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A SIMULATION MODEL FOR PROBABILISTIC ANALYSIS
OF SPACE SHUTTLE ABORT MODES

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This report presents a simulation model which has been developed to provide a probabilistic analysis tool to study the various space transportation system abort mode situations. The simulation model is based on Monte Carlo simulation of an event-tree diagram which accounts for events during the space transportation system's ascent and its abort modes. The simulation model considers just the propulsion elements of the shuttle system (i.e., external tank, main engines, and solid boosters). The model was developed to provide a better understanding of the probability of occurrence and successful completion of abort modes during the vehicle's ascent. The results of the simulation runs discussed in this report are for demonstration purposes only, they are not official NASA probability estimates.

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LISTS OF ACRONYMS

ACLS   augmented contingency landing site

AOA   abort once around

APU   auxiliary power unit

ATO   abort to orbit

EO   engine out

ET   external tank

GSE   ground support equipment

LEO   low Earth orbit

LS   landing site

MECO   main engine cut-off

MET   mission elapsed time

OMS   orbital maneuvering system

PTA   press to abort to orbit

PTM   press to main engine cut-off

RCS   reaction control system

RPL   rated power level

RTLS   return to launch site

SRB   solid rocket booster

SSME   space shuttle main engine

STS   space transportation system

TAL   transoceanic abort landing

VI   inertial velocity

LIST OF SYMBOLS

a	coefficient
ACC(1,104)	acceleration of shuttle in abort mode with one SSME functioning at 104 percent
ACC(1,109)	acceleration of shuttle in abort mode with one SSME functioning at 109 percent
ACC(2,104)	acceleration of shuttle in abort mode with two SSME's functioning at 104 percent
b	coefficient
T	mission elapsed time*
T(E.RTLS)	time for earliest RTLS attempt possibility
T(init.)	time of initiation of abort mode
T(L.RTLS)	time for last RTLS attempt possibility
T(second failure)	time of second SSME failure
TENGBF(1)	time of first SSME benign engine failure
TENGBF(2)	time of second SSME benign engine failure
Tmeco	time of main engine cut-off
Treqd	time required for the SSME's to run to complete the abort mode
Treqd(1)	time required for one SSME to run to complete the abort mode
Treqd(1-E RTLS)	time required for the SSME to run to complete a one SSME RTLS abort mode
Treqd(2)	time required for two SSME's to run to complete the abort mode
Treqd(2-E RTLS)	time required for the SSME's to run to complete a two SSME RTLS abort mode
VI	vehicle's inertial velocity
VITBF(1)	vehicle's inertial velocity at the time of the first SSME benign failure
VITMCO	vehicle's inertial velocity at the time of main engine cut-off

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*Time in all cases mentioned refers to the vehicle's mission elapsed time.

TECHNICAL MEMORANDUM

A SIMULATION MODEL FOR PROBABILISTIC ANALYSIS OF SPACE SHUTTLE ABORT MODES

I. INTRODUCTION

The NASA space shuttle system is a reusable manned vehicle capable of transporting large payloads to low Earth orbit (LEO). The system is designed to provide abort options to accommodate "contained" system failures. Because of the complexity of the system, it is almost impossible to analytically evaluate the risk due to the various abort modes. This report presents a simulation model which has been developed to provide a probabilistic analysis tool to study the various space shuttle abort mode situations. The simulation model considers just the propulsion elements of the shuttle system (i.e., external tank (ET), main engines, and solid boosters). Specifically, the model was developed to provide a better understanding of the probability of occurrence and successful completion of the abort modes during the ascent phase of the mission. The purpose of this document is to demonstrate the use of the simulation program based on the assumptions and the principles used. The results from the simulation runs discussed are for demonstration purposes only and are not official NASA probability estimates.

1.1 Background

1.1.1 Space Shuttle Description. The space shuttle is a system that has been designed to provide a manned reusable transport vehicle capable of transporting large payloads to LEO. The launch configuration of the system is shown in figure 1. The system consists of three main elements: the orbiter, the ET, and the solid rocket boosters (SRB's). The orbiter is the manned vehicle that accommodates payload that is transferred between the ground and orbit. The orbiter ascends in a vertical configuration and returns to Earth as a transatmospheric plane. The propulsion systems that support the orbiter are two SRB's, three space shuttle main engines (SSME's), the ET, orbital maneuvering system engines, and reaction control system thrusters.

The SSME's provide thrust to help the orbiter attain ascent or successfully complete an abort. Three SSME's are located at the aft end of the orbiter. The engine is throttlable, uses oxygen and hydrogen propellant, and is designed to function for 55 starts (27,000 s). The rated power level (RPL) of the SSME is 470,000 lb of thrust in a vacuum, which corresponds to about 375,000 lb at sea level. The engines can be throttled from 65 to 109 percent of the RPL. During the ascent of the space shuttle, each engine burns for about 520 s during which it undergoes a throttling profile. A typical throttling profile (for STS–26) is shown in figure 2. The engines are throttled up to 100-percent RPL prior to SRB ignition. They then achieve 104 percent before being throttled down to 65 percent during a period of maximum aerodynamic pressure for the vehicle. After the period of maximum aerodynamic pressure on the vehicle has been passed, the engines are throttled back up to 104 percent where they remain before being throttled down prior to main engine cut-off (MECO).

The ET is the "propellant tank" for the shuttle orbiter. It contains liquid hydrogen and liquid oxygen for use by the SSME's. The ET is the backbone of the launch configuration in that it is attached to both the orbiter and the SRB's. After MECO of the SSME's, the ET reenters the atmosphere and disintegrates; the remnants of the ET land in the ocean.
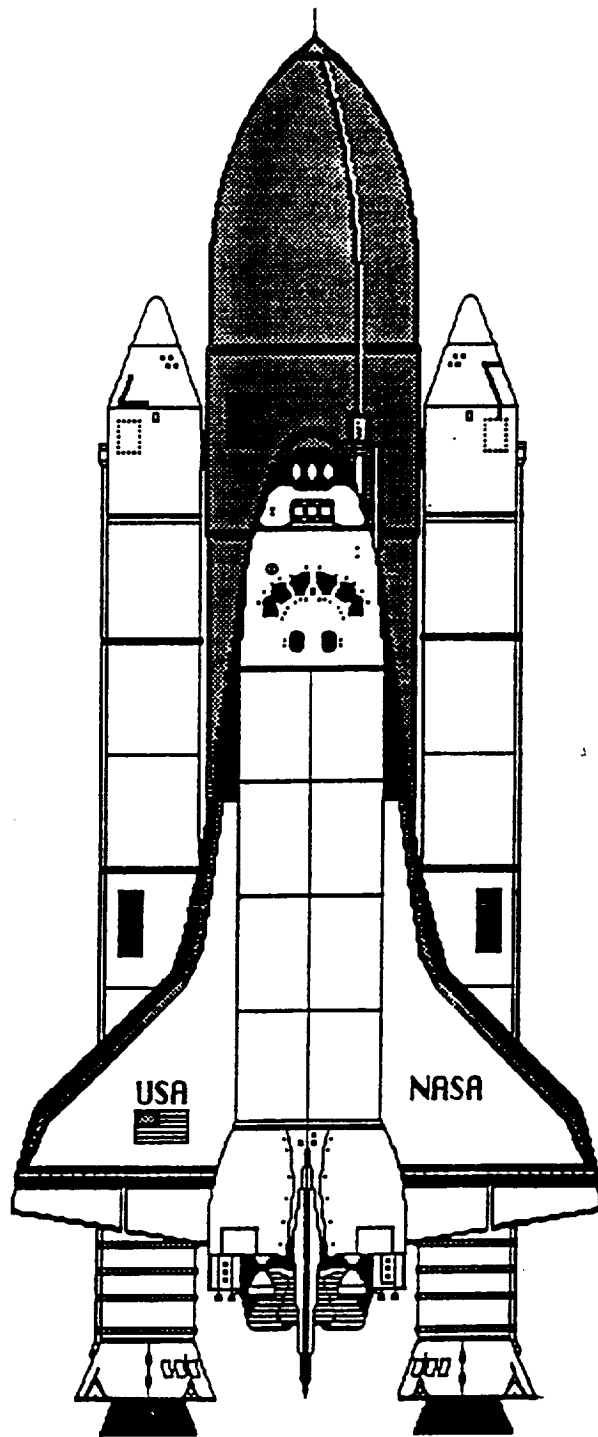
Figure 1. The space transportation system.

STS-26 MISSION PROFILE
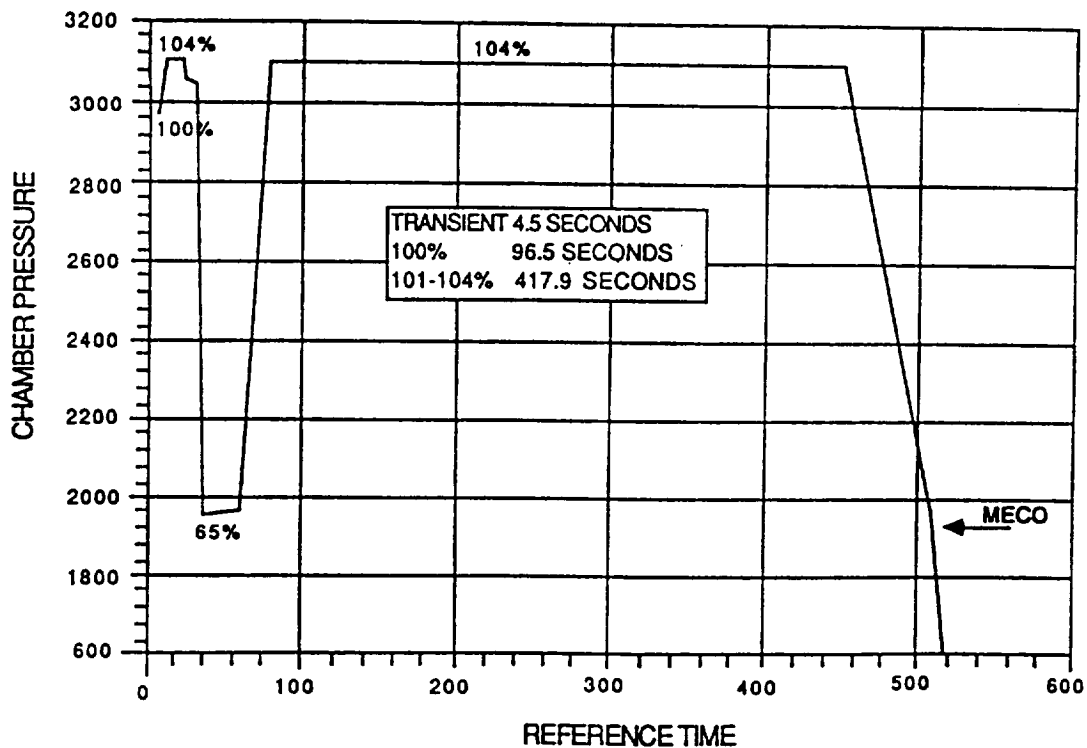
Figure 2. An SSME mission thrust profile.

The SRB's provide thrust to propel the space shuttle to orbit and serve as the launch pad mounts for the vehicle prior to lift-off. There are two SRB's located on opposite sides of the ET. Each SRB produces approximately 2.9 million lb of thrust. The SRB's complete their burn when the vehicle has reached about 150,000 ft, at which time they separate from the ET and drop into the ocean, with parachutes slowing their fall. The cases of the SRB's are recovered and reused.

The orbital maneuvering system (OMS) engines provide thrust to support the orbit attainment, orbit adjustments, and reentry of the vehicle. There are two OMS engines located on the aft end of the orbiter. The OMS engines use monomethylhydrazine and nitrogen tetroxide for their propellant. Each engine produces 6,000 lb of thrust in a vacuum.

The reaction control system (RCS) thrusters provide thrust for pitch, yaw, and roll control of the vehicle. There are 44 thrusters in all, and they are located in the fore and aft portions of the orbiter. The RCS thrusters use monomethylhydrazine and nitrogen tetroxide for their propellant. The RCS thrusters include primary thrusters for major adjustments, which produce 870 lb of thrust in a vacuum each, and vernier thrusters, for finer adjustments, which produce 24 lb of thrust each in a vacuum.

1.1.2 Space Shuttle Ascent and Abort Modes. The process of inserting the orbiter into orbit consists of four phases: the prelaunch phase, the first stage, the second stage, and the orbit insertion.

The prelaunch period is the time during which the vehicle is held down and the SSME's are fired.

After the prelaunch time has been completed, the SRB's are ignited, the vehicle is released from the pad, and the first stage operation begins. After lift-off, the SSME's are throttled down before a

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period of maximum aerodynamic pressure is experienced by the vehicle. After the period of maximum pressure has been passed, the engines are throttled back up. After the SRB's have completed their operation, they are separated from the ET.

The second stage begins after SRB separation. The SSME's are throttled down prior to MECO in order to achieve the desired insertion velocity. Once MECO is completed, the second stage has also been completed.

After MECO, the ET separates from the orbiter, the OMS engines are then used to place the vehicle in the desired orbit. Either one or two OMS burns will be used, depending on the type of mission that is being performed.

The STS has several abort options: return to launch site (RTLS), transoceanic abort landing (TAL), press to abort to orbit, press to MECO, late TAL, and contingency aborts.

RTLS is the abort option which occurs during the first window for the shuttle. The window for this option varies from flight to flight, but, in general, it extends from shortly after SRB separation until the first capability for TAL.

The RTLS is performed in three phases as shown in figure 3: powered flight, ET separation, and glide-flight. During the power-flight portion of the RTLS, if the vehicle is not at the boundary of RTLS capability, the pitch attitude is changed to allow the vehicle to be lofted out of the atmosphere. This will be performed until the required amount of fuel in the ET has been depleted. The pitch-around maneuver is then executed (at approximately 10°/s) to begin the flyback phase for the vehicle. The vehicle then aims itself at a target position and velocity for completing the RTLS. When the desired altitude is reached, the vehicle pitches down to an attitude of approximately –4°. The SSME's are throttled down to 65 percent and MECO is then performed. Shortly after MECO, the ET is separated from the orbiter. After ET separation, the vehicle pitches back up, and resumes a glide path for the RTLS runway.
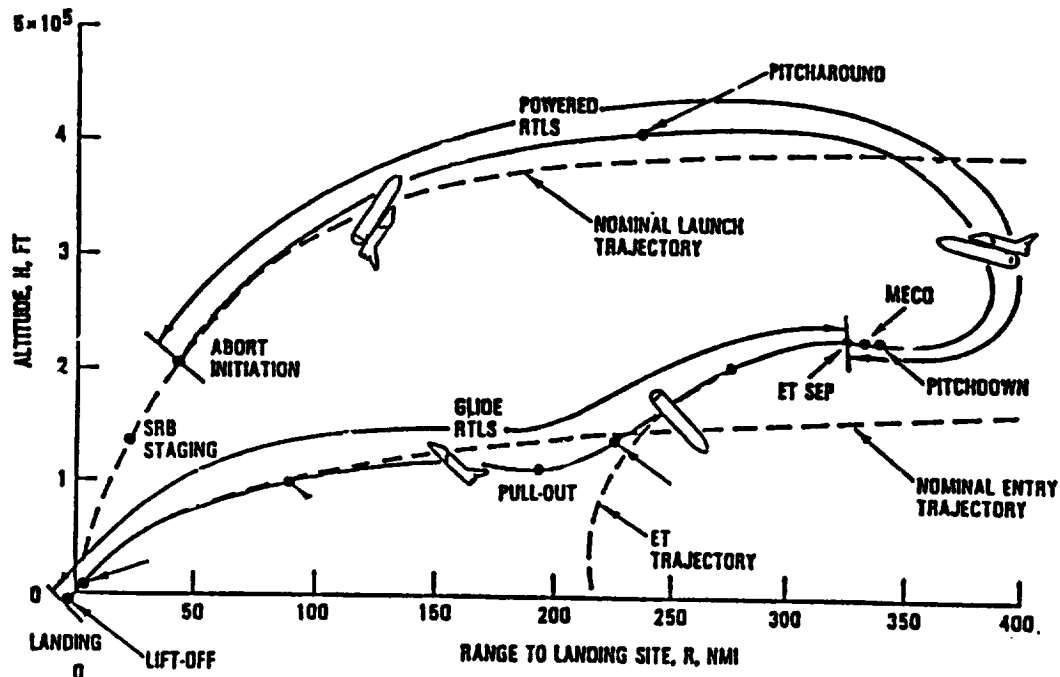
Figure 3. A typical RTLS profile.

TAL is more complex than RTLS in that for a typical flight there are several possible TAL landing sites, and different criteria determine which site will be attempted. Some of the possible landing sites for TAL aborts are shown in figure 4. In general, the window for the initiation of this option extends from the inertial velocity at the RTLS/TAL window to the velocity of first press-to-abort (PTA) to orbit capability.
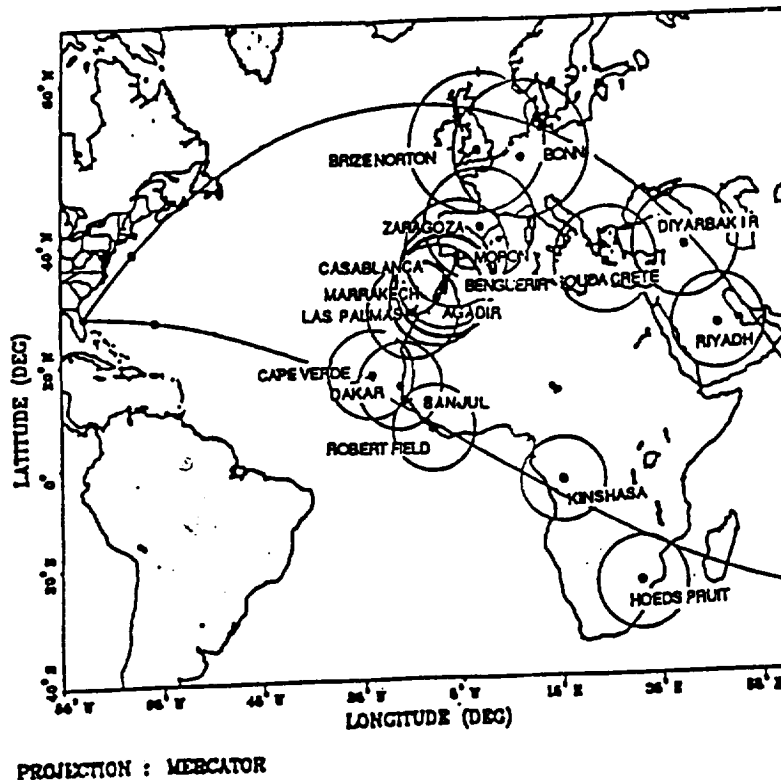
Figure 4. Some TAL landing sites.

The steps in performing a TAL include: selecting the TAL site, performing an OMS propellant dump, achieving the desired MECO altitude and velocity, performing MECO, and gliding to the landing site. The TAL site is selected based on the vehicle's position in the ascent when the abort is initiated and will be discussed in detail in later sections. After the site has been selected, dumping of the OMS propellant will be initiated, and the vehicle will begin steering toward the selected landing site. After the vehicle has reached the desired altitude and velocity, the MECO will be performed. After MECO, the vehicle will glide to the runway at the target site.

PTA is an abort option in which the vehicle attempts to achieve an off-nominal orbit. The lower orbit is attained because there is insufficient energy to attain a nominal orbit, and/or systems performance suggests that an early reentry may be desired. In general, the window for this option extends from the TAL/PTA boundary to the press-to-main (PTM) engine cut-off boundary.

The procedure for a PTA is similar to the procedure for a nominal ascent, with the exception that the orbit which is attempted to achieve is shallower than the nominal orbit. After the PTA option is selected, the engines run until the desired MECO velocity and position is reached. After MECO, the two OMS engine burns place the vehicle in the desired orbit, as shown in figure 5.

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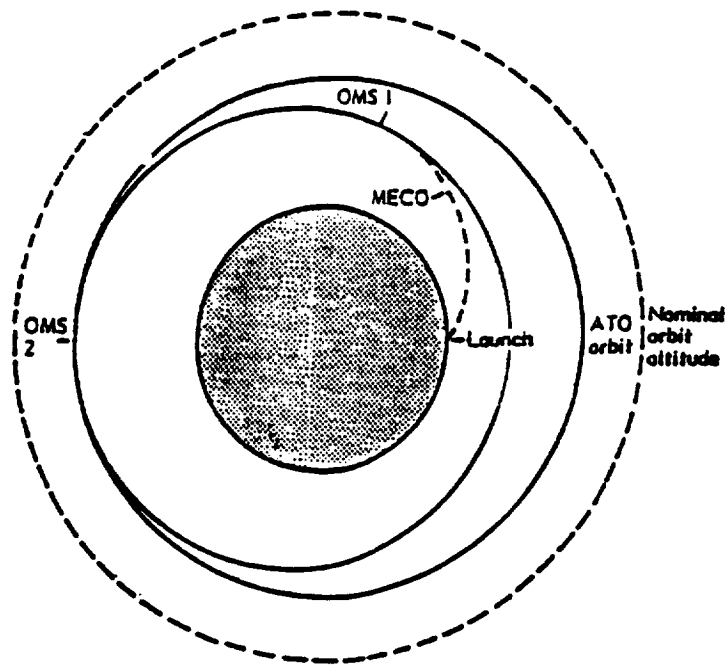
NOTE: This drawing is not to scale.

Figure 5. Comparison of ATO and nominal orbits.

PTM involves the vehicle attempting to achieve its desired orbit despite its problems. This option involves adjusting vehicle thrust and trajectory in order to achieve the desired orbit. The window for this option extends from the PTA/PTM boundary until MECO. The procedure for this abort option is similar to the PTA option, with the exception that the nominal orbit is attempted rather than a shallower one.

Late TAL is an abort to a landing site that is performed because of an early MECO. This abort option is used when the vehicle cannot attain an orbit and it is past the region for the normal TAL option. This option is generally available during the last minute of flight. This option involves "gliding in" to the landing site that has been chosen based on the vehicles situation at the time of MECO.

