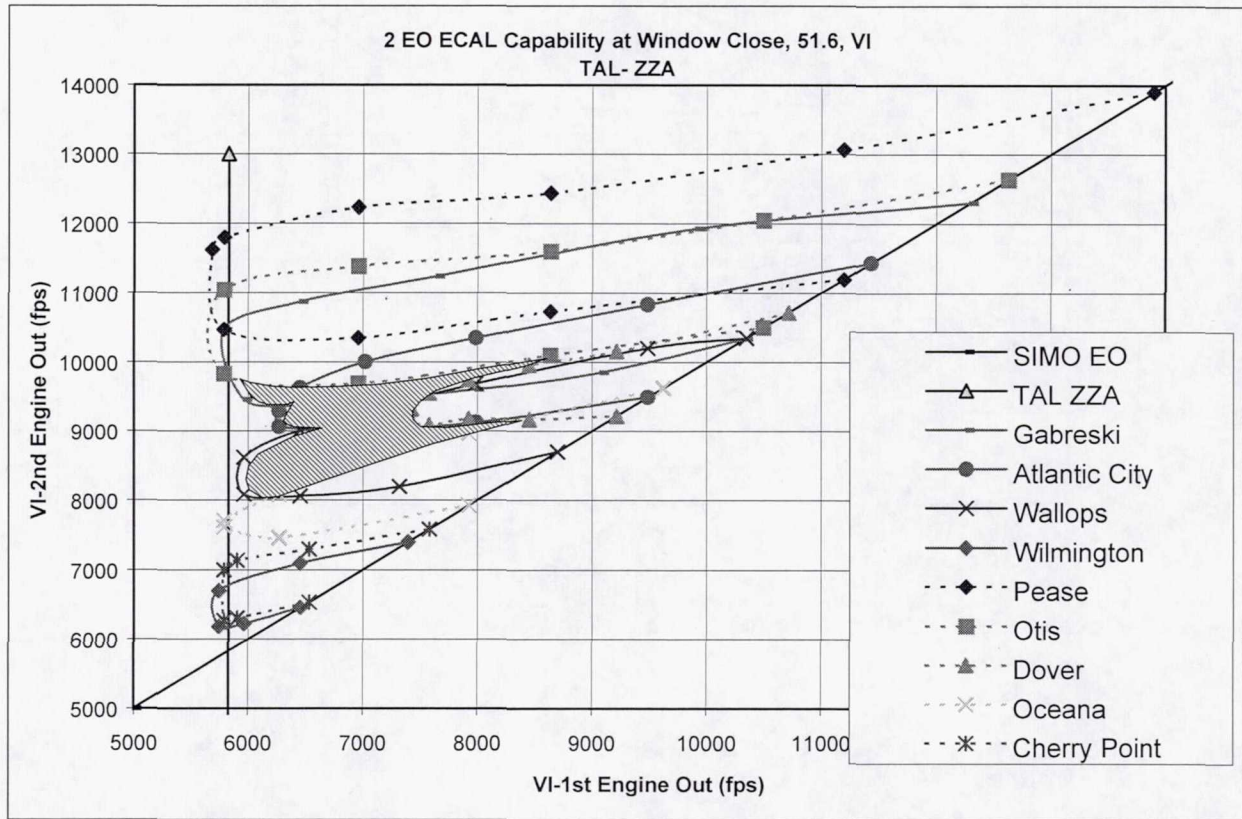


Figure 15 – New landing sites provide capability in previous gaps.

