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SPACE TRANSPORTATION ARCHITECTURE: RELIABILITY SENSITIVITIES

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13. ABSTRACT *(Maximum 200 words)*

This report is a sensitivity analysis of the benefits and drawbacks associated with a proposed Earth-to-orbit vehicle architecture. The architecture represents a fleet of six vehicles (two existing, four proposed) that would be responsible for performing various missions as mandated by NASA and USAF. Each vehicle has a prescribed flight rate per year for a period of 31 years.

By exposing this fleet of vehicles to a probabilistic environment where the fleet experiences failures, downtimes, setbacks, etc., the analysis involves determining the resiliency and costs associated with the fleet of specific vehicle/subsystem reliabilities.

The resources required were actual observed data on the failures and downtimes associated with existing vehicles, data based on engineering judgment for proposed vehicles, and the development of a sensitivity analysis program.

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LIST OF ACRONYMS

A&O	avionics and other
ASRM	advanced solid rocket motor
CBH	cost of ownership
CF	cost of failure
COP	cost of payload
CP	cost of payload due to failure
CPF	cost per flight
DDT&E	design, development, testing, and evaluation
$B	dollars in billions
ELR	effective launch rate
ET	external tank
ETD	external tank derived
ETD1	ETD vehicle 1.5 stage
ETD2	ETD vehicle with 2 ETD boosters
ETD3	ETD vehicle with 3 ETD boosters
LCC	life cycle cost
MPS	main propulsion system
MSFC	Marshall Space Flight Center
NASA	National Aeronautics and Space Administration
NLS	National Launch Strategy
OTA	Office of Technical Assessment
PLS	personnel launch system
PRA	probability risk assessment
RSRM	redesigned solid rocket motor

SLAM	simulation language for alternative modeling
SRB	solid rocket booster
SRM	solid rocket motor
SSME	spacc shuttlc main engine
STME	space transportation main engine
STS	space transportation system
TIV	Titan IV
ULV	unmanned launch vehicle
USAF	United States Air Force

TECHNICAL MEMORANDUM

SPACE TRANSPORTATION ARCHITECTURE: RELIABILITY SENSITIVITIES

I. INTRODUCTION

"... for the 1990's, Space Station *Freedom*, our critical next step in all our space endeavors..." President George Bush, July 20, 1989.

The article "Fleeing Freedom"[1] points out that along with living in space or on Earth comes the chance of injury, illness, and death. One thing the numbers show is that, after 3 to 7 years of space operation, a rescue mission or vehicle would be needed just to return a crew member deconditioned by zero-gravity. The Space Station *Freedom* project manager says "several times in the 30-year life of the station" injury or illness will force return to Earth. He further stated that "looking at the history of manned space flight, we've had two failures in space that forced returns—*Gemini 8's* stuck-on attitude thrusters and the *Apollo 13* explosion. Applying these over the base of U.S. man-hours in space would point to a rescue at the station several times a year! Figuring we should be able to do an order of magnitude better comes out to once every 2 to 3 years. Over 30 years, this means about 20 rescues."

A rescue craft, either on-orbit or ground-based, may become a reality even without cost-benefit analysis overwhelmingly in its favor. The prospect of all the world seeing the ordeal of a stranded crew or a dying crew member nightly on television is chilling. The national nightmare of a crew in trouble with no timely way home, no matter what the chances of occurrence, is reason enough for many, both within and outside of NASA, to push for a rescue vehicle as a political necessity.

Possibly the most emotional crew risk is that of another catastrophic loss of an orbiter and grounding of the shuttle fleet. Apart from the operations trauma, this would deny access to or from the space station if another type of vehicle were not available.

A joint NASA-USAF (United States Air Force) effort proposes several approaches to providing a safe and reliable transportation system not only for space station but for other concepts of space-based installations.

The approaches, known as "architectures," combine several types of launch vehicles to bring about a transportation system capable of supporting the Space Station *Freedom* construction phase, as well as support of other space-based installations.

The predominant objective of this report is to investigate one of the proposed architectures.

A sensitivity analysis model will be developed to reveal the probable occurrences of failures, the costs associated with the failures, as well as the life cycle costs related to the vehicles that comprise the architecture. In addition, the model should be of value in bringing to light a more achievable launch capability of these vehicles.

II. LITERATURE SURVEY

NASA's position on vehicle reliability fluctuates from one engineer to another. Some engineers have a very optimistic view of vehicle reliabilities, and others have a very pessimistic view. The purpose of this report was not to prove or disprove either view, merely to establish the outcome and sensitivity of both views, and how these views affect variables such as launch rate, life cycle cost, and cost of failure. A sensitivity analysis is necessary to substantiate these results.

The general purpose of a sensitivity analysis[2] is:

> To identify sensitive parameters, to try to estimate these parameters closely, and then to select a solution that remains a good one over the range of likely values of the sensitive parameters.

Sensitivity analysis involves changing one parameter at a time in the original model to check its effect on the solution. The changed parameter in this model will be the reliability value associated with the Space Transportation System (STS) comprised of four orbiters.

A simulation model was built to accomplish the sensitivity analysis. A model may be used as a representation of a system to be brought into being, or to analyze a system already in being.[3] Simulation is defined as an imitation of the operation of a real-world process or system over time.[4] The behavior of a system over some specified time can be studied by developing a simulation model. The model simply takes on the characteristics in terms of mathematical and logical relationships embedded in the system. Once the simulation model has been augmented, verified, and validated, a variety of questions can be answered about the real-world system. Simulations permit inferences to be drawn about systems by eliminating the need to do the following:[5]

1. Build the system. Building the system would be unnecessary especially if it is a proposed system.

2. Disturb the system. Disturbing the system may be unfavorable if the system is operational and is costly to experiment with.

3. Destroy the system. It would be useless to perform a limit of stress test on a system that could be destroyed in the process.

Four of the vehicles analyzed in this report are proposed vehicles, and, although it would be helpful to have a prototype of the vehicles to reveal vehicle performance, it would also be unprofitable to spend billions of dollars on a vehicle that may not be approved. Therefore, a simulation would be the most rational approach.

The simulation model and sensitivity analysis combination will hereafter be referred to as a "sensitivity analysis model."

The sensitivity analysis model for this report is primarily concerned with five factors. These factors are:

1. Reliability

2. Downtime

3. Effective launch rate

4. Life cycle cost

5. Cost per vehicle failure.

A. Reliability

The Office of Technical Assessment of the United States Congress speaks of reliability as follows:[6]

> Reliability is the probability with which a system will perform an intended function. A system designed to perform several distinct functions will give a reliability corresponding to each function. For example, a fully reusable vehicle would be designed to transport payloads to orbit safely and return safely. The probability that it will reach orbit and safely deploy a payload (its ascent reliability) is greater than its mission success reliability—the probability that it will reach orbit, safely deploy a payload, and return. Mission success reliability is a commonly used criterion, but reliabilities of noncritical subsystems are also of interest because they affect maintenance costs . . . . One of the difficulties in using reliability as a criterion is the uncertainty in estimates of the reliabilities of operational vehicles and, especially, proposed vehicles.

The many definitions of reliability that exist depend upon the viewpoint of the user. However, they all have a common core that contains the statement that reliability, $R(t)$, is the probability that a device performs adequately over the time interval $[0,t]$. The device under consideration may be an entire system, a subsystem, or a component.[2]

B. Downtime

Downtime is the time the system is nonoperational following a system failure. Downtime can also be described as the time required to repair the system after a failure has occurred.

C. Effective Launch Rate

The effective launch rate (ELR) is the actual launch rate. All vehicles will have a prescribed or nominal launch rate. This prescribed launch rate is mandated by the flight manifest (table 1). However, by subjecting these vehicles to a probabilistic environment, the prescribed launch rate will not be achieved. Therefore, the flights actually launched become the ELR.

Table 1. Flight manifest.

VEHICLE	FISCAL YEAR 1990	1991	1992	1993	1994	1995	1996	1997	1998	1999	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019	2020	TOTAL
TITAN IV	6	8	9	9	8	9	9	10	9	10	6	8	7	7	3	4	3	4	3	3	3	4	3	4	3	4	3	4	3	4	3	173
STS W/ RSRM	8	10	11	11	12	9	6	3	6	6	6	5	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	169
STS W/ ASRM	0	0	0	0	0	3	6	9	6	6	6	6	5	4	5	4	4	4	5	4	5	5	5	5	5	5	5	5	5	5	5	132
ET/CORE/PLS	0	0	0	0	0	0	0	0	0	0	0	0	0	1	1	1	0	1	1	1	0	1	1	1	1	1	1	1	1	1	1	16
ET/CORE/1.5 STAGE	0	0	0	0	0	0	0	0	0	0	6	8	9	8	7	7	6	7	6	6	6	6	7	6	6	6	7	6	6	6	6	138
ET/CORE W/ 2 BSTR	0	0	0	0	0	0	0	0	0	0	0	0	0	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	36
ET/CORE W/ 3 BSTR	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	6	4	4	4	0	0	4	23

D. Life Cycle Cost

Life cycle cost refers to all costs associated with the system or product as applied to the defined life cycle. Life cycle cost is determined by identifying the applicable functions in each phase of the life cycle, costing these functions, applying the appropriate costs by function on a year-to-year schedule, and ultimately accumulating the costs for the entire span of the life cycle.[3] It should be noted that all life cycle costs may be difficult (if not impossible) to predict and measure. For instance, some indirect costs caused by the interaction effects of one system on another, social costs, and so on, may be impossible to quantify. Thus, the emphasis should relate primarily to those costs that can be directly attributed to a given system or product.[3] A life cycle cost breakdown is presented in table 2.

Table 2. Cost categories.[3]

1. Research and development
   (a) Program development
   (b) Advanced research and development
   (c) Engineering design
   (d) Equipment development and test
   (e) Engineering data

2. Investment
   (a) Manufacturing
   (b) Construction
   (c) Initial logistic support

3. Operations and maintenance
   (a) Operations
   (b) Maintenance
   –Maintenance personnel and support
   –Spare/repair parts
   –Test and support equipment maintenance
   –Transportation and handling
   –Maintenance training
   –Maintenance facilities
   –Technical data
   (c) System/equipment modifications
   (d) System phase-out and disposal

E. Cost Per Vehicle Failure

The cost per vehicle failure is simply the cost associated with each vehicle failure. This cost includes the cost of losing flight hardware and payload.

III. PROBLEM DESCRIPTION

For permanent human presence in space, NASA has taken a close look at the ramifications associated with humans living and working in space. Of course, one demand of humans residing in space is food and water. Items for personal hygiene and health maintenance are also necessary.

Currently, the only space transportation system available for any type of emergency rescue or logistics delivery is NASA's STS. However, studies have been accomplished to examine the potential of STS performing these functions. One study[7] determined that the reliability of the shuttle system for support of the space station may not adequately support the deployment phases and possible day-to-day support required by a permanently manned space station. Also, having a manned vehicle to carry out all the flight requests of space station greatly increases the risks associated with manned space programs. Still other possibilities exist when there may be periods in the shuttle program when shuttle rescue missions are not possible. For example:

– There may not be sufficient orbiters or boosters in inventory to have the shuttle cycling fast enough to be ready for a rescue mission at a short notice.

– The shuttle may be grounded for a time, in the same way that aircraft are grounded from time to time.

In November 1989, President Bush reaffirmed a National Space Policy that established the following goals:[8]

1. Strengthen the security of the United States.

2. Obtain scientific, technological, and economic benefits.

3. Encourage continuing U.S. private sector investment.

4. Promote international cooperative efforts.

5. Expand human presence and activity beyond Earth orbit into the solar system.

6. Assure access to space, sufficient to achieve all U.S. space policy goals. This is the key element of the National Space Policy.

7. U.S. space transportation systems must provide a balanced, robust, and flexible capability with sufficient resiliency to allow continued operations despite failures in a single system.

One of the National Space Policy guidelines states that the National Space Transportation capability will be based on a mix of vehicles consisting of the current STS, unmanned launch vehicles (ULV's), and in-space transportation systems.

As a result of this National Space Policy, NASA and the USAF launched a project to review the Nation's space transportation capability. The review was conducted in three phases:

Phase I – Define current launch situation.

Phase II – Identify alternatives to resolve capabilities/needs mismatches.

Phase III – Assess policy, procedure, and investment actions to meet U.S. space launch objectives.

Several architectures were developed as possible candidates for meeting the aforementioned goals. The architecture analyzed in this report (fig. 1) is one of the several NASA chose to investigate. Architecture is defined as any design or orderly arrangement perceived by man.[9]

Since the life expectancy of a launch vehicle is about 30 years, each architecture has a flight manifest (table 1) of 30 years. A vehicle data sheet for each vehicle is provided in appendix A.

The architecture is divided into four categories: cargo vehicles, new elements, manned vehicles, and facilities. It is also divided into six 5-year time frames beginning in 1990 and ending in the year 2020.

A. Cargo Category

The Titan IV vehicle would fly a prescribed number of flights each year from 1990 through 2020. The ET/Core 1.5 (External Tank Derived Vehicle/1.5 Stage) would come on line in the year 2000 and fly its prescribed flights. The other vehicles would come on line as indicated and do likewise. The ET/Core vehicles will hereafter be referred to as ETD1 (ET/Core 1.5 stage), ETD2 (ET/Core with 2 core-derived booster), and ETD3 (ET/Core with 3 core-derived booster).

B. New Elements Category

An advanced solid rocket motor (ASRM) would be available for integration into the transportation system by the year 1995. At that time, the STS would use both the new element (ASRM) and the existing element redesigned solid rocket motor (RSRM) for the duration of the architecture. The space transportation main engine (STME) would come on line at the designated time for use with the ET-derived vehicles. The use of dual elements is an attempt to provide resiliency to the architecture. Resiliency is defined as the ability of an STS to adhere to launch schedules despite failures—to "spring back" after failure.[6]

C. Manned Category

The STS, as referenced in the previous category, would fly with RSRM's until the ASRM's came on line, at which time the SRM's would be interchangeable. The STS is to be used for both personnel and cargo delivery to the space station. The personnel launch system (PLS) would come on line in the year 2000 and utilize the ETD1 as its launch vehicle. The primary purpose of the PLS is to transfer personnel to and from Space Station *Freedom* and to serve as an emergency rescue vehicle if necessary. However, when the shuttle system (STS) experiences a failure or is in the nonoperational state, both PLS and ETD1 flight rates would be increased to accommodate the number of proposed shuttle personnel and cargo launches. However, STS failures that occur prior to these vehicles coming on line will not have replacement flights.