Contingency aborts are performed because of either structural failures, multiple systems failures, or multiple engine failures. A contingency abort is performed for multiple SSME failures whenever the thrust of the engines is inadequate for either the vehicle achieving orbit or an intact abort. The profile of a typical contingency abort is shown in figure 6. During a contingency abort due to multiple SSME failures, an attempt will be made to achieve a gliding path for the vehicle from which either a vehicle ditch or a crew bailout can be performed. The vehicle and crew will be lost if the vehicle is in a "black zone," a region in which the vehicle's structural constraints are exceeded, at the time of multiple engine failures. The current contingency capability for multiple engine failures during the ascent is shown in figure 7.

Aborts for the space shuttle can be initiated for either systems problems or SSME failures.

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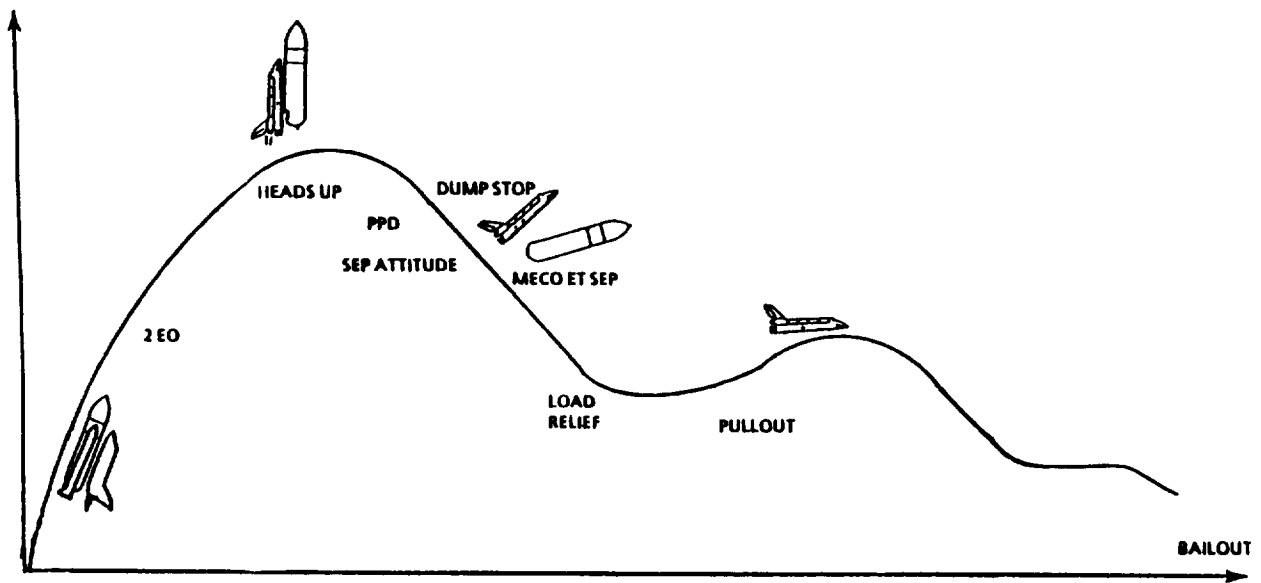
Figure 6. A typical contingency abort profile.
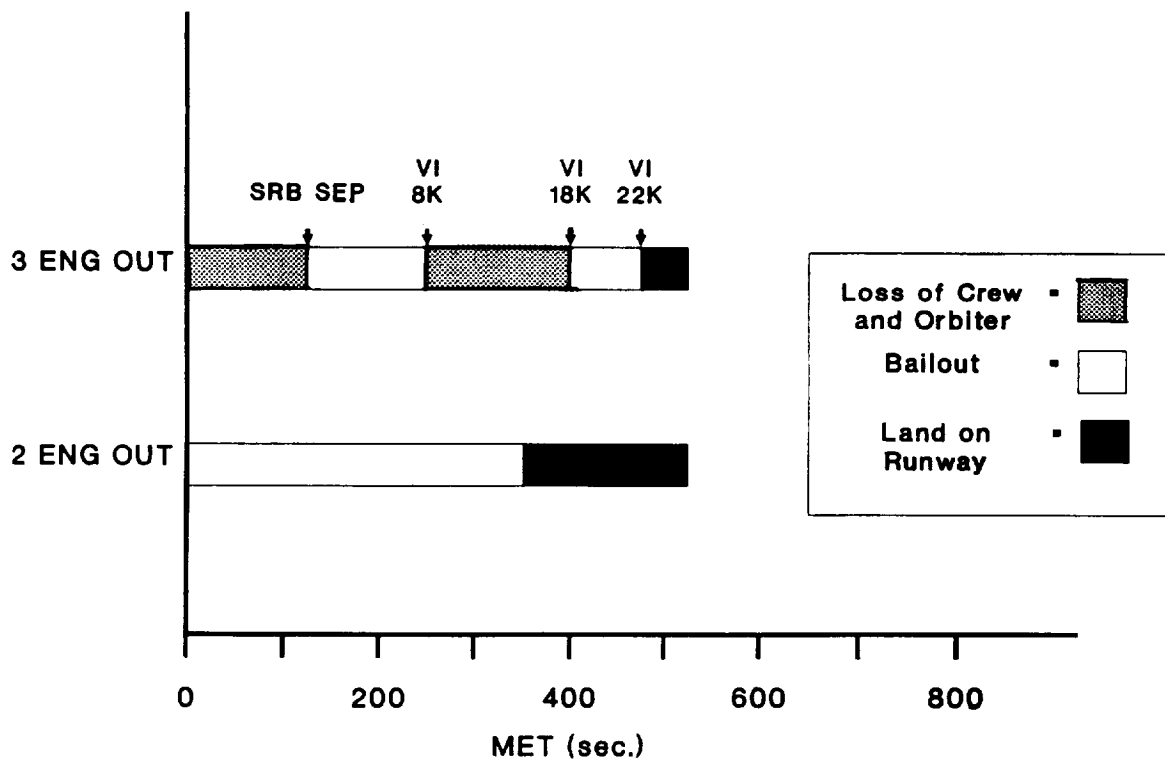
Figure 7. Contingency abort capability.

The procedures for selecting abort options for SSME failures is based on interaction between Mission Control and the astronauts. Flight procedures and checklists are used to minimize the decision time in the abort selection process. The earliest time at which an abort can be initiated is approximately 2 min 30 s into the flight, which is shortly after SRB separation. The many different possible situations for SSME failures causes the abort selection process to be very complex, as the abort selected is largely a function of when the SSME failure(s) occurred during the STS ascent and aborts.

1.1.2.1 <u>STS Operational Flight Rules—All Flights</u>. The purpose of the flight rules discussed in the document "STS Operational Flight Rules—All Flights" is stated as: "The flight rules outline pre-planned decisions designed to minimize the amount of real-time rationalization required when non-nominal situations occur from the start of the terminal countdown through crew egress or ground support equipment (GSE) cooling activation, whichever occurs later."[4]

In the "Flight Operations Rules" section of the document, rules relating to abort procedures are discussed. In this section, the topics that are discussed include: shuttle abort criteria, ascent mode priorities for performance cases, aborts for systems failures, and contingency ascents/aborts.

The shuttle abort criteria subsection states that the nominal ascent will not be continued if any of the following conditions occur: engine problems occur in a region where their performance is required, deorbit maneuver capability is lost, attitude control is lost, or consumables, cooling, or systems lifetime problems occur that will not support a first day landing to the primary landing site. The aborts that will be used due to engine problems will be chosen based on the region in which the engine(s) problems occurred.

The subsection that discusses the ascent mode priorities for performance cases discusses the order of precedence for the selection of abort modes and provides some discussion on the performance of the aborts. The order of precedence for the abort modes is as follows: press-to-orbit (including press-to-MECO and press-to-abort-to-orbit (ATO)), TAL, RTLS, late TAL, and abort-once-around (AOA). The press-to-orbit decisions will be based on such factors as the ET impact location and post-MECO performance capability.

The subsection that discusses the abort modes that will be used for systems failures describes systems failures that will result in abort initiation, and which aborts will be used for the various systems failures. Examples of systems failures that would result in aborts include: loss of a thermal windowpane, a cabin leak that results in a significant rate of pressure loss, two leaking or failed OMS tanks, the loss of two Freon loops, and the loss of two main busses. The abort modes that are considered in this section are RTLS, TAL, late TAL, and AOA. The abort modes that are used based on the systems failures are selected based on the option that provides the earliest available landing time or to avoid requiring a lost capability.

The contingency ascents/aborts subsection provides a general discussion of contingency ascents/aborts and the possible outcomes. Contingency aborts will be used when structural failures or multiple systems or SSME failures have occurred. Possible contingency abort cases include the following: crew bailout or orbiter ditch due to the loss of multiple SSME's in a region where no acceptable landing site is available; an attempt to land at an RTLS, TAL, AOA, or ACLS due to structural or multiple orbiter systems problems which necessitate landing at the earliest possible time; or an attempt to land at an RTLS, TAL, AOA, LS, or ACLS due to multiple SSME failures coupled with other orbiter failures which result in severe ascent performance loss. The contingency abort may result in the loss of the vehicle and the crew if there is total SSME thrust loss in a "black zone," which is a region where the contingency abort would result in a violation of the vehicle's constraints (such as structural constraints).

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1.1.2.2 Flight Procedure Handbook—Ascent/Aborts. The purpose of the "Flight Procedure Handbook—Ascent/Aborts" is stated as: "to describe and provide rationale for the flight procedures used using space shuttle ascent and aborts. It has been prepared for shuttle flight crews and ground operations personnel as an ascent flight training supplement and convenient reference source."[5]

The Flight Procedure Handbook discusses in detail the procedures that the crew must be trained for during the ascent and during the performance of shuttle aborts. This document was a valuable reference in understanding the process that is involved in the ascent, and selecting and performing the abort options.

When performance problems occur that will have to be compensated for by using aborts, a certain amount of time is required by the crew (and possibly mission control) to discuss the problem and decide on the appropriate abort option to select. The time between the occurrence of the problem and the initiation of the selected abort option is referred to as the decision time. The decision time that is required is generally 15 s.

The inhibit/enable switch is a device that is used to control whether or not the SSME's will be automatically shut down due to exceedence of red-line limits of certain performance parameters. If the switch is in the enable position, the SSME's are shutdown if the red-lines are exceeded. If the switch is in the inhibit position, the SSME's are not shutdown if the red-lines are exceeded. The switch is in the enable position initially. If an engine fails while the vehicle has not yet reached a region of single engine capability, the switch is placed in the inhibit position. The switch may be placed back in the enable position if the engines achieve single engine capability while two engines are still functioning.

1.1.2.3 Ascent Checklist. The ascent checklist[7] is a document that summarizes the procedures that the crew must perform during a shuttle ascent and during the performance of aborts. The checklist consists of a generic document that pertains to all flights and flight supplements that are used for the specific flight. Part of the ascent checklist flight supplement for STS-32 is contained in appendix A.

The ascent checklist contains information that can be used by the shuttle crew to select the abort mode if performance problems occur with the vehicle and the crew does not have communication with mission control. The information contained in the ascent checklist is in the form of cards. During the flight, the cards are placed in a pad for the commander and pilot, and they may be referenced during the vehicle's ascent and during abort attempts. Items of interest to this study that are contained in the ascent checklist include: the systems flight rules card, the no comm mode boundaries card, the auto TAL card, the late TAL card, the ascent ADI-nominal card, and the TAL redesignation cards.

The systems flight rules card states which abort option (s) will be used for certain systems failures. The systems rules card is a summary of the information that is provided in the operational flight rules pertaining to the abort modes that will be used for systems failures.

The no comm mode boundaries card is used by the crew if they do not have communication with mission control. This card contains vehicle inertial velocity boundary value information from which the abort options can be selected.

The auto TAL card states the inertial velocity at which MECO would be performed for a TAL attempt.

The late TAL card states the boundary inertial velocity values at MECO for late TAL attempts as well as the lowest inertial velocity at MECO for which a successful late TAL landing may be achieved.

The ascent ADI-nominal card provides information on the vehicle's inertial velocity versus the altitude of the vehicle.

The TAL redesignation cards are used to select a landing site for a one-engine TAL attempt if a two-engine TAL attempt was selected and a second engine failed before the two-engine TAL attempt could be completed. TAL redesignation cards are included for two-engine TAL attempts to the primary two-engine TAL site, Benguerier, and the second two-engine TAL site, Moron. In using the TAL redesignation cards, the column that contains the first EO VI value is first entered by choosing the column that corresponds to the value of the inertial velocity at the time of the first engine failure and rounding to the nearest 100 value. The correct row item is chosen by selecting the row with the VI value that contains a value that is less than or equal to the inertial velocity at the time of the second engine failure and that contains the value closest to the inertial velocity value at the time of the second engine failure.

1.2 Objective

The purpose of this study was to develop a simulation model that could be used to analyze the various space shuttle abort mode situations and that could provide a better understanding of the probability of occurrence and successful completion of the abort modes during the ascent phase of the mission.

1.3 Scope

This study focuses on the effect of propulsion system failures on the ascent phase and the related abort modes for the space shuttle. Systems failures (such as APU failures, Freon loop failures, etc.) are not considered in this analysis.

The space shuttle items which were considered (the propulsive elements) were: the SSME's, the SRB's, and the ET.

The simulation program has been designed for supporting analysis of various mission situations. In addition to supporting analyses of specific missions, the program supports sensitivity analyses of the effects of various ascent and abort parameters.

II. SIMULATION MODEL DEVELOPMENT

2.1 Basic Approach to Model Development

The basic approach to model development is described by an event tree diagram which accounts for all the events during the space shuttle ascent and its abort modes. The event tree diagram was constructed by referring to NASA flight rules and procedures. The paths in the tree are determined based on the failure times of the propulsion system elements. The propulsion elements considered in the analysis are the ET, the SRB's, and the SSME's. A failure model described by a probability distribution is constructed for each of the three elements. A failure of either the ET or the SRB at any time during their flight times will result in a catastrophic failure of the vehicle. For the SSME's, the probability

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distribution is used to generate a failure time for each of the three engines. The failure time is then checked against the mission profile to determine if the mission is a success or if a failure has occurred that would result in loss of the vehicle or a mission abort. In case of an abort, the vehicle performance model is taken into consideration. The vehicle performance model considers the vehicle velocity versus mission time and the conditions for the successful completion of the abort modes. The vehicle velocity versus mission time is used to determine the velocity at which the engine failure occurs. Given this velocity, the time required for the engines to complete a successful abort is determined by the conditions for abort completion. A summary of the model elements that where developed is shown in figure 8.
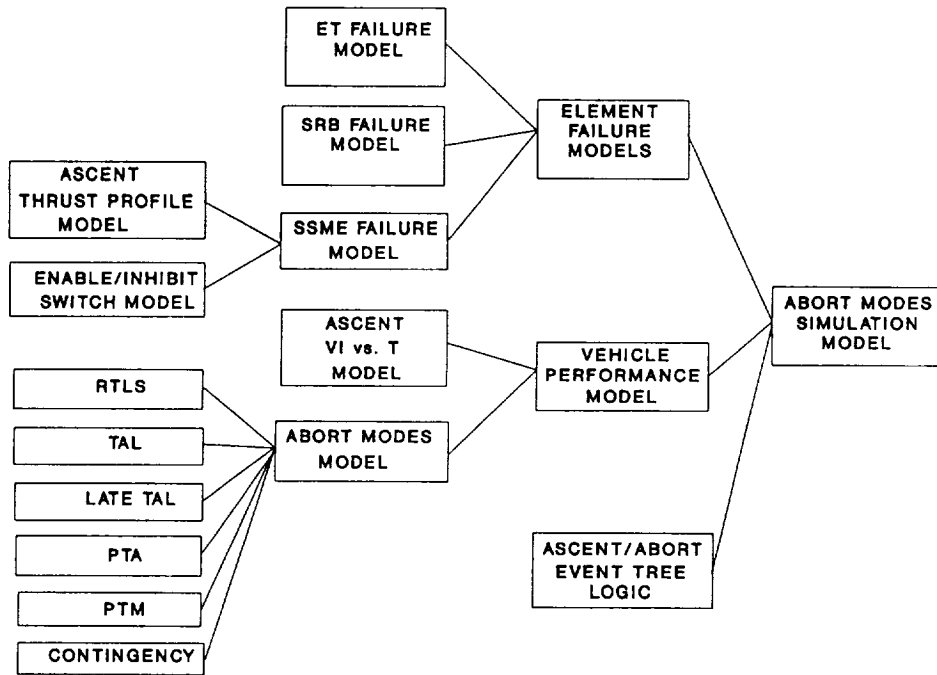
Figure 8. Basic approach to model development.

2.2 Element Failure Modes

Although various nonpropulsive systems failures would result in the initiation of abort options, this study only considered the effect of performance of space shuttle propulsive elements on ascent/aborts. The items which were considered in the model development were: the SSME's, the SRB's, and the ET. The models that were developed to represent the performance of these items are discussed in the following sections.

2.2.1 SSME's Failure Model. The SSME's were the most difficult elements to model since their design and operation are the most complex of the three items considered. The SSME's operate at various performance levels and are subject to both benign (self-contained) failures and catastrophic (criticality 1) failures. An additional factor which must be considered in the modeling of the time-to-failure of the SSME's is whether or not the engines are "inhibited" from shutting themselves down due to off-normal measurements.

The SSME's operate from the beginning of the prelaunch phase until they either shut down because of a failure or MECO is performed.

The time-to-failure for the engines was treated as an exponential distribution. This distribution was considered for this case because the SSME's are very complex, with many parts. For systems with many parts, an exponential distribution is sometimes used because the items are just as likely to experience "random" failures any time during their life. Another distribution considered was a Wiebull distribution that is modeled to predict higher probability of failure during the early time of the items lifetime. This distribution has been shown to more accurately predict the failures for the SSME's and should be used for future applications of the simulation program that was developed. The exponential distribution was used in this study for the initial demonstration of this simulation program because of its ease of use and simplified approximation of the predicted failure times of the SSME's.

Since various power levels, catastrophic and benign failures, and inhibited and enabled engines are being considered, distribution parameters are required for each case. The power levels that were considered were 100, 104, and 109 percent. Catastrophic failures are those failures that correspond to criticality 1 failures. Benign failures are those failures that correspond to failures that result in a safe engine shutdown. Inhibited engine failures are failures that occur when the engine is inhibited from failing due to red-line exceedence of its various performance items. Enabled engine failures are failures that occur when the engine is not inhibited from failing due to red-line exceedence of the various performance items.

The source for obtaining the estimates for the exponential parameters for the various situations was the SSME reliability study by Dr. Safie.[9] The method for obtaining exponential time-to-failure estimates for the engines from the reliability study and estimates that are obtained are presented in the referenced study.

For simplicity, the thrust profile that is used during the ascent phase was modeled using both 100- and 104-percent RPL's. A model of the thrust profile is shown in figure 9. The thrust level that was used for the various abort situations also used both 100- and 104-percent RPL's. Abort mode attempts
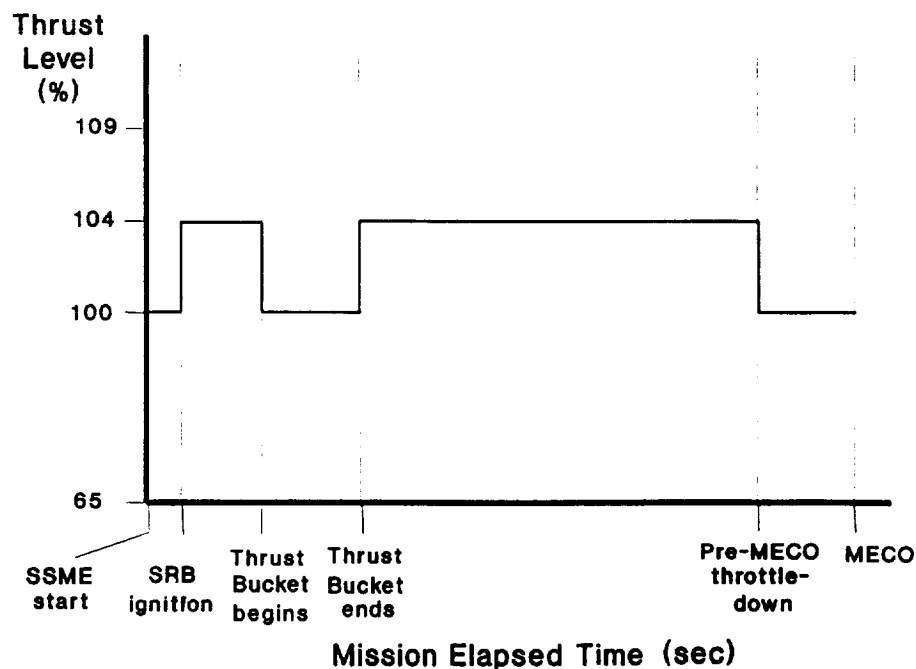
Figure 9. The SSME mission thrust profile model.

that will be said to have engines functioning at 104 percent are: 2-E RTLS, 2-E TAL, 2-E PTA, 1-E PTM, 1-E TAL to the primary TAL site, and 1-E TAL redesignation site attempts that require engines at 104 percent. Abort modes attempts that will be said to have engines functioning at 109 percent are: 1-E RTLS and 1-E TAL redesignation sites that required engines functioning at 109 percent.

The model for the operation of the enable/inhibit switch was based largely on discussions with engineers familiar with it. A diagram summarizing the operation of the switch, a summary of the development of the switch model, and a flowchart that depicts how the switch's operation is modeled is presented in appendix B. As can be seen from the diagram, the switch is initially in the enable position. If a first engine failure occurs before the inertial velocity required for a one-engine abort capability has been reached, the switch is placed in the inhibit position. If there are no further engine failures before the one-engine abort capability is achieved, the switch is placed in the enable position when the VI boundary value for one-engine capability has been reached. If a second engine failure occurs, the switch is placed in the inhibit position, where it remains.

From conversations with engineers familiar with the SSME, some general observations were provided concerning the performance of inhibited SSME's in relation to the performance of enabled SSME's. Approximately 50 percent of the failures that would lead to an engine shutdown due to red-line exceedance for the enabled SSME's would lead to catastrophic failures in the case of inhibited SSME's. An additional observation was that about 1 percent of the benign failures in the enabled SSME case would be benign failures in the case of the inhibited SSME. The use of the approximations that were suggested by the engineers in the development of the model for the switch is discussed in appendix B.