### 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.

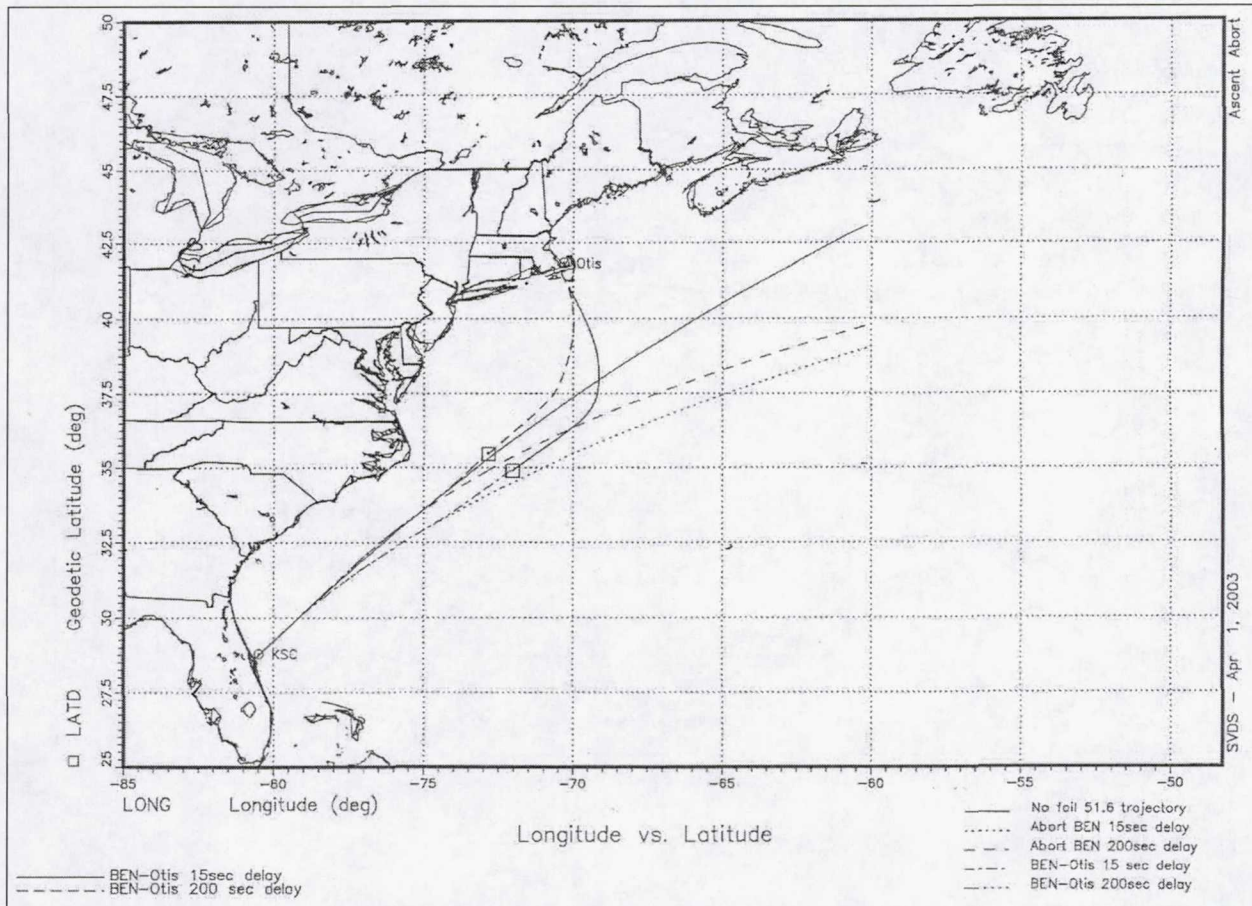


Figure 16 – Delayed TAL groundtrack compared to standard abort.

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.