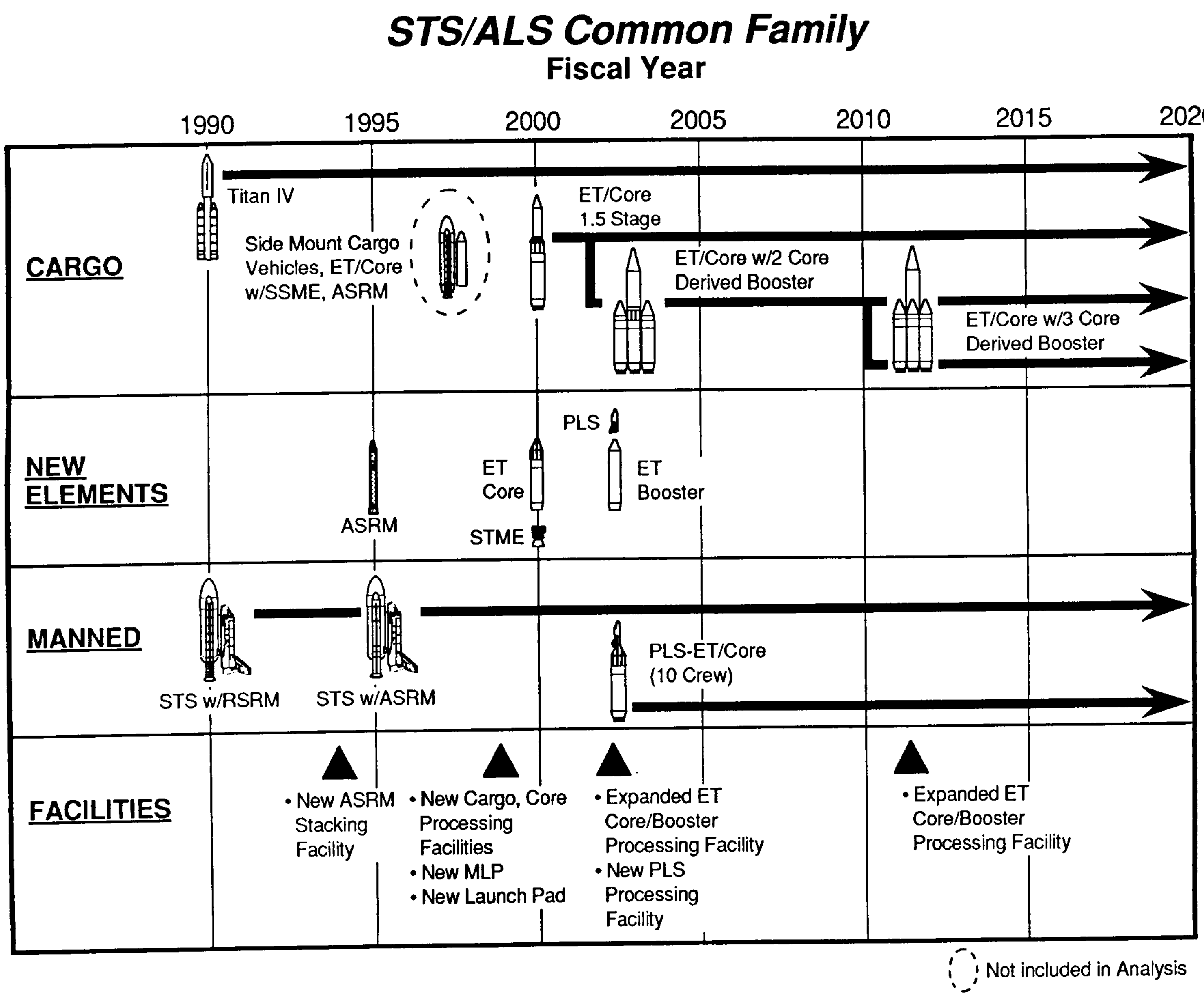

Figure 1. Architecture.

D. Facilities Category

This category simply identifies the new facilities required to support the proposed architecture and indicates when these facilities would be required.

Although the architecture consists of six vehicles, only five would be used for space station support. These are: STS, PLS, ETD1, ETD2, and Titan IV. ETD3 is designated as a lunar/Mars support vehicle. The lunar/Mars project will not be addressed in this report.

The questions to be answered are:

1. How resilient is this system?

2. What costs are associated with the life of the system as well as with vehicle failures?

IV. DATA ACQUISITION AND GENERATION

This section discusses the acquisition and generation of the data necessary for the sensitivity analysis model. The variables of interest are as follows:

1. Vehicle Flight Rates

2. Vehicle/Subsystem Reliabilities and Downtimes

3. Vehicle Operation Time

4. Costs

   (a) Design, Development, Test, and Evaluation (DDT&E)

   (b) Ownership

   (c) Lost Payload

   (d) Lost Hardware (vehicles)

   (e) Flight.

A. Vehicle Flight Rates

The vehicle flight rates were obtained from NASA during the initial definition of the architectures.

B. Vehicle/Subsystem Reliabiity Estimation and Downtimes

One of the purposes of this report is to determine the sensitivity of the architecture to vehicle reliabilties. As stated in section III, one of the difficulties in using reliability as a criterion is the uncertainty in estimates of the reliabilities of operational vehicles and, especially, proposed vehicles.

An OTA publication[10] had this to say about "reliability estimation"...

> The most difficult and least credible part of this procedure is estimating the probability of failure for each vehicle. This is particularly true for proposed vehicles that have not been fully designed, much less built, tested, and flown. The only completely objective method of estimating a vehicle's probability of failure is by statistical analysis of the number of failures observed in actual launches of identical vehicles under conditions representative of those under which future launches will be attempted.

The design reliability of proposed vehicles is generally estimated using:[10]

- Data from laboratory tests of vehicle systems (e.g., engines and avionics) and components that have already been built
- Engineers' judgments about the reliability achievable in systems and components that have not been built
- Analyses of whether a failure in one system or component would cause other systems and components, or the vehicle, to fail
- Assumptions (often tacit) that:
  - The laboratory conditions under which systems were tested precisely duplicate conditions under which the system will operate
  - The conditions under which the systems will operate are those under which they were designed to operate
  - The engineers' judgments about reliability are correct
  - The failure analyses considered all circumstances and details that influence reliability.

Such "engineering estimates" of design reliability are incomplete and subjective. However, the subjectivity and uncertainty often are not exhibited. There are methods for assessing and exhibiting the uncertainties of experts called upon to estimate reliabilities of components, and probabilistic risk assessment (PRA) methods for estimating risks posed by unreliability, considering the uncertainties in the estimates of components' reliabilities. However, it is more difficult and time-consuming to use them than to provide a single "best estimate" of reliability showing no uncertainty. The latter has been standard engineering practice except for tasks—such as safety analyses of nuclear reactors—for which the increased rigor has been deemed worth the effort.[10]

The shuttle occupies a commanding position over other existing vehicles and, therefore, was selected as the vehicle on which the proposed vehicle reliabilities will be contingent. In other words, the space shuttle main engine (SSME) reliability will be the assumed STME reliability, and the shuttle avionics & other reliability will be the assumed proposed vehicle avionics & other reliability.

The actual reliability of the shuttle system is unknown, but may lie between 97 and 99 percent.[11] For the purpose of the sensitivity analysis, the values of 0.97, 0.98, and 0.99 were selected for the reliability variable. These reliabilities were then allocated to the various vehicle subsystems in two categories: common failures and unique failures (table 3). This allocation procedure was developed by Dr. James W. Steincamp, NASA-MSFC, Chief, Operations Analysis Branch/Preliminary Design Office.[12] Appendix B contains a detailed description of this allocation procedure. A common subsystem failure affects all vehicles that share the failed subsystem. This means that any vehicle requiring the failed subsystem is blocked until the failure has been repaired or until the failed subsystem is flight ready. A unique subsystem failure affects only the vehicle on which the failure occurred. Any other vehicle requiring that subsystem does not get blocked and is allowed to launch. Section V will discuss in detail the activity of common and unique subsystem failures.

Titan IV failure probability was obtained from an OTA special report.[10] The OTA reliability estimate for Titan IV is 96.2 percent. The OTA reliability estimate for STS is 96.6 percent. With that information, a relationship must be developed between STS and Titan IV so that as STS reliability varies, Titan IV reliability can vary conformably. This can best be demonstrated as follows:

$$\frac{0.962}{0.966} = \frac{x \text{ (Titan IV)}}{0.970 \text{ (STS)}}$$

$$x = 0.966 \ .$$

Therefore, the relationship between STS and Titan IV can be presented as in table 4.

Since the Titan IV vehicle is independent of the other vehicles in the architecture (its failure or success has no effect on any other vehicle), its failures were not categorized. Once a failure occurred, the vehicle is nonoperational for some specified time. The downtimes and probability of occurrence for the Titan IV vehicle were obtained from L Systems, Inc., El Segundo, California.[6] This data is as shown in table 5.

Downtimes (with the exception of Titan IV) were also categorized into common and unique. The triangular distribution generated the downtimes in the sensitivity analysis model. The triangular distribution is utilized when a most likely value can be ascertained along with minimum and maximum values, and a piecewise linear density function seems appropriate.[5] Figure 2 gives the density function for the triangular distribution and its graph.

For common failure downtime, the values of a (minimum), m (mode), and b (maximum), are equal to 273.75 (0.75*365), 365.0, and 638.75 (1.75*365) (days), respectively. Since the common failures correspond to subsystems shared by several vehicles (e.g., SSME, avionics & other), a minimum of 9 months and a modest chance of exceeding 18 months seems appropriate, with a slight bias toward the shorter downtimes (fig. 3).[12]

Table 3. Reliability allocations.

STS	0.97 Reliability	0.97 Odds (1:x)	0.98 Reliability	0.98 Odds (1:x)	0.99 Reliability	0.99 Odds (1:x)
COMMON ELEMENTS						
mps (3ssme)	0.9904	104	0.9936	156	0.9968	313
2 x srb	0.9900	100	0.9933	150	0.9967	300
avionics & other	0.9962	266	0.9975	400	0.9988	800
TOTAL	0.9767	43	0.9845	65	0.9922	129
UNIQUE ELEMENTS						
avionics & other	0.9970	332	0.9980	500	0.9990	1000
operations	0.9962	266	0.9975	400	0.9988	800
TOTAL	0.9932	148	0.9955	222	0.9978	445
STS SYSTEM	0.9701	33	0.9801	50	0.9900	100
P(COMMON)	0.7748	4.44	0.7751	4.45	0.7754	4.45
P(UNIQUE)	0.2252	1.29	0.2249	1.29	0.2246	1.29
P(ssme)	0.41	1.71	0.41	1.70	0.41	1.70
P(srb)	0.43	1.76	0.43	1.76	0.43	1.75
P(a&o)	0.16	1.19	0.16	1.19	0.16	1.19
PLS/ETD1						
COMMON ELEMENTS						
mps (5stme w 2sus)	0.9935	154	0.9957	233	0.9979	465
avionics & other	0.9962	266	0.9975	400	0.9988	800
TOTAL	0.9898	98	0.9932	147	0.9966	294
UNIQUE ELEMENTS						
avionics & other	0.9970	332	0.9980	500	0.9990	1000
operations	0.9962	266	0.9975	400	0.9988	800
TOTAL	0.9932	148	0.9955	222	0.9978	445
PLS/ETD1 SYSTEM	0.9831	59	0.9887	89	0.9944	177
P(COMMON)	0.6016	2.51	0.6017	2.51	0.6017	2.51
P(UNIQUE)	0.3984	1.66	0.3983	1.66	0.3983	1.66
P(stme)	0.63	2.73	0.63	2.73	0.63	2.72
P(a&o)	0.37	1.58	0.37	1.58	0.37	1.58
ETD2						
COMMON ELEMENTS						
mps (17stme)	0.9235	13	0.9492	20	0.9746	39
avionics & other	0.9962	266	0.9975	400	0.9988	800
TOTAL	0.9200	13	0.9468	19	0.9734	38
UNIQUE ELEMENTS						
avionics & other	0.9970	332	0.9980	500	0.9990	1000
operations	0.9962	266	0.9975	400	0.9988	800
TOTAL	0.9932	148	0.9955	222	0.9978	445
ETD2 SYSTEM	0.9138	12	0.9426	17	0.9712	35
P(COMMON)	0.9220	12.82	0.9221	12.83	0.9221	12.84
P(UNIQUE)	0.0780	1.08	0.0779	1.08	0.0779	1.08
P(stme)	0.96*	23.00	0.96*	22.41	0.95	21.85
P(a&o)	0.05	1.05	0.05	1.05	0.05	1.05
ETD3						
COMMON ELEMENTS						
mps (24 stme)	0.9093	11	0.9398	17	0.9699	33
avionics & other	0.9962	266	0.9975	400	0.9988	800
TOTAL	0.9059	11	0.9375	16	0.9687	32
UNIQUE ELEMENTS						
avionics & other	0.9970	332	0.9980	500	0.9990	1000
operations	0.9962	266	0.9975	400	0.9988	800
TOTAL	0.9932	148	0.9955	222	0.9978	445
ETD3 SYSTEM	0.8998	10	0.9332	15	0.9665	30
P(COMMON)	0.9329	14.91	0.9330	14.92	0.9330	14.92
P(UNIQUE)	0.0671	1.07	0.0670	1.07	0.0670	1.07
P(stme)	0.96	27.48	0.96	26.62	0.96	25.83
P(a&o)	0.04	1.04	0.04	1.04	0.04	1.04

* >1 (Round-off Error)

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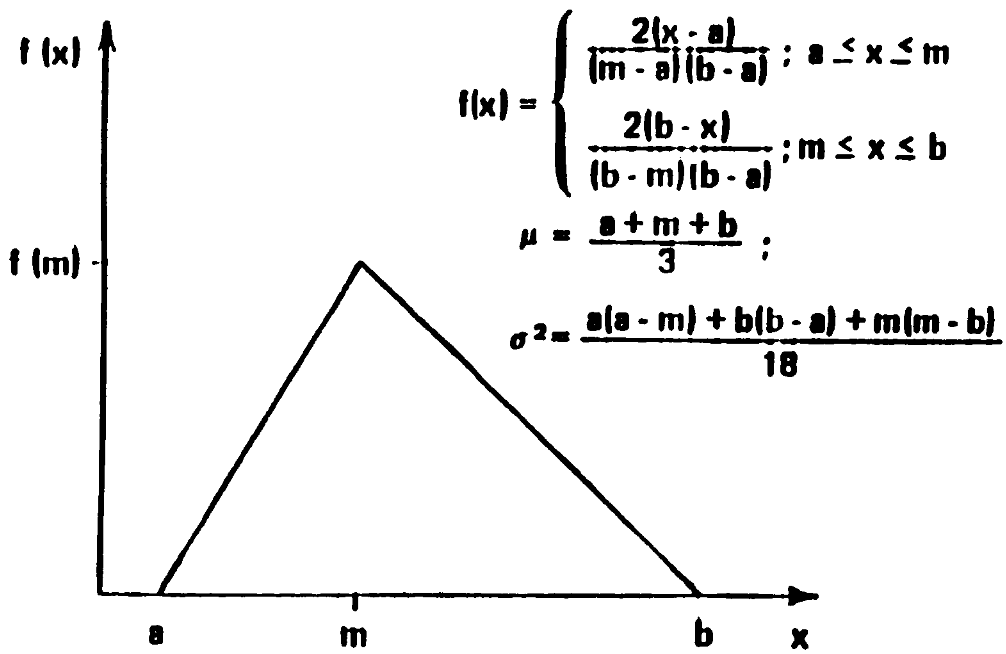
Table 4. STS/Titan IV reliability relationship.

STS Reliability	Titan IV Reliability
0.970	0.966
0.980	0.976
0.990	0.986

Table 5. Titan IV failure statistics.

Downtime (days)	Probability
60	0.3
90	0.1
120	0.1
180	0.2
210	0.1
240	0.1
570	0.1



$$f(x) = \begin{cases} \dfrac{2(x-a)}{(m-a)(b-a)} ; & a \le x \le m \\ \dfrac{2(b-x)}{(b-m)(b-a)} ; & m \le x \le b \end{cases}$$

$$\mu = \frac{a+m+b}{3} ;$$

$$\sigma^2 = \frac{a(a-m)+b(b-a)+m(m-b)}{18}$$

Figure 2. Triangular density function.