2.2.2 SRB's Failure Model. The operation of the SRB's was considered from the time of their ignition to the time of their separation (or, for the first stage).

Since the performance of the SRB's is largely driven by the manufacturing process, they were modeled somewhat differently than the SSME's. The probability of the successful operation of the SRB's up until separation was treated as a Bernoulli distribution, with the SRB's either catastrophically failing or successfully completing their burn time. If it is determined that the SRB's will fail, the time of the SRB failure is then determined. The time to failure for the SRB's is treated as being uniformly distributed, with the earliest time occurring at ignition and the last time occurring at separation.

2.2.3 ET Failure Model. The operation of the ET was considered from the time of the beginning of prelaunch until either an abort was initiated or nominal MECO of the SSME's occurred.

The performance of the ET was treated similarly to that of the SRB's. The probability of success was treated as a Bernoulli distribution. If a failure occurred, the time to failure was treated as being uniformly distributed, with the minimum time occurring at the beginning of the prelaunch phase and the last time occurring at the time of MECO.

2.3 Vehicle Performance Model

A model was developed for the performance of the vehicle during the ascent and during the abort modes. The model for the ascent involved obtaining an estimate for the vehicle's inertial velocity as a function of time. The models for the vehicle's performance during the abort modes involved estimating the time or inertial velocity that was required for successful completion of the abort options.

2.3.1 <u>Ascent Flight Phase Model</u>. Since inertial velocity is the parameter that is used to decide between different abort options and since the run time of the engines is the value that is obtained based on the distributed times to failure for the engines, a model was required for the simulation that depicted the vehicle's inertial velocity as a function of the time during the ascent at which the failure occurred. The development of the vehicle ascent is discussed in its entirety in appendix C.

By plotting the VI as a function of MET for space shuttle ascent performance data, it was observed that the function can be modeled as an exponential function during the second stage. Since no aborts can be initiated before the beginning of the second stage, only the values in this region were considered. The VI versus mission elapsed time for the second stage can be modeled as:

$$VI = \exp(a+b{*}T) \ , \tag{1}$$

where

VI = the vehicle's inertial velocity

a = a coefficient

b = a coefficient

T = the mission elapsed time.

2.3.2 <u>Return to Launch Site Mode Model</u>. An RTLS attempt is said to be successful if the time of the engine failure(s) are greater than the time that is required for an RTLS completion. The development of the model of the RTLS required time for completion is discussed in its entirety in appendix E.

In developing the model, VI versus the MET data for an RTLS attempt was considered. The model considered two phases during the RTLS attempt, the fuel dissipation phase, and the flyback and powered pitchdown phase. During the fuel dissipation phase, the vehicle is heading down range prior to heading back to the launch site. This phase is therefore very dependent on the time at which the abort was initiated. The data that appeared to represent the fuel dissipation phase were linear and appeared to be dependent on the time that the first engine failed. The flyback and powered pitchdown phases are performed to attain a proper attitude to release the ET and to attain a proper range and velocity at MECO so that a successful RTLS abort may be performed. It appears reasonable that the total duration of the flyback and powered pitchdown phases should be fairly constant over the range of initiation times for the RTLS attempt since there is not much flexibility in the position that vehicle should be in for performing ET separation and MECO. The data that appeared to represent this phase exhibited very nonlinear characteristics, but the total time duration seemed to be relatively constant for different abort initiation times. Models for the required time for the completion of both of the phases was combined to obtain an estimate for the required run time to complete an abort.

The required remaining run time for engines for the successful completion of a two-SSME RTLS abort is therefore:

$$Treqd(2{\text-}E \ RTLS) = 350+(270/(T(L.RTLS){-}T(E.RTLS))){*}(T(L.RTLS){-}T(\text{init.})) \ . \tag{2}$$

The required remaining run time for the remaining engine functioning at 109-percent RPL is therefore:

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$$\text{Treqd}(1\text{-E RTLS}) = 1.91*(\text{Treqd}(2\text{-E RTLS})-T(\text{second failure})) \ . \tag{3}$$

2.3.3 <u>Transoceanic Abort Landing Mode Model</u>. A TAL attempt is said to be successful if the vehicle attains the inertial velocity that is required for a successful TAL attempt. The development of the model of the TAL VI versus t is discussed in appendix F.

Since the VI value of the vehicle is the criteria that must be known for making the TAL option selections, an estimate was required for the vehicle acceleration in order to relate the mission elapsed time to the current vehicle VI value.

In order to see if the programming could remain simpler, acceleration estimates for TAL, PTA, and PTM were made and compared with each other to see if they could be combined into one estimate. The estimation of the vehicle acceleration is discussed in appendix D. The acceleration values that will be used for the vehicle for the abort options at the various number of functioning engines and engine power levels are therefore:

$$\text{ACC}(1,104) = 22.8 \text{ ft/s}^2$$

$$\text{ACC}(1,109) = 23.8 \text{ ft/s}^2$$

$$\text{ACC}(2,104) = 45.5 \text{ ft/s}^2 \ .$$

The 2-E TAL attempts occur with the engines functioning at 104 percent, and the 1-E TAL attempts occur with the engines functioning at either 104 or 109 percent. For a 2-E TAL attempt,

$$\text{Treqd} = (\text{VITMCO}-\text{VITBF}(1))/\text{ACC}(2,104) \ . \tag{4}$$

For a 1-E TAL attempt with the engine functioning at 104-percent RPL,

$$\text{Treqd} = (\text{VITMCO}-\text{VITBF}(1)-\text{ACC}(2,104)*(\text{TENGBF}(2)-\text{TENGBF}(1)))/\text{ACC}(1,104) \ . \tag{5}$$

For a 1-E TAL attempt with the engine functioning at 109-percent RPL,

$$\text{Treqd} = (\text{VITMCO}-\text{VITBF}(1)-\text{ACC}(2,104)*(\text{TENGBF}(2)-\text{TENGBF}(1)))/\text{ACC}(1,109). \tag{6}$$

2.3.4 <u>Late TAL Mode Model</u>. A late TAL attempt is said to be successful if the vehicle's VI value at the time of the premature MECO is greater than the minimum value required for the completion of a late TAL attempt and less than the maximum value for the selected late TAL option.

2.3.5 <u>Press to MECO Mode Model</u>. The abort attempt is said to be a success if the vehicle achieves the inertial velocity that is required to achieve the orbit. The development of the model of the PTM required time to completion is discussed in appendix G. For a 2-E PTM with the engines at 104-percent RPL,

$$\text{Treqd}(2) = (3/2)*(\text{TASCNT}(5)-\text{TENGBF}(1)) \ . \tag{7}$$

For a 1-E PTM with the engine at 104-percent RPL,

$$\text{Treqd}(1) = 3*\text{TASCNT}(5)-\text{TENGBF}(1)-2*\text{TENGBF}(2) \ . \tag{8}$$

2.3.6 Press to Abort to Orbit to Mode Model. The abort attempt is said to be a success if the vehicle achieves the inertial velocity that is required to achieve the orbit. The development of the PTA required time to completion is discussed in appendix G. For a 2-E PTA with the engines functioning at 104-percent RPL,

$$\text{Treqd}(2) = (3/2)*(\text{TASCNT}(5)-\text{TENGBF}(1)) \, . \tag{9}$$

2.3.7 Contingency Mode Model. Contingency aborts that are initiated when there are two failed SSME's in a region where no other abort options are available are said to result in crew bailouts with the loss of the vehicle. The results of contingency aborts that are initiated when there are three failed SSME's in a region where no other abort options are available are said to result in either a crew bailout with the loss of the vehicle or the loss of the crew and vehicle due to the exceedence of constraints on the vehicle. The crew will be said to bail out if the three engines failed in a region not in the contingency abort "black zone." The crew and the vehicle will be said to be lost when the three engines failed within the "black zone." The region of the black zone will be said to extend from a VI value of 8,000 ft/s up to a VI value of 18,000 ft/s.

2.4 Ascent/Abort Event Tree Diagram

The event tree that was developed to model the space shuttle ascent and its abort options is based on NASA procedures and conversations with personnel involved with analysis of space shuttle ascent/aborts. The event tree is shown in appendix H.

2.4.1 Example Event Tree Description. A hypothetical portion of an event tree is shown in figure 10. This event tree is for description purposes only and is not part of the actual ascent/abort event tree.

The tree is continued from a previous path after the first engine failure occurred. If the time between the first and second failures is greater than the time required to make a decision, the inertial velocity of the vehicle is compared with the inertial velocity required for the initiation of a two-engine abort to the abort site. If the inertial velocity is greater than that required for the initiation of a two-engine abort, the event path is continued on chart 2; otherwise the path is continued on chart 3. If the time between the second and the first failures is less than the decision time, the criticality of the engine failure is checked. If a catastrophic failure occurred, the crew and vehicle are lost. If a catastrophic failure did not occur, the inertial velocity of the vehicle is compared to the inertial velocity required for a one-engine abort attempt. If the inertial velocity is less than that required for a one-engine abort, the crew bails out of the vehicle. If the inertial velocity is not less than the required velocity, a one-engine abort is attempted. If the third engine failure occurs before the completion of the one-engine abort, the criticality of the failure is checked. If the engine failure was catastrophic, the crew and vehicle are lost. If the failure was not catastrophic, the inertial velocity of the vehicle is checked to see if the vehicle is in a black zone. If the vehicle is in a black zone, the vehicle and crew are lost, otherwise the crew bails out of the vehicle.

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ABRT1 = Successful 1-SSME Abort
B9 = Benign SSME failure
BZY = Vehicle is an a blackzone
C1 = Catastrophic SSME failure
DTME21 = Time between 1st and 2nd SSME failures
LC = Loss of the vehicle and crew

LV = Loss of the vehicle – crew bailout
TDEC = Required decision time
VI = Vehicle inertial velocity
VIABRT1 = 1-SSME Abort VI boundary
VIABRT2 = 2-SSME Abort VI boundary

Figure 10. A hypothetical event tree segment.

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III. COMPUTER CODE DEVELOPMENT

3.1 Computer Program Overview

The computer code that was developed in Fortran 77 can be obtained by requesting it from the NASA Marshall Space Flight Center Program Development Office (PD22). A simplified overview of the program is shown in figure 11. As can be seen from the diagram, during the simulations the failure times of the elements are first generated. The failure times are generated from statistical distributions, the values of which are determined by pseudo-randomly generated numbers. The failure times are checked to see if any failures occurred before the completion of the ascent. If a failure did occur, the type of failure is checked to determine if the failure was an ET, SRB, or SSME failure. If either an ET or SRB failure occurred, the crew and vehicle are counted as being lost. If an SSME failure occurred, the criticality of the failure is checked. If the failure was catastrophic, the vehicle is lost. If the SSME failure was not catastrophic, the vehicle attempts an abort. If the abort is successful the vehicle is safe; otherwise, the vehicle is lost.
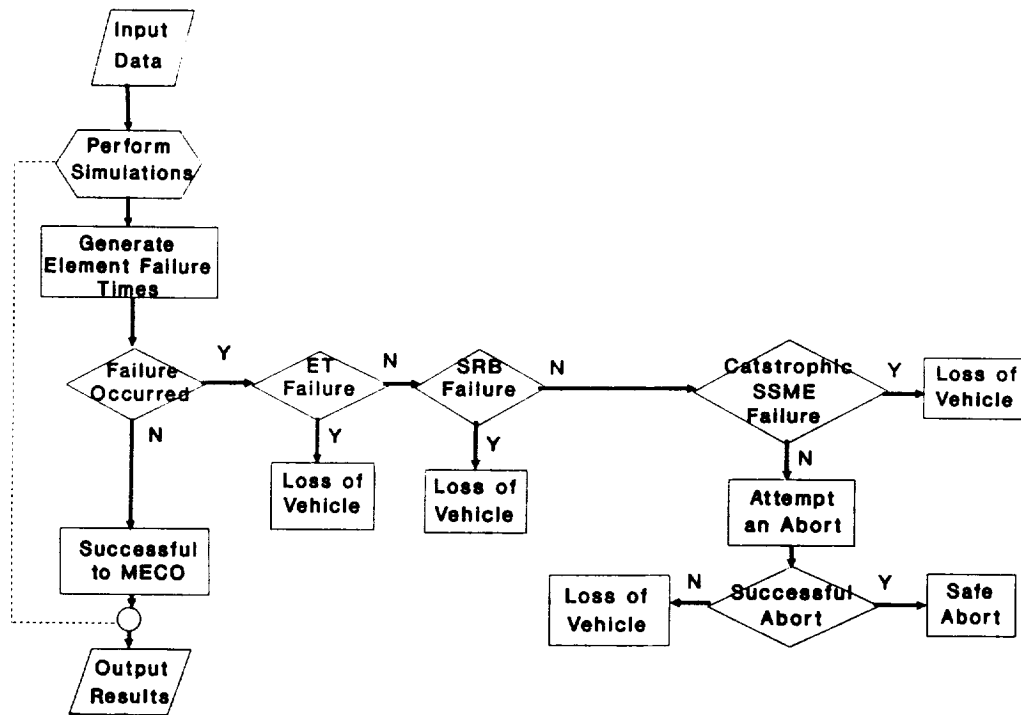
Figure 11. Simulation program overview.

3.2 Program Modules

3.2.1 Initial Abort Selection. Subroutine ABTSLCT represents the selection of abort modes for one-engine out. The subroutine is called when there is one shutdown SSME on the vehicle in a region of the ascent where an abort may be initiated. The region during which a one SSME shutdown abort may be initiated begins at approximately 150 MET and lasts until the time of MECO.

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If there is sufficient time between the first two engine failures to make a decision, the appropriate subroutine (RTLS, TAL, or PRESS) is called based on the vehicle's inertial at the time of the engine failure.

If there is not sufficient time between the first two engine failures to make a decision and if the second failure was not catastrophic, the time of the third engine failure is checked to see if there was enough time before the third engine failure to make a decision. If there is not enough time before the third engine failure and the engine failure is not catastrophic, a subroutine is called to determine if the vehicle successfully completes a late TAL.

If there is enough time between the second and third engine failure to make a decision, the one-SSME abort option is chosen based on the vehicle's VI. If a one-SSME PTM is attempted and the engine fails before abort completion and it is a benign failure, a subroutine is called to simulate a late TAL attempt. If a one-SSME TAL or late TAL is attempted and a benign engine failure occurs before abort completion, the vehicle and crew are lost if they are in a black zone or the vehicle is lost and the crew bails out. If the one-SSME VI is less than the VI required for a TAL droop, the crew is said to bail out and the vehicle is said to be lost.

3.2.2 RTLS Performance. Subroutine RTLS represents the RTLS success/failure logic. This subroutine is called from ABTSLCT when an RTLS attempt is selected based on the ascent VI value at which there was one shutdown SSME.

If a benign second engine failure occurs before the completion of a two-SSME RTLS and there is adequate time between either the first and second failures or the second and third failures to make a decision, a one-SSME RTLS is attempted. If there is a benign failure of the third engine before the completion of the one-SSME RTL's, the VI of the vehicle is checked to see if it is in a black zone. If the vehicle is in a black zone, the vehicle and crew are said to be lost, otherwise the vehicle is lost and the crew bails out.

If there are three engine failures of which none are catastrophic before a decision can be made, either the vehicle and crew will be lost or just the vehicle will be lost, depending on whether or not the vehicle is in a black zone region.

3.2.3 TAL Performance. Subroutine TAL represents the TAL success/failure logic. This subroutine is called from ABTSLCT when a TAL attempt is selected based on the ascent VI value at which there was one shutdown SSME.

If a second benign engine failure occurs before the completion of a two-SSME TAL and there is enough time to make a decision before a third engine failure, a one-SSME TAL redesignation option is selected by calling the subroutine TALSLCT. If the vehicle's VI is too low, a crew bailout is performed, otherwise an attempt for the selected one-E TAL site is attempted. If a third benign engine failure occurs before the abort is completed, the crew either bails out or is lost depending on whether or not the vehicle is in a black zone.

If there is not enough time between the first and second engine failures to make a decision, either a one-SSME TAL attempt to the primary site or a TAL droop will be attempted if the vehicle has an adequate VI value. If a third benign engine failure occurs before the completion of either a one-E TAL or TAL droop attempt, a contingency abort is attempted. If the VI value is less than the VI boundary value for a TAL droop, the crew is said to bail out and the vehicle is said to be lost.

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3.2.4 <u>TAL Redesignation Option Selection</u>. Subroutine TALSLCT represents the logic for selection of a two-engine out TAL redesignation site. If the rounded value for the VI at the time of the first engine failure is greater or equal to the lowest VI value for one-SSME TAL capability, the subprogram of the value of the first engine out entry that matches up with the VI at which the first engine failed is found by performing a loop for the total number of TAL redesignation velocities. When a value is found that corresponds to the VI at the first failure, the integer parameter that corresponds to this value is assigned the value that the counter has at that time.

After the proper column is found on the TAL redesignation chart, the option that will be selected at that value of the first engine failure is chosen. To select the correct option, a loop is first entered that will be performed for the total number of redesignation options for two engines out. Whenever the rounded value for the VI of the second failure is greater than or equal to the boundary value at an option, the option variable is assigned the value of the counter corresponding to that option. After the loop is completed, the option variable will contain the value that corresponds to the redesignation option that has been chosen.

3.2.5 <u>Late TAL Performance</u>. Subroutine LATETAL represents the late TAL success/failure logic. This subroutine is called from ABTSLCT, TAL, and PRESS after an early MECO occurs in a region where a late TAL can be attempted.

If the inertial velocity of the vehicle is less than that required for the earliest late TAL capability, a contingency abort is attempted. If the VI value is less than or equal to the boundary for the first option but greater than or equal to the earliest late TAL boundary value, then the vehicle is said to successfully land at the first late TAL site. For the subsequent late TAL options, if the VI value is less than the boundary value, the vehicle is said to successfully land at the late TAL site corresponding to that option. If the VI value is greater than the value for the last option (the option with the highest VI boundary value), then contingency abort will be attempted.

3.2.6 <u>PTM and PTA Performance</u>. Subroutine PRESS represents the PTA and PTM success/failure logic. This subroutine is called from ABTSLCT when a PTA or PTM attempt is selected based on the ascent VI value at which there was one shutdown SSME.

Whether a two-SSME PTA attempt or a two-SSME PTM attempt will be made is first determined. The logic for both a two-SSME PTA and a two-SSME PTM attempt are similar to each other with the only difference being the two-SSME attempts.

If a second benign SSME failure occurs during the completion of the two-SSME abort attempt, and there is adequate decision time between the times of the engine failures, either a crew bailout, a TAL droop, a one-SSME TAL to the primary site, or one-SSME PTM is attempted. If the vehicle has an inertial velocity less than that required for a TAL droop attempt, the crew bails out and the vehicle is lost. If a benign engine failure occurs before the completion of an attempted one-SSME abort option, the subroutine LATETAL is called to determine if the vehicle successfully completes a late TAL.

If there is not enough decision time before the second benign engine failure and if the third benign engine failure does not happen before the required decision time, logic similar to the case where the time between the first and second failures is not less than the decision time is followed. If there is not enough time to make a decision between either the first and the second or the second and third engine

failure times, the subroutine LATETAL is called to determine if the vehicle successfully completes a late TAL attempt.

3.2.7 <u>Random Number Generation</u>. Function RANDOM is the pseudo-random number generator for the program.

3.2.8 <u>Exponential Distribution Value Generation</u>. Function EXPON creates exponentially distributed random variables. The generated random number is converted in this function to an exponentially distributed random variable by using the formula:

$$EXPON = -THETA*LN(RANDOM) \ , \tag{10}$$

where:

EXPON = an exponentially distributed random number

THETA = the MTBF for the exponential distribution

RANDOM = a randomly generated number, Unif(0..1) .

3.2.9 <u>Uniform Distribution Value Generation</u>. Function UNFRM creates uniformly distributed random variables. The generated random number is converted in this function to a uniformly distributed random variable by using the formula:

$$UNFRM = A+(B-A)*RANDOM \ , \tag{11}$$

where:

UNFRM = a uniformly distributed random number

A = the lowest possible value

B = the highest possible value

RANDOM = a randomly generated number, Unif(0..1) .

3.2.10 <u>SRB Time to Failure Generation</u>. Function SRBFT determines the failure time for the SRB pair. As can be seen from the code, it is first determined whether the SRB pair will fail, based on the probability of failure. If it is determined that it will fail, a time of failure is generated which will lie in the time from SRB ignition to SRB separation. If it is determined that it will not fail, the failure time is set to be a very high number.

3.2.11 <u>ET Time to Failure Generation</u>. Function ETFT determines the failure time for the ET. As can be seen from the code, it is first determined whether the ET will fail, based on the probability of failure. If it is determined that it will fail, a time of failure is generated which will lie in the time from SRB ignition to nominal MECO separation. If it is determined that it will not fail, the failure time is set to be a very high number.

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3.2.12 <u>SSME Time to Failure Generation</u>. Subroutine FLRTIME determines engine failure times. This function is used for calculating several different times-to-failure for the SSME's: the time-to-failure for the first engine at 100 percent, the time-to-failure for the first engine at 104 percent, the time-to-failure for an inhibited SSME for the second failure, the time-to-failure for an enabled SSME for the second failure, the time-to-failure at 104 percent for an inhibited SSME for the third failure, the time-to-failure at 104 percent for an enabled SSME for the third failure, the time-to-failure at 109 percent for an inhibited SSME for the third failure, and the time-to-failure at 109 percent for an enabled SSME for the third failure.

FLRTIME(1) is called to determine the failure times before a failure occurs. The engines are first sorted according to their times-to-failure at 100 percent. The position of the engine that experiences the first failure, its time-to-failure (ENGT(1)), and the criticality of the failure are the returned values. The engines are then sorted according to their times-to-failure at 104 percent. The position of the engine that experiences the first failure, its time-to-failure (ENGT(2)), and the criticality of the failure are the returned values.

FLRTIME(2) is called to determine the failure times after one engine failure occurs. The inhibited engine at 104 percent that experiences the second failure is determined by comparing the inhibited engine failure times at 104 percent. The position of the second engine that failed, its time-to-failure (ENGT(3)), and its criticality are the returned values. The enabled engine at 104 percent that experiences the second failure is determined by comparing the enabled engine failure times at 104 percent. The position of the second engine that failed, its time-to-failure (ENGT(4)), and its criticality are the returned values.

