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EXPECTED VALUE ANALYSIS  
FOR AN UNMANNED EXPENDABLE LAUNCH  
VEHICLE PAYLOAD ESCAPE SYSTEM  
THESIS

Fred E. Wagner  
Captain, USAF  
AFIT/GSO/ENS/87D-13

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SECURITY CLASSIFICATION OF THIS PAGE

A189 494

REPORT DOCUMENTATION PAGE

Form Approved OMB No. 0704-0188

1a. REPORT SECURITY CLASSIFICATION <b>UNCLASSIFIED</b>		1b. RESTRICTIVE MARKINGS	
2a. SECURITY CLASSIFICATION AUTHORITY		3. DISTRIBUTION / AVAILABILITY OF REPORT Approved for public release; distribution unlimited	
2b. DECLASSIFICATION / DOWNGRADING SCHEDULE		4. PERFORMING ORGANIZATION REPORT NUMBER(S) AFIT/GSO/ENS/87D-13	
6a. NAME OF PERFORMING ORGANIZATION School of Engineering		6b. OFFICE SYMBOL (if applicable) AFIT/ENS	7a. NAME OF MONITORING ORGANIZATION
6c. ADDRESS (City, State, and ZIP Code) Air Force Institute of Technology Wright-Patterson AFB OH 45433		7b. ADDRESS (City, State, and ZIP Code)	
8a. NAME OF FUNDING / SPONSORING ORGANIZATION See Box 19	8b. OFFICE SYMBOL (if applicable) AFWAL/FIER	9. PROCUREMENT INSTRUMENT IDENTIFICATION NUMBER	
8c. ADDRESS (City, State, and ZIP Code) Wright-Patterson AFB OH 45433		10. SOURCE OF FUNDING NUMBERS	
		PROGRAM ELEMENT NO.	PROJECT NO.
		TASK NO.	WORK UNIT ACCESSION NO.
11. TITLE (Include Security Classification) See Box 19			
12. PERSONAL AUTHOR(S) Fred E. Wagner, B.S., Capt, USAF			
13a. TYPE OF REPORT MS Thesis	13b. TIME COVERED FROM _____ TO _____	14. DATE OF REPORT (Year, Month, Day) 1987 December	15. PAGE COUNT 79
16. SUPPLEMENTARY NOTATION			
17. COSATI CODES		18. SUBJECT TERMS (Continue on reverse if necessary and identify by block number)	
FIELD	GROUP	Escape Systems, Recovery Vehicles, Space Systems	
22	02	Recoverable Spacecraft, Unmanned Spacecraft	
22	05		
19. ABSTRACT (Continue on reverse if necessary and identify by block number)			
Sponsoring Organization: Crew Escape and Subsystems Branch Flight Dynamics Laboratory			
Title: EXPECTED VALUE ANALYSIS FOR AN UNMANNED EXPENDABLE LAUNCH VEHICLE PAYLOAD ESCAPE SYSTEM			
Thesis Advisor: Thomas F. Schuppe, Lt Col, USAF			
Abstract: See Back			
20. DISTRIBUTION / AVAILABILITY OF ABSTRACT <input checked="" type="checkbox"/> UNCLASSIFIED/UNLIMITED <input type="checkbox"/> SAME AS RPT. <input type="checkbox"/> DTIC USERS		21. ABSTRACT SECURITY CLASSIFICATION UNCLASSIFIED	
22a. NAME OF RESPONSIBLE INDIVIDUAL Thomas F. Schuppe, Lt Col, USAF		22b. TELEPHONE (Include Area Code) (513) 255-3362	22c. OFFICE SYMBOL AFIT/ENS

Approved for public release: IAW AFR 150-17.  
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 Air Force Institute of Technology  
 Wright-Patterson AFB OH 45433

Since the beginning of the U.S. Space Program there have been numerous schemes for humans to escape from spacecraft in distress. This has not been the case for payloads of unmanned, expendable launch vehicles (ELV), however. The literature review revealed no concepts or design in the U.S. Space Program for saving or salvaging unmanned payloads if an ELV failed during the boost phase.

The purpose of this thesis was to develop a methodology to define a mathematical cost relation for a payload escape system (PES). That relation demonstrates when it is economically feasible to use a payload escape system.

This methodology draws heavily upon Decision Analysis Techniques, although a classical decision analysis involving a decision maker was not performed. A mathematical relation was developed for two launch cases: the first assumed 100 percent insurance coverage for losses and the other assumed no insurance coverage for losses.

The study found that the mathematical relations could be used to develop graphs defining when it is economically feasible to use a PES. The model is flexible and could be modified for use with a particular payload program.

AFIT/GSO/ENS/87D-13

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EXPENDABLE LAUNCH VEHICLE PAYLOAD ESCAPE SYSTEM

THESIS

Presented to the Faculty of the School of Engineering  
of the Air Force Institute of Technology

Air University

In Partial Fulfillment of the  
Requirements for the Degree of  
Master of Science in Space Operations

Fred E. Wagner, B.S.

Captain, USAF

December 1987

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Acknowledgements

I really had a lot of help and encouragement from some very special people. Many thanks go to my faculty advisor, Lt Col Tom Schuppe for his guidance on this project. His patience and understanding, especially when I missed so many deadlines, was deeply appreciated. I want to also thank Major Bruce Morlan and Major Stu Kramer for freely giving of their time and their patience. It seems like they spent as many hours re-answering my old questions as they did answering my new ones; thanks. Thanks also to Capt Ralph Garman, a fellow classmate, whose friendship and thoughts helped ease me through the trauma that is AFIT.

Mostly, I could not have made it without my belief in a personal God, who is interested in all my problems. Throughout my time at AFIT the patience, love and understanding of my wonderful wife Gail and two kids, Erin and Joshua kept me going. This is their thesis also. I think I understand Proverbs 31: 10-31 a little better now. Thanks again to everyone.

Fred E. Wagner

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## Model Variables and Notation

<u>Decision Variable</u>	<u>Outcomes</u>
D - to choose an escape system	YES / NO

<u>State Variables</u>	<u>Outcomes</u>
B - booster condition	WORKS / FAILS
E - escape system condition	WORKS / FAILS

### General Value Function

$$\text{COST} = F(C_B, C_{ES}, C_I, C_R, C_S, I, P, P_b, P_e, R_f, R_I)$$

where

$C_B$	= cost of the booster (ELV)
$C_{ES}$	= cost of the escape system (ES)
$C_I$	= cost of insurance premiums
$C_R$	= cost of refurbishing the satellite or payload
$C_S$	= cost of the satellite or payload
$I$	= inflation rate
$P$	= insurance payoffs
$R_f$	= satellite or payload refurbishment rate
$R_I$	= insurance premium rate

### Probabilities

$P_b$	= probability of booster failure
$P_e$	= probability of escape system failure

Abstract

Since the beginning of the U.S. Space Program there have been numerous schemes for humans to escape from spacecraft in distress. This has not been the case for payloads of unmanned, expendable launch vehicles (ELV), ~~however~~. The literature review revealed no concepts or design in the U.S. Space Program for saving or salvaging unmanned payloads if an ELV failed during the boost phase.

The purpose of this thesis was to develop a methodology to define a mathematical cost relation for a payload escape system (PES). That relation demonstrates when it is economically feasible to use a payload escape system.

This methodology draws heavily upon Decision Analysis Techniques, although a classical decision analysis involving a decision maker was not performed. A mathematical relation was developed for two launch cases: the first assumed 100 percent insurance coverage for losses and the other assumed no insurance coverage for losses.

The study found that the mathematical relations could be used to develop graphs defining when it is economically feasible to use a PES. The model is flexible and could be modified for use with a particular payload program.

EXPECTED VALUE ANALYSIS FOR AN  
UNMANNED EXPENDABLE LAUNCH VEHICLE  
PAYLOAD ESCAPE SYSTEM

I. Introduction

Background

Since the beginning of the United States Space Program, there have been numerous schemes for humans to escape from spacecraft in distress (20). Indeed, much effort was expended to "man-rate" the ICBMs used for boosting early astronauts into space, since the safety of the astronauts was "of utmost importance" (5:315). It is difficult to argue the value of human life. The added expenses associated with manned spacecraft crew escape systems may be a prudent investment even though an escape system may restrict vehicle performance.

Although the value of human life is difficult to argue, it is surely a different story for the value of payloads or satellites. The literature review for this thesis revealed no design in the U.S. Space Program for an unmanned payload escape system. There were no concepts for saving, rescuing or salvaging unmanned payloads from destruction when an expendable launch vehicle (ELV) failed during the boost phase of flight. However, there was one

concept for recovering a satellite payload from orbit or sub-orbital velocities in a non-emergency situation (4:304). It is apparent that intrinsic worth, dollar value, mission importance, launch costs (including insurance) or other measures were not considered important enough to justify the added expense and possible performance degradation necessary to provide a mechanism for payload escape. Indeed, for example, some in the space community prefer off-loading small quantities of precious fuel and accepting greater risk that an ELV may not reach orbital velocity, in exchange for more payload capacity (6).

1985 and 1986 were devastating years for getting payloads into space. "This unprecedented string of failures included four major losses - the Space Shuttle Challenger, two Titan 34D's and a Delta" (7:58). The payloads destroyed in these accidents included a \$100 million NASA Tracking and Data Relay Satellite, two DOD satellites and a \$57.5 million GOES weather satellite (19:20, 8:13). In March 1987, an Atlas/Centaur failed, causing the loss of an \$83 million FltSatCom satellite (14:23-24).

Each launch vehicle failure means the certain loss of its payload and lost payloads represent more than just lost dollars. If the payload was unique, such as NASA's Galileo Jupiter Probe, its loss is a lost opportunity in addition to its \$1 billion price tag. If it was a DOD payload, its

loss could have a significant impact on national security in addition to its dollar cost. If the payload was a commercial venture, its loss represents lost revenue, lost cost and probably increased insurance premiums as well.

There is historical precedence for "payload" escape systems in the Mercury, Gemini, Apollo and Soviet Soyuz manned spaceflight programs. An escape system that partially or totally salvages payloads from destruction during the boost phase may significantly reduce the risk, real costs, and opportunity costs associated with launching payloads into space.

#### Problem Statement

A need exists for research concerning the feasibility of using escape mechanisms for payloads on unmanned ELVs. Based on discussions with some managers in the space community, it would seem that current attitudes about this topic are speculative or purely subjective at best.

Is a payload escape system economically feasible when evaluated as a function of satellite cost, escape system cost, launch insurance premiums, probability of booster failure and probability of escape system failure? This research develops a methodology which will define a mathematical relationship between these parameters to indicate when a payload escape system might be feasible.

## Study Objective

The main objective of this research was to develop a methodology that defines a mathematical relation to demonstrate the economic feasibility of a payload escape system. Specific subobjectives were:

1. To use the costs of actual past booster failure events to demonstrate use of the mathematical relation
2. To identify pertinent background information on various manned spacecraft escape system technologies that could be useful in unmanned escape system applications
3. To identify specific unmanned escape system topics for future research.

## Scope

This thesis deals with the economic feasibility of a payload escape system for use with unmanned ELVs. The space shuttle was not considered in this research. Any escape system was presumed to operate from the surface of the earth to the point of orbital insertion, thus eliminating from consideration failures that occur in transfer orbits. Because of this assumption, data was only collected on booster failure rates. The analysis, then, does not include failures of orbital transfer stages. A further assumption was that any escape system operation would be independent of booster failure rates.

The time needed to refurbish recovered payloads was not addressed. However, payload refurbishment costs were allowed for in the model as a refurbishment rate multiplied

by the payload cost. This allowance gave the model the flexibility to account for varied estimates of payload refurbishment costs. In addition, the somewhat emotional question of how much payload weight to trade-off for an escape system was not addressed. It was assumed that if it was economically feasible, a payload escape system's intrinsic value would be more "valuable" than added payload capacity. These are very important questions but ultimately this thesis was limited to defining a necessary (but not necessarily sufficient) condition for economic feasibility. Factors considered, then, in this analysis were satellite cost, satellite refurbishment cost, escape system cost, booster cost, launch insurance premiums, probability of booster failure and probability of escape system failure.

Engineering analysis of designs was beyond the scope of this effort as were any suggestions of a particular design. The allusion to certain manned spacecraft escape systems or to certain other space vehicle subsystems was intended to demonstrate that a great deal of escape system technology already exists. Although developed mainly for manned spacecraft, this technology could be useful in unmanned escape system applications.

## II. Review of the Literature

### Introduction

This literature review revealed no equipment or design in the U.S. Space Program for an unmanned payload escape system. There were no concepts for saving, rescuing or salvaging unmanned payloads from destruction when an expendable launch vehicle (ELV) failed during the boost phase. On the other hand, it is obvious that a manned escape system is indifferent to its cargo. Perhaps some of these systems could be adapted to ejecting or saving payloads. This review briefly looks at some launch vehicles, escape systems and recovery systems.

### Unmanned Launch Vehicles

The Air University Space Handbook describes three current, U.S., unmanned launch vehicles, the Delta, Atlas and Titan (1).

Delta Booster. According to the Space Handbook, the original Delta created by NASA in 1959 was an intermediate size launch vehicle that could place a 600 pound payload into a 100 mile orbit. The original Delta launch vehicle has been heavily modified to increase its payload capacity. The configuration consists of three liquid fuel stages with either three or nine solid rocket motors strapped to the first stage for thrust augmentation. The latest Delta, designated as the 3900 series, can develop over 630,000

pounds of thrust at liftoff and place 2,800 pounds into a 160 mile by 19,323 mile elliptical orbit.

McDonnell Douglas Astronautics Company quotes a 6.70 percent failure rate for the Delta, whereas an insurance broker quoted a 7.18 percent failure rate (25, 16).

Atlas Booster. Even though the various versions range from the basic Atlas model, through the Atlas-H model, its design has not changed much since its development started in the middle 1940's. The Space Handbook describes the Atlas as a liquid propellant rocket having three main engines. Two of these engines comprise the booster section of the rocket and are only used during the first two minutes of flight, after which they are jettisoned. The third engine is called the sustainer section of the rocket and it burns for the duration of the flight. An Atlas can develop 378,000 pounds of thrust at liftoff and can place 5,200 pounds into a 100 mile by 19,323 mile elliptical orbit.

General Dynamics Convair Division quotes a 9.29 percent failure rate for all Atlas boosters, whereas an insurance broker quoted a 15.32 percent rate (9, 16).

Titan Booster. The Titan family of launchers, like the Delta launchers, has gone through many modifications in its lifetime. The generic family included the Titan I, Titan II, Titan III and Titan 34 models with various versions of each model. Two strap-on solid rocket motors

augment the thrust on the Titan IIIC and IIID and on the Titan 34B and 34D boosters. The Titan 34D is the largest of these launch vehicles. It is capable of placing 27,600 pounds into a 100 mile high orbit or 1,859 pounds into a 19,323 mile orbit while generating 2,920,000 pounds of thrust at liftoff.