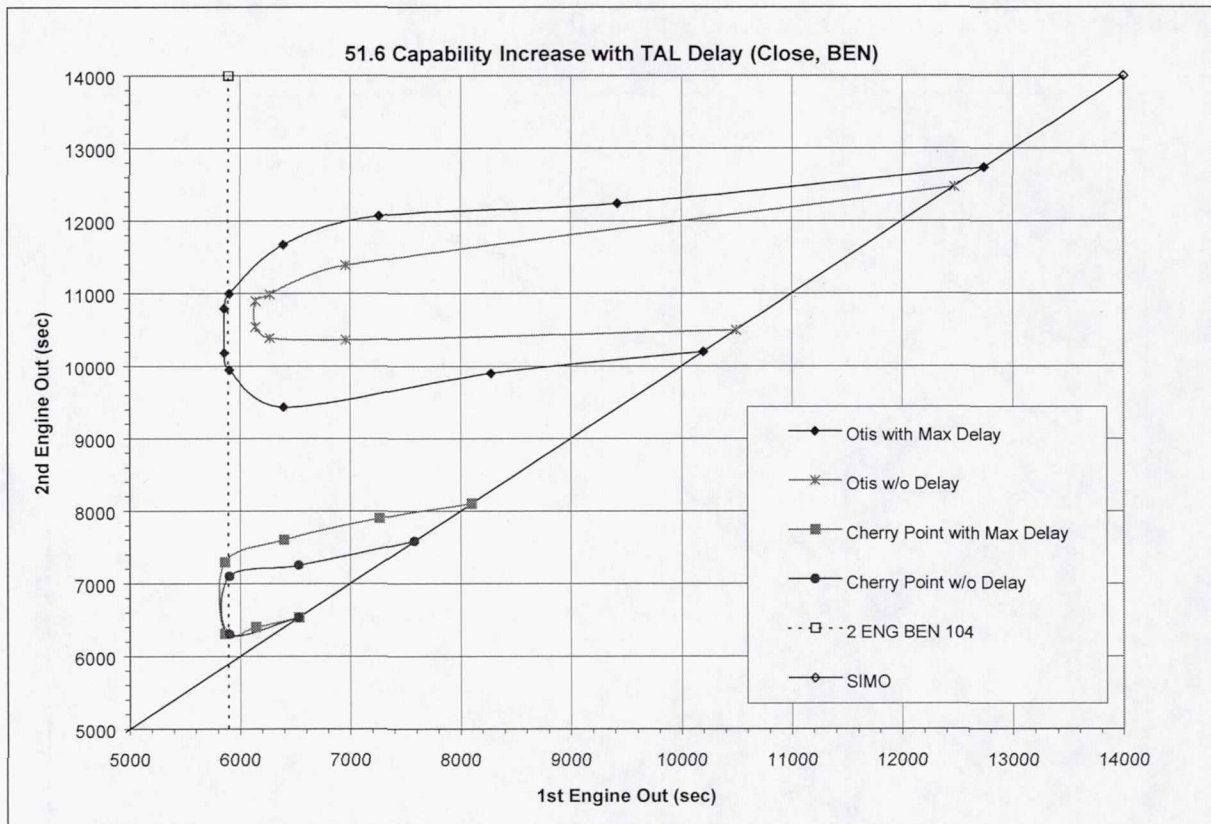


Figure 17 – Expanded ECAL capability with TAL Delay.



### 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.

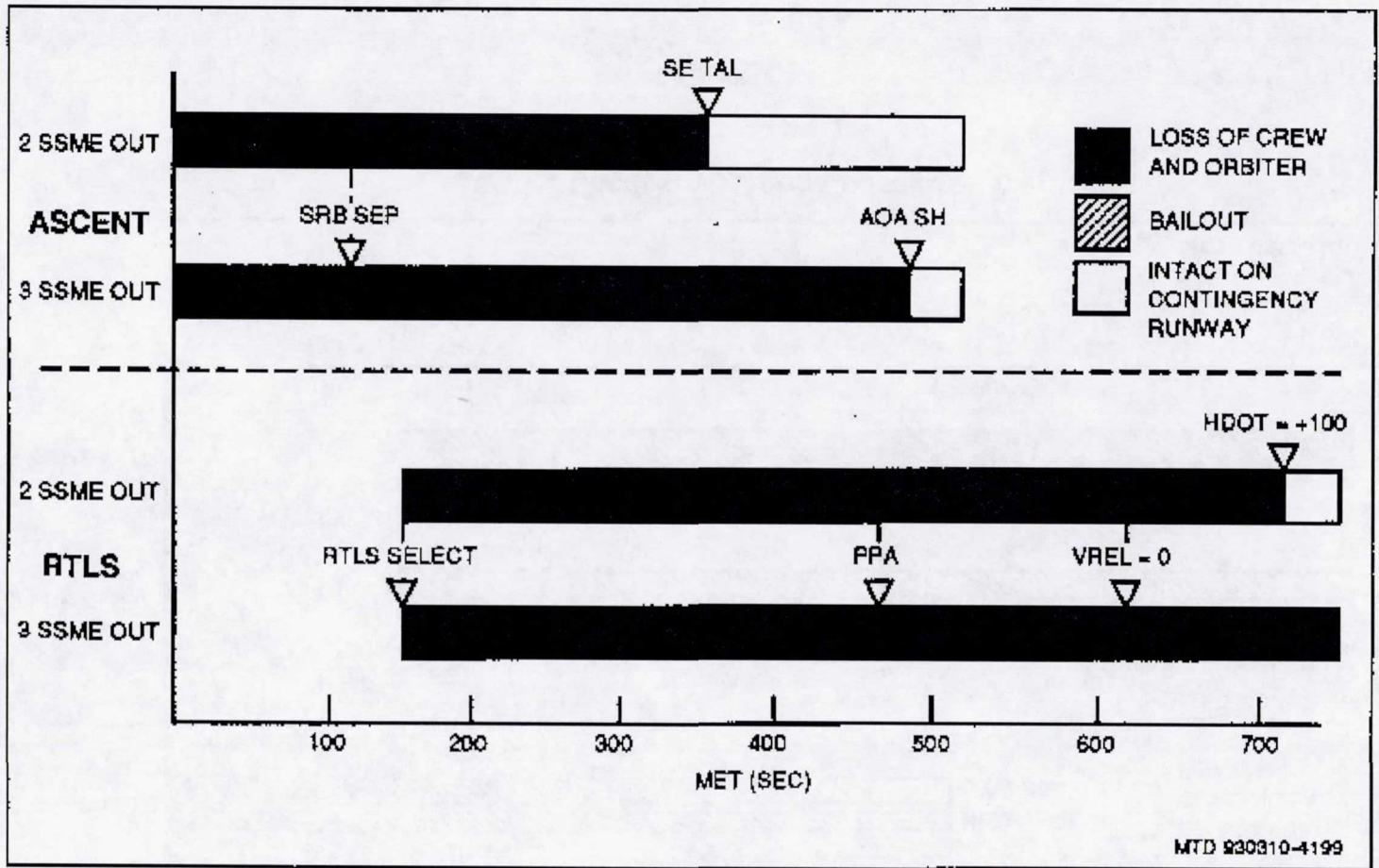
The compilation of these improvements provides almost complete coverage of ECAL capability for the later half of the launch window, as illustrated in Appendix E. The increase in coverage is an improvement in regions that previously required the crew to bailout and ditch the Space Shuttle in the ocean.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

