NASA-CR-167549

DEVELOPMENT OF STS/CENTAUR FAILURE PROBABILITIES LIFTOFF TO CENTAUR SEPARATION

Technical Report No. 82-1404

Prepared for

National Aeronautics and Space Administration
Johnson Space Center
Houston, Texas

Contract No. NAS 9-16259

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(NASA-CR-167549) DEVELOPMENT OF STS/CENTAUR FAILURE PROBABILITIES LIFTOFF TO CENTAUR SEPARATION Final Report (Wiggins (J. H.) Co., Redondo Beach, Calif.) 82 p HC A05/MF A01 CSCL 22B G3/15
N82-19255
Unclas
09220

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February 1982

ABSTRACT

This report presents the results of an analysis to determine STS/Centaur catastrophic vehicle response probabilities for the phases of vehicle flight from STS Liftoff to Centaur separation from the Orbiter. The analysis considers only category one component failure modes as contributors to the vehicle response mode probabilities. The relevant component failure modes are grouped into one of fourteen categories of potential vehicle behavior. By assigning failure rates to each component, for each of its failure modes, the STS/Centaur vehicle response probabilities in each phase of flight can be calculated. The results of this study will be used in a DOE analysis to ascertain the hazard from carrying a nuclear payload on the STS.

GLOSSARY

APU	Auxiliary Power Unit
CISS	Centaur Integrated Support System
ET	External Tank
ETS	External Tank Separation
GSE	Ground Support Equipment
IUS	Inertial Upper Stage
ME	Main Engine
MECO	Main Engine Cutoff
MMH	Monomethyl Hydrazine
MPS	Main Propulsion System
OMS	Orbital Maneuvering System
ORB	Orbiter
PBK	Payload-Bay Kit
RCS	Reaction Control System
RSCD	Range Safety Command Destruct
STAGING	SRB Separation
SRB	Solid Rocket Booster
SSME	Space Shuttle Main Engines
STS	Space Transport System
TPS	Thermal Protection System
TVC	Thrust Vector Control

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1. INTRODUCTION

The purpose of this study is to determine the catastrophic failure probabilities, for the Galileo mission, for each identified STS/Centaur response mode from liftoff through Centaur deployment.

Only failures leading to loss of vehicle and hence the payload are considered. The results of this study will be used as input to an analysis of the risk associated with carrying a nuclear payload on the STS. This nuclear payload risk study is being undertaken by the DOE for NASA. The study approach is outlined by the following tasks:

1. Assess which failure modes (in addition to those developed under Contract NAS 10-9374 for the STS) require to be included in the analysis. List such additional failure modes with the item or items of Centaur hardware involved. Only category one failure modes will be included and this will require reference to General Dynamics documentation and other references as necessary.

2. Group failure modes according to their affect on the combined STS/Centaur vehicle in each of the relevant STS/Centaur flight phases.

3. Assign failure rates to each hardware component contributing to catastrophic failure in each of the flight phases, for each vehicle response mode.

4. Compute failure probabilities for each combined STS/Centaur vehicle response mode (resulting from a category one failure) from liftoff to Centaur separation from the Orbiter.

Section 2 outlines the limits of this study and lists the assumptions made in the analysis. Certain failures were considered to be outside the scope of this analysis since they would not pose a problem to the nuclear payload. Note that some of these excluded failures could play a significant role in the likelihood that the STS will return to base safely after the payload has been deployed. The failure definition, i.e., that which results in loss of payload, constrained which STS failures were to be included in the analysis. Once the payload has successfully been deployed, a re-entry failure of the STS is of no consequence.

Loss of payload is directly relatable to failure of components and/or systems of the STS/Centaur. Failure of certain critical components and systems could lead directly to catastrophic failure of the combined vehicle. This is the approach taken in this study, where component failures are grouped according to expected vehicle response modes. These catastrophic vehicle response modes are listed in Section 3.

The Reactor Safety Study, WASH-1400 [Reference 1], data base was used as a starting point for the development of failure rates as outlined in Section 4. The WASH-1400 study collected data from numerous sources including NASA data. It is important to point out that the WASH-1400 data base was merely used to obtain an indication of suitable bounds for component failure rates. Many of the components used on the STS/Centaur compromise pumps, pipes, valves, pressure vessels, etc., whose failure rates are expected to fall within the ranges for similar components as presented in the WASH-1400 document.

Section 5 outlines the method of calculation of the failure probabilities for each relevant STS/Centaur response mode which could compromise the nuclear payload. The method of calculation used certain simplifying assumptions which, given the expected low probability of event occurrence, are not likely to significantly affect the final results. A previously-developed computer program was used in this stage of the analysis.

Finally, Section 6 presents the results of this combined STS/Centaur analysis.

2. ASSUMPTIONS AND LIMITS OF STUDY

This study was limited to calculating STS/Centaur failure response probabilities from liftoff to Centaur-STS separation.

The list of potentially hazardous failures for the STS was obtained from the Critical Items List (CIL) documentation and various interfacing systems documentation, etc. [References 2, 3, 4, 5, 6 and 7]. This list of STS failure modes was defined in previous J.H. Wiggins Company studies under contract NAS 10-9374. The list of Centaur failure modes was drawn up from Centaur technical description documentation [References 8 and 9] and through consultation with General Dynamics personnel.

The CIL documents for the Orbiter, External Tank and SRBs listed failures as criticality 1, 2, 3, 1R, 2R or 3 which are defined as follows [Reference 2]:

CATEGORY	POTENTIAL EFFECT OF FAILURE
1	Loss of life or vehicle
1R	Redundant hardware element, the failure of which could cause loss of life or vehicle
2	Loss of mission; for GSE, loss of vehicle system
2R	Redundant hardware element, the failure of which could cause loss of mission
3	All others

Only Category 1 failures as defined here were included in this study, which is consistent with the earlier JHW analyses. There is a critical time period prior to liftoff which has not been included, i.e., from To-45 minutes to To, where liftoff occurs at To. This time period was excluded by NASA from initial JHW studies and has been excluded from this analysis.

For the purposes of this study, the following assumptions were made:

1. Criticality 1 failures will contribute almost entirely to catastrophic events.

2. Failure probabilities per unit time of STS components are lognormally distributed.

3. The omission of presently unrecognized criticality 1 failure modes will not significantly affect the final results.

4. Common cause failures (sometimes referred to as common mode failures) will not significantly contribute to the hazard potential.

The implications of Assumption 4 are explained in detail in Reference 10.

3. VEHICLE RESPONSE MODES

For this study Centaur failure modes are considered to contribute to four categories of expected STS/Centaur behavior from liftoff to Centaur separation. These four categories are the following:

- External Tank punctured
- Fire and explosion in payload bay and Orbiter tumbles to earth (prior to orbit insertion)
- Fire and explosion in payload bay - on orbit
- Centaur recontact with Orbiter at separation

Table 3-1 outlines the relevant Centaur failure modes which contribute to each of the above combined vehicle response modes. The expected response modes of the STS, excluding the effects of Centaur, are outlined in Tables 3-2 and 3-3 and described in detail in References 10 and 11.

Table 3-4 defines all potential response modes of the combined STS/Centaur vehicle, from liftoff through Centaur deployment from the orbiter. The carrying of Centaur in the Orbiter payload bay does not change the vehicle response probabilities previously computed for case numbers 1, 2, 3, 4, 5, 7, 8 and 9 (see Reference 11) and 12 and 13 (see Reference 10) of Table 3-4. Cases 6, 10, 11 and 14 are either affected by, or result directly from, carrying Centaur in the Orbiter. The computed vehicle response probabilities for these latter four cases are the central requirements of this study. These results, along with those computed in earlier studies, are presented in Section 6.

A summary of the failure modes relevant to this study from liftoff to Centaur separation from the Orbiter are listed in Tables A-1 through A-3, B1 and C1 through C4 of the Appendix. (Tables B1 and C1 through C4 are extracted from References 11 and 10, respectively.) These tables

Table 3-1. Vehicle Response Modes and Centaur Failure Mode Contributors

NO.	VEHICLE RESPONSE MODE	CRITICAL TIME PERIOD	CENTAUR FAILURE MODES CONTRIBUTING TO THE HAZARD[1]
1	EXTERNAL TANK PUNCTURED	LIFTOFF TO ET SEPARATION (LIFTOFF TO MECO + 16 SECS.)	FAILURES IN THE FOLLOWING SYSTEMS WHICH PROPAGATE TO THE EXTERNAL TANK[2]: ● FUEL TANKS ● PROPULSION ● TANK PRESSURIZATION ● PRESSURE REGULATION ● PURGE ● VENTING ● FILL, DRAIN, & DUMP ● INTERMEDIATE BULKHEAD RELIEF ● CISS HELIUM SUPPLY ● CENTAUR HELIUM SUPPLY ● REACTION CONTROL ● HYDRAULICS ● PNEUMATIC VALVE CONTROL ● CENTAUR SUPPORT STRUCTURES
2	FIRE & EXPLOSION IN PAYLOAD BAY - ORBITER TUMBLES TO EARTH	MECO + 16 SECONDS TO ORBIT INSERTION (END OMS1 BURN)	SAME FAILURE MODES AS FOR NO. 1.
3	FIRE & EXPLOSION IN PAYLOAD BAY - ON ORBIT[3]	(a) END OMS 1 BURN TO OPENING OF PAYLOAD BAY DOORS (b) OPENING PAYLOAD BAY DOORS TO DEPLOYMENT[4]	(a) SAME FAILURE MODES AS FOR NO. 1. (b) SAME FAILURE MODES AS FOR NO. 1 EXCLUDING THOSE WHERE H_2 TANK RUPTURES FIRST.
4	CENTAUR RECONTACT AT SEPARATION WITH ORBITER	DEPLOYMENT	● FAIL TO SEPARATE RISE-OFF FLUID DISCONNECTS

[1]External tank and orbiter failure modes which contribute to this hazard (vehicle response - external tank punctured) are contained in References 10 and 11.

[2]A fire and explosion in the payload bay, resulting from direct or propagated rupture of Centaur fuel tanks, could propagate directly through the base of the Orbiter, or indirectly via an OMS/RCS pod or the main engine compartment.

[3]This vehicle response mode is broken into two distinct time periods according to failure mode contributors. In the first time period (a), the payload bay doors are closed and all failure modes for case number 1 vehicle response are relevant. Once the payload bay doors are opened, an atmosphere must be available to support a fire and explosion. If the hydrogen tank fails, this need not lead to a failure of the oxygen tank and so, with no atmosphere, the result is likely to be benign.

[4]Hydrogen tank failure modes have been excluded as contributors to vehicle response number 3(b), for the time period beginning when the payload bay doors open. With the payload bay doors closed, however, an atmosphere is available to support an explosion initiated by a hydrogen tank rupture. If the oxygen tank ruptures first then the hydrogen tank is likely to fail with a resulting mixing of hydrogen and oxygen. A suitable ignition source could cause this partially confined mixture of propellants to explode, even with the payload-bay doors open. Although there would be no pressure wave with an explosion in this environment, the large volume of propellants would result in an explosion of quite high yield which would impart considerable energy to fragmented components of the Centaur and Orbiter.

Table 3-2. STS Vehicle Response Modes - Liftoff to MECO

NO.	VEHICLE BEHAVIOR	FAILURE MODES CAUSING HAZARD
1	TIPOVER ON PAD	• 1 SRB IGNITION FAILURE • HIGH THRUST IMBALANCE BETWEEN SRB's
2	LOSS OF CONTROL AND TUMBLE (SRB CASE OR NOZZLE FAILURE)	• SRB MOTOR CASE BURNTHROUGH • SRB NOZZLE BURNTHROUGH • SRB INADVERTANT DESTRUCT
3	INADVERTANT SEPARATION AT AN SRB/ET AFT ATTACHMENT	• STRUCTURAL FAILURE AT THE AFT SRB/ET ATTACHMENT • INADVERTANT DETONATION OF THE ATTACHMENT FITTING • TPS FAILURE AT THE AFT SRB ATTACHMENT RING (100-124 SEC's ONLY)
4	INADVERTANT SEPARATION AT AN SRB/ET FORWARD ATTACHMENT	• STRUCTURAL FAILURE AT THE FORWARD SRB/ET ATTACHMENT • INADVERTANT DETONATION OF THE FORWARD ATTACHMENT FITTING
5	CORKSCREW MOTION (COMBINED PITCH, YAW, ROLL MOTION)	• FIRE/EXPLOSION IN THE SRB AFT SKIRT (CAUSING LOSS OF SRB TVC) • LOSS OF SRB TVC (SERVOACTUATOR FEEDBACK LINKAGE FRACTURE, JAMMED POWER SPOOL OR MANUAL BYPASS AND LOCK VALVE, ETC.) • SRB TPS FAILURE AT THE THERMAL CURTAIN HEAT SHIELD OR THE CABLE TRAY • LOSS OF AVIONICS CAUSING SRB AND ME TVC LOSS W/O ME COLLISION (DUE TO AN EXPLOSION IN THE FORWARD RCS SYSTEM WHICH PENETRATES INTO THE IMU COMPARTMENT OR THE RUPTURE OF AN AUXILIARY STORAGE TANK [OXYGEN, NITROGEN, ETC.]
6	ET PUNCTURED	• FIRE/EXPLOSION IN THE ME COMPARTMENT • ME NOZZLE COLLISION DUE TO TVC LOSS FOR ONE ME • FIRE/EXPLOSION IN THE OMS/RCS POD WHICH PROPAGATES TO THE ME COMPARTMENT • FAILURE AT AN ORBITER/ET ATTACHMENT

Table 3-2. STS Vehicle Response Modes - Liftoff to MECO (Cont'd)

NO.	VEHICLE BEHAVIOR	FAILURE MODES CAUSING HAZARD
		• TPS FAILURE AND BLOWOUT AT THE LH_2 TANK BARREL OR LOX TANK OGIVE (100-125 SEC ONLY) OR AT THE LH_2 TANK AFT DOME (LIFTOFF) • TPS FAILURE AT THE SRB THERMAL CURTAIN HEAT SHIELD • ET INADVERTANT DESTRUCT • LOSS OF AVIONICS CAUSING LOSS OF ME TVC AND COLLISION OF NOZZLES [SEE ALSO CASE 5, FAILURE MODE 4] • LOSS OF LH_2 TANK ULLAGE (JOINT, RELIEF VALVE, LINE, ETC. FAILURE); GROSS LEAKS ONLY • RUPTURE OF THE EXTERNAL LOX FEED LINE • RUPTURE OF THE LOX LINE (THROUGH MECO) AND LH_2 LINE (PRIOR TO SRB STAGING ONLY) INTERNAL TO THE ORBITER
7	ET INTERTANK AND/OR AFT LOX TANK DOME FAILURE	• TPS FAILURE AT THE ET INTERTANK • STRUCTURAL FAILURE OF THE LOX TANK AFT DOME (WELD FAILURE, LOSS OF ULLAGE, ETC.)
8	SRB RECONTACT AT SEPARATION	• FAILURE TO FRACTURE AT THE FORWARD OR AFT SRB/ET ATTACHMENT • TPS FAILURE AT THE AFT SEPARATION MOTOR • PREMATURE OPERATION OF THE FORWARD OR AFT SEPARATION MOTORS
9	LOSS OF MAIN ENGINE (ME) PROPULSION	• LOSS OF 3 MEs • PUNCTURE OF THE EXTERNAL LH_2 FEED LINE (THROUGH MECO) • RUPTURE OF THE LH_2 LINE INTERNAL TO THE ORBITER (AFTER SRB STAGING ONLY)

Table 3-3. STS Vehicle Response Modes - MECO to Payload Deployment

Case No.	VEHICLE BEHAVIOR	CRITICAL TIME PERIOD	NECESSARY CONDITIONS
(a)	External Tank Punctured	MECO to ET separation (MECO to MECO + 16 seconds)	• Failures in Main Propulsion System releasing residual propellant into aft ME compartment and ignition from within ME compartment • LH_2 tank rupture • Failures in the Orbiter/ET Separation System • Failures of forward or aft Orbiter ET attachments • Inadvertent operation of the PSCD
		During Orbiter/ET Separation Maneuver (MECO + 11 seconds to end of RCS separation burn)	• Failure of the forward or aft RCS system • Failures of the OMS systems which propagate and cause loss of RCS
		MECO to MECO + 11 seconds	• Aft RCS or OMS failures which propagate to ME compartment and cause fire and explosion with residual ME propellants
(b)	Loss of Maneuverability & Orbiter Tumbles to Earth	MECO to orbit insertion (end of OMS1 burn)	• Failures of forward RCS which propagate and cause failure of all 3 IMUs • Failures of aft RCS which propagate and lead to loss of OMS in one pod (with lost capability to cross feed to other OMS engine). • Failures of OMS in one pod (with lost capability to cross feed to other OMS engine) • Failures of electrical power or atmosphere revitalization system tank sub-assemblies which propagate and cause failure of all 3 IMUs
(c)	Loss of Maneuverability on Orbit	End OMS1 burn to payload deployment	• Same conditions as for (b)
(d)	Fire & Explosion in ME Compartment and Orbiter Tumbles to Earth	MECO + 16 seconds to Orbit Insertion (end OMS1 burn)	• Failures in the aft RCS or OMS which propagate to the ME compartment causing fire and explosion

Table 3-4. Combined STS/Centaur Vehicle Response Modes

NO.	VEHICLE RESPONSE MODE	CRITICAL TIME PERIOD
1.	TIPOVER ON PAD	LIFTOFF
2.	LOSS OF CONTROL AND TUMBLE (SRB CASE/NOZZLE FAILURE)	LIFTOFF THROUGH END OF STAGE 1 BOOST
3.	INADVERTANT SEPARATION OF AN SRB/ET AFT ATTACHMENT (SRB BREAKS FREE AND TUMBLES)	LIFTOFF THROUGH SRB STAGING
4.	INADVERTANT SEPARATION AT AN SRB/ET FORWARD ATTACHMENT (SRB BREAKS FREE IN A QUASI-STABLE MODE)	LIFTOFF THROUGH END OF STAGE 1 BOOST
5.	CORKSCREW MOTION (RESULTING FROM AN SRB TVC FAILURE)	LIFTOFF THROUGH SRB STAGING
6.	EXTERNAL TANK PUNCTURED (SEE TABLES 3-1, 3-2, AND 3-3 FOR CONTRIBUTORS)	LIFTOFF THROUGH ET SEPARATION
7.	ET INTERTANK AND/OR AFT LOX TANK FAILURE	LIFTOFF THROUGH ET SEPARATION
8.	SRB RECONTACT AT STAGING	SRB STAGING
9.	LOSS OF MAIN ENGINE PROPULSION	LIFTOFF THROUGH MECO
10.	FIRE/EXPLOSION IN PAYLOAD BAY - ORBITER TUMBLES TO EARTH (SEE TABLES 3-1 AND 3-3* FOR CONTRIBUTORS)	ET SEPARATION TO ORBIT INSERTION
11.	FIRE/EXPLOSION IN PAYLOAD BAY - ON ORBIT (SEE TABLE 3-1 FOR CONTRIBUTORS)	(a) END OMS 1 BURN TO OPENING PAYLOAD DOORS (b) OPENING PAYLOAD DOORS TO CENTAUR DEPLOYED

Table 3-4. Combined STS/Centaur Vehicle Response Modes (Cont'd)

NO.	VEHICLE RESPONSE MODES	CRITICAL TIME PERIOD
12.	LOSS OF MANEUVERABILITY AND ORBITER/CENTAUR TUMBLES TO EARTH	MECO TO END OF OMS 1 BURN
13.	LOSS OF MANEUVERABILITY ON ORBIT	END OMS 1 BURN TO CENTAUR DEPLOYMENT
14.	CENTAUR RECONTACT WITH ORBITER AT SEPARATION (SEE TABLE 3-1 FOR CONTRIBUTORS)	CENTAUR DEPLOYMENT

*A fire and explosion in the Orbiter ME compartment is likely to spread to the payload bay resulting in the combined vehicle response mode as defined in case number 10 of this table. Therefore failure modes contributing to case number 4 of Table 3-3 (Orbiter only) will contribute to case number 10 for the combined Centaur/Orbiter vehicle.

describe which particular item failed, the numbers of items involved, the types of failure modes, the subsystems affected (critical time periods) upper and lower bounds on the item failure rates and any assumptions made.

Weighting factors have been included in Tables A1 through A3, B1 and C1 through C4 to reflect the conditional probability that, given failure of an item of hardware, a criticality 1 condition will occur. For Tables C1 through C4, this is a departure from the approach taken in the earlier analysis (Reference 10). Because these conditional probabilities, provided by NASA, were considered to be realistic for the "Space Shuttle Range Safety Hazards Analysis" (Reference 11) it is reasonable to be consistent and include them for all hardware items. These conditional probabilities are specified in the tables of the Appendix using mnemonics as follows:

ACT: actual loss. The probability of a criticality 1 condition is 100 percent.

PROB: probable loss. The probability of a criticality 1 condition is between 5 and 100 percent, except for SRB components where a value between 10 and 100 percent was used.

POSS: possible loss. The probability of a criticality 1 condition is between 0 and 5 percent, except for SRB components where a value between 0 and 10 percent was used.

NONE: The probability of a criticality 1 condition is essentially 0.

The weighting factor is used as a multiplier on the hardware failure rate to obtain the "critical" failure rate used in this analysis. The median value of the weighting factors were used (i.e., 10 to 100 percent is 55 percent).

4. DATA BASE AND ASSIGNMENT OF FAILURE RATES

WASH-1400's data sources included Department of Defense data, NASA data and general industrial operating experience as well as nuclear power plant data. The Reactor Safety Study assessed the data sources and defined the five percent lower bound and ninety-five percent upper bound on component failure rates and demand probabilities. The five percent lower bound indicates that five percent of failure rates are expected to be found below this value. The ninety-five percent upper bound value indicates that ninety-five percent of the failure rate values are expected to be found below this value. Thus, there is a ninety percent probability that the failure rate values will fall within the five percent and ninety-five percent bounds.

By comparing components of the STS/Centaur with those of similar components of the WASH-1400 data base, judgements were made as to the expected range of failure rates for STS/Centaur vehicle components. The expected upper and lower bounds of failure rates of components relevant to this study are included in Tables A-1 through A-3, B1 and C1 through C4 of the Appendix. Thus, the component failure rates are treated as random variables viewed as having a range of possible values. The exact nature of the variability of the component failure rates is described by the probability density function. The probability density functions for STS/Centaur component failure rates are assumed to be log normal distributions. This is in keeping with the variability in failure rates found by the Reactor Safety Study on analyzing data from mechanical components.

The log normal distribution, describing the variability in failure rates of components making up the STS/Centaur systems, is written mathematically as follows:

$$F(\lambda) = \frac{1}{\lambda\sigma\sqrt{2\pi}} \cdot \exp\left[-\frac{(\ln\lambda-\mu)^2}{2\sigma^2}\right] \quad \text{for } \lambda>0 \ \& \ \sigma>0$$

Mode: $\lambda_m = \exp(\mu-\sigma^2)$

Median: $\lambda_{0.5} = \exp(\mu) = \sqrt{\lambda_u \lambda_\ell}$

Mean: $\bar{\lambda} = \exp(\mu+\sigma^2/2)$

Variance: $\beta^2 = \exp(2\mu+\sigma^2) \cdot [\exp(\sigma^2)-1]$

Where λ is the component failure rate in number of failures per a given time period; λ_u is the failure rate upper bound and λ_ℓ is the failure rate lower bound.

The logarithms of the values of the random variables of a log normal distribution are normally distributed (i.e., belong to a normal or Gaussian distribution function). The skewedness of the log normal distribution allows one to account for rather high, or unlikely, component failure rates. The log normal distribution was therefore used to bound the expected failure rate values for STS/Centaur components. Failure rates were assumed to remain constant with time. In other words, e.g., a shift in the mean value of a failure rate for a component with time was not considered in this analysis. This assumes (a) that the incidence of burn in failures will not significantly affect the results and (b) that the incidence of wear-out failure will not significantly affect the results.