Martin Marietta Denver Aerospace quotes a 6.16 percent failure rate for the Titan III, whereas an insurance broker quoted an 8.45 percent rate (24, 16).

### Escape Systems

Three escape systems used for manned launches were reviewed, the Soyuz, Gemini and Apollo.

Soyuz. Boris Kolesov, a Soviet engineer, provides a limited view of the emergency escape system (EES) used on Soyuz 4 and 5 (15). The EES is attached to the tip of the main fairing on top of the rocket in much the same way as the Apollo launch escape system. The system is intended for rescuing the crew in case the launch vehicle fails in any phase of flight: from launch through all phases of powered flight.

It is interesting to note that Kolesov describes the EES as a complicated and automated system. In the event of an emergency, the EES can activate emergency programs and can also command other Soyuz systems as well.

Gemini. Philip H. Bolger provides a good, brief description of the escape system used on Gemini

(2:130-137). Above 70,000 feet, the spacecraft itself was the escape system, while ejection seats were used for escape below that altitude and for on-the-pad aborts. During the boost phase between 70,000 feet and up to vehicle staging, the capsule was separated from the launcher by a salvo fire of the retrorockets. Once the first stage was jettisoned (vehicle staging) escape was initiated by shutting down the second stage engine and firing the rendezvous propulsion system to "push" the capsule away from the launcher.

Bolger notes that the Gemini was originally designed to use a Rogallo parawing during its landing. This concept was discarded in favor of using a parachute landing system.

Apollo. Townsend describes the operation of the Apollo escape system (23:6-7). The Launch Escape System (LES) tower provided a means to pull the Apollo Command Module (CM) away from the Saturn launch vehicle. Aborts on-the-pad and up to 100,000 feet were initiated by firing the LES main rocket motor and above this altitude the crew would also activate the CM reaction control system to provide a positive "heat shield first" positioning for the LES and CM. The maximum altitude for operation of the LES was set at 320,000 feet. Above this altitude the LES was jettisoned and emergency separation provided by the Apollo Service Module (SM) propulsion system. Figure 2.1 shows the Apollo spacecraft configuration.

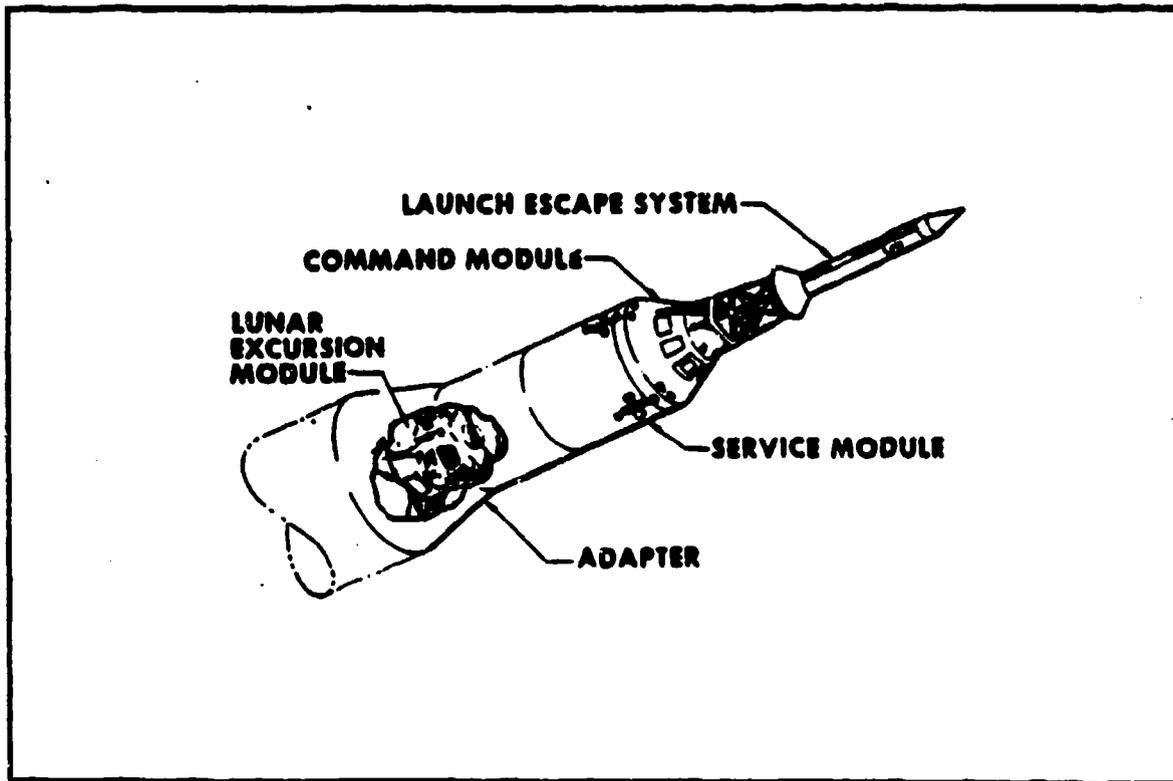


Figure 2.1 Apollo Spacecraft (3:376)

### Recovery Systems

Vostok. The Soviet Vostok landing system contained a noteworthy component that could prove useful in recovery of satellites. "To reduce the impact at landing, small retrorockets were used which complement the main parachutes and reduce the velocity of fall from 10 m/s to only a few cm/s at the moment of contact" (17:5).

Paraglider System. Crawford and McNerney discuss Space-General Corporation's study of three applications of paragliders as recovery systems (4:293). The first, was a paraglider assembly designed to recover the Saturn SI-C



## Summary

As mentioned previously, the review found no concepts specifically designed for saving, rescuing or salvaging unmanned payloads from destruction when a booster fails. The closest concept to a payload escape system was the recovery system concept mentioned above. It should be noted that that concept was a recovery system and not an escape system.

The brief review contained in this chapter did help set the tone for this study. It discussed the main launch vehicles currently in use in the U.S., the Delta, Atlas and Titan. It discussed past, manned escape systems for the Soyuz, Gemini and Apollo spacecraft. Finally, a striking feature of the Vostok recovery system was noted and another recovery system concept was discussed.

The limited sources quoted here were not intended to prove the viability of a payload escape system, but rather to demonstrate some historical examples of "payload" escape system concepts from manned spaceflight programs. After all, these are evidently the only "payload" escape system examples available.

### III. Methodology

#### Introduction

The main objective of this thesis was to develop a methodology to define a mathematical relationship between a payload escape system's cost and its payload or satellite cost. This chapter discusses the method used for building the framework necessary to discover that mathematical cost relationship. Chapter IV looks at the findings that came from this necessary framework.

#### Decision Analysis Method

The problem for this research can be stated in terms of a decision to be made: Should a payload escape system be used on space launch vehicles? With the problem formulated as a decision, one naturally considers the use of decision analysis as a good, general approach toward solving it. Decision analysis "is the result of combining aspects of systems analysis and statistical decision theory" (10:21). It is a methodology that can help a decision maker reason logically about a decision under conditions of uncertainty.

Carl-Axel S. Stael von Holstein gives a short description of the decision analysis approach depicted in Figure 3.1:

The decision analysis cycle is made up of three phases: the deterministic, probabilistic, and informational phases. The deterministic phase is

concerned with the basic structuring of the problem. The structuring entails defining relevant variables, characterizing their relationships in formal models, and assigning values to possible outcomes. The importance of the different variables is measured through sensitivity analysis.

Uncertainty is explicitly incorporated in the probabilistic phase by assigning probability distributions to the important variables. These distributions are transformed in the model to exhibit the uncertainty in the final outcome, which again is represented by a probability distribution. After the decision maker's attitude toward risk has been evaluated and taken into account, the best alternative in the face of uncertainty is then established.

The informational phase determines the economic value of information by calculating the worth of reducing uncertainty in each of the important variables in the problem. The value of additional information can then be compared with the cost of obtaining it. If the gathering of information is profitable, the three phases are repeated again. The analysis is completed when further analysis or information gathering is no longer profitable.

Throughout, the analysis is focused on the decision and the decision maker. That is, expanding the analysis is considered of value only if it helps the decision maker choose between the available alternatives (22:132).

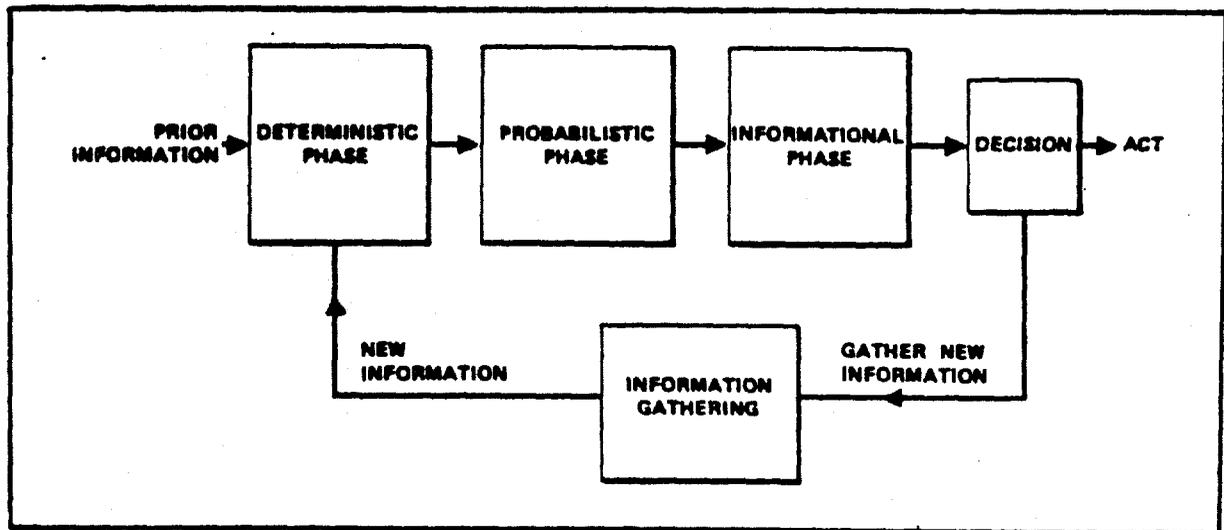


Figure 3.1 The Decision Analysis Cycle (22:132)

Classical decision analysis, as described by Stael von Holstein above, tailors the analysis to the risk attitudes and preferences of a specific decision maker. One purpose of this thesis is to make the results useful to many decision makers. To this end, the complexity of the problem model was reduced and a subset of the decision analysis cycle, as described above, was used. That subset guides model formulation. In this methodology, the main model formulation effort occurs in the deterministic phase and part of the probabilistic phase (10:27,30). Reducing the model's complexities made the problem more manageable in terms of the analysis and more applicable to a wider audience of decision makers. The goal of following this methodology was not to perform a decision analysis but rather to build the framework needed to define the mathematical cost relationship for this thesis.

Deterministic Phase. The following steps are generally used as a guide to the deterministic phase of analysis and were adapted from Stael von Holstein's paper, A Tutorial in Decision Analysis (22:134):

1. define and bound the decision problem
2. identify the alternatives
3. establish the outcomes
4. select decision variables and state variables
5. build a structural model
6. build a value model

7. specify time preference
8. eliminate dominated alternatives
9. measure sensitivity to identify crucial state variables.

The first step was to define and bound the decision problem. As mentioned above, the problem for this research has been stated as a decision to be made. The decision was: Should a payload escape system be used on space launch vehicles? Specifically, the decision was limited to unmanned, vertical liftoff, expendable launch vehicles. This assumption ruled out the space shuttle from consideration. It was noted that the decision was whether an escape system would be used and not whether an escape system would be built.

The next step was to identify the alternatives. In this case the alternatives were to use an escape system or to not use an escape system. Figure 3.2 shows the decision (D) and its two alternatives: YES and NO.

Outcomes are generally what should be known to determine how the problem was resolved (10:27). Clearly the choice made on the decision is an outcome that is desirable to know and is, in fact, the object of this thesis. Another outcome was whether or not the launch vehicle fails. If one knew that outcome with certainty, the decision would be obvious. Finally, one would like to know if the payload escape system would fail when it was

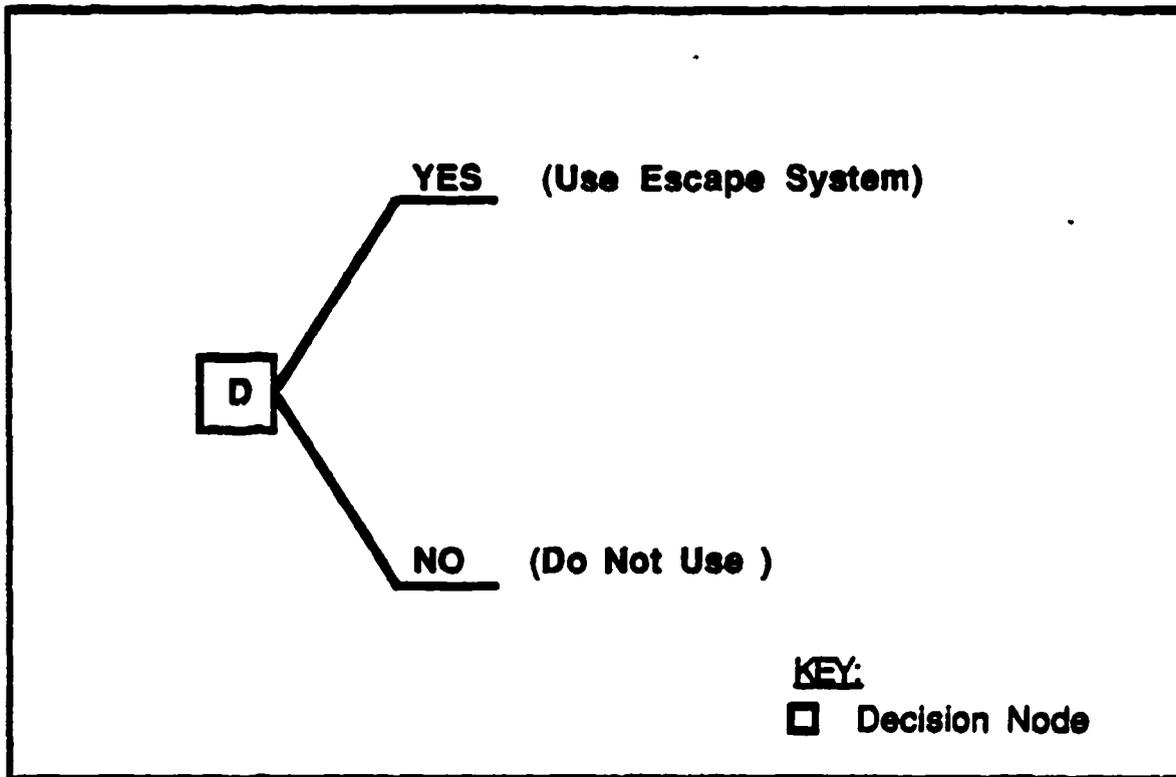


Figure 3.2 Decision Alternatives

needed. The basic outcomes of interest in this problem are: the decision, whether the launch vehicle would fail, and whether the payload escape system would fail. Figure 3.3 shows these outcomes.