## Bibliography

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- [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.

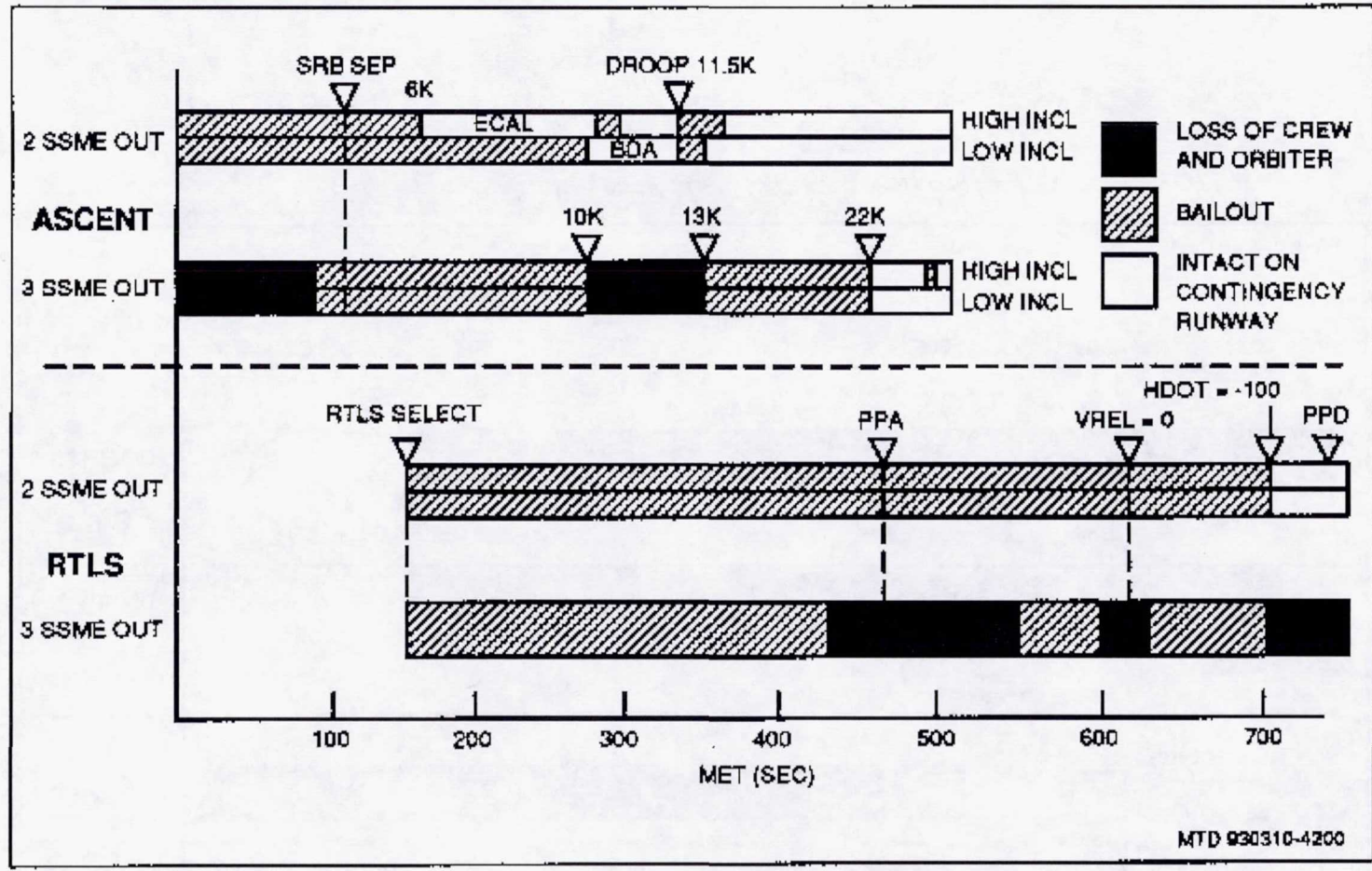