5. VEHICLE RESPONSE MODE FAILURE PROBABILITY CALCULATIONS

Since only category 1 failures are considered in this analysis, the failure rate for each STS/Centaur response mode can be calculated from the following Boolean expression:

$$X = X_1 \cup X_2 \cup X_3 \cup \cdots \cup X_n \qquad (1)$$

where X_i are the individual component failure rates for each response mode and U represents the union of events, i.e., plus in Boolean notation.

Expansion of this Boolean equation into probability form is obtained using the following expression:

$$P(X) = \sum_{i=1}^{n} P(X_i) - \sum_{i=2}^{n}\sum_{j=1}^{i-1} P(X_i)P(X_j) + \sum_{i=3}^{n}\sum_{j=2}^{i-1}\sum_{k=1}^{j-1} P(X_i)P(X_j)P(X_k)$$

$$- \cdots + (-1)^{n-1} \prod_{i=1}^{n} P(X_i) \qquad (2)$$

or P(X) = Sum of individual probabilities
- Sum of products of two at a time
+ Sum of products of three at a time
- etc.

.
.
.

± Product of all

For two components

$$P(X) = P(X_1) + P(X_2) - P(X_1 \wedge X_2) \qquad (3)$$

where $P(X_1 \wedge X_2)$ is written as $P(X_2/X_1) \cdot P(X_1)$

For independent events where failures X_1 and X_2 are not correlated

$$P(X) = P(X_1) + P(X_2) - P(X_1) \cdot P(X_2) \quad (4)$$

For small failure rates, terms such as $P(X_1) \cdot P(X_2)$ can be neglected.

Then

$$P(X) = P(X_1) + P(X_2) \quad (5)$$

Neglecting 2nd and higher order terms in this analysis will have negligible effect on the final results, as the individual expected failure rates of STS/Centaur components are expected to be small (see Tables A-1 through A-3, B1, and C1 through C4 of the Appendix).

Equation (2) neglecting 2nd and higher order terms becomes

$$P(X) = \sum_{i=1}^{n} P(X_i) \quad (6)$$

This is the form for P(X) used in this analysis.

The computer program developed under contract NAS 10-9374 was used to calculate the mean and 90% bounds of P(X) for each combined vehicle response mode from liftoff to Centaur-STS separation. Input to the program is the upper and lower bounds of each lognormally distributed component failure rate.

Each response mode failure probability can be presented as an a-priori probability or as an a posteriori probability. The a-priori value is an unconditional probability and is only concerned with the event at time t i.e., it is the probability of failure in the interval t to t + dt without any regard to whether prior failure has occurred. The a-posteriori probability is a conditional probability and is a more complete answer since it is calculated with regard to whether prior failure has occurred.

The failure probabilities/second as calculated by the program are the a-posteriori failure probabilities. It will, however, be useful to quote these probabilities over the complete time period during which each response mode can occur. The equation for performing this calculation is derived in the following manner, assuming a negative exponential distribution for component mortality:

$$P_{failure} = \int_T^{T+t} f(T)dT = \int_T^{T+t} \lambda e^{-\lambda t} dT$$

$$= e^{-\lambda T}(1-e^{-\lambda t}) \qquad (7)$$

Equation (7) is the a-priori probability of failure in the period T to T+t. This equation must be divided by the probability of survival up to time T to obtain the a-posteriori probability of failure.

Therefore

$$P_{failure} = \frac{e^{-\lambda T}(1-e^{-\lambda t})}{e^{-\lambda T}} = 1-e^{-\lambda t} \qquad (8)$$

i.e., for the exponential distribution of mortality and constant failure rate λ, the equation is identical to that for the cumulative probability of failure from T=0 to T=t. In this analysis however, t is the time period during which each response mode can occur.

6. RESULTS

The results of this study are presented in Table 6-1. The results of the study covering flight phases from liftoff to MECO, which excludes the impact of Centaur failure modes, are presented in Tables 6-2 and 6-3 (taken from Reference 11). The results of the study covering flight phases from MECO to payload deployment, which also excludes the impact of Centaur failure modes, are presented in Table 6-4 (taken from Reference 10). Table 6-5 consolidated table for all flight phases, from liftoff through payload deployment, which includes the impact of carrying Centaur in the STS. Table 6-6 defines the item failure modes, in terms of the tables of the Appendix, relevant to each vehicle response mode.

All of these tables, 6-1 through 6-5, contain the conditional failure probabilities per second from liftoff to payload separation, i.e., the failure probabilities in the time period t to t+1 seconds given that a failure has not occurred prior to t. The probability values are presented as a mean with upper and lower bounds, consistent with the use of the lognormal distribution to describe the uncertainty in component failure rates. Given the nature of the uncertainty in an analysis of this nature, a point estimate value would prove to be less than useful.

The interval failure probabilities from liftoff to payload separation can be calculated using the failure rates of Table 6-5 and equation 8 of Section 5 where t is the time period in each interval. It is apparent from equation 8 that these interval probability values will increase with increasing value of t, i.e., the longer the interval, the higher the probability of failure. The interval failure probabilities have not been calculated here since, at the time of writing, the exact time values for the Galileo flight (with Centaur) were not known. (References 8 and 12 offer conflicting interval time values, from liftoff through payload deployment.) However, these interval failure probabilities can be calculated in a few minutes with the aid of a calculator.

Table 6-1. Response Mode Failure Rates - Including Impact Of Centaur

NO.	FAILED VEHICLE RESPONSE MODE	NO. COMPONENT FAILURE MODES	NO. OF COMPONENTS	FAILURE RATES*		
				MEAN	90% CONFIDENCE BOUNCE	
					LOWER	UPPER
6	EXTERNAL TANK PUNCTURED					
	• LIFTOFF THROUGH STAGING	269	994	4.4E-7	1.9E-7	8.2E-7
	• STAGING THROUGH MECO	263	901	3.9E-7	1.7E-7	7.7E-7
	• MECO TO START RCS SEPARATION BURN	217	631	3.1E-7	1.2E-7	7.4E-7
	• DURING RCS SEPARATION BURN	234	807	4.6E-7	1.8E-7	1.0E-6
10	FIRE/EXPLOSION IN PAYLOAD BAY-ORBITER TUMBLES TO EARTH (FROM END OF RCS SEPARATION BURN TO ORBIT INSERTION)	190	561	3.2E-7	9.3E-8	6.3E-7
11	FIRE/EXPLOSION IN PAYLOAD BAY - ON ORBIT					
	• END OMS 1 BURN TO PAYLOAD BAY DOORS OPEN	170	456	2.6E-7	7.8E-8	5.7E-7
	• OPENING OF PAYLOAD BAY DOORS TO CENTAUR DEPLOYED	135	363	1.5E-7	4.0E-8	3.9E-7
14	CENTAUR RE-CONTACT WITH ORBITER AT SEPARATION**	2	4	3.8E-9	6.0E-10	1.1E-8

*PROBABILITY OF FAILURE PER SECOND (Except For #14)
**PROBABILITY OF FAILURE PER EVENT

Table 6-2. Response Mode Failure Rates - Excluding Impact of Centaur[1]

FAILED VEHICLE RESPONSE MODE	NO. COMPONENT FAILURE MODES	NO. OF COMPONENTS	FAILURE RATES*		
			MEAN	90% CONFIDENCE BOUND	
				LOWER	UPPER
1. TIPOVER ON PAD	7	14	3.3E-5**	1.6E-5**	6.0E-5**
2. LOSS OF CONTROL AND TUMBLE	SEE TABLE 6-3				
3. INADVERTANT SEPARATION AT AN SRB/ET AFT ATTACHMENT					
• LIFTOFF TO 100 SECONDS	5	34	4.5E-9	3.1E-9	6.5E-9
• 100 SECONDS TO STAGING	6	36	5.3E-9	3.6E-9	7.4E-9
4. INADVERTANT SEPARATION AT AN SRB/ET FORWARD ATTACHMENT	3	8	1.5E-9	7.2E-10	2.4E-9
5. CORKSCREW MOTION (RESULTING FROM AN SRB TVC FAILURE)	38	442	4.2E-7	2.3E-7	7.4E-7
6. EXTERNAL TANK PUNCTURED[2]					
• LIFTOFF TO STAGING	99	538	2.0E-7	8.4E-8	4.6E-7
• STAGING TO MECO	93	445	~1.8E-7	~7.5E-8	~4.1E-7
7. ET INTERTANK AND/OR AFT LOX TANK FAILURE***	15	98	7.7E-8	2.6E-8	1.6E-7
8. SRB RECONTACT AT SEPARATION	18	168	1.1E-5**	7.1E-6**	1.7E-5**
9. LOSS OF ME PROPULSION					
• LIFTOFF TO STAGING	18	60	6.6E-9	1.2E-9	2.3E-8
• STAGING TO MECO	23	71	3.4E-[illegible]	3.9E-9	1.2E-7

*PROBABILITY OF FAILURE PER SECOND. (EXCEPT FOR RESPONSE MODES 1 AND 8)
**PROBABILITY OF FAILURE PER EVENT.
***THIS MODE IS MUCH MORE LIKELY TO OCCUR DURING STAGE I FLIGHT WHEN THE LOADS AND HEATING ARE HIGH.

1. TAKEN FROM REFERENCE 1T. (Liftoff to MECO)
2. CONTRIBUTES TO NO. 6. of TABLE 6-1

Table 6-3. Estimated 'Loss of Control and Tumble' (SRB Case/Nozzle Failure) Failure Rates (From Reference 11)

TIME SPAN (SEC.)	FAILURE RATE (1/SEC.)	
	CASE 1 (TOTAL PROBABILITY = 2×10^{-3})	CASE 2 (TOTAL PROBABILITY = 2×10^{-4})
0-10	7.2E-5	7.2E-6
10-70	1.9E-5	1.9E-6
70-125	2.6E-6	2.6E-7

Table 6-4. Response Mode Failure Rates - Excluding Impact Of Centaur[1] (MECO To Payload Deployment)

FAILED VEHICLE RESPONSE MODE	NO. COMPONENT FAILURE MODES	NO. OF COMPONENTS	FAILURE RATES*		
			MEAN	90% CONFIDENCE BOUND	
				LOWER	UPPER
a. EXTERNAL TANK PUNCTURED[2]					
• MECO TO START RCS SEPARATION BURN	50	255	1.8E-7	7.6E-8	4.2E-7
• DURING RCS SEPARATION BURN	73	461	1.3E-6	5.5E-7	2.1E-6
b. LOSS OF MANUEVERABILITY & ORBITER TUMBLES TO EARTH					
• MECO TO START RCS SEPARATION BURN	15	93	6.0E-8	1.6E-8	1.1E-7
• DURING RCS SEPARATION BURN**	4	11	-	-	-
• END RCS SEPARATION BURN TO OMS-1 COMPLETE	46	360	2.2E-7	9.0E-8	4.6E-7
c. LOSS OF MANUEVERABILITY ON ORBIT (ORBITAL DECAY)					
• OMS-1 COMPLETE TO PAYLOAD SEPARATION	46	360	2.2E-7	9.0E-8	4.6E-7
d. FIRE & EXPLOSION IN MAIN ENGINE COMPARTMENT[3]					
• END RCS SEPARATION BURN TO ORBIT INSERTION (OMS-1 COMPLETE)	23	185	1.1E-7	4.4E-8	3.0E-7

*PROBABILITY OF FAILURE PER SECOND

**VALUES ARE INSIGNIFICANT

[1] TAKEN FROM REFERENCE 10 (MECO TO PAYLOAD DEPLOYMENT)

[2] CONTRIBUTES TO NO. 6 OF TABLE 6-1

[3] CONTRIBUTES TO NO. 10 OF TABLE 6-1

Table 6-5. Response Mode Failure Rates - Including Impact of Centaur (Liftoff To Payload Deployment)

NO.	FAILED VEHICLE RESPONSE MODE	NO. COMPONENT FAILURE MODES	NO. OF COMPONENTS	FAILURE RATES*		
				MEAN	90% CONFIDENCE BOUNCE	
					LOWER	UPPER
1.	TIPOVER ON PAD	7	14	3.3E-5**	1.6E-5**	6.0E-5*
2.	LOSS OF CONTROL AND TUMBLE	SEE TABLE 6-3				
3.	INADVERTANT SEPARATION AT AN SRB/ET AFT ATTACHMENT					
	● LIFTOFF TO 100 SECONDS	5	34	4.5E-9	3.1E-9	6.5E-9
	● 100 SECONDS TO STAGING	6	36	5.3E-9	3.6E-9	7.4E-9
4.	INADVERTANT SEPARATION AT AN SRB/ET FORWARD ATTACHMENT	3	8	1.5E-9	7.2E-10	2.4E-9
5.	CORKSCREW MOTION (RESULTING FROM AN SRB TVC FAILURE)	38	442	4.2E-7	2.3E-7	7.4E-7
6.	EXTERNAL TANK PUNCTURED					
	● LIFTOFF THROUGH STAGING	269	994	4.4E-7	1.9E-7	8.2E-7
	● STAGING THROUGH MECO	263	901	3.9E-7	1.7E-7	7.7E-7
	● MECO TO START RCS SEPARATION BURN	217	631	3.1E-7	1.2E-7	7.4E-7
	● DURING RCS SEPARATION BURN	234	807			
7.	ET INTERTANK AND/OR AFT LOX TANK FAILURE***	15	96	7.7E-8	2.6E-8	1.6E-7
8.	SRB RECONTACT AT SEPARATION	18	168	1.1E-5**	7.1E-6**	1.7E-5
9.	LOSS OF ME PROPULSION					
	O LIFTOFF TO STAGING	18	60	6.6E-9	1.2E-9	2.3E-8
	O STAGING TO MECO	23	71	3.4E-8	3.9E-9	1.2E-7

Table 6-5. Response Mode Failure Rates - Including Impact of Centaur (Liftoff To Payload Deployment) (Cont'd)

NO.	FAILED VEHICLE RESPONSE MODE	NO. COMPONENT FAILURE MODES	NO. OF COMPONENTS	FAILURE RATES*		
				MEAN	90% CONFIDENCE BOUNCE	
					LOWER	UPPER
10.	FIRE/EXPLOSION IN PAYLOAD BAY-ORBITER TUMBLES TO EARTH (FROM END OF RCS SEPARATION BURN TO ORBIT INSERTION)	190	561	3.2E-7	9.3E-8	6.3E-7
11.	FIRE/EXPLOSION IN PAYLOAD BAY - ON ORBIT					
	• END OMS 1 BURN TO PAYLOAD BAY DOORS OPEN	170	456	2.6E-7	7.8E-8	5.7E-7
	• OPENING OF PAYLOAD BAY DOORS TO CENTAUR DEPLOYED	135	363	1.5E-7	4.0E-8	3.9E-7
12.	LOSS OF MANEUVERABILITY & ORBITER TUMBLES TO EARTH					
	• MECO TO START RCS SEPARATION BURN	15	93	6.0E-8	1.6E-8	1.1E-7
	• DURING RCS SEPARATION BURN**	4	11	-	-	-
	• END RCS SEPARATION BURN TO OMS-1 COMPLETE	46	360	2.2E-7	9.0E-8	4.6E-7
13.	LOSS OF MANEUVERABILITY ON ORBIT (ORBITAL DECAY)					
	• OMS-1 COMPLETE TO PAYLOAD SEPARATION	46	360	2.2E-7	9.0E-8	4.6E-7
14.	CENTAUR RE-CONTACT WITH ORBITER AT SEPARATION**	2	4	3.8E-9	6.0E-10	1.1E-8

*PROBABILITY OF FAILURE PER SECOND. (EXCEPT FOR RESPONSE MODES 1, 8 & 14)
**PROBABILITY OF FAILURE PER EVENT.
***THIS MODE IS MUCH MORE LIKELY TO OCCUR DURING STAGE I FLIGHT WHEN THE LOADS AND HEATING ARE HIGH.

Table 6-6. Item Failure Modes Relevant to Each Vehicle Behavior Mode - Liftoff to Payload Separation

VEHICLE RESPONSE MODE	——▶INCREASING TIME FROM LIFTOFF (NOT TO SCALE)						
6	TABLE A1 TABLE B1	TABLE A1 TABLE B1	TABLE A1 TABLE C1 TABLE C3	TABLE A1 TABLE C1 TABLE C2	N/A	N/A	NA/
10	N/A	N/A	N/A	N/A	TABLE A1 TABLE C3	N/A	N/A
11(a)	N/A	N/A	N/A	N/A	N/A	TABLE A1	N/A
11(b)	N/A	N/A	N/A	N/A	N/A	N/A	TABLE A2
14	N/A	N/A	N/A	N/A	N/A	N/A	N/A TABLE A-3

It is worthwhile noting some interesting results as outlined in Tables 6-1 through 6-5. The first of these is that the Category 6 vehicle response mode probabilities, for the period liftoff through MECO, are roughly a factor of two higher with Centaur in the Orbiter payload bay as contrasted with an empty payload bay. This is evident from a comparison of the failure rates for case number 6 of Table 6-1 with case number 6 of Table 6-2.

The failure rates generated for case number 6, for the period MECO to completion of RCS separation burn, cannot be directly compared from the results of Table 6-1 and Table 6-4. Table 6-4, case (a), was generated under a previous contract (Reference 10) without the application of weighting factors on the component failure rates.* If weighting factors had been employed in this earlier study, the effect would have been to reduce the case (a) (External Tank Punctured) failure probabilities quite significantly. The application of weighting factors on the component failure rates, for this combined STS/Centaur study (but not in the earlier STS study from MECO to payload separation), accounts for the apparent anomaly between the results of category 6 (Table 6-1) and case (a) of Table 6-4 (for the period during RCS separation burn).

A further comparison can be made between case number 10 of Table 6-1 and case (d) of Table 6-4. These are essentially the same cases, where number 10 of Table 6-1 is for the combined STS/Centaur vehicle and case (d) is for the STS only. (The failure modes contributing to case (d) of the earlier study contributed to case number 10 of this study for the combined vehicle. All component failure rates were assigned a weighting factor in this combined vehicle analysis.) The effect of carrying Centaur in the Orbiter is to increase the failure rate for case number

*The application of weighting factors was suggested by NASA, and implemented by the J.H. Wiggins Company, for the STS Range Safety Hazards Analysis (Reference 11). This analysis was completed about 21 months after the STS failure probabilities, from MECO to payload separation, were produced (Reference 10).

10 by a factor greater than two. This difference would be even more marked than is evident from a comparison of Tables 6-1 (case 10) and 6-4 (case (d)), if weighting factors had been applied to the component failure rates in the earlier analysis (case (d)).

Table 6-5 presents all fourteen combined STS/Centaur response mode failure rates from liftoff to payload deployment. This combined table is an amalgamation of Tables 6-1, 6-2 and 6-4.

Cases 12 and 13 of Table 6-5 present failure rates which were computed from an earlier analysis (Reference 10). As a consequence, and because transporting Centaur in the Orbiter did not impact cases 12 and 13, their probability values do not reflect the impact of weighting factors on the component failure rates. For cases 12 and 13 of Table 6-5, therefore, the failure rates quoted are likely to be high by a factor estimated between 2 and 5 (assuming the NASA weighting factors are valid).

One further point is worth noting; that is that the results presented in Table 6-5 do not include the impact of potential Spacecraft failure modes. Although the inclusion of Spacecraft failure modes was outside the scope of this study, their potential impact should be considered. On the positive side, however, the impact of Spacecraft failure modes on the final results, as presented in Table 6-5, is likely to be small.

It is important to note that no credit has been taken in this study for emergency procedures which could in certain circumstances mitigate the effects of certain component failure modes. These procedures will have increasing chances of success with successively higher time periods in which action can take place. The time available for mitigating actions related to vehicle response modes 1 through 10 (Table 6-5) are relatively short and, given the nature of these vehicle failure modes, any action is likely to be unsuccessful. Mitigating actions are, however, likely to be highly relevant to vehicle behavior mode 13. The component failures listed for the aft RCS and OMS contributing to response mode 13 may, in certain circumstances, be circumvented by actions of the crew. Although it was not part of the objective of this study to consider mitigating actions, the results quoted must be considered against this backdrop.

REFERENCES

1. "Reactor Safety Study - WASH-1400. An Assessment of Accident Risks in U.S. Commercial Nuclear Power Plants." United States Atomic Energy Commission. August 1974.

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4. "Orbiter 102 Critical Items List, Revision B." JSC 10686. April 1979.

5. "Shuttle Element Interface Functional Analysis for the Space Shuttle Main Engine/Orbiter." SD75-SH-0200A.

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8. "Shuttle/Centaur Orientation At NASA LeRC." General Dynamics Convair Division. May/June 1981.

9. "Centaur F Technical Description, A High Performance Upper Stage For The NASA Space Transportation System." Report CFTD, General Dynamics Convair Division. Sept./Oct. 1981.

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11. "Space Shuttle Range Safety Hazards Analysis." Technical Report No. 81-1329. Prepared for National Aeronautics and Space Administration. J.H. Wiggins Company, Redondo Beach, CA. July 1981.