Selecting the decision variables and state variables followed from the previous step. Variables that are controlled by the decision maker are the decision variables, i.e. the decision. Variables that can not be controlled by the decision maker are known as the state variables (22:134). The choice of outcomes helped bound this problem and determine the variables. The variables were related to the outcomes in the next step of the methodology.

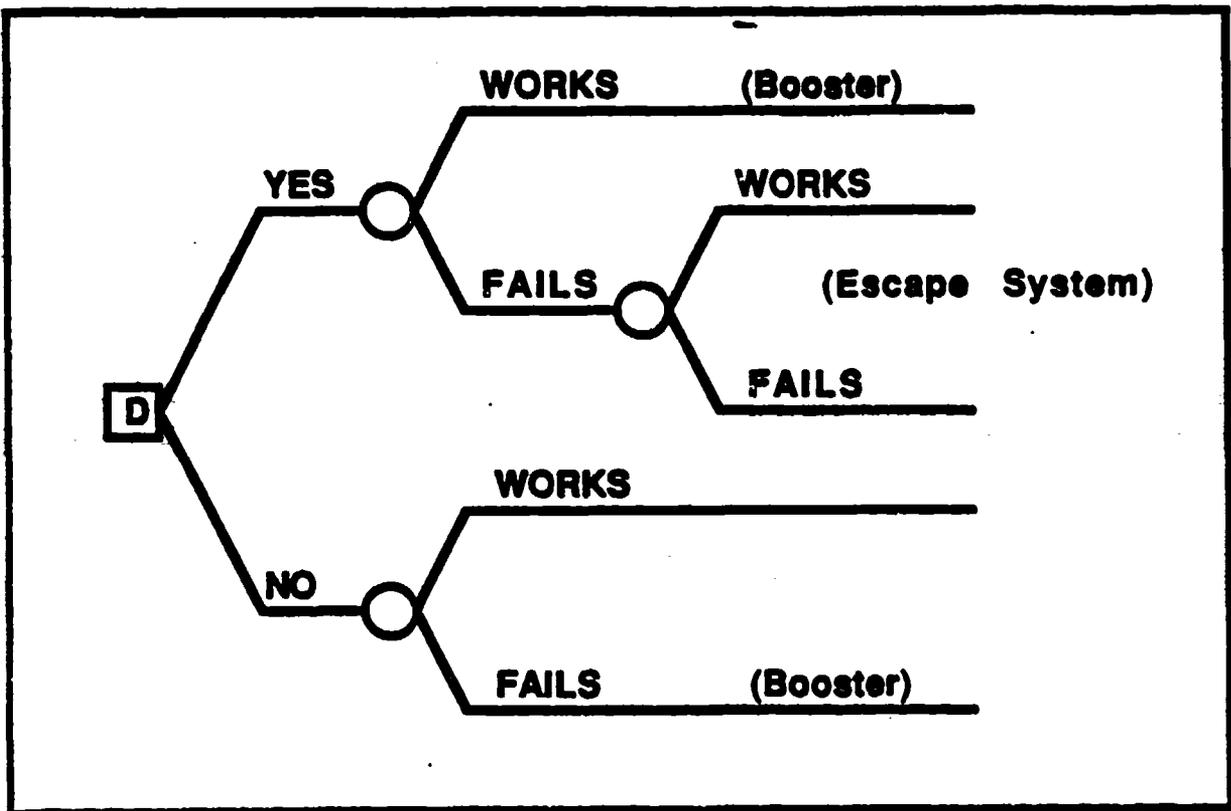


Figure 3.3 Decision Outcomes

Building a structural model or a framework tied together all the steps discussed above. The model was crucial to this thesis since it set the stage for finding a mathematical relationship between the escape system cost and its payload cost. Figure 3.4 shows the decision tree structure of the model. One can easily see the relationship between the decision variable (D), the alternatives, the outcomes and the state variables (B,E).

In the model, D represents the decision variable. Its outcomes (alternatives) are to use an escape system (YES) and to not use an escape system (NO). The first node in the decision tree represents the state variable (B) for

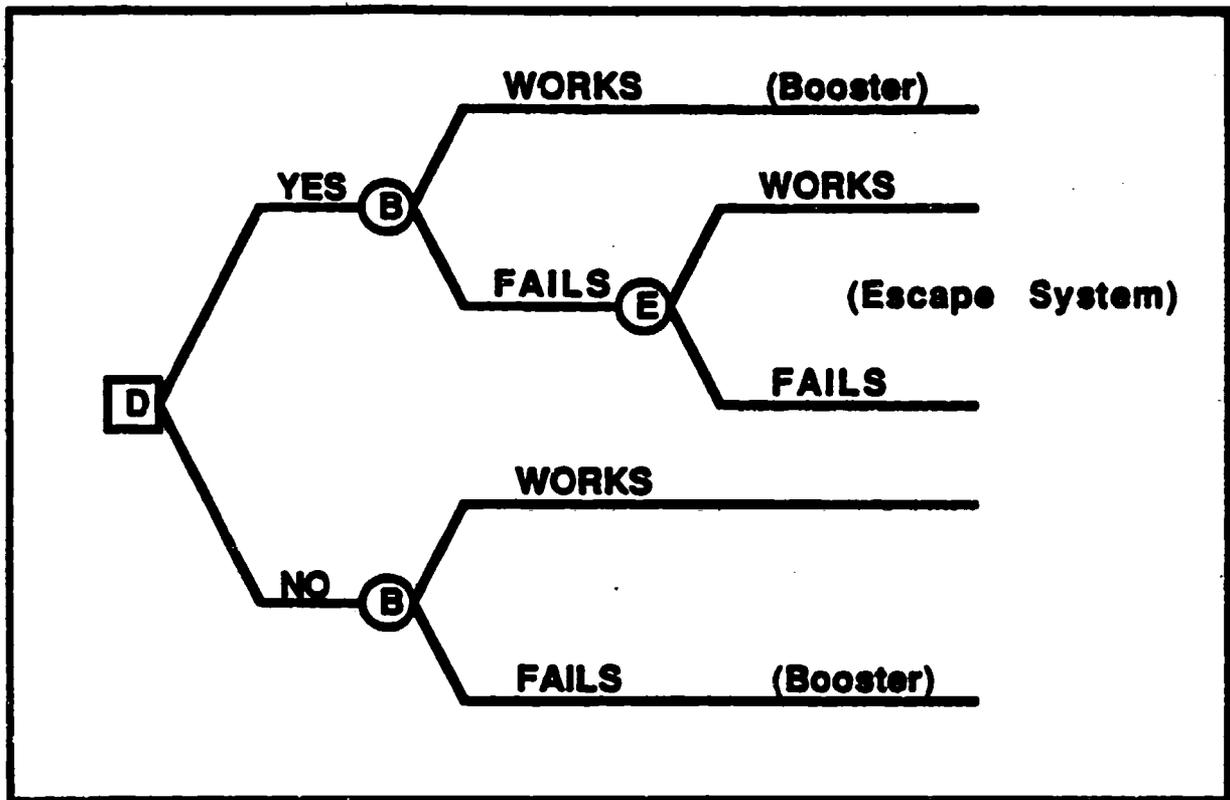


Figure 3.4 The Decision Tree Model

booster vehicle failure. Its associated outcomes are that the booster "WORKS" and that the booster "FAILS". The second node in the decision tree represents the state variable (E) for escape system failure. Its associated outcomes are that the escape system "WORKS" and that it "FAILS". It should be noted that state variables are also known as uncertainty nodes, probabilistic nodes or chance nodes.

Building the value model was the next step in this deterministic phase. It was natural for the values to represent costs and in most cases were lost costs. However, a cost could also represent a gain if an insurance payoff was received. The rational decision, then, would be

the alternative from the decision tree model with the minimum expected value loss.

Private concerns purchasing satellites usually buy some form of insurance to hedge against failures (16). Failures could occur during the launch phase of flight, during orbital transfers or after a satellite was on orbit. It was assumed that costs in this model represented launch phase losses. In general, the government launches satellites without insurance coverage (16). Therefore, two sets of values were created. One set of values represented the launch case with insurance coverage and the other set the case with no insurance coverage. It was further assumed that the insurance was replacement cost insurance and not purchase cost insurance.

Value Function. The values were determined from a value function that related cost in terms of a value function's variables. The value function with its general variables was written as:

$$\text{COST} = F(C_B, C_{ES}, C_I, C_R, C_S, I, P, P_b, P_e, R_f, R_I) \quad (3.1)$$

where

- $C_B$  = cost of the booster (ELV)
- $C_{ES}$  = cost of the escape system (ES)
- $C_I$  = cost of insurance premiums
- $C_R$  = cost of refurbishing the satellite or payload
- $C_S$  = cost of the satellite or payload
- $I$  = inflation rate
- $P$  = replacement cost insurance payoffs
- $P_b$  = probability of booster failure
- $P_e$  = probability of escape system failure
- $R_f$  = satellite or payload refurbishment rate
- $R_I$  = insurance premium rate.

The values can be seen in Figures 3.5 and 3.6 at each end of the branches in the decision tree. These values represent the losses that were the consequences of a particular set of outcomes. For example, if the outcome of the decision was YES and the outcome of the booster chance node was WORKS then the value for that branch is the top set of values shown in Figure 3.5 ( $-C_B - C_S - C_{I2} - C_{ES}$ ). The model in this figure includes variables representing insurance costs. Figure 3.6 shows the model for the no insurance case and does not include insurance cost variables in the values. In this figure, the value for the same outcomes mentioned above was the same as before ( $-C_B - C_S - C_{ES}$ ) except for the insurance cost variable ( $-C_{I2}$ ).

Value Variable Definitions. The following list defines each variable used in the values depicted in Figures 3.5 and 3.6:

- $C_B$  = the cost of the booster (ELV)
- $C_{ES}$  = the cost of the escape system (ES)
- $C_{I1}$  = the cost of insurance assuming no ES is on the ELV
- $C_{I2}$  = the cost of insurance assuming an ES is on the ELV
- $C_{NB}$  = the cost of the next ELV for use on the subsequent launch attempt
- $C_{NES}$  = the cost of the next ES for use on the subsequent launch attempt
- $C_{NI1}$  = the cost of insurance on the subsequent launch attempt assuming no ES was on the ELV