## Appendices

Appendix A: Contingency Abort Capability in 1986



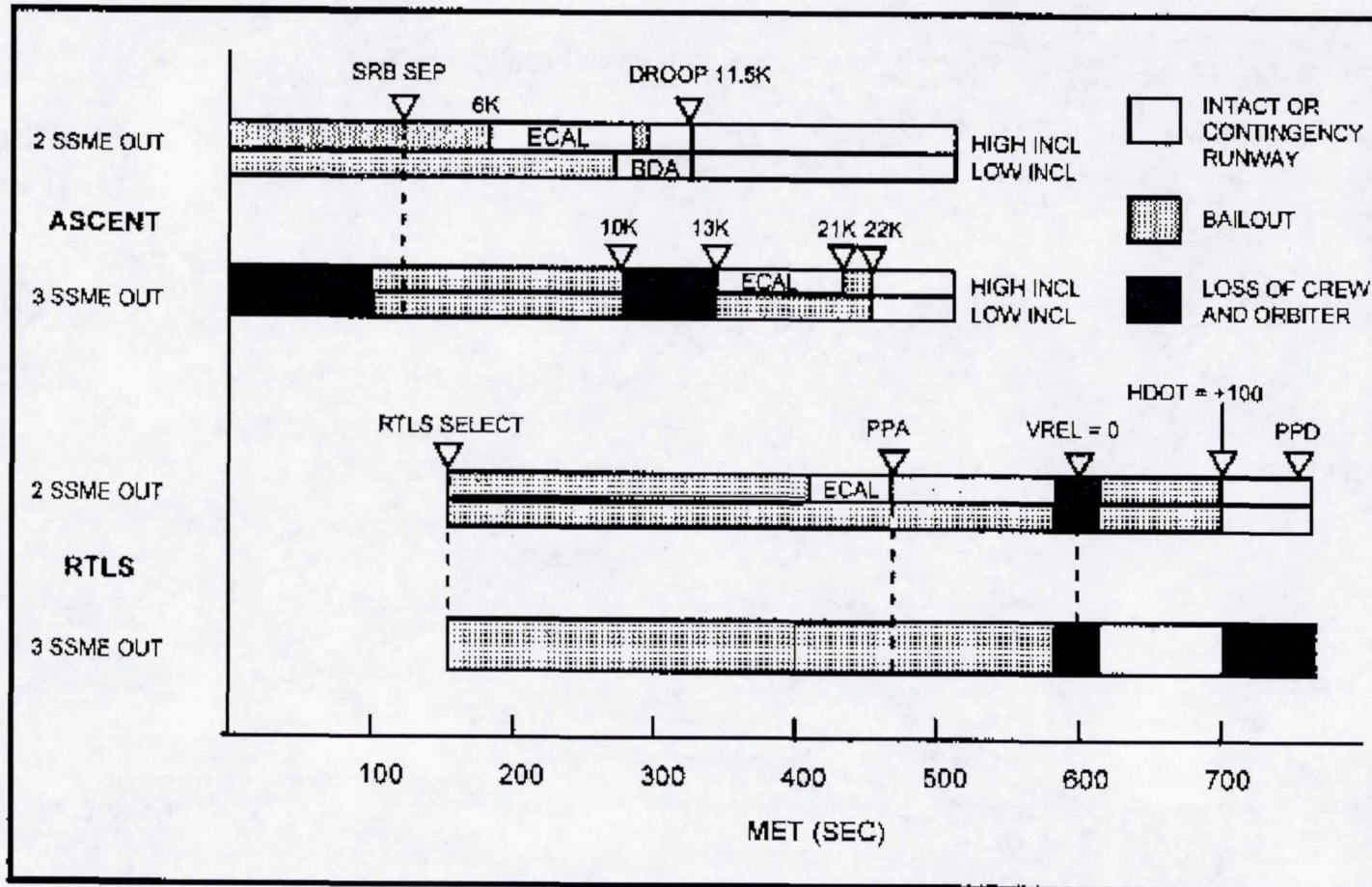
Contingency Abort Capability-STS-51L

Appendix B: Contingency Abort Capability in 1991



Contingency Abort Capability-1991