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APPENDIX A

CENTAUR FAILURE MODES

(Liftoff to Centaur Deployment)
(Contributing To Combined STS/Centaur Behavior Modes
Nos. 6, 10, 11(a), 11(b) and 14, As Outlined In Table 3-4)

The failure rates quoted in this Appendix are in units of hour, $^{-1}$ unless otherwise stated

Table A-1. Centaur Failure Modes Contributing To STS/Centaur Behavior Modes - Categories 6, 10 and 11(a) (Page 1 of 8)

NO.	VEHICLE AND SUB-SYSTEM	ITEM	NO. ITEMS	FAILURE MODE	FAILURE RATE λ_H, λ_R	WEIGHTING FACTOR
1	TANK STRUCTURE[1]	CYLINDRICAL LH_2 TANK WELDS	8	WELD RUPTURE	1.00E-07 1.00E-10	ACT
2	TANK STRUCTURE	FORWARD BULKHEAD WELDS	12	WELD RUPTURE	1.00E-07 1.00E-10	ACT
3	TANK STRUCTURE	FORWARD TANK RING WELDS	2	WELD RUPTURE	1.00E-07 1.00E-10	ACT
4	TANK STRUCTURE	AFT LH_2 TANK RING WELDS	2	WELD RUPTURE	1.00E-07 1.00E-10	ACT
5	TANK STRUCTURE	LH_2 TANK CONICAL TRANSITION WELDS	11	WELD RUPTURE	1.00E-07 1.00E-10	ACT
6	TANK STRUCTURE	LO_2 TANK AFT RINGS WELDS	4	WELD RUPTURE	1.00E-07 1.00E-10	ACT
7	TANK STRUCTURE	CYLINDRICAL LO_2 TANK WELDS	2	WELD RUPTURE	1.00E-07 1.00E-10	ACT
8	TANK STRUCTURE	DOUBLE WALLED INTERMEDIATE BULKHEAD WELDS	24	WELD RUPTURE	1.00E-07 1.00E-10	ACT
9	TANK STRUCTURE	AFT BULKHEAD WELDS	8	WELD RUPTURE	1.00E-07 1.00E-10	ACT
10	TANK STRUCTURE	FORWARD DOOR WELD	1	WELD RUPTURE	1.00E-07 1.00E-10	ACT
11	TANK STRUCTURE	LH_2 TANK ENGINE FEED FITTING	1	RUPTURE OF FITTING OR AT TANK TO FITTING WELD	1.00E-05 1.00E-08	ACT
12	TANK STRUCTURE	LO_2 TANK ENGINE FEED FITTING	1	RUPTURE OF FITTING OR AT TANK TO FITTING WELD	1.00E-05 1.00E-08	ACT
13	PROPULSION SYSTEM[2]	LO_2 FEED DUCT[3] (FROM TANK TO LO_2 PRE-VALVE)	1 SET	RUPTURE OR GROSS LEAKAGE	2.00E-04 2.00E-07	ACT
14	PROPULSION SYSTEM	LO_2 FEED DUCT PRE-VALVE	1	RUPTURE OR GROSS LEAKAGE	2.00E-07 2.00E-09	ACT
15	PROPULSION SYSTEM	LH_2 FEED DUCT[3] (FROM TANK TO LH_2 PRE-VALVE)	1 SET	RUPTURE OR GROSS LEAKAGE	2.00E-04 2.00E-07	ACT
16	PROPULSION SYSTEM	LH_2 FEED DUCT PRE-VALVE	1	RUPTURE OR GROSS LEAKAGE	2.00E-07 2.00E-09	ACT
17	TANK PRESSURIZATION SYSTEM[4]	FLEXIBLE LINE (BETWEEN CISS & DEPLOYMENT ADAPTER)	1	GROSS RUPTURE	2.00E-05 2.00E-08	PROB
18	TANK PRESSURIZATION SYSTEM	LINES & FITTINGS (4000 PSI SECTION UP TO ORIFACE IN DE-PLOYMENT ADAPTER)	1 SET	GROSS RUPTURE	2.00E-04 2.00E-07	PROB
19	TANK PRESSURIZATION SYSTEM	MANUAL SHUTOFF VALVE (IN DE-PLOYMENT ADAPTER)	2	GROSS RUPTURE	1.00E-07 1.00E-09	PROB
20	TANK PRESSURIZATION SYSTEM	DEPLOYMENT ADAPTER FILTER	1	GROSS RUPTURE	1.00E-05 1.00E-08	PROB
21	TANK PRESSURIZATION SYSTEM	PILOT OPERATED SOLENOID VALVE (IN DEPLOYMENT ADAPTER)	20	GROSS RUPTURE	1.00E-07 1.00E-09	PROB
22	TANK PRESSURIZATION SYSTEM	ORIFACE (IN DEPLOYMENT ADAPTER)	6	GROSS RUPTURE	1.00E-07 1.00E-09	PROB
23	TANK PRESSURIZATION SYSTEM	LINES & FITTINGS (BETWEEN ORIFACES & DISCONNECT PANELS << 4000 PSI)	1 SET	GROSS RUPTURE	5.00E-05 5.00E-08	POSS
24	TANK PRESSURIZATION SYSTEM	FLEXIBLE LINE (BETWEEN CENT-AUR & DEPLOYMENT ADAPTER)	3	GROSS RUPTURE	1.00E-05 1.00E-08	POSS

Table A-1. Centaur Failure Modes Contributing To STS/Centaur Behavior Modes - Categories 6, 10 and 11(a) (Page 2 of 8)

NO.	VEHICLE AND SUB-SYSTEM	ITEM	NO. ITEMS	FAILURE MODE	FAILURE RATE $\lambda_\mu, \lambda_\ell$	WEIGHTING FACTOR
25	TANK PRESSURIZATION SYSTEM	OXIDIZER & FUEL DISCONNECTS	3	GROSS RUPTURE	1.00E-07 1.00E-09	POSS
26	TANK PRESSURIZATION SYSTEM	CHECK VALVE (LO_2 TANK SIDE IN CENTAUR)	1	RUPTURE OR GROSS LEAKAGE[5]	2.00E-07 2.00E-09	ACT
27	TANK PRESSURIZATION SYSTEM	CHECK VALVE (LH_2 TANK SIDE IN CENTAUR)	1	RUPTURE OR GROSS LEAKAGE[5]	2.00E-07 2.00E-09	ACT
28	TANK PRESSURIZATION SYSTEM	CHECK VALVES (FURTHEST FROM LO_2 & LH_2 TANKS)	2	GROSS RUPTURE	1.00E-07 1.00E-09	POSS
29	TANK PRESSURIZATION SYSTEM	ORIFACES (IN CENTAUR LO_2 TANK SIDE)	2	RUPTURE OR GROSS LEAKAGE[5]	2.00E-07 2.00E-09	ACT
30	TANK PRESSURIZATION SYSTEM	ORIFACES (IN CENTAUR LH_2 TANK SIDE)	4	RUPTURE OR GROSS LEAKAGE[5]	2.00E-07 2.00E-09	ACT
31	TANK PRESSURIZATION SYSTEM	PILOT OPERATED SOLENOID VALVE (LO_2 TANK SIDE NEAREST ORIFACE)	2	RUPTURE OR GROSS LEAKAGE[5]	2.00E-07 2.00E-09	ACT
32	TANK PRESSURIZATION SYSTEM[6]	PILOT OPERATED SOLENOID VALVE (LH_2 TANK SIDE)	6	RUPTURE OR GROSS LEAKAGE[5]	2.00E-07 2.00E-09	ACT
33	TANK PRESSURIZATION SYSTEM	LINES & FITTINGS (FROM LO_2 TANK TO 1ST SOLENOID VALVE & 1ST CHECK VALVE)	1 SET	RUPTURE OR GROSS LEAKAGE[5]	2.00E-04 2.00E-07	ACT
34	TANK PRESSURIZATION SYSTEM	LINES & FITTINGS (FROM LH_2 TANK TO 1ST SOLENOID VALVE & 1ST CHECK VALVE)	1 SET	RUPTURE OR GROSS LEAKAGE[5]	4.00E-04 4.00E-07	ACT
35	TANK PRESSURIZATION SYSTEM	PILOT OPERATED SOLENOID VALVES (TWO VALVES ON EACH TANK SIDE FURTHEST FROM ORIFACES)	4	GROSS RUPTURE	1.00E-07 1.00E-09	POSS
36	TANK PRESSURIZATION SYSTEM[7]	CHECK VALVES (NEAREST LH_2 TANK ON GH_2 CHARGE LINE)	2	RUPTURE OR GROSS LEAKAGE[5]	2.00E-07 2.00E-09	ACT
37	TANK PRESSURIZATION SYSTEM	ORIFACE (BETWEEN LH_2 PRESSURIZATION LINE & GH_2 CHARGE LINE)	1	RUPTURE OR GROSS LEAKAGE[5]	2.00E-07 2.00E-09	ACT
38	TANK PRESSURIZATION SYSTEM	LO_2 TANK PRESSURE TRANSDUCERS & FITTINGS	5	RUPTURE OR GROSS LEAKAGE[5]	2.00E-05 2.00E-08	ACT
39	TANK PRESSURIZATION SYSTEM	LH_2 TANK PRESSURE TRANSDUCERS & FITTINGS	5	RUPTURE OR GROSS LEAKAGE[5]	2.00E-05 2.00E-08	ACT
40	CISS PRESSURE REGULATION SYSTEM[4,8]	CISS MANUAL SHUTOFF VALVES	2	GROSS RUPTURE	1.00E-07 1.00E-09	PROB
41	CISS PRESSURE REGULATION SYSTEM	CISS FILTER	1	GROSS RUPTURE	1.00E-05 1.00E-08	PROB
42	CISS PRESSURE REGULATION SYSTEM	CISS DISCONNECT	1	GROSS RUPTURE	1.00E-07 1.00E-09	PROB
43	CISS PRESSURE REGULATION SYSTEM	CISS LINES & FITTINGS (UPSTREAM OF REGULATORS)	1 SET	GROSS RUPTURE (BETWEEN REGULATOR & 1ST SOLENOID VALVE)	1.00E-04 1.00E-07	PROB
44	CISS PRESSURE REGULATION SYSTEM	CISS SOLENOID OPERATED VALVES (UPSTREAM OF REGULATORS)	3	GROSS RUPTURE (VALVES NEAREST TO REGULATORS)	1.00E-07 1.00E-09	PROB
45	CISS PRESSURE REGULATION SYSTEM	CISS CHECK VALVES	6	GROSS RUPTURE	1.00E-07 1.00E-09	POSS
46	CISS PRESSURE REGULATION SYSTEM	CISS PRESSURE TRANSDUCERS & FITTINGS	3	GROSS RUPTURE	1.00E-05 1.00E-08	POSS
47	CISS PRESSURE REGULATION SYSTEM	CISS REGULATORS	3	GROSS RUPTURE	1.00E-07 1.00E-09	PROB

Table A-1. Centaur Failure Modes Contributing To STS/Centaur Behavior Modes - Categories 6, 10 and 11(a) (Page 3 of 8)

NO.	VEHICLE AND SUB-SYSTEM	ITEM	NO. ITEMS	FAILURE MODE	FAILURE RATE λ_u, λ_s	WEIGHTING FACTOR
48	CISS PRESSURE REGULATION SYSTEM	CISS LINES & FITTINGS (DOWNSTREAM OF REGULATORS)	1 SET	GROSS RUPTURE (FROM REGULATOR TO LAST SET OF PARALLEL VALVES)	2.00E-04 2.00E-07	POSS
49	CISS PRESSURE REGULATION SYSTEM	CISS SOLENOID OPERATED VALVES (DOWNSTREAM OF REGULATORS)	2	GROSS RUPTURE (VALVES NEAREST TO REGULATORS)	1.00E-07 1.00E-09	POSS
50	CISS PRESSURE REGULATION SYSTEM	CISS/DEPLOYMENT ADAPTER FLEXIBLE LINE	1	GROSS RUPTURE	1.00E-05 1.00E-08	POSS
51	CISS PRESSURE REGULATION SYSTEM	CISS SOLENOID VALVES (UPSTREAM OF REGULATORS)	3	GROSS RUPTURE (VALVES FURTHEST FROM REGUATORS)	1.00E-07 1.00E-09	PROB
52	CISS PRESSURE REGULATION SYSTEM	CISS SOLENOID VALVES (DOWNSTREAM OF REGULATORS)	3	GROSS RUPTURE (VALVES FURTHEST FROM REGULATORS)	1.00E-07 1.00E-09	POSS
53	CISS PRESSURE REGULATION SYSTEM	CISS LINES & FITTINGS (UPSTREAM OF REGULATORS)	1 SET	GROSS RUPTURE (FROM He SUPPLY TO 1ST SET OF PARALLEL VALVES)	1.00E-04 1.00E-07	PROB
54	CISS PRESSURE REGULATION SYSTEM	CISS LINES & FITTINGS (DOWNSTREAM OF REGULATORS)	1 SET	GROSS RUPTURE (FROM LAST SET OF PARALLEL VALVES TO CISS/DEPLOYMENT ADAPTER FLEXIBLE LINE)	1.00E-04 1.00E-07	POSS
55	PURGE SYSTEM[9]	He PURGE LINES TO 28 Vdc RECIRC PUMP MOTORS	2 SETS	RUPTURE OR LEAKAGE AND LOSS OF MOTOR PURGE[10] (LINE FROM ORIFACE IN PNEUMATIC SYSTEM TO MOTOR)	2.00E-04 2.00E-07	POSS
56	PURGE SYSTEM	CISS FLEXIBLE LINES	2	GROSS RUPTURE	1.00E-05 1.00E-08	POSS
57	PURGE SYSTEM	DEPLOYMENT ADAPTER SOLENOID VALVES	15	GROSS RUPTURE (1ST SET OF PARALLEL VALVES TO INSULATION & ENGINE PURGES AND ALL VALVES TO LO_2/LH_2 FILL/DRAIN/VENT)	1.00E-07 1.00E-09	POSS
58	PURGE SYSTEM	DEPLOYMENT ADAPTER LINES & FITTINGS (BETWEEN CISS/DEPLOYMENT ADAPTER FLEX LINE & 1ST SOLENOID VALVES)	1 SET	GROSS RUPTURE	5.00E-05 5.00E-08	POSS
59	PURGE SYSTEM	DEPLOYMENT ADAPTER LINES & FITTINGS (CONNECTING SOLENOID VALVES, ORIFACES, CHECK VALVES ETC.)	1 SET	GROSS RUPTURE	4.00E-04 4.00E-08	POSS
60	PURGE SYSTEM	DEPLOYMENT ADAPTER LINES & FITTINGS (BETWEEN ORIFACES & FLEXIBLE LINE TO TANK INSULATION)	1 SET	GROSS RUPTURE	1.00E-04 1.00E-08	POSS
61	PURGE SYSTEM	DEPLOYMENT ADAPTER LINES & FITTINGS (BETWEEN ORIFACES & ENGINE PURGES)	1 SET	GROSS RUPTURE	1.00E-04 1.00E-08	POSS
62	PURGE SYSTEM	DEPLOYMENT ADAPTER FLEXIBLE LINE (TO ENGINE PURGE)	1	GROSS RUPTURE	1.00E-05 1.00E-08	POSS
63	PURGE SYSTEM	DEPLOYMENT ADAPTER FLEXIBLE LINE (TO TANK INSULATION)	1	GROSS RUPTURE	1.00E-05 1.00E-08	POSS
64	PURGE SYSTEM	DEPLOYMENT ADAPTER TANK INSULATION DISCONNECT	1	GROSS RUPTURE	1.00E-07 1.00E-09	POSS
65	PURGE SYSTEM	CENTAUR LINES & FITTINGS (TO LO_2 & LH_2 TANK PRESSURIZATION LINE, LO_2 VENT STAND PIPE, LO_2 TANK PRESSURE TRANSDUCERS ETC.)	1 SET	RUPTURE OR LEAKAGE[11]	4.00E-04 4.00E-07	ACT

Table A-1. Centaur Failure Modes Contributing To STS/Centaur Behavior Modes - Categories 6, 10 and 11(a) (Page 4 of 8)

NO.	VEHICLE AND SUB-SYSTEM	ITEM	NO. ITEMS	FAILURE MODE	FAILURE RATE λ_u, λ_s	WEIGHTING FACTOR
66	PURGE SYSTEM	CENTAUR ORIFACES (TO LO_2 TANK PRESSURE TRANSDUCERS, ETC.)	4	RUPTURE OR LEAKAGE	2.00E-07 2.00E-09	ACT
67	PURGE SYSTEM	CENTAUR ORIFACE (BETWEEN PYRO VALVE AND INSULATION PURGE LINE)	1	GROSS RUPTURE	1.00E-07 1.00E-09	POSS
68	PURGE SYSTEM	CENTAUR ORIFACE (TO HYDRAULIC RECIRC. MOTOR PURGE)	2	GROSS RUPTURE	1.00E-07 1.00E-09	POSS
69	PURGE SYSTEM	CENTAUR CHECK VALVE (NEAREST TO LO_2 TANK PRESSURE TRANSDUCERS)	1	RUPTURE OR LEAKAGE	2.00E-07 2.00E-09	ACT
70	PURGE SYSTEM	CENTAUR CHECK VALVE (FURTHEST FROM LO_2 TANK PRESSURE TRANSDUCERS)	1	GROSS RUPTURE	1.00E-07 1.00E-09	POSS
71	PURGE SYSTEM	CENTAUR PYRO OPERATED VALVE (TO PRESS. TRANS. PURGE, ETC.)	1	GROSS RUPTURE	1.00E-07 1.00E-09	POSS
72	PURGE SYSTEM	CENTAUR SOLENOID OPERATED VALVE (TO PRESSURE TRANS. PURGE, ETC.)	2	RUPTURE OR LEAKAGE	2.00E-07 2.00E-09	ACT
73	PURGE SYSTEM	CENTAUR SOLENOID CONTROLLED SELF REGULATING VALVE (TO LO_2 VENT STAND-PIPE)	1	GROSS RUPTURE	1.00E-07 1.00E-09	POSS
74	PURGE SYSTEM	LH_2 TANK, INSULATION PURGE VENT, ΔP TRANSDUCERS	3	GROSS RUPTURE	1.00E-05 1.00E-08	POSS
75	PURGE SYSTEM	LH_2 TANK, INSULATION PURGE VENT, RELIEF VALVES	2	GROSS RUPTURE	1.00E-07 1.00E-09	POSS
76	PURGE SYSTEM	LH_2 TANK, INSULATION PURGE VENT, LINES & FITTINGS	1 SET	GROSS RUPTURE	1.00E-04 1.00E-07	POSS
77	VENT SYSTEMS[12]	LH_2 TANK SELF REGULATING VENT VALVE	1	RUPTURE OR LEAKAGE	2.00E-07 2.00E-09	ACT
78	VENT SYSTEMS	LH_2 PNEUMATIC OPEN, SPRING-LOAD CLOSED, BALL VALVE	1	RUPTURE OR LEAKAGE	2.00E-07 2.00E-09	ACT
79	VENT SYSTEMS	LINES & FITTINGS (BETWEEN LH_2 TANK & MECHANICAL VENT VALVES)	1 SET	RUPTURE OR LEAKAGE	5.00E-05 5.00E-08	ACT
80	VENT SYSTEMS	LH_2 TANK THROTTLING REGULATORS	2	RUPTURE OR LEAKAGE	2.00E-07 2.00E-09	ACT
81	VENT SYSTEMS	LH_2 TANK THERMO VENT SYSTEM SHUTOFF VALVES	2	RUPTURE OR LEAKAGE	2.00E-07 2.00E-09	ACT
82	VENT SYSTEMS	LINES & FITTINGS (BETWEEN LH_2 TANK HX & VALVES)	3 SETS	RUPTURE OR LEAKAGE	5.00E-05 5.00E-08	ACT
83	VENT SYSTEMS	LH_2 TANK 3-WAY PNEUMATIC VALVES	2	RUPTURE OR LEAKAGE	2.00E-07 2.00E-09	ACT
84	VENT SYSTEMS[13]	LINES & FITTINGS (BETWEEN LH_2 VENT VALVES & DISCONNECT)	1 SET	RUPTURE OR LEAKAGE	5.00E-05 5.00E-08	POSS
85	VENT SYSTEMS	LH_2 TANK HEAT EXCHANGER	1	FAILURE OF HX TANK MOUNTING	3.00E-08 3.00E-11	PROB
86	VENT SYSTEMS	LH_2 TANK ELECTRICALLY DRIVEN PUMP	1	FAILURE OF PUMP OR MOTOR TANK MOUNTINGS	3.00E-08 3.00E-11	PROB
87	VENT SYSTEMS	LH_2 TANK VENT DISCONNECT	1	RUPTURE OR LEAKAGE	2.00E-07 2.00E-09	POSS

Table A-1. Centaur Failure Modes Contributing To STS/Centaur Behavior Modes - Categories 6, 10 and 11(a) (Page 5 of 8)

NO.	VEHICLE AND SUB-SYSTEM	ITEM	NO. ITEMS	FAILURE MODE	FAILURE RATE λ_u, λ_s	WEIGHTING FACTOR
88	VENT SYSTEMS	LO_2 TANK SELF REGULATING VENT VALVE	1	RUPTURE OR LEAKAGE	2.00E-07 2.00E-09	ACT
89	VENT SYSTEMS	LO_2 TANK PNEUMATIC OPEN, SPRING-LOAD CLOSED, BALL VALVE	1	RUPTURE OR LEAKAGE	2.00E-07 2.00E-09	ACT
90	VENT SYSTEMS	LINES & FITTINGS (BETWEEN LO_2 TANK & MECHANICAL VENT VALVES)	1 SET	RUPTURE OR LEAKAGE	5.00E-05 5.00E-07	ACT
91	VENT SYSTEMS	LO_2 TANK ELECTRICALLY DRIVEN PUMP	1	FAILURE OF PUMP OR MOTOR TANK MOUNTING	6.00E-08 6.00E-11	PROB
92	VENT SYSTEMS	LH_2 TANK VENT SYSTEM CISS TELESCOPING LINE	1	RUPTURE OR LEAKAGE	2.00E-05 2.00E-08	POSS
93	VENT SYSTEMS	LH_2 TANK VENT SYSTEM ORBITER 1307 BULKHEAD FLEXIBLE LINE	1	RUPTURE OR LEAKAGE	2.00E-05 2.00E-08	POSS
94	VENT SYSTEMS	LH_2 TANK VENT SYSTEM ORBITER MID-BODY FLEXIBLE LINE	1	RUPTURE OR LEAKAGE	2.00E-05 2.00E-08	POSS
95	VENT SYSTEMS	LH_2 TANK VENT SYSTEM ORBITER 1307 BULKHEAD DISCONNECT	1	RUPTURE OR LEAKAGE	2.00E-07 2.00E-09	POSS
96	VENT SYSTEMS	LH_2 TANK VENT SYSTEM ORBITER MID-BODY DISCONNECT	1	RUPTURE OR LEAKAGE	2.00E-07 2.00E-09	POSS
97	VENT SYSTEMS	LH_2 TANK VENT SYSTEM CISS PNEUMATIC SHUTOFF BALL VALVES	4	RUPTURE OR LEAKAGE	2.00E-07 2.00E-09	POSS
98	VENT SYSTEMS	LINES & FITTINGS (BETWEEN LH_2 VENT SYSTEM CISS VALVES & FUEL DISCONNECT PANEL FLEX. LINE	2 SETS	RUPTURE OR LEAKAGE	5.00E-05 5.00E-08	POSS
99	VENT SYSTEMS	LINES & FITTINGS (BETWEEN CISS LH_2 SHUTOFF VALVES & 1307 BULKHEAD FLEX. LINE	1 SET	RUPTURE OR LEAKAGE	5.00E-05 5.00E-08	POSS
100	VENT SYSTEMS	LINES & FITTINGS (BETWEEN CISS LH_2 SHUTOFF VALVES & ORBITER MID-BODY VENT)	1 SET	RUPTURE OR LEAKAGE	5.00E-05 5.00E-08	POSS
101	FILL DRAIN DUMP SYSTEM	LH_2 TANK PYRO SHUTOFF VALVES	2	RUPTURE OR LEAKAGE	1.00E-07 1.00E-09	ACT
102	FILL DRAIN DRUMP SYSTEM	LINES & FITTINGS (BETWEEN LH_2 TANK AND PYRO SHUTOFF VALVES)	1 SET	RUPTURE OR LEAKAGE	7.00E-05 7.00E-08	ACT
103	FILL DRAIN DUMP SYSTEM	LH_2 TANK DUMP LINE QUICK-DISCONNECT	1	RUPTURE OR LEAKAGE	1.00E-07 1.00E-09	ACT
104	FILL DRAIN DUMP SYSTEM	LO_2 TANK PYRO SHUTOFF VALVES	2	RUPTURE OR LEAKAGE	1.00E-07 1.00E-09	ACT
105	FILL DRAIN DUMP SYSTEM	LINES & FITTINGS (BETWEEN LO_2 TANK AND PYRO SHUTOFF VALVE)	1 SET	RUPTURE OR LEAKAGE	7.00E-05 7.00E-08	ACT
106	FILL DRAIN DUMP SYSTEM	LO_2 TANK DUMP LINE QUICK-DISCONNECT	1	RUPTURE OR LEAKAGE	1.00E-07 1.00E-09	ACT
107	INTERMEDIATE BULK-HEAD RELIEF SYSTEM	PRESSURE TRANSDUCERS	3	RUPTURE OR LEAKAGE	2.00E-05 2.00E-08	ACT
108	INTERMEDIATE BULK-HEAD RELIEF SYSTEM	CHECK VALVES	2	RUPTURE OR LEAKAGE	2.00E-07 2.00E-09	ACT
109	INTERMEDIATE BULK-HEAD RELIEF SYSTEM	DISCONNECT (AT AFT FUEL PANEL)	1	RUPTURE OR LEAKAGE	2.00E-07 2.00E-09	ACT

Table A-1. Centaur Failure Modes Contributing To STS/Centaur Behavior Modes - Categories 6, 10 and 11(a) (Page 6 of 8)