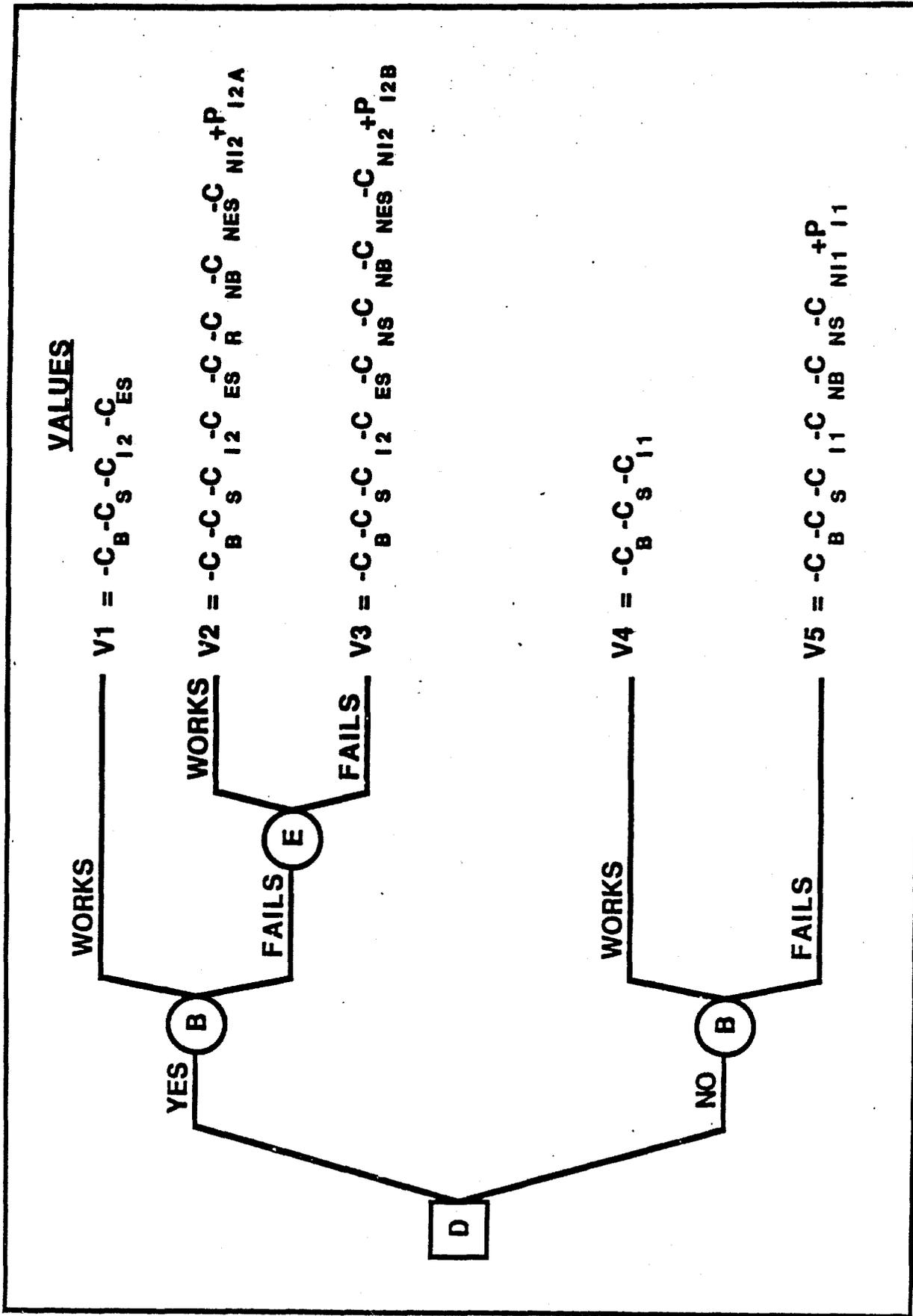


Figure 3.5 Value Variables With Insurance

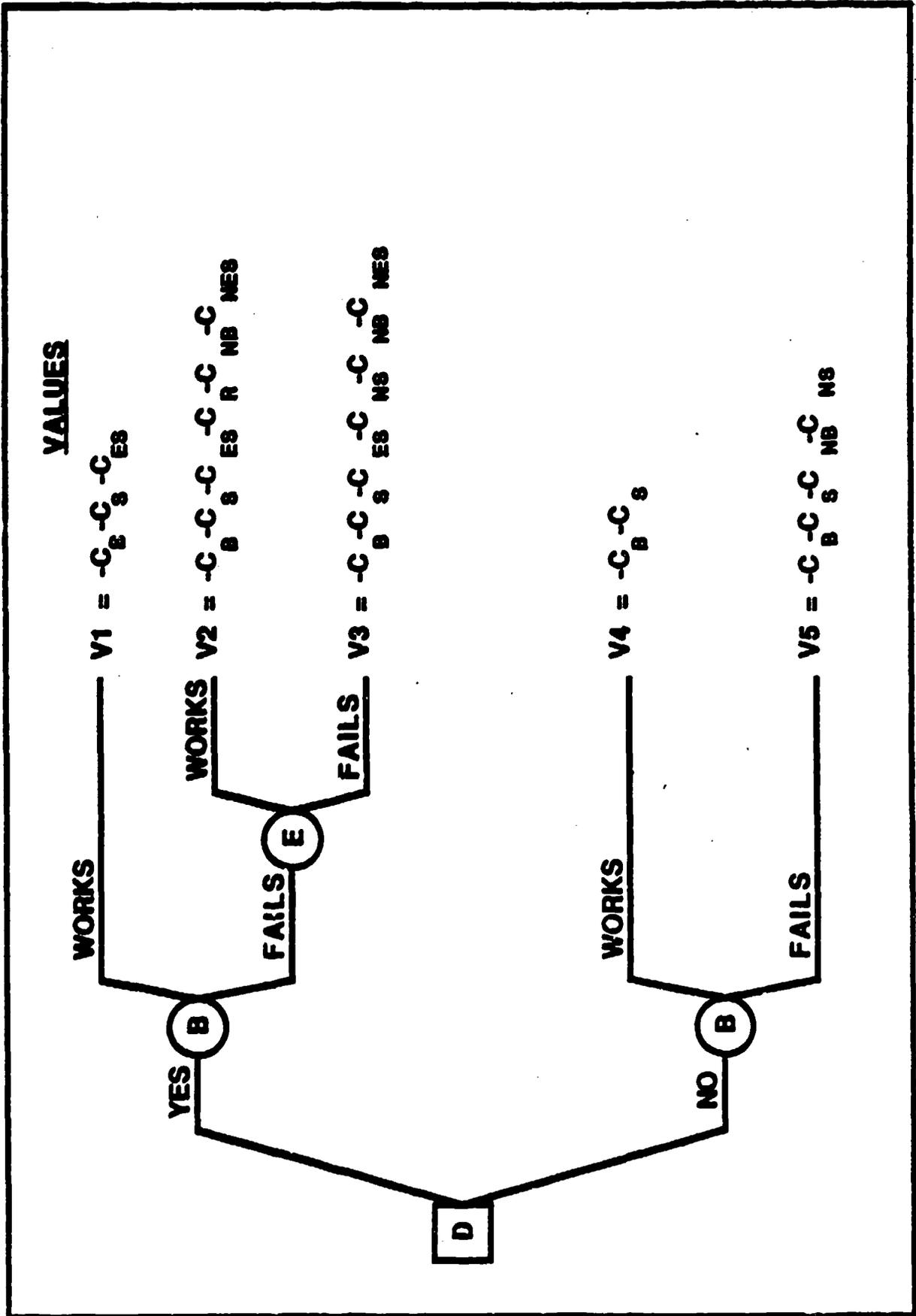


Figure 3.6 Value Variables With No Insurance

- $C_{NI2}$  = the cost of insurance on the subsequent launch attempt assuming an ES was on the ELV  
 $C_{NS}$  = the cost of the next replacement satellite or payload for use on the subsequent launch  
 $C_R$  = the cost of refurbishing the original satellite or payload for use on the subsequent launch  
 $C_S$  = the cost of the original satellite or payload  
 $P_{I1}$  = the amount of gain from the insurance payoff after a booster failure and no ES assuming the satellite or payload was lost  
 $P_{I2A}$  = the amount of gain from the insurance payoff after a booster failure with an ES assuming the satellite or payload was salvaged  
 $P_{I2B}$  = the amount of gain from the insurance payoff after a booster failure with an ES assuming the satellite or payload was lost.

Some of the value variables involved changeable costs because of their dependence on certain rates. Those value variables and rates are now defined.

$$C_{I1} = (R_{I1}) (C_S) \quad (3.2)$$

where  $R_{I1}$  = the rate of insurance assuming no ES was on the ELV.

$$C_{I2} = (R_{I2}) (C_S) \quad (3.3)$$

where  $R_{I2}$  = the rate of insurance assuming an ES was on the ELV.

$$C_R = (R_f) (C_S) \quad (3.4)$$

where  $R_f$  = the rate of refurbishment for a salvaged satellite or payload.

It was assumed that several of the value variables were equivalent. This assumption simplified the calculations for this model while still providing for many of the cost factors in the real world problem. These value variables were included for completeness of this model. They allow the model to be used later to help solve similar but expanded problems using this same framework. The following value variables were assumed to be equal for the purposes of this thesis:

C <sub>B</sub>	=	C <sub>NB</sub>
C <sub>ES</sub>	=	C <sub>NES</sub>
C <sub>I1</sub>	=	C <sub>NI1</sub>
C <sub>I2</sub>	=	C <sub>NI2</sub>
C <sub>S</sub>	=	C <sub>NS</sub>
P <sub>I1</sub>	=	C <sub>NS</sub>
P <sub>I2A</sub>	=	C <sub>R</sub>
P <sub>I2B</sub>	=	C <sub>NS</sub>

The value model accounted for the component costs of the total loss for each outcome. This is illustrated in Figures 3.5 and 3.6. The value model accounts for two sets of values. One set of values represents the insurance case and the other set the no insurance case.

The next step in this deterministic phase was to consider time preference. According to Ronald Howard time preference concerns what worth to place on values over time (11:70). One way to treat this time preference would be to use some form of present value discounted for time. Another would be to inflate the value variables relating costs in this model according to the relations:

$$\begin{array}{l}
C_{NB} = (1+I) (C_B) \\
C_{NES} = (1+I) (C_{NES}) \\
C_{NI1} = (1+I) (C_{I1}) \\
C_{NI2} = (1+I) (C_{I2}) \\
C_{NS} = (1+I) (C_S)
\end{array}$$

where I = an inflation rate.

Time preference is, of course, highly dependent on a decision maker's preferences. In this early investigation of this problem no specific decision maker's preferences were addressed. Since these variables were already assumed to be equivalent, no further attempt to define a time preference was taken in this model. These inflated variables do, however, demonstrate where a time preference relation would fit into this model.

The next step in a classical decision analysis would be to eliminate dominated alternatives. The nature of this problem was to construct a framework to look at a specific decision. That framework was constructed on the basis of two alternatives: use an escape system and do not use an escape system. The decision analysis methodology was used to help build a framework and not necessarily to perform a decision analysis. Not all the decision analysis steps were appropriate to this problem. This step was not performed since it was important to keep both alternatives in the problem framework.

The last step in the deterministic phase measures the importance of the variables through sensitivity analysis. Usually, one variable at a time in the value function would

be varied in turn, from its high to its low value while the others remained at a nominal value. The effect on the functional value would be observed and those variables having minimal effect would not be used in further analyses. In this model, the goal was not to eliminate variables but rather to build the methodology to find a mathematical relationship. For this reason, each variable was considered important enough to remain in the model. It was decided to carry each variable forward to the point where the model was fully developed. The model would then be solved mathematically with all its variables. Therefore, sensitivity analysis was not performed at this step.

Probabilistic Phase. According to Spetzler and Zamora the main purpose of the probabilistic phase is to explicitly bring uncertainty into the analysis (21:239). If the decision maker knew for certain when a booster would fail there would be no need for this research. Of course, the problem is that uncertainty is involved no matter how reliable boosters are or may become. The following steps generally make up the probabilistic phase although not all were needed to finish this framework (21:239):

1. encode uncertainty on the variables
2. develop profit lottery
3. determine best action

4. encode risk preferences
5. perform further sensitivity analysis.

The first step in this phase completed the framework. Both state variables, B and E, were assigned a discrete probability to their outcomes. The booster variable was assigned the probability  $P_b$  for a FAILS outcome and  $1-P_e$  for a WORKS outcome. The escape system variable was assigned the probability  $P_e$  for a FAILS outcome and  $1-P_e$  for a WORKS outcome. Figure 3.7 shows the completed model framework with the assigned probabilities on their corresponding outcome branches.

These probabilities were allowed to vary over a range of discrete probabilities.  $P_b$  depended on the booster type and the source for the probabilities. Booster manufacturers and an insurance broker were sources for booster failure rates.  $P_e$  was always assumed to be as good as or better than  $P_b$ .

#### Model Analysis

After using a subset of decision analysis to build a framework, the next major step was to analyze the model. This step of the methodology culminated in the calculation of a mathematical relation for the payload escape system's cost. Three actions were taken in this model analysis step:

1. risk preference assumption
2. determine the best alternative
3. sensitivity analysis.

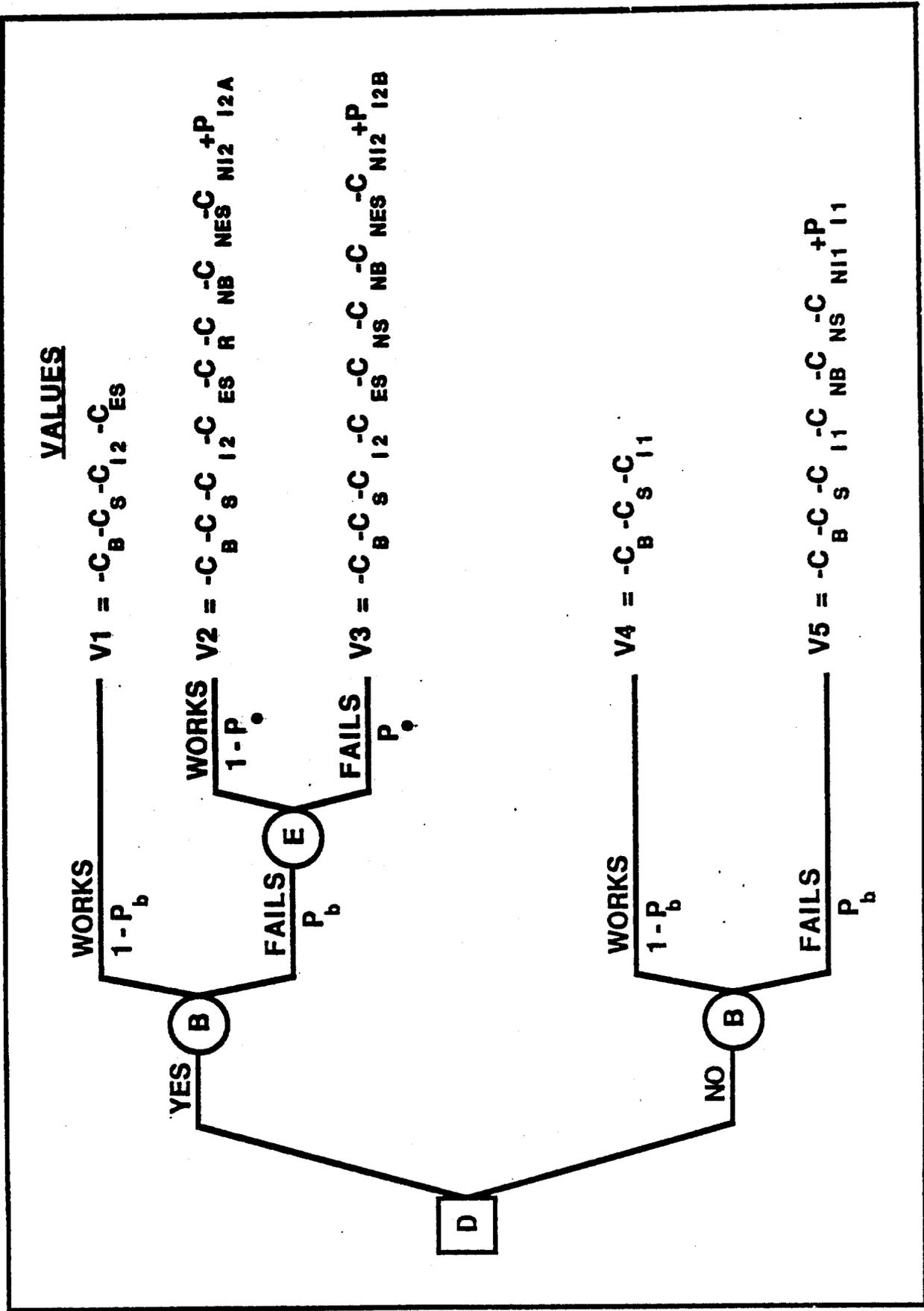


Figure 3.7 Finished Model With Probabilities

Risk Preference Assumption. According to Stael von Holstein, risk attitudes should be considered whenever a decision is made. He goes on to say that it would be typical for decision makers to choose amounts less than the expected value of a lottery (22:146).

Figure 3.8 illustrates Stael von Holstein's example of a lottery with equal chances for winning \$20 million and losing \$5 million. If a decision maker were to choose \$7.5 million, the expected value of this lottery, as a substitute for playing the lottery then that person would be a risk neutral or expected value decision maker. If, on the other hand, the decision maker were to choose some amount less than the expected value, say \$2 million, as a substitute for playing the lottery then that person would be a risk averse decision maker.