FLRTIME(3) is called to determine the failure times after a second engine failure occurs. The inhibited engine at 104 percent that experiences the third failure is determined by comparing the inhibited engine failure times at 104 percent. The position of the third engine that failed, its time-to-failure (ENGT(5)), and its criticality are the returned values. The enabled engine at 104 percent that experiences the third failure is determined by comparing the enabled engine failure times at 104 percent. The position of the third engine that failed, its time-to-failure (ENGT(6)), and its criticality are the returned values. The inhibited engine at 109 percent that experiences the third failure is determined by comparing the inhibited engine failure times at 109 percent. The position of the third engine that failed, its time-to-failure (ENGT(7)), and its criticality are the returned values. The enabled engine at 109 percent that experiences the third failure is determined by comparing the enabled engine failure times at 109 percent. The position of the third engine that failed, its time-to-failure (ENGT(8)), and its criticality are the returned values.

3.2.13 <u>SSME Failure Time Determination</u>. Function TIMEF determines the corresponding mission times at which engine failures occur. This function is used to calculate engine failure time for several different conditions during a mission: the time of failure for engines exposed to prelaunch operation, the time of failure for the engines exposed to first stage operation, the time of the second engine failure, the time of failure for engines exposed to second stage operation, the time interval between the first and second engine failures, the time interval between the second and third engine failures, the time of failure of the third engine at 104 percent, the time of failure of the third engine for TAL redesignation option attempts, and the time of failure of the third engine at 109 percent.

For TIMEF(1), the time of the first engine failure at 100 percent is determined. The engine with the earliest failure time at 100 percent, its failure time, and criticality are returned.

For TIMEF(2), the time of a failure for the first stage is determined. It is determined if a failure occurs before, during, or after the throttle-bucket based on the earliest engine failures at 100 and 104 percent. If a failure occurs during one of the three phases, the appropriate time of the engine failure is determined by considering the engine times to failure at 100 and 104 percent. The returned values are the time of the first engine failure, the position of the engine, the criticality of failure, and a value that represents the number of engine failures at 104 percent.

For TIMEF(3), the time of a second engine failure is determined by considering whether the engines are inhibited, and whether there was a previous engine failure at 104 percent. The returned values are the time of the second engine failure, the position of the engine, and the criticality of the failure.

For TIMEF(4), the time of an engine failure for the second stage is determined. The failure time is determined by considering if a failure occurs either before pre-MECO throttle-down or during pre-MECO throttle-down. If a failure occurs during either phase, the appropriate time of the engine failure is determined by considering the engine times to failure at 100 and 104 percent. The returned values are the time of the first engine failure, the position of the engine, and the criticality of the failure.

For TIMEF(5), the time between the first and second engine failures is determined by considering whether the engines are inhibited, and whether there was a previous engine failure at 104 percent. The returned values are the time between the first and second engine failures, the time of the second engine failure, the position of the engine that fails second, and the criticality of the second engine failure.

For TIMEF(6), the time between the second and the third engine failures is determined by considering whether engines are inhibited. The returned values are the time between the second and third engine failures, the time of the third engine failure, the position of the engine that fails third, and the criticality of the third engine failure.

For TIMEF(7), the time that a third engine fails while performing at 104 percent is determined by considering whether the engines are inhibited. The returned values are the time of the third engine failure, the position of the failed engine, and the criticality of the failure.

For TIMEF(8), the time that a third engine fails while a TAL redesignation attempt is being performed is determined by considering whether the engines are inhibited and what thrust level is being used with the engine to complete the abort attempt. The returned values are the time of the third engine failure, the position of the failed engine, and the criticality of the failure.

For TIMEF(9), the time that a third engine fails while performing at 109 percent is determined by considering whether the engines are inhibited. The returned values are the time of the third engine failure, the position of the failed engine, and the criticality of the failure.

3.2.14 SSME Required Run Time Determination. Function TREQD determines the required engine run times. This function is used to calculate the required engine run times for several different situations: the time required for the remaining engine to run to complete a one-engine PTM, the time required for the remaining engine to run to complete a one-engine TAL at 104 percent, the time required for the remaining engine to run to complete a TAL droop, the time required for the remaining engines to run to complete a two-engine RTLS, the time required for the remaining engine to run to complete a one-engine RTLS, the time required for the remaining engines to run to complete a two-engine PTA, the time required for the remaining engines to run to complete a two-engine PTM, the time required for the

remaining engine to run to complete a one-engine TAL to a redesignation site, the time required to complete the throttle-bucket phase of the first stage, the time required to complete the 104-percent portion of the first stage, the time required to complete the pre-MECO throttle-down phase of the second stage, the time required for the remaining engines to run to complete a two-engine TAL, and the time required to complete the 104-percent portion of the second stage.

For TREQD(1), the time that is required for the completion of a 1-E PTM, which is a function of the times of the first and second engine failures, is returned.

For TREQD(2), the time that is required for the completion of a 1-E TAL at 104 percent, which is a function of the times of the engine failures and the vehicle acceleration values, is returned.

For TREQD(3), the time that is required for the completion of a TAL droop, which is a function of the times of the engine failures and the vehicle acceleration values, is returned.

For TREQD(4), the time that is required for the completion of a 2-E RTLS, which is a function of the time of the engine failure, is returned.

For TREQD(5), the time that is required for the completion of a 1-E RTLS, which is a function of the times of engine failures, is returned.

For TREQD(6), the time that is required for the completion of a 2-E PTA, which is a function of the time of the engine failure, is returned.

For TREQD(7), the time that is required for the completion of a 2-E PTM, which is a function of the time of the engine failure, is returned.

For TREQD(8), the time that is required for the completion of a 1-E TAL to a redesignation site, which is a function of the times of the engine failures and the acceleration values, is returned.

For TREQD(9), the time that is required for the engines to operate at 100 percent during the prelaunch and the first stage is returned.

For TREQD(10), the time that is required for the engines to operate at 104 percent during the first stage is returned.

For TREQD(11), the time that is required for the engines to operate at 100 percent during the second stage is returned.

For TREQD(12), the time that is required for the completion of a 2-E TAL, which is a function of the vehicle's acceleration, is returned.

For TREQD(13), the time that is required for the engines to operate at 104 percent during the second stage is returned.

3.2.15 Vehicle's Black Zone Status Determination. Function BLKZONE determines whether or not the vehicle is in a three-engine out black zone.

As can be seen from the code, this subprogram compares the VI at the time of the third engine failure with the boundaries of the black zone VI boundaries for three-SSME's out. The vehicle is said to be in a black zone if the VI at the time of the third engine failure is greater than or equal to 8,000 and less than or equal to 18,000.

3.2.16 <u>Vehicle Inertial Velocity Determination</u>. Function VI determines the inertial velocity which corresponds to the engine failure times. This function is used to calculate the vehicle's inertial velocity for various engine failure situations: the inertial velocity of the vehicle at the time of the first engine failure, the inertial velocity at the time of the second engine failure, the inertial velocity at the time of the third engine failure for the last engine functioning at 104 percent, and the inertial velocity at the time of the third engine failure for the last engine functioning at 109 percent.

For VI(1), the vehicle's inertial velocity at the time of the first engine failure, which is a function of the ascent trajectory coefficients, is returned.

For VI(2), the vehicle's inertial velocity at the time of the second engine failure, which is a function of times of the engine failures and the acceleration values, is returned.

For VI(3), the vehicle's inertial velocity at the time of the third engine failure for the last engine functioning at 104 percent, which is a function of the times of engine failures and the acceleration values, is returned.

For VI(4), the vehicle's inertial velocity at the time of the third engine failure for the last engine functioning at 109 percent, which is a function of the times of the engine failures and the acceleration values, is returned.

IV. SAMPLE APPLICATION

Data were input into the simulation program to determine the frequency of occurrence of the various ascent/abort options for the flight of STS-32. The results are limited by the assumptions and may indicate where further refinement of the shuttle system element models, ascent trajectory, or abort mode models are required. The results presented are for the purpose of demonstrating the use of the program only and are not official NASA estimates of probabilities. The summary from the simulation is shown in appendix I.

4.1 Model Input

Data for the simulation were obtained from the ascent checklist—STS-32 flight supplement, SSME reliability studies, ET and SRB reliability studies, and mission duration information. The input data used are as follows:

Number of simulations: 1,000,000

<u>TAL Sites</u>:

Primary two-engine TAL site:	Ben Guerir (BEN)
Primary one-engine TAL site:	Banjul (BYD)
Primary TAL droop target:	Banjul
Last two-engine TAL site:	Moron (MRN)
First late TAL site:	Amilcar Cabral (AML)
Second late TAL site:	Banjul

Third late TAL site:	Kinshasa (KIM)
Fourth late TAL site:	Hoedspruit (HDS)
First TAL redesignation option:	Droop to Banjul
Second TAL redesignation option:	TAL to Banjul
Third TAL redesignation option:	TAL to Ben Guerir

VI Boundary Values (ft/s)

Two-engine to primary TAL:	6,200
MECO for TAL:	24,000
Nominal MECO:	25,918
Negative return:	8,400
Two-engine Press to ATO:	9,600
Two-engine Press to MECO:	13,900
One-engine Press to MECO:	16,800
One-engine to primary TAL:	13,700
TAL droop to primary target:	12,000
Last two-engine TAL:	13,500
First late TAL:	22,700
Second late TAL:	24,500
Third late TAL:	25,200
Fourth late TAL:	25,500
Earliest late TAL:	22,000
Lower black zone boundary:	8,000
Upper black zone boundary:	18,000

First Engine-Out TAL Redesignation Increments (ft/s)

#		#		#		#	
1	6,200	11	7,200	21	8,200	31	9,200
2	6,300	12	7,300	22	8,300	32	9,300
3	6,400	13	7,400	23	8,400	33	9,400
4	6,500	14	7,500	24	8,500	34	9,500
5	6,600	15	7,600	25	8,600		
6	6,700	16	7,700	26	8,700		
7	6,800	17	7,800	27	8,800		
8	6,900	18	7,900	28	8,900		
9	7,000	19	8,000	29	9,000		
10	7,100	20	8,100	30	9,100		

Droop to BYD TAL (109 percent) Redesignation Option (ft/s)

#		#		#		#	
1	10,900	11	11,100	21	11,300	31	11,500
2	10,900	12	11,200	22	11,300	32	11,500
3	11,000	13	11,200	23	11,400	33	11,500
4	11,000	14	11,200	24	11,400	34	11,500
5	11,000	15	11,200	25	11,400		
6	11,000	16	11,200	26	11,400		
7	11,000	17	11,300	27	11,400		
8	11,100	18	11,300	28	11,400		
9	11,100	19	11,300	29	11,400		
10	11,100	20	11,300	30	11,500		

BYD TAL (104 percent) Redesignation Option (ft/s)

1	—	11	—	21	13,900	31	13,600
2	—	12	—	22	13,900	32	13,600
3	—	13	—	23	13,800	33	13,600
4	—	14	—	24	13,800	34	13,600
5	—	15	—	25	13,800		
6	—	16	14,300	26	13,700		
7	—	17	14,200	27	13,700		
8	—	18	14,100	28	13,700		
9	—	19	14,000	29	13,700		
10	—	20	13,900	30	13,700		

BEN TAL (109 percent) Redesignation Option (ft/s)

1	16,400	11	14,900	21	14,000	31	13,800
2	16,300	12	14,800	22	14,000	32	13,800
3	16,100	13	14,700	23	13,900	33	13,700
4	16,000	14	14,600	24	13,900	34	13,700
5	15,800	15	14,400	25	13,900		
6	15,700	16	14,300	26	13,900		
7	15,500	17	14,300	27	13,800		
8	15,400	18	14,200	28	13,800		
9	15,200	19	14,100	29	13,800		
10	15,100	20	14,100	30	13,800		

Element Failure Probabilities

SRB pair failure:	1/258
ET failure:	1/10,000

SSME Time-to-Failure Parameters

Benign failures (100 percent):	22,277.7 s
Benign failures (104 percent):	22,889.6 s
Benign failures (109 percent):	9,744.1 s
Catastrophic failures (100 percent):	149,693.5 s
Catastrophic failures (104 percent):	77,252.4 s
Catastrophic failures (109 percent):	13,181.1 s

Launch/Ascent Phase Times (s)

Duration of the prelaunch phase:	6.6
Beginning of "throttle bucket":	25
End of the "throttle bucket":	70
Time of SRB separation:	130
Time of RTLS capability:	150
Beginning of throttle down:	460
Time of MECO:	516

Vehicle Acceleration Values (ft/s^2)

Two functioning SSME's
104-percent thrust: 44.31
One functioning SSME
104-percent thrust: 22.16
109-percent thrust: 23.23

Required Decision Time

15 s

Enable/Inhibit Switch Status

Enabled

4.2 Model Output

The frequency of occurrence of the ascent and abort events during the mission phases and abort modes (for 1,000,000 simulations) are as follows:

Prelaunch

On-pad shutdown	802
Catastrophic SSME failure	2

First Stage

Crew bail-out	142
Catastrophic SSME failure	4,197
ET failure	2
SRB failure	2,921

Second Stage

Nominal ascent	914,416
Successful one-engine TAL to BYD	36
Successful TAL droop to BYD	35
Successful one-engine PTM	2
Crew bail-out	110
Catastrophic SSME failure	13,338

Return to Launch Site

Successful two-engine RTLS	20,017
Successful one-engine RTLS	1,333
Catastrophic SSME failure	327

TAL

Successful two-engine TAL to Ben	13,191
Successful redesignation TAL droop to BYD	107
Successful redesignation TAL to BEN	219
Crew bail-out	74
Catastrophic SSME failure	37

Press to MECO and Abort to Orbit

Successful two-engine PTM	1,198
Successful two-engine ATO	514
Successful one-engine PTM	361
Successful one-engine TAL to BYD	145
Successful TAL droop to BYD	36
Crew bail-out	35
Catastrophic SSME failure	73

4.3 Results

For the sample application that was considered, several interesting observations can be made. The results showed that the shuttle achieved orbit without problems 91.442 percent of the time. The system was safely shut down on the pad 0.080 percent of the time. An ET failure occurred 0.0002 percent of the time, and an SRB failure occurred 0.292 percent of the time. The vehicle successfully completed an abort 6.352 percent of the time. Catastrophic main engine failures occurred 1.797 percent of the time. The crew survived by bailing out of the vehicle 0.036 percent of the time. The crew and vehicle survived the performance of abort attempts 99.147 percent of the time.

V. SUMMARY AND CONCLUSIONS

5.1 Conclusions

The model developed was a significant effort toward the use of probabilistic characterization of the performance of the space shuttle in relation to its abort modes. The model allows the estimation of percentages of occurrences of various abort options for provided input for a mission.

The computer program that was developed can be used to analyze the effects of the variation in parameters on the space shuttle performance of abort modes. The program can be used to analyze specific missions or the general effect of parameter variations on the space shuttle missions.

5.2 Recommendations for Future Research

The model that has been developed is intended to be a first step toward the development of a simulation model for the analysis of space shuttle aborts. Future work should be performed in relation to the following areas:

1. Incorporation of abort modes that are initiated for system failures

2. Refinement of the approaches that were used to estimate the performance of abort options

3. Expansion of the model to include other mission phases, such as aborts that occur from orbit

4. Improvement of the propulsion element failure models.

5. Incorporation of the use of a more accurate probability distribution, such as a Weibull distribution, into the program code to provide for a more accurate representation of the time to failure behavior of the SSME's.

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APPENDIX A

Ascent Checklist—STS-32 Flight Supplement

No Comm Mode Boundaries card definitions:

NEG RETURN (104)	= Last RTLS capability
PRESS TO ATO (104)	= First two-engine Press-to-ATO capability
DROOP BYD (109)	= First TAL droop capability at 109-percent RPL
PRESS TO MECO (104)	= First Press-to-MECO capability at 104-percent RPL
LAST MRN (104)	= Last two-engine TAL to Moron capability
SE BYD (104)	= First one-engine TAL to Banjul capability at 104-percent RPL
LAST BEN (104)	= Last two-engine TAL to Benguier capability
SE PRESS (104)	= First one-engine Press-to-MECO capability at 104-percent RPL
LAST AUTO BYD	
2 or 3 engine (65)	= Last Auto TAL capability to Banjul with two or three engines at 65-percent RPL
1 engine (104)	= Last Auto TAL capability to Banjul with one engine at 104-percent RPL
LAST LATE TAL BYD	= Last late TAL to Banjul capability
LAST LATE TAL KIN	= Last late TAL to Kinshasa capability
LAST LATE TAL HDS	= Last TAL to HDS capability
2 ENG BEN (104)	= First two-engine TAL capability to Benguier at 104-percent RPL
ABORT TAL BEN	
EO VI	= VI value at the time of the first engine failure
DROOP AML (109)	= TAL redesignation value for the first TAL droop capability at 109-percent RPL
SE BYD (109)	= TAL redesignation value for the first one-engine TAL capability to Banjul at 109-percent RPL
SE BEN (109)	= TAL redesignation value for the first one-engine TAL capability at Benguier at 109-percent RPL
2 ENG MRN (104)	= First two-engine TAL capability to Moron at 104-percent RPL
ABORT TAL MRN	
EO VI	= VI value at the time of the first engine failure
DROOP GDV (109)	= TAL redesignation value for the first TAL droop capability at 109-percent RPL
SE BYD (109)	= TAL redesignation value for the first one-engine TAL capability to Banjul at 109-percent RPL
SE BEN (109)	= TAL redesignation value for the first one-engine TAL capability to Banguier at 109-percent RPL
SE MRN (109)	= TAL redesignation value for the first one-engine TAL capability to Banguier at 109-percent RPL

BAILOUT
EGRESS

| PILE |
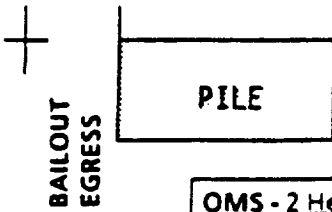
SYS FLIGHT RULES

	RTLS	TAL/ LATE TAL
OMS - 2 He TKs		X
1 OX & 1 FU TKS (diff pods)		X
2 OX or 2 FU TKS		X
APU/HYD - 2+ & 1 failing	X	X
CABIN LEAK - dp/dt ≥ .15	X	X
CRYO - All O_2 (H_2)	X	X
2 FREON LOOPS +	X	X
2 MAIN BUSSES +	X	
THERMAL WINDOW PANE	X	

NO COMM MODE BOUNDARIES

NEG RETURN (104)	8400	2 ENG BEN (104)	6200
PRESS TO ATO (104)	9600	**ABORT TAL BEN (2)**	
DROOP BYD (109)	12000	EO VI	[ ]
		DROOP BYD (109)(5)	[ ]
LAST MRN (104)	13500	SE BYD (104) (5)	[ ]
SE BYD (104)	13700	SE BEN (109) (2)	[ ]
PRESS TO MECO (104)	13900		
SE PRESS (104)	16800		
		2 ENG MRN (104)	6800
LAST BEN (104)	17600	**ABORT TAL MRN (3)**	
LAST AUTO BYD		EO VI	[ ]
2 or 3 engine (65)	20000		
1 engine (104)	21500	DROOP BEN (109)(2)	[ ]
LAST LATE TAL		SE BEN (104) (2)	[ ]
AML	22700		
BYD	24500	SE BYD (104) (5)	[ ]
KIN	25200		
HDS	25500	SE MRN (109) (3)	[ ]

FB 2-4   ASC/32/FIN A

PILE

AUTO TAL CDR

ABORT TAL
* No joy: G51 TAL ABORT *
* If GUID unconverged: *
*   CSS, $\theta = 60°$, $\beta = 0$ *
* When $\theta_{CMD} \leq 60°$: AUTO *
G50 SEL SITE, RWY (PASS/BFS)

SITE	RWY	TACANS			MLS	LENGTH
2	BEN 36	BEN 118 -	CBA 116 (DME)		6	12730
	BEN 18	BEN 118 -	CBA 116 (DME)		.	12730
3	MRN 21	MRN 100 -	AOG 23		6	11800
	MRN 03	MRN 100 -	AOG 23		.	11800
5	BYD 32	BYD 121Y	-	BJ76 (DME)	6	10420
	BYD 14	BYD 121Y	-	BJ76 (DME)	.	10420

$V_I \sim$ 15.4K   Roll to Heads Up
                   /AUTO THROT
---------- **MECO** --- BFS - C/O BUG (V_I approx 24.0K) -- **MECO** ----------

MECO+18   /ET SEP, /AUTO -Z TRANS
MECO+35   /MM104 ————————————————————
           /P=10±30, Y=0±30; RATES < .5°/sec
           /ET DOORS MOVING
            PASS OPS 301 PRO (Start watch)

            * No joy in 68 sec: BFS - ENGAGE *
            * BFS, OPS 301 PRO   *
------------------------- **MM304** -------------------------

           /P,Y - SPDBK, BDY FLP - AUTO
            BFS, OPS 301 PRO (/MM304)
           /G50 SPDBK, ITEM 39   50K
           /Bugs, HDG, RANGE, $\alpha = 40°$ 40
            * Low energy: CSS, $\alpha = 40°$ * 30
            *   WINGS LVL   * 20
            * At $\dot{H} = 0$: fly $\alpha = 31°$ * 7
            * Maintain $\Delta AZ \leq 20$ * SURF
            Adjust seat
V = 10   /SPDBK → 81%   SPDBK @ 3000 FT

           /TACAN MODE (three) - GPC

V = 5   AIR DATA PROBES (two) - DEPLOY, (/Heat)
           /RUD, AIL TRIM
M = 3.2   /SPDBK → 65%
M = 2.7   HUD PWR (two) - ON
M = 2.0   Ensure ADTA to G&C else THETA limits
M = 0.9   P,R/Y - CSS, SPDBK - MAN (as reqd)
           /NWS - GPC
POST LANDING: ENT C/L, POST LANDING

WINDS

| / |
| / |
| / |
| / |
| / |
| / |
| |

RTLS

FB 2-14   ASC/32/FIN A

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LATE TAL CDR

V_I = [24.0K] ME SHUTDN pb (three) - push
*If 1 SSME out at PTA, subtract 200 fps *

```
PILE
```