NO.	VEHICLE AND SUB-SYSTEM	ITEM	NO. ITEMS	FAILURE MODE	FAILURE RATE λ_u, λ_ℓ	WEIGHTING FACTOR
110	INTERMEDIATE BULK-HEAD RELIEF SYSTEM	ORIFACE (FROM ORBITER GN_2 PURGE)	1	RUPTURER OR LEAKAGE	2.00E-07 2.00E-09	ACT
111	INTERMEDIATE BULK-HEAD RELIEF SYSTEM	CISS FLEXIBLE LINES	2	RUPTURE OR LEAKAGE	2.00E-05 2.00E-08	ACT
112	INTERMEDIATE BULK-HEAD RELIEF SYSTEM	CISS VENT	1	RUPTURE OR LEAKAGE	2.00E-07 2.00E-09	ACT
113	INTERMEDIATE BULK-HEAD RELIEF SYSTEM	LINES & FITTINGS (BETWEEN CAVITY & DISCONNECT)	1 SET	RUPTURE OR LEAKAGE	2.00E-04 2.00E-07	ACT
114	INTERMEDIATE BULK-HEAD RELIEF SYSTEM	LINES & FITTINGS (IN CISS)	1 SET	RUPTURE OR LEAKAGE	5.00E-05 5.00E-08	ACT
115	INTERMEDIATE BULK-HEAD RELIEF SYSTEM	CHECK VALVES	2	BLOCKAGE	2.00E-07 2.00E-09	ACT
116	CISS HELIUM SUPPLY[16]	HELIUM BOTTLES	20	GROSS RUPTURE	1.00E-7 1.00E-9	PROB
117	CISS HELIUM SUPPLY	CISS/ORBITER DISCONNECT	1	GROSS RUPTURE	1.00E-07 1.00E-09	PROB
118	CISS HELIUM SUPPLY	FLEXIBLE LINE	1	GROSS RUPTURE	1.00E-05 1.00E-08	PROB
119	CISS HELIUM SUPPLY	PILOT OPERATED SOLENOID VALVE	4	GROSS RUPTURE	1.00E-07 1.00E-09	PROB
120	CISS HELIUM SUPPLY	CHECK VALVES	2	GROSS RUPTURE	1.00E-07 1.00E-09	PROB
121	CISS HELIUM SUPPLY	LINES & FITTINGS	1 SET	GROSS RUPTURE	2.00E-04 2.00E-07	PROB
122	CENTAUR HELIUM SUPPLY	FILTER	1	GROSS RUPTURE	1.00E-05 1.00E-08	PROB
123	CENTAUR HELIUM SUPPLY	CHECK VALVES	4	GROSS RUPTURE	1.00E-07 1.00E-09	PROB
124	CENTAUR HELIUM SUPPLY	LINES & FITTINGS (BETWEEN CENTAUR/CISS DISCONNECT & REGULATOR)	1 SET	GROSS RUPTURE	2.00E-04 2.00E-07	PROB
125	CENTAUR HELIUM SUPPLY	PRESSURE REGULATOR	1	GROSS RUPTURE	1.00E-07 1.00E-09	PROB
126	CENTAUR HELIUM SUPPLY	RELIEF VALVES	1	GROSS RUPTURE	1.00E-07 1.00E-09	PROB
127	CENTAUR HELIUM SUPPLY	HELIUM BOTTLES	2	RUPTURE & FRAGMENT PROPAGATION	1.00E-7 1.00E-9	PROB
128	CENTAUR HELIUM SUPPLY	LINES & FITTINGS (BETWEEN REGULATOR & 1ST PYRO VALVES OF N_2H_4 & ENGINE CONTROLS SYSTEMS)	1 SET	GROSS RUPTURE	1.00E-04 1.00E-07	POSS
129	REACTION CONTROL SYSTEM[17]	HYDRAZINE (N_2H_4) SUPPLY TANK (FUEL SIDE)	1	RUPTURE OR LEAKAGE	2.00E-07 2.00E-09	PROB
130	REACTION CONTROL SYSTEM	HYDRAZINE SUPPLY TANK (GHe SIDE ABOVE LINER)	1	GROSS RUPTURE	1.00E-07 1.00E-09	PROB
131	REACTION CONTROL SYSTEM	N_2H_4 TANK ISOLATION PYRO VALVES (ON UPSTREAM TANK PRESSURIZATION SIDE)	2	GROSS RUPTURE	1.00E-07 1.00E-09	POSS
132	REACTION CONTROL SYSTEM	N_2H_4 TANK ISOLATION PYRO VALVES (ON DOWNSTREAM N_2H_4 SIDE)	2	RUPTURE OR LEAKAGE	2.00E-07 2.00E-09	PROB

Table A-1. Centaur Failure Modes Contributing To STS/Centaur Behavior Modes - Categories 6, 10 and 11(a) (Page 7 of 8)

NO.	VEHICLE AND SUB-SYSTEM	ITEM	NO. ITEMS	FAILURE MODE	FAILURE RATE λ_b, λ_l	WEIGHTING FACTOR
133	REACTION CONTROL SYSTEM	LINE (ON UPSTREAM GHe SIDE OF TANK)	1 SET	GROSS RUPTURE (LINE BETWEEN N_2H_4 TANK AND ISOLATION PYRO VALVES	5.00E-05 5.00E-08	POSS
134	REACTION CONTROL SYSTEM	LINE (ON DOWNSTREAM N_2H_4 SIDE)	1 SET	RUPTURE OR LEAKAGE (LINE BETWEEN N_2H_4 TANK AND ISOLATION PYRO VALVES)	5.00E-05 5.00E-08	PROB
135	REACTION CONTROL SYSTEM	FILL & VENT VALVE (ON UPSTREAM GHe SIDE OF TANK)	1	GROSS RUPTURE	1.00E-07 1.00E-09	POSS
136	REACTION CONTROL SYSTEM	FILL & DRAIN VALVE (ON DOWNSTREAM SIDE OF N_2H_4 TANK)	1	RUPTURE OR LEAKAGE	1.00E-07 1.00E-09	PROB
137	REACTION CONTROL SYSTEM	PRESSURE TRANSDUCERS (ON FUEL SIDE OF TANK)	2	RUPTURE OR LEAKAGE AT TANK FITTING	1.00E-05 1.00E-08	PROB
138	HYDRAULIC SYSTEM[18]	PRESSURE & RETURN LINES (INCLUDING JOINTS & FITTINGS)	2 SETS	GROSS RUPTURE (PRESSURE LINE ~ 100 PSI WHEN IN SHUTTLE)	2.00E-04 2.00E-07	POSS
139	HYDRAULIC SYSTEM	SERVO VALVE	4	GROSS RUPTURE	1.00E-07 1.00E-09	POSS
140	HYDRAULIC SYSTEM	MANIFOLD ASSEMBLY	2	GROSS RUPTURE	1.00E-07 1.00E-09	POSS
141	HYDRAULIC SYSTEM	ENGINE DRIVEN PUMP	2	CASE RUPTURE	1.00E-07 1.00E-09	POSS
142	HYDRAULIC SYSTEM	RECIRCULATION PUMP	2	CASE RUPTURE	1.00E-07 1.00E-09	POSS
143	HYDRAULIC SYSTEM	RELIEF VALVES	6	GROSS RUPTURE	1.00E-07 1.00E-09	POSS
144	HYDRAULIC SYSTEM	CHECK VALVES	4	GROSS RUPTURE	1.00E-07 1.00E-09	POSS
145	HYDRAULIC SYSTEM	PRESSURE TRANSDUCER	2	GROSS RUPTURE AT FITTING	1.00E-05 1.00E-08	POSS
146	HYDRAULIC SYSTEM	TEMPERATURE TRANSDUCER	2	GROSS RUPTURE AT FITTING	1.00E-05 1.00E-08	POSS
147	HYDRAULIC SYSTEM	DISCONNECTS	4	GROSS RUPTURE	1.00E-07 1.00E-09	POSS
148	PNEUMATIC VALVE CONTROL SYSTEM[19]	DEPLOYMENT ADAPTER LINES & FITTINGS TO PNEUMATIC ACTIVATED VALVES	2 SETS	GROSS RUPTURE (FROM SOLENOID VALVES TO FLEXIBLE LINE)	3.00E-05 3.00E-08	POSS
149	PNEUMATIC VALVE CONTROL SYSTEM	DEPLOYMENT ADAPTER SOLENOID VALVE (TO PNEUMATIC ACTIVATED VALVES)	1	GROSS RUPTURE	1.00E-07 1.00E-09	POSS
150	PNEUMATIC VALVE CONTROL SYSTEM	DEPLOYMENT ADAPTER FLEXIBLE LINES (TO PNEUMATIC ACTIVATED VALVES)	2	GROSS RUPTURE	1.00E-05 1.00E-08	POSS
151	PNEUMATIC VALVE CONTROL SYSTEM	DEPLOYMENT ADAPTER-CENTAUR PNEUMATIC VALVE ACTUATION DISCONNECT	2	GROSS RUPTURE	1.00E-07 1.00E-09	POSS
152	PNEUMATIC VALVE CONTROL SYSTEM	CENTAUR CHECK VALVES (TO PNEUMATIC ACTIVATED VALVES)	4	GROSS RUPTURE	1.00E-07 1.00E-09	POSS
153	PNEUMATIC VALVE CONTROL SYSTEM	LINES & FITTINGS (DOWNSTREAM OF REGULATORS IN CISS TO FILL/DUMP & VENT VALVES)	4 SETS	GROSS RUPTURE	1.00E-04 1.00E-07	POSS
154	PNEUMATIC VALVE CONTROL SYSTEM	CISS 3-WAY SOLENOID VALVE ACTUATORS	20	GROSS RUPTURE	1.00E-07 1.00E-09	POSS
155	PNEUMATIC VALVE CONTROL SYSTEM	CISS SOLENOID CROSS CONNECTION VALVES	3	GROSS RUPTURE	1.00E-07 1.00E-09	POSS

Table A-1. Centaur Failure Modes Contributing To STS/Centaur Behavior Modes - Categories 6, 10 and 11(a) (Page 8 of 8)

NO.	VEHICLE AND SUB-SYSTEM	ITEM	NO. ITEMS	FAILURE MODE	FAILURE RATE λ_μ, λ_s	WEIGHTING FACTOR
156	PNEUMATIC VALVE CONTROL SYSTEM	CISS PRESSURE TRANSDUCERS	10	GROSS RUPTURE	1.00E-05 1.00E-08	POSS
157	PNEUMATIC VALVE CONTROL SYSTEM	CENTAUR SOLENOID CROSS CONNECTION VALVES	2	GROSS RUPTURE	1.00E-07 1.00E-09	POSS
158	PNEUMATIC VALVE CONTROL SYSTEM	LINES & FITTINGS (TO VENT & DUMP VALVES IN CENTAUR)	5 SETS	GROSS RUPTURE	1.00E-04 1.00E-07	POSS
159	PNEUMATIC VALVE CONTROL SYSTEM	CENTAUR 3-WAY SOLENOID VALVE ACTUATORS	10	GROSS RUPTURE	1.00E-07 1.00E-09	POSS
160	PNEUMATIC VALVE CONTROL SYSTEM	CENTAUR LH_2 TANK VENT VALVE 3-WAY SOLENOID ACTUATORS	3	INADVERTENT OPERATION[20]	3.00E-05 3.00E-06	ACT
161	PNEUMATIC VALVE CONTROL SYSTEM	CENTAUR LO_2 TANK VENT VALVE 3-WAY SOLENOID ACTUATOR	1	INADVERTENT OPERATION[20]	3.00E-05 3.00E-06	ACT
162	CENTAUR STRUCTURES[21]	CONICAL SPACECRAFT ADAPTER	1	STRUCTURAL COLLAPSE[22] SHUTTLE g LOADS)	3.00E-08 3.00E-11	POSS
163	CENTAUR STRUCTURES	FORWARD ORBITER CENTAUR SUPPORT STRUCTURE (INCLUDING TRUNIONS)	3	COLLAPSE OF SILL (2) OR KEEL (1) STRUCTURE[23] (SHUTTLE g LOADS)	3.00E-05 3.00E-11	PROB
164	CENTAUR STRUCTURES	FORWARD ORBITER CENTAUR ATTACHMENTS	3	COLLAPSE OF FORWARD SILL LATCH (2) FORWARD KEEL LATCH (1)[23] (SHUTTLE g LOADS)	3.00E-06 3.00E-11	PROB
165	CENTAUR STRUCTURES	CENTAUR SUPPORT STRUCTURE (AFT) (INCLUDING TRUNIONS)	1 UNIT	STRUCTURAL COLLAPSE[24] (SHUTTLE g LOADS)	3.00E-08 3.00E-11	PROB
166	CENTAUR STRUCTURES	CENTAUR SUPPORT STRUCTURE (AFT) ATTACHMENTS	5	STRUCTURAL COLLAPSE[24] (SHUTTLE g LOADS)	3.00E-08 3.00E-11	PROB
167	CENTAUR STRUCTURES	CYLINDRICAL STUB ADAPTER	1	STRUCTURAL COLLAPSE[23] (SHUTTLE g LOADS)	3.00E-08 3.00E-11	PROB
168	CENTAUR STRUCTURES	AFT ADAPTER	1	STRUCTURAL COLLAPSE[24] (SHUTTLE g LOADS)	3.00E-08 3.00E-11	PROB
169	CENTAUR STRUCTURES	DEPLOYMENT ADAPTER (INCLUDING TRUNIONS)	1 UNIT	STRUCTURAL COLLAPSE[24] (SHUTTLE g LOADS)	3.00E-08 3.00E-11	PROB
170	CENTAUR STRUCTURES	ROTATION MECHANISM SUPPORT STRUCTURE (INCLUDING KEEL PIN)	1 UNIT	STRUCTURAL COLLAPSE[24] (SHUTTLE g LOADS)	3.00E-05 3.00E-11	PROB

Table A-2. Centaur Failure Modes Contributing to STS/Centaur Behavior Mode Category 11(b) of Table 3-4 (Page 1 of 6)

NO.	VEHICLE AND SUB-SYSTEM	ITEM	NO. ITEMS	FAILURE MODE	FAILURE RATE λ_u, λ_ℓ	WEIGHTING FACTOR
1	TANK STRUCTURE	LO_2 TANK AFT RINGS WELDS	4	WELD RUPTURE	1.00E-07 1.00E-10	ACT
2	TANK STRUCTURE	CYLINDRICAL LO_2 TANK WELDS	2	WELD RUPTURE	1.00E-07 1.00E-10	ACT
3	TANK STRUCTURE	DOUBLE WALLED INTERMEDIATE BULKHEAD WELDS	24	WELD RUPTURE	1.00E-07 1.00E-10	ACT
4	TANK STRUCTURE	AFT BULKHEAD WELDS	8	WELD RUPTURE	1.00E-07 1.00E-10	ACT
5	TANK STRUCTURE	LO_2 TANK ENGINE FEED FITTING	1	RUPTURE OF FITTING OR AT TANK TO FITTING WELD	1.00E-05 1.00E-08	ACT
6	PROPULSION SYSTEM[2]	LO_2 FEED DUCT[3] (FROM TANK TO LO_2 PRE-VALVE)	1 SET	RUPTURE OR GROSS LEAKAGE	2.00E-04 1.00E-07	ACT
7	PROPULSION SYSTEM	LO_2 FEED DUCT PRE-VALVE	1	RUPTURE OR GROSS LEAKAGE	2.00E-07 2.00E-09	ACT
8	TANK PRESSURIZATION SYSTEM[4]	FLEXIBLE LINE (BETWEEN CISS & DEPLOYMENT ADAPTER)	1	GROSS RUPTURE	2.00E-05 2.00E-08	PROB
9	TANK PRESSURIZATION SYSTEM	LINES & FITTINGS (4000 PSI SECTION UP TO ORIFACE IN DEPLOYMENT ADAPTER)	1 SET	GROSS RUPTURE	2.00E-04 2.00E-07	PROB
10	TANK PRESSURIZATION SYSTEM	MANUAL SHUTOFF VALVE (IN DEPLOYMENT ADAPTER)	2	GROSS RUPTURE	1.00E-07 1.00E-09	PROB
11	TANK PRESSURIZATION SYSTEM	DEPLOYMENT ADAPTER FILTER	1	GROSS RUPTURE	1.00E-05 1.00E-08	PROB
12	TANK PRESSURIZATION SYSTEM	PILOT OPERATED SOLENOID VALVE (IN DEPLOYMENT ADAPTER)	20	GROSS RUPTURE	1.00E-07 1.00E-09	PROB
13	TANK PRESSURIZATION SYSTEM	ORIFACE (IN DEPLOYMENT ADAPTER)	6	GROSS RUPTURE	1.00E-07 1.00E-09	PROB
14	TANK PRESSURIZATION SYSTEM	LINES & FITTINGS (BETWEEN ORIFACES & DISCONNECT PANELS << 4000 PSI)	1 SET	GROSS RUPTURE	5.00E-05 5.00E-08	POSS
15	TANK PRESSURIZATION SYSTEM	FLEXIBLE LINE (BETWEEN CENTAUR & DEPLOYMENT ADAPTER)	3	GROSS RUPTURE	1.00E-05 1.00E-08	POSS
16	TANK PRESSURIZATION SYSTEM	OXIDIZER & FUEL DISCONNECTS	3	GROSS RUPTURE	1.00E-07 1.00E-09	POSS
17	TANK PRESSURIZATION SYSTEM	CHECK VALVE (LO_2 TANK SIDE IN CENTAUR)	1	RUPTURE OR GROSS LEAKAGE[5]	2.00E-07 2.00E-09	ACT
18	TANK PRESSURIZATION SYSTEM	CHECK VALVES (FURTHEST FROM LO_2 & LH_2 TANKS)	2	GROSS RUPTURE	1.00E-07 1.00E-09	POSS
19	TANK PRESSURIZATION SYSTEM	ORIFACES (IN CENTAUR LO_2 TANK SIDE)	2	RUPTURE OR GROSS LEAKAGE[5]	2.00E-07 2.00E-09	ACT
20	TANK PRESSURIZATION SYSTEM	PILOT OPERATED SOLENOID VALVE (LO_2 TANK SIDE NEAREST ORIFACE)	2	RUPTURE OR GROSS LEAKAGE[5]	2.00E-07 2.00E-09	ACT
21	TANK PRESSURIZATION SYSTEM	LINES & FITTINGS (FROM LO_2 TANK TO 1ST SOLENOID VALVE & 1ST CHECK VALVE)	1 SET	RUPTURE OR GROSS LEAKAGE[5]	2.00E-04 2.00E-07	ACT
22	TANK PRESSURIZATION SYSTEM	PILOT OPERATED SOLENOID VALVES (TWO VALVES ON EACH TANK SIDE FURTHEST FROM ORIFACES)	4	GROSS RUPTURE	1.00E-07 1.00E-09	POSS
23	TANK PRESSURIZATION SYSTEM	LO_2 TANK PRESSURE TRANSDUCERS & FITTINGS	5	RUPTURE OR GROSS LEAKAGE[5]	2.00E-05 2.00E-08	ACT

Table A-2. Centaur Failure Modes Contributing to STS/Centaur Behavior Mode Category II(b) of Table 3-4 (Page 2 of 6)

NO.	VEHICLE AND SUB-SYSTEM	ITEM	NO. ITEMS	FAILURE MODE	FAILURE RATE λ_u, λ_s	WEIGHTING FACTOR
24	CISS PRESSURE REGULATION SYSTEM[4,8]	CISS MANUAL SHUTOFF VALVES	2	GROSS RUPTURE	1.00E-07 1.00E-09	PROB
25	CISS PRESSURE REGULATION SYSTEM	CISS FILTER	1	GROSS RUPTURE	1.00E-05 1.00E-08	PROB
26	CISS PRESSURE REGULATION SYSTEM	CISS DISCONNECT	1	GROSS RUPTURE	1.00E-07 1.00E-09	PROB
27	CISS PRESSURE REGULATION SYSTEM	CISS LINES & FITTINGS (UPSTREAM OF REGULATORS)	1 SET	GROSS RUPTURE (BETWEEN REGULATOR & 1ST SOLENOID VALVE)	1.00E-04 1.00E-07	PROB
28	CISS PRESSURE REGULATION SYSTEM	CISS SOLENOID OPERATED VALVES (UPSTREAM OF REGULATORS)	3	GROSS RUPTURE (VALVES NEAREST TO REGULATORS)	1.00E-07 1.00E-09	PROB
29	CISS PRESSURE REGULATION SYSTEM	CISS CHECK VALVES	6	GROSS RUPTURE	1.00E-07 1.00E-09	POSS
30	CISS PRESSURE REGULATION SYSTEM	CISS PRESSURE TRANSDUCERS & FITTINGS	3	GROSS RUPTURE	1.00E-05 1.00E-08	POSS
31	CISS PRESSURE REGULATION SYSTEM	CISS REGULATORS	3	GROSS RUPTURE	1.00E-07 1.00E-09	PROB
32	CISS PRESSURE REGULATION SYSTEM	CISS LINES & FITTINGS (DOWNSTREAM OF REGULATORS)	1 SET	GROSS RUPTURE (FROM REGULATOR TO LAST SET OF PARALLEL VALVES)	2.00E-04 2.00E-07	POSS
33	CISS PRESSURE REGULATION SYSTEM	CISS SOLENOID OPERATED VALVES (DOWNSTREAM OF REGULATORS)	2	GROSS RUPTURE (VALVES NEAREST TO REGULATORS)	1.00E-07 1.00E-09	POSS
34	CISS PRESSURE REGULATION SYSTEM	CISS/DEPLOYMENT ADAPTER FLEXIBLE LINE	1	GROSS RUPTURE	1.00E-05 1.00E-08	POSS
35	CISS PRESSURE REGULATION SYSTEM	CISS SOLENOID VALVES (UPSTREAM OF REGULATORS)	3	GROSS RUPTURE (VALVES FURTHEST FROM REGULATORS)	1.00E-07 1.00E-09	PROB
36	CISS PRESSURE REGULATION SYSTEM	CISS SOLENOID VALVES (DOWNSTREAM OF REGULATORS)	3	GROSS RUPTURE (VALVES FURTHEST FROM REGULATORS)	1.00E-07 1.00E-09	POSS
37	CISS PRESSURE REGULATION SYSTEM	CISS LINES & FITTINGS (UPSTREAM OF REGULATORS)	1 SET	GROSS RUPTURE (FROM He SUPPLY TO 1ST SET OF PARALLEL VALVES)	1.00E-04 1.00E-07	PROB
38	CISS PRESSURE REGULATION SYSTEM	CISS LINES & FITTINGS (DOWNSTREAM OF REGULATORS)	1 SET	GROSS RUPTURE (FROM LAST SET OF PARALLEL VALVES TO CISS/DEPLOYMENT ADAPTER FLEXIBLE LINE)	1.00E-04 1.00E-07	POSS
39	PURGE SYSTEM[9]	He PURGE LINES TO 28 Vdc RECIRC. PUMP MOTORS	2 SETS	RUPTURE OR LEAKAGE & LOSS OF MOTOR PURGE[10] (LINE FROM ORIFACE IN PNEUMATIC SYSTEM TO MOTOR)	2.00E-04 2.00E-07	POSS
40	PURGE SYSTEM	CISS FLEXIBLE LINES	2	GROSS RUPTURE	1.00E-05 1.00E-08	POSS
41	PURGE SYSTEM	DEPLOYMENT ADAPTER SOLENOID VALVES	15	GROSS RUPTURE (1ST SET OF PARALLEL VALVES TO INSULATION & ENGINE PURGES & ALL VALVES TO LO_2/LH_2 FILL/DRAIN/VENT)	1.00E-07 1.00E-09	POSS
42	PURGE SYSTEM	DEPLOYMENT ADAPTER LINES & FITTINGS (BETWEEN CISS DEPLOYMENT ADAPTER FLEXIBLE LINE & 1ST SOLENOID VALVES)	1 SET	GROSS RUPTURE	5.00E-05 5.00E-08	POSS
43	PURGE SYSTEM	DEPLOYMENT ADAPTER LINES & FITTINGS (CONNECTING SOLENOID VALVES, ORIFACES, CHECK VALVES ETC.)	1 SET	GROSS RUPTURE	4.00E-04 4.00E-08	POSS

Table A-2. Centaur Failure Modes Contributing to STS/Centaur Behavior Mode Category 11(b) of Table 3-4 (Page 3 of 6)