Stael von Holstein stated that the risk averse decision maker is the more typical one. The risk averse attitude can be closely approximated with utility functions. Expected utility instead of expected value would then become the criteria for choosing alternatives. Stael von Holstein also stated that a decision maker "could be expected to be risk neutral when the value of the project is not too large in relation to the organization's total worth" (22:146). Moskowitz and Wright add:

The decision maker basing selections on the expected value criterion, over the long run, does better on the average than will the decision maker who relies on any other criterion - but only if the "run" is long

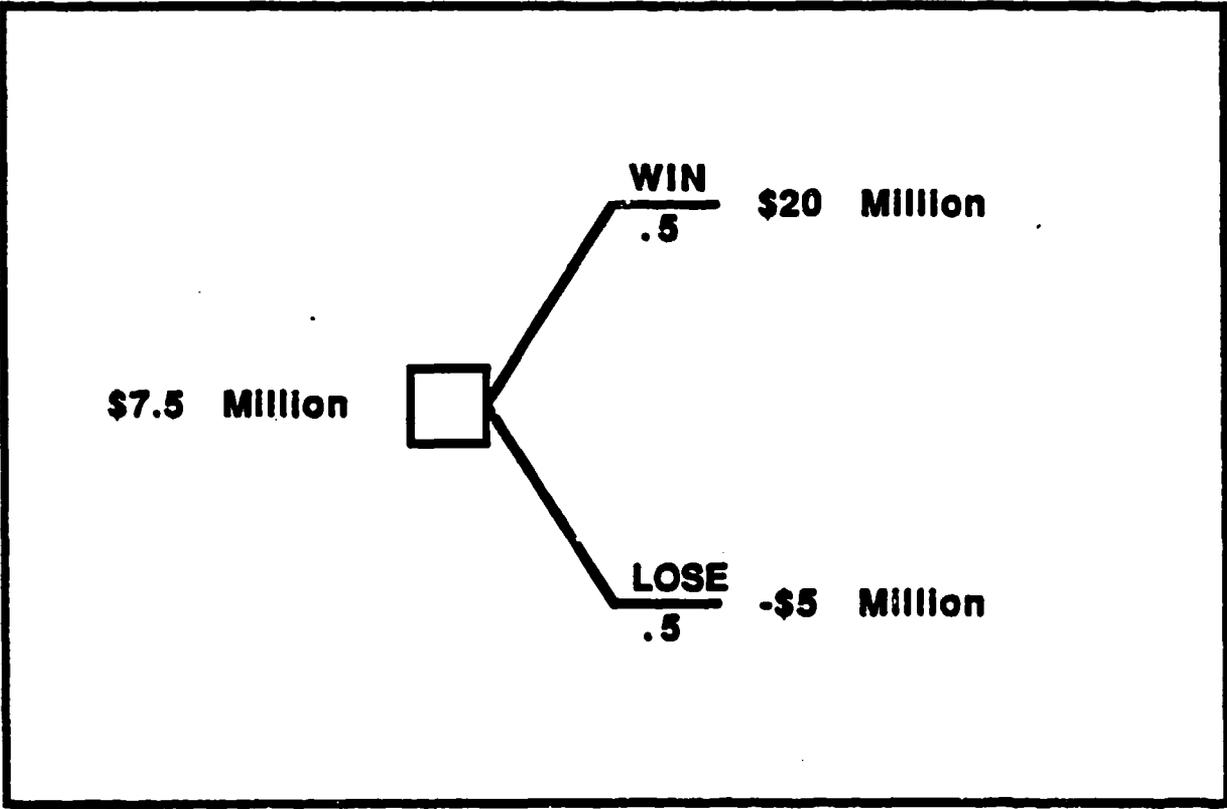


Figure 3.8 Expected Value Lottery Example

enough and the decision maker both survives the short-term ups and downs and is a continual participant in comparable decision problems (18:148).

For the purpose of demonstrating the method of this thesis the decision maker was assumed to be an expected value decision maker.

Determine the Best Alternative. In this step one had to choose between the two alternatives. Since the decision maker was assumed to be an expected value decision maker, it was not necessary to find a utility function. The procedure was to use the maximum expected value selection criterion adapted for this problem to find the minimum expected value (MEV), i.e. the minimum loss. The MEV was

found for each alternative and then mathematically compared. For the payload escape system to be feasible, its MEV or minimum lost costs had to be less than those for the no escape system alternative. In other words, this relation had to be true:

$$\text{MEV (escape system)} < \text{MEV (no escape system)}$$

Moskowitz and Wright give one description of how to take the expected value (18:123):

1. assign a probability to each event with the probabilities summing to 1
2. compute the expected value of each action by multiplying each value by its corresponding probability and summing these products
3. choose an action whose expected value is largest.

Again, in this problem one would choose the smallest expected value so as to find the minimum loss.

Sensitivity Analysis. This sensitivity analysis was performed on the mathematical relation found in the previous step. The analysis was performed by varying the range of values of each variable in the equation and observing the effect on the payload escape system's cost.

#### Justification of the Methodology

The problem for this thesis was a decision: to use an escape system or to not use an escape system. Uncertainty exists in the problem because of unknown booster reliability and unknown attitudes toward risk. Decision analysis is a methodology that can help decision makers

reason logically about a decision under conditions of uncertainty. It was, therefore, incorporated into the methodology for solving this problem.

Although a classical decision analysis was not performed, a subset of the methodology was used to build the model for this problem. The decision analysis method is strongly oriented to models for describing problems and can factor uncertainty into those models. The structure of this model could be expanded to include other pertinent variables and the methodology would still work.

Chapter IV looks at the findings that resulted from the methodology described in this chapter.

## IV. Findings

### Introduction

This chapter discusses the findings that are based on the Chapter III methodology. The findings relate directly to the study objective and first subobjective as stated in Chapter I. The other subobjectives will be addressed in Chapter V.

First, the model that was developed from the Chapter III methodology was solved. This defined the payload escape system mathematical cost relation and demonstrated the methodology. Developing that methodology was the main objective of this thesis. Next, a sensitivity analysis was performed on the cost relation. Finally, use of the cost relation was demonstrated with some past booster failure events. An application of the cost relation was the first subobjective of this thesis.

### Mathematical Cost Relation

The methodology described in Chapter III was used to build the problem model shown in Figure 3.7. Now the model is solved by successively taking the expected value (EV) of each node backwards through the decision tree. The expected value procedure is completed when the decision node is the sole remaining node in the tree. At that point the decision tree would look like the tree in Figure 3.2.

Each outcome of the decision node will have an associated, final expected value. In reality, a decision maker would choose the outcome with the most desirable associated value. In this model, one can not choose between values while the variables are still unknown. Therefore, the values were compared in an inequality and solved for the escape system cost,  $C_{ES}$ .

A decision maker would generally choose the escape system option if its associated value was less than the no escape system value, as follows:

$$EV(\text{escape system}) < EV(\text{no escape system}) .$$

Since the expected values represent losses, those losses were defined with negative values.

Taking Expectation. The expected value of the escape system node was solved first. From Figure 3.7, the value associated with escape system YES, booster FAILS, and escape system WORKS is  $V_2$ , where:

$$V_2 = -C_B - C_S - C_{I2} - C_{ES} - C_R - C_{NB} - C_{NES} - C_{NI2} + P_{I2A} \quad (4.1)$$

The value associated with escape system YES, booster FAILS, and escape system FAILS is  $V_3$ , where:

$$V_3 = -C_B - C_S - C_{I2} - C_{ES} - C_{NS} - C_{NB} - C_{NES} - C_{NI2} + P_{I2B} \quad (4.2)$$

EV of Node (E). The expected value of the escape system node, (E), is calculated as:

$$EV(E) = (1-P_e) (V2) + (P_e) (V3) \quad (4.3)$$

which gives:

$$EV(E) = -2C_{I2} - 2C_{ES} - C_R - C_B + P_{I2A} + P_e C_{NS} - P_e P_{I2A} - P_e P_{I2B} \quad (4.4)$$

Figure 4.1 shows the new decision tree with EV(E) substituted for the escape system node, (E).

The next step is to calculate the expected value for both booster nodes. The expected value for escape system YES was calculated first. From Figure 4.1, the value associated with escape system YES and booster WORKS is V1, where:

$$V1 = -C_B - C_S - C_{I2} - C_{ES} \quad (4.5)$$

From Figure 4.1, the value associated with escape system YES and booster FAILS is EV(E), Eq (4.4).

EV of ES (YES). The expected value for the escape system (YES) choice, is calculated as:

$$EV(YES) = (1-P_b) (V1) + (P_b) ( EV(E) ) \quad (4.6)$$

which gives:

$$EV(YES) = -C_{ES} - P_b C_{ES} - C_{I2} - P_b C_{I2} - P_b C_{NS} - P_b C_{I2A} + P_b P_{I2A} + P_b P_{I2B} - P_b P_{I2A} - P_b P_{I2B} \quad (4.7)$$

Figure 4.2 shows the new decision tree with EV(YES) substituted for the "upper" booster node, (B).

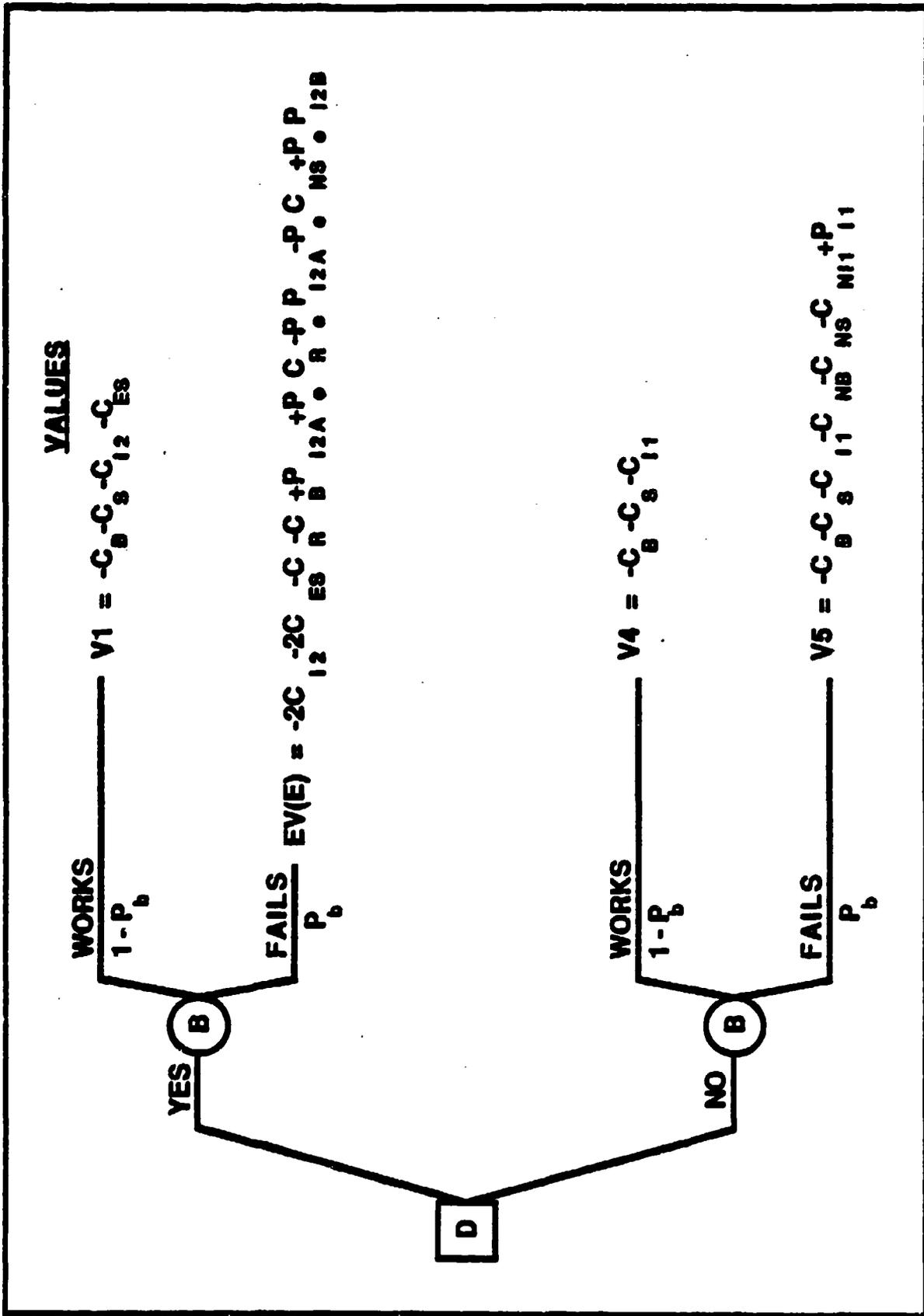


Figure 4.1 Expectation on Node (E)



The next step is to calculate the expected value on the remaining, "lower", booster node, (B). From Figure 4.1, the value associated with escape system NO and booster WORKS is V4, where:

$$V4 = -C_B - C_S - C_{I1} \quad (4.8)$$

The value associated with escape system NO and booster FAILS is V5, where:

$$V5 = -C_B - C_S - C_{I1} - C_{NB} - C_{NS} - C_{NI1} + P_{I1} \quad (4.9)$$

EV of ES (NO). The expected value for the escape system (NO) choice, is calculated as:

$$EV(NO) = (1 - P_b) (V4) + (P_b) (V5) \quad (4.10)$$

which gives:

$$EV(NO) = -C_{I1} - P_b C_{I1} - P_b C_B - P_b C_{NS} + P_b P_{I1} \quad (4.11)$$

Figure 4.3 shows the new decision tree with EV(NO) substituted for the "lower" booster node, (B).

Comparing Expectations. As mentioned previously, the decision maker would only choose the escape system (YES) option if its expected value, i.e. lost costs, was less than the expected value of the escape system (NO) option. Solving for  $C_{ES}$  under this condition will give the payload escape system cost relation. The following relation exists when the payload escape system (YES) choice is optimal:

$$EV (YES) < EV (NO) \quad (4.12)$$

**VALUES**

$$EV(\text{YES}) = -C_{ES} - P_{12} C_{12} - P_{Rb} C_{Rb} - P_{12A} C_{12A} + P_{Bb} P_{Rb} C_{Rb} + P_{12B} C_{12B} - P_{NSb} P_{12B} C_{12B} + P_{NSb} P_{12B} C_{12B}$$

$$EV(\text{NO}) = -C_{11} - P_{11} C_{11} - P_{Bb} C_{Bb} + P_{NSb} C_{NSb}$$

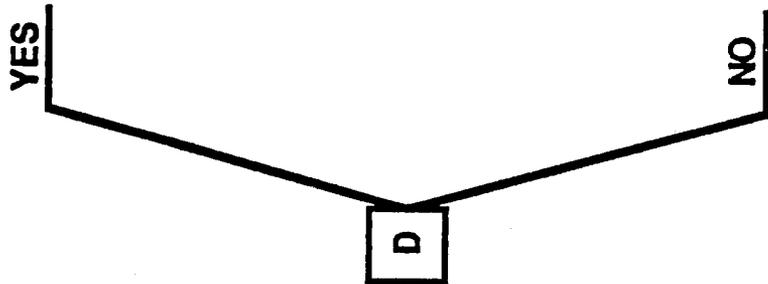


Figure 4.3 Final Expected Value Choices

Substituting Eqs (4.7) and (4.11) into Eq (4.12) and solving for  $C_{ES}$  yields the general relation for payload escape system cost:

$$C_{ES} < [ P_b (C_{NS} + C_{I1} - C_{I2} + P_{I2A} - P_{I1} - C_R) + P_b P_e (C_R - P_{I2A} - C_{NS} + P_{I2B}) + C_{I1} - C_{I2} ] / (1 + P_b) \quad (4.13)$$

Two Launch Cases. As mentioned previously, a decision maker may or may not have access to insurance coverage. This immediately presents two cases: Case A, a launch with insurance coverage and Case B, a launch without insurance coverage.