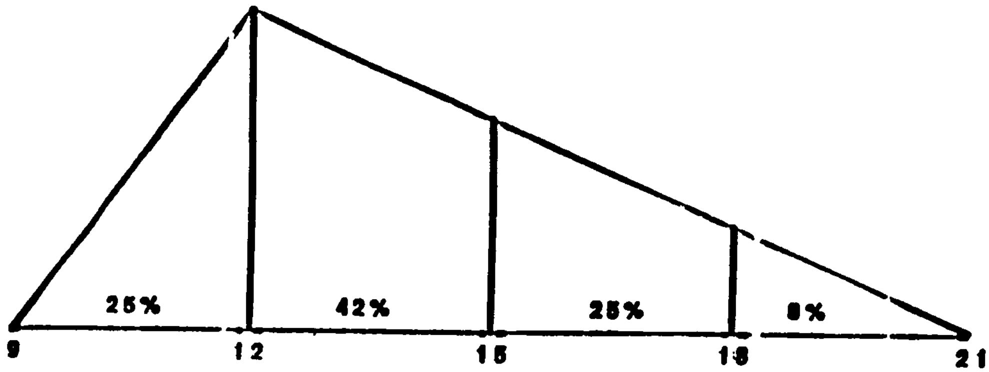


Figure 3. Common failure downtime assumption.

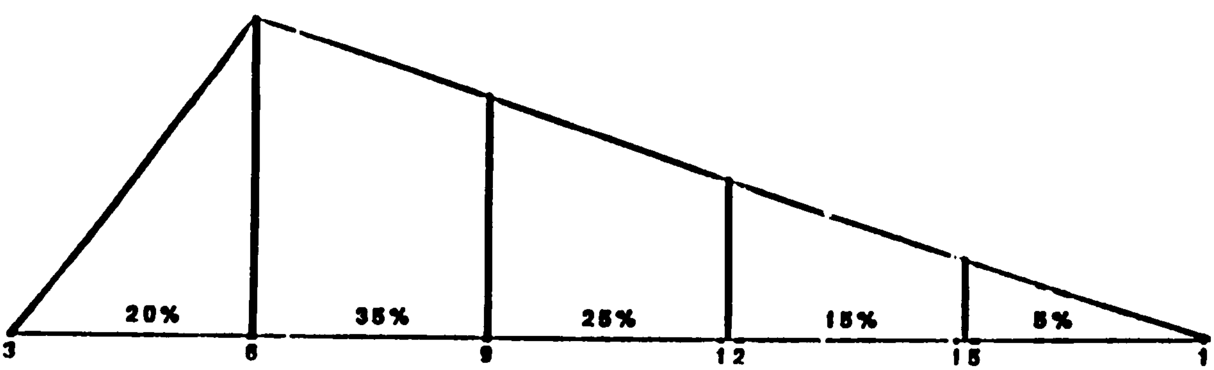


Figure 4. Unique failure downtime assumption.

For unique failure downtimes, the values of a, m, and b are equal to 91.25 (0.25*365), 182.5 (0.5*365), and 547.5 (1.5*365) (days), respectively. Since the unique failures correspond to subsystems not shared by other vehicles (e.g., landing gear, aerosurfaces, and actuators), the choice of 6 months as a mode reflects a belief that most (80 percent) of the downtimes will last less than a year, and only a few (5 percent) will last longer than 15 months (fig. 4).[12]

C. Vehicle Operation Time

The time of vehicle operation (years) was determined by the vehicle manifest (table 1). It is viewed as the year of the first launch to the year of the last launch (even if there are zero flights in a year somewhere in between).

D. Costs

All costs entered into the model were provided by the Engineering Cost Group/Preliminary Design Office, NASA-MSFC.[13] However, government-developed costs for proposed vehicles are "sensitive." Consequently, the empirical data was coded to preserve the sensitive nature of the data.

The definition of these costs are as follows:

DDT&E—All costs associated with the actual design, development, testing, and evaluation of the vehicle.

Ownership—The base cost of owning the vehicle.

Lost Payload—The payload cost incurred when a failure occurs.

Lost Hardware—The cost of the lost vehicle due to failure.

Flight—All costs associated with launching the vehicle.

V. MODEL DEVELOPMENT

After subjecting a nominal launch schedule to a probabilistic environment, what would be the achieved launch rate? How would the failures and downtimes affect costs? How resilient would the architecture be? Questions like these can be answered after simulation runs of the sensitivity model have been accomplished.

The components of the model are as follows:

1. Representation of the architecture
2. Variables used in the execution of the model
3. Data input to the model
4. Actual runs of the model
5. Tabulation of the model results.

A. Simulation Language

The simulation language SLAM (Simulation Language for Alternative Modeling) developed by A. Alan B. Pritsker and C. Dennis Pegden was utilized for the purpose of building this model. SLAM is a widely used simulation language capable of modeling a variety of systems. With SLAM, systems can be depicted using a combination of network symbols, discrete events, or continuous representations. This flexibility permits one to accurately model virtually any process, including manufacturing operations, transportation systems, communication networks, computer systems, military operations, and material handling systems. Symbols, rather than complicated commands, provide the framework for all model building. Most important perhaps is the ability to build, simulate, analyze, compare, and present models of a wide variety without ever leaving SLAM (SLAMSYSTEM).

B. Basic Assumptions

Simulating a system such as this is a complicated procedure, especially when several of the vehicles are only proposed. It is unlikely that every possibility and condition can be taken into account.

A number of assumptions have been made in the development of this model. Assumptions were made to avoid an abundance of detail that would obstruct the true goals of this model. The following assumptions have been made concerning the vehicles that will be studied in this model:

1. Only subsystem downtimes can affect vehicle availability.

2. There will always be enough subsystems (boosters, cores, engines, etc.) available for integration.

3. Once all subsystems required by a particular vehicle are available, the vehicle will attempt launch.

4. Ground operation tasks of preparing the vehicles are assumed effective and are not modeled.

5. Any failure of major subsystems at launch is catastrophic.

6. All vehicles except STS are produced at a rate that would not affect the flight rate even if a failure occurs.

7. Downtimes are assumed triangularly distributed.

8. STME reliability is assumed to be the same as SSME reliability.

9. The STS is comprised of four orbiters (initially).

10. No time value of money considerations (cost in 1990 constant dollars).

C. Data Input and Initialization

Before executing the model, the user must input various information such as the vehicle reliability, probability of common and unique failures, reliability of subsystems, and the prescribed flight rates.

The reliability of the PLS and three ETD vehicles are derived from the reliability of STS, while Titan IV reliability was obtained from an OTA publication (see section IV). Depending upon the assumed reliability of STS (0.97, 0.98, and 0.99), the other vehicles will take on reliability values comparable to STS using the same subsystem reliabilities assigned to STS subsystems.

D. Model Characteristics

Basic to the description of model characteristics are the following variables:

1. Flight Requests—Flight requests are generated based on the flight manifest (table 1). A flight request does not guarantee a vehicle launch.

2. Launch Authorization—All vehicles have one launch authorization. Once the launch authorization has been issued, and all subsystems are operational, the vehicle can attempt launch. The launch authorization for any vehicle is not issued again until the current vehicle (in possession of the launch authorization) either launches successfully, in which case the launch authorization is returned to the launch authorization center, or until the vehicle/subsystem experiences downtime (in the case of a failure) and is again flight ready.

3. Launch Authorization Center—The launch authorization center is where the flight requests must wait for launch authorization. All vehicles have one launch authorization center.

4. Vehicle—A vehicle is the entity that makes the launch attempt. It is the union of a flight request and a launch authorization.

Certain criteria must be met before a vehicle attempts a launch:

1. All subsystems must be operational

2. The launch authorization must be issued.

In addition to the above criteria, STS must also have an available orbiter.

A flight request is made to wait in the launch authorization center when:

1. The launch authorization is being used by another vehicle at the time of the flight request arrival.

2. A common subsystem has failed and has thereby halted flights of any vehicle requiring the subsystem (the launch authorization has not been released).

STS flight requests do not wait but are immediately routed to the PLS and ETD1 launch authorization centers where they are given priority over any waiting PLS and ETD1 flight requests. This is done to ensure that all STS personnel and cargo flights are launched. STS is the primary space station support system. The other vehicles alleviate the flight demands placed on STS.

The general flow of the sensitivity analysis model is as follows:

1. The flight request arrives at the launch authorization center.

2. The flight request resides at the launch authorization center until a launch authorization is available. If a launch authorization is available upon the arrival of the flight request, it seizes the launch authorization.

3. The vehicle (flight request plus launch authorization) now attempts launch.

(a) Following a successful launch, the launch authorization is released and returned to the launch authorization center. For STS, an orbiter is released as well.

(b) Following an unsuccessful launch, the launch authorization is not released until the failure cause has been determined and repaired (downtime). For STS, the current orbiter is destroyed and a new orbiter must take its place. The time required to replace the orbiter is approximately 5 years.[11]

4. The launch authorization having been returned to the launch authorization center, the flight request exits the system.

A flowchart of the sensitivity model is presented in figures 5, 6, 7, and 8.

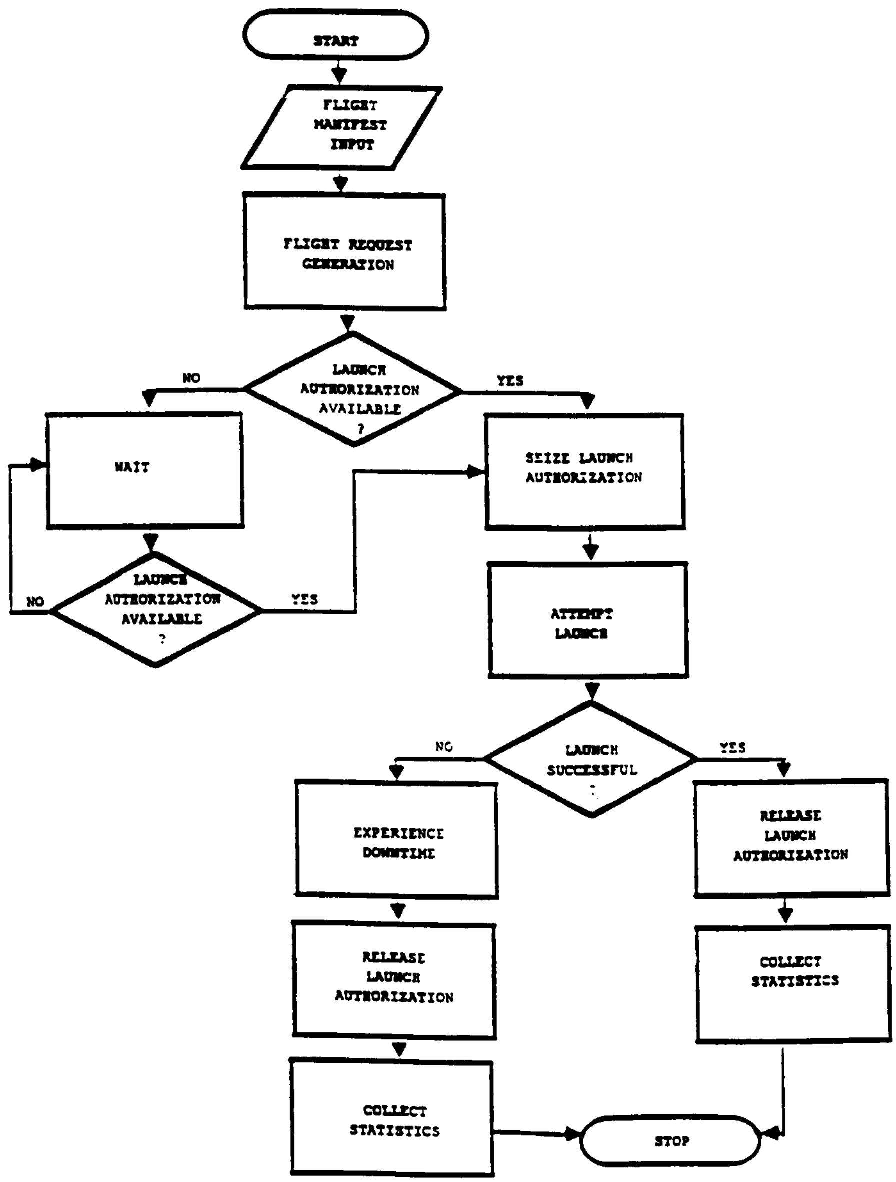


Figure 5. Sensitivity analysis model (Titan IV flow).

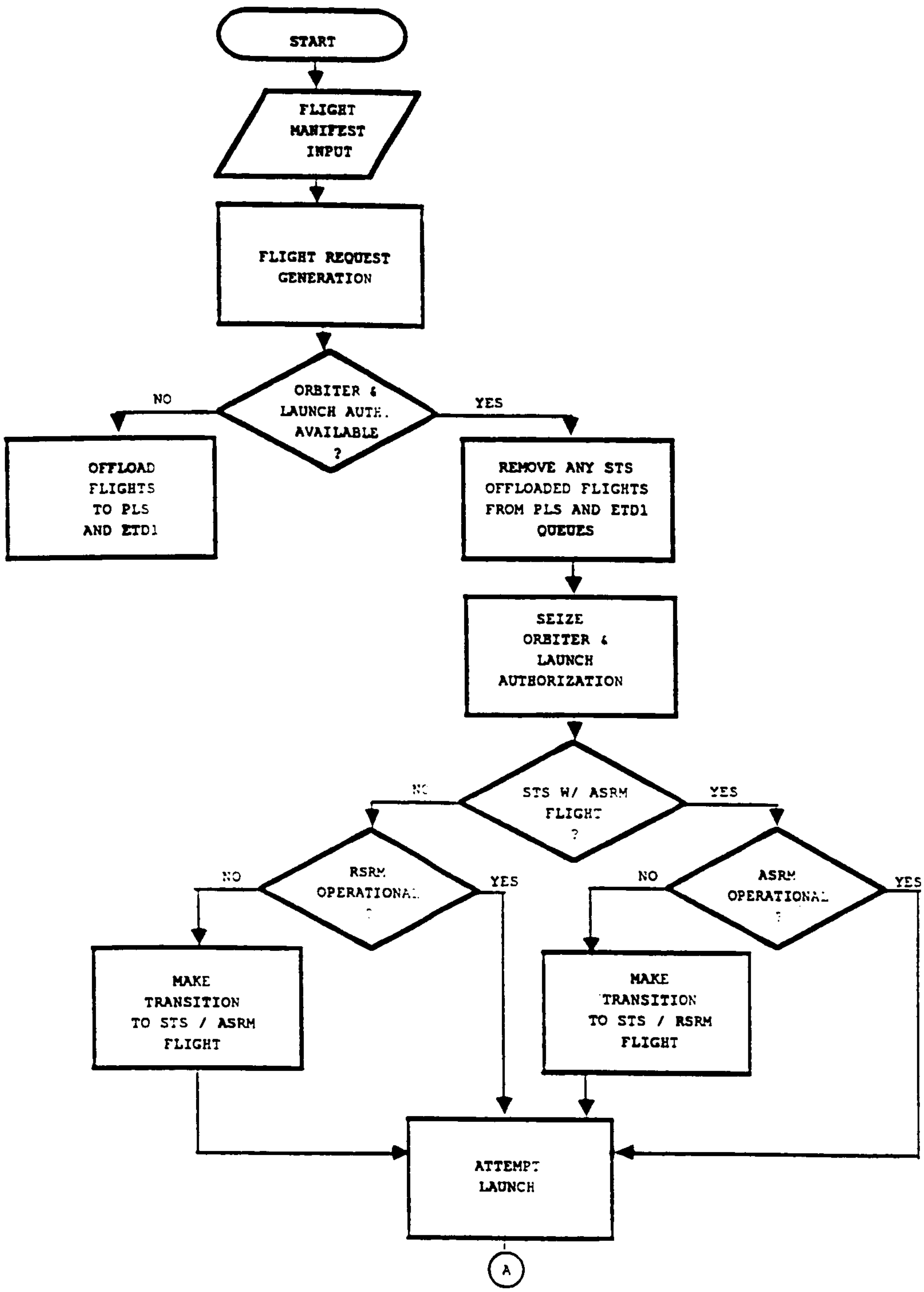


Figure 6. Sensitivity analysis model (STS flow).