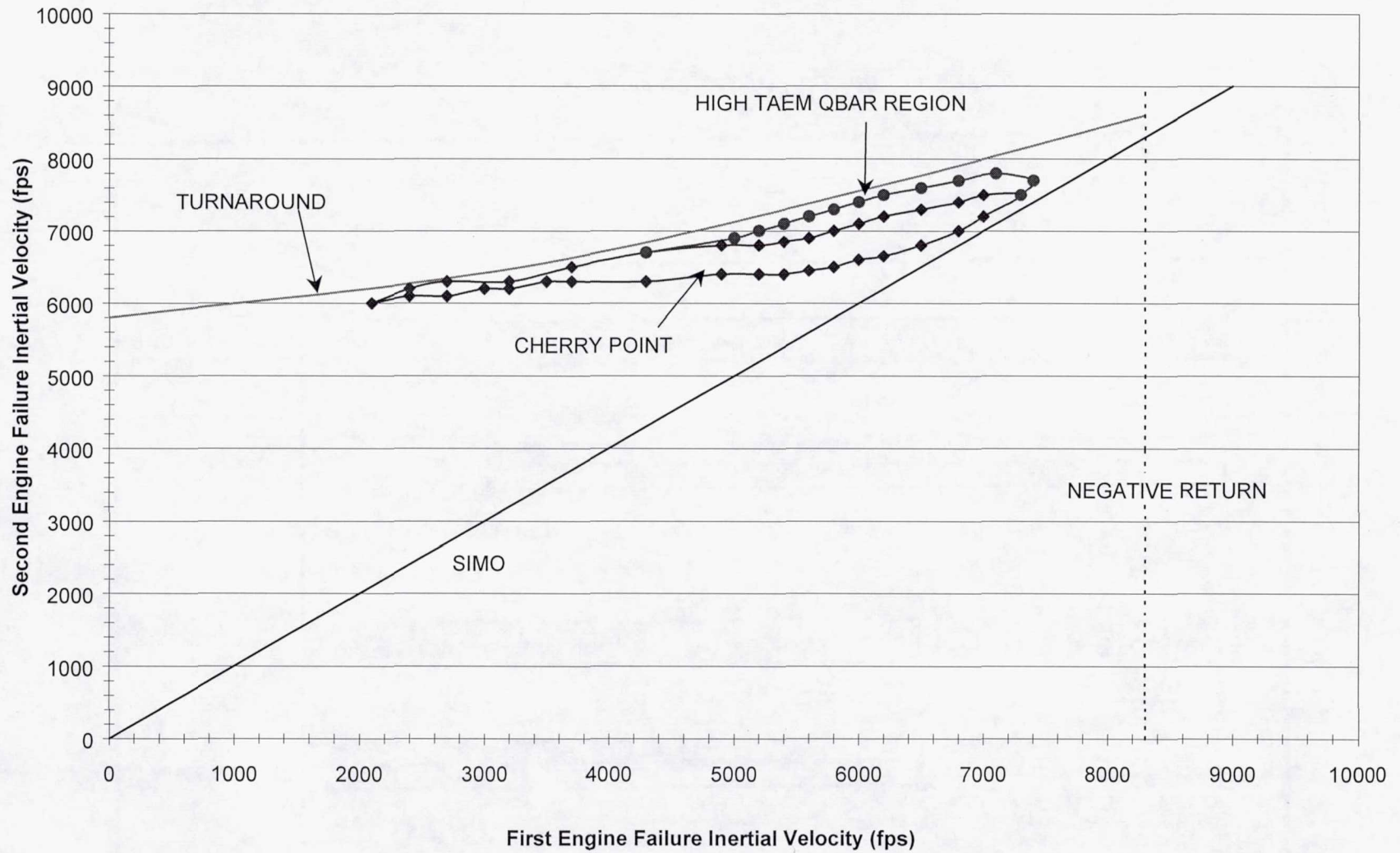
Appendix C: Contingency Abort Capability in 1998



Contingency Abort Capability - 1998

Appendix D: ECAL Capability from RTLS Abort.

