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**NASA Technical Memorandum**

NASA TM - 108432

(NASA-TM-108432) A SIMULATION MODEL FOR PROBABILISTIC ANALYSIS OF SPACE SHUTTLE ABORT MODES (NASA) 104 p N94-21859

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# A SIMULATION MODEL FOR PROBABILISTIC ANALYSIS OF SPACE SHUTTLE ABORT MODES

By R.T. Hage

Preliminary Design Office
Program Development

November 1993

National Aeronautics and
Space Administration
**George C. Marshall Space Flight Center**

# REPORT DOCUMENTATION PAGE

*Form Approved*
*OMB No. 0704-0188*

Public reporting burden for this collection of information is estimated to average 1 hour per response, including the time for reviewing instructions, searching existing data sources, gathering and maintaining the data needed, and completing and reviewing the collection of information. Send comments regarding this burden estimate or any other aspect of this collection of information, including suggestions for reducing this burden, to Washington Headquarters Services, Directorate for Information Operations and Reports, 1215 Jefferson Davis Highway, Suite 1204, Arlington, VA 22202-4302, and to the Office of Management and Budget, Paperwork Reduction Project (0704-0188), Washington, DC 20503.

**1. AGENCY USE ONLY** *(Leave blank)*

**2. REPORT DATE**
November 1993

**3. REPORT TYPE AND DATES COVERED**
Technical Memorandum

**4. TITLE AND SUBTITLE**
A Simulation Model for Probabilistic Analysis
of Space Shuttle Abort Modes

**5. FUNDING NUMBERS**

**6. AUTHOR(S)**
R.T. Hage

**7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)**
George C. Marshall Space Flight Center
Marshall Space Flight Center, Alabama 35812

**8. PERFORMING ORGANIZATION REPORT NUMBER**

**9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)**
National Aeronautics and Space Administration
Washington, DC 20546

**10. SPONSORING/MONITORING AGENCY REPORT NUMBER**
NASA TM-108432

**11. SUPPLEMENTARY NOTES**
Prepared by Preliminary Design Office, Program Development

**12a. DISTRIBUTION/AVAILABILITY STATEMENT**
Unclassified—Unlimited

**12b. DISTRIBUTION CODE**

**13. ABSTRACT** *(Maximum 200 words)*

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.

**14. SUBJECT TERMS**
space shuttle abort modes, space transportation system, abort modes, risk assessment, Monte Carlo simulation

**15. NUMBER OF PAGES**
110

**16. PRICE CODE**
NTIS

**17. SECURITY CLASSIFICATION OF REPORT**
Unclassified

**18. SECURITY CLASSIFICATION OF THIS PAGE**
Unclassified

**19. SECURITY CLASSIFICATION OF ABSTRACT**
Unclassified

**20. LIMITATION OF ABSTRACT**
Unlimited

NSN 7540-01-280-5500
Standard Form 298 (Rev. 2-89)

# ACKNOWLEDGMENTS

The author has several people to thank for their help in this effort. Thanks are due to Dr. Fayssal Safie for his assistance with this research effort. Thanks also are due to Bob Walsh and Rick Schmidgall of Johnson Space Center for their expertise on space shuttle abort procedures. Thanks also to Richard W. Brown of Marshall Space Flight Center for his knowledge on this subject.

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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.

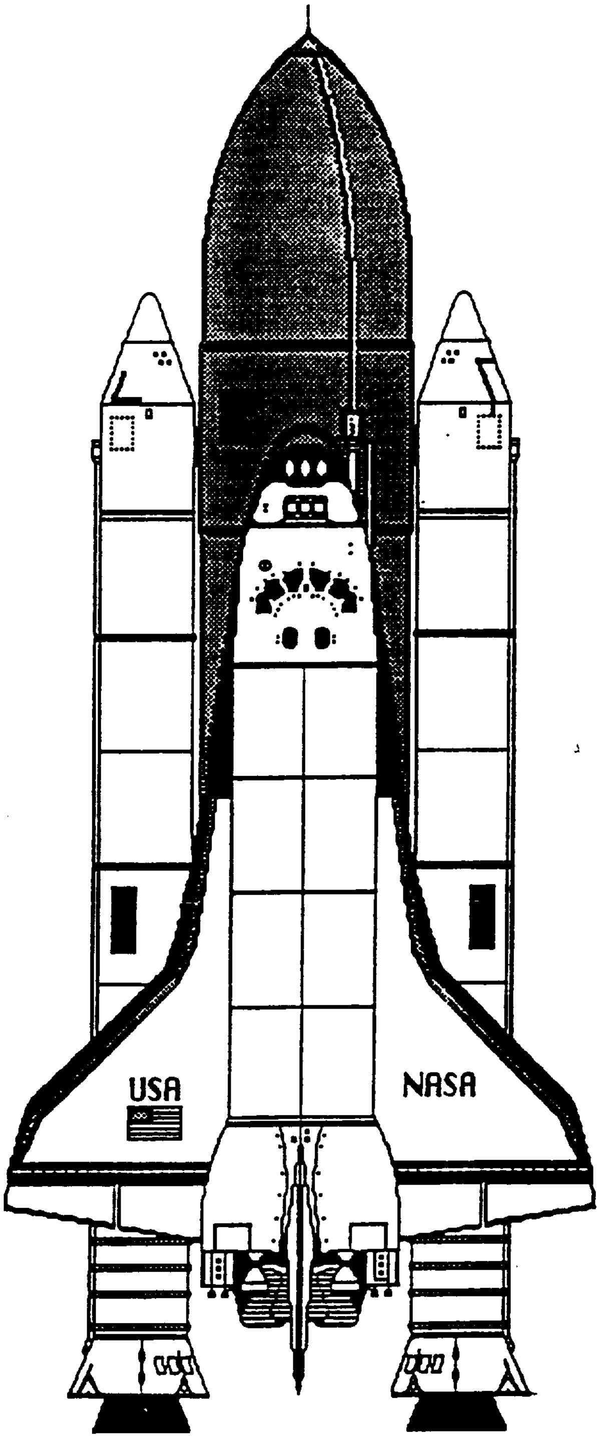


Figure 1. The space transportation system.

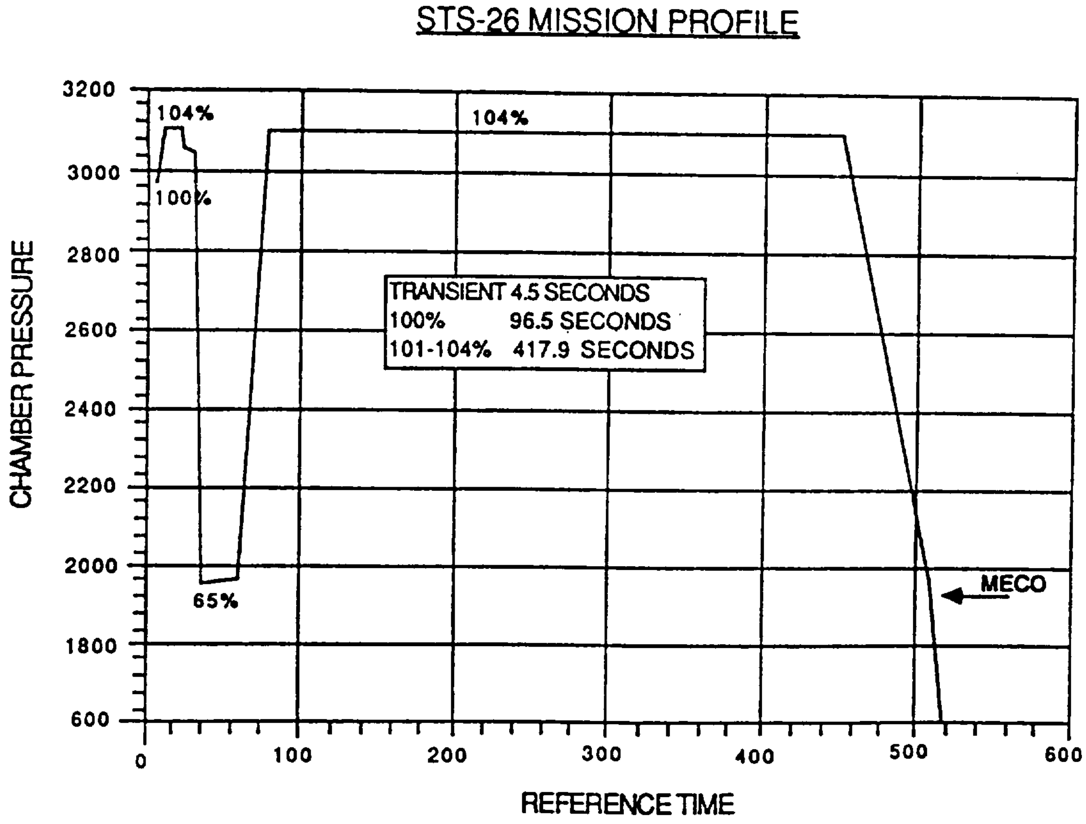


Figure 2. An SSME mission thrust profile.

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 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.