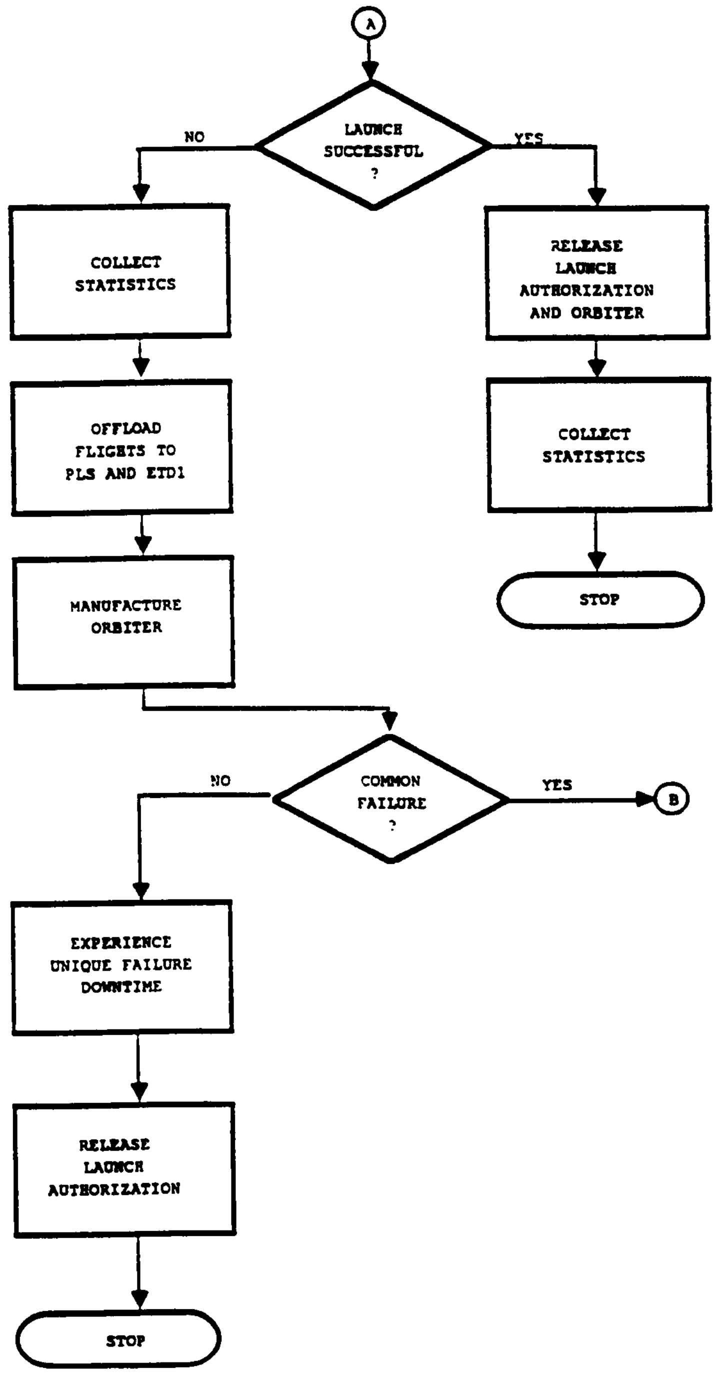


Figure 6. Sensitivity analysis model (STS flow) (continued).

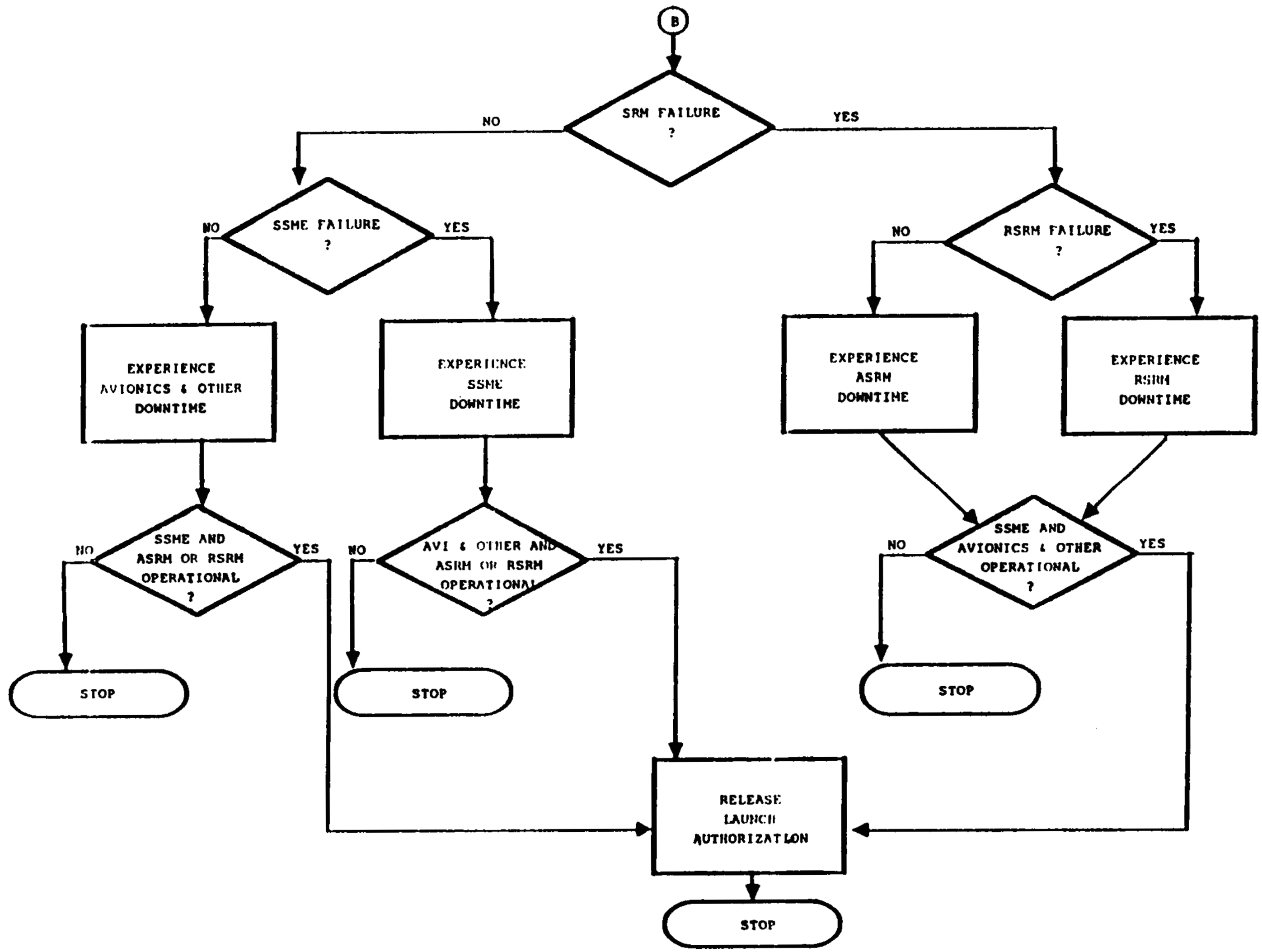


Figure 6. Sensitivity analysis model (STS flow) (continued).

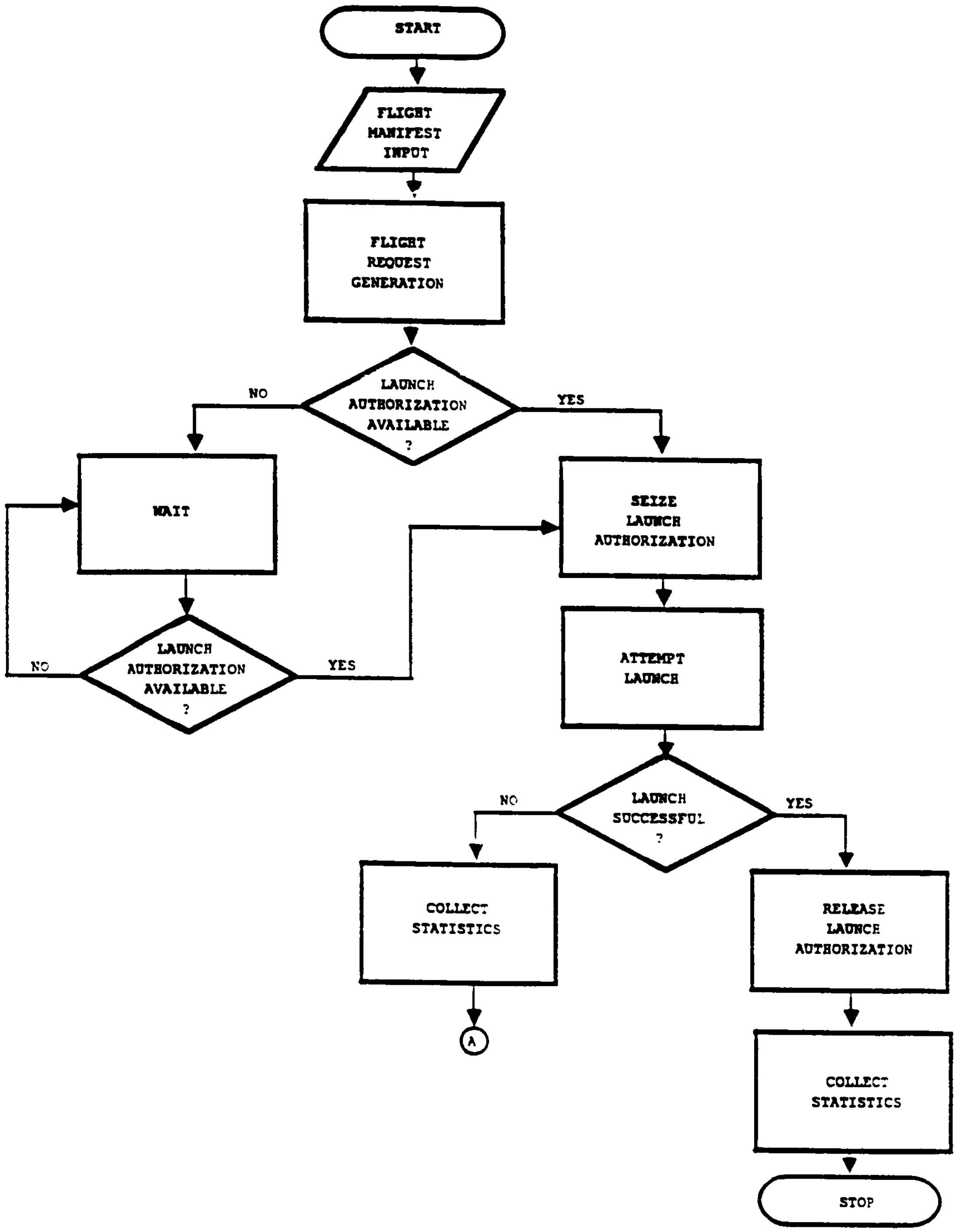


Figure 7. Sensitivity analysis model (ETD vehicle flow).

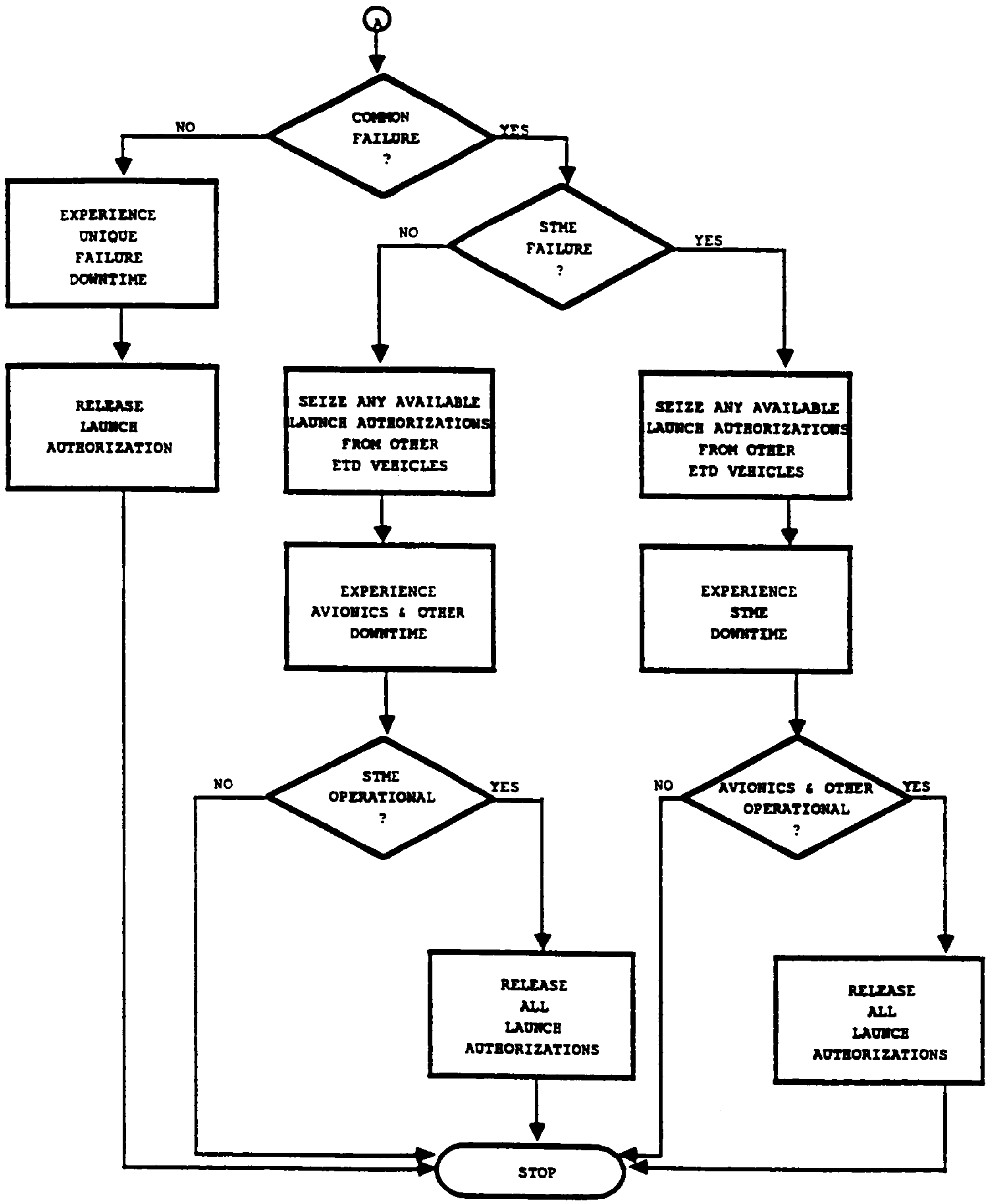
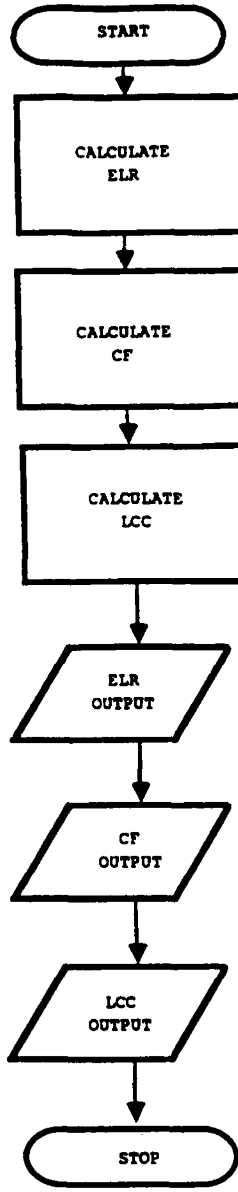


Figure 7. Sensitivity analysis model (ETD vehicle flow) (continued).