NO.	VEHICLE AND SUB-SYSTEM	ITEM	NO. ITEMS	FAILURE MODE	FAILURE RATE λ_M, λ_E	WEIGHTING FACTOR
[illegible]	[illegible]	DEPLOYMENT ADAPTER LINES & FITTINGS (BETWEEN ORIFACES & FLEXIBLE LINE TO TANK INSULATION)	1 SET	GROSS RUPTURE	1.00E-04 1.00E-08	POSS
[illegible]	PURGE SYSTEM	DEPLOYMENT ADAPTER LINES & FITTINGS (BETWEEN ORIFACES & ENGINE PURGES)	1 SET	GROSS RUPTURE	1.00E-04 1.00E-08	POSS
46	PURGE SYSTEM	DEPLOYMENT ADAPTER FLEXIBLE LINE (TO ENGINE PURGE)	1	GROSS RUPTURE	1.00E-05 1.00E-08	POSS
47	PURGE SYSTEM	DEPLOYMENT ADAPTER FLEXIBLE LINE (TO TANK INSULATION)	1	GROSS RUPTURE	1.00E-05 1.00E-08	POSS
48	PURGE SYSTEM	DEPLOYMENT ADAPTER TANK INSULATION DISCONNECT	1	GROSS RUPTURE	1.00E-07 1.00E-09	POSS
49	PURGE SYSTEM	CENTAUR LINES & FITTINGS (TO LO_2 TANK PRESSURIZATION LINE, LO_2 VENT STAND PIPE, LO_2 TANK PRESSURE TRANSDUCERS ETC.)	1 SET	RUPTURE OR LEAKAGE[11]	4.00E-04 4.00E-07	ACT
50	PURGE SYSTEM	CENTAUR ORIFACES (TO LO_2 TANK PRESSURE TRANSDUCERS, ETC.)	4	RUPTURE OR LEAKAGE	2.00E-07 2.00E-09	ACT
[illegible]	PURGE SYSTEM	CENTAUR ORIFACE (BETWEEN PYRO VALVE & INSULATION PURGE LINE)	1	GROSS RUPTURE	1.00E-07 1.00E-09	POSS
52	PURGE SYSTEM	CENTAUR ORIFACE (TO HYDRAULIC RECIRC. MOTOR PURGE	2	GROSS RUPTURE	1.00E-07 1.00E-09	POSS
53	PURGE SYSTEM	CENTAUR CHECK VALVE (NEAREST TO LO_2 TANK PRESSURE TRANSDUCERS)	1	RUPTURE OR LEAKAGE	2.00E-07 2.00E-09	ACT
54	PURGE SYSTEM	CENTAUR CHECK VALVE (FURTHEST FROM LO_2 TANK PRESSURE TRANSDUCERS)	1	GROSS RUPTURE	1.00E-07 1.00E-09	POSS
55	PURGE SYSTEM	CENTAUR PYRO OPERATED VALVE (TO PRESS. TRANS. PURGE, ETC.)	1	GROSS RUPTURE	1.00E-07 1.00E-09	POSS
56	PURGE SYSTEM	CENTAUR SOLENOID CONTROLLED SELF REGULATING VALVE (TO LO_2 VENT STAND-PIPE)	1	GROSS RUPTURE	1.00E-07 1.00E-09	POSS
57	PURGE SYSTEM	LH_2 TANK, INSULATION PURGE VENT, ΔP TRANSDUCERS	3	GROSS RUPTURE	1.00E-05 1.00E-08	POSS
58	PURGE SYSTEM	LH_2 TANK, INSULATION PIPE VENT, RELIEF VALVES	2	GROSS RUPTURE	1.00E-07 1.00E-09	POSS
59	PURGE SYSTEM	LH_2 TANK, INSULATION PURGE VENT, LINES & FITTINGS	1 SET	GROSS RUPTURE	1.00E-04 1.00E-07	POSS
60	VENT SYSTEMS[12]	LH_2 TANK SELF REGULATING VENT VALVE	1	RUPTURE OR LEAKAGE	2.00E-07 2.00E-09	ACT
61	VENT SYSTEMS[13]	LINES & FITTINGS (BETWEEN LH_2 VENT VALVES & DISCONNECT)	1 SET	RUPTURE OR LEAKAGE	5.00E-05 5.00E-08	POSS
[illegible]	VENT SYSTEMS	LH_2 TANK HEAT EXCHANGER	1	FAILURE OF HX TANK MOUNTING	3.00E-08 3.00E-11	PROB
[illegible]	VENT SYSTEMS	LH_2 TANK ELECTRICALLY DRIVEN PUMP	1	FAILURE OF PUMP OR MOTOR TANK MOUNTING	3.00E-08 3.00E-11	PROB
64	VENT SYSTEMS	LH_2 TANK VENT DISCONNECT	1	RUPTURE OR LEAKAGE	2.00E-07 2.00E-09	POSS
65	VENT SYSTEMS	LO_2 TANK SELF REGULATING VENT VALVE	1	RUPTURE OR LEAKAGE	2.00E-07 2.00E-09	ACT

Table A-2. Centaur Failure Modes Contributing to STS/Centaur Behavior Mode Category II(b) of Table 3-4 (Page 4 of 6)

NO.	VEHICLE AND SUB-SYSTEM	ITEM	NO. ITEMS	FAILURE MODE	FAILURE RATE λ_u, λ_s	WEIGHTING FACTOR
66	VENT SYSTEMS	LO_2 TANK PNEUMATIC OPEN, SPRING-LOAD CLOSED, BALL VALVE	1	RUPTURE OR LEAKAGE	2.00E-07 2.00E-09	ACT
67	VENT SYSTEMS	LINES & FITTINGS (BETWEEN LO_2 TANK & MECHANICAL VENT VALVES)	1 SET	RUPTURE OR LEAKAGE	5.00E-05 5.00E-07	ACT
68	VENT SYSTEMS	LO_2 TANK ELECTRICALLY DRIVEN PUMP	1	FAILURE OF PUMP OR MOTOR TANK MOUNTING	6.00E-06 6.00E-11	PROB
69	VENT SYSTEMS	LH_2 TANK VENT SYSTEM CISS TELESCOPING LINE	1	RUPTURE OR LEAKAGE	2.00E-05 2.00E-08	POSS
70	VENT SYSTEMS	LH_2 TANK VENT SYSTEM ORBITER 1307 BULKHEAD FLEXIBLE LINE	1	RUPTURE OR LEAKAGE	2.00E-05 2.00E-08	POSS
71	VENT SYSTEMS	LH_2 TANK VENT SYSTEM ORBITER MID-BODY FLEXIBLE LINE	1	RUPTURE OR LEAKAGE	2.00E-05 2.00E-08	POSS
72	VENT SYSTEMS	LH_2 TANK VENT SYSTEM ORBITER 1307 BULKHEAD DISCONNECT	1	RUPTURE OR LEAKAGE	2.00E-07 2.00E-09	POSS
73	VENT SYSTEMS	LH_2 TANK VENT SYSTEM ORBITER MID-BODY DISCONNECT	1	RUPTURE OR LEAKAGE	2.00E-07 2.00E-09	POSS
74	VENT SYSTEMS	LH_2 TANK VENT SYSTEM CISS PNEUMATIC SHUTOFF BALL VALVES	4	RUPTURE OR LEAKAGE	2.00E-07 2.00E-09	POSS
75	VENT SYSTEMS	LINES & FITTINGS (BETWEEN LH_2 VENT SYSTEM CISS VALVES & FUEL DISCONNECT PANEL FLEX. LINE)	2 SETS	RUPTURE OR LEAKAGE	5.00E-05 5.00E-08	POSS
76	VENT SYSTEMS	LINES & FITTINGS (BETWEEN CISS LH_2 SHUTOFF VALVES & 1307 BULKHEAD FLEX. LINE	1 SET	RUPTURE OR LEAKAGE	5.00E-05 5.00E-08	POSS
77	VENT SYSTEMS	LINES & FITTINGS (BETWEEN CISS LH_2 SHUTOFF VALVES & ORBITER MID-BODY VENT)	1 SET	RUPTURE OR LEAKAGE	5.00E-05 5.00E-08	POSS
78	FILL DRAIN/DUMP SYSTEM	LO_2 TANK PYRO SHUTOFF VALVES	2	RUPTURE OR LEAKAGE	1.00E-07 1.00E-09	ACT
79	FILL DRAIN/DUMP SYSTEM	LINES & FITTINGS (BETWEEN LO_2 TANK AND PYRO SHUTOFF VALVE)	1 SET	RUPTURE OR LEAKAGE	7.00E-05 7.00E-08	ACT
80	FILL DRAIN/DUMP SYSTEM	LO_2 TANK DUMP LINE QUICK-DISCONNECT	1	RUPTURE OR LEAKAGE	1.00E-07 1.00E-09	ACT
81	INTERMEDIATE BULK-HEAD RELIEF SYSTEM	PRESSURE TRANSDUCERS	3	RUPTURE OR LEAKAGE	2.00E-05 2.00E-08	ACT
82	INTERMEDIATE BULK-HEAD RELIEF SYSTEM	CHECK VALVES	2	RUPTURE OR LEAKAGE	2.00E-07 2.00E-09	ACT
83	INTERMEDIATE BULK-HEAD RELIEF SYSTEM	DISCONNECT (AT AFT FUEL PANEL)	1	RUPTURE OR LEAKAGE	2.00E-07 1.00E-09	ACT
84	INTERMEDIATE BULK-HEAD RELIEF SYSTEM	ORIFACE (FROM ORBITER GN_2 PURGE)	1	RUPTURE OR LEAKAGE	2.00E-07 2.00E-09	ACT
85	INTERMEDIATE BULK-HEAD RELIEF SYSTEM	CISS FLEXIBLE LINES	2	RUPTURE OR LEAKAGE	2.00E-05 2.00E-08	ACT
86	INTERMEDIATE BULK-HEAD RELIEF SYSTEM	CISS VENT	1	RUPTURE OR LEAKAGE	2.00E-07 2.00E-09	ACT
87	INTERMEDIATE BULK-HEAD RELIEF SYSTEM	LINES & FITTINGS (BETWEEN CAVITY & DISCONNECT)	1 SET	RUPTURE OR LEAKAGE	2.00E-04 2.00E-07	ACT
88	INTERMEDIATE BULK-HEAD RELIEF SYSTEM	LINES & FITTINGS (IN CISS)	1 SET	RUPTURE OR LEAKAGE	5.00E-05 5.00E-08	ACT

Table A-2. Centaur Failure Modes Contributing to STS/Centaur Behavior Mode Category 11(b) of Table 3-4 (Page 5 of 6)

NO.	VEHICLE AND SUB-SYSTEM	ITEM	NO. ITEMS	FAILURE MODE	FAILURE RATE λ_μ, λ_R	WEIGHTING FACTOR
89	INTERMEDIATE BULK-HEAD RELIEF SYSTEM	CHECK VALVES	2	BLOCKAGE	2.00E-07 2.00E-09	ACT
90	CISS HELIUM SUPPLY[16]	HELIUM BOTTLES	20	GROSS RUPTURE	1.00E-7 1.00E-9	PROB
91	CISS HELIUM SUPPLY	CISS/ORBITER DISCONNECT	1	GROSS RUPTURE	1.00E-07 1.00E-09	PROB
92	CISS HELIUM SUPPLY	FLEXIBLE LINE	1	GROSS RUPTURE	1.00E-05 1.00E-08	PROB
93	CISS HELIUM SUPPLY	PILOT OPERATED SOLENOID VALVE	4	GROSS RUPTURE	1.00E-07 1.00E-09	PROB
94	CISS HELIUM SUPPLY	CHECK VALVES	2	GROSS RUPTURE	1.00E-07 1.00E-09	PROB
95	CISS HELIUM SUPPLY	LINES & FITTINGS	1 SET	GROSS RUPTURE	2.00E-04 2.00E-07	PROB
96	CENTAUR HELIUM SUPPLY	FILTER	1	GROSS RUPTURE	1.00E-05 1.00E-08	PROB
97	CENTAUR HELIUM SUPPLY	CHECK VALVES	4	GROSS RUPTURE	1.00E-07 1.00E-09	PROB
98	CENTAUR HELIUM SUPPLY	LINES & FITTINGS (BETWEEN CENTAUR/CISS DISCONNECT & REGULATOR)	1 SET	GROSS RUPTURE	2.00E-04 2.00E-07	PROB
99	CENTAUR HELIUM SUPPLY	PRESSURE REGULATOR	1	GROSS RUPTURE	1.00E-07 1.00E-09	PROB
100	CENTAUR HELIUM SUPPLY	RELIEF VALVE	1	GROSS RUPTURE	1.00E-07 1.00E-09	PROB
101	CENTAUR HELIUM SUPPLY	HELIUM BOTTLES	2	RUPTURE & FRAGMENT PROPAGATION	1.00E-7 1.00E-9	PROB
102	CENTAUR HELIUM SUPPLY	LINES & FITTINGS (BETWEEN REGULATOR & 1ST PYRO VALVES OF N_2H_4 & ENGINE CONTROLS SYSTEMS)	1 SET	GROSS RUPTURE	1.00E-04 1.00E-07	POSS
103	REACTION CONTROL SYSTEM	HYDRAZINE SUPPLY TANK (GHe SIDE ABOVE LINER)	1	GROSS RUPTURE	1.00E-07 1.00E-09	PROB
104	REACTION CONTROL SYSTEM	N_2H_4 TANK ISOLATION PYRO VALVES (ON UPSTREAM TANK PRESSURIZATION SIDE)	2	GROSS RUPTURE	1.00E-07 1.00E-09	POSS
105	REACTION CONTROL SYSTEM	LINE (ON UPSTREAM GHe SIDE OF TANK)	1 SET	GROSS RUPTURE (LINE BETWEEN N_2H_4 TANK AND ISOLATION PYRO VALVES)	5.00E-05 5.00E-08	POSS
106	REACTION CONTROL SYSTEM	FILL & VENT VALVE (ON UPSTREAM GHe SIDE OF TANK)	1	GROSS RUPTURE	1.00E-07 1.00E-09	POSS
107	HYDRAULIC SYSTEM[18]	PRESSURE & RETURN LINES (INCLUDING JOINTS & FITTINGS)	2 SETS	GROSS RUPTURE (PRESSURE LINE ~ 100 PSI WHEN IN SHUTTLE)	2.00E-04 2.00E-07	POSS
108	HYDRAULIC SYSTEM	SERVO VALVES	4	GROSS RUPTURE	1.00E-07 1.00E-09	POSS
109	HYDRAULIC SYSTEM	MANIFOLD ASSEMBLY	2	GROSS RUPTURE	1.00E-07 1.00E-09	POSS
110	HYDRAULIC SYSTEM	ENGINE DRIVEN PUMP	2	CASE RUPTURE	1.00E-07 1.00E-09	POSS
111	HYDRAULIC SYSTEM	RECIRCULATION PUMP	2	CASE RUPTURE	1.00E-07 1.00E-09	POSS
112	HYDRAULIC SYSTEM	RELIEF VALVES	6	GROSS RUPTURE	1.00E-07 1.00E-09	POSS

Table A-2. Centaur Failure Modes Contributing to STS/Centaur Behavior Mode Category 11(b) of Table 3-4 (Page 6 of 6)

NO.	VEHICLE AND SUB-SYSTEM	ITEM	NO. ITEMS	FAILURE MODE	FAILURE RATE λ_u, λ_R	WEIGHTING FACTOR
113	HYDRAULIC SYSTEM	CHECK VALVES	4	GROSS RUPTURE	1.00E-07 1.00E-09	POSS
114	HYDRAULIC SYSTEM	PRESSURE TRANSDUCER	2	GROSS RUPTURE AT FITTING	1.00E-05 1.00E-08	POSS
115	HYDRAULIC SYSTEM	TEMPERATURE TRANSDUCER	2	GROSS RUPTURE AT FITTING	1.00E-05 1.00E-08	POSS
116	HYDRAULIC SYSTEM	DISCONNECTS	4	GROSS RUPTURE	1.00E-07 1.00E-09	POSS
117	PNEUMATIC VALVE CONTROL SYSTEM[19]	DEPLOYMENT ADAPTER LINES & FITTINGS TO PNEUMATIC ACTIVATED VALVES	2 SETS	GROSS RUPTURE (FROM SOLENOID VALVES TO FLEXIBLE LINE)	3.00E-05 3.00E-08	POSS
118	PNEUMATIC VALVE CONTROL SYSTEM	DEPLOYMENT ADAPTER SOLENOID VALVE (TO PNEUMATIC ACTIVATED VALVES)	1	GROSS RUPTURE	1.00E-07 1.00E-09	POSS
119	PNEUMATIC VALVE CONTROL SYSTEM	DEPLOYMENT ADAPTER FLEXIBLE LINES (TO PNEUMATIC ACTIVATED VALVES)	2	GROSS RUPTURE	1.00E-05 1.00E-08	POSS
120	PNEUMATIC VALVE CONTROL SYSTEM	DEPLOYMENT ADAPTER/CENTAUR PNEUMATIC VALVE ACTUATION DISCONNECT	2	GROSS RUPTURE	1.00E-07 1.00E-09	POSS
121	PNEUMATIC VALVE CONTROL SYSTEM	CENTAUR CHECK VALVES (TO PNEUMATIC ACTIVATED VALVES)	4	GROSS RUPTURE	1.00E-07 1.00E-09	POSS
122	PNEUMATIC VALVE CONTROL SYSTEM	LINES & FITTINGS (DOWNSTREAM OF REGULATORS IN CISS TO FILL/DUMP & VENT VALVES)	4 SETS	GROSS RUPTURE	1.00E-04 1.00E-07	POSS
123	PNEUMATIC VALVE CONTROL SYSTEM	CISS 3-WAY SOLENOID VALVE ACTUATORS	20	GROSS RUPTURE	1.00E-07 1.00E-09	POSS
124	PNEUMATIC VALVE CONTROL SYSTEM	CISS SOLENOID CROSS CONNECTION VALVES	3	GROSS RUPTURE	1.00E-07 1.00E-09	POSS
125	PNEUMATIC VALVE CONTROL SYSTEM	CISS PRESSURE TRANSDUCERS	10	GROSS RUPTURE	1.00E-05 1.00E-08	POSS
126	PNEUMATIC VALVE CONTROL SYSTEM	CENTAUR SOLENOID CROSS CONNECTION VALVES	2	GROSS RUPTURE	1.00E-07 1.00E-09	POSS
127	PNEUMATIC VALVE CONTROL SYSTEM	LINES & FITTINGS (TO VENT & DUMP VALVES IN CENTAUR)	5 SETS	GROSS RUPTURE	1.00E-04 1.00E-07	POSS
128	PNEUMATIC VALVE CONTROL SYSTEM	CENTAUR 3-WAY SOLENOID VALVE ACTUATORS	10	GROSS RUPTURE	1.00E-07 1.00E-09	POSS
129	PNEUMATIC VALVE CONTROL SYSTEM	CENTAUR LO_2 TANK VENT VALVE 3-WAY SOLENOID ACTUATOR	1	INADVERTENT OPERATION[20]	3.00E-05 3.00E-08	ACT
130	CENTAUR STRUCTURES[21]	CONICAL SPACECRAFT ADAPTER	1	STRUCTURAL COLLAPSE[22] (SHUTTLE g LOADS)	3.00E-08 3.00E-11	POSS
131	CENTAUR STRUCTURES	CENTAUR SUPPORT STRUCTURE (AFT) (INCLUDING TRUNIONS)	1 UNIT	STRUCTURAL COLLAPSE[24] (SHUTTLE g LOADS)	3.00E-08 3.00E-11	PROB
132	CENTAUR STRUCTURES	CENTAUR SUPPORT STRUCTURE (AFT) ATTACHMENTS	5	STRUCTURAL COLLAPSE[24] (SHUTTLE g LOADS)	3.00E-08 3.00E-11	PROB
133	CENTAUR STRUCTURES	AFT ADAPTER	1	STRUCTURAL COLLAPSE[24] (SHUTTLE g LOADS)	3.00E-08 3.00E-11	PROB
134	CENTAUR STRUCTURES	DEPLOYMENT ADAPTER (INCLUDING TRUNIONS)	1 UNIT	STRUCTURAL COLLAPSE[24] (SHUTTLE g LOADS)	3.00E-08 3.00E-11	PROB
135	CENTAUR STRUCTURES	ROTATION MECHANISM SUPPORT STRUCTURE (INCLUDING KEEL PIN)	1 UNIT	STRUCTURAL COLLAPSE[24] (SHUTTLE g LOADS)	3.00E-08 3.00E-11	PROB

Table A-3. Centaur Failure Modes Contributing To STS/Centaur Behavior Mode - Category 14 of Table 3-4

NO.	VEHICLE AND SUB-SYSTEM	ITEM	NO. ITEMS	FAILURE MODE	FAILURE PROBABILITIES* λ_{μ}, λ_{ℓ}	WEIGHTING FACTOR
1	CENTAUR/DEPLOYMENT ADAPTER PANEL[25]	LH_2 RISE-OFF FLUID DIS-CONNECTS	2 (>2")	FAIL TO SEPARATE[26]	1.00E-07 1.00E-09	POSS
2	CENTAUR/DEPLOYMENT ADAPTER PANEL	LO_2 RISE-OFF FLUID DIS-CONNECTS	2 (>2")	FAIL TO SEPARATE[26]	1.00E-07 1.00E-09	POSS

*Since these failures can only occur at a discrete instant in time, the 'rates' quoted are estimates of total failure probability on demand.

FOOTNOTES FOR TABLES A-1, A-2 AND A-3

1. Rupture of the LO_2 tank is considered to lead directly to the failure of the LH_2 tank with resulting oxidizer propellant mixing and fire and explosion in the payload bay. Rupture of the LH_2 tank will not necessarily lead to failure of the LO_2 tank, but sufficient oxygen is likely to be present in the payload bay (until payload bay doors opened) to support combustion.

2. Duct includes tank-to-duct transition pieces, elbows, etc.

3. It is assumed that fuel and oxidizer is present in feed lines up to pre-valves only. Not concerned with ruptures of feed ducts, flexible joints, etc., downstream of pre-valves when Centaur is in Orbiter.

4. Some parts of the system are under pressure equal to, or in excess of, 4000 p.s.i. Other parts under considerably less pressure (< 500 psi). Parts subjected to > 4000 psi pressure are assigned a weighting factor of 'probable'; parts subjected to << 4000 psi pressure are assigned a weighting factor of 'possible.'

5. These failure modes (rupture and gross leakage) are considered to result in direct and rapid failure of the tank. They have been assigned a single failure rate. Relatively small leaks are not considered catastrophic, since Centaur propellants can be dumped and abort procedures initiated before tank collapse occurs. Back up means are available for maintaining fuel tank pressures in the event propellants are dumped.

6. Six of the solenoid valves on the LH_2 tank side and two on the LO_2 tank side (in Centaur) are under back pressure from the tanks. Gross leakage is therefore a potentially catastrophic failure mode.

7. While Centaur is in the Orbiter, only two of the check valves in the GH_2 pressurization lines are under back pressure from the LH_2 tank. The rest of the dormant GH_2 tank pressurization lines, valves, and fittings are excluded from the analysis.

8. Leakage failure modes have been excluded. Even if the system is shut down (system leaks sensed from the Orbiter) the centaur helium supply, and related pressure regulation, will take over essential functions.

9. Except for Nos. 55, 65, 66, 69, and 72, leakage failure modes have been excluded. Even if the system is shut down (system leaks sensed from the Orbiter) time is available, even in extreme cases, to dump propellants and initiate abort procedures. There is no requirement for tank insulation system purge during the boost phase.

10. Loss of motor purge is considered to potentially cause explosion and fire of the recirculation pump of the hydraulic system.

11. Leakage or rupture, in certain line sections, could result in direct failure of the fuel tanks.

12. Venting of the LO_2 tank is not necessary during the boost phase, assuming the tank can absorb all energy input when LO_2 is adequately mixed via the electrically driven pump. Therefore, failures downstream of LO_2 tank vent valves are not considered to be Category 1 and have been excluded from the analysis.

13. Ruptures or leakages downstream of the LH_2 vent valves could result in gaseous hydrogen being released to the Orbiter payload bay, with the possibility of fire and explosion.

14. With the pyrotechnic shutoff valves on the fill/drain and dump system normally closed (unless opened to dump fuel in an abort mode) failures downstream of the 1st set of pyro valves (closest to tanks) cannot be classified as Cat 1 and therefore are excluded from the analysis.