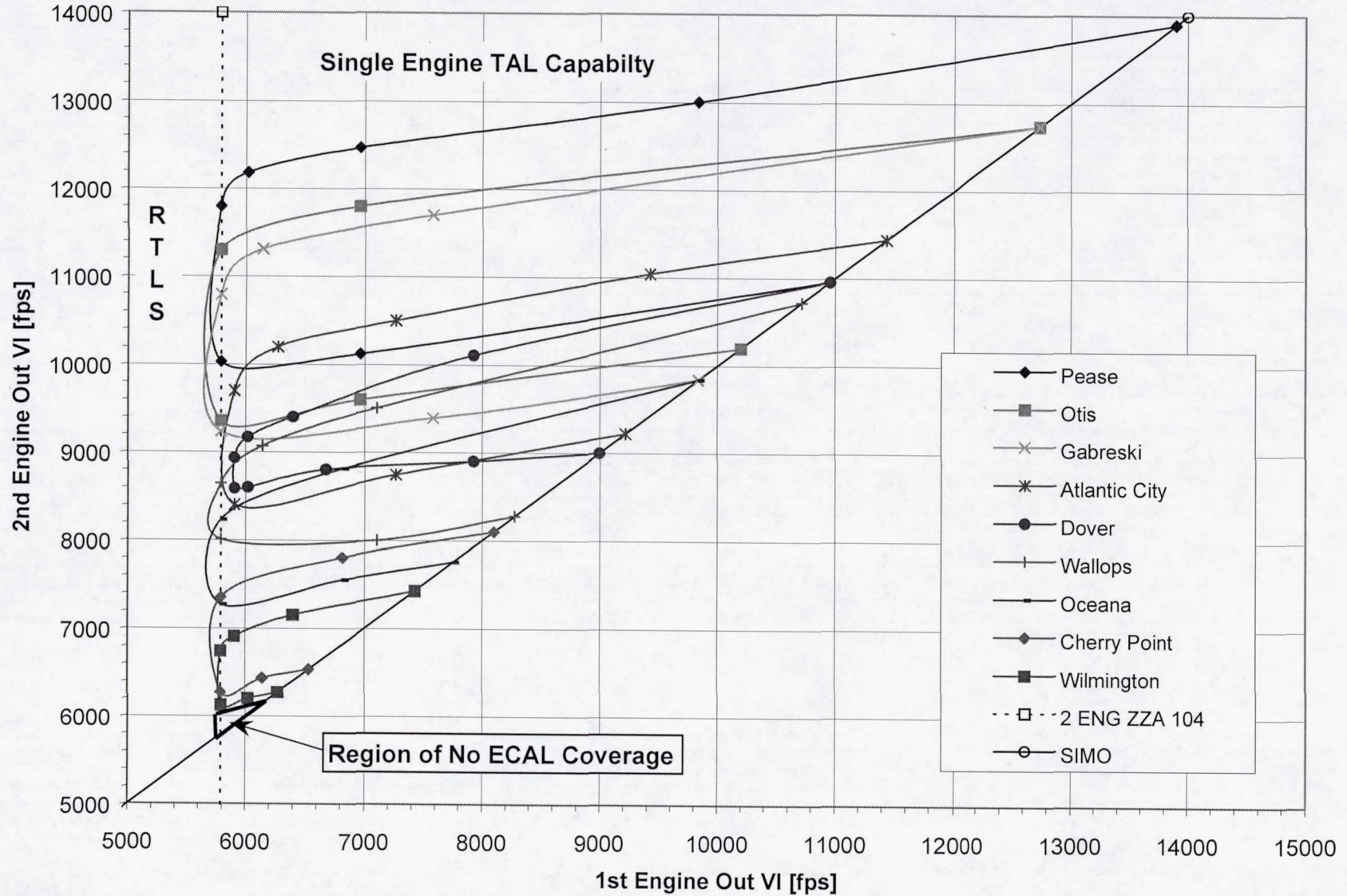
RTLS ECAL Capability for 51.6 inclination, LWC





Appendix E: ECAL Capability with all improvements.