* End of run activity

Figure 8. Sensitivity analysis model (common to all vehicle flows).

E. Model Output

The sensitivity analysis model is evaluated by examining the output of the model. The output aids the user in determining the accuracy of the model's performance; and in this analysis, it allows the user to recognize the sensitivity of the model to various changes in the data input.

The SLAM II output summary report includes the following:

1. General information such as project name, modeler name, date, run number, and current time at end of run.

2. Statistics for selected collection points including mean, standard deviation, coefficient of variation, minimum values, maximum values, and number of observations.

3. File statistics for queues/AWAIT nodes such as file number, file label, file type, average length, standard deviation, maximum length, current length, and average wait time.

4. Regular activity statistics such as index/label, average utilization, standard deviation, maximum utilization, current utilization, and entity count.

5. Service activity statistics such as activity number, activity label or start node, server capacity, average utilization, standard deviation, current utilization, average block, maximum idle time per server, maximum busy time per server, and entity count.

F. Model Versatility

The model is structured such that the user may input any flight manifest for the vehicles. This feature is useful in determining the sensitivity of the model to increased or decreased flights per vehicle. The user may also decrease the number of vehicles in the model. The user can change the number of SRM's from two (dual subsystem) to one. This is useful to study the effects of having dual versus single boosters. The user can change the downtime length to discover the implication of shorter versus longer downtimes.

G. Model Limitations

Due to the structure of the NLS architecture, the maximum vehicle types allowed in the model is six.

Uncertainty in connection with the actual reliability of existing vehicles introduces additional limitations to the model. Allowing the reliability to be determined by a random process, rather than using assigned reliability values (0.97, 0.98, 0.99), would enhance the real world portrayal of the model.

VI. MODEL VALIDATION

Before the end results of a developed simulation model are analyzed, the simulation program needs to be validated. It is necessary to determine if the program sufficiently simulates real world occurrences. This entails making a comparison between the results of the program and observed data in the real world.[4]

> Validation is the determination that a model is an accurate representation of the real system. Validation is usually achieved through the calibration of the model, an iterative process of comparing the model to actual system behavior and using the discrepancies between the two, and the insights gained, to improve the model.[4]

The basis of this report is a sensitivity analysis model. There is no real-world data with which to compare program results. Without any real data as a standard of comparison, the only way to validate the overall model is to have knowledgeable people carefully check the credibility of output data for a variety of situations.[2] It is virtually impossible to prove that any model is 100-percent valid; however, there are ways to demonstrate a high level of validity.

Two sets of statistics that can give a quick indication of model reasonableness are "current contents" and "total count." These statistics apply to any system having items of some kind flowing through it, whether these items are called customers, transactions, inventory, or vehicles. Current contents refers to the number of items in each component of the system at a given time. Total count refers to the total number of items that have entered each component of the system by a given time.[4] The SLAM summary report produces both statistics. For purposes of validating the sensitivity analysis model, the statistic of interest will be total count.

The method chosen to evaluate the model will be to run the model for extreme conditions. One such extreme condition is vehicle reliabilities of 100 percent. At 100 percent reliability, one would expect no failures to occur and the effective launch rate to equal the nominal launch rate. Another extreme condition worth consideration is to eliminate downtimes, or to introduce a downtime so small that it would have little or no effect on the model. For example, if the downtimes are assigned as zero you would expect all flight requests to be launched since the launch authorization cannot be delayed by downtimes and therefore would always be available. However, this does not mean that all launches will be successful.

A. 100-Percent Vehicle Reliability

Table 6 shows the results of 100-percent vehicle reliability. Results readily identified are the failure values recorded. All vehicle failure observations are listed as "No Values Recorded." This means that there were no failures. The effective ELR observation equals the nominal launch rate. To obtain the SLAM II ELR values, the total number of flights from the manifest must be divided by the number of operational years for each vehicle. For example, Titan IV has a nominal launch rate of 5.58 flights per year (173 flights in 31 years). From column 7 of table 6, Titan IV shows 5,190 flights; 5,190 flights in 30 years equals 173 flights per year and 173 flights in 31 years equals 5.58 flights per year. Therefore, because the launch rate at 100-percent vehicle reliability does generate the anticipated "perfect" run results, the 100-percent vehicle reliability condition adds validity to the model.

Table 6. 100-percent vehicle reliability case.

```
                    S L A M   I I   S U M M A R Y   R E P O R T

SIMULATION PROJECT THESIS                         BY WILLIAMS

DATE  2/11/1991                                   RUN NUMBER   30 OF   30


CURRENT TIME     .1131E+05
STATISTICAL ARRAYS CLEARED AT TIME    .0000E+00

              **STATISTICS FOR VARIABLES BASED ON OBSERVATION**
```

(1)	(2) MEAN VALUE	(3) STANDARD DEVIATION	(4) COEFF. OF VARIATION	(5) MINIMUM VALUE	(6) MAXIMUM VALUE	(7) NO.OF OBS
TIT SUCC	.870E+02	.499E+02	.574E+00	.100E+01	.173E+03	5190
TIT FAIL			NO VALUES	RECORDED		
STS SUCC	.151E+03	.869E+02	.575E+00	.100E+01	.301E+03	9030
STS FAIL			NO VALUES	RECORDED		
PLS SUCC	.850E+01	.461E+01	.543E+00	.100E+01	.160E+02	480
PLS FAIL			NO VALUES	RECORDED		
ETD1 SUCC	.695E+02	.398E+02	.573E+00	.100E+01	.138E+03	4140
ETD1 FAIL			NO VALUES	RECORDED		
ETD2 SUCC	.185E+02	.104E+02	.562E+00	.100E+01	.360E+02	1080
ETD2 FAIL			NO VALUES	RECORDED		
ETD3 SUCC	.120E+02	.664E+01	.553E+00	.100E+01	.230E+02	690
ETD3 FAIL			NO VALUES	RECORDED		

B. Zero Downtime

A smaller number of runs (10) was necessary for this case in order to include sections of the summary report.

If the model is performing as expected, 10 runs of the model with zero downtimes should generate vehicle launch attempts as follows: 1,730 for Titan IV, 3,100 for STS, 160 plus any STS failure offloads for PLS, 1,380 plus any STS failure offloads for ETD1, 360 for ETD2, and 230 for ETD3. The success or failure values recorded in table 7 (column 7) plainly show that all flight requests were honored for Titan IV, STS, ETD2, and ETD3; however, this is not readily identified with the PLS and ETD1 recorded values. The summary report provides data that will substantiate the postulation that all PLS and ETD1 flight requests were honored.

Table 7. Zero downtime case.

S L A M I I S U M M A R Y R E P O R T

SIMULATION PROJECT THESIS BY WILLIAMS

DATE 2/11/1991 RUN NUMBER 10 OF 10

CURRENT TIME .1131E+05
STATISTICAL ARRAYS CLEARED AT TIME .0000E+00

STATISTICS FOR VARIABLES BASED ON OBSERVATION

(1)	(2) MEAN VALUE	(3) STANDARD DEVIATION	(4) COEFF. OF VARIATION	(5) MINIMUM VALUE	(6) MAXIMUM VALUE	(7) NO.OF OBS
TIT SUCC	.853E+02	.490E+02	.574E+00	.100E+01	.172E+03	1696
TIT FAIL	.259E+01	.156E+01	.602E+00	.100E+01	.700E+01	34
STS SUCC	.148E+03	.853E+02	.576E+00	.100E+01	.298E+03	2955
STS FAIL	.365E+01	.234E+01	.641E+00	.100E+01	.110E+02	55
PLS SUCC	.100E+02	.556E+01	.556E+00	.100E+01	.210E+02	189
PLS FAIL	.100E+01	.000E+00	.000E+00	.100E+01	.100E+01	1
ETD1 SUCC	.708E+02	.406E+02	.574E+00	.100E+01	.143E+03	1405
ETD1 FAIL	.171E+01	.825E+00	.481E+00	.100E+01	.300E+01	14
ETD2 SUCC	.174E+02	.981E+01	.563E+00	.100E+01	.360E+02	338
ETD2 FAIL	.195E+01	.999E+00	.511E+00	.100E+01	.400E+01	22
ETD3 SUCC	.112E+02	.620E+01	.555E+00	.100E+01	.230E+02	213
ETD3 FAIL	.165E+01	.786E+00	.477E+00	.100E+01	.300E+01	17

Section III explained that for every STS flight request when STS is nonoperational or when STS has experienced a failure, two flights are offloaded; one to PLS and one to ETD1. Section III further explained that the ETD1 and PLS do not become available until 2000 and 2003, respectively. For that reason, the absence of flights in the total count for these vehicles can be attributed to failures that occurred prior to the ETD1 and PLS coming on line. Activities of interest (see "Activity Index/Label" column) are numbers 49, 50, and 91. Activity 49 represents the number of flights per run offloaded to PLS, activity 50 represents the number of flights per run offloaded to ETD1, and activity 91 represents the total number of attempted offloads. These values are tabulated in table 8.

Ignoring the initial operational dates for PLS and ETD1, the 55 STS failures, as identified in column 7 of table 7, would increase the number of flights of the PLS and ETD1 vehicles from 160 to 215 for PLS and from 1,380 to 1,435 for ETD1. The summary report of table 7 shows 190

Table 8. Tabulation of STS offloads.

Run #	Offloads To PLS (Act #49)	Offloads To ETD1 (Act #50)	Total Offloads (Act #91)
1	5	5	5
2	2	3	6
3	5	6	7
4	2	2	5
5	4	4	5
6	3	4	5
7	5	8	11
8	2	3	4
9	1	1	3
10	1	3	4
Total	30	39	55

(189 successes, 1 failure) PLS flights and 1,419 (1,405 successes, 14 failures) ETD flights. This yields a delta of 25 (215–190) PLS flights and 16 (1,435–1,419) ETD1 flights. However, as table 8 reveals, of the 55 attempted offloads, only 30 were successfully offloaded to PLS and 39 to ETD1, thus accounting for the deltas of 25 and 16 since 30+25=55, and 39+16=55. The unsuccessful offloads occurred prior to the PLS and ETD1 operational dates. Therefore, as expected, all launch requests were honored. Because the anticipated launch attempts are equal to the number of flight requests the zero downtime condition also adds validity to the model.

VII. RESULTS

This analysis closely examines the implications of vehicle reliabilities ranging from 0.97 to 0.99. The analysis involved determining the effective or expected launch rates (ELR) for all vehicles in the architecture and the costs connected with the failure (CF) and life (LCC) of those vehicles. The tools used were observed vehicle failure probabilities and downtimes, data based on engineering judgment, and the development of a sensitivity analysis program.

The ELR was calculated as follows:

ELR = number of launch attempts/horizon (flights per year)

where horizon is defined as the number of operational years of the vehicle. The launch attempts are summed by the program.

The CF was calculated as follows:

$$CF = \underbrace{(COP * APC)}_{CP} * (\text{number of failures}) \quad (\$B)$$

where CP is the cost of payload due to a failure ($B), COP is the cost of lost payload ($k/lb), and APC is the adjusted payload capability (100 klb/flight). This equation is modified by adding a vehicle manufacturing cost for STS and PLS to accommodate the loss of a reusable vehicle. The other vehicles are considered expendable and do not require any additional cost considerations.

The LCC was calculated as follows:

$$LCC = CPF * (\text{number of attempts}) + CBH * \text{horizon} + CF + DDTE \quad (\$B)$$

where CPF is the cost per flight ($B/flight), CBH is the cost of vehicle ownership ($B/year), and DDTE is the design, development, testing, and evaluation phase of the vehicle's life ($B).

The sensitivity analysis program allows the user to gather information about each vehicle's expected launch rate, or the actual number of flights launched. The results show (fig. 9), as expected, that the effective launch rate is directly related to vehicle reliabilities. As vehicle reliabilities increase, the effective launch rates increase. Note, however, that as the shuttle reliability increases, the PLS and ETD1 ELR's decrease. This is due to the elimination of offloading to these vehicles caused by shuttle failures. In the section III discussion on manned vehicles, it was noted that STS offloads flights when a failure occurs, or if a flight is requested and the STS system is not operational. As a result of that, as STS becomes more reliable, the lower flight rates will be for the PLS and ETD1 vehicles; and conversely, as STS becomes less

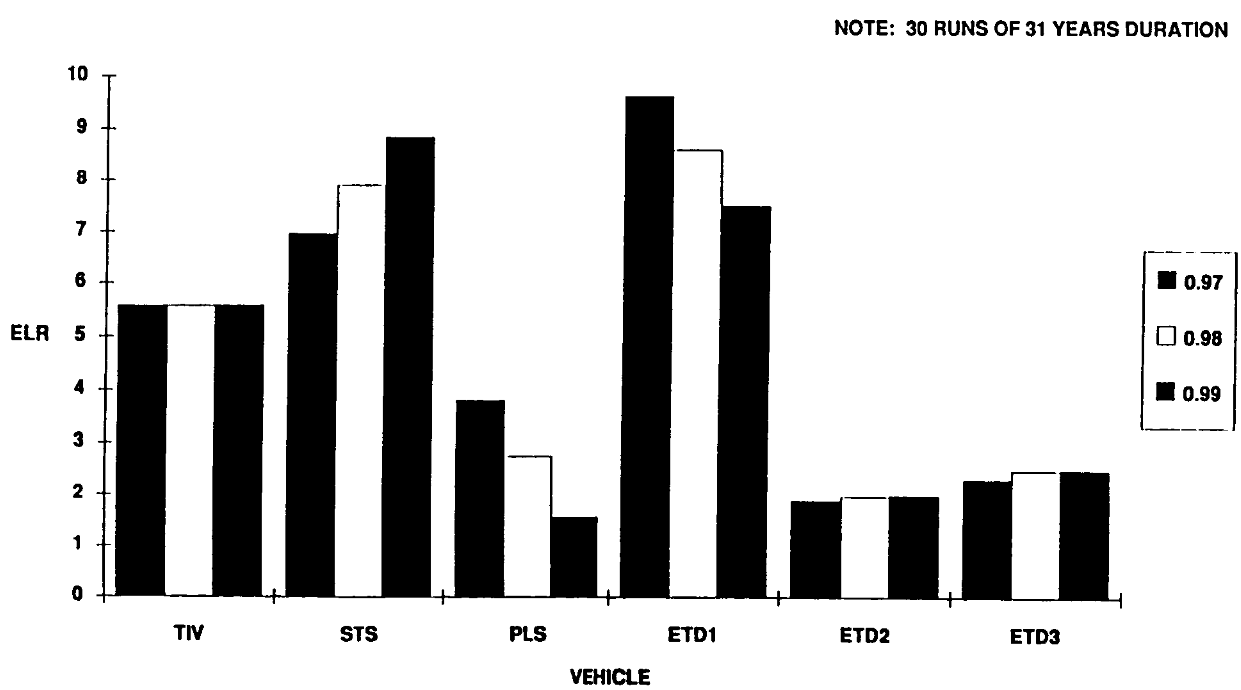


Figure 9. Effective launch rates.

reliable, the higher the flight rates will be for the PLS and ETD1 vehicles. The vehicles that are not assigned very demanding flight rates (ETD2 and ETD3) are really not gaining anything by having a higher reliability. Both ETD2 and ETD3 are averaging approximately the same ELR for all three cases (0.97, 0.98, and 0.99). Also, the Titan IV vehicle, which operates independent of other vehicles, does not show improvement or decline with separate reliability assignments.