The Case With Insurance. In Case A, it was assumed that insurance payoffs covered 100 percent of a loss. Applying this assumption to Eq (4.13) allows equivalent terms to subtract out of the equation:

$$\begin{array}{l} C_{NS} \text{ and } P_{I1} \\ C_R \text{ and } P_{I2A} \\ C_{NS} \text{ and } P_{I2B} . \end{array}$$

This gives the Case A payload escape system cost relation:

$$C_{ES} < [ P_b (C_{I1} - C_{I2}) + (C_{I1} - C_{I2}) ] / (1 + P_b) \quad (4.14)$$

By substituting Eqs (3.2) and (3.3) into Eq (4.14), this relation is reduced to its final form:

$$C_{ES} < (R_{I1} - R_{I2}) (C_S) \quad (4.15)$$

where

$R_{I1}$  = the insurance rate with no payload escape system on the booster (ELV)

$R_{I2}$  = the insurance rate with a payload escape system on the booster (ELV).

This relation, Eq (4.15), may be surprising in that the cost of the payload escape system does not depend on the probabilities of booster failure or escape system failure. The cost only depends on the insurance rates and the original satellite cost. This is what should be expected, however. In Case A, the insurance broker is assuming all of the risk because the payoff equals the loss. Therefore, the funds for building a payload escape system would come solely from insurance premium savings. These savings presume that insurance rates would be less expensive when a payload escape system was used. If the estimated cost of building a payload escape system exceeded the expected savings on insurance premiums, then there would be a new decision to be made. The decision would then be based on other factors such as the "intrinsic" value of the payload escape system itself.

The Case With No Insurance. In both cases, it was assumed that a salvaged satellite could be refurbished. Also, that the refurbishment cost of the satellite would be some fraction of a satellite's original cost, base on a refurbishment rate,  $R_f$ . Of course, for Case B, there are no insurance costs or payoffs. Applying this assumption to

Eq (4.13) gives the Case B, no insurance, payload escape system cost relation:

$$C_{ES} < [ P_b (C_{NS}-C_R) + P_b P_e (C_R-C_{NS}) ] / (1+P_b) \quad (4.16)$$

By using the previous assumption that  $C_S = C_{NS}$  and by substituting Eq (3.4) into Eq (4.16), this relation is reduced to its final form:

$$C_{ES} < [ P_b (1-P_e) (1-R_f) C_S ] / (1+P_b) \quad (4.17)$$

The payload escape system cost,  $C_{ES}$ , depends on the probability of booster failure, probability of escape system failure, the refurbishment rate and the satellite cost. The payload escape system option will be most desirable when the right hand side of Eq (4.17) is large. One can see that higher cost satellites will make a payload escape system more feasible. Also, as  $P_e$  and  $R_f$  tend toward zero, the permissible cost of the escape system becomes higher. Finally, as the probability of booster failure gets larger, the permissible cost of the escape system would tend to be higher.

A mathematical cost relation was developed for two launch cases using the Chapter III methodology. Eq (4.15) represents the "with insurance", Case A, relation. The "no insurance", Case B, relation is Eq (4.17).

## Sensitivity Analysis

A classical decision analysis would look at the underlying probability distributions for the variables involved in the sensitivity analysis. The distributions over the variables are usually obtained from the decision maker or from some other expert familiar with the problem.

No decision maker was used for this problem. Therefore, the sensitivity analysis performed was an example of the methodology using representative data. The general results demonstrate the methodology and indicate trends. The sensitivity analysis can be performed again later as more accurate data becomes available.

Case A Analysis. Analysis was first performed on Case A, the "with insurance" case. Sources suggest that insurance rates can be 22 percent of the satellite cost (13:22). Discussions with an insurance broker also suggested that satellite insurance could be in the neighborhood of 25 percent of the satellite cost (16).

The analysis of Case A, Eq (4.15), was performed as five subcases and is depicted graphically in Figures 4.4 through 4.8. Each subcase was based on a unique value for  $R_{I1}$ , the insurance rate for no escape system. Within each subcase,  $R_{I2}$ , the insurance rate with an escape system, was varied from a rate of zero percent to a maximum rate equal to  $R_{I1}$ . In each subcase, the feasible region is the area beneath the lines. When the cost of an escape system