15. Inadvertent opening of normally closed fill/drain and dump valves is not of concern since two or more valves would have to be affected before inadvertent dump could occur. This is not a Category 1 failure mode and therefore is excluded from the analysis.

16. Leakage failures are excluded as contributors to potential catastrophic events. Instrumentation on the Orbiter will sense these leaks and cause shut-down of the system. Back-up means are available for providing essential helium supplies (Centaur helium system) or essential functions in the event that CISS helium is not available.

17. If rupture occurs on the GHe (tank pressurization) side then concern is for possible propagated effects. If rupture or leakage occurs on N_2H_4 (hydrazine fuel) side then fire and explosion is considered probable up to opening of the payload bay doors.

18. All lines are assumed to be under approximately 100 psi pressure while Centaur is in the Orbiter.

19. Rupture of any one line in the CISS or Centaur pneumatic valve control system will not prevent operation of fill/dump and vent solenoid actuators, unless the failure propagates.

20. Inadvertent operation of solenoid actuation valves of the valve control system could result in inadvertent operation of LH_2 and/or

LO_2 tank vent valves. Of concern is inadvertent opening of normally closed vent valves, which could lead to excessive venting and tank collapse. Inadvertent closure of normally closed valves is of no concern since redundant paths for venting are available.

21. Failures of Centaur engine support structures have been excluded even though they could result in failure of Centaur fuel lines. It is assumed that fuel lines are empty upstream of tank pre-valves and so any failures in this upstream section would be benign.

22. This failure mode could result in tilting of the spacecraft and failure of its hydrazine or helium bottles which could lead to fire and explosion in the payload bay.

23. This failure mode could result in tilting of Centaur, failure of the LH_2 tank and fire and explosion in the payload bay.

24. This failure mode could result in tilting of Centaur and failure of the LO_2 tank (followed by the LH_2 tank) or failure of Centaur He bottles. The end result could be fire and explosion in the payload bay.

25. Should the Centaur fail to separate from the orbiter, because of failure for example of the Super*Zip, the Centaur would be rotated back down into the payload bay and an abort sequence undertaken. These types of failure modes are therefore excluded from the analysis since they are not Category 1.

    Two or more adjacent deployment adapter springs would need to fail to cause a recontact of Centaur with the deployment adapter. This is not a Category 1 failure mode and so is excluded from the analysis.

26. Rise-off fluid disconnects on lines less than 2 inches in diameter will not pose a potential threat from re-contact of Centaur with the Orbiter at separation. These small lines are not considered strong enough to pose a threat if they become hung up.

APPENDIX B

STS FAILURE MODES
(Liftoff to MECO)

(Contributing To Combined STS/Centaur Behavior Mode
No. 6 As Outlined In Table 3-4)

The failure rates quoted in this Appendix are in units
of hour,$^{-1}$ unless otherwise stated

Table B-1. Criticality 1 Component Failure Modes by Vehicle Response Mode Category (Page 1 of 6)

CATEGORY 6: EXTERNAL TANK PUNCTURED (FROM ORBITER IMPACT, SHRAPNEL, TPS FAILURES, ETC.)

NO.	VEHICLE AND SUB SYSTEM	ITEM	FAILURE MODE	TIME PERIOD	NO. ITEMS	DOC./PAGE	NOTES	FAILURE RATES λ_v	FAILURE RATES λ_f	WEIGHTING FACTOR*
1	MPS (ORB)	12" LO_2 FEEDLINES TO EACH SSME	RUPTURE OR LEAKAGE	L,B,S,P	3	B/966		1.00E-04	1.00E-07	PROB
2	MPS (ORB)	2" LH_2 RECIRCULATION BY-PASS AND RETURN LINES OF SSMEs	RUPTURE OR LEAKAGE	L,B,S,P	3	B/967,970		4.00E-05	4.00E-08	PROB
3	MPS (ORB)	LO_2 BLEED, RECIRCULATION POGO SUPPRESSION LINE ASSEMBLY	RUPTURE OR LEAKAGE	L,B,S,P	1	B/971		5.00E-05	5.00E-08	PROB
4	MAIN PROPULSION SYSTEM (ORB)	LH_2 FEED DISCONNECT PNEUMATIC SHUT-OFF VALVE	FAIL TO REMAIN OPEN CAUSED BY FLAPPER LINKAGE STRUCTURAL FAILURE	L,B,S,P	1	B/959		1.00E-07	1.00E-09	PROB
5	MPS (ORB)	LO_2 FEED DISCONNECT PNEUMATIC SHUT-OFF VALVE	FAIL TO REMAIN OPEN CAUSED BY FLAPPER LINKAGE STRUCTURAL FAILURE	L,B,S,P	1	B/960		1.00E-07	1.00E-09	PROB
6	MAIN PROPULSION SYSTEM (ORB)	HELIUM ACCUMULATOR (TO MPS VALVES)	RUPTURE WITH RESULTING DAMAGE TO SURROUNDING COMPONENTS	L,B,S,P	2	B/941	ITEM CALLED "SURGE CHAMBER" IN 11/15/79 CIL	1.00E-07	1.00E-09	POSS
7	MPS (ORB)	GO_2 CHECK VALVE SSME ISOLATION	FAILS TO REMAIN OPEN (STOPS FLOW TO ET)	L,B,S,P	3	B/983		1.00E-06	1.00E-07	PROB
8	MPS (ORB)	LO_2 RELIEF LINE	RUPTURE OR LEAKAGE	L,B,S,P	1	B/969		5.00E-06	5.00E-08	POSS
9	GIMBAL ASSEMBLY (ORB)	GIMBAL BEARING	GIMBAL STUCK CAUSED BY BEARING SEIZURE	L,B,S,P	3	ME/4-78, 5-10		1.00E-05	1.00E-08	POSS
10	MAIN PROPULSION SYSTEM (ORB)	HELIUM STORAGE TANKS (4,000 PSI)	GROSS RUPTURE	L,B,S,P	5	B/939,945, 946,947		1.00E-07	1.00E-09	POSS
11	HYDRAULICS (ORB)	TVC SERVO ACTUATOR CYLINDER	RUPTURE OR LEAKAGE	L,B,S,P	6	B/339	(b)	5.00E-08	5.00E-10	ACT
12	HYDRAULICS (ORB)	TVC SERVO ACTUATOR POWER VALVE	STUCK POWER VALVE SPOOL	L,B,S,P	6	B/340	(b)	5.00E-07	5.00E-09	ACT
13	HYDRAULICS (ORB)	TVC SERVO ACTUATOR FILTER ELEMENT	CLOGGED FILTER ELEMENT	B,S,P	6	B/341	(b)	5.00E-06	5.00E-09	ACT
14	HYDRAULICS (ORB)	TVC SERVO ACTUATOR FEEDBACK MECHANISM	JAMMED OR SEPARATED MECHANISM OR BROKEN	L,B,S,P	6	B/348	(b)	5.00E-07	5.00E-08	PROB
15	HYDRAULICS (ORB)	RUDDER/SPEED BRAKE SWITCHING VALVE OUTPUT MANIFOLD	RUPTURE OR LEAKAGE	L,B,S,P	1	M-B/1-21	(b)	5.00E-08	5.00E-10	PROB
16	HYDRAULICS (ORB)	RUDDER/SPEED BRAKE 4 CHANNEL SERVO VALVE	RUPTURE OR LEAKAGE	L,B,S,P	2	M-B/1-21	(b)	5.00E-08	5.00E-10	PROB
17	HYDRAULICS (ORB)	ELEVON SERVO ACTUATOR CYLINDER ASSEMBLY	RUPTURE OR LEAKAGE	L,B,S,P	4	M-B/1-21	(b)	5.00E-08	5.00E-10	PROB
18	AUXILIARY POWER (ORBITER)	APU GAS GENERATOR	LEAKAGE FROM DECOMPRESSION CHAMBER SEAL FAILURE OR INJECTION TUBE STRUCTURAL FAILURE	L,B,S,P	3	B/1253-1254	(b)	5.00E-05	5.00E-08	POSS
19	AUXILIARY POWER (ORBITER)	APU TURBINE SHUT-OFF SOLENOID VALVE	FAILS TO SHUT FROM CRACKED SEAT, CONTAMINATION, LOGIC FAIL, ETC.	L,B,S,P	3	B/1272-1273	(b),(c)	5.00E-07	5.00E-08	POSS
20	AUXILIARY POWER (ORBITER)	APU MMH FUEL STORAGE TANKS	GROSS RUPTURE FROM MATERIAL DEFECTS	L,B,S,P	3	B/1259	(b)	5.00E-08	5.00E-10	PROB

Table B-1. Criticality 1 Component Failure Modes by Vehicle Response Mode Category (Page 2 of 6)

CATEGORY 6: EXTERNAL TANK PUNCTURED (FROM ORBITER IMPACT, SHRAPNEL, TPS FAILURES, ETC.)

NO.	VEHICLE AND SUB SYSTEM	ITEM	FAILURE MODE	TIME PERIOD	NO. ITEMS	DOC./PAGE	NOTES	FAILURE RATES λ_v	λ_s	WEIGHTING FACTOR*
21	ACTIVE THERMAL CONTROL (ORB)	WATER SPRAY BOILER WATER TANK	GROSS RUPTURE	L,B,S,P	3	B/717	(b)	5.00E-08	5.00E-10	POSS
22	ACTIVE THERMAL CONTROL (ORB)	WATER SPRAY BOILER N_2 TANK	GROSS RUPTURE	L,B,S,P	3	B/718	(b)	5.00E-08	5.00E-10	POSS
23	ACTIVE THERMAL CONTROL	AMMONIA BOILER AND PIPING	OVERPRESSURE RUPTURE	L,B,S,P	2	B/714	(b)	1.00E-07	1.00E-09	POSS
24	AFT REACTION CONTROL ASSEMBLY (ORB)	MONOMETHYL HYDRAZINE (MMH) FEEDLINE AND FITTINGS	RUPTURE OR LEAKAGE OF LINES, VALVES OR FITTINGS	L,B,S,P	2	B/1038-1039	(d)	1.00E-04	1.00E-07	POSS
25	AFT REACTION CONTROL ASSEMBLY (ORB)	N_2O_4 OXIDIZER FEEDLINE AND FITTINGS	RUPTURE OR LEAKAGE OF LINES, VALVES OR FITTINGS	L,B,S,P	2	B/1040-1041	(d)	1.00E-04	1.00E-07	POSS
26	AFT REACTION CONTROL ASSEMBLY (ORB)	MMH AND N_2O_4 TANK ASSEMBLIES	RUPTURE, LEAKAGE, OR TANK SEAL FAILURE	L,B,S,P	4	B/1042	(d)	2.00E-08 2.00E-05	2.00E-10 2.00E-08	PROB
27	AFT REACTION CONTROL ASSEMBLY (ORB)	MMH AND N_2O_4 TANK FLEXIBLE GIMBLE JOINT	RUPTURE OR LEAKAGE	L,B,S,P	12	B/1046	(d)	2.00E-06	2.00E-09	POSS
28	ORBITAL MANEUVER SYSTEM (ORB)	MMH AND N_2O_4 STORAGE TANKS	RUPTURE, LEAKAGE, OR TANK SEAL FAILURE	L,B,S,P	10	B/1114-1115	(d)	2.00E-08 2.00E-05	2.00E-10 2.00E-08	PROB
29	ORBITAL MANEUVER SYSTEM (ORB)	MMH AND N_2O_4 FILL AND DRAIN COUPLINGS	RUPTURE OR LEAKAGE	L,B,S,P	2	B/1162	(c),(d)	2.00E-06	2.00E-09	PROB
30	ORBITAL MANEUVER SYSTEM (ORB)	MMH AND N_2O_4 FEEDLINES VALVES	RUPTURE OR LEAKAGE	L,B,S,P	4	B/1116-1117	(d)	1.00E-04	1.00E-07	PROB
31	ORBITAL MANEUVER SYSTEM (ORB)	GN_2 TANK SUPPLY TO VALVE (2,500 PSI) ACTUATORS	GROSS RUPTURE	L,B,S,P	2	B/1130-1131	(d)	2.00E-08	2.00E-10	POSS
32	ORBITAL MANEUVER SYSTEM (ORB)	GN_2 ACCUMULATOR	GROSS RUPTURE	L,B,S,P	2	B/1188-1189	(c),(d)	2.00E-08	2.00E-10	POSS
33	ORBITAL MANEUVER SYSTEM (ORB)	MMH AND N_2O_4 FLEXIBLE GIMBLE JOINT	RUPTURE OR LEAKAGE	L,B,S,P	12	B/1132-1133	(d)	2.00E-06	2.00E-09	PROB
34	ORBITAL MANEUVER SYSTEM (ORB)	H_e STORAGE TANKS (4,800 PSI)	GROSS RUPTURE	L,B,S,P	5	B/1110-1111	(d)	2.00E-08	2.00E-10	POSS
35	ORBITAL MANEUVER SYSTEM (ORB)	ENGINE TO VEHICLE FLEXIBLE CONNECTOR	STRUCTURAL FAILURE ALLOWING LEAKAGE	L,B,S,P	4	B/1118-1119	(d)	2.00E-06	2.00E-09	PROB
36	ORBITAL MANEUVER SYSTEM (ORB)	GIMBLE RING FORGING (ENGINE ATTACHMENT)	STRUCTURAL FAILURE CAUSING FAILURE OF FLEXIBLE CONNECTOR	L,B,S,P	2	B/1134-1135	(c),(d)	2.00E-08	2.00E-10	PROB
37	ORBITAL MANEUVER SYSTEM (ORB)	PROPELLANT PBK AND POD CROSSFEED COUPLING	EXTERNAL LEAKAGE FROM STRUCTURAL FAILURE	L,B,S,P	6	B/1201-1202	(c),(d)	2.00E-06	2.00E-09	POSS
38	AFT REACTION CONTROL (ORB) ASSEMBLY	H_e STORAGE TANKS (4,000 PSI)	GROSS RUPTURE WITH PROPOGATED FRAGMENTS RUPTURING PROPELLANT TANKS	L,B,S,P	4	B/1032-1033	(d)	2.00E-08	2.00E-10	POSS
39	AFT REACTION CONTROL (ORB) ASSEMBLY	ENGINE BELLOWS ASSEMBLY	EXTERNAL LEAKAGE FROM STRUCTURAL FAILURE	L,B,S,P	56	B/1070-1071	(c),(d)	2.00E-06	2.00E-09	PROB
40	SEPARATION MECHANISM (ORB/ET)	DETONATOR OF AFT ATTACHMENT FRANGIBLE NUT	INADVERTENT DETONATION SIGNAL	L,B,S,P	4	B/96		3.00E-06	3.00E-07	ACT

Table B-1. Criticality 1 Component Failure Modes by Vehicle Response Mode Category (Page 3 of 6)

CATEGORY 6: EXTERNAL TANK PUNCTURED (FROM ORBITER IMPACT, SHRAPNEL, TPS FAILURES, ETC.)

NO.	VEHICLE AND SUB SYSTEM	ITEM	FAILURE MODE	TIME PERIOD	NO. ITEMS	DOC./PAGE	NOTES	FAILURE RATES λ_v	FAILURE RATES λ_t	WEIGHTING FACTOR*
41	SEPARATION MECHANISM (ORB/ET)	AFT FRANGIBLE NUT	PREMATURE FRACTURE THROUGH STRUCTURAL FAILURE	L,B,S,P	2	B/98-99		3.00E-08	3.00E-11	ACT
42	SEPARATION MECHANISM (ORB/ET)	AFT BOLT	STRUCTURAL FAILURE	L,B,S,P	2	B/101		3.00E-08	3.00E-11	ACT
43	SEPARATION MECHANISM (ORB/ET)	AFT FRANGIBLE NUT CARTRIDGE BOOSTER	INADVERTENT OPERATION	L,B,S,P	4	B/102		3.00E-06	3.00E-07	ACT
44	SEPARATION MECHANISM (ORB/ET)	PRESSURE CARTRIDGE OF FORWARD SEPARATION BOLT	INADVERTENT OPERATION	L,B,S,P	2	B/103		3.00E-06	3.00E-07	ACT
45	SEPARATION MECHANISM (ORB/ET)	FORWARD BOLT	STRUCTURAL FAILURE	L,B,S,P	1	B/104		3.00E-08	3.00E-11	ACT
46	ORB/ET FORWARD ATTACHMENT	SUPPORT STRUCTURE	STRUCTURAL FAILURE	L,B,S,P	1	E-B/6-9		3.00E-08	3.00E-11	ACT
47	ORB/ET AFT ATTACHMENT	SUPPORT STRUCTURE	STRUCTURAL FAILURE	L,B,S,P	2	E-B/6-10		3.00E-08	3.00E-11	ACT
48	ORB/ET FORWARD ATTACHMENT	SPINDLES	SEIZED (ROTATION SEIZURE)	L,B,S,P	2	E/P-C-55		1.00E-05	1.00E-08	POSS
49	ORB/ET FORWARD ATTACHMENT	ET BIPOD FITTINGS	SEIZED (ROTATION SEIZURE)	L,B,S,P	2	E/P-C-56		1.00E-05	1.00E-08	POSS
50	ORB/ET AFT ATTACHMENT	PIVOTAL SUPPORTS	SEIZURE	L,B,S,P	12	E/P-C-9		1.00E-05	1.00E-08	POSS
51	ORB/ET AFT ATTACHMENT	SLIDING SUPPORTS	SEIZURE	L,B,S,P	2	E/P-C-58		1.00E-05	1.00E-08	POSS
52	EXTERNAL TANK	LH_2 TANK BARREL TPS	SEPARATION FROM ET OR STRUCTURAL FAILURE DUE TO UNCLEAN SURFACE OR INADEQUATE QUALITY	100-124 SEC.	1	NOT IN 'CIL' DOC'S		3.00E-06	3.00E-07	POSS
53	EXTERNAL TANK	LH_2 TANK AFT DOME TPS	SEPARATION FROM ET OR STRUCTURAL FAILURE DUE TO UNCLEAN SURFACE OR INADEQUATE QUALITY	LIFTOFF	1	NOT IN 'CIL' DOC'S		3.00E-06	3.00E-07	POSS
54	EXTERNAL TANK	LO_2 TANK OGIVE TPS	SEPARATION FROM ET OR STRUCTURAL FAILURE DUE TO UNCLEAN SURFACE OR INADEQUATE QUALITY	100-124 SEC.	1	NOT IN 'CIL' DOC'S		3.00E-06	3.00E-07	PROB
55	SRB	THERMAL CURTAIN HEAT SHIELD TPS	SEPARATION FROM SRB OR STRUCTURAL FAILURE DUE TO UNCLEAN SURFACE OR INADEQUATE QUALITY	100-124 SEC.	2	NOT IN 'CIL' DOC'S		3.00E-06	3.00E-07	POSS
56	ELECTRICAL POWER (ORB)	O_2 TANK SUBASSEMBLY NUMBERS 1, 2 AND 3	OVERPRESSURE RUPTURE; EXCESS HEAT INPUT FROM HEATERS OR MATERIAL DEFECT	L,B	3	B/467,468,471	(a) SEE 5-37	1.00E-08	1.00E-10	PROB
57	ELECTRICAL POWER (ORB)	H_2 TANK SUBASSEMBLY NUMBERS 1, 2 AND 3	OVERPRESSURE RUPTURE; EXCESS HEAT INPUT FROM HEATERS OR MATERIAL DEFECT	L,B	3	B/469,470,472	(a) SEE 5-38	1.00E-08	1.00E-10	PROB
58	ATMOSPHERIC REVITALIZATION	AUXILIARY O_2 STORAGE TANK (900 PSI)	OVERPRESSURE RUPTURE	L,B	1	B/558	(a) SEE 5-39	5.00E-09	5.00E-11	PROB
59	ATMOSPHERIC REVITALIZATION	N_2 STORAGE TANKS (3,000 PSI)	OVERPRESSURE RUPTURE	L,B	4	B/568	(a) SEE 5-40	5.00E-09	5.00E-11	POSS

Table B-1. Criticality 1 Component Failure Modes by Vehicle Response Mode Category (Page 4 of 6)

CATEGORY 6: EXTERNAL TANK PUNCTURED (FROM ORBITER IMPACT, SHRAPNEL, TPS FAILURES, ETC.)

NO.	VEHICLE AND SUB SYSTEM	ITEM	FAILURE MODE	TIME PERIOD	NO. ITEMS	DOC./PAGE	NOTES	FAILURE RATES λ_u	FAILURE RATES λ_t	WEIGHTING FACTOR*
60	ELECTRICAL POWER (ORB)	O_2 TANK SUBASSEMBLY NUMBERS 1, 2 AND 3	OVERPRESSURE RUPTURE; EXCESS HEAT INPUT FROM HEATERS OR MATERIAL DEFECT	P	3	B/467,468, 471	SAME AS #56	2.00E-08	2.00E-10	PROB
61	ELECTRICAL POWER (ORB)	H_2 TANK SUBASSEMBLY NUMBERS 1, 2 AND 3	OVERPRESSURE RUPTURE; EXCESS HEAT INPUT FROM HEATERS OR MATERIAL DEFECT	P	3	B/469,470, 472	SAME AS #57	2.00E-08	2.00E-10	PROB
62	ATMOSPHERIC REVITALIZATION	AUXILIARY O_2 STORAGE TANK (900 PSI)	OVERPRESSURE RUPTURE	P	1	B/558	SAME AS #58	1.00E-08	1.00E-10	PROB
63	ATMOSPHERIC REVITALIZATION	N_2 STORAGE TANKS (3,000 PSI)	OVERPRESSURE RUPTURE	P	4	B/568	SAME AS #59	1.00E-08	1.00E-10	POSS
64	FORWARD REACTION CONTROL ASSEMBLY (ORB)	MMH AND N_2O_4 LINE FLEXIBLE ASSEMBLIES	RUPTURE OR LEAKAGE	L,B,S	2	B/1085	(a) SEE 5-31	5.00E-07	5.00E-10	POSS
65	FORWARD REACTION CONTROL ASSEMBLY (ORB)	MMH AND N_2O_4 TANK ASSEMBLIES	RUPTURE, LEAKAGE OR TANK SEAL FAILURE	L,B,S	2	B/1086	(a) SEE 5-32	5.00E-09 5.00E-06	5.00E-11 5.00E-09	PROB
66	FORWARD REACTION CONTROL ASSEMBLY (ORB)	MMH FUEL FEEDLINE AND FITTINGS	RUPTURE OR LEAKAGE OF LINES, VALVES, OR FITTINGS	L,B,S	1	B/1096-1097	(a) SEE 5-33	3.00E-06	3.00E-08	POSS
67	FORWARD REACTION CONTROL ASSEMBLY (ORB)	N_2O_4 OXIDIZER FEEDLINE AND FITTINGS	RUPTURE OR LEAKAGE OF LINES, VALVES, OR FITTINGS	L,B,S	1	B/1096-1097	(a) SEE 5-34	3.00E-06	3.00E-08	POSS
68	FORWARD REACTION CONTROL ASSEMBLY (ORB)	H_e STORAGE TANKS (4,000 PSI)	GROSS RUPTURE WITH PROPAGATED FRAGMENTS RUPTURING PROPELLANT TANK(S)	L,B,S	2	B/1089-1090	(a) SEE 5-35	5.00E-09	5.00E-11	POSS
69	FORWARD REACTION CONTROL ASSEMBLY (ORB)	FLEXIBLE COUPLINGS AND FITTINGS	RUPTURE AT PRIMARY OR VERNIER THRUSTER	L,B,S	32	B/1084	(a) SEE 5-36	1.00E-06	1.00E-09	POSS
70	FORWARD REACTION CONTROL ASSEMBLY (ORB)	MMH AND N_2O_4 LINE FLEXIBLE ASSEMBLIES	RUPTURE OR LEAKAGE	P	2	B/1085	SAME AS #64	1.00E-06	1.00E-09	POSS
71	FORWARD REACTION CONTROL ASSEMBLY (ORB)	MMH AND N_2O_4 TANK ASSEMBLIES	RUPTURE, LEAKAGE OR TANK SEAL FAILURE	P	2	B/1086	SAME AS #65	1.00E-08 1.00E-05	1.00E-10 1.00E-08	PROB
72	FORWARD REACTION CONTROL ASSEMBLY (ORB)	MMH FUEL FEEDLINE AND FITTINGS	RUPTURE OR LEAKAGE OF LINES, VALVES, OR FITTINGS	P	1	B/1096-1097	SAME AS #66	5.00E-05	5.00E-08	POSS
73	FORWARD REACTION CONTROL ASSEMBLY (ORB)	N_2O_4 OXIDIZER FEEDLINE AND FITTINGS	RUPTURE OR LEAKAGE OF LINES, VALVES, OR FITTINGS	P	1	B/1096-1097	SAME AS #67	5.00E-05	5.00E-08	POSS
74	FORWARD REACTION CONTROL ASSEMBLY (ORB)	H_e STORAGE TANKS (4,000 PSI)	GROSS RUPTURE WITH PROPAGATED FRAGMENTS RUPTURING PROPELLANT TANK(S)	P	2	B/1089-1090	SAME AS #68	1.00E-08	1.00E-10	POSS
75	FORWARD REACTION CONTROL ASSEMBLY (ORB)	FLEXIBLE COUPLINGS AND FITTINGS	RUPTURE AT PRIMARY OR VERNIER THRUSTER	P	32	B/1084	SAME AS #69	2.00E-06	2.00E-09	POSS
76	MPS (ORB)	LH_2 RECIRCULATION PUMP	HOUSING RUPTURE	L,B,S	3	B/958	SEE 9-14	1.00E-07	1.00E-09	POSS
77	MPS (ORB)	12" LH_2 FEEDLINES TO EACH SSME	RUPTURE OR LEAKAGE	L,B,S	3	B/963	SEE 9-15	1.00E-04	1.00E-07	PROB

Table B-1. Criticality 1 Component Failure Modes by Vehicle Response Mode Category (Page 5 of 6)

CATEGORY 6: EXTERNAL TANK PUNCTURED (FROM ORBITER IMPACT, SHRAPNEL, TPS FAILURES, ETC.)