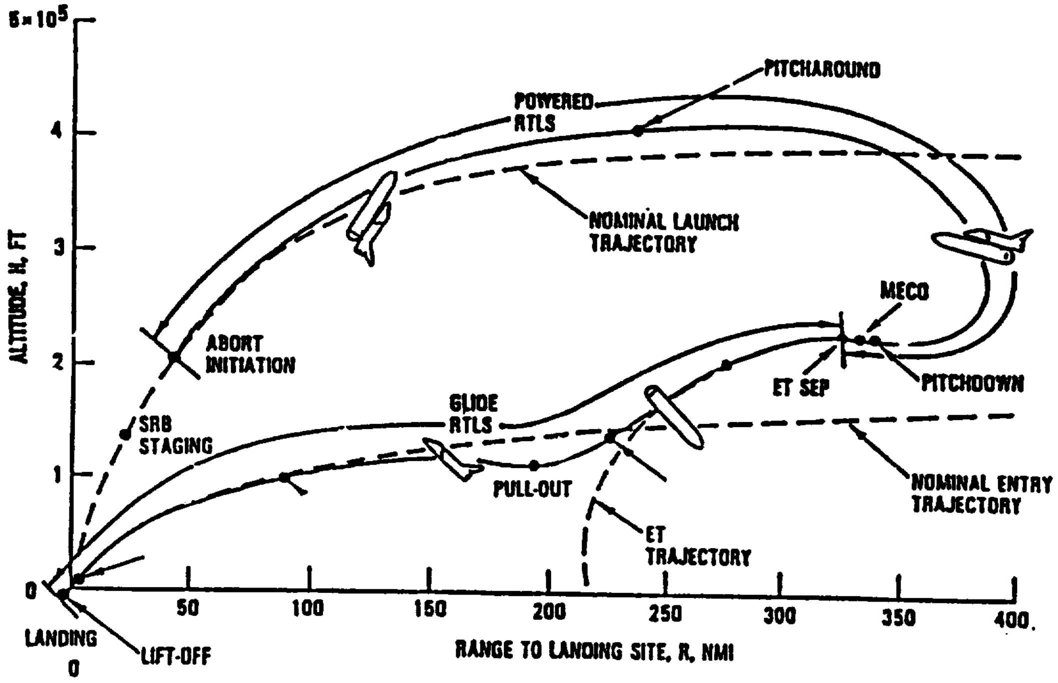
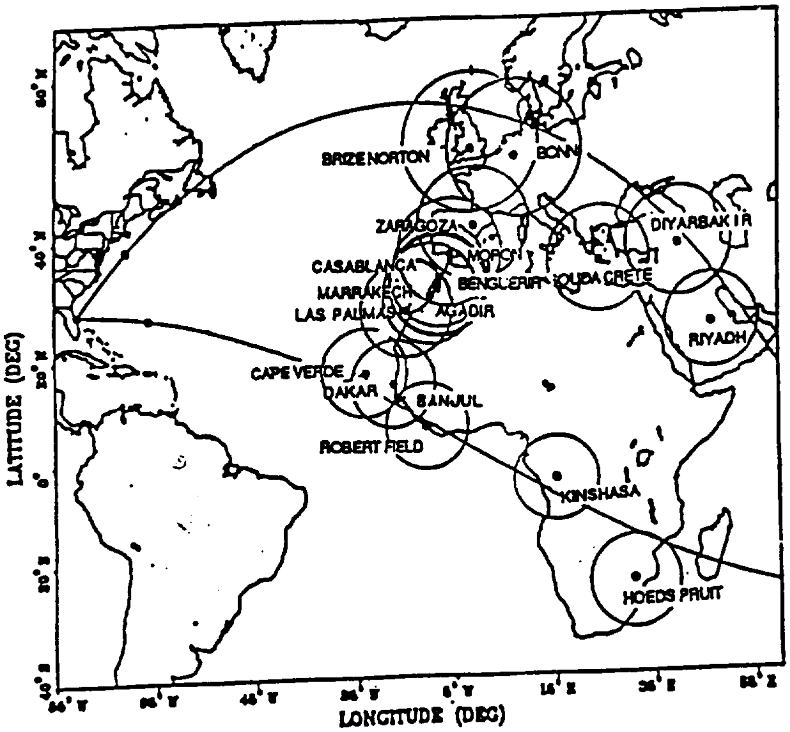


Figure 3. A typical RTLS profile.

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.



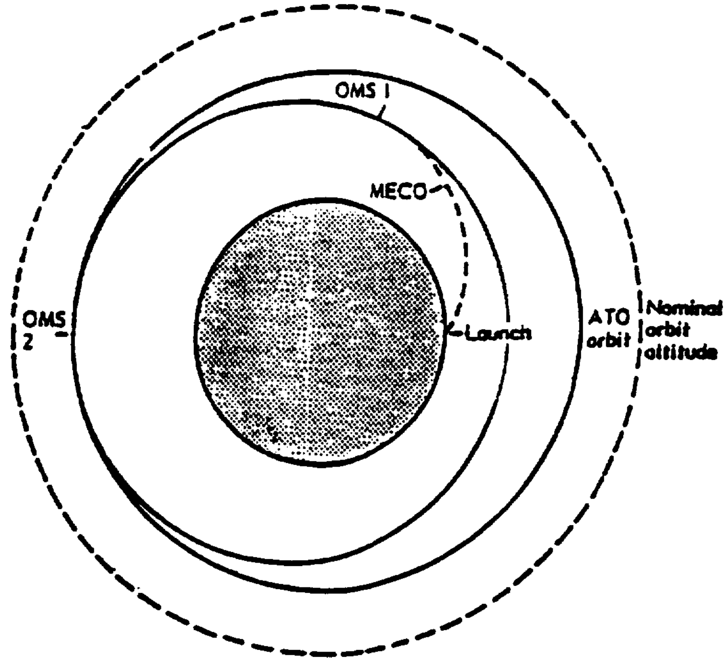
PROJECTION : MERCATOR

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.



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.

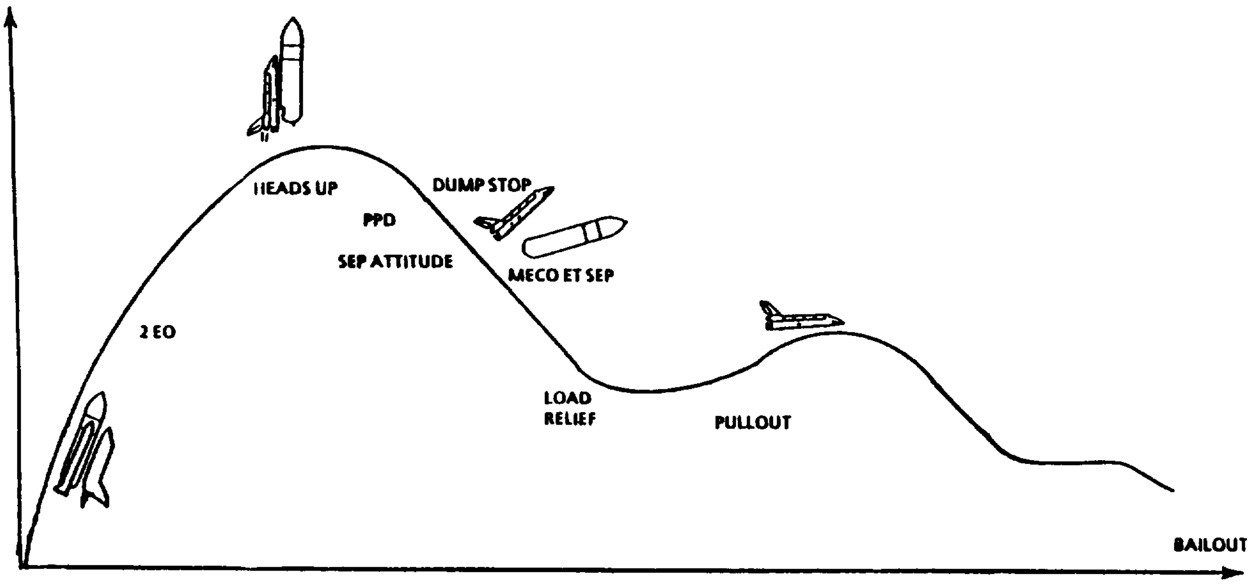


Figure 6. A typical contingency abort profile.

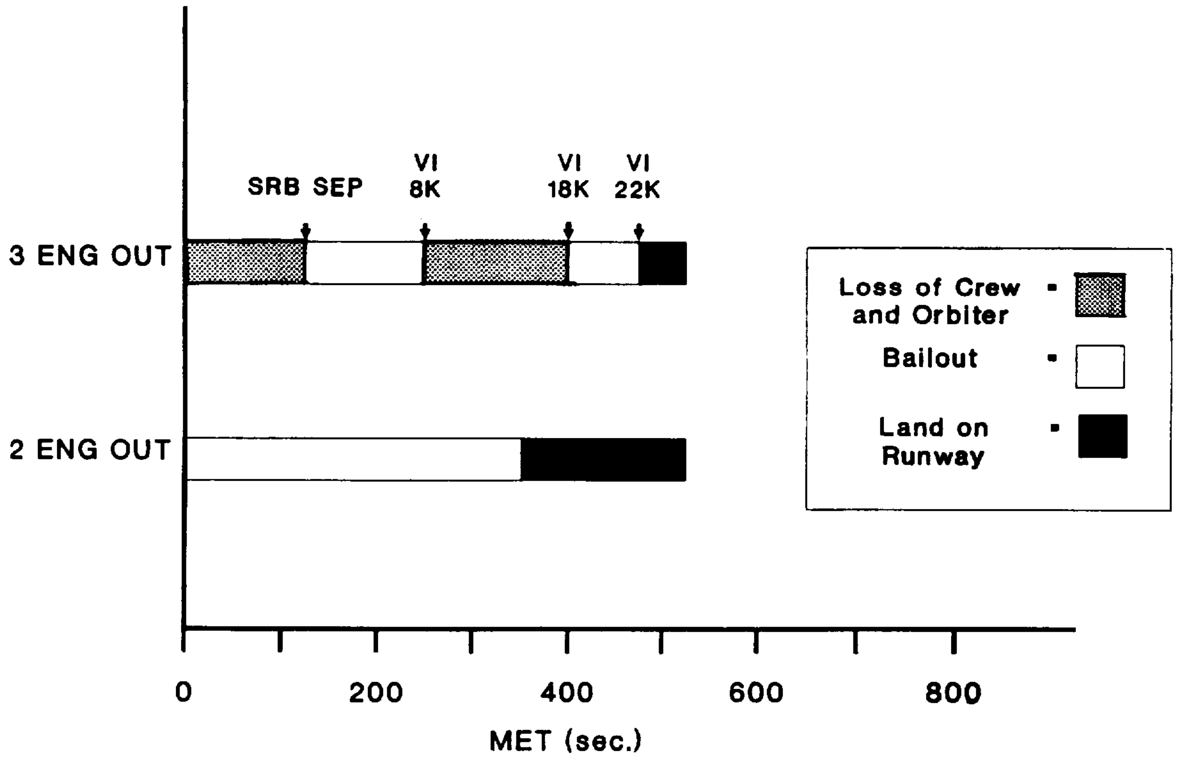


Figure 7. Contingency abort capability.

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 STS Operational Flight Rules—All Flights. The purpose of the flight rules discussed in the document "STS Operational Flight Rules—All Flights" is stated as: "The flight rules outline preplanned decisions designed to minimize the amount of real-time rationalization required when nonnominal 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).

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 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.

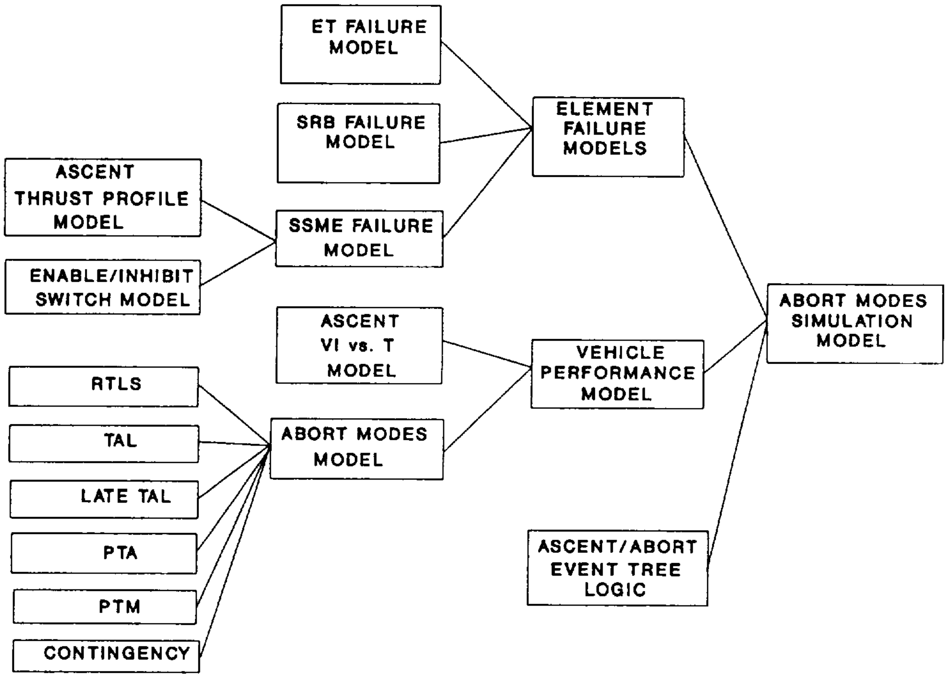


Figure 8. Basic approach to model development.