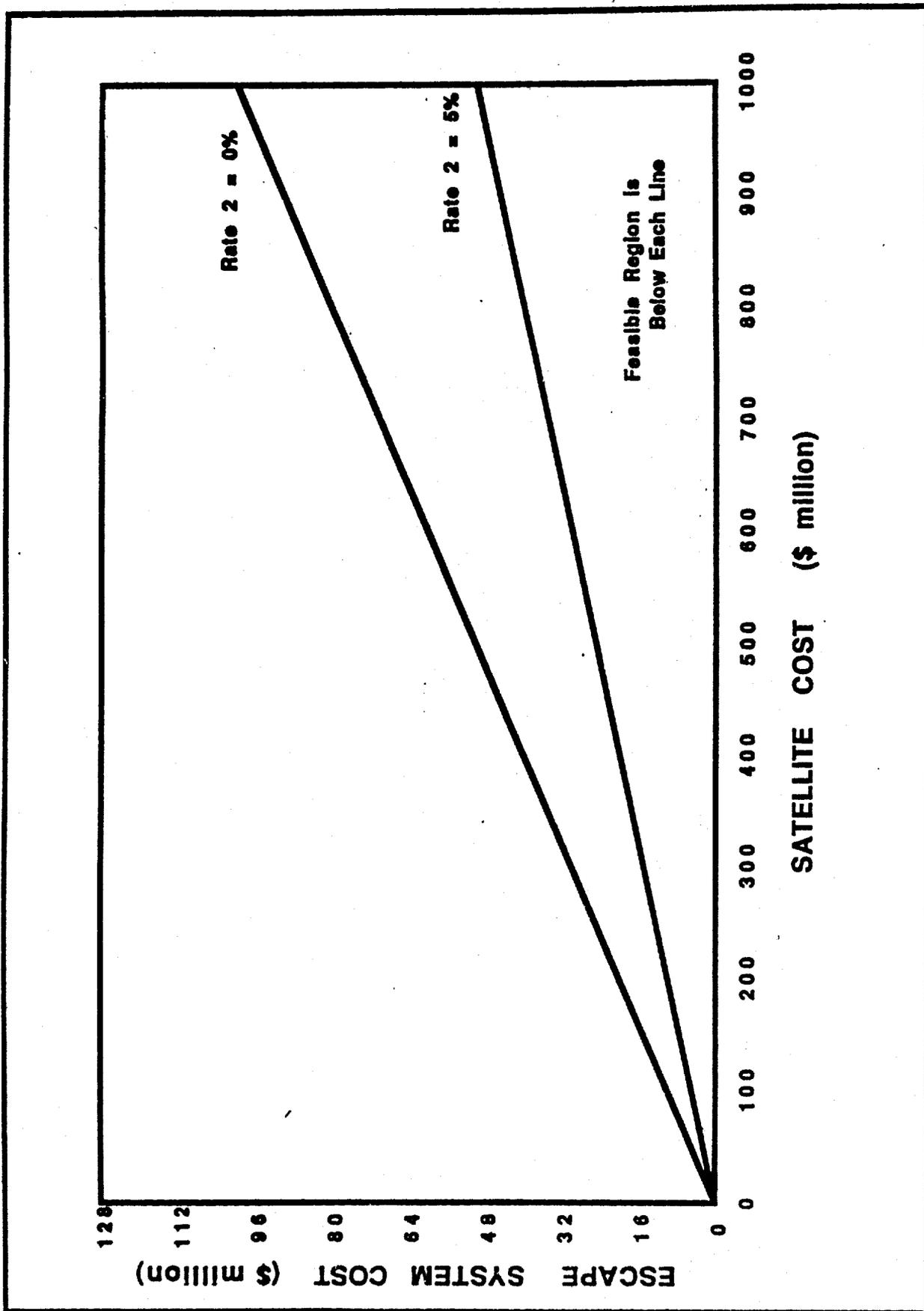


Figure 4.4 Insurance Case With Rate 1 = 10%

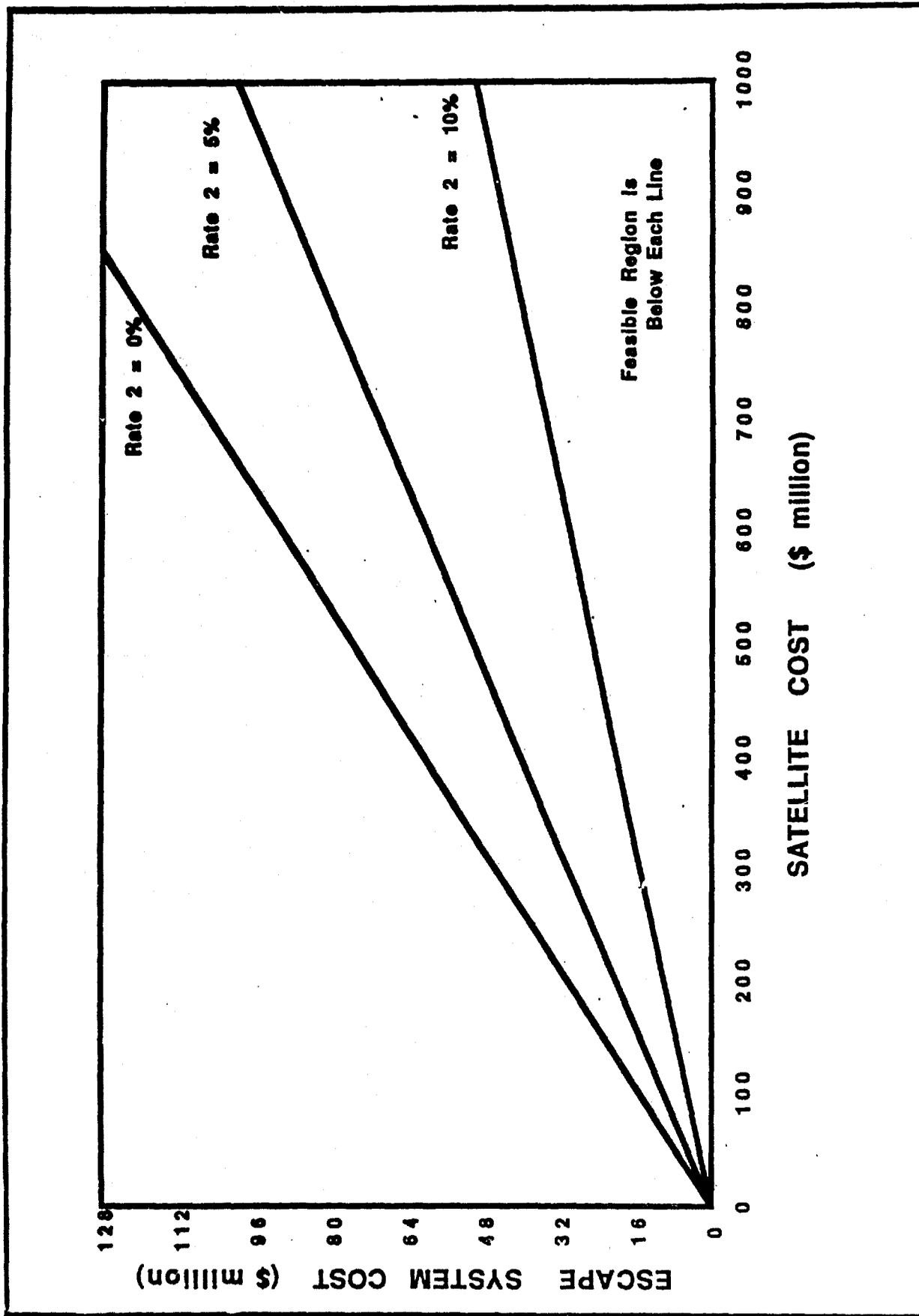


Figure 4.5 Insurance Case With Rate 1 = 15%

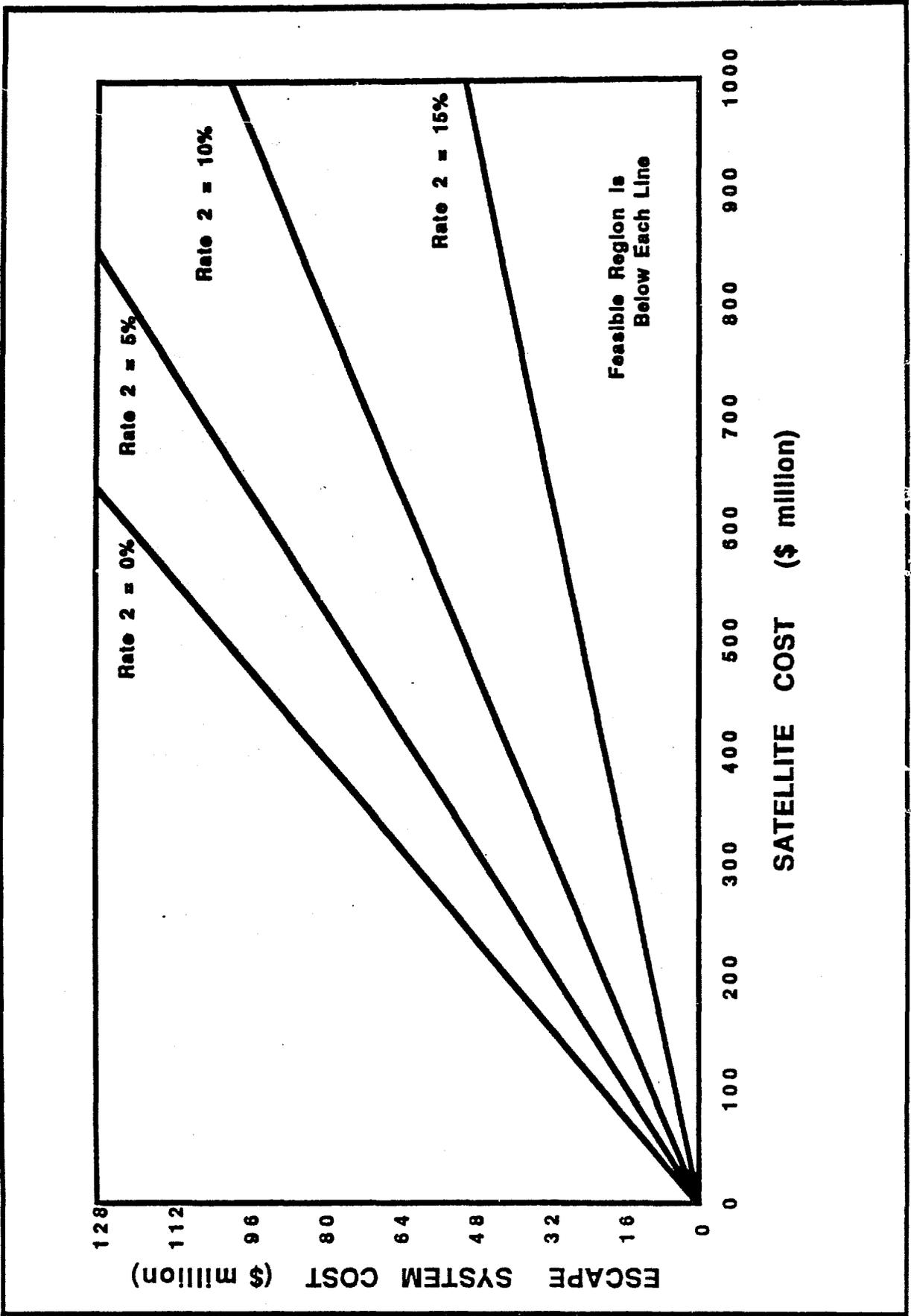


Figure 4.6 Insurance Case With Rate 1 = 20%

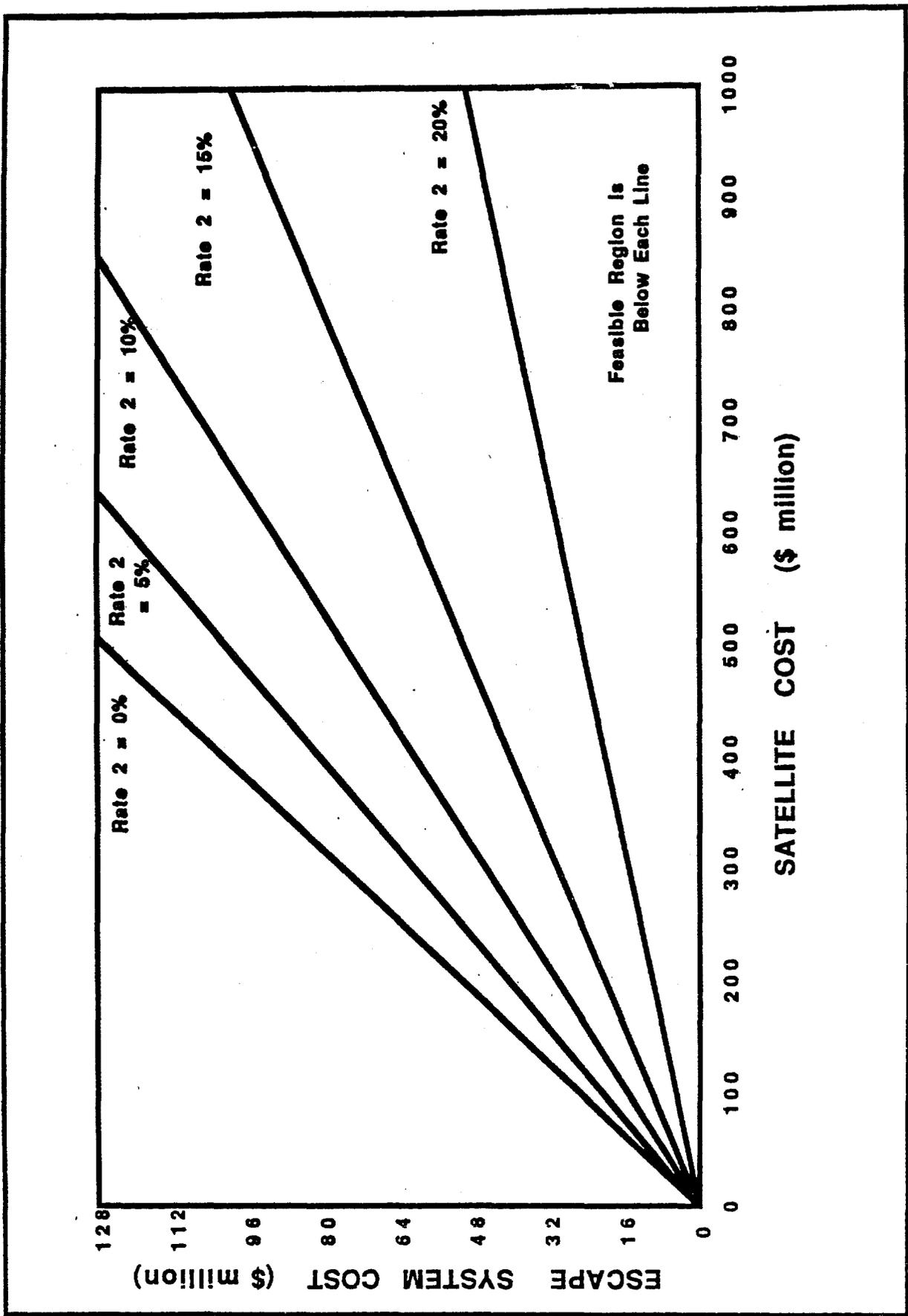


Figure 4.7 Insurance Case With Rate 1 = 25%

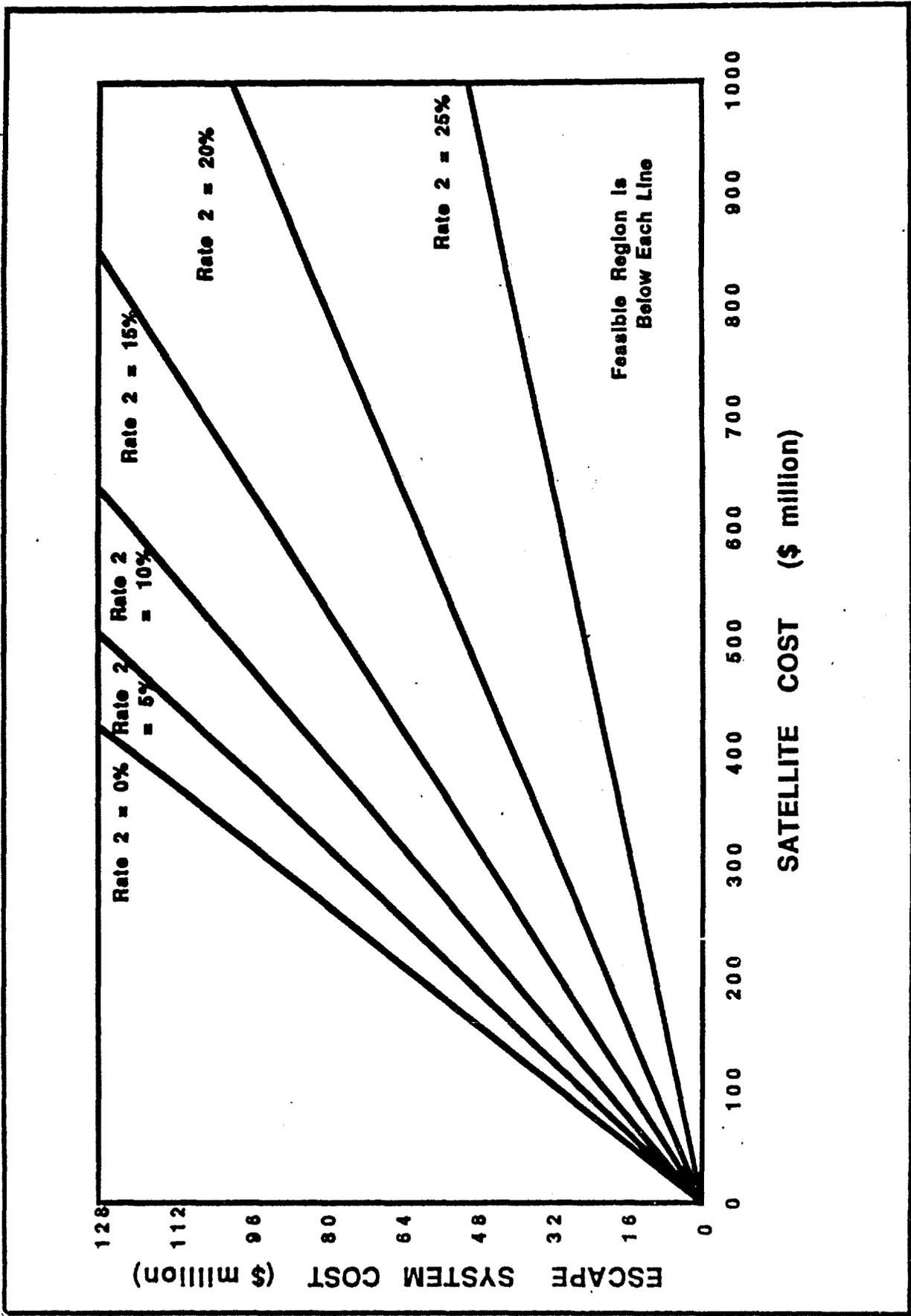


Figure 4.8 Insurance Case With Rate 1 = 30%

versus the cost of a satellite falls within the feasible region, a decision maker should consider using a payload escape system. For example, in Figure 4.4, if  $R_{I2}$  is five percent, escape system cost is \$16 million dollars and satellite cost is \$700 million, then using the escape system should be considered logical.

As expected from Eq (4.15) and as seen in the figures, when  $R_{I1}$  tends toward some maximum and  $R_{I2}$  tends toward zero, the feasible region for escape system use is maximized. In general, the more money that is saved on insurance premiums would mean more money is available to be spent on an escape system.

Case B Analysis. This analysis was performed with representative data. Data was not available for the probability of escape system failure,  $P_e$ . It was assumed that  $P_e$  would be as good as or better than  $P_b$ . There was also no refurbishment data. Values for these variables were estimated. Two sources were used to obtain booster failure probabilities. An insurance broker and the booster manufacturer for each booster type were consulted to obtain the data in Table I.

The data used in this analysis, as in Case A, was representative data based upon factual data and upon estimation. Table II shows the data points used for this analysis.

**TABLE I**  
**Booster Failure Probabilities, P<sub>b</sub>**

Booster Type	Insurance Broker (16)	Booster Manufacturer
Titan IIIs	8.45%	6.16% (24)
All Atlas	15.32%	9.29% (9)
All Deltas	7.18%	6.70% (25)

**TABLE II**  
**Representative Rates Used in the Case B Analysis**

Booster Failure Rate	Escape System Failure Rate	Refurbishment Rate
6%	2%	15%
8%	5%	
10%	10%	
15%		

The analysis of Case B, Eq (4.17), was performed by allowing each variable in Table II to vary over its range while holding the others at their nominal values. The nominal value chosen for  $P_b$  was eight percent. The results are depicted graphically in Figures 4.9 through 4.11.

Again, it is obvious that the feasible region grows larger as satellite cost increases. In general, the escape system cost is sensitive to booster failure rates and to the refurbishment rate. Escape system cost does not appear to be sensitive to escape system reliability; Figure 4.10. This information could be useful when designing a payload escape system. Building an escape system with a lower reliability would probably mean a lower construction cost.

Figure 4.12 shows a best case/worst case scenario for payload escape system cost. The top line represents the highest  $P_b$ , best  $P_e$  and best  $R_f$ . This is the largest feasible region expected for this data. The bottom line represents the least feasibility for an escape system.  $P_b$  is the lowest in this instance while  $P_e$  and  $R_f$  are at their highest value. The larger feasible region means that an escape system could have a higher cost, but could still be expected to reduce economic losses in the long run.

Figures 4.4 through 4.12 are graphical tools for helping a decision maker answer the question of when to use an escape system. The methodology can help develop graphs suited to a particular decision maker's situation.