The results cited thus far all have to do with the launch rates of the vehicles. However, costs are closely connected with launch rates. The cost accrued with vehicle failures, as well as the life cycle costs, can be accessed by the user without difficulty.

As expected, costs are inversely related to vehicle reliabilties. The more reliable the vehicle, the less the costs accrued over the life of the vehicle, as well as the costs due to vehicle failure. Note that both the cost of failure and life cycle cost values are decreasing as the reliability of the vehicles increase. Figure 10 demonstrates the inverse relationship between cost of failure and reliability. Figure 11 demonstrates the inverse relationship between life cycle cost and reliability. A consolidation of figures 9 and 11 generated figures 12 to 17. For each vehicle, these figures demonstrate both ELR and LCC sensitivity to the reliability range 0.97 to 0.99.

Other results obtainable at the end of each run are:

1. Number of failures of a specific type (SSME, ASRM, avionics, etc.)

2. Number of flight attempts, successes, and failures.

3. Number of attempted and actual offloaded flights.

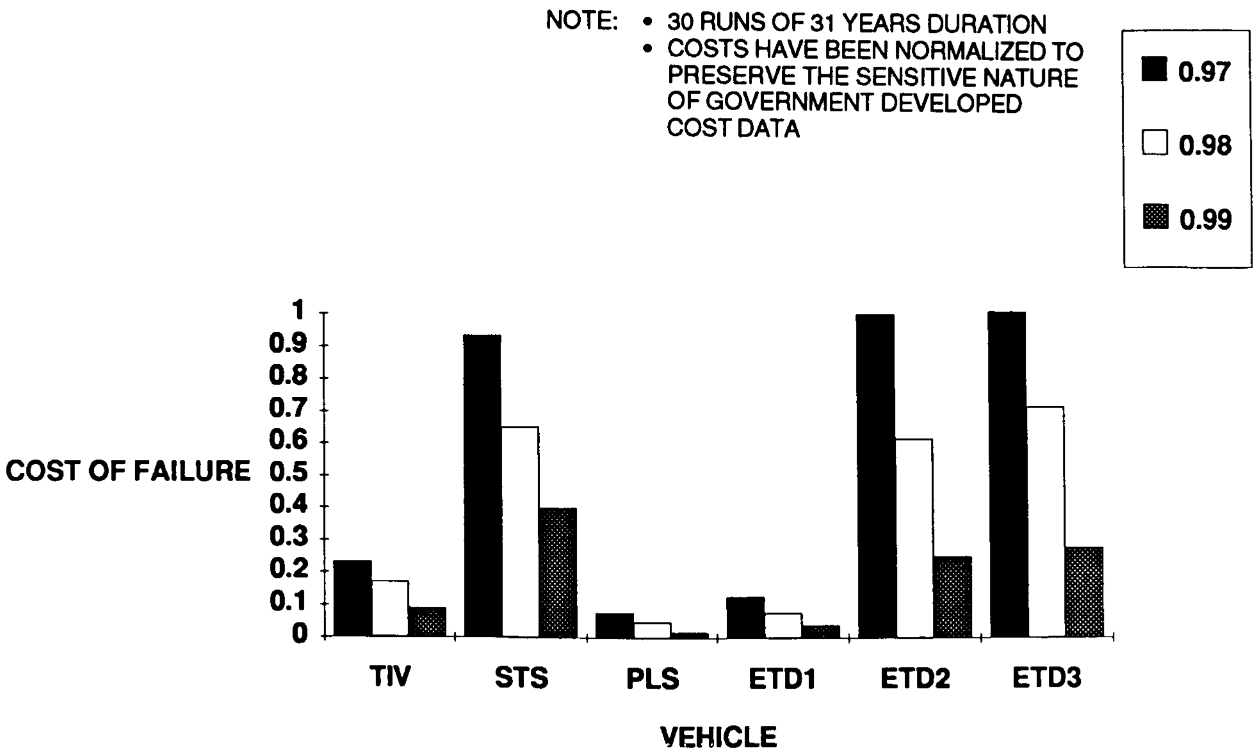


Figure 10. Cost of failure.

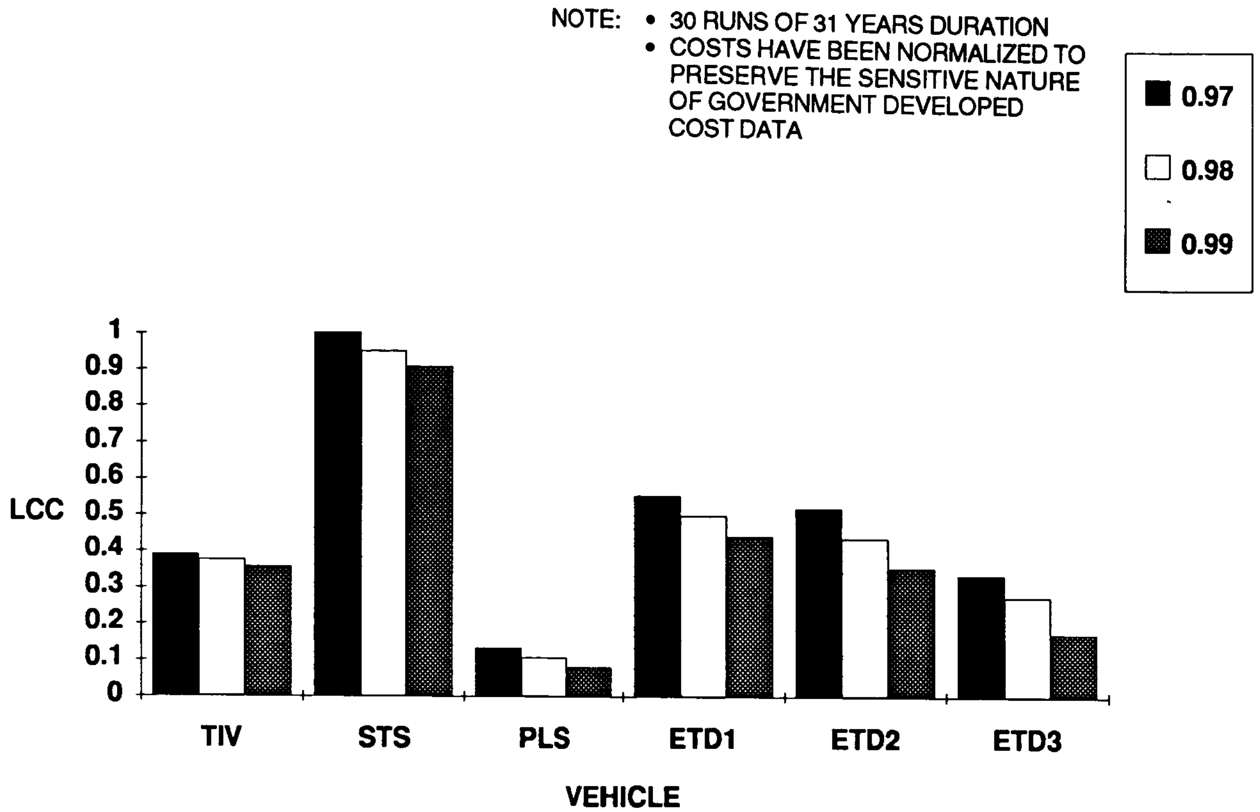


Figure 11. Life cycle cost.

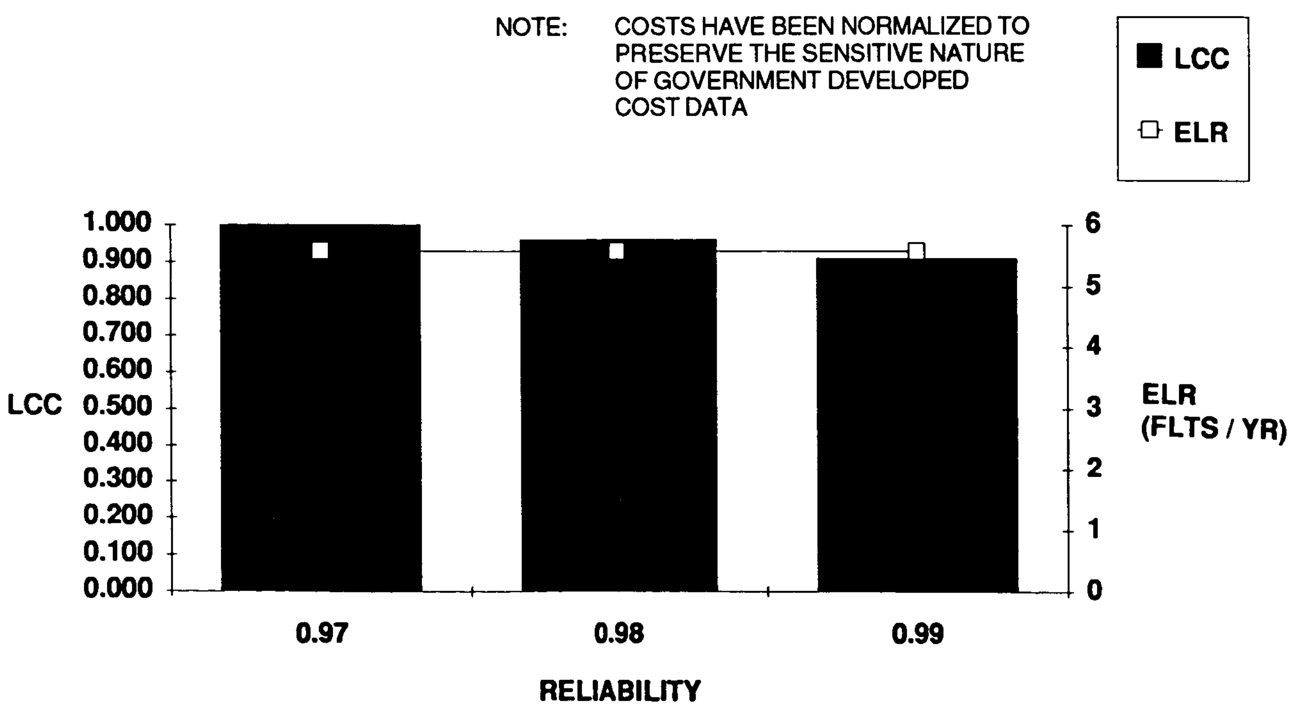


Figure 12. TIV ELR and LCC sensitivity to reliability.

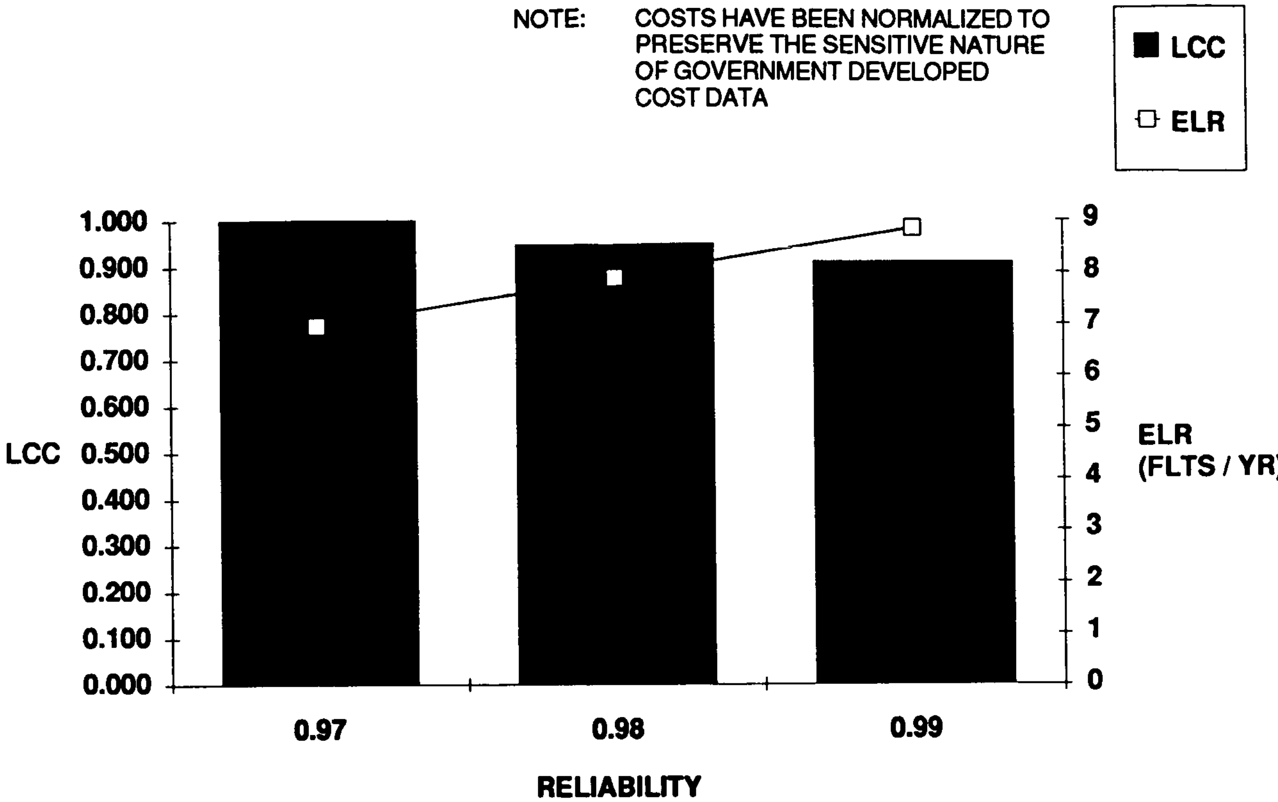


Figure 13. STS ELR and LCC sensitivity to reliability.