## 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

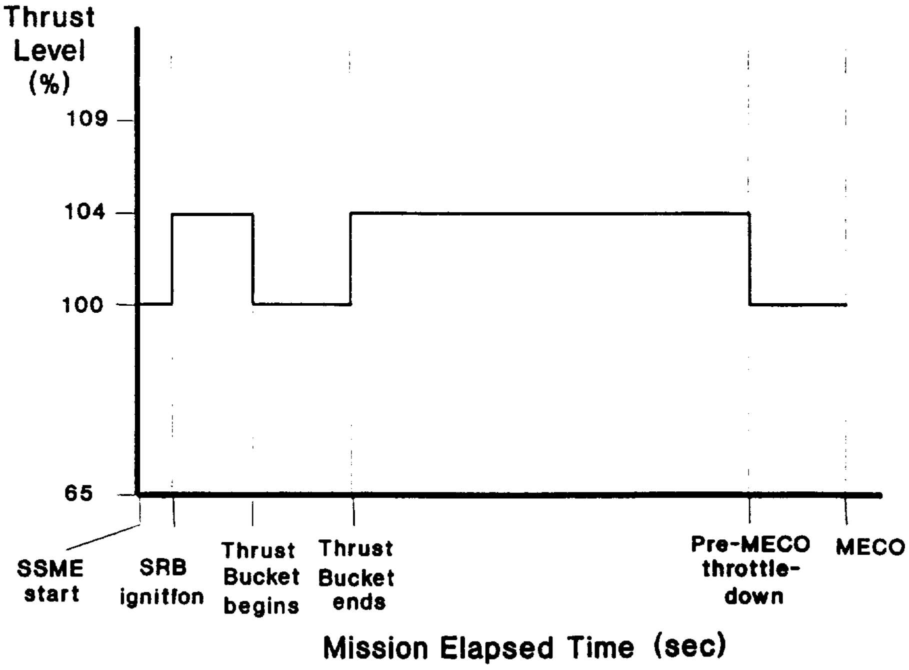


Figure 9. The SSME mission thrust profile model.

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 Ascent Flight Phase Model. 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:

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

where

VI = the vehicle's inertial velocity

$a$ = a coefficient

$b$ = a coefficient

$T$ = the mission elapsed time.

2.3.2 Return to Launch Site Mode Model. 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:

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

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

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

2.3.3 Transoceanic Abort Landing Mode Model. 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 Late TAL Mode Model. 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 Press to MECO 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 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.

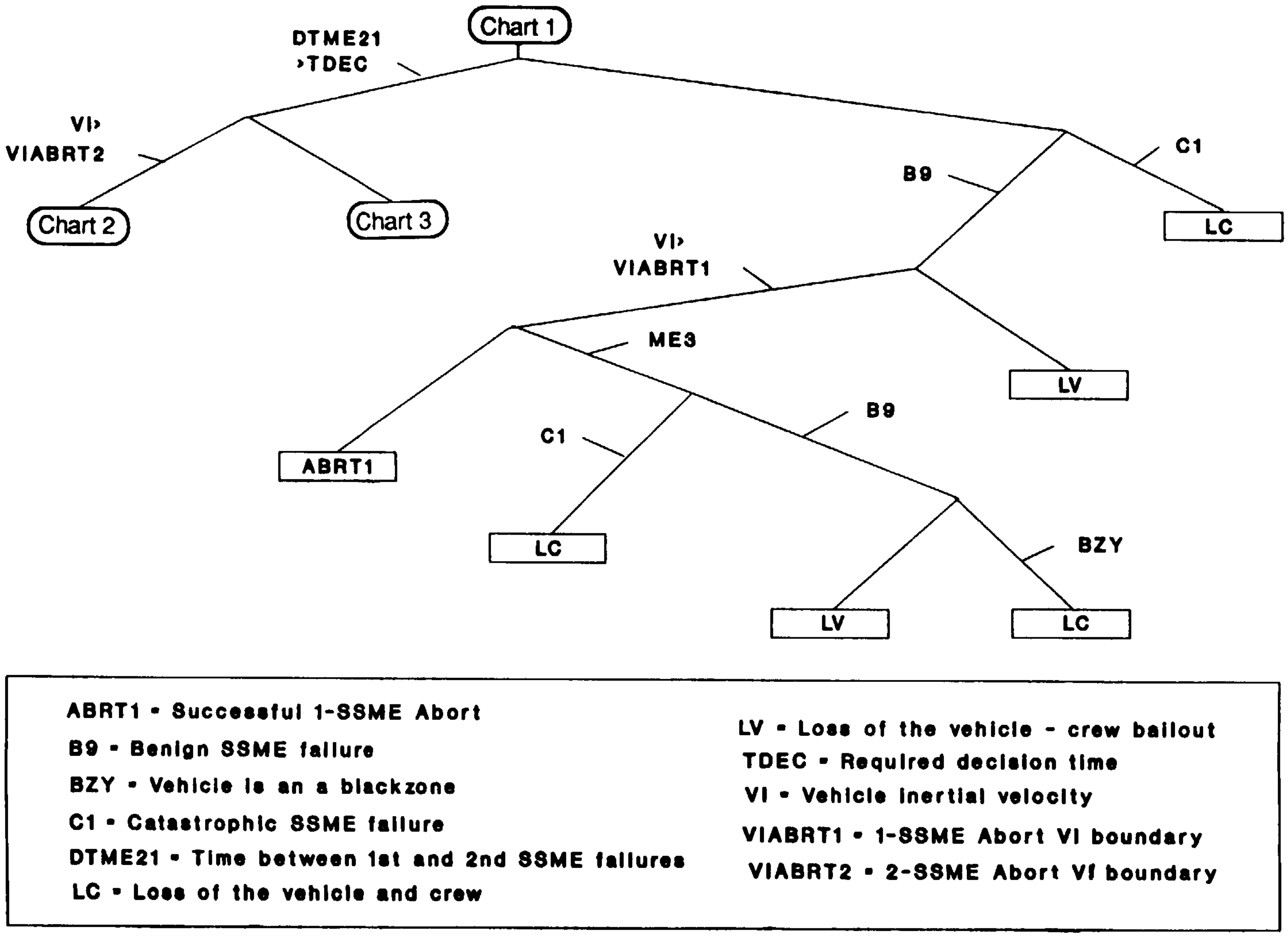


Figure 10. A hypothetical event tree segment.

# 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.

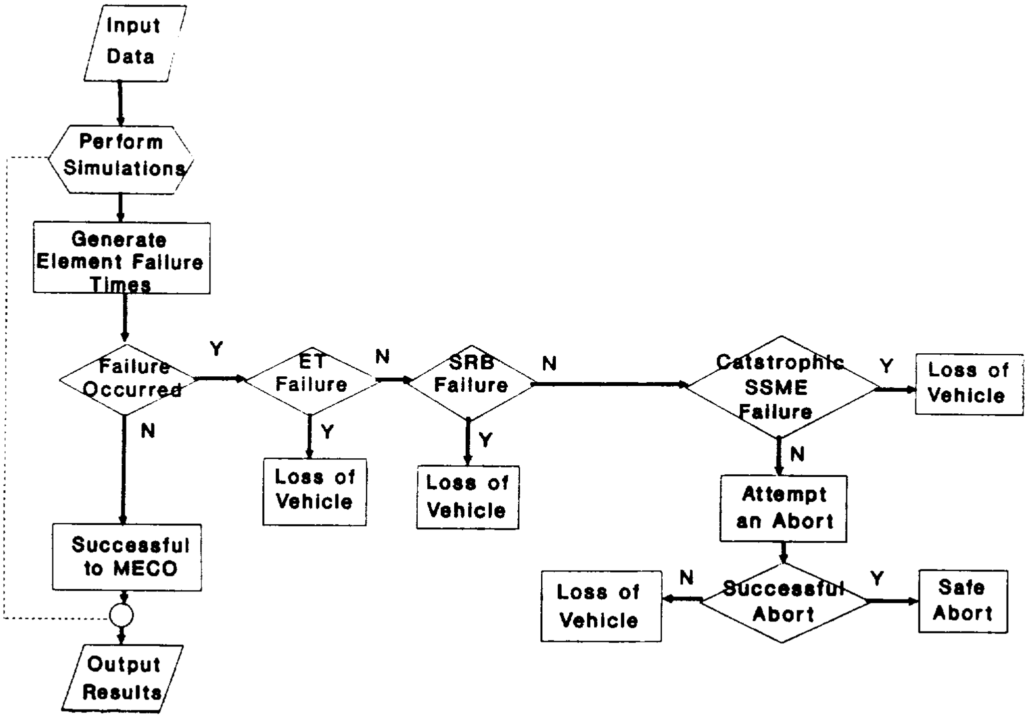


Figure 11. Simulation program overview.

## 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.

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.

3.2.4 TAL Redesignation Option Selection. 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 Late TAL Performance. 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 PTM and PTA Performance. 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 Random Number Generation. Function RANDOM is the pseudo-random number generator for the program.

3.2.8 Exponential Distribution Value Generation. 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:

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

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 Uniform Distribution Value Generation. 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:

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

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 SRB Time to Failure Generation. 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 ET Time to Failure Generation. 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.