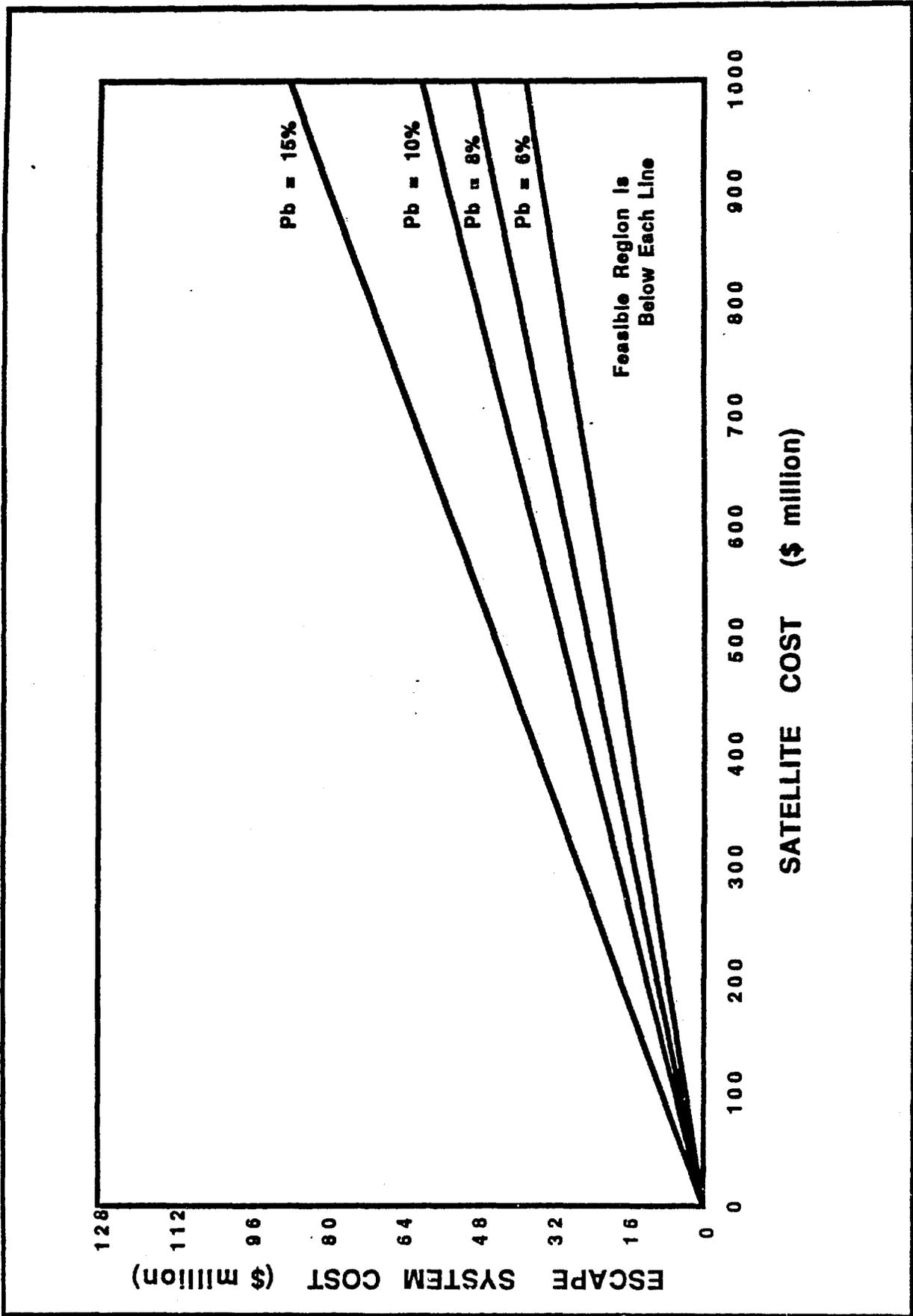


Figure 4.9 Case With No Insurance and Booster Failure Rate Varied

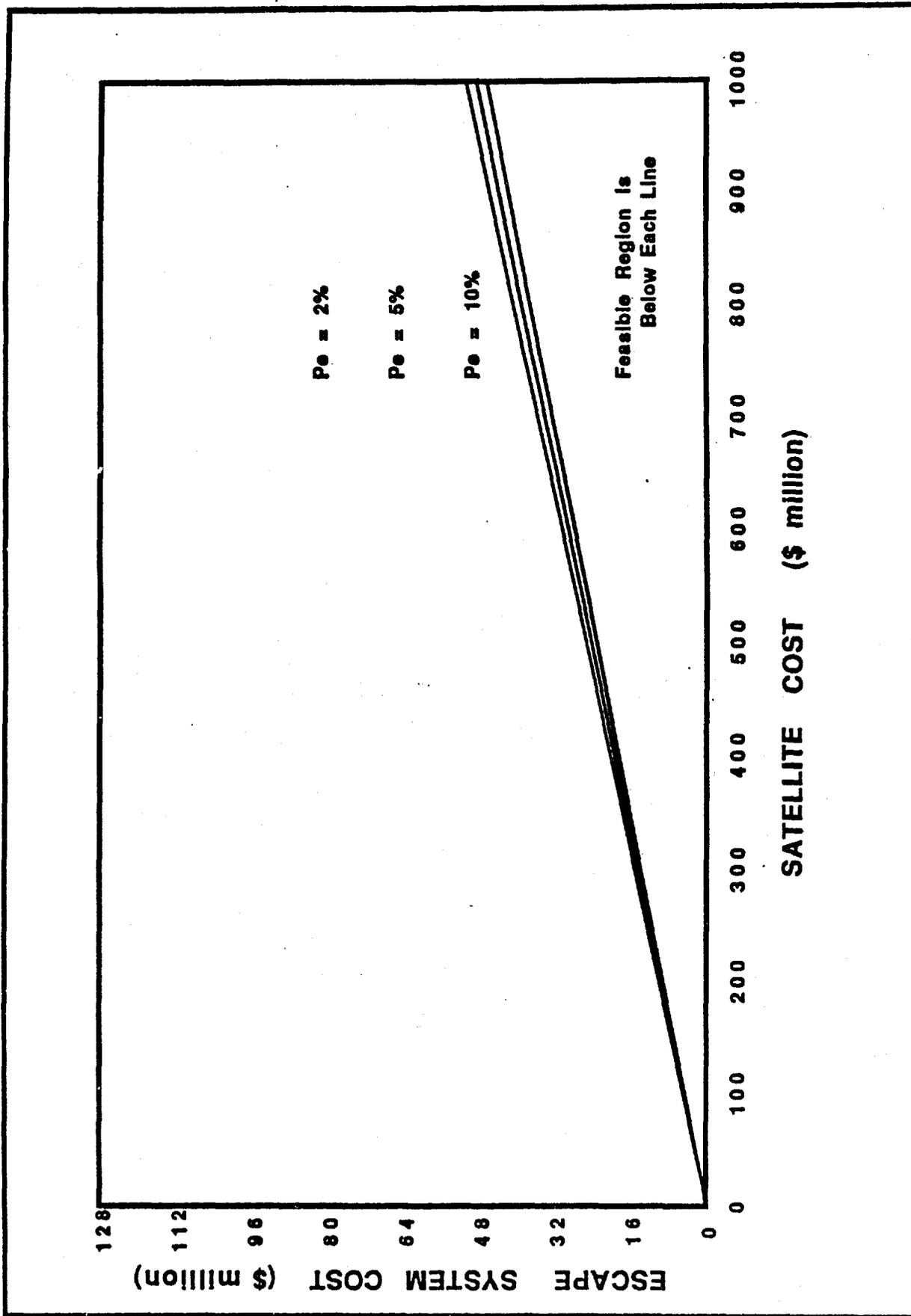


Figure 4.10 Case With No Insurance and Escape System Failure Rate Varied

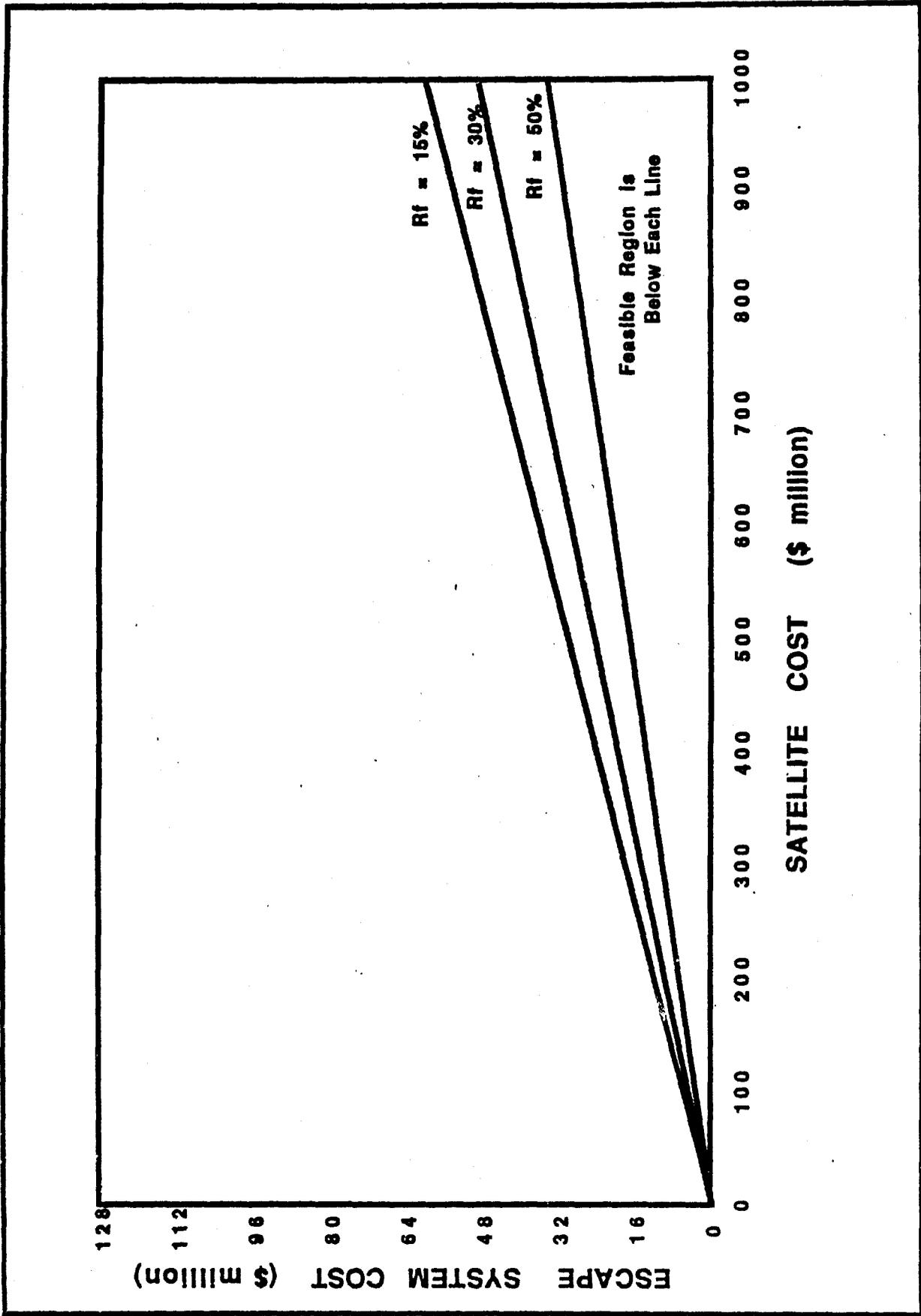


Figure 4.11 Case With No Insurance and Refurbishment Rate Varied

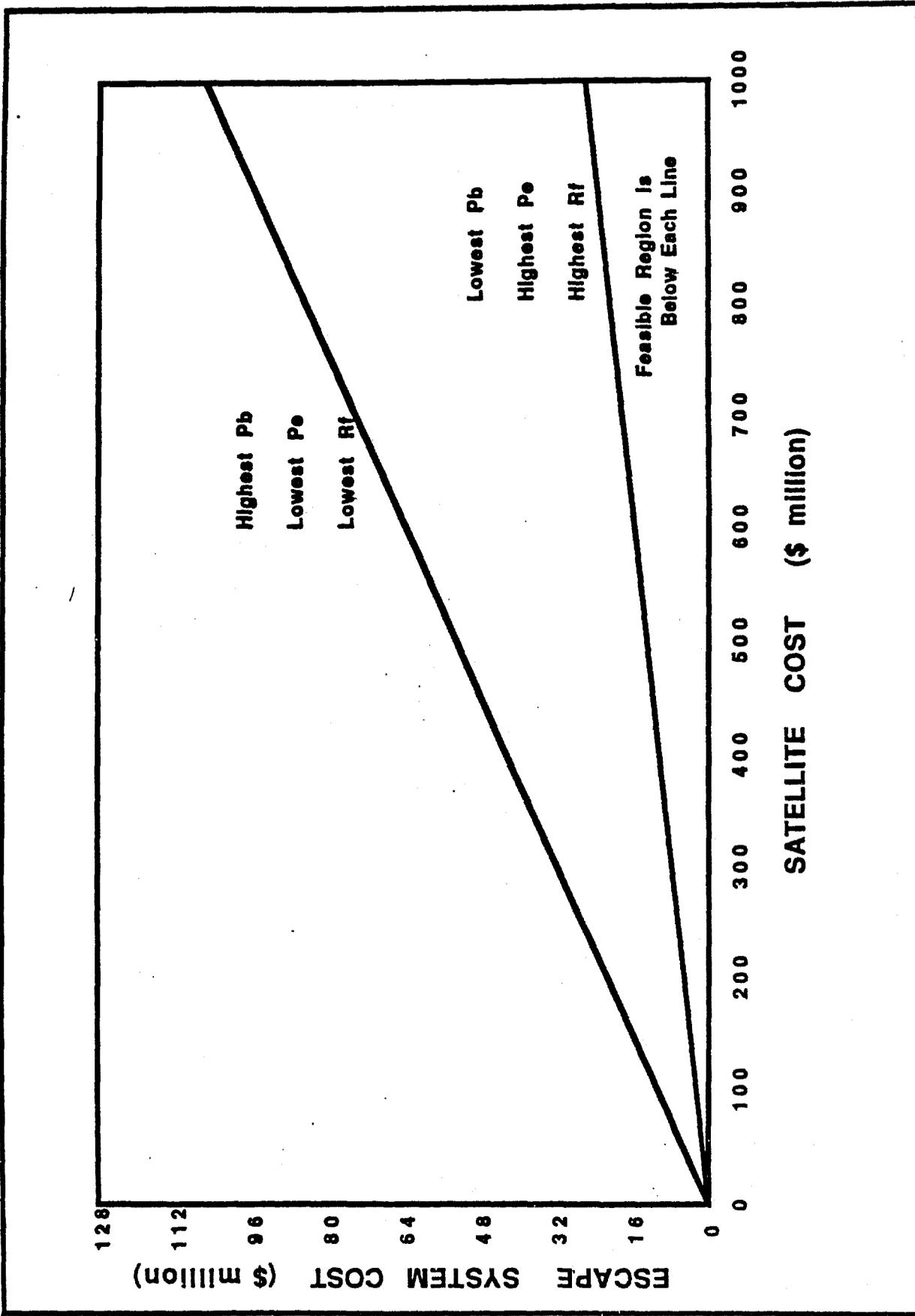


Figure 4.12 Best Case/Worst Case for Payload Escape System

## An Application of the Methodology

The payloads destroyed in four launch failures in 1985 and 1986 included a \$100 million NASA Tracking and Data Relay Satellite (TDRS), two DOD satellites and a \$57.5 million GOES weather satellite (19:20, 8:13). In March 1987, an Atlas/Centaur failed, destroying an \$83 million FltSatCom satellite (14:23-24). The two DOD satellites are rumored to cost roughly \$200 - \$300 million each. These figures could not be substantiated for this thesis.

Eq (4.17) used a TDRS cost of \$100 million, a FltSatCom cost of \$83 million, and a GOES cost of \$57.5 million. Table I and Table II provided the other data to the equation. Although the TDRS actually flew on the space shuttle, for the purpose of this exercise it is assumed to have flown on a Titan booster. For the TDRS it was assumed that  $P_e = .05$ ,  $P_b = .0845$  and  $R_f = .30$ . For the FltSatCom and the GOES it was assumed that  $P_e = .05$ ,  $P_b = .1532$  and  $R_f = .30$ .

Based on these figures for these satellites, a payload escape system would have to cost less than the amounts calculated from Eq (4.17). These escape system costs would make it economically feasible to use an escape system. The costs are as follows:

for TDRS:	CES	<	\$5.18 million
for FltSatCom:	CES	<	\$7.33 million
for GOES:	CES	<	\$5.08 million.

If an actual escape system would cost less than the figures calculated above, given the assumptions and methodology of this thesis, then the rational decision would be: YES, use a payload escape system. In the long run and on the average then, it would be economically advantageous to use the payload escape system.

### Chapter Summary

This chapter described the application of the methodology of Chapter III. The methodology was used to find a payload escape system cost relation for two cases. Case A, with insurance, Eq (4.15) and Case B, with no insurance, Eq (4.17). A sensitivity analysis of the cost relations was performed and represented graphically. The graphs demonstrated the methodology and showed the region over which a payload escape system was economically feasible. Finally, one of the two cost relations was used to find the maximum feasible cost of an escape system for three different satellites.

## V. Conclusions and Recommendations

### Introduction

This thesis constitutes work that has not formally been done previously. Much has been studied about manned vehicle escape