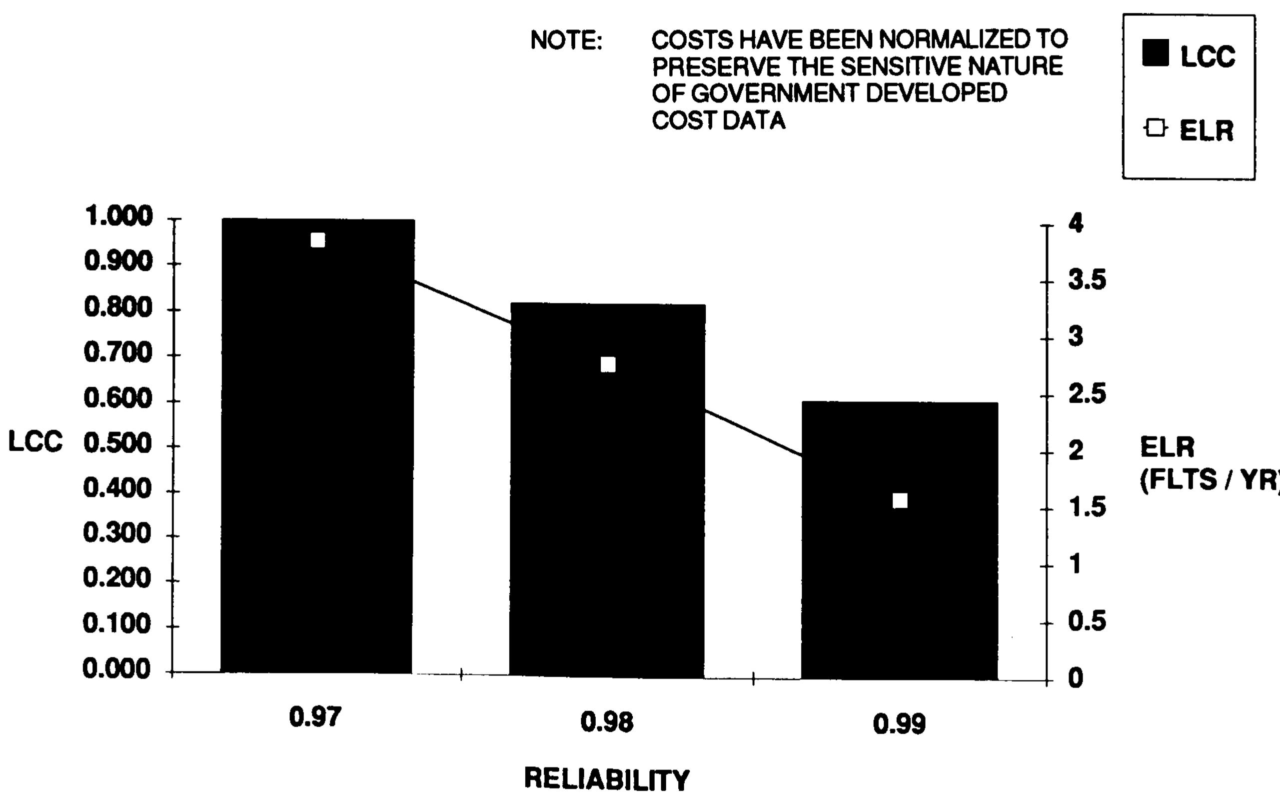


Figure 14. PLS ELR and LCC sensitivity to reliability.

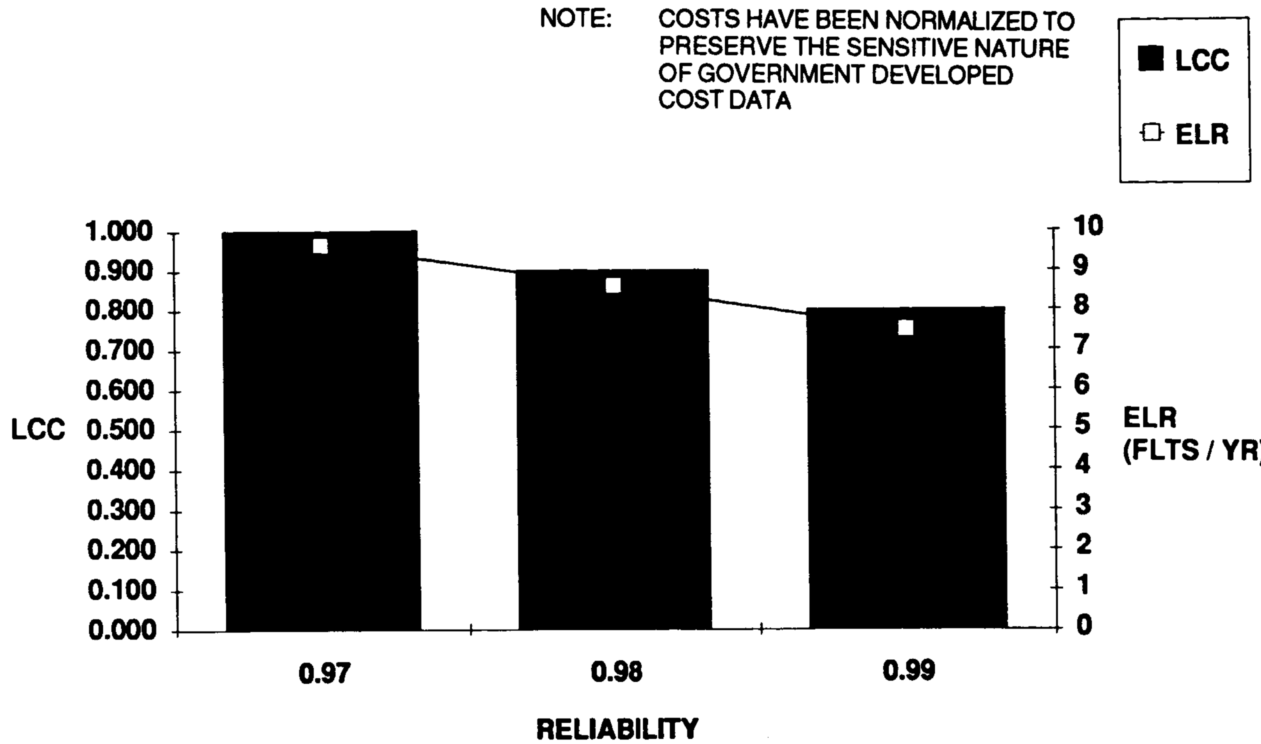


Figure 15. ETD1 ELR and LCC sensitivity to reliability.

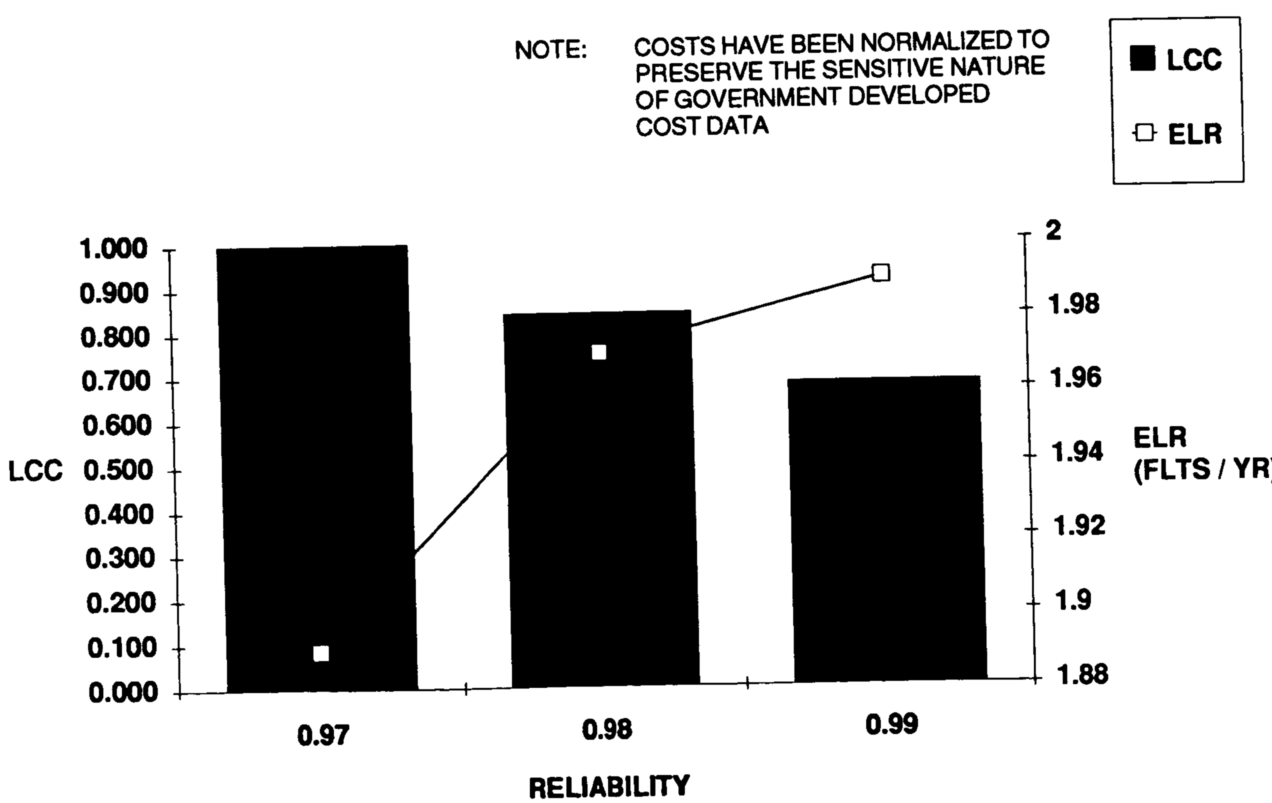


Figure 16. ETD2 ELR and LCC sensitivity to reliability.

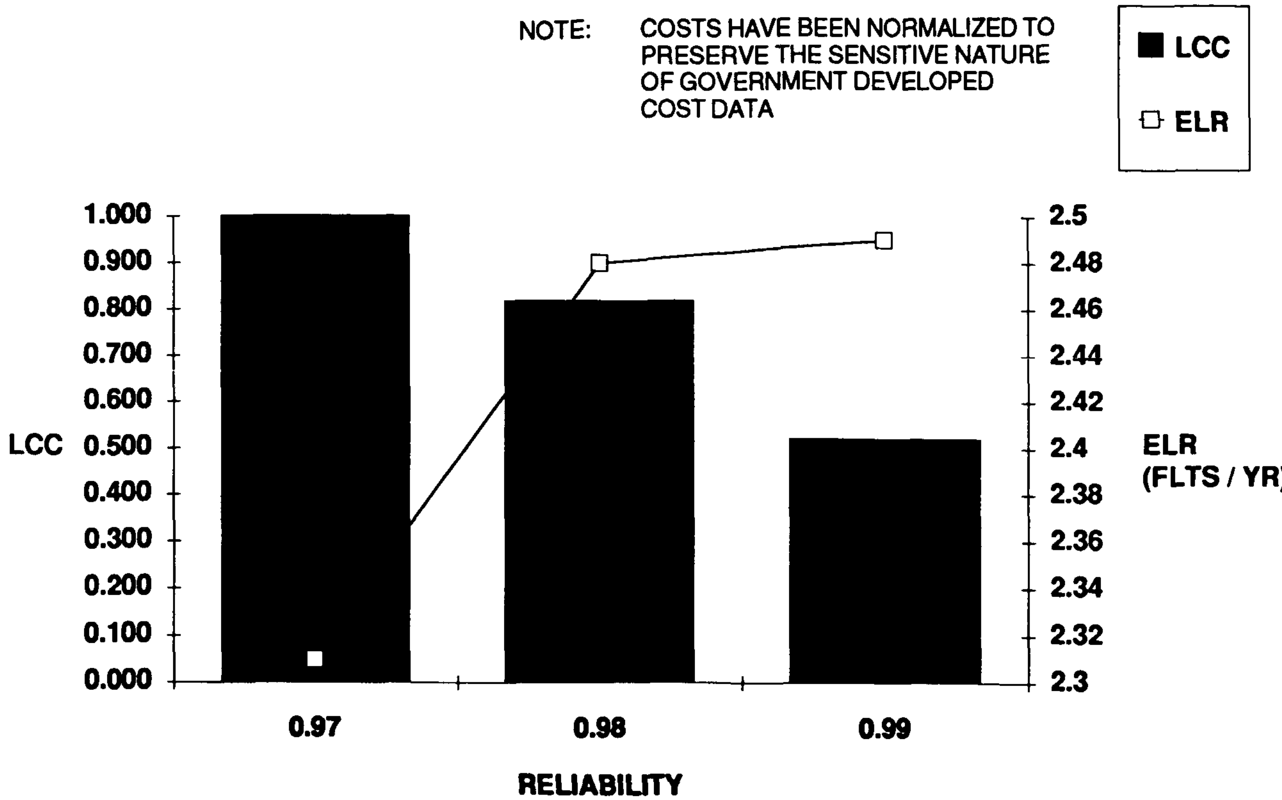


Figure 17. ETD3 ELR and LCC sensitivity to reliability.

VIII. CONCLUSIONS AND RECOMMENDATIONS

NASA has an increasing determination to once again be the forerunner in space endeavors. Permanent lunar bases and Space Station *Freedom* are just two concepts that NASA envisions for the next century. However, these concepts would require transportation systems responsible for cargo or logistics delivery, as well as transfer of personnel to and from these installations. The architecture studied in this report is one possible transportation system to satisfy these requirements.

Most of the vehicles that comprise the architecture are proposed. The only existing vehicle with similar subsystems has not been operational long enough to provide reliability data that would support proposed vehicles. As shown in this study, a sensitivity analysis model is a valuable tool to evaluate the architecture.

The purpose of this report was not to certify or annul any particular reliability estimate of the vehicles, but to reveal the sensitivity of the architecture to varied reliability allocations.

It has been shown that effective launch rate is directly related to vehicle reliability. It has also been shown that both life cycle cost and failure cost are inversely related to reliability. Furthermore, there is evidence that vehicles in the architecture with complete autonomy, such as Titan IV, will more likely achieve the planned launch rate. Moreover, the ELR/reliability relationships for ETD2 and ETD3 suggest that vehicles with low flight rates are scarcely affected by reliability. Low flight rates present fewer chances for failure.

At this stage of NASA's analysis of this and other architectures, two considerations must be taken into account before making recommendations:

1. Funding is a limiting factor on how much the architectures may be modified. For example, to bring new elements on line earlier than scheduled may enhance the performance of the system; however, this action may also prove to be more costly than the present funding will allow.

2. The plans and designs of the architecture at this point are flexible. A fixed program with fixed funding presents less of a challenge to design, develop, and implement.

With this in mind, recommendations are somewhat constrained. However, facts revealed during the analysis of this architecture will be presented.

It is intuitively obvious from the results of section VII that it would be to NASA's advantage to look closely at the human risk involved with a vehicle's failure to respond to emergencies or deliver logistics in a timely fashion. Even at an assumed reliability of 99 percent there will be failures.

The cost activity generated by the model is inversely related to reliability. This suggests that in order to lower costs one must design a very reliable vehicle. Although it is impossible to design a vehicle to meet a specified reliability value exactly, a system may be designed for reliability.

Blanchard and Fabrycky[3] explain that reliability is an inherent characteristic of design and must be an integral part of the overall systems engineering process. Reliability requirements are defined in conceptual design, reliability analyses and predictions are accomplished throughout preliminary and detail system/product design, reliability is considered in formal design reviews, and reliability testing is accomplished as part of system test and evaluation. Thus, reliability (along with other major design parameters) is considered throughout the system life cycle and is particularly relevant during the early phases of system design and development.

Therefore, the only practicable recommendations regarding lowering costs are as outlined in the aforementioned book. The objective is to plan a program effort that will assure reliability involvement throughout all aspects of system design and development, production or construction, and system utilization. A reliability program plan is usually prepared at program inception and may be included as part of the system engineering management plan.