NO.	VEHICLE AND SUB SYSTEM	ITEM	FAILURE MODE	TIME PERIOD	NO. ITEMS	DOC./PAGE	NOTES	FAILURE RATES λ_v	FAILURE RATES λ_L	WEIGHTING FACTOR*
78	MAIN PROPULSION SYSTEM (ORB)	2" GH_2 PRESSURIZATION DISCONNECT VALVE	VALVE FAILS CLOSED CAUSING LH_2 TANK STRUCTURAL FAILURE	L,B,S,P	1	E-B/4-7		1.00E-07	1.00E-09	POSS
79	SSME (ORB)	BURST DIAPHRAGMS	RUPTURE OF H_2 LINES DIAPHRAGMS	L,B,S	30	MSC/3-52	SEE 9-16	1.00E-05	1.00E-08	ACT
80	MPS (ORB)	LH_2 RELIEF LINE	RUPTURE OR LEAKAGE	L,B,S	1	B/968	SEE 9-17	5.00E-06	5.00E-08	PROB
81	MAIN PROPULSION SYSTEM (ORB/ET)	4" DIAMETER LH_2 RECIRCULATION LINE	RUPTURE	L,B,S	1	B/952	SEE 9-18	2.00E-04	2.00E-07	PROB
82	MAIN PROPULSION SYSTEM (ORB/ET)	17" LH_2 FEEDLINE AND MANIFOLD ASSEMBLY	RUPTURE OR LEAKAGE	L,B,S	1	B/961-962	SEE 9-19 & 20; (1)	5.00E-05	5.00E-08	ACT
83	LO_2 FEEDLINE (ET)	17" RACO-CREAVY SEALS	EXCESS LEAKAGE	L,B,S,P	8	E/P-C-4	(e)	1.00E-04	1.00E-07	POSS
84	LO_2 FEEDLINE (ET)	17" FLEXIBLE COUPLING (RIGID LINE AND BELLOWS)	EXCESS LEAKAGE FROM STRUCTURAL FAILURE OF FUSION WELDS LINE TO BELLOWS	L,B,S,P	5	E/P-C-3	(e)	1.00E-05 1.00E-07 (COUPLING AND WELD)	1.00E-08 1.00E-10	POSS
85	LO_2 FEEDLINE (ET)	17" FLEXIBLE COUPLING (RIGID LINE AND BELLOWS)	SEIZURE (BALL AND SOCKET) CAUSING LO_2 FEEDLINE STRUCTURAL FAILURE	L,B,S,P	5	E/P-C-8	(e)	1.00E-05 1.00E-07 (COUPLING AND WELD)	1.00E-08 1.00E-10	PROB
86	LO_2 FEEDLINE (ET)	PIVOTAL SUPPORTS	SEIZURE (BALL AND SOCKET) CAUSING LO_2 FEEDLINE STRUCTURAL FAILURE	L,B,S,P	27	E/P-C-9	(e)	1.00E-05	1.00E-08	POSS
87	LO_2 ANTIGEYSER LINE (ET)	4" FLEXIBLE COUPLING (RIGID LINE AND BELLOWS)	EXCESS LEAKAGE FROM STRUCTURAL FAILURE OF FUSION WELDS LINE TO BELLOWS	L,B,S,P	6	E/P-C-12	(e)	1.00E-05 1.00E-07 (COUPLING AND WELD)	1.00E-08 1.00E-10	PROB
88	LO_2 ANTIGEYSER LINE (ET)	4" RACO-CREAVEY SEAL	EXCESS LEAKAGE	L,B,S,P	8	E/P-C-4	(e)	1.00E-04	1.00E-07	POSS
89	LO_2 ANTIGEYSER LINE (ET)	4" FLEXIBLE COUPLING (RIGID LINE AND BELLOWS)	SEIZURE (BALL AND SOCKET) CAUSING LO_2 ANTIGEYSER LINE STRUCTURAL FAILURE	L,B,S,P	6	E/P-C-14	(e)	1.00E-05	1.00E-08	POSS
90	LO_2 ANTIGEYSER LINE (ET)	TEFLON COVERED SLIDING SUPPORTS	SEIZURE CAUSING LO_2 ANTIGEYSER LINE STRUCTURAL FAILURE	L,B,S,P	14	E/P-C-15	(e)	1.00E-05 1.00E-07 (COUPLING AND WELD)	1.00E-08 1.00E-10	PROB
91	LO_2 H_e INJECT SYSTEM	CHECK VALVES	EXCESS LEAKAGE OR RUPTURE (EXTERNAL)	L,B,S,P	2	E/P-C-4, P-C-25	(e)	1.00E-07	1.00E-09	POSS
92	LO_2 H_e INJECT SYSTEM	HARRISON-K SEALS	EXCESS LEAKAGE	L,B,S,P	2	E/P-C-26	(e)	1.00E-04	1.00E-07	POSS
93	LH_2 PRESSURIZATION LINE (ET)	2" FLEXIBLE COUPLING (RIGID LINE AND BELLOWS)	EXCESS LEAKAGE FROM WELD OR STRUCTURAL FAILURE	L,B,S,P	6	E/P-C-19		1.00E-05 1.00E-07 (COUPLING AND WELD)	1.00E-08 1.00E-10	POSS
94	LH_2 PRESSURIZATION LINE (ET)	NAFLEX SEALS	EXCESS LEAKAGE	L,B,S,P	6	E/P-C-20		1.00E-04	1.00E-07	POSS
95	LH_2 PRESSURIZATION LINE (ET)	PIVOTAL SUPPORTS	SEIZURE (BALL AND SOCKET) CAUSING LH_2 PRESSURIZATION LINE STRUCTURAL FAILURE	L,B,S,P	8	E/P-C-9		1.00E-05	1.00E-08	POSS
96	LH_2 PRESSURIZATION LINE (ET)	TEFLON COVERED SLIDING SUPPORTS	SEIZURE CAUSING LH_2 PRESSURIZATION LINE STRUCTURAL FAILURE	L,B,S,P	15	E/P-C-15		1.00E-05	1.00E-08	PROB
97	LH_2 VENT-RELIEF ASSEMBLY (ET)	CALMEC V/R VALVE GASKETS (5) AND SEALS (2)	EXCESS LEAKAGE	L,B,S,P	7	E/P-C-4, P-C-25		1.00E-04	1.00E-07	POSS

Table B-1. Criticality 1 Component Failure Modes by Vehicle Response Mode Category (Page 6 of 6)

CATEGORY 6: EXTERNAL TANK PUNCTURED (FROM ORBITER IMPACT, SHRAPNEL, TPS FAILURES, ETC.)

NO.	VEHICLE AND SUB SYSTEM	ITEM	FAILURE MODE	TIME PERIOD	NO. ITEMS	DOC./PAGE	NOTES	FAILURE RATES λ_u	FAILURE RATES λ_f	WEIGHTING FACTOR*
98	LH_2 VENT-RELIEF ASSEMBLY (ET)	PIVOTAL SUPPORTS	SEIZURE (BALL AND SOCKET) CAUSING V/R ASSEMBLY LINE STRUCTURAL FAILURE	L,B,S,P	4	E/P-C-9		1.00E-05	1.00E-08	PROB
99	LH_2 TANK (ET)	FORWARD DOME FEED THROUGH COVER SEALS	EXCESS LEAKAGE RESULTING IN LOSS OF ULLAGE AND LH_2 TANK FAILURE	L,B,S,P	5	E/P-C-4, P-C-26		1.00E-04	1.00E-07	ACT
100	LH_2 TANK (ET)	FORWARD DOME ACCESS COVER NAFLEX SEAL	EXCESS LEAKAGE RESULTING IN LOSS OF ULLAGE AND LH_2 TANK FAILURE	L,B,S,P	1	E/P-C-20		1.00E-04	1.00E-07	ACT
101	LH_2 TANK (ET)	AFT DOME SCREEN ACCESS COVER NAFLEX SEAL	EXCESS LEAKAGE RESULTING IN LH_2 TANK FAILURE	L,B,S,P	1	E/P-C-20		1.00E-04	1.00E-07	ACT
102	LH_2 TANK (ET)	AFT DOME ACCESS COVER NAFLEX SEAL	EXCESS LEAKAGE RESULTING IN LH_2 TANK FAILURE	L,B,S,P	1	E/P-C-20		1.00E-04	1.00E-07	ACT
103	LH_2 TANK (ET)	AFT LONGERON COVER RACO SEAL	EXCESS LEAKAGE RESULTING IN LH_2 TANK FAILURE	L,B,S,P	1	E/P-C-4		1.00E-04	1.00E-08	ACT
104	LH_2 VENT-RELIEF ASSEMBLY	VENT VALVE	INADVERTENT OPENING	L,B,S,P	1	M-Ø/1-17		3.00E-05	3.00E-06	PROB
105	LH_2 TANK (ET)	WELDS (ASSUME 50 DEFFERENT WELD RUNS)	WELD RUPTURE	L,B,S,P	1	M-Ø/4-6		6.00E-06	6.00E-09	ACT
106	MPS (ORB)	0.63" GH_2 PRESSURIZATION LINE (TO MODULE)	RUPTURE OR LEAKAGE	L,B,S,P	3	Ø/978		1.50E-04	1.50E-07	POSS
107	MPS (ORB)	2" GH_2 PRESSURIZATION LINE ASSEMBLY + 1" SECTION TO CHECK VALVE	RUPTURE OR LEAKAGE CAUSING LOSS OF ULLAGE PRESSURE	L,B,S,P	1	Ø/980		2.50E-04	2.50E-07	POSS
108	MPS (ORB/ET)	17" LO_2 FEEDLINE AND MANIFOLD ASSEMBLY	RUPTURE OR LEAKAGE	L,B,S,P	1	Ø/964-965	(e)	7.00E-05	7.00E-08	ACT
109	RANGE SAFETY COMMAND DESTRUCT (ET)	NSI DETONATOR	INADVERTENT DETONATION FROM LIGHTNING, STRAY EMI OR RFI, ELECTROSTATIC DISCHARGE, OR AUTOIGNITION	L,B,S,P	2	E/A-2		3.00E-06	3.00E-07	ACT
110	RANGE SAFETY COMMAND DESTRUCT (ET)	SAFE AND ARM ASSEMBLY	INADVERTENT DETONATION OF PETN INSERTS DUE TO AUTOIGNITION	L,B,S,P	1	E/A-3		3.00E-06	3.00E-07	ACT
111	RANGE SAFETY COMMAND DESTRUCT (ET)	CDF ASSEMBLY	INADVERTENT DETONATION OF EXPLOSIVE INSERTS FROM AUTOIGNITION	L,B,S,P	7	E/A-3		3.00E-06	3.00E-07	ACT
112	RANGE SAFETY COMMAND DESTRUCT (ET)	CDF MANIFOLD	INADVERTENT DETONATION OF EXPLOSIVE INSERTS FROM AUTOIGNITION	L,B,S,P	2	E/A-4		3.00E-06	3.00E-07	ACT
113	RANGE SAFETY COMMENT DESTRUCT (ET)	LINEAR SHAPED CHARGE	INADVERTENT DETONATION CAUSED BY AUTOIGNITION	L,B,S,P	2	E/A-4		3.00E-06	3.00E-07	ACT

APPENDIX C

STS FAILURE MODES
(MECO To Centaur Deployment)

(Contributing To Combined STS/Centaur Behavior Modes
Nos. 6, 10, 12 and 13 As Outlined In Tables 3-1 and 3-3)

The failure rates quoted in this Appendix are in units
of hour,$^{-1}$ unless otherwise stated

Table C-1.

VEHICLE BEHAVIOR: Category (6) of Table 3-4

External Tank Punctured

CRITICAL TIME PERIOD: MECO to External Tank Separation Complete (MECO to MECO + 16 seconds)

NO.	VEHICLE AND SUB-SYSTEM	ITEM	NO. ITEMS.	FAILURE MODE	λ_p/HR; λ_u/HR	ASSUMPTIONS
1.	Main Propulsion System	12" LO_2 Feed-lines to each SSME	3	Rupture or Leakage	1.00E-07 1.00E-04	Feedline failures on External Tank are not considered to be a problem for the period between MECO to External Tank separation. Failures 4 and 5 could cause overpressurization of aft main engine compartment, structural damage and rupture of feedlines etc. Failures 6 & 7 could also cause rupture of main engine components. Failures 1 through 7 assumes an ignition source is present within the ME compartment up to ET separation is complete (5100 lbs. of propellant vented at start of OMS 1 until after OMS 1 complete).
2.		LO_2 Bleed, Recirculation Pogo Suppression Line Assembly	1	" "	5.00E-08 5.00E-05	
3.		17" LO_2 Feed-line and Manifold Assembly	1	" "	7.00E-08 7.00E-05	
4.		1" LO_2 Relief Line	1	" "	5.00E-08 5.00E-05	
5		1" LH_2 Relief Line	1	" "	5.00E-08 5.00E-05	
6.		Helium Accumulator to MPS Valves	2	Gross Rupture	1.00E-09 1.00E-07	
7.		Helium Storage Tanks (4000 psi)	5	" "	1.00E-09 1.00E-07	

Weighting Factors: Nos. 1, 2 & 5 - PROB
No. 3 - ACT
Nos. 4, 6, 7 - POSS

Table C-1. (continued)

VEHICLE BEHAVIOR: Category (6) of Table 3-4

External Tank Punctured

CRITICAL TIME PERIOD: MECO to External Tank Separation Complete (MECO to MECO + 16 seconds)

NO.	VEHICLE AND SUB-SYSTEM	ITEM	NO. ITEMS.	FAILURE MODE	λ_{ℓ}/HR;λ_{u}/HR	ASSUMPTIONS
8.	Separation Mechanism	Aft Frangible Nut	2	Premature Fracture Caused by Structural Failure	3.00E-11 3.00E-08	
9.		Aft Frangible Nut Detonator	2	Inadvertant Detonation Signal	3.00E-07 3.00E-06	Failures 9 through 13 cause collision of Orbiter with External Tank through premature release of attachments
10.		Aft Bolt	2	Structural Failure	3.00E-11 3.00E-08	
11.		Aft Frangible Nut Cartridge Booster	4	Inadvertant Operation	3.00E-07 3.00E-06	
12.		Forward Bolt	1	Structural Failure	3.00E-11 3.00E-08	
13.		Pressure Cartridge of Forward Bolt	1	Inadvertant Operation	3.00E-07 3.00E-06	Failures 14, 15, 16, and 17 occur at the instant the command for fracture is required i.e. at start of RCS 1st burn. The associated probabilities are failures on demand.
14.		Umbilical Plate Frangible Nuts	6	Fail to Fracture	3.00E-07 3.00E-06	
15.		Aft Frangible Nut	2	" "	3.00E-07 3.00E-06	

Weighting Factors: Nos. 8 through 15 - ACT

Table C-1. (continued)

VEHICLE BEHAVIOR: Category (6) of Table 3-4

External Tank Punctured

CRITICAL TIME PERIOD: MECO to External Tank Separation Complete (MECO to MECO + 16 seconds)

NO.	VEHICLE AND SUB-SYSTEM	ITEM	NO. ITEMS.	FAILURE MODE	λ_c/HR; λ_u/HR	ASSUMPTIONS
16.	Separation Mechanism	Forward Bolt	1	Fail to Fracture	3.00E-07 3.00E-06	
17.	Forward Attachment	Support Structure	1	Structural Failure	3.00E-11 3.00E-08	Failures 17, 18 & 19 cause collision of Orbiter with External Tank through premature release of attachments
18.		Spindles	2	Rotation Seizure	1.00E-08 1.00E-05	
19.		ET Bipod Fittings	2	" "	1.00E-08 1.00E-05	
20.	Aft Attachment	Support Structure	2	Structural Failure	3.00E-11 3.00E-08	Failures 20, 21 & 22 cause collision of Orbiter with External Tank through premature release of attachments
21.		Pivotal Supports	12	Seizure	1.00E-08 1.00E-05	
22.		Sliding Supports	2	Seizure	1.00E-08 1.00E-05	
23.	Range Safety Command Destruct	Linear Shaped Charge	2	Inadvertant Detonation	3.00E-07 3.00E-06	

Weighting Factors: Nos. 16 through 23 - ACT

Table C-1. (continued)

VEHICLE BEHAVIOR: Category (6) of Table 3-4
External Tank Punctured

CRITICAL TIME PERIOD: MECO to External Tank Separation Complete (MECO to MECO + 16 seconds)

NO.	VEHICLE AND SUB-SYSTEM	ITEM	NO. ITEMS	FAILURE MODE	λ_ℓ/HR; λ_u/HR	ASSUMPTIONS
24.	Range Safety Command Destruct	NSI Detonator	2	Inadvertant Detonation	3.00E-07 3.00E-06	
25.		Safe & Arm Assembly	1	Inadvertant Detonation of PETN Inserts	3.00E-07 3.00E-06	
26.		CDF Assembly	7	Inadvertant Detonation of Explosive Inserts	3.00E-07 3.00E-06	
27.		CDF Manifold	2	" "	3.00E-07 3.00E-06	

Weighting Factors: Nos. 24 through 27 - ACT

Table C-2.

VEHICLE BEHAVIOR: Category (6) of Table 3-4

External Tank Punctured

CRITICAL TIME PERIOD: During Orbiter External Tank Separation Maneuver (MECO + 11 seconds to end of RCS separation burn)

NO.	VEHICLE AND SUB-SYSTEM	ITEM	NO. ITEMS.	FAILURE MODE	λ_ℓ/HR;λ_u/HR	ASSUMPTIONS
1.	Forward Reaction Control Assembly	MMH and N_2O_4 Line Flexible Assemblies	2	Rupture or Leakage	1.00E-08 1.00E-05	Failures 1 through 8 could conce..ably propagate through fire and explosion and lead to loss of all 3 IMUs and hence loss of avionics. However, during this critical time period, the failure of RCS is considered to be the dominant one.*
2.		MMH and N_2O_4 Tank Assemblies	2	Rupture, Leakage or Tank Seal Failure	1.00E-09 | Tank 1.00E-07 | 1.00E-07 | Seal 1.00E-04 |	
3.		MMH Fuel Feedline and Fittings	1 assy	Rupture or Leakage of Lines, Valves or Fittings	5.00E-07 5.00E-04	
4.		N_2O_4 Oxidizer Feedline and Fittings	1 assy	" "	5.00E-07 5.00E-04	Failures 9 and 11 through 13 are not considered likely to propagate, but to cause forward pod damage and loss of RCS.
5.		Flexible Coupling and Fittings (Engine Bellows Assembly)	32	Rupture at Primary or Vernier Thruster	2.00E-08 2.00E-05	Failure 9, 10, 13 and 14 are considered to occur when RCS is required for external tank separation maneuver with no time to cross feed.
6.		He Storage Tanks (4000 psi)	2	Gross Rupture With Propagated Fragments Puncturing Propellant Tanks	1.00E-09 1.00E-07	
7.		Propellant Tank Drain, Vent & Bleed Quick Disconnect	6	Fail Open of Spring Loaded Poppet Valve or Excess Leakage from Seals or Cap	3.00E-06 | Valve 3.00E-05 | 1.00E-07 | Seal 1.00E-04 |	
8.		Propellant Tank Purge Quick Disconnect	14	" "	3.00E-06 | Valve 3.00E-05 | 1.00E-07 | Seal 1.00E-04 |	

*The failure rates quoted include the possibility of propagation, but the dominant effect during this time period is considered to be the result of RCS loss with or without propagation i.e. Orbiter Impacts External Tank. It is assumed that loss of one RCS unit, without propagation and prior to this critical time period, need not be catastrophic.

Weighting Factors: Nos. 1 & 3 through 8 - POSS

No. 2 - PROB

Table C-2. (continued)

VEHICLE BEHAVIOR Category (6) of Table 3-4

External Tank Punctured

CRITICAL TIME PERIOD: During Orbiter External Tank Separation Maneuver (MECO + 11 seconds to end of RCS separation burn)

NO.	VEHICLE AND SUB-SYSTEM	ITEM	NO. ITEMS.	FAILURE MODE	λ_r/HR; λ_u/HR	ASSUMPTIONS
9.	Forward Reaction Control Assembly	He Feedlines Valve & Regulators to Propellant Tanks	2 assys	Rupture or Excess Leakage	3.00E-06 3.00E-05	Failures 11 and 12 are likely to occur during the firing of the RCS i.e. the exposure time for failure is relative short.
10.		MMH & N_2O_4 Tank Acquisition Device (Pad)	2	Structural Failure causing tank blockage	3.00E-11 3.00E-08	
11.		Thrust Chamber Primary Thruster	28	Structural Failure Burn Through or Rupture	2.00E-09 2.00E-07	
12.		Primary Thruster Nozzle Extension	28	" "	2.00E-09 2.00E-07	
13.		He Pressurization Tank Quick Fill Disconnect	2	Fail Open of Spring Loaded Poppet Valve or Excess Leakage From Seals or Cap	3.00E-06 Valve 3.00E-05 Valve 1.00E-07 Seal 1.00E-04 Seal	
14.		Propellant Tank Compartment Screens	2	Structural Failure Causing Tank Blockage	1.00E-09 1.00E-07	
15.	Aft Reaction Control Assembly	MMH and N_2O_4 Tank Flexible Gimble Joint	12	Rupture or Leakage	1.00E-08 1.00E-05	Failures 15 through 20, could conceivably propagate through fire and explosion and lead to loss of all OMS in one aft pod.* However, during
16.		MMH and N_2O_4 Tank Assemblies	4	Rupture, Leakage or Tank Seal Failure	1.00E-09 Tank 1.00E-07 Tank 1.00E-07 Seal 1.00E-04 Seal	

*The failure rates quoted include the possiblity of propagation, but the dominant effect during this time period is considered to be the result of RCS loss with or without propagation i.e. Orbiter Impacts External Tank. It is assumed that loss of one RCS unit, without propagation and prior to this critical time period, need not be catastrophic.