3.2.12 SSME Time to Failure Generation. 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 SSME Failure Time Determination. 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 Vehicle Inertial Velocity Determination. 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

TAL Sites:

| | |
|---|---|
| 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

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BAILOUT
EGRESS

PILE

## SYS FLIGHT RULES

| | RTLS | TAL/<br>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 |
| PRESS TO ATO (104) | 9600 |
| DROOP BYD (109) | 12000 |
| LAST MRN (104) | 13500 |
| SE BYD (104) | 13700 |
| PRESS TO MECO (104) | 13900 |
| SE PRESS (104) | 16800 |
| LAST BEN (104) | 17600 |
| LAST AUTO BYD | |
| 2 or 3 engine (65) | 20000 |
| 1 engine (104) | 21500 |
| LAST LATE TAL | |
| AML | 22700 |
| BYD | 24500 |
| KIN | 25200 |
| HDS | 25500 |

| | |
|---|---|
| 2 ENG BEN (104) | 6200 |
| **ABORT TAL BEN (2)** | |
| EO VI | |
| DROOP BYD (109) (5) | |
| SE BYD (104) (5) | |
| SE BEN (109) (2) | |
| 2 ENG MRN (104) | 6800 |
| **ABORT TAL MRN (3)** | |
| EO VI | |
| DROOP BEN (109) (2) | |
| SE BEN (104) (2) | |
| SE BYD (104) (5) | |
| SE MRN (109) (3) | |

TOP
BACK OF 'RTLS PLT'

PILE

## AUTO TAL CDR

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

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

$V_I$~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
✓Bugs, HDG, RANGE, α = 40°
* Low energy: CSS, α = 40° *
* WINGS LVL *
* At $\dot{H}$ = 0: fly α = 31° *
* Maintain ΔAZ ≤ 20 *
Adjust seat

| WINDS | |
|---|---|
| 50K | / |
| 40 | / |
| 30 | / |
| 20 | / |
| 7 | / |
| SURF | / |
| **SPDBK @ 3000 FT** | |

**RTLS**

V = 10 ✓SPDBK → 81%

✓TACAN MODE (three) - GPC

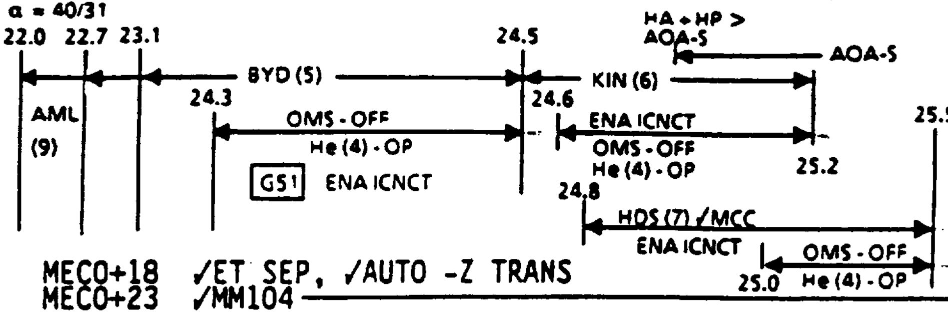
V = 5 AIR DATA PROBES (two) - DEPLOY, (✓Heat)
✓RUD, AIL TRIM
M = 3.2 ✓SPDBK → 65%
M = 2.7 HUD PWR (two) - ON
M = 2.0 Ensure ADTA to G&C else THETA limits
M = 0.9 P,R/Y - CSS, SPDBK - MAN (as reqd)
✓NWS - GPC
POST LANDING: ENT C/L, <u>POST LANDING</u>

TOP
BACK OF 'AUTO TAL PLT'

PILE

## LATE TAL CDR

$V_I$ = $\boxed{24.0K}$ ME SHUTDN pb (three) - push
* If 1 SSME out at PTA, subtract 200 fps *



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<br>BYD 14 | BYD 121Y · BJ 76 (DME)<br>BYD 121Y · BJ 76 (DME) | 6<br>- | 10420<br>10420 |
| 6 | ROB 04<br>KIN 25 | ROB 85 (DME) —<br>BZ 78 (DME) — | -<br>- | 11160<br>15510 |
| 7 | KKI 15<br>HDS 18 | RIY 92 —<br>HS 73 (DME) — | -<br>- | 13700<br>13120 |
| 9 | AML 02<br>DON 29 | CVS 100(DME) ---<br>DN 84 --- | -<br>- | 10890<br>11260 |

PASS $\boxed{G50}$ SEL SITE, RWY
BFS OPS 301 → 304 PRO
BFS $\boxed{G50}$ SEL SITE, RWY

* Low energy: CSS, α = 40° *
* WINGS LVL *
* At $\dot{H}$ = 0: fly α = 31° *
* Maintain ΔAZ ≤ 20 *

$\boxed{G50}$ SHORT SPDBK,
ITEM 39 EXEC
Adjust seat

WINDS

| | |
|---|---|
| 50K | / |
| 40 | / |
| 30 | / |
| 20 | / |
| 7 | / |
| SURF | / |
| **SPDBK @ 3000 FT** | |

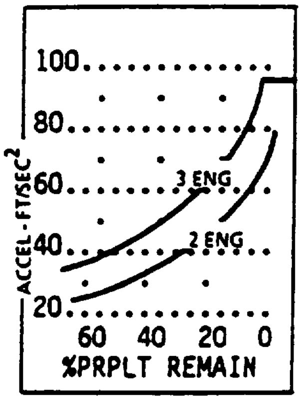
V = 10 ✓SPDBK → 81%

**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

## ASCENT ADI - NOMINAL
## (32 CY 2R)

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



HOOK VELCRO

HOOK VELCRO

-STAGING-

| $V_I$ | $\theta$ | $\dot{H}$ | 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/B

## 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 | 9600 |
|---|---|---|---|---|---|
| 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

# 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

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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.

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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,

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

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

where

$ict$ = 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:

$$t(100) = 110 \text{ s}$$

$$t(104) = 405 \text{ s}$$

$$t(109) = 350 \text{ s} \, .$$

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

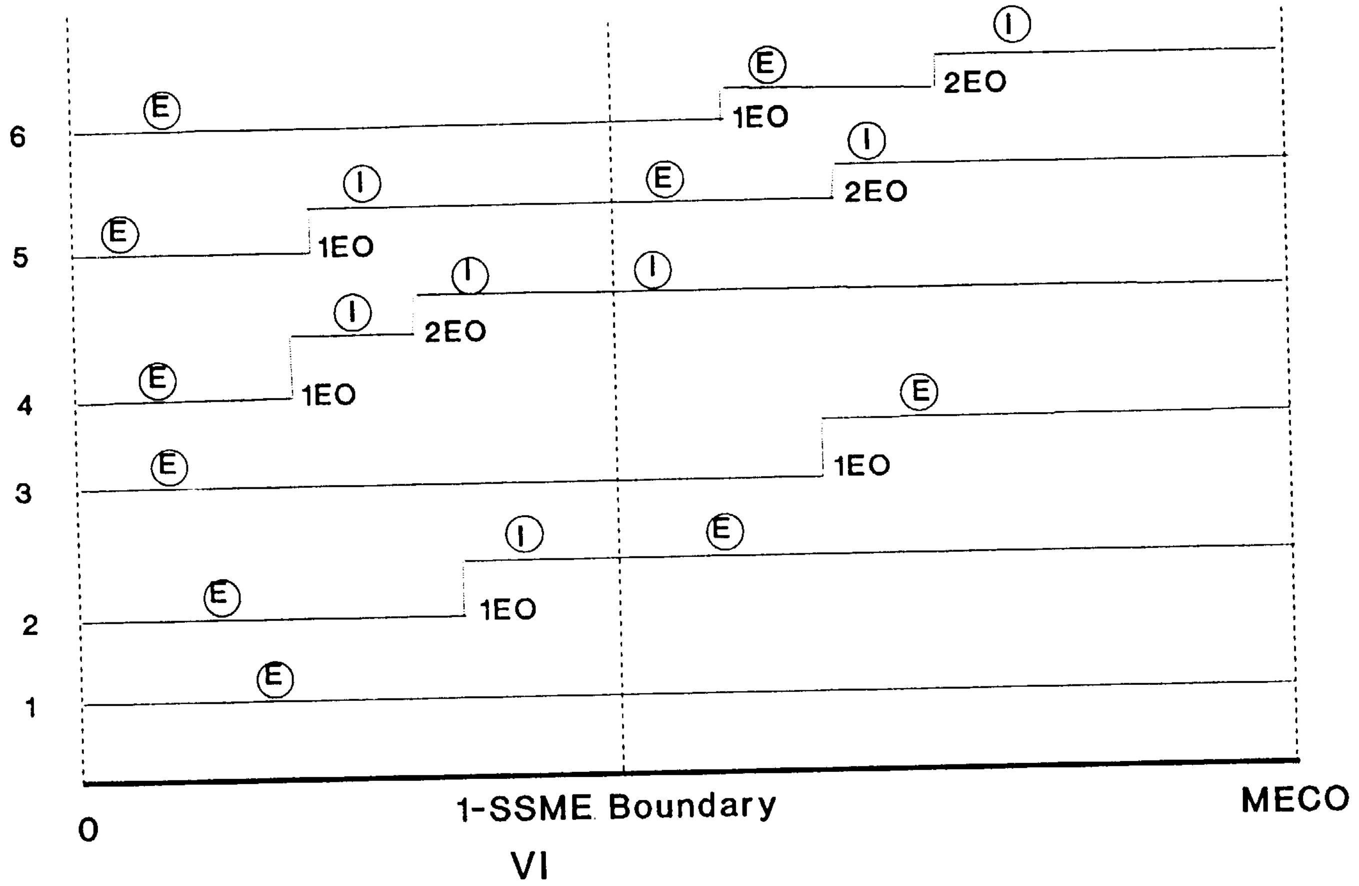
where

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

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

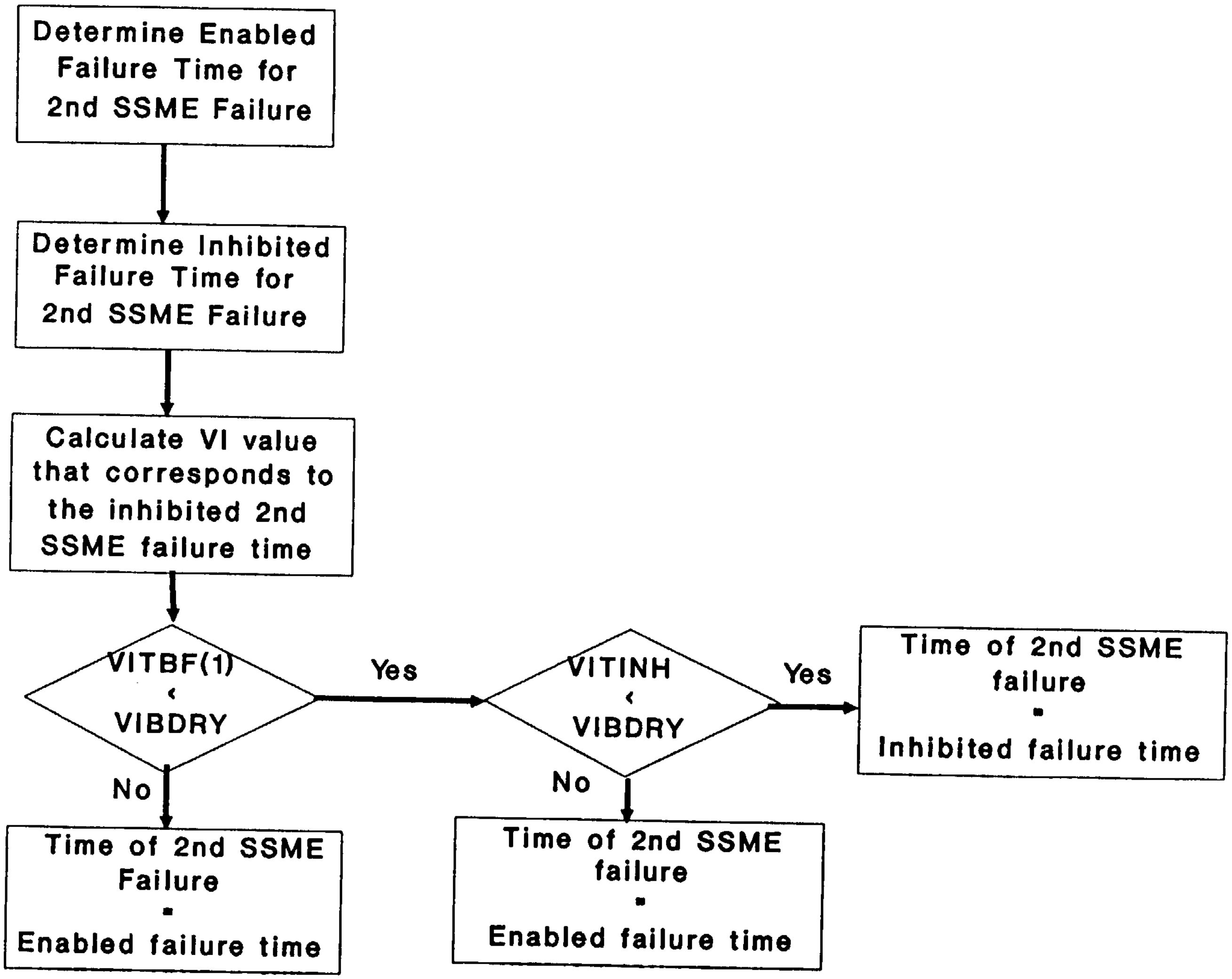
109 percent: $P(ic) = -350/(-0.693+\ln(1+\exp(-350/P(eb))))$

# ENABLE/INHIBIT SWITCH LOGIC SUMMARY



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

# ENABLE/INHIBIT SWITCH MODEL FLOWCHART



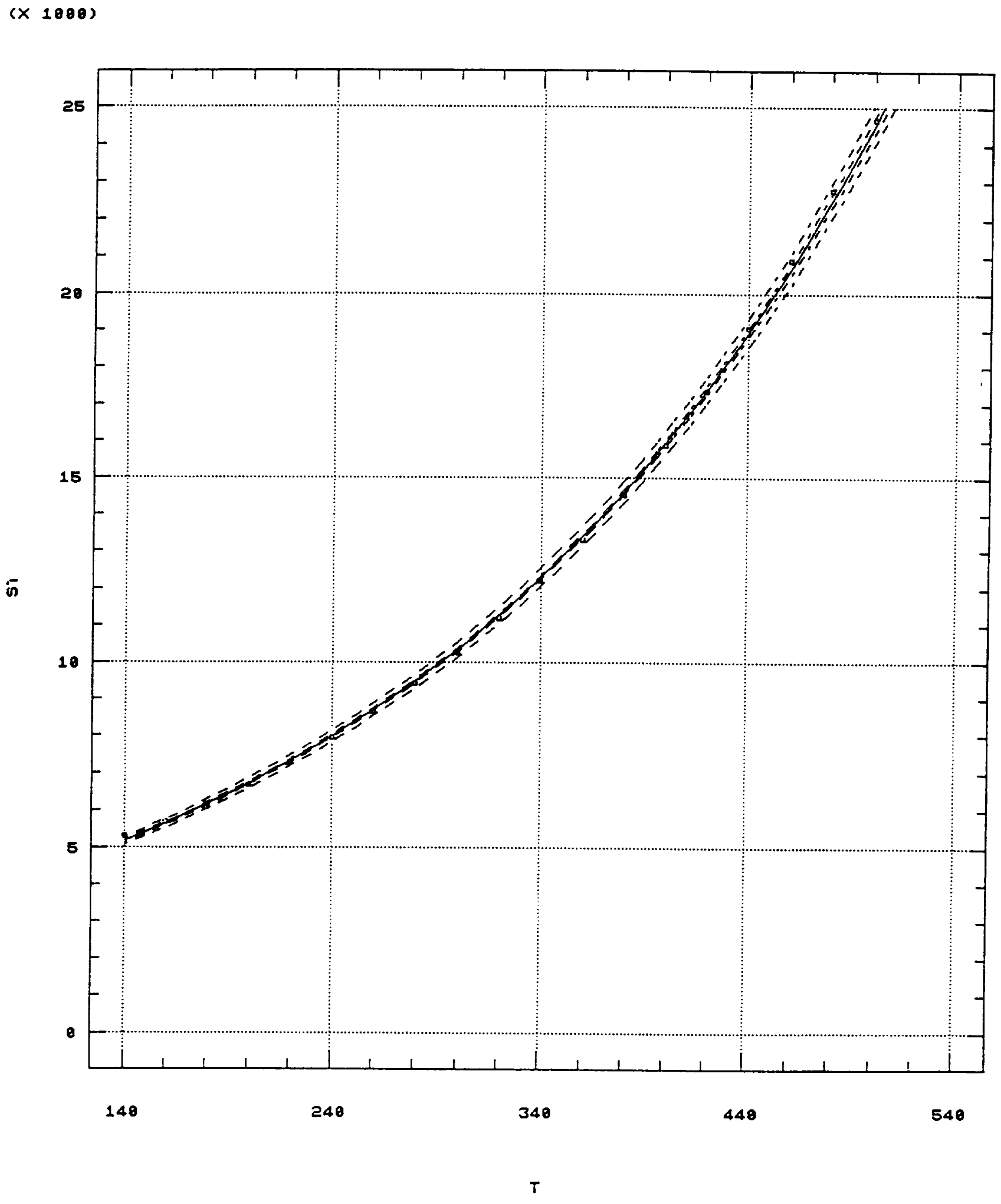
# APPENDIX C

## 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:

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

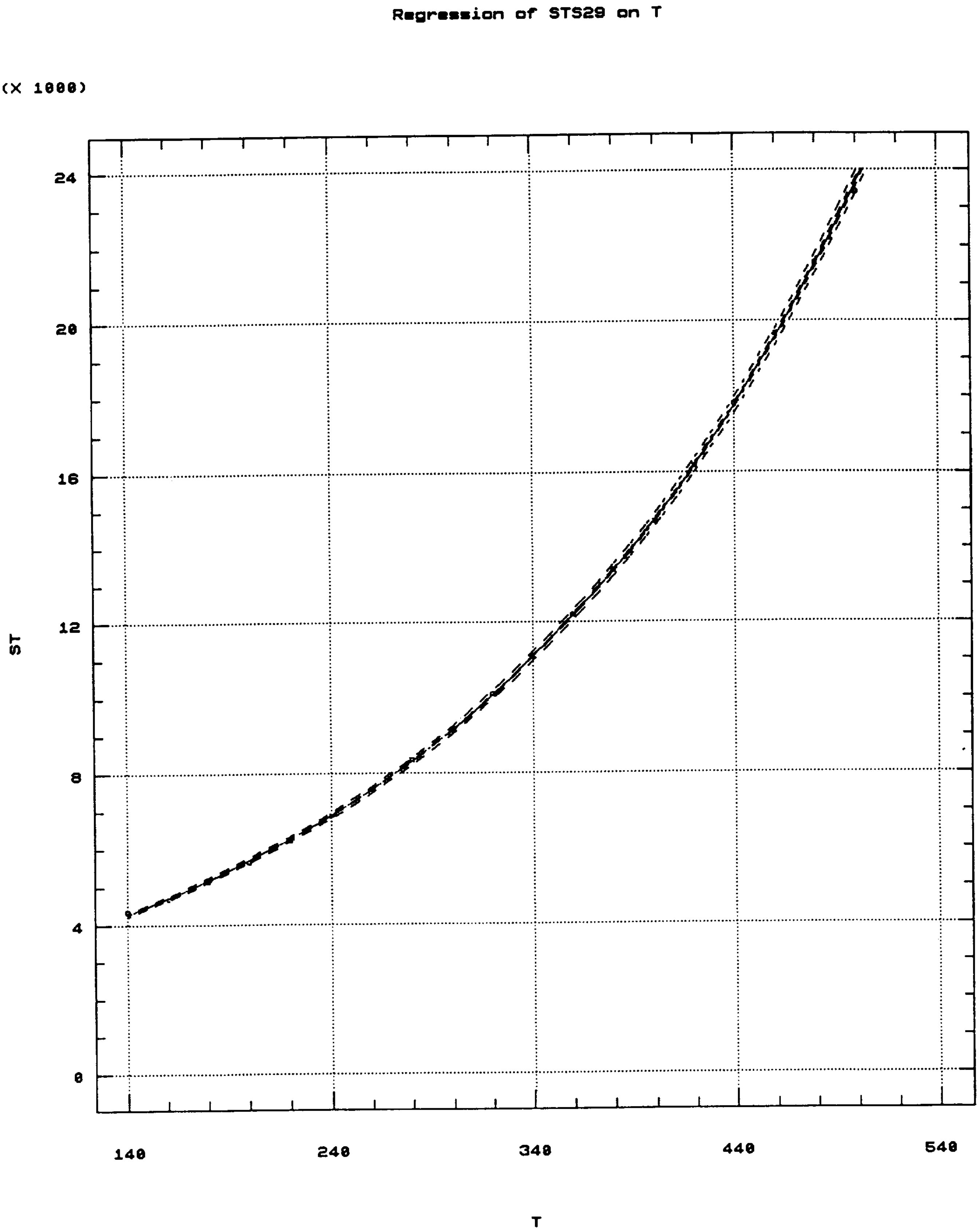
Regression of STS27 on T



```
Regression Analysis - Exponential model: Y = exp(a+bX)
--------------------------------------------------------------------------------
Dependent variable: STS27                               Independent variable: T
--------------------------------------------------------------------------------
                                Standard              T              Prob.
Parameter        Estimate         Error             Value            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
```



Regression of STS29 on T
(X 1000)
24
20
16
12
8
4
0
ST
140
240
340
440
540
T

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

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

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

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

where

$T$meco = time of nominal MECO

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

$T$(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,

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

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

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:

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

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

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

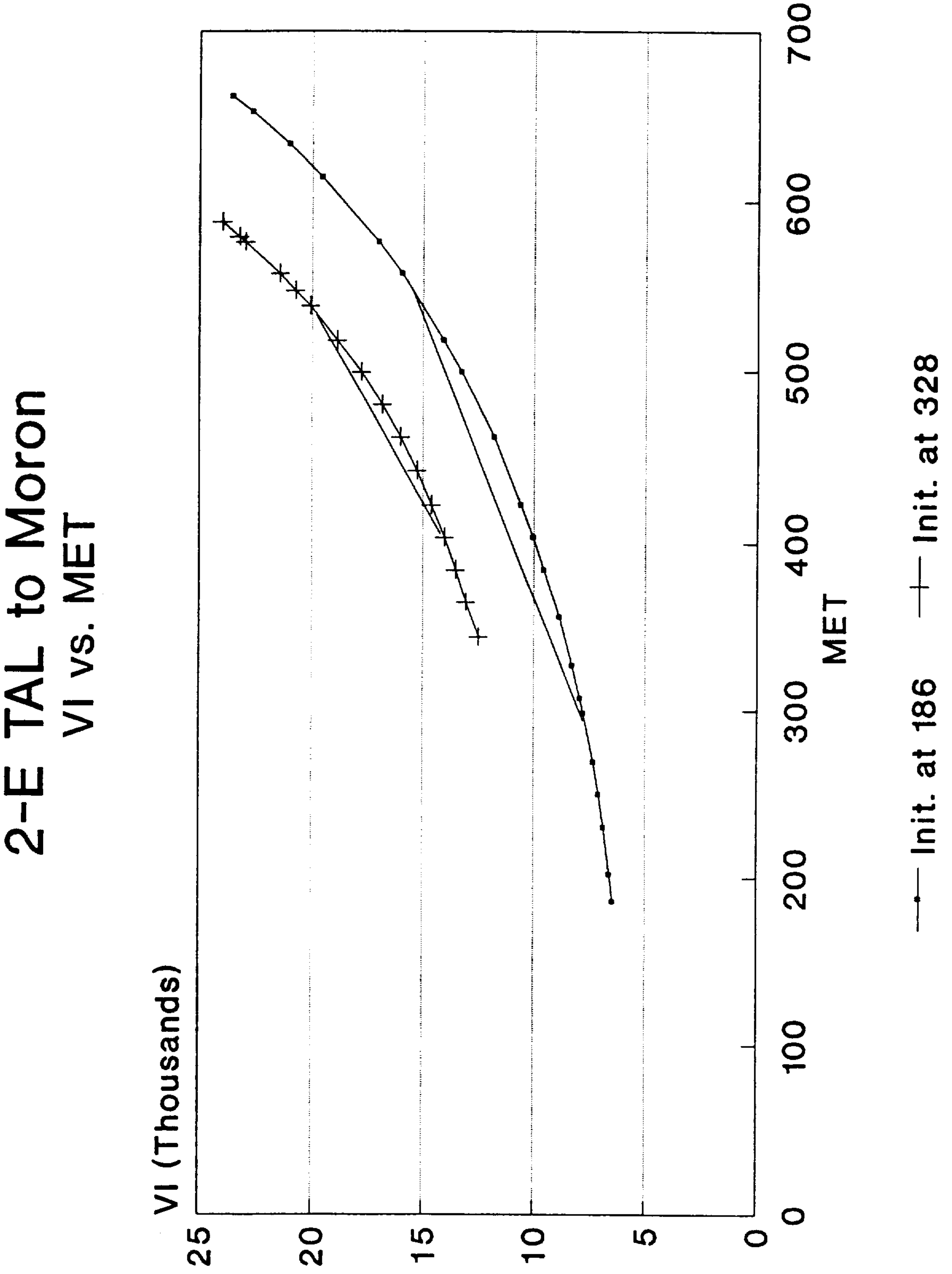

Fig. D-1 - TAL VI vs. MET

# 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

$T(fb$ and $PPD)$ = time required for flyback and powered pitchdown.

From the data (fig. E-1),

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

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

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),

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

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

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:

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

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:

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

where

$T$(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:

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

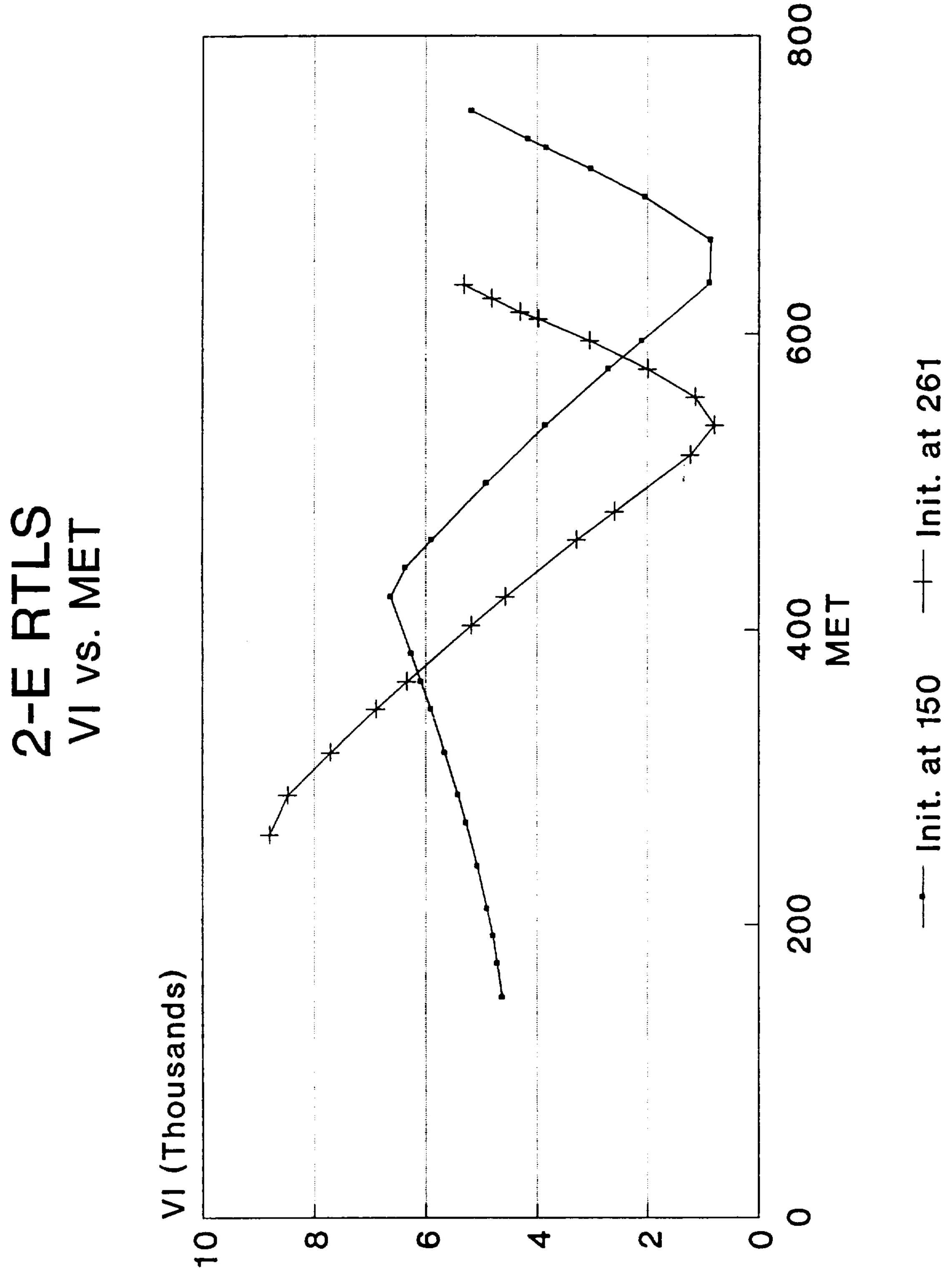

Fig. E-1 - RTLS VI vs. MET

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# 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:

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

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:

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

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:

$$\mathrm{VI} = \mathrm{VI}(\mathrm{1stEO}) + (T(\mathrm{2ndEO}) - T(\mathrm{1stEO})) * ACC(\text{2-ENG at 104 percent})$$
$$+ (T(\mathrm{3rdEO}) - T(\mathrm{2ndEO})) * ACC(\text{1-ENG at 109 percent}),$$

where

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

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# 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:

<u>Assumption</u>: 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,

$$\mathrm{VI(MECO)} = \exp(a+b*T\mathrm{MECO})\ ,$$

where

$a,b$ = VI versus $t$ profile parameters

$T$MECO = time of MECO.

<u>Assumption</u>: The acceleration of the vehicle is proportional to its thrust.

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

$$\mathrm{VI(MECO)} = ACC(\mathrm{3E,104\%})*(T\mathrm{MECO} = ACC(\mathrm{3E,104\%})*T(\mathrm{1stEO})+ACC(\mathrm{2E,104\%})*T\mathrm{reqd}\ ,$$

where

$T$reqd = required remaining run time for the two remaining engines

$T(\mathrm{MECO}) = T(\mathrm{1stEO})+2/3*T\mathrm{reqd}$

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

For a 2-ENG PTM:

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

For a 1-ENG PTM attempt:

$$ACC(\mathrm{3E,104\%})*T\mathrm{MECO} = ACC(\mathrm{3E,104\%})*T(\mathrm{1stEO})+ACC(\mathrm{2E,104\%})$$

$$*(T(\mathrm{2ndEO})-(\mathrm{1stEO}))+ACC(\mathrm{1E,104\%})*T\mathrm{reqd}\ ,$$

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

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

For a 2-ENG PTA attempt:

Assumption: 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,

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

# APPENDIX H

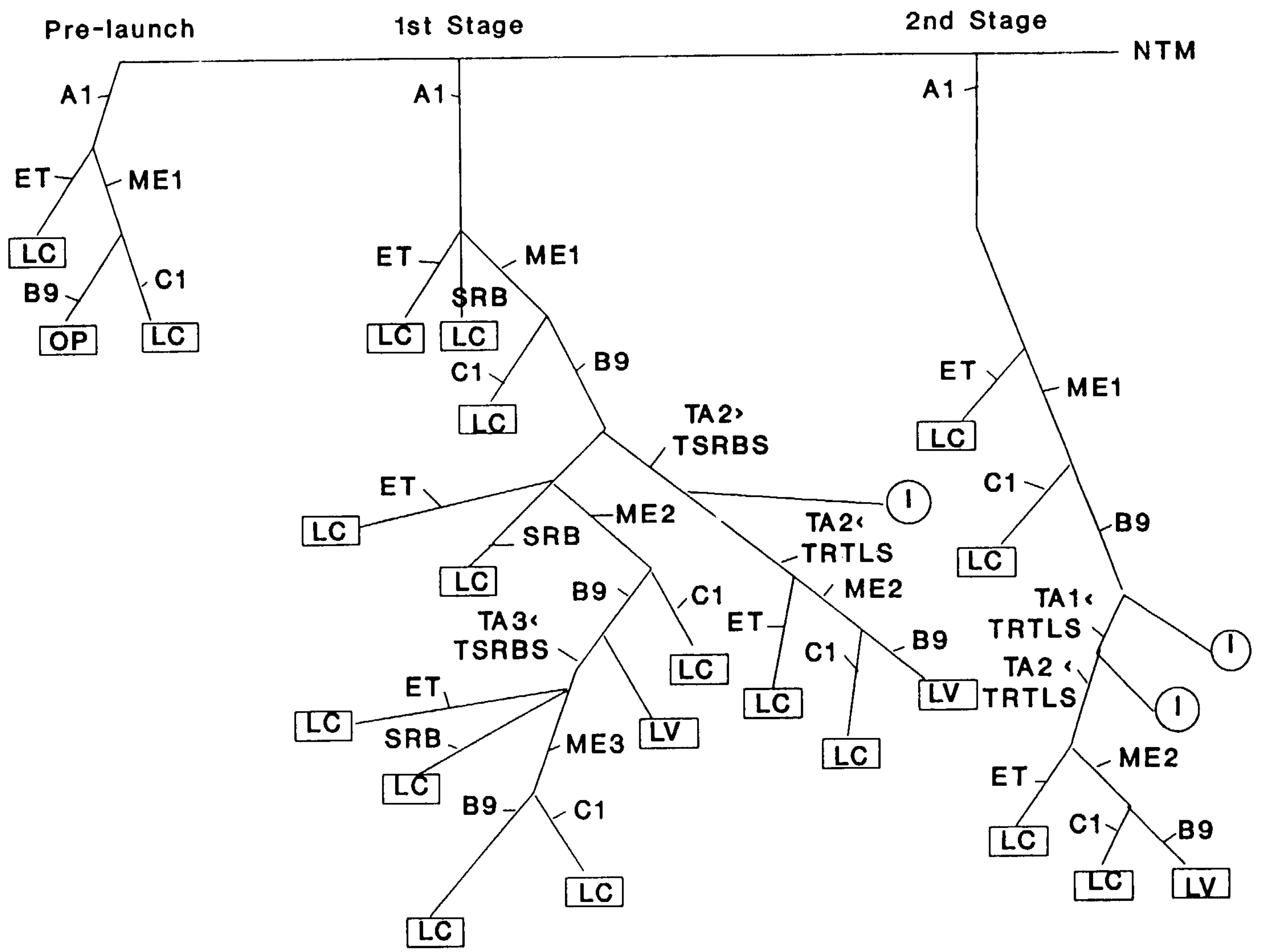
## STS Ascent/Abort Event Tree Diagram

Definition of Symbols

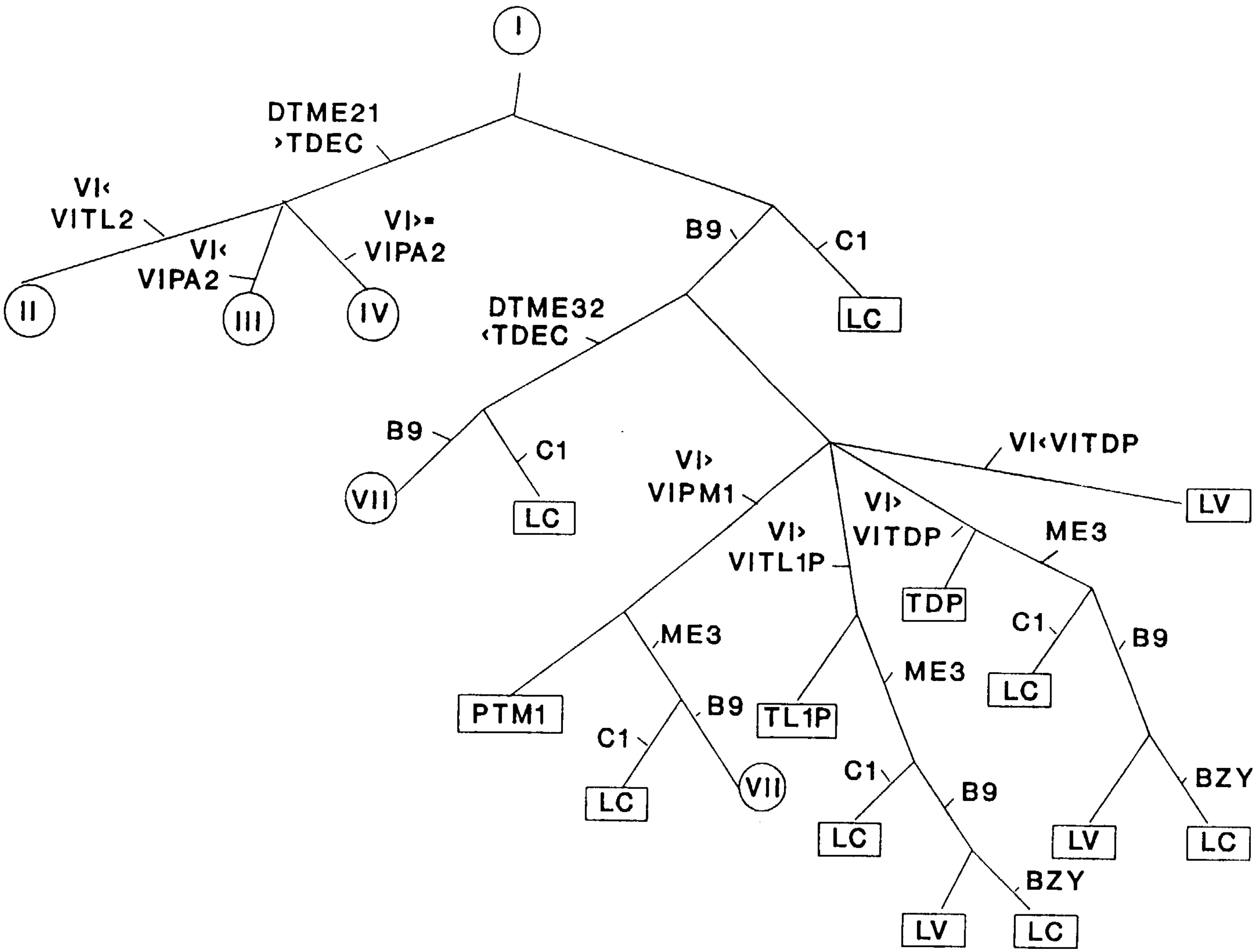
| Symbol | Definition |
|---|---|
| A1 | First anomaly occurs |
| A2 | Second anomaly occurs |
| AT02 | Successful 2-SSME ATO |
| BZN | Vehicle is in a black zone |
| BZY | Vehicle is not in a black zone |
| B9 | Benign SSME failure |
| C1 | Catastrophic SSME failure |
| DTME21 | Time between ME2 and 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 |