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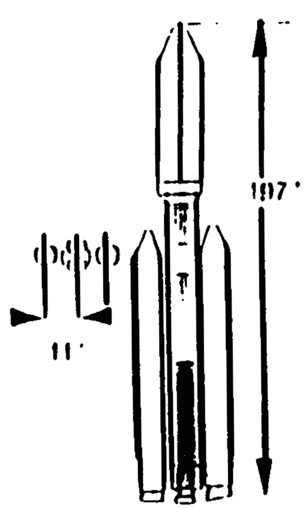
APPENDIX A

VEHICLE DATA SHEETS

EARTH TO ORBIT:
VEHICLE DATA SHEET



VEHICLE TIV(SRMU)

GLOW :	2,049,327.7 lbm
P/L to 220 Circ :	41,000.0 lbm
CORE: Titan IV Core	
TOTAL MASS :	359,079 lbm
DRY MASS :	19,042 lbm
PROP TYPE :	N2O4 / AeroZINE 50
ENG. TYPE/# :	LR-87 AJ-11 / 2
VAC/SL THRUST(EA.) :	260 / 219 Klb
ENG. EXIT AREA/DIAM. :	2745 / 4.92 in2 / ft
DIMENSIONS:	10ft dia X 86 ft length
REUSABLE PARTS :	
BOOSTER: TIV SRMU	
NUMB. OF BOOSTERS :	2
TOTAL MASS(EA.) :	774,055 lbm
DRY MASS(EA.) :	65,293 lbm
PROP TYPE :	AP/Al
ENG. TYPE/# (EA.) :	
VAC/SL THRUST(EA.) :	0 / 195 Klb
ENG. EXIT AREA/DIAM. :	13250 / 10 in2 / ft
DIMENSIONS:	10.5 ft dia. x 112.4 ft length
REUSABLE PARTS :	
FAIRING: Titan IV/Centaur Fairing	
P/L ENVELOPE :	15 ft dia x 60 ft length
FAIRING MASS :	14,425 lbm

COMMENTS:

Payload to 80 Nmi x 95 Nmi = 50,000 lb
2nd stage mass = 125,911.4 lb (Aerozine, N2O4)
2nd stage engine = LR91-AJ-11 (49:1 exp. ratio)
LR91-AJ-11 = 100,850 Vac Thrust, 318 sec. Vac Isp

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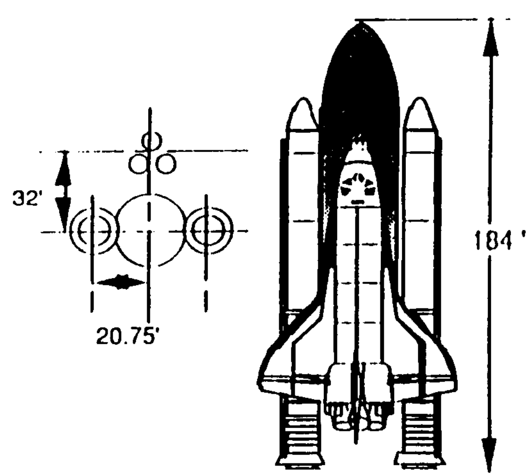
EARTH TO ORBIT: VEHICLE DATA SHEET



IEDB sion June 13, 1990

VEHICLE STS w/ASRMs

GLOW :	4,614,559.0 lbm
P/L to 220 Circ :	52,000.0 lbm

ORBITER: STS Orbiter

TOTAL MASS :	216,048 lbm
DRY MASS :	178,778 lbm
PROP TYPE :	LOX / LH2
ENG. TYPE/# :	SSME / 3
VAC/SL THRUST(EA.) :	470 / 362 Klb
ENG. EXIT AREA/DIAM. :	7298 / 8.03 in2 / ft
DIMENSIONS:	122 ft len. X 78 ft span X 57 ft ht
REUSABLE PARTS :	All major parts incl. 3 SSMEs

BOOSTER: ASRM

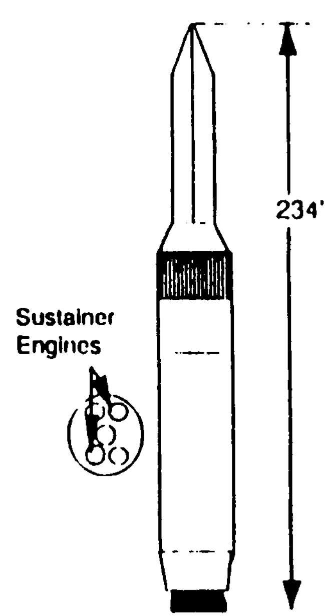
NUMB. OF BOOSTERS :	2
TOTAL MASS(EA.) :	1,345,297 lbm
DRY MASS(EA.) :	139,490 lbm
PROP TYPE :	AP/Al
ENG. TYPE/# (EA.) :	
VAC/SL THRUST(EA.) :	2624 / 2364 Klb
ENG. EXIT AREA/DIAM. :	17655 / 12 in2 / ft
DIMENSIONS:	12.5 ft dia. x 150 ft len.
REUSABLE PARTS :	Case, Nozzle, Chutes

FAIRING:

P/L ENVELOPE :	15 ft dia. X 60 ft length
FAIRING MASS :	lbm

COMMENTS:

EARTH TO ORBIT: VEHICLE DATA SHEET



ETDV ...sion June 13, 1990

VEHICLE ETD1.5

GLOW :	1,808,962 0 lbm
P/L to 220 Circ :	38,437 0 lbm

CORE: LIDC1.5

TOTAL MASS :	1,756,807 lbm
DRY MASS :	157,807 lbm
PROP TYPE :	LOX / LH2
ENG. TYPE/# :	STE-40 / 5
VAC/SL THRUST(EA.) :	580 / 498 Klb
ENG. EXIT AREA/DIAM. :	5537.4 / 6.99 in2 / ft
DIMENSIONS:	27.6 ft diam x 167 ft len
REUSABLE PARTS :	

BOOSTER:

NUMB OF BOOSTERS :	
TOTAL MASS(EA.) :	lbm
DRY MASS(EA.) :	lbm
PROP TYPE :	
ENG. TYPE/# (EA.) :	
VAC/SL THRUST(EA.) :	Klb
ENG. EXIT AREA/DIAM. :	in2 / ft
DIMENSIONS:	
REUSABLE PARTS :	

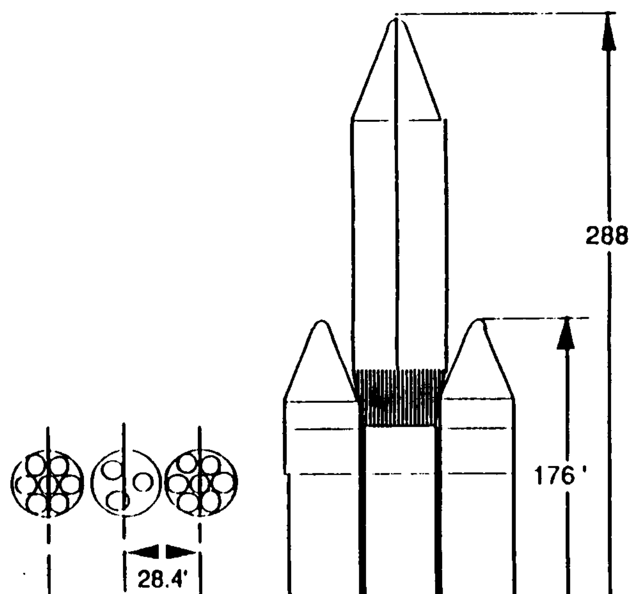
FAIRING: SDV 15 x 60 ft Fairing

P/L ENVELOPE :	15 ft diam x 60 ft length
FAIRING MASS :	13,718 lbm

COMMENTS:

Payload to 30 Nmi x 220 = 39,961 lbs (Sust Engine out)
50 x 100 = 42,078 lbs (Sust. engine out)
80 x 95 = 71,106 lbs (No engine out)
Kick stage of 1,524 required to circularize at 220 Nmi
Ref payload is with sustainer engine out

EARTH TO ORBIT: VEHICLE DATA SHEET



TEDB Version June 13, 1990

VEHICLE ET DerCore w/2ET Der Bstr

GLOW :	5,677,458.0 lbm
P/L to 220 Circ :	300,103.0 lbm

CORE: ET Derived Core

TOTAL MASS :	1,749,500 lbm
DRY MASS :	150,500 lbm
PROP TYPE :	LOX / LH2
ENG. TYPE/# :	STE-40 / 3
VAC/SL THRUST(EA.) :	580 / 498 Klb
ENG. EXIT AREA/DIAM. :	5537.4 / 6.99 in2 / ft
DIMENSIONS:	27.5 ft dia X 167.0 ft length
REUSABLE PARTS :	

BOOSTER: ET Derived Booster

NUMB. OF BOOSTERS :	2
TOTAL MASS(EA.) :	1,788,600 lbm
DRY MASS(EA.) :	189,600 lbm
PROP TYPE :	LOX / LH2
ENG. TYPE/# (EA.) :	STE-40 / 7
VAC/SL THRUST(EA.) :	580 / 498 Klb
ENG. EXIT AREA/DIAM. :	5537.4 / 6.99 in2 / ft
DIMENSIONS:	27.6 ft diam. X 176.0 ft length
REUSABLE PARTS :	

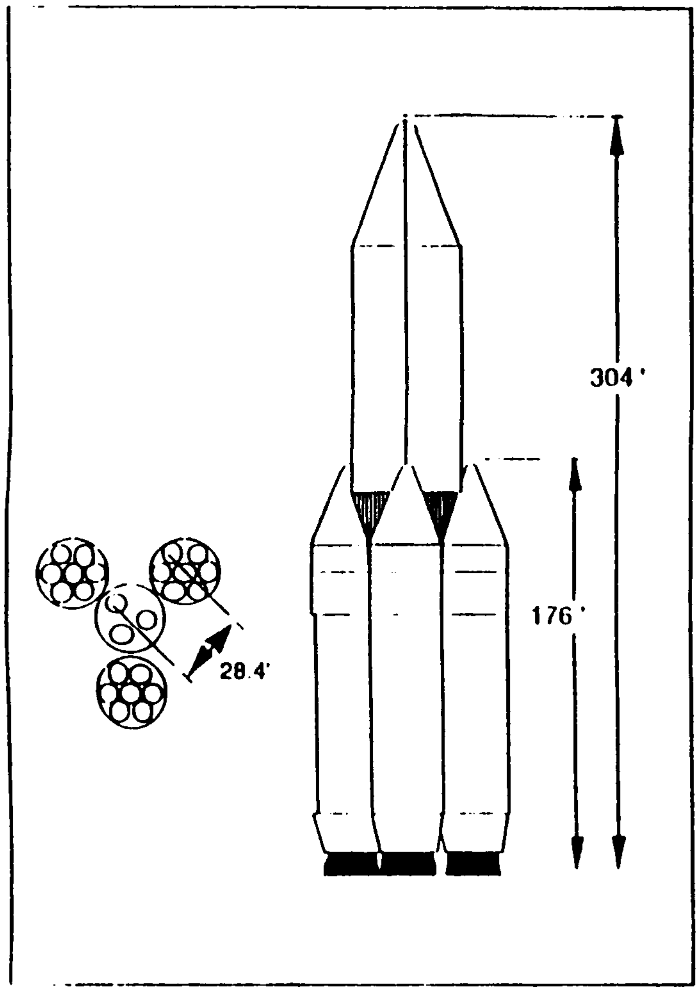
FAIRING: SDV 33 X 100ft Fairing

P/L ENVELOPE :	33 ft dia X 100 ft length
FAIRING MASS :	50,655 lbm

COMMENTS:

Payload shown with engine out on each booster
Payload to 30 Nmi x 220 = 312,100 lbs
11,997 lb Kick stage required to circularize at 220.

EARTH TO ORBIT: VEHICLE DATA SHEET



IEDB Version June 13, 1990

VEHICLE ET DerCore w/3ET Der Bstr

GLOW :	7,592,650 0 lbm
P/L to 220 Circ :	413,123 0 lbm

CORE: ET Derived Core

TOTAL MASS :	1,749,500 lbm
DRY MASS :	150,500 lbm
PROP TYPE :	LOX / LH2
ENG. TYPE/# :	STE-40 / 3
VAC/SL THRUST(EA.) :	580 / 498 Klb
ENG. EXIT AREA/DIAM. :	5537 4 / 6.99 in2 / ft
DIMENSIONS:	27.5 ft dia X 167 0 ft length
REUSABLE PARTS :	

BOOSTER: ET Derived Booster

NUMB. OF BOOSTERS :	3
TOTAL MASS(EA.) :	1,788,600 lbm
DRY MASS(EA.) :	189,600 lbm
PROP TYPE :	LOX / LH2
ENG. TYPE/# (EA.) :	STE-40 / 7
VAC/SL THRUST(EA.) :	580 / 498 Klb
ENG. EXIT AREA/DIAM. :	5537 4 / 6.99 in2 / ft
DIMENSIONS:	27 6 ft diam. X 176 0 ft length
REUSABLE PARTS :	

FAIRING: SDV 40 X 100ft Fairing

P/L ENVELOPE :	40 ft dia X 100 ft length
FAIRING MASS :	64,227 lbm

COMMENTS:

Payload shown with engine out on all 3 boosters
Payload to 30 Nmi x 220 = 429,500 lbs
16,377 lb Kick stage required to circularize

APPENDIX B

RELIABILITY ALLOCATION PROCEDURE

APPENDIX B

RELIABILITY ALLOCATION PROCEDURE

This procedure was developed by Dr. James W. Steincamp, Chief, Operations Analysis Branch, Preliminary Design Office, NASA-Marshall Space Flight Center.

The main propulsion system (mps) reliabilities varied among vehicles:

STS (3 SSME'S) = 0.9936 (1:156)

PLS/ETD1 (5 STME'S INCLUDING 2 SUSTAINERS) = 0.9957 (1:233)

ETD2 (17 STME'S) = 0.9492 (1:20)

ETD3 (24 STME'S) = 0.9398 (1:17)

The corresponding odds (chances of failure) were calculated as follows

$$odds=1/(1-R)$$

The STS common elements and unique elements were assumed

Common

SRB's	=	1:150	R=0.9933
avionics & other	=	1:400	R=0.9975

Unique

avionics & other	=	1:500	R=0.9980
operations	=	1:400	R=0.9975

With these values the corresponding reliabilities were calculated as follows

$$R = 1-1/odds$$

The common/unique element subsystems have a serial relationship, the reliability calculation for STS common elements then is,

STS Common Element Reliability=R(mps)*R(srb)*R(a&o)

The elements also have a serial relationship and the system reliability is calculated as,

STS System Reliability=R(Common)*R(Unique)

The elements are mutually exclusive and non-independent. Therefore, the probability of an element failure is calculated as in this example of the probability of a common failure.

$$P(\text{common}) = \frac{1-R(\text{common element})}{1-R(\text{common element})+(1-R(\text{unique element}))}$$

The probability that a particular subsystem will fail is calculated as in this example of the probability of an SRB failure.

$$P(SRB) = \frac{1-R(SRB)}{1-R(\text{Common Element})}$$

The transition from 0.97 to 0.98 to 0.99 is simple. Since 0.97 is 1:33 and 0.98 is 1:50 and 0.99 is 1:100 (see above equation for calculating odds), the relationship between them is obvious. The relationship between 0.98 and 0.97 is 33/50 and the relationship between 0.99 and 0.98 is 100/50. Therefore to make the transition from 0.98 to 0.97 you can simply multiply the 0.98 odds by 0.667 and likewise to make the transition from 0.98 to 0.99 you can multiply the 0.98 odds by 2.