51.6 degree ECAL with TAL Delay, ZZA, Close (All sites)



## 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

I		N		P		U		T								
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																
<b>FLAGS &amp; I-LOADS</b> FSW = OI28 HAC = Auto-select APPCH = Auto-select AIMPT = Nominal NAV = Off		<b>MASS PROPERTIES</b> ETSEP WT = 247181 lb ETSEP CG = 1090.2, 0.0, 370.0 in M3.5 Iyy = 7500000 slug-ft^2				<b>ENVIRONMENTAL MODEL FLAGS</b> ATMOS = 62Standard DESC = 1962 Standard Reference ALT_BIAS= -83.4 ft WIND = None				<b>LANDING SITE DATA</b> RWY-ID = FMH32 RWY-AZ = 308 deg RWY-HD = -83 ft RWY-LATD= 41.6516 deg RWY-LONG= -70.5109 deg						
GAMSGS= -18 deg WRTLS = 7397 slugs DNZMAX= 3.90 g ALPRCU= 58.0 deg CASTRT= EO2		<b>PROPELLANT DUMPS</b> Fwd RCS Duration = 0 sec Aft RCS Duration = 130 sec MPS LO2 8* F&D Delay = 20 sec MPS LH2 8* F&D Delay = 0 sec OMS Dump Mode = 1				VEHICLE = 103				<b>INITIAL RANGE TO RUNWAY</b> Flat-Earth Range= 435.5 nm Geocentric Range= 408.1 nm						
IPH (nd)	TIME (sec)	RPRED (nm)	VE (fps)	HD (ft)	QBAR (psf)	LFCGZ (g)	HDOT (fps)	GAMMAE (deg)	ALPHA (deg)	ROLLC (deg)	DPSAC (deg)	PSIE (deg)	LATD (deg)	LONG (deg)	PSHA (deg)	S S M 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 \*\*\*\*\*

ETSEP & MM602 STATE VECTORS

EVENT	TIME (sec)	RPRED (nm)	LATD (deg)	LONG (deg)	HD (ft)	VE (fps)	PSIE (deg)	GAMME (deg)	ALPHA (deg)	ROLL (deg)	BETA (deg)	P (deg/s)	Q (deg/s)	R (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

	VALUE	IPHASE (nd)	TIME (sec)	RPRED (nm)	VE (fps)	HEG (ft)
OVERALL						
Max  HDOT  (1st peak)	-fps -2419	6	41.04	438.8	11032	183661
Max  HDOT  (2nd peak)	-fps -269	4	203.76	165.3	5734	126376
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
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

DURING ETSEP & PULLOUT PHASES

Max ALPHA	-deg 58.0	6	21.12	425.1	11203	229961
Max NZC	-g 2.29	5	84.00	327.9	8677	114942
Max  DPSAC	-deg -33.5	5	76.32	348.3	9041	119222
Max  ROLL	-deg -66	4	93.60	296.5	8241	112932

DURING TAEM PHASES

Max  HDOT	-fps -618	1	335.52	77.6	3189	94422
Max QBAR	-psf 313	1	367.20	62.5	2651	79211
Max  LFCGZ	-g -1.80	1	353.28	69.1	2914	84216
Min HAC RF	-ft	<<<<<<< No HAC shrink >>>>>>>>				

BALLISTIC MAX HD

Time	-sec -53.05
HD	-ft 315887
VE	-fps 10998

LOAD FACTOR LIMITS

@ Max LF (1st)	-g 2.19
@ Max LF (2nd)	-g 2.20

MAXIMUM HINGE MOMENTS

CONTROL SURFACE	DEF (deg)	HM (in-lbf)	LIMIT (in-lbf)
Inboard Elevon	-4.3	-762357	1260000
Outboard Elevon	0.7	-358128	600000
Bodyflap	7.1	-960120	1560000
Speedbrake	64.8	950641	1230000

MASS PROPERTIES

	WT (lb)	CGX (in)
ETSEP Initiation	247181	1090.2
MM602 Initiation	247043	1090.3
TAEM Interface (Mach=3.2)	240993	1081.8
A&L Interface	240993	1081.8

PROPELLANT DUMP SUMMARY

DUMP TYPE	START TIME (sec)	END HD (ft)	END VE (fps)	DUMP WT (lb)
Fwd RCS	5.28	261405	11151	-9999
Aft RCS	25.44	128025	6317	1618
MPS LH2	0.00	233995	11202	304
MPS LO2	5.28	131591	9599	3870
OMS OME	5.28	261405	11151	0

NOMINAL A&L INTERFACE

	VALUE	ERROR	LIMIT
HEG	-ft 9964	-58 (high)	993
Y	-ft -62	-62 (left)	993
GAMMAE	-deg -18.3	-0.3 (shallow)	4.0
QBARF	-psf 306	-1 (high)	24

ENERGY SUMMARY

Minimum Delta RPRED To:	S-Turn = 5.2 nm
	MEP Alert = -56.4 nm
	St-In Alert = -59.0 nm
Integrated EOW Error During TAEM	= 1.2 nm

=====  
 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	

=====