Weighting Factors: Nos. 9 through 14 - POSS
Nos. 15 & 16 - PROB

Table C-2. (continued)

VEHICLE BEHAVIOR: Category (6) of Table 3-4
External Tank Punctured

CRITICAL TIME PERIOD: During Orbiter External Tank Separation Maneuver (MECO + 11 seconds to end of RCS separation burn)

NO.	VEHICLE AND SUB-SYSTEM	ITEM	NO. ITEMS	FAILURE MODE	λ_1/HR; λ_u/HP	ASSUMPTIONS
17	Aft Reaction Control Assembly	MMH Fuel Feedline and Fittings	2 assys	Rupture or Leakage of Lines, Valves or Fittings	5.00E-07 5.00E-04	this critical time period, the failure of RCS is considered to be the dominant one. These failures could further propagate to the ME compartment causing fire and explosion with residual propellants*. The ultimate affect of this failure coupled with impact between the orbiter and ET is considered to be the same as simply Orbiter/ET impact.
18.		N_2O_4 Oxidizer Feedline and Fittings	2 assys	" "	5.00E-07 5.00E-04	
19.		He Storage Tanks (4000 [illegible])	4	Gross Rupture	1.00E-09 1.00E-07	
20.		Propellant Tank Vent and Bleed Quick Disconnect	12	Fail Open of Spring Loaded Poppet Valve or Excess Leakage from Seals or Cap	3.00E-06 VALVE 3.00E-05 VALVE 1.00E-07 SEAL 1.00E-04 SEAL	
21.		He Feedlines Valve & Regulators to Prop. Tanks	4 assys	Rupture or Excess Leakage	3.00E-06 3.00E-05	Failures 21, 23 through 25 could propagate and cause aft pod damage and loss of aft OMS engine.** This possibility is less likely than for failures 15 through 20 where a fire and explosion could be caused as a direct result of failure. However, during this critical time period, failure of RCS is considered to be the dominant one.
22.		MMH & N_2O_4 Tank Acquisition Device (Pad)	4	Structural Failure Causing Tank Blockage	3.00E-11 3.00E-08	
23.		Thrust Chamber Primary Thruster	24	Structural Failure Burn Through or Rupture	2.00E-09 2.00E-07	
		Rupture of any engine bellows assembly was originally included here but a recent design change will allow isolation of such failures. Because these failures were no longer designated category 1, they were removed from the analysis				

*Approximately 5400 lbs. of residual propellants will be vented to atmosphere. This venting procedure lasts until after OMS 1 burn is completed.

**The failure rates quoted include the possibility of propagation, but the dominant effect during this time period is considered to be the result of RCS loss with or without propagation i.e. Orbiter Impacts External Tank. It is assumed that loss of one RCS unit, without propagation and prior to this critical time period, need not be catastrophic.

Weighting Factors: Nos 17 through 23 - POSS

Table C-2. (continued)

VEHICLE BEHAVIOR: Category (6) of Table 3-4
External Tank Punctured

CRITICAL TIME PERIOD: During Orbiter External Tank Separation Maneuver (MECO + 11 seconds to end of RCS separation burn).

NO.	VEHICLE AND SUB-SYSTEM	ITEM	NO. ITEMS	FAILURE MODE	λ_L/HR; λ_U/HR	ASSUMPTIONS
24.	Aft Reaction Control Assembly	Primary Thruster Nozzle Extension	24	Structural Failure Burn Through or Rupture	2.00E-09 2.00E-07	Failures 21, 22, 25 and 26 are considered to occur when RCS is required for external tank separation maneuver with no time to cross feed.
25.		He Pressurization Tank Quick Fill Disconnect	4	Fail Open of Spring Loaded Poppet Valve or Excess Leakage From Seals or Cap	3.00E-06 | Valve 3.00E-05 | 1.00E-07 | Seal 1.00E-04 |	
26.		Propellant Tank Compartment Screens	4	Structural Failure Causing Tank Blockage	1.00E-09 1.00E-07	
27.	Orbital Maneuvering System	Propellant Payload Bay Kit and Pod Cross Feed Couplings	6	Rupture or Leakage	1.00E-08 1.00E-05	Failures 27 through 37 are considered to lead to fire and explosion either directly or indirectly within the aft OMS/RCS pod. The result will be loss of RCS which for this critical time period is considered to be dominant. Conceivably, failures in the aft OMS/RCS pod could further propagate to the ME compartment causing fire and explosion with residual propellants.*(See also first asterisked note on page A-8.) The ultimate affect is considered
28.		MMH and N_2O_4 Tank Assemblies	10	Rupture, Leakage or Tank Seal Failure	1.00E-09 | Tank 1.00E-07 | 1.00E-07 | Seal 1.00E-04 |	
29.		MMH and N_2O_4 Fill and Drain Couplings	2	Rupture or Leakage	1.00E-08 1.00E-05	
30.		MMH and N_2O_4 Feedlines and Valves	4 assys	" "	5.00E-07 5.00E-04	
31.		GN_2 Tank Supply To Valve Actuators (2500 psi)	2	Gross Rupture	1.00E-09 1.00E-07	

*The failure rates quoted include the possibility of propagation to the ME compartment. As noted however, the ultimate affect on the vehicle is considered to be the same as Orbiter/ET impact

Weighting Factors: Nos. 24 through 27 & 31 - POSS
Nos. 28 through 30 - PROB

Table C-2. (continued)

VEHICLE BEHAVIOR: Category (6) of Table 3-4
External Tank Punctured

CRITICAL TIME PERIOD: During Orbiter External Tank Separation Maneuver (MECO + 11 seconds to end of RCS separation burn)

NO.	VEHICLE AND SUB-SYSTEM	ITEM	NO. ITEMS	FAILURE MODE	λ_ℓ/HR; λ_u/HR	ASSUMPTIONS
32.	Orbital Maneuvering System	GN_2 Accumulator	2	Gross Runture	1.00E-09 1.00E-07	to be the same as simply Oribter/ET impact.
33.		MMH and N_2O_4 Flexible Gimble Joint	12	Ruoture or Leakage	1.00E-08 1.00E-05	Failures 36 and 37 are considered to cause breaking of the OMS propellant lines
34.		He Storage Tanks (4800 psi)	5	Gross Ruoture	1.00E-09 1.00E-07	Other OMS failure modes have been excluded as irrelevant to this mode of vehicle behavior.
35.		Engine to Vehicle Flexible Connector	4	Structural Failure	1.00E-08 1.00E-05	
36.		Gimbal Ring Forging (Engine Attachment)	2	" "	1.00E-09 1.00E-07	
37.		Engine and Gimbal Ring Mounting Pad	8	" "	3.00E-11 3.00E-08	

Weighting Factors: Nos. 32 & 34 - POSS
Nos. 33 & 35 through 37 - PROB

Table C-3.

VEHICLE BEHAVIOR: Categories (6) & (10) of Table 3-4
(6) External Tank Punctured
(10) Fire and Explosion in ME Compartment and Orbiter Tumbles to Earth

CRITICAL TIME PERIOD(S): (6) MECO TO MECO + 11 seconds*
(10) MECO + 16 seconds to Orbit Insertion (end OMS1 burn)

NO.	VEHICLE AND SUB-SYSTEM	ITEM	NO. ITEMS.	FAILURE MODE	λ_k/HR; λ_u/HR	ASSUMPTIONS
1.	Aft Reaction Control Assembly**	MMH and N_2O_4 Tank Flexible Gimble Joint	12	Rupture or Leakage	2.00E-09 2.00E-06	For failures 1 to 20, the failure rates quoted are exclusively for propagation of OMS/RCS fire and explosion to the Orbiter ME compartment
2.		MMH and N_2O_4 Tank Assemblies	4	Rupture, Leakage or Tank Seal Failure	2.00E-10 } Tank 2.00E-08 } 2.00E-08 } Seal 2.00E-05 }	
3.		MMH Fuel Feedline and Fittings	2	Rupture or Leakage of Lines, Valves or Fittings	1.00E-07 1.00E-04	
4.		N_2O_4 Oxidizer Feedline and Fittings	2	" "	1.00E-07 1.00E-04	
5.		He Storage Tanks (4000 psi)	4	Gross Rupture	2.00E-10 2.00E-08	
6.		Propellant Tank Vent and Bleed Quick Disconnect	12	Fail Open of Spring Loaded Poppet Valve or Excess Leakage From Seals or Cap	6.00E-07 } Valve 6.00E-06 } 2.00E-08 } Seal 2.00E-05 }	
7.	Orbital Maneuvering System	Propellant Payload Bay Kit and Pod Cross Feed Couplings	6	Rupture or Leakage	2.00E-09 2.00E-06	

*For the critical period MECO+11 seconds to MECO+16 seconds, during Orbiter/ET Separation, the effect of propagated failures has been considered as being the same as the effect of loss of RCS and is considered in Table C-2.

**Rupture of any engine bellows assembly was originally included here but a recent design change will allow isolation of such failures. Because these failures were no longer designated category 1, they were removed from the analysis.

WEIGHTING FACTORS: Nos. 1 & 2 - PROB
Nos. 3 through 7 - POSS

Table C-3. (continued)

VEHICLE BEHAVIOR: Categories (6) & (10) of Table 3-4
(6) External Tank Punctured
(10) Fire and Explosion in Aft ME Compartment and Orbiter Tumbles to Earth

CRITICAL TIME PERIOD(S): (6) MECO to MECO + 11 seconds
(10) MECO + 16 seconds to Orbit Insertion (end)MS1 burn)

NO.	VEHICLE AND SUB-SYSTEM	ITEM	NO. ITEMS.	FAILURE MODE	λ_ℓ/HR; λ_u/HR	ASSUMPTIONS
8.	Orbital Maneuvering System	MMH and N_2O_4 Tank Assemblies	10	Rupture, Leakage or Tank Seal Failure	2.00E-10 | 2.00E-08 | Tank 2.00E-08 | 2.00E-05 | Seal	
9.		MMH and N_2O_4 Fill and Drain Couplings	2	Rupture or Leakage	2.00E-09 2.00E-06	
10.		MMH and N_2O_4 Feedlines and Valves	4 assys	" "	1.00E-07 1.00E-04	
11.		GN_2 Tank Supply To Valve Actuators (2500 psi)	2	Gross Rupture	2.00E-10 2.00E-08	
12.		GN_2 Accumulator	2	" "	2.00E-10 2.00E-08	
13.		MMH and N_2O_4 Flexible Gimble Joint	12	Rupture or Leakage	2.00E-09 2.00E-06	
14.		He Storage Tanks (4800 psi)	5	Gross Rupture	2.00E-10 2.00E-08	
15.		Engine To Vehicle Flexible Connector	4	Structural Failure	2.00E-09 2.00E-06	

WEIGHTING FACTORS: Nos. 8 through 10, 13 & 15 - PROB
Nos. 11, 12 & 14 - POSS

Table C-3. (continued)

VEHICLE BEHAVIOR: Categories (6) & (10) of Table 3-4
(6) External Tank Punctured
(10) Fire and Explosion in Aft ME Compartment and Orbiter Tumbles to Earth

CRITICAL TIME PERIOD(S): (6) MECO to MECO + 11 seconds
(10) MECO + 16 seconds to orbit Insertion (end OMS1 burn)

NO.	VEHICLE AND SUB-SYSTEM	ITEM	NO. ITEMS	FAILURE MODE	λ_R/HR; λ_U/HR	ASSUMPTIONS
16.	Orbital Maneuvering System	Gimble Ring Forging (Engine Attachment)	2	Structural Failure	2.00E-10 2.00E-08	Failures 18, 19 and 20 are relevant only during OMS burn periods
17.		Engine and Gimbal Ring Mounting Pad	8	" "	6.00E-12 6.00E-09	
18.		Engine Thrust Chamber*	2	Structural Failure Burn Through or Rupture	4.00E-10 4.00E-08	
19.		Engine Nozzle Extension*	5	" "	4.00E-10 4.00E-08	
20.		Engine Injection*	2	" "	4.00E-10 4.00E-08	

*Since the OMS burn periods are so small in comparison to the overall period at risk, these failures (18, 19 & 20) can effectively be excluded from the analysis as having negligible effect especially since their failure rates are relatively insignificant.

WEIGHTING FACTORS: Nos. 16 & 17 - PROB
Nos. 18 through 20 - POSS

Table C-4.

VEHICLE BEHAVIOR: Categories (12) and 13) of Table 3-4
(12) Loss of Maneuverability & Orbiter Tumbes to Earth
(13) Loss of Maneuverability on Orbit

CRITICAL TIME PERIOD: (12) MECO to Orbit Insertion (end OMS1 burn)
(13) End OMS1 burn to Payload Deployment

NO.	VEHICLE AND SUB-SYSTEM	ITEM	NO. ITEMS.	FAILURE MODE	λ_ℓ/HR;λ_u/HR	ASSUMPTIONS
1.	Forward Reaction Control Assembly	MMH and N_2O_4 Line Flexible Assemblies	2	Rupture or Leakage	1.00E-09 1.00E-06	Failures 1 through 8 could conceivably propagate and lead to loss of all 3 IMUs and hence loss of avionics leading ultimately to loss of orbiter maneuverability Failures 1 through 8 apply from MECO to MECO+11 secs, from MECO+16 secs to end OMS1 burn and from end OMS1 burn to payload separation. The failure rates quoted are exclusively for propagation and loss of IMUs
2.		MMH and N_2O_4 Tank Assemblies	2	Rupture, Leakage or Tank Seal Failure	1.00E-10 } Tank 1.00E-08 } 1.00E-08 } Seal 1.00E-05 }	
3.		MMH Fuel Feedline and Fittings	1 assy	Rupture or Leakage of Lines, Valves or Fittings	5.00E-08 5.00E-05	
4.		N_2O_4 Oxidizer Feedline and Fittings	1 assy	Rupture or Leakage of Lines, Valves or Fittings	5.00E-08 5.00E-05	
5.		Flexible Couplings and Fittings (Engine Bellows Assembly)	32	Rupture at Primary or Vernier Thruster	2.00E-09 2.00E-06	
6.		He Storage Tanks (4000 psi)	2	Gross Rupture With Propagated Fragments Rupturing Propellant Tanks	1.00E-10 1.00E-08	
7.		Propellant Tank Drain, Vent & Bleed Quick Disconnect	6	Fail Open of Spring Loaded Poppet Valve or Excess Leakage From Seal or Caps	3.00E-07 } Tank 3.00E-05 } 1.00E-08 } Valve 1.00E-05 }	
8.		Propellant Tank Purge Quick Disconnect	14	" "	3.00E-07 } Valve 3.00E-06 } 1.00E-08 } Seal 1.00E-05 }	

WEIGHTING FACTORS: Nos. 1 & 3 through 8 - POSS
NO. 2 - PROB

Table C-4. (continued)

VEHICLE BEHAVIOR: Categories (12) and (13) of Table 3-4
(12) Loss of Maneuverability & Orbiter Tumbles to Earth
(13) Loss of Maneuverability on Orbit

CRITICAL TIME PERIOD: (12) MECO to Orbit Insertion (end OMS1 burn)
(13) End OMS1 burn to Payload Deployment

NO.	VEHICLE AND SUB-SYSTEM	ITEM	NO. ITEMS	FAILURE MODE	λ_ℓ/HR;λ_u/HR	ASSUMPTIONS
9.	Aft Reaction Control Assembly***	MMH and N_2O_4 Tank Flexible Gimble Joint	12	Rupture or Leakage	3.00E-09 3.00E-06	Failures 9 through 15 could conceivably propagate through fire and explosion and lead to loss of all OMS and RCS in one aft pod. These failures could further propagate to ME compartment causing fire and explosion with residual propellants.* This affect is likely to be felt sooner than loss of maneuverability alone.
10.		MMH and N_2O_4 Tank Assemblies	4	Rupture, Leakage or Tank Seal Failure	3.00E-10 / 3.00E-08 Tank 4.00E-08 / 4.00E-05 Seal	
11.		MMH Fuel Feedline and Fittings	2 assys	Rupture or Leakage of Lines, Valves or Fittings	2.00E-07 2.00E-04	
12.		N_2O_4 Oxidizer Feedline and Fittings	2 assys	" "	2.00E-07 2.00E-04	
13.		He Storage Tanks (4000 psi)	4	Gross Rupture	3.00E-10 3.00E-08	Failures 15 and 16 could propagate and cause aft pod damage and loss of aft OMS engine.** This possibility is expected to be less likely than for failures 9 through 14 where a fire and explosion could be caused as a direct result of failure.
14.		Propellant Tank Vent and Bleed Quick Disconnect	12	Fail Open of Spring Loaded Poppet Valve or Excess Leakage from Seal or Cap	8.00E-07 / 8.00E-06 Valve 4.00E-08 / 4.00E-05 Seal	
15.		Thrust Chamber Primary Thruster	24	Structural Failure Burn Through or Rupture	6.00E-10 6.00E-08	

*Approximately 5400 lbs of residual propellants will be vented to atmosphere. This venting procedure lasts until after OMS1 burn is completed. The failure rates quoted are conditional upon non-propagation to the ME compartment, but for propagation and loss of OMS and RCS in one pod.

**These values are relevant during RCS burn periods. Since the RCS is used approximately 70% of the time from MECO to payload separation and since the failure rates quoted are relatively small, the effect of assuming continuous operation is negligible.

***Rupture of any engine bellows assembly was originally included here but a recent design change will allow isolation of such failures. Because these failures were no longer designated category 1, they were removed from the analysis.

WEIGHTING FACTORS: Nos. 9 & 10 - PROB
Nos. 11 through 15 - POSS

Table C-4. (continued)

VEHICLE BEHAVIOR: Categories (12) and (13) of Table 3-4
(12) Loss of Maneuverability & Orbiter Tumbles to Earth
(13) Loss of Maneuverability on Orbit

CRITICAL TIME PERIOD: (12) MECO to Orbit Insertion (end OMS1 burn)
(13) End OMS1 burn to Payload Deployment

NO.	VEHICLE AND SUB-SYSTEM	ITEM	NO. ITEMS.	FAILURE MODE	λ_ℓ/HR;λ_u/HR	ASSUMPTIONS
16.	Aft Reaction Control Assembly	Primary Thruster Nozzle Extension	24	Structural Failure Burn Through or Rupture	6.00E-10 6.00E-08	Failures 15 and 16 are only relevant during RCS burn periods
17.	Orbital Maneuvering System	Propellant Payload Bay Kit and Pod Cross Feed Couplings	6	Rupture or Leakage	3.00E-09 3.00E-06	Failures 17 through 27 are considered to cause fire and explosion either directly or indirectly within the aft OMS/RCS pod and lead to loss of OMS the dominant failure during this critical time period. These failures could also further propagate to ME compartment causing fire and explosion with residual propellants. (See also asterisked note on page A-15.) This affect is likely to be felt sooner than loss of maneuverability alone. The failures in the aft RCS and OMS (nos. 9 through 35) apply from End ET separation maneuver to payload separation.
18.		MMH and N_2O_4 Tank Assemblies	10	Rupture, Leakage or Tank Seal Failure	3.00E-10 | 3.00E-08 | Tank 4.00E-08 | 4.00E-05 | Seal	
19.		MMH and N_2O_4 Fill and Drain Couplings	2	Rupture or Leakage	3.00E-09 3.00E-06	
20.		MMH and N_2O_4 Feedlines & Valves	4 assys	" "	2.00E-07 2.00E-04	
21.		GN_2 Tank Supply To Valve Actuators (2500 psi)	2	Gross Rupture	3.00E-10 3.00E-08	
22.		GN_2 Accumulator	2	" "	3.00E-10 3.00E-08	
23.		MMH and N_2O_4 Flexible Gimble Joint	12	Rupture or Leakage	3.00E-09 3.00E-06	

WEIGHTING FACTORS: Nos. 16, 17 & 21 through 23 - POSS
Nos. 18 through 20 - PROB

Table C-4. (continued)

VEHICLE BEHAVIOR: Categories (12) and (13) of Table 3-4
(12) Loss of Maneuverability & Orbiter Tumbles to Earth
(13) Loss of Maneuverability on Orbit

CRITICAL TIME PERIOD: (12) End External Tank Separation Maneuver to Orbit Insertion (end OMS1 burn)
(13) End OMS1 burn to Payload Deployment

NO.	VEHICLE AND SUB-SYSTEM	ITEM	NO. ITEMS.	FAILURE MODE	λ_ℓ/HR;λ_u/HR	ASSUMPTIONS
24.	Orbital Maneuvering System	He Storage Tanks (4800 psi)	5	Gross Rupture	3.00E-10 3.00E-08	
25.		Engine To Vehicle Flexible Connector	4	Structural Failure	3.00E-09 3.00E-06	
26.		Gimbal Ring Forging (Engine Attachment)	2	Structural Failure	3.00E-10 3.00E-08	Failures 26 and 27 are considered to cause breaking of the OMS propellant lines
27.		Engine and Gimbal Ring Mounting Pad	8	Structural Failure	9.00E-12 9.000-09	
28.		Helium Fill Coupling	3	Structural Failure Rupture or Leakage	3.00E-09 3.00E-06	Failures 28 through 32 cause loss of OMS engines through inability to use propellant
29.		Helium Feedlines, Valves and Regulators to Propellant Tanks	3 assys	Rupture or Excess Leakage	8.00E-07 8.00E-06	
30.		Propellant Fill and Vent Coupling	6	Structural Failure Rupture or Leakage	3.00E-09 3.00E-06	
31.		MMH & N_2O_4 Tank Acquisition Device (Pad)	10	Structural Failure Causing Tank Blockage	9.00E-12 9.00E-09	

WEIGHTING FACTORS: Nos. 24 & 28 through 31 - POSS
Nos. 25, 26 & 27 - PROB

Table C-4. (continued)

VEHICLE BEHAVIOR: Categories (12) and (13) of Table 3-4
(12) Loss of Maneuverability & Orbiter Tumbles to Earth
(13) Loss of Maneuverability on Orbit

CRITICAL TIME PERIOD: (12) MECO to Orbit Insertion (end OMS1 burn)
(13) End OMS1 burn to Payload Deployment

NO.	VEHICLE AND SUB-SYSTEM	ITEM	NO. ITEMS.	FAILURE MODE	λ_ℓ/HR;λ_u/HR	ASSUMPTIONS
32.	Orbital Maneuvering System	Propellant Tank Compartment Screens	10	Structural Failure Causing Tank Blockage	3.00E-10 3.00E-08	Failures 33, 34 and 35 lead to a fire and explosion hazard in the aft OMS/RCS pod leading to loss of OMS (during OMS burn period only). These failures could also further propagate to ME compartment causing fire & explosion with residual propellants. (See 1st asterisked note on page A-15) This is likely to be felt sooner than loss of maneuverability alone.
33.		Engine Injector*	2	Structural Failure Burn Through or Rupture	6.00E-10 6.00E-08	
34.		Engine Thrust Chamber*	2	" "	6.00E-10 6.00E-08	
35.		Engine Nozzle Extension*	8	" "	6.00E-10 6.00E-08	
36.	Electrical Power	O_2 Tank Sub-Assemblies 1, 2 & 3	3	Gross Rupture Caused by Excessive Heat Input From Heaters or Material Defect	2.00E-10 2.00E-08	Failures 36 through 39 could conceivably propagate and lead to loss of all 3 IMUs and hence loss of avionics leading ultimately to loss of orbiter maneuverability
37.		H_2 Tank Sub-Assemblies 1, 2 & 3	3	" "	2.00E-10 2.00E-08	
38.	Atmospheric Revitalization	Auxiliary O_2 Storage Tank (900 psi)	1	Gross Rupture Caused by Material Defect	1.00E-10 1.00E-08	Failures 36 through 39 apply from MECO to payload separation. The failure rates quoted are exclusively for propagation.
39.		N_2 Storage Tanks (300 psi)	4	" "	1.00E-10 1.00E-08	

*Approximately 5400 lbs of residual propellants will be vented to atmosphere. This venting procedure lasts until after OMS1 burn is completed. The failure rates quoted are conditional upon non-propagation to the ME compartment, but for propagation and loss of OMS and RCS in one pod.

WEIGHTING FACTORS: Nos. 32 through 35 & 39 - POSS
Nos. 36 through 38 - PROB