α = 40/31
22.0 22.7 23.1

| AML (9) |

24.3

BYD (5) ──────────→ 24.5 ←── KIN (6) ──→ HA→HP > AOA-S ←── AOA-S

OMS-OFF ──────────→ 24.6 ENA ICNCT
He (4)-OP   OMS-OFF
[G51] ENA ICNCT   He (4)-OP 25.2   25.5

24.8

HDS (7) /MCC ──────────→
ENA ICNCT   OMS-OFF
25.0 He (4)-OP
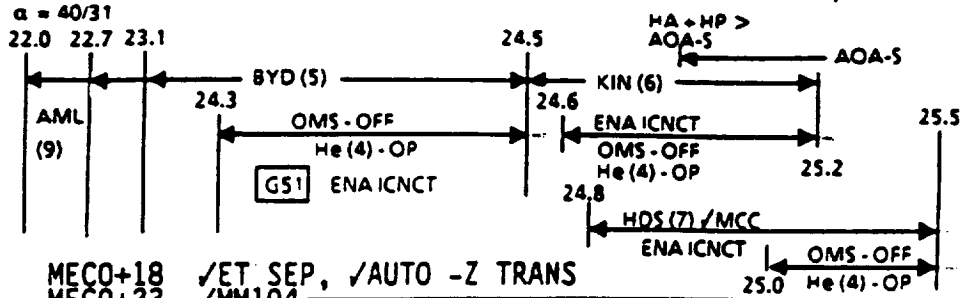
MECO+18   ✓ET SEP, ✓AUTO -Z TRANS
MECO+23   ✓MM104
          ✓P = 10±30, Y = 0±30; RATES < .5°/sec
          ✓ET DOORS MOVING
          PASS OPS 301 → 304 PRO

-------- MM304 ------------------------------------- MM304 -----

SITE	RWY	TACANS		MLS	LENGTH
5	BYD 32	BYD 121Y ·	BJ 76 (DME)	6	10420
	BYD 14	BYD 121Y ·	BJ 76 (DME)	·	10420
6	ROB 04	ROB 85 (DME)	—	·	11160
	KIN 25	BZ 78 (DME)	—	·	15510
7	KKI 15	RIY 92	—	·	13700
	HDS 18	HS 73 (DME)	—	·	13120
9	AML 02	CVS 100 (DME)	···	·	10890
	DON 29	DN 84	···	·	11260

PASS [G50] SEL SITE, RWY
BFS OPS 301 → 304 PRO
BFS [G50] SEL SITE, RWY

* Low energy: CSS, α = 40° *
*   WINGS LVL   *
* At Ḣ = 0: fly α = 31°   *
* Maintain ΔAZ ≤ 20   *

[G50] SHORT SPDBK,
      ITEM 39 EXEC   WINDS
      Adjust seat

	50K
	40
	30
	20
	7
	SURF

V = 10   ✓SPDBK → 81%

SPDBK @ 3000 FT

AUTO
TAL

V = 5   AIR DATA PROBES (two) - DEPLOY (✓Heat)
         ✓RUD, AIL TRIM
M = 3.2 ✓SPDBK → 65%
M = 2.7 HUD PWR (two) - ON
M = 2.0 Ensure ADTA to G&C else THETA limits
M = 0.9 P,R/Y - CSS
         ✓NWS - GPC
POST LANDING: ENT C/L, POST LANDING

FB 2-16   ASC/32/FIN A

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ASCENT ADI - NOMINAL
(32 CY 2R)

TIME	θ	$\dot{H}$	H
:30	70	640	9K
:50	64	940	25K
1:10	60	1360	47K
1:30	43	1880	80K
1:50	35	2250	122K
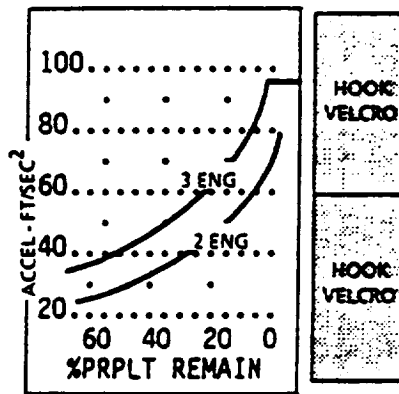
-STAGING-

V$_I$	θ	$\dot{H}$	H
6	19	1800	38nm
7	16	1330	48
8	13	960	54
9	11	670	58
10	9	430	60
12	6	80	62
14	3	-130	62
16	2	-240	61
18	0	-240	60
20	-1	-160	59
22	-1	-10	58
24	-1	180	59
25918	-0	400	60

ASC-14b/32/A/8

BEN TAL REDESIGNATION
(32 CY 2R)

NOTE: DROOP IS 109% THROTTLE;
        FOR 104% THROTTLE, ADD 300 FPS

1ST E.O. VI		6200	6300	6400	6500	6600	6700
SE DROOP BYD (109)	(5)	10900	10900	11000	11000	11000	11000
SE BYD (104)	(5)	---	---	---	---	---	---
SE BEN (109)	(2)	16400	16300	16100	16000	15800	15700

1ST E.O. VI		6800	6900	7000	7100	7200	7300
SE DROOP BYD (109)	(5)	11000	11100	11100	11100	11100	11200
SE BYD (104)	(5)	---	---	---	---	---	---
SE BEN (109)	(2)	15500	15400	15200	15100	14900	14800

1ST E.O. VI		7400	7500	7600	7700	7800	7900
SE DROOP BYD (109)	(5)	11200	11200	11200	11200	11300	11300
SE BYD (104)	(5)	---	---	---	14300	14200	14100
SE BEN (109)	(2)	14700	14600	14400	14300	14300	14200

1ST E.O. VI		8000	8100	8200	8300	8400	8500
SE DROOP BYD (109)	(5)	11300	11300	11300	11300	11400	11400
SE BYD (104)	(5)	14000	13900	13900	13900	13800	13800
SE BEN (109)	(2)	14100	14100	14000	14000	13900	13900

1ST E.O. VI		8600	8700	8800	8900	9000	9100
SE DROOP BYD (109)	(5)	11400	11400	11400	11400	11400	11500
SE BYD (104)	(5)	13800	13700	13700	13700	13700	13700
SE BEN (109)	(2)	13900	13900	13800	13800	13800	13800

1ST E.O. VI		9200	9300	9400	9500
SE DROOP BYD (109)	(5)	11500	11500	11500	11500
SE BYD (104)	(5)	13600	13600	13600	13600
SE BEN (109)	(2)	13800	13800	13700	13700

ASC-8a/32/A/B

MS ONLY   FS 2-30   ASC/32/FIN A

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MRN TAL REDESIGNATION
(32 CY 2R)

NOTE: DROOP IS 109% THROTTLE;
FOR 104% THROTTLE, ADD 300 FPS

1ST E.O. VI		6900	7000	7100	7200	7300	7400
SE DROOP BEN (109)	(2)	11000	11000	11000	11000	11000	11100
SE BEN (104)	(2)	15800	15700	15600	15500	15400	15300
SE BYD (104)	(5)	---	---	---	---	---	---
SE MRN (109)	(3)	16700	16500	16400	16300	16200	16000

1ST E.O. VI		7500	7600	7700	7800	7900	8000
SE DROOP BEN (109)	(2)	11100	11100	11100	11100	11100	11100
SE BEN (104)	(2)	15200	15100	15000	14900	14800	14700
SE BYD (104)	(5)	---	---	---	---	---	---
SE MRN (109)	(3)	15900	15800	15700	15600	15500	15400

1ST E.O. VI		8100	8200	8300	8400	8500	8600
SE DROOP BEN (109)	(2)	11200	11200	11200	11200	11200	11300
SE BEN (104)	(2)	14700	14600	14500	14500	14400	14400
SE BYD (104)	(5)	15200	15100	14900	14800	14700	14500
SE MRN (109)	(3)	15300	15300	15200	15100	15100	15100

1ST E.O. VI		8700	8800	8900	9000	9100	9200
SE DROOP BEN (109)	(2)	11300	11300	11300	11300	11300	11400
SE BEN (104)	(2)	14300	14300	14300	14200	14200	14200
SE BYD (104)	(5)	14400	14300	14200	14100	14100	14000
SE MRN (109)	(3)	15000	15000	15000	15000	15000	14900

1ST E.O. VI		9300	9400	9500
SE DROOP BEN (109)	(2)	11400	11400	11400
SE BEN (104)	(2)	14100	14100	14100
SE BYD (104)	(5)	14000	14000	13900
SE MRN (109)	(3)	14900	14900	14900

ASC-8b/32/A/B

MS ONLY   FS 2-31   ASC/32/FIN A

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APPENDIX B

Enable/Inhibit Switch Model

From conversations with engineers familiar with the SSME, there were two general observations about the performance of the SSME's with the switch in the inhibit position in relation to the performance of the SSME's with the switch in the enable position:

1. Approximately 50 percent of the failures that would have resulted in engine shutdown due to red-line exceedence for the enabled engine case would lead to catastrophic engine failure in the inhibited engine case.

2. The percentage of benign failures that occur in the inhibit situation is a small percentage of the total number of failures. The number of benign failures for the inhibited situation is about 1 percent of the number of benign failures for the enabled situation.

Solving for the time-to-failure parameter estimates for the inhibited engines:

Using the exponential distribution,

$$R(t) = \exp(-L*t) = \exp(-t/P) ,$$

where

$R(t)$ = reliability at time t

L = failure rate

P = mean time to failure .

For catastrophic failures of inhibited engines:

$$1-R(ic)(t) = 1/2*(1-R(eb)(t))$$

$$1-\exp(-t/P(ic)) = 1/2*(1-\exp(-t/P(eb)))$$

$$\exp(-t/P(ic)) = 1/2+1/2*\exp(-t/P(eb))$$

$$-t/P(ic) = \ln(1/2*(1+\exp(-t/P(eb)))) = \ln(1/2)+\ln(1+\exp(-t/P(eb)))$$

$$P(ic) = -t/(\ln(1/2)+\ln(1+\exp(-t/P(ib))))$$

$$P(ic) = -t/(-0.693+\ln(1+\exp(-t/P(eb)))) ,$$

where:

t = time of the engine's exposure at the power level

ic = parameter for catastrophic failures of an inhibited engine

eb = parameter for benign failures of an enabled engine.

Since the catastrophic failures of an inhibited engine can result from either catastrophic failures that would have occurred in an enabled engine or catastrophic failures that are due to the engine being inhibited,

$$L(ict) = L(ic)+L(ec)$$

where

$$P(ict) = (P(ic)*(P(ec))/(P(ic)+P(ec))) \ ,$$

ict = the parameter for the total catastrophic failures of inhibited engines.

For benign failures of an inhibited engine:

$$1-R(ib)(t) = 1/100*(1-R(eb)(t))$$

$$1-\exp(-t/P(ib)) = 1/100-1/100*\exp(-t/P(eb))$$

$$\exp(-t/P(ib)) = 99/100+1/100*\exp(-t/P(eb))$$

$$-t/P(ib) = \ln((1/100)*(99+\exp(-t/P(eb))))$$

$$P(ib) = -t/(-4.60517+\ln(99+\exp(-t/P(eb)))) \ .$$

Estimating the engine power level exposure time:

Using typical values:

$$t(100) = 110 \ s$$

$$t(104) = 405 \ s$$

$$t(109) = 350 \ s \ .$$

Time-to-failure parameter estimate functions for inhibited engines:

Benign, 100 percent: $P = -110/(-4.60517+\ln(99+\exp(-110/P(eb))))$

Benign, 104 percent: $P = -405/(-4.60517+\ln(99+\exp(-405/P(eb))))$

Benign, 109 percent: $P = -350/(-4.60517+\ln(99+\exp(-350/P(eb))))$

Catastrophic: $P = (P(ic)*P(ec))/(P(ic)+P(ec)) \ ,$

where

100 percent: $P(ic) = -110/(-0.693+\ln(1+\exp(-110/P(eb))))$

104 percent: $P(ic) = -405/(-0.693+\ln(1+\exp(-405/P(eb))))$

109 percent: $P(ic) = -350/(-0.693+\ln(1+\exp(-350/P(eb))))$

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ENABLE/INHIBIT SWITCH LOGIC SUMMARY

6

5

4

3

2

1

0

MECO

VI

1-SSME Boundary

2EO

1EO

2EO

1EO

1EO

2EO

1EO

1EO

1EO
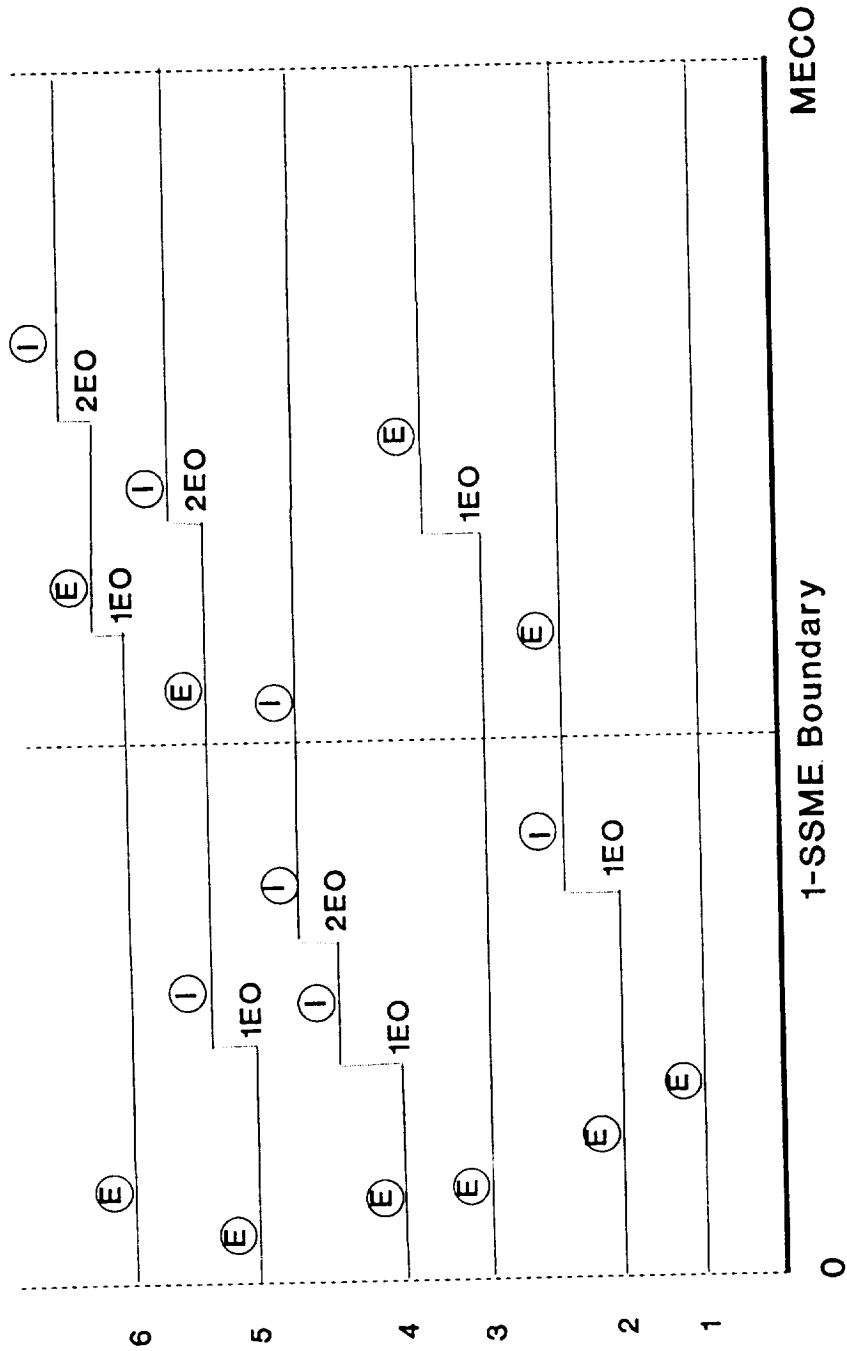
1EO = 1st SSME failure
2EO = 2nd SSME failure
E = Switch in Enable position
I = Switch in Inhibit position

ENABLE/INHIBIT SWITCH MODEL FLOWCHART
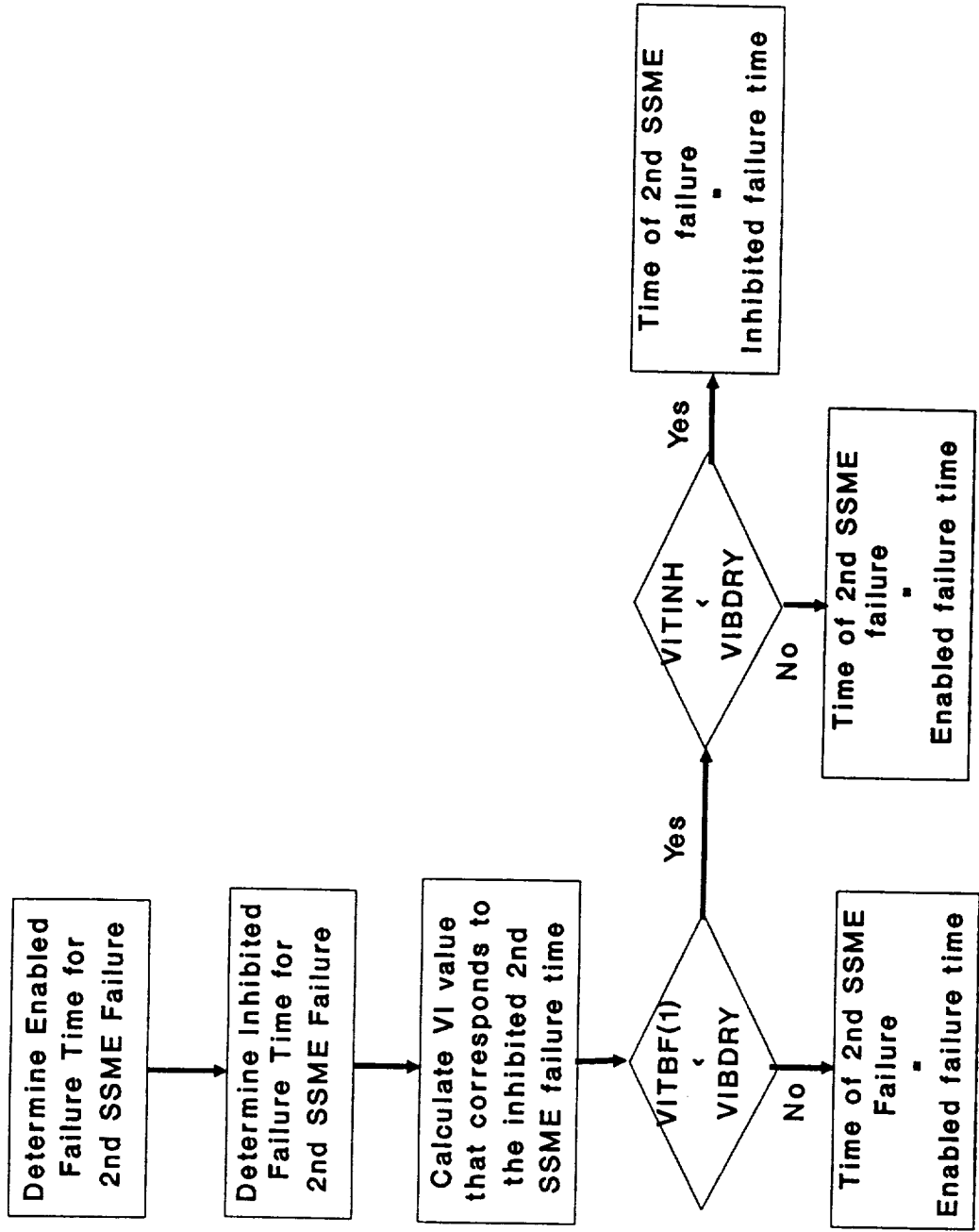
APPENDIX C

Vehicle Ascent Model

The vehicle ascent model was an attempt to determine the inertial velocity of the vehicle as a function of the time in the ascent. Ascent simulation information for STS-27 and STS-29 was referenced. Curves were fit to the VI versus t data for the second stage for each of the missions. It was determined that an exponential function provided a good fit to both sets of data. The function is of the form:

$$VI = \exp(a + b*t) \ .$$

(X 1000)

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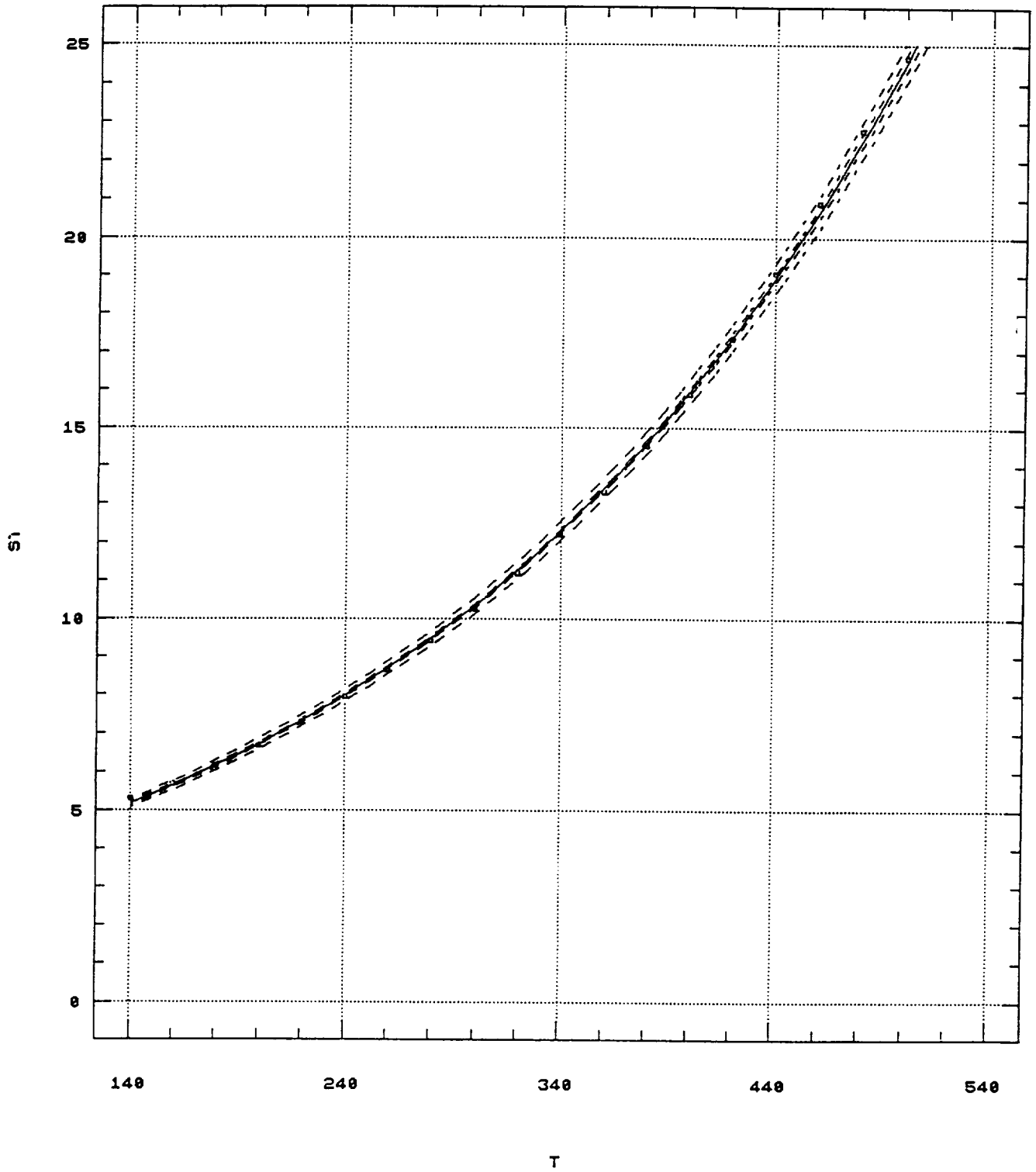
Regression Analysis - Exponential model: Y = exp(a+bX)

Dependent variable: STS27   Independent variable: T

Parameter	Estimate	Standard Error	T Value	Prob. Level
Intercept	7.94512	6.5458E-3	1213.77	.00000
Slope	4.32715E-3	1.93531E-5	223.59	.00000

Analysis of Variance

Source	Sum of Squares	Df	Mean Square	F-Ratio	Prob. Level
Model	4.269	1	4.269	49992.44	.00000
Error	.001452	17	.000085		

| Total (Corr.) | 4.270571 | 18 | | | |

Correlation Coefficient = 0.99983   R-squared = 99.97 percent
Stnd. Error of Est. = 9.24096E-3

(X 1000)

Regression Analysis - Exponential model: Y = exp(a+bX)

ᵣ ᵉndent variable: STS29   Independent variable: T

                              Standard   T   Prob.
Parameter   Estimate   Error   Value   Level

Intercept   7.69441   3.73546E-3   2059.83   .00000
Slope   4.75395E-3   1.10441E-5   430.451   .00000

                          Analysis of Variance

Source   Sum of Squares   Df   Mean Square   F-Ratio   Prob. Level
Model   5.15   1   5.15   185287.7   .00000
Error   .000473   17   .000028

Total (Corr.)   5.153279   18

Correlation Coefficient = 0.999954   R-squared = 99.99 percent
Stnd. Error of Est. = 5.2735E-3

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APPENDIX D

Vehicle Acceleration Estimation

The acceleration of the STS vehicle for the TAL, PTA, and PTM abort modes was estimated by combining information from each of the abort modes to arrive at an estimate that could be used to represent all three of them. The data sources that were referenced to obtain the acceleration estimate were STS-31 TAL simulation data and the Briscoe presentation material.

Estimating the vehicle acceleration for TAL, PTA, and PTM attempts:

For TAL attempts (fig. D-1):

For a 2-E TAL initiated at 186 s MET,

$$ACC = dVI/dT = 34.09 \text{ ft/s}^2 .$$

For a 2-E TAL initiated at 328 s MET,

$$ACC = dVI/dT = 47.24 \text{ ft/s}^2 .$$

Estimating the acceleration for a 2-E TAL with the engines functioning at 104-percent RPL,

$$ACC(TAL) = (34.09+47.24)/2 = 40.7 \text{ ft/s}^2 .$$

For PTM attempts:

Using STS-26 data from reference 1:

$$Tmeco = 516 \text{ s}$$

$$T(\text{init.}) = 320 \text{ s}$$

$$T(\text{comp.}) = 600 \text{ s} ,$$

where

$Tmeco$ = time of nominal MECO

$T(\text{init.})$ = time of the 2-E TAL at 104-percent initiation

$T(\text{comp.})$ = time of the 2-E TAL at 104-percent completion .

From the previous,

$$VI(\text{init.}) = \exp(a+b*320) .$$

From the STS-26 data,

$$a = 7.97$$

$$b = 0.0042766$$

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$$VI(\text{init.}) = 11{,}367 \text{ ft/s} .$$

Similarly,

$$VI\text{meco} = \exp(a+b*516) ,$$

$$VI\text{meco} = 26{,}284 \text{ ft/s} .$$

Estimating the acceleration for a PTM attempt,

$$ACC(PTM) = (VI\text{meco}-VI(\text{init.}))/(T(\text{comp.})-T\text{meco}) = (26{,}284-11{,}367)/(600-320)$$

$$ACC(PTM) = 46.6 .$$

For a 2-E PTM with the engines functioning at 104-percent RPL,

$$ACC(PTM) = 46.6 \text{ ft/s}^2 .$$

For PTA attempts:

Using a similar approach as was used in determining the PTM acceleration estimate value,

$$T\text{meco} = 516 \text{ s}$$

$$T(\text{init.}) = 281 \text{ s}$$

$$T(\text{comp.}) = 619 .$$

$$VI\text{meco} = 26{,}284 \text{ ft/s}$$

$$VI(\text{init.}) = 9{,}621 \text{ ft/s} .$$

For a 2-E PTA with the engines functioning at 104-percent RPL,

$$ACC(PTA) = 49.3 \text{ ft/s} .$$

Combining the TAL, PTA, and PTM results to obtain an overall estimate,

$$ACC = (ACC(TAL)+ACC(PTA)+ACC(PTM))/3 = (40.7+46.6+49.3)/3$$

$$ACC = 45.5 \text{ ft/s}^2 .$$

Assuming that the vehicle's acceleration is proportional to the number of engines functioning and the power level at which the engines are performing,

$$ACC(\text{Engines},\%RPL) = (\text{Engines}/2)*(\%RPL/104)*ACC(2,104)$$

$$= (\text{Engines}/2)*(\%RPL/104)*45.5 ,$$

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where

Engines = number of engines functioning

%RPL = percent of the RPL at which the engines are functioning.

The acceleration values that will be used for the vehicle for the abort options at the various number of functioning engines and engine power levels are therefore:

$$ACC(1,104) = 22.8 \text{ ft/s}^2$$

$$ACC(1,109) = 23.8 \text{ ft/s}^2$$

$$ACC(2,104) = 45.5 \text{ ft/s}^2 .$$
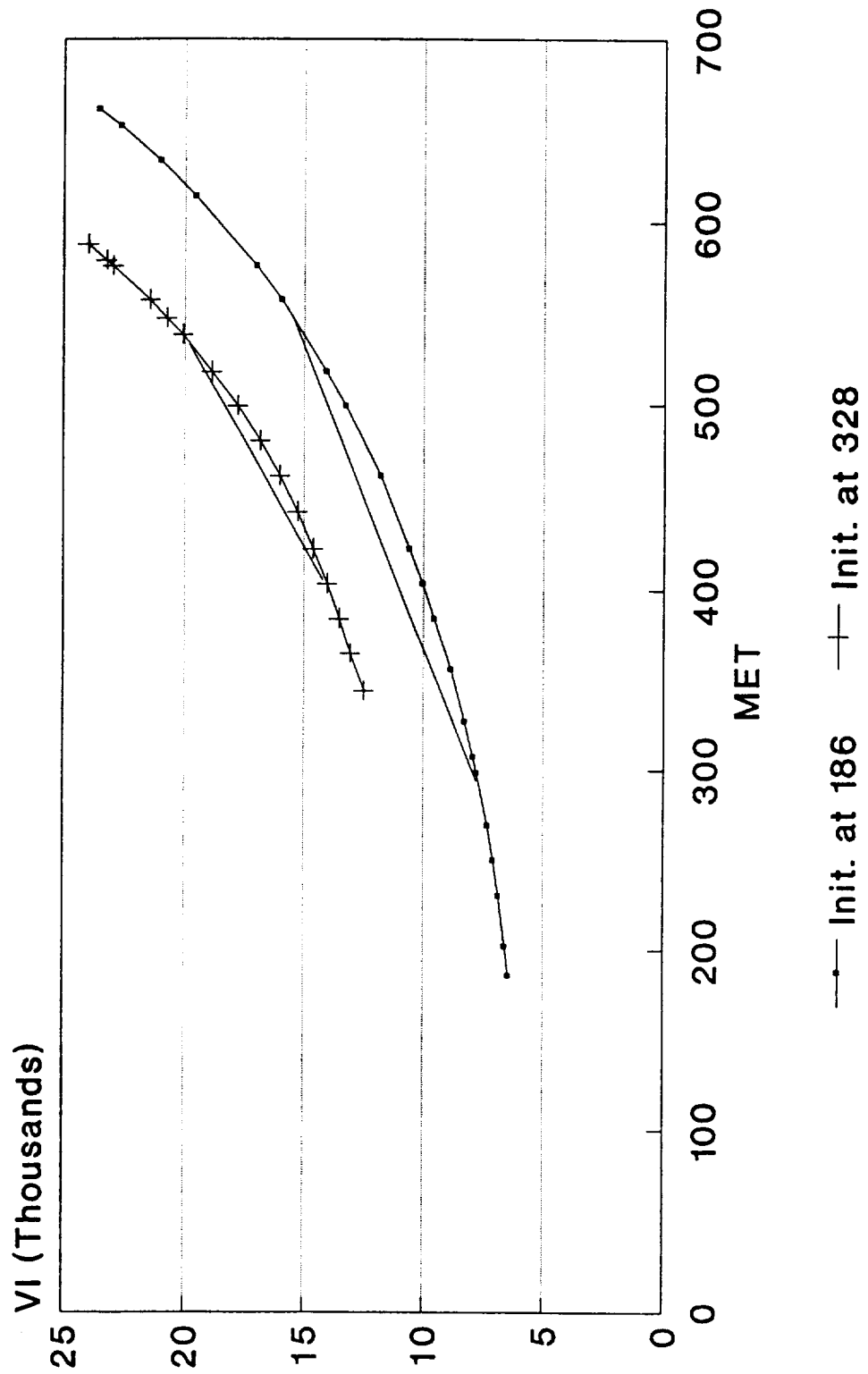
Fig. D-1 - TAL VI vs. MET

APPENDIX E

RTLS Model Development

The RTLS model involved determining the time that would be required to complete an RTLS based on the vehicle's current situation. Data sources that were referenced during the development of the model were the Flight Procedures Handbook—Ascent/Aborts and STS-31 RTLS simulation data.

Developing the RTLS required to complete model:

From the Flight Procedures Handbook, it appears that an RTLS attempt can be divided into two phases, the fuel dissipation phase and the flyback and powered pitchdown phase.

$$T(\text{reqd}) = T(fd) + T(fb \text{ and } PPD) \ ,$$

where

$T(\text{reqd})$ = time required for RTLS completion

$T(fd)$ = time required for fuel dissipation

$T(fb \text{ and } PPD)$ = time required for flyback and powered pitchdown.

From the data (fig. E-1),

$$T(fb \text{ and } PPD) = C = 350 \text{ s}$$

$$T(fd) = b + m*T(\text{init}) = (270/(T(L.\text{RTLS}) - T(E, \text{RTLS})))*(T(L.RTLS) - T(\text{init.})) \ ,$$

where

$T(\text{init})$ = time of RTLS initiation

$T(L.\text{RTLS})$ = time of last RTLS capability

$T(E,\text{RTLS})$ = time of earliest RTLS initiation capability .

Since the VI value for the last RTLS is given (from the no comm mode boundary cards),

$$VI(\text{Last RTLS}) = \exp(a + b*T(\text{last RTLS})) \ , \text{ or}$$

$$T(\text{Last RTLS}) - (\ln(VI(\text{Last RTLS})) - a)/b \ ,$$

where

VI(Last RTLS) = the VI value for last RTLS capability.

The required remaining run time for engines for the successful completion of a two-SSME RTLS abort is therefore:

$$Treqd(2\text{-E RTLS}) = 350+(270/(T(L.RTLS)-T(E.RTLS)))*(T(L.RTLS)-T(init.)) \; .$$

For the completion of an RTLS attempt with one function SSME, the thrust of the remaining engine is at 109 percent. Assuming that the acceleration of the vehicle (dVI/dT) is proportional to the number of engines functioning and the power level of the engines, we obtain:

$$Treqd(1\text{-E RTLS}) = (Treqd(2\text{-E RTLS})-T(\text{second failure}))*((2*104)/(1*109)) \; ,$$

where

$T(\text{second failure})$ = the time of the second SSME failure relative to the beginning of the 2-E RTLS attempt.

The required remaining run time for the remaining engine with it function at 109-percent RPL is therefore:

$$Treqd(2\text{-E RTLS}) = 1.91*(Treqd(2\text{-E RTLS})-T(\text{second failure})) \; .$$

2-E RTLS
VI vs. MET
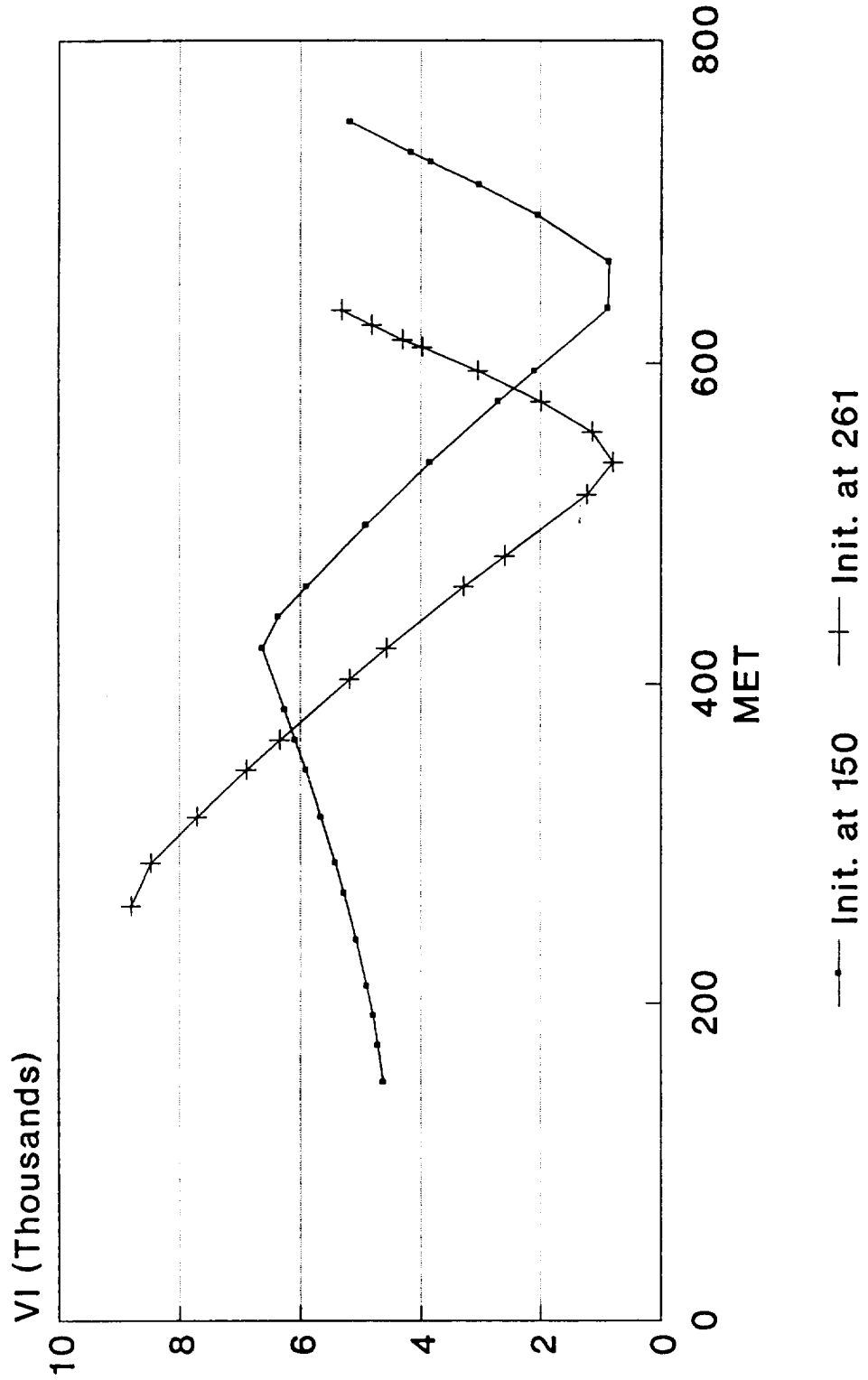
Fig. E-1 - RTLS VI vs. MET

APPENDIX F

TAL Model Development

The TAL model is used to determine the vehicle's inertial velocity as a function of the times of the engine failures. TAL situations that were considered were 2-ENG TAL attempts at 104 percent to the primary site, 1-ENG TAL attempts at 104 percent to the primary site, 1-ENG TAL attempts at 104 percent to a redesignation site, and 1-ENG TAL attempts at 109 percent to a redesignation site. The estimates of the vehicle's acceleration are used in the model.

Developing the TAL VI = f(time of engine failure) model:

For a 2-ENG TAL attempt at 104 percent:

$$VI = VI(1stEO)+(T(2ndEO)-T(1stEO))*ACC(2\text{-}ENG \text{ at } 104 \text{ percent}) \text{,}$$

where

VI(1stEO) = inertial velocity at the time of the first engine failure

T(2ndEO) = time of the second engine failure

T(1stEO) = time of the first engine failure

ACC(2-ENG at 104 percent) = the vehicle's acceleration with two engines functioning at 104 percent.

For a 1-ENG TAL attempt at 104 percent:

$$VI = VI(1stEO)+(T(2ndEO)-T(1stEO))*ACC(2\text{-}ENG \text{ at } 104 \text{ percent})$$

$$+(T(3rdEO)-T(2ndEO))*ACC(1\text{-}ENG \text{ at } 104 \text{ percent}) \text{,}$$

where

T(3rdEO) = time of the third engine failure

ACC(1-ENG at 104 percent) = vehicle's acceleration with two engines functioning at 104 percent.

For a 1-ENG TAL attempt at 109 percent:

$$VI = VI(1stEO)+(T(2ndEO)-T(1stEO))*ACC(2\text{-}ENG \text{ at } 104 \text{ percent})$$

$$+(T(3rdEO)-T(2ndEO))*ACC(1\text{-}ENG \text{ at } 109 \text{ percent}) \text{,}$$

where

ACC(1-ENG at 109 percent) = vehicle's acceleration with two engines functioning at 109 percent.

APPENDIX G

PTA and PTM Model Development

The PTA and PTM models involved determining the time that would be required to complete a PTA and PTM based on the vehicle's current situation. Abort situations that were considered were 2-ENG PTM and PTA attempts at 104 percent and a 1-ENG PTM attempt at 104 percent.

Developing the PTA and PTM required time to completion model:

For a 2-ENG PTM attempt:

Assumption: For a PTM attempt to be successful, the vehicle must attain the VI that would have been attained at the time of MECO for a nominal ascent.

Using the vehicle performance model,

$$VI(MECO) = \exp(a+b*TMECO) ,$$

where

a,b = VI versus t profile parameters

$TMECO$ = time of MECO.

Assumption: The acceleration of the vehicle is proportional to its thrust.

$$ACC(2E,104\%) = 2/3*104/104*ACC(3E,104\%)$$

$$VI(MECO) = ACC(3E,104\%)*(TMECO = ACC(3E,104\%)*T(1stEO)+ACC(2E,104\%)*Treqd ,$$

where

$Treqd$ = required remaining run time for the two remaining engines

$T(MECO) = T(1stEO)+2/3*Treqd$

$Treqd = 3/2*(T(MECO)-T(1stEO)) .$

For a 2-ENG PTM:

$$Treqd = 3/2*(T(MECO)-T(1stEO)) .$$

For a 1-ENG PTM attempt:

$$ACC(3E,104\%)*TMECO = ACC(3E,104\%)*T(1stEO)+ACC(2E,104\%)$$

$$*(T(2ndEO)-(1stEO))+ACC(1E,104\%)*Treqd ,$$

$$TMECO = T(\text{1stEO})+2/3*(T(\text{2ndEO})-T(\text{1stEO}))+1/3*T\text{reqd} ,$$

$$T\text{reqd} = 3*TMECO-2*T(\text{2ndEO})-T(\text{1stEO}) .$$

For a 2-ENG PTA attempt:

     <u>Assumption</u>: The inertial velocity required for PTA completion is about the same as the inertial velocity required for PTM completion.

Using the same procedure as for the PTM case,

$$T\text{reqd} = 3/2*(TMECO-T(\text{1stEO})) .$$

APPENDIX H

STS Ascent/Abort Event Tree Diagram

Definition of Symbols

Symbol	Definition
A1	First anomaly occurs
A2	Second anomaly occurs
ATO2	Successful 2-SSME ATO
BZN	Vehicle is in a black zone
BZY	Vehicle is not in a black zone
B9	Benign SSME failure
C1	Catastrophic SSME failure
DTME21	Time between ME2 and ME1
DTME32	Time between ME3 and ME2
ET	ET failure
LC	Loss of vehicle and crew
LV	Loss of vehicle—crew bailout
ME1	First SSME failure
ME2	Second SSME failure
ME3	Third SSME failure
NTM	Nominal ascent to MECO
OP	On-pad engine shutdown
PTM1	Successful 1-SSME PTM
PTM2	Successful 2-SSME PTM
RTLS1	Successful 1-SSME RTLS
RTLS2	Successful 2-SSME RTLS
SRB	SRB failure
TA1	Time of first anomaly
TA2	Time of second anomaly
TA3	Time of third anomaly
TAL2	Successful 2-SSME TAL
TDEC	Required decision time
TDP	Successful TAL droop
TL1P	Successful primary 1-SSME TAL
TLR1	Successful first redesignation site TAL
TLR2	Successful second redesignation site TAL
TLRN	Successful Nth redesignation site TAL
TRTLS	Earliest RTLS initiation time
TSRBS	Time of SRB separation
VI	Vehicle inertial velocity
VILT1	VI boundary for first late TAL
VILT2	VI boundary for second late TAL
VILTN	VI boundary for Nth late TAL
VILTERLY	Early VI boundary for late TAL
VIPA2	2-SSME PTA VI boundary

VIPM1	1-SSME PTM VI boundary
VIPM2	2-SSME PTM VI boundary
VITDP	VI boundary for TAL droop
VITL1P	1-SSME primary TAL VI boundary
VITL2	2-SSME TAL VI boundary
VITLR1	First TAL redesignation TAL boundary
VITLR2	Second TAL redesignation TAL boundary
VITLRN	Nth TAL redesignation TAL boundary

Ascent/Abort Event Tree — 1

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Ascent/Abort Event Tree - 2

66
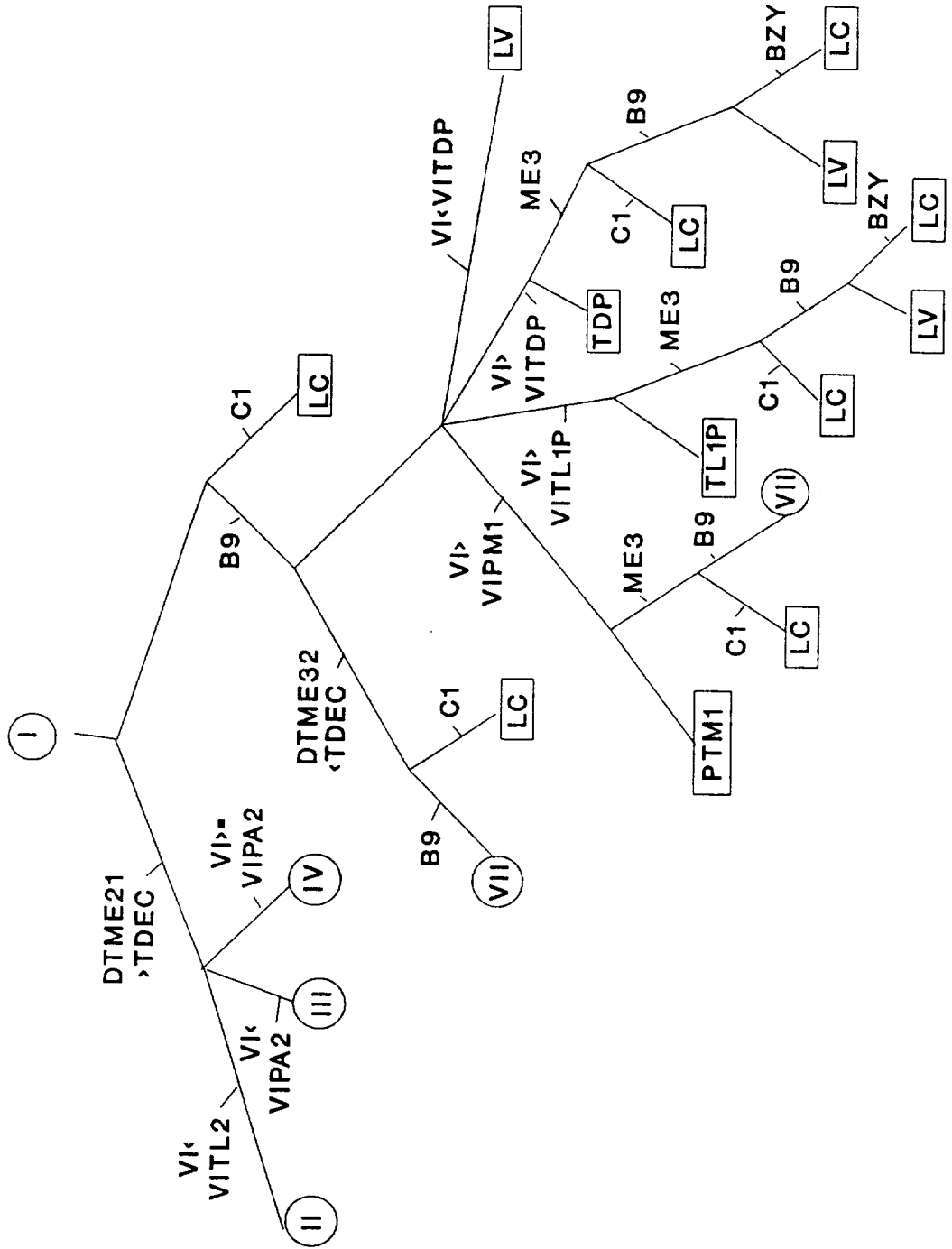
Ascent/Abort Event Tree - 3

Ascent/Abort Event Tree - 4
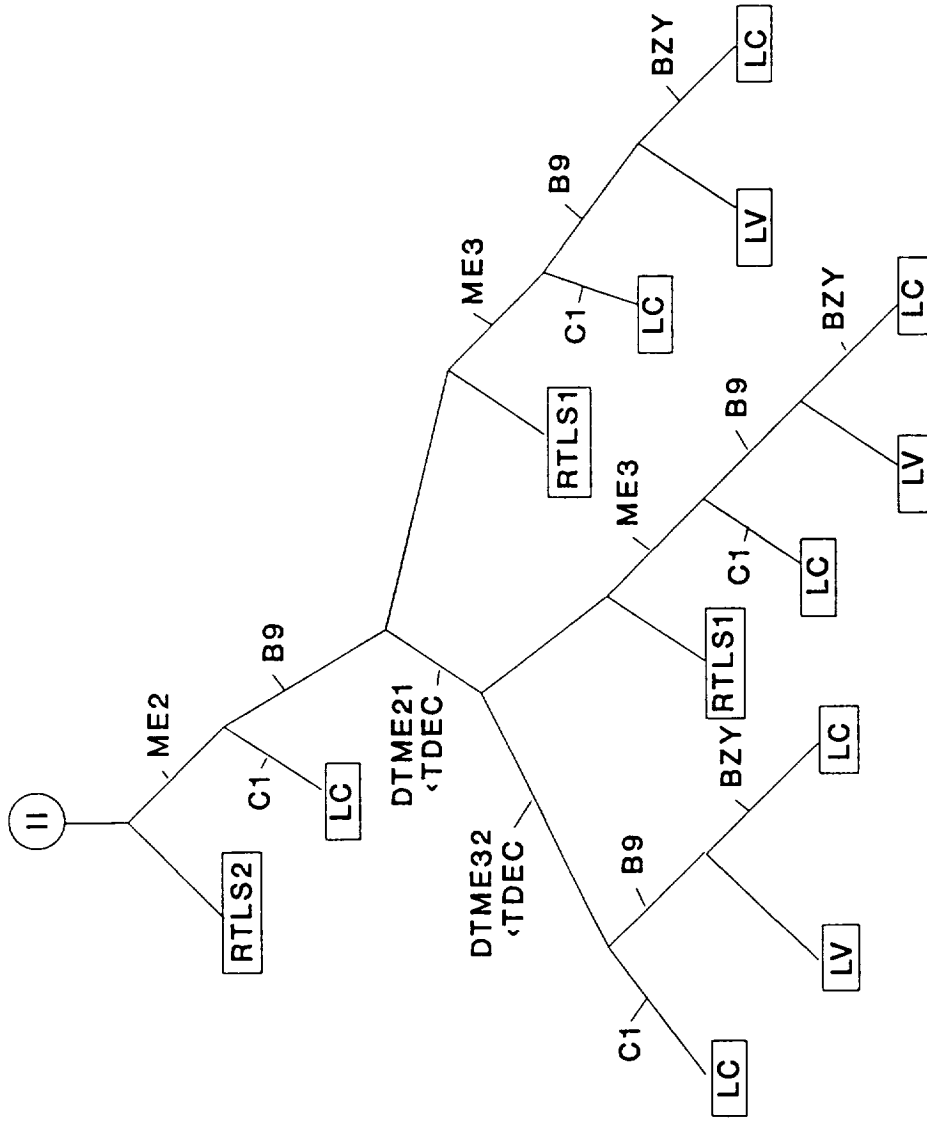
Ascent/Abort Event Tree - 5

Ascent/Abort Event Tree - 6

DTME21<TDEC

DTME32<TDEC

C1

B9

LC

V

VI

VI

VII

70
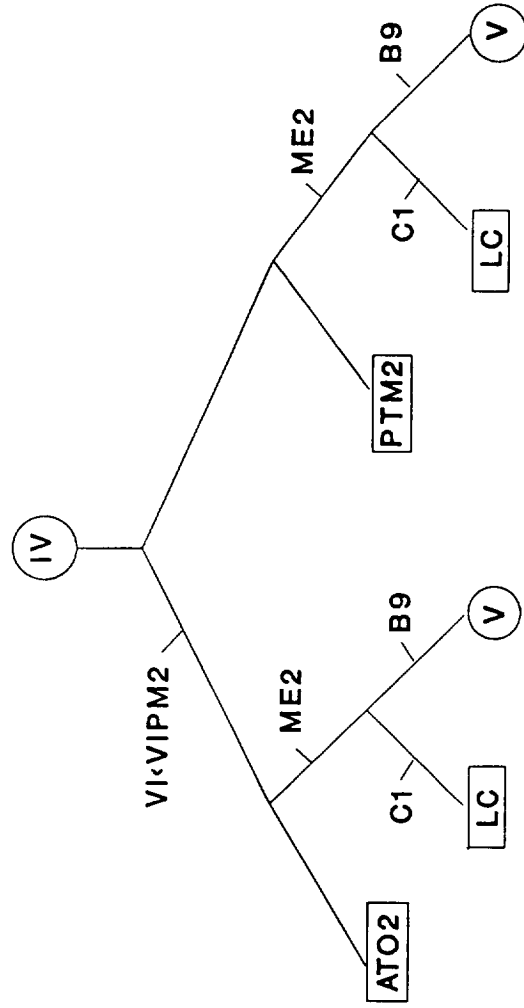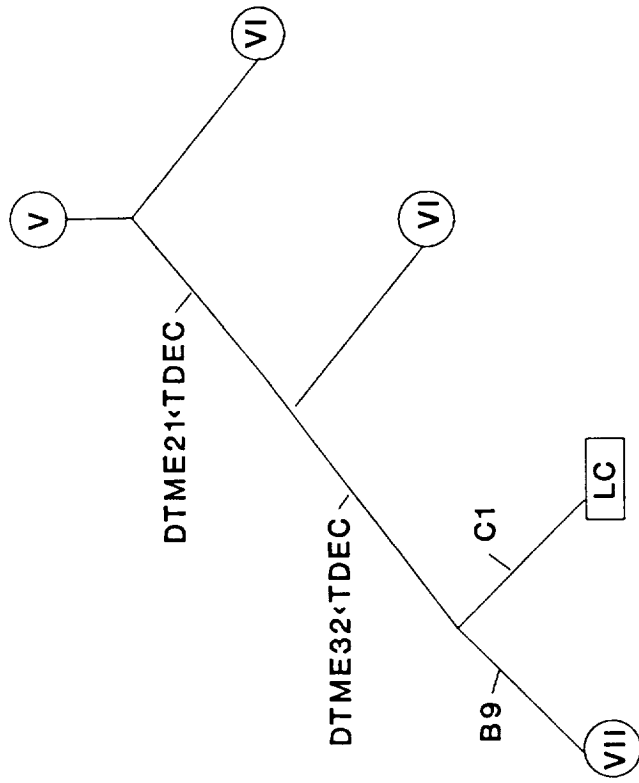
Ascent/Abort Event Tree - 7
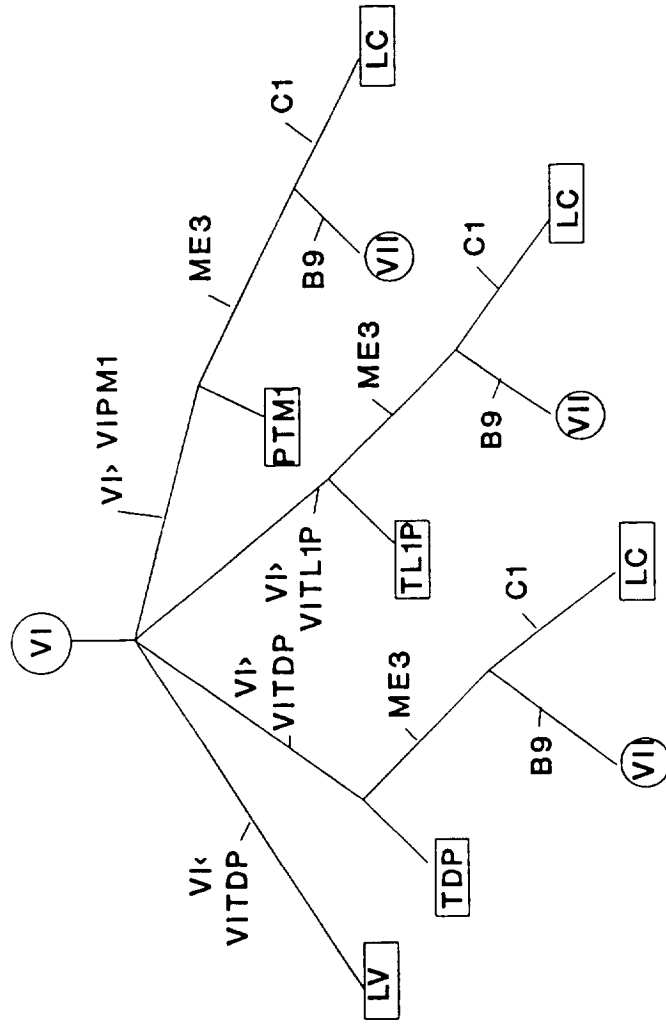
Ascent/Abort Event Tree - 8

72
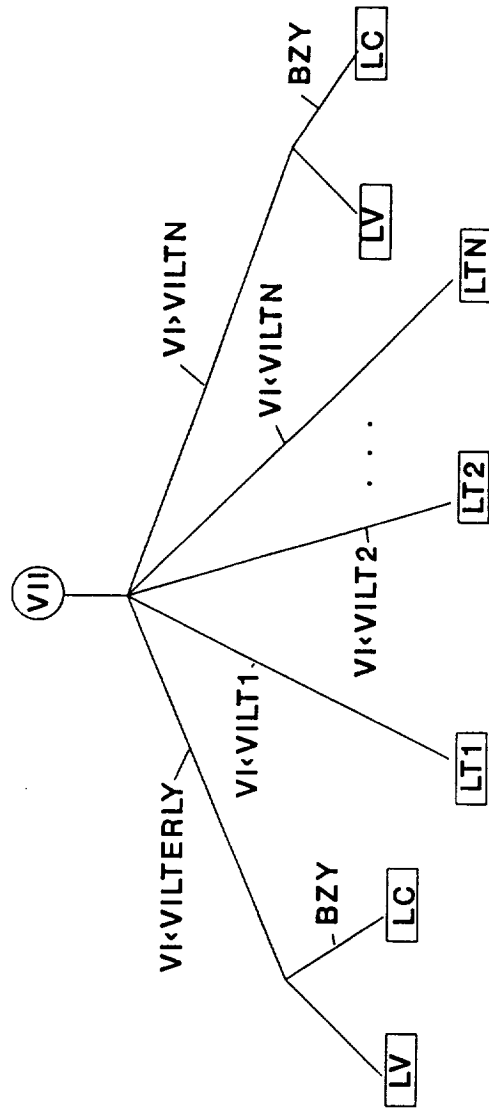
APPENDIX I

Sample Application Simulation Output

```
*****************************************
*****   SPACE SHUTTLE ABORT MODES  *****
*****        SIMULATION RESULTS     *****
*****************************************
```

```
              SIMULATION INPUT DATA
          *-*-*-*-*-*-*-*-*-*-*-*-*-*
```

```
Name of data:                      STS-32
Number of simulations:            1000000
```

```
- - - - - - - - - - - - - - - - - - - -
```

Ascent Checklist values:

```
    2 ENG (104)
      Name of landing site         BEN
      VI boundary value            6200
      VI value for Abort MECO      24000
      VI value for Nominal MECO    25918
    NEG RETURN (104)               8400
    PRESS TO ATO (104)             9600
    PRESS TO MECO (104)            13900
    SE PRESS (104)                 16800
    SE (104)
      Name of landing site         BYD
      VI boundary value            13700
    DROOP (109)
      Name of target site          BYD
      VI boundary value            12000
    LAST (104)
      Name of landing site         MRN
      VI boundary value            13500
    Late TALs
      Total number of sites          4
      Late TAL site:               AML
        VI boundary value          22700
      Late TAL site:               BYD
        VI boundary value          24500
      Late TAL site:               KIN
        VI boundary value          25200
      Late TAL site:               HDS
        VI boundary value          25500
      Earliest Late TAL            22000
```

  TAL Redesignations

```
    Total number of 1st EO values        34
```

Number	VI Value
1	6200
2	6300
3	6400
4	6500
5	6600
6	6700
7	6800
8	6900

```
              9               7000
             10               7100
             11               7200
             12               7300
             13               7400
             14               7500
             15               7600
             16               7700
             17               7800
             18               7900
             19               8000
             20               8100
             21               8200
             22               8300
             23               8400
             24               8500
             25               8600
             26               8700
             27               8800
             28               8900
             29               9000
             30               9100
             31               9200
             32               9300
             33               9400
             34               9500
```

Number of redesig. options   3

TAL redesignation option: SE DROOP B
Option power level: 109

Number	VI Value
1	10900
2	10900
3	11000
4	11000
5	11000
6	11000
7	11000
8	11100
9	11100
10	11100
11	11100
12	11200
13	11200
14	11200
15	11200
16	11200
17	11300
18	11300
19	11300
20	11300
21	11300
22	11300
23	11400
24	11400
25	11400
26	11400

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```
            27            11400
            28            11400
            29            11400
            30            11500
            31            11500
            32            11500
            33            11500
            34            11500
```

TAL redesignation option: SE BYD
Option power level: 104

```
       Number            VI Value
       ------            --------
          1              16400
          2              16300
          3              16100
          4              16000
          5              15800
          6              15700
          7              15500
          8              15400
          9              15200
         10              15100
         11              14900
         12              14800
         13              14700
         14              14600
         15              14400
         16              14300
         17              14200
         18              14100
         19              14000
         20              13900
         21              13900
         22              13900
         23              13800
         24              13800
         25              13800
         26              13700
         27              13700
         28              13700
         29              13700
         30              13700
         31              13600
         32              13600
         33              13600
         34              13600
```

TAL redesignation option: SE BEN
Option power level: 109

```
       Number            VI Value
       ------            --------
          1              16400
          2              16300
          3              16100
          4              16000
          5              15800
          6              15700
```

```
            7                    15500
            8                    15400
            9                    15200
           10                    15100
           11                    14900
           12                    14800
           13                    14700
           14                    14600
           15                    14400
           16                    14300
           17                    14300
           18                    14200
           19                    14100
           20                    14100
           21                    14000
           22                    14000
           23                    13900
           24                    13900
           25                    13900
           26                    13900
           27                    13800
           28                    13800
           29                    13800
           30                    13800
           31                    13800
           32                    13800
           33                    13700
           34                    13700
```

- -

Probability of SRB pair failure   3.875969E-03

Probability of ET failure   1.000000E-04

- -

Enabled SSME time-to-failure parameters:

```
    Self-contained - 100% RPL            22277.700000
    Self-contained - 104% RPL            22889.600000
    Self-contained - 109% RPL             9744.100000
    Catastrophic   - 100% RPL           149693.500000
    Catastrophic   - 104% RPL            77252.400000
    Catastrophic   - 109% RPL            13181.100000
```

- -

Launch/ascent phase times (sec):

```
    Duration of the pre-launch phase          6.600000
    Beginning of "throttle bucket"           25.000000
    End of the "throttle bucket"             70.000000
    Time of SRB separation                  130.000000
    Time of RTLS capability                 150.000000
    Beginning of throttle down              460.000000
    Time of MECO                            516.000000
```

- -

76

Vehicle acceleration values (ft/sec^2):

```
2 functioning SSMEs  - 104% RPL      44.310000
1 functioning SSME   - 104% RPL      22.160000
1 functioning SSME   - 109% RPL      23.230000
```

- - - - - - - - - - - - - - - - - - - -

Required decision time (sec):   15.000000

- - - - - - - - - - - - - - - - - - - -

Enable/inhibit switch status: ON

- - - - - - - - - - - - - - - - - - - -

Black zone VI boundaries (ft/sec):

```
Lower boundary                     8000.000000
Upper boundary                    18000.000000
```

ASCENT/ABORT SUMMARY
* * * * * * * * * * * *

```
Nominal to MECO                         914416
On-pad shutdown                            802
Successful RTLS                          21350
Successful TAL                           13769
Successful Aborts to Orbit               10413
Successful Aborts to MECO                17992
Non-intact abort - crew bailout            361
Non-intact abort - loss of crew              0
Benign SSME failure                      67796
Catastrophic SSME failure                17974
External Tank failure                        2
Solid Rocket Booster failure              2921
```

PRE-LAUNCH SUMMARY
+-+-+-+-+-+-+-+-+-+-+

```
On-pad shutdown                            802
Benign 1st SSME failure                    802
Catastrophic 1st SSME failure                2
External Tank failure                        0
```

FIRST STAGE SUMMARY
+-+-+-+-+-+-+-+-+-+-+

```
Non-intact abort - crew bailout            142
Non-intact abort - loss of crew              0
Benign 1st SSME failure                  15801
Benign 2nd SSME failure                    142
Benign 3rd SSME failure                      0
```

```
Catastrophic 1st SSME failure              4196
Catastrophic 2nd SSME failure                 1
Catastrophic 3rd SSME failure                 0
External Tank failure                         2
Solid Rocket Booster failure               2921
```

```
                SECOND STAGE SUMMARY
                +-+-+-+-+-+-+-+-+-+-+

Nominal to MECO                          914416
Successful 1-E TAL      BYD                  36
Successful TAL Droop    BYD                  35
Successful 1-E Press to MECO                  2
Successful Late TAL     AML                   0
Successful Late TAL     BYD                   0
Successful Late TAL     KIN                   0
Successful Late TAL     HDS                   0
Non-intact abort - crew bailout             110
Non-intact abort - loss of crew               0
Benign 1st SSME failure                   48522
Benign 2nd SSME failure                     183
Benign 3rd SSME failure                       0
Catastrophic 1st SSME failure             13338
Catastrophic 2nd SSME failure                 0
Catastrophic 3rd SSME failure                 0
External Tank failure                         0
```

```
Return to Launch Site (RTLS) Summary
~ ~ ~ ~ ~ ~ ~ ~ ~ ~ ~ ~ ~ ~ ~ ~ ~ ~ ~

Successful 2-E RTLS                       20017
Successful 1-E RTLS                        1333
Non-intact abort - crew bailout               0
Non-intact abort - loss of crew               0
Benign 2nd SSME failure                    1369
Benign 3rd SSME failure                       0
Catastrophic 2nd SSME failure               291
Catastrophic 3rd SSME failure                36
```

```
Trans-oceanic Abort Landing (TAL) Summary
~ ~ ~ ~ ~ ~ ~ ~ ~ ~ ~ ~ ~ ~ ~ ~ ~ ~ ~ ~ ~

Successful 2-E TAL      BEN               13191
Successful 1-E TAL      BYD                   0
Successful TAL Droop    BYD                   0
Successful 1-E TAL      SE DROOP B          107
Successful 1-E TAL      SE BYD                0
Successful 1-E TAL      SE BEN              219
Successful Late TAL     AML                   0
Successful Late TAL     BYD                   0
Successful Late TAL     KIN                   0
Successful Late TAL     HDS                   0
Non-intact abort - crew bailout              74
Non-intact abort - loss of crew               0
```

```
Benign 2nd SSME failure                      400
Benign 3rd SSME failure                        0
Catastrophic 2nd SSME failure                 37
Catastrophic 3rd SSME failure                  0



        Press to MECO and ATO Summary
        ~ ~ ~ ~ ~ ~ ~ ~ ~ ~ ~ ~ ~ ~ ~

Successful 2-E PTM                         17629
Successful 2-E ATO                         10413
Successful 1-E PTM                           361
Successful 1-E TAL      BYD                  145
Successful TAL Droop    BYD                   36
Successful Late TAL     AML                    0
Successful Late TAL     BYD                    0
Successful Late TAL     KIN                    0
Successful Late TAL     HDS                    0
Non-intact abort - crew bailout               35
Non-intact abort - loss of crew                0
Benign 2nd SSME failure                      577
Benign 3rd SSME failure                        0
Catastrophic 2nd SSME failure                 73
Catastrophic 3rd SSME failure                  0
```

APPENDIX J

Program Tutorial

This section is intended to acquaint the program user with how to use the program by walking them through an example application. The example application involves assessing the expected risk involved for STS-32.

Start the Program

The simulation program has been developed for use with a Microsoft FORTRAN version 4.1 or an equivalent compiler. The executable file for this program must first be loaded into the directory that contains the compiler.

To begin the program enter: ABTSIM

Entering Program Input

This section will show the sample input of data. The default values included Ascent Checklist values for STS-26 and values that appeared reasonable to the author. The entered data includes values from the STS-32 Ascent Checklist—Flight Supplement and information that is intended to be for illustration purposes only. The reader is encouraged in particular to follow the Ascent Checklist data as they are entered and to locate their position within the document. The reader should also note that when data are entered for the TAL redesignation values, if an option is not available at a particular first engine out inertial velocity value, the inertial velocity value of the next possible option at that first engine out inertial velocity value is entered in its position. If the last option is not available at the first engine out velocity value, a very large number is entered as the velocity value for that option. The data that are requested and the information that is entered in response for this application is as follows:

What is the name of the data?
STS-32

**Would you like to have the results sent
to an output file (Y or N)?**
Y

What is the name for the output file?
STS-32

How many simulation runs are desired?
10000

Please enter your selection.
1

– 2 ENG (104)? {6300}
6200

Name of landing site? {BEN}
BEN

VI value for Abort MECO? {24000}
24000

VI value for Nominal MECO?? {25918}
25918

– NEG RETURN (104)? {8300}
8400

– PRESS TO ATO (104)? {9800}
9600

– PRESS TO MECO (104)? {12200}
13900

– SE PRESS (104)? {18600}
16800

– SE (104)? {14000)
13700

Name of landing site? {BYD}
BYD

– DROOP (109)? {11100}
12000

Name of target site? {BYD}
BYD

– LAST (104)? {24600}
13500

Name of the landing site? {BEN}
MRN

What is the total number of Late TAL sites? {3}
4

– LAST LATE TAL VI Value   1
22700

Name of the landing site?
AML

– LAST LATE TAL VI Value 2
24500

Name of the landing site?
BYD

– LAST LATE TAL VI Value 3
25200

Name of the landing site?
KIN

– LAST LATE TAL VI Value 4
25500

Name of the landing site?
HDS

– Earliest Late TAL? {24000}
22000

Total number of TAL redesignation options? {3}
3

Total number of TAL redesignation velocities? {33}
34

**Do you wish to use all the default 1st engine
out VI redesignation values? (Y or N)**
N

1st EO VI 1
6200

1st EO VI 2
6300

1st EO VI 3
6400

1st EO VI 4
6500

1st EO VI 5
6600

1st EO VI 6
6700

1st EO VI 7
6800

1st EO VI 8
6900

1st EO VI 9
7000

1st EO VI 10
7100

1st EO VI 11
7200

1st EO VI 12
7300

1st EO VI 13
7400

1st EO VI 14
7500

1st EO VI 15
7600

1st EO VI 16
7700

1st EO VI 17
7800

1st EO VI 18
7900

1st EO VI 19
8000

1st EO VI 20
8100

1st EO VI 21
8200

1st EO VI 22
8300

1st EO VI 23
8400

1st EO VI 24
8500

1st EO VI 25
8600

1st EO VI 26
8700

1st EO VI 27
8800

1st EO VI 28
8900

1st EO VI 29
9000

1st EO VI 30
9100

1st EO VI 31
9200

1st EO VI 32
9300

1st EO VI 33
9400

1st EO VI 34
9500

Name of the TAL redesignation option 1
DROOP BYD

Power level required for this option (104 or 109)
109

Name of the TAL redesignation option 2
BYD

Power level required for this option (104 or 109)
104

Name of the TAL redesignation option 3
BEN

Power level required for this option (104 or 109)
109

**Do you wish to use all the default 2nd engine
out VI redesignation values for option 1? (Y or N)**
N

– TAL REDES VI Value 1 1
10900

– TAL REDES VI Value 1 2
10900

– TAL REDES VI Value 1 3
11000

– TAL REDES VI Value 1 4
11000

– TAL REDES VI Value 1 5
11000

– TAL REDES VI Value 1 6
11000

– TAL REDES VI Value 1 7
11000

– TAL REDES VI Value 1 8
11100

– TAL REDES VI Value 1 9
11100

– TAL REDES VI Value 1 10
11100

– TAL REDES VI Value 1 11
11100

– TAL REDES VI Value 1 12
11200

– TAL REDES VI Value 1 13
11200

– TAL REDES VI Value 1 14
11200

– TAL REDES VI Value 1 15
11200

– TAL REDES VI Value 1 16
11200

– TAL REDES VI Value 1 17
11300

– TAL REDES VI Value 1 18
11300

– TAL REDES VI Value 1 19
11300

– TAL REDES VI Value 1 20
11300

– TAL REDES VI Value 1 21
11300

– TAL REDES VI Value 1 22
11300

– TAL REDES VI Value 1 23
11400

– TAL REDES VI Value 1 24
11400

– TAL REDES VI Value 1 25
11400

– TAL REDES VI Value 1 26
11400

– TAL REDES VI Value 1 27
11400

– TAL REDES VI Value 1 28
11400

– TAL REDES VI Value 1 29
11400

– TAL REDES VI Value 1 30
11500

– TAL REDES VI Value 1 31
11500

– TAL REDES VI Value 1 32
11500

– TAL REDES VI Value 1 33
11500

– TAL REDES VI Value 1 34
11500

**Do you wish to use all the default 2nd engine out
VI redesignation values for option 2? (Y or N)**
N

– TAL REDES VI Value 2 1
16400

– TAL REDES VI Value 2 2
16300

– TAL REDES VI Value 2 3
16100

– TAL REDES VI Value 2 4
16000

– TAL REDES VI Value 2 5
15800

– TAL REDES VI Value 2 6
15700

– TAL REDES VI Value 2 7
15500

– TAL REDES VI Value 2 8
15400

– TAL REDES VI Value 2 9
15200

– TAL REDES VI Value 2 10
15100

– TAL REDES VI Value 2 11
14900

– TAL REDES VI Value 2 12
14800

– TAL REDES VI Value 2 13
14700

– TAL REDES VI Value 2 14
14600

– TAL REDES VI Value 2 15
14400

– TAL REDES VI Value 2 16
14300

– TAL REDES VI Value 2 17
14200

– TAL REDES VI Value 2 18
14100

– TAL REDES VI Value 2 19
14000

– TAL REDES VI Value 2 20
13900

– TAL REDES VI Value 2 21
13900

– TAL REDES VI Value 2 22
13900

– TAL REDES VI Value 2 23
13800

– TAL REDES VI Value 2 24
13800

– TAL REDES VI Value 2 25
13800

– TAL REDES VI Value 2 26
13700

– TAL REDES VI Value 2 27
13700

– TAL REDES VI Value 2 28
13700

– TAL REDES VI Value 2 29
13700

– TAL REDES VI Value 2 30
13700

– TAL REDES VI Value 2 31
13600

– TAL REDES VI Value 2 32
13600

– TAL REDES VI Value 2 33
13600

– TAL REDES VI Value 2 34
13600

**Do you wish to use all the default 2nd engine out
VI redesignation values for option 3? (Y or N)**
N

– TAL REDES VI Value 3 1
16400

– TAL REDES VI Value 3 2
16300

– TAL REDES VI Value 3 3
16100

– TAL REDES VI Value 3 4
16000

– TAL REDES VI Value 3 5
15800

– TAL REDES VI Value 3 6
15700

– TAL REDES VI Value 3 7
15500

– TAL REDES VI Value 3 8
15400

– TAL REDES VI Value 3 9
15200

– TAL REDES VI Value 3 10
15100

– TAL REDES VI Value 3 11
14900

– TAL REDES VI Value 3 12
14800

– TAL REDES VI Value 3 13
14700

– TAL REDES VI Value 3 14
14600

– TAL REDES VI Value 3 15
14400

– TAL REDES VI Value 3 16
14300

– TAL REDES VI Value 3 17
14300

– TAL REDES VI Value 3 18
14200

– TAL REDES VI Value 3 19
14100

– TAL REDES VI Value 3 20
14100

– TAL REDES VI Value 3 21
14000

– TAL REDES VI Value 3 22
14000

– TAL REDES VI Value 3 23
13900

– TAL REDES VI Value   3 24
13900

– TAL REDES VI Value   3 25
13900

– TAL REDES VI Value   3 26
13900

– TAL REDES VI Value   3 27
13800

– TAL REDES VI Value   3 28
13800

– TAL REDES VI Value   3 29
13800

– TAL REDES VI Value   3 30
13800

– TAL REDES VI Value   3 31
13800

– TAL REDES VI Value   3 32
13800

– TAL REDES VI Value   3 33
13700

– TAL REDES VI Value   3 34
13700

Please enter your selection.
2

What is the probability of SRB failure?
{.00388}
.00388

Please enter your selection.
3

What is the probability of ET failure?
{.0001}
.0001

Please enter your selection.
4

92

Enabled – catastrophic parameter values:

-- **for 100% SSME thrust: {149693.5}**
149693.5

-- **for 104% SSME thrust: {77252.4}**
77252.4

-- **for 109% SSME thrust: {13181.1}**
13181.1

Enabled – benign parameter values:

-- **for 100% SSME thrust: {22277.7}**
22277.7

-- **for 104% SSME thrust: {22889.6}**
22889.6

-- **for 109% SSME thrust: {9744.1}**
9744.1

Please enter your selection.
5

– **duration of the prelaunch phase: {6.6}**
6.6

– **beginning of the "throttle bucket": {25}**
25

– **end of the "throttle bucket": {70}**
70

– **time of SRB separation: {130}**
130

– **time of RTLS capability: {150}**
150

– **time of pre-MECO throttle down: {460}**
460

– **time of MECO: {516}**
516

Please enter your selection.
6

What is the required decision time? {15}
15

Please enter your selection.
7

**Will the SSMEs be inhibited during black zones
(Y or N)? (Y)**
Y

Please enter your selection.
8

– the lower back zone VI bound: {8000}
8000.

– the upper black zone VI bound: {18000}
18000.

Please enter your selection.
9

Viewing Program Summaries

The results of the simulation are summarized on the screen and, since the output file option was chosen

, a summary of the results is also sent to a file. The output to the screen is menu-driven and straight forward. The output to the file may be sent to a printer. The output file for the input data in this tutorial is shown in this appendix.

```
*******************************************
*****  SPACE SHUTTLE ABORT MODES  *****
*****      SIMULATION RESULTS      *****
*******************************************


            SIMULATION INPUT DATA
          *-*-*-*-*-*-*-*-*-*-*-*-*

Name of data:                       STS-32
Number of simulations:              10000


- - - - - - - - - - - - - - - - - - - - -


Ascent Checklist values:

   2 ENG (104)
     Name of landing site           BEN
     VI boundary value             6200
     VI value for Abort MECO      24000
     VI value for Nominal MECO    25918
   NEG RETURN (104)                 8400
   PRESS TO ATO (104)               9600
   PRESS TO MECO (104)             13900
   SE PRESS (104)                  16800
   SE (104)
     Name of landing site           BYD
     VI boundary value            13700
   DROOP (109)
     Name of target site            BYD
     VI boundary value            12000
   LAST (104)
     Name of landing site           MRN
     VI boundary value            13500
   Late TALs
     Total number of sites            4
     Late TAL site:                 AML
       VI boundary value          22700
     Late TAL site:                 BYD
       VI boundary value          24500
     Late TAL site:                 KIN
       VI boundary value          25200
     Late TAL site:                 HDS
       VI boundary value          25500
     Earliest Late TAL            22000

   TAL Redesignations

   Total number of 1st EO values       34

          Number          VI Value
          ------          --------
              1             6200
              2             6300
              3             6400
              4             6500
              5             6600
              6             6700
              7             6800
              8             6900
```

C-2

Number	VI Value
9	7000
10	7100
11	7200
12	7300
13	7400
14	7500
15	7600
16	7700
17	7800
18	7900
19	8000
20	8100
21	8200
22	8300
23	8400
24	8500
25	8600
26	8700
27	8800
28	8900
29	9000
30	9100
31	9200
32	9300
33	9400
34	9500

Number of redesig. options   3

TAL redesignation option: DROOP BYD
Option power level: 109

Number	VI Value
1	10900
2	10900
3	11000
4	11000
5	11000
6	11000
7	11000
8	11100
9	11100
10	11100
11	11100
12	11200
13	11200
14	11200
15	11200
16	11200
17	11300
18	11300
19	11300
20	11300
21	11300
22	11300
23	11400
24	11400
25	11400
26	11400

Number	VI Value
27	11400
28	11400
29	11400
30	11500
31	11500
32	11500
33	11500
34	11500

TAL redesignation option: BYD
Option power level: 104

Number	VI Value
1	16400
2	16300
3	16100
4	16000
5	15800
6	15700
7	15500
8	15400
9	15200
10	15100
11	14900
12	14800
13	14700
14	14600
15	14400
16	14300
17	14200
18	14100
19	14000
20	13900
21	13900
22	13900
23	13800
24	13800
25	13800
26	13700
27	13700
28	13700
29	13700
30	13700
31	13600
32	13600
33	13600
34	13600

TAL redesignation option: BEN
Option power level: 109

Number	VI Value
1	16400
2	16300
3	16100
4	16000
5	15800
6	15700

```
7               15500
8               15400
9               15200
10              15100
11              14900
12              14800
13              14700
14              14600
15              14400
16              14300
17              14300
18              14200
19              14100
20              14100
21              14000
22              14000
23              13900
24              13900
25              13900
26              13900
27              13800
28              13800
29              13800
30              13800
31              13800
32              13800
33              13700
34              13700
```

- - - - - - - - - - - - - - - - - - - -

Probability of SRB pair failure   3.875969E-03

Probability of ET failure   1.000000E-04

- - - - - - - - - - - - - - - - - - - -

Enabled SSME time-to-failure parameters:

```
Self-contained - 100% RPL          22277.700000
Self-contained - 104% RPL          22889.600000
Self-contained - 109% RPL           9744.100000
Catastrophic   - 100% RPL         149693.500000
Catastrophic   - 104% RPL          77252.400000
Catastrophic   - 109% RPL          13181.100000
```

- - - - - - - - - - - - - - - - - - - -

Launch/ascent phase times (sec):

```
Duration of the pre-launch phase        6.600000
Beginning of "throttle bucket"         25.000000
End of the "throttle bucket"           70.000000
Time of SRB separation                130.000000
Time of RTLS capability               150.000000
Beginning of throttle down            460.000000
Time of MECO                          516.000000
```

- - - - - - - - - - - - - - - - - - - -

Vehicle acceleration values (ft/sec^2):

```
2 functioning SSMEs  - 104% RPL        44.310000
1 functioning SSME   - 104% RPL        22.160000
1 functioning SSME   - 109% RPL        23.230000
```

- - - - - - - - - - - - - - - - - - -

Required decision time (sec):   15.000000

- - - - - - - - - - - - - - - - - - -

Enable/inhibit switch status: ON

- - - - - - - - - - - - - - - - - - -

Black zone VI boundaries (ft/sec):

```
Lower boundary                        8000.000000
Upper boundary                       18000.000000
```

ASCENT/ABORT SUMMARY
* * * * * * * * * * * *

```
Nominal to MECO                         9146
On-pad shutdown                           14
Successful RTLS                          206
Successful TAL                           134
Successful Aborts to Orbit                96
Successful Aborts to MECO                190
Non-intact abort - crew bailout            2
Non-intact abort - loss of crew            0
Benign SSME failure                      667
Catastrophic SSME failure                178
External Tank failure                      1
Solid Rocket Booster failure              33
```

PRE-LAUNCH SUMMARY
+-+-+-+-+-+-+-+-+-+-+

```
On-pad shutdown                           14
Benign 1st SSME failure                   14
Catastrophic 1st SSME failure              2
External Tank failure                      0
```

FIRST STAGE SUMMARY
+-+-+-+-+-+-+-+-+-+-+

```
Non-intact abort - crew bailout            0
Non-intact abort - loss of crew            0
Benign 1st SSME failure                  163
Benign 2nd SSME failure                    0
Benign 3rd SSME failure                    0
```

99

```
Catastrophic 1st SSME failure              36
Catastrophic 2nd SSME failure               1
Catastrophic 3rd SSME failure               0
External Tank failure                       1
Solid Rocket Booster failure               33
```

SECOND STAGE SUMMARY
```
+-+-+-+-+-+-+-+-+-+-+-+
```

```
Nominal to MECO                          9146
Successful 1-E TAL     BYD                  0
Successful TAL Droop   BYD                  0
Successful 1-E Press to MECO                2
Successful Late TAL    AML                  0
Successful Late TAL    BYD                  0
Successful Late TAL    KIN                  0
Successful Late TAL    HDS                  0
Non-intact abort - crew bailout            1
Non-intact abort - loss of crew            0
Benign 1st SSME failure                  471
Benign 2nd SSME failure                    3
Benign 3rd SSME failure                    0
Catastrophic 1st SSME failure            134
Catastrophic 2nd SSME failure              0
Catastrophic 3rd SSME failure              0
External Tank failure                      0
```

Return to Launch Site (RTLS) Summary
```
~ ~ ~ ~ ~ ~ ~ ~ ~ ~ ~ ~ ~ ~ ~ ~ ~ ~ ~
```

```
Successful 2-E RTLS                       198
Successful 1-E RTLS                         8
Non-intact abort - crew bailout            0
Non-intact abort - loss of crew            0
Benign 2nd SSME failure                     8
Benign 3rd SSME failure                     0
Catastrophic 2nd SSME failure              4
Catastrophic 3rd SSME failure              0
```

Trans-oceanic Abort Landing (TAL) Summary
```
~ ~ ~ ~ ~ ~ ~ ~ ~ ~ ~ ~ ~ ~ ~ ~ ~ ~ ~ ~ ~ ~
```

```
Successful 2-E TAL     BEN               130
Successful 1-E TAL     BYD                  0
Successful TAL Droop   BYD                  0
Successful 1-E TAL     DROOP BYD            0
Successful 1-E TAL     BYD                  0
Successful 1-E TAL     BEN                  3
Successful Late TAL    AML                  0
Successful Late TAL    BYD                  0
Successful Late TAL    KIN                  0
Successful Late TAL    HDS                  0
Non-intact abort - crew bailout            3
Non-intact abort - loss of crew            0
```

Benign 2nd SSME failure   4
Benign 3rd SSME failure   0
Catastrophic 2nd SSME failure   1
Catastrophic 3rd SSME failure   0

Press to MECO and ATO Summary
~ ~ ~ ~ ~ ~ ~ ~ ~ ~ ~ ~ ~ ~

Successful 2-E PTM		185
Successful 2-E ATO		96
Successful 1-E PTM		3
Successful 1-E TAL	BYD	1
Successful TAL Droop	BYD	0
Successful Late TAL	AML	0
Successful Late TAL	BYD	0
Successful Late TAL	KIN	0
Successful Late TAL	HDS	0
Non-intact abort - crew bailout		0
Non-intact abort - loss of crew		4
Benign 2nd SSME failure		0
Benign 3rd SSME failure		0
Catastrophic 2nd SSME failure		0
Catastrophic 3rd SSME failure		0

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APPROVAL

A SIMULATION MODEL FOR PROBABILISTIC ANALYSIS OF SPACE SHUTTLE ABORT MODES

By R.T. Hage

The information in this report has been reviewed for technical content. Review of any information concerning Department of Defense or nuclear energy activities or programs has been made by the MSFC Security Classification Officer. This report, in its entirety, has been determined to be unclassified.

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