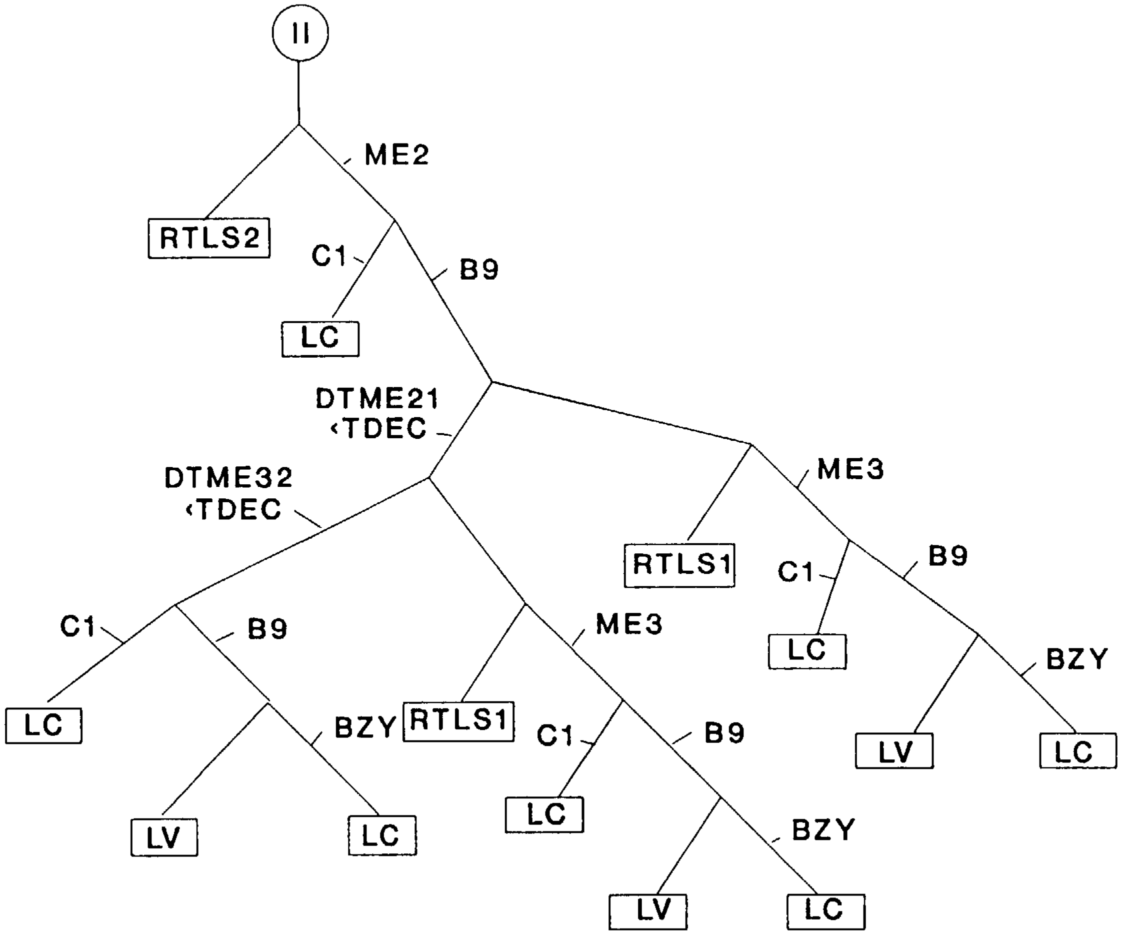
# Ascent/Abort Event Tree - 1



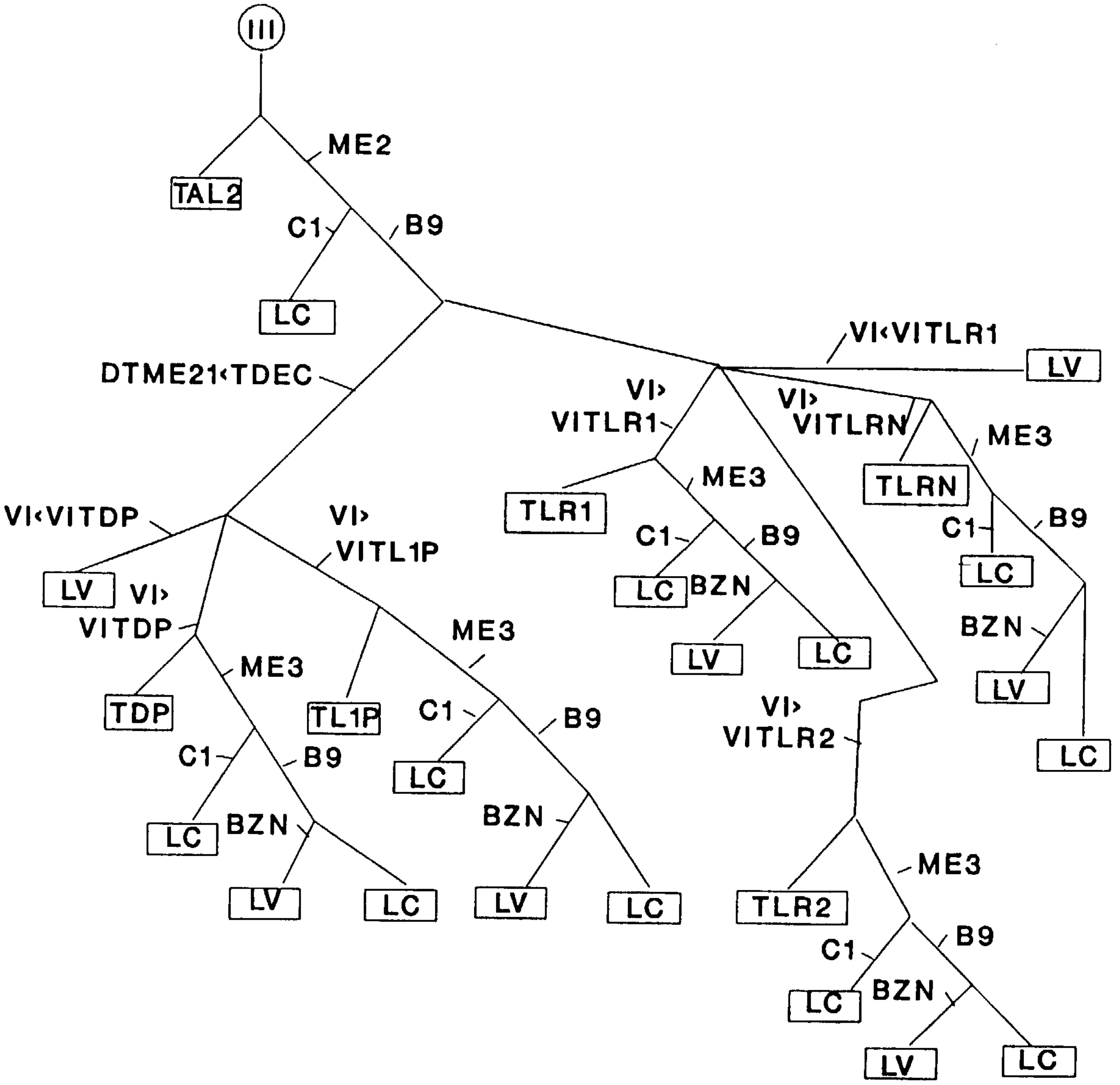
# Ascent/Abort Event Tree - 2



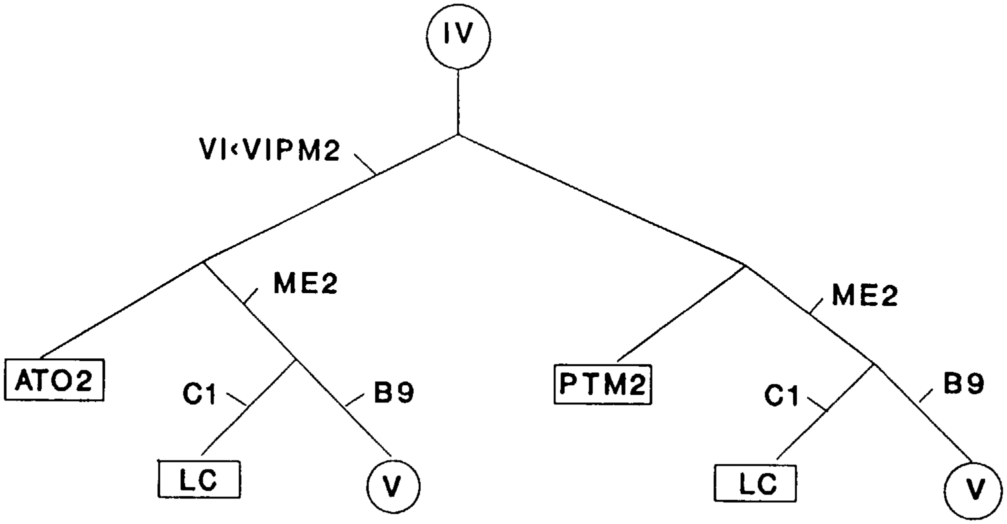
# Ascent/Abort Event Tree - 3



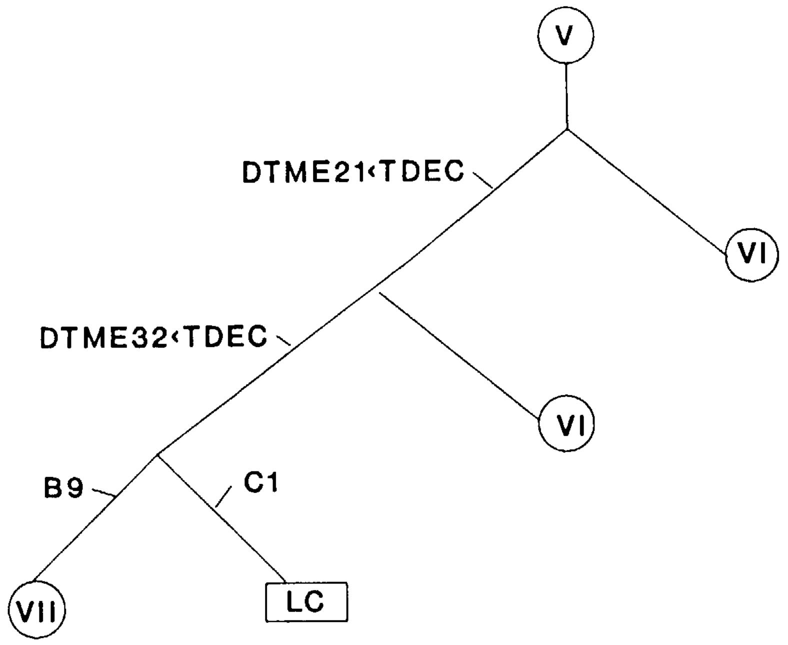
# Ascent/Abort Event Tree - 4



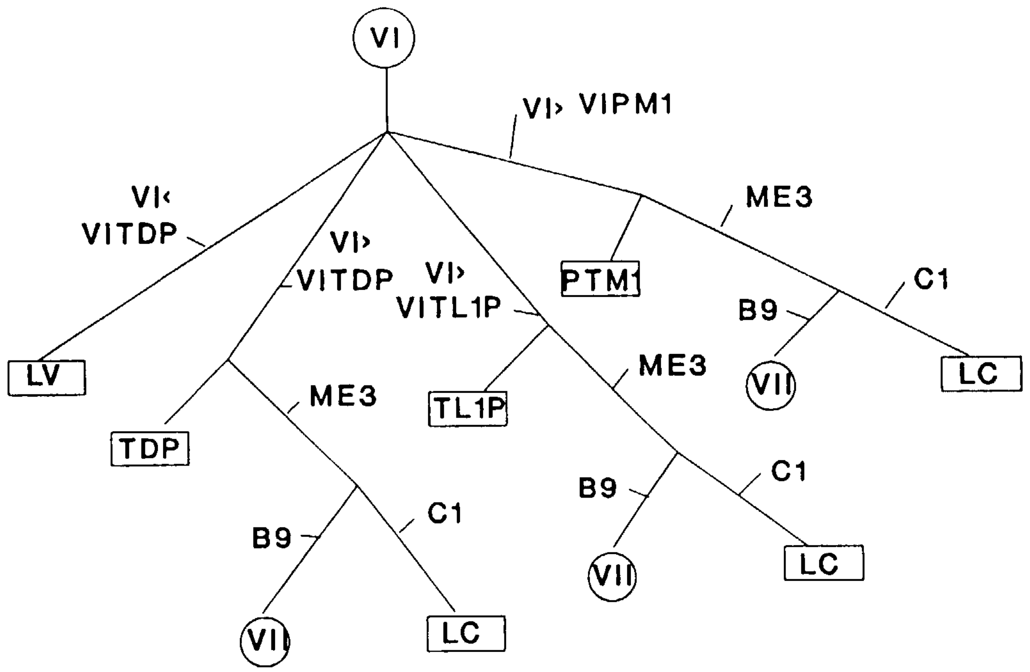
# Ascent/Abort Event Tree - 5



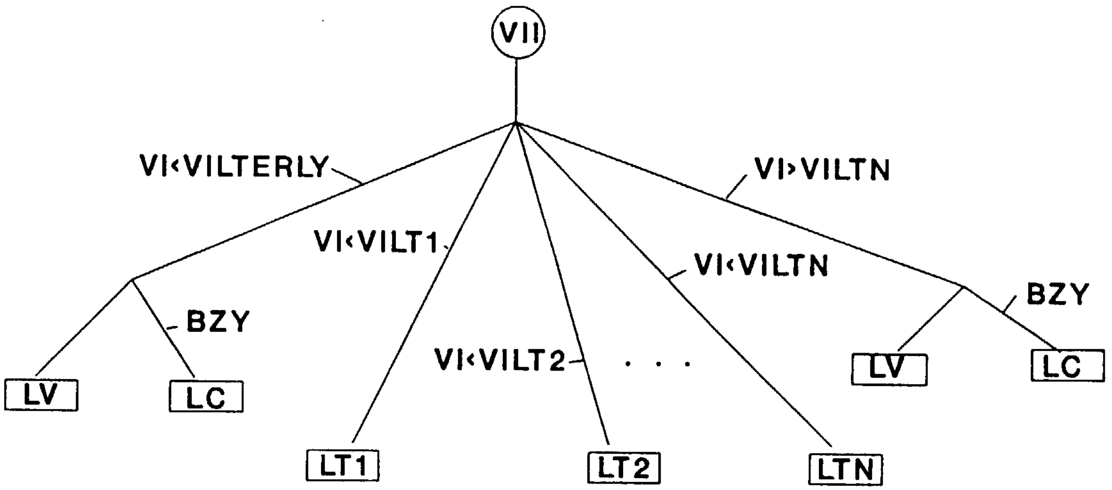
# Ascent/Abort Event Tree - 6



# Ascent/Abort Event Tree - 7



# Ascent/Abort Event Tree - 8



# 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
```

| | |
|---|---|
| 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

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

```
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
```

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# 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

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**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
```

```
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
```

```
          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
```

| | |
|---|---|
| 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
```

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

# 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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for W.K. FIKES
Director, Preliminary Design Office, Program Development

☆ U.S. GOVERNMENT PRINTING OFFICE 1993—533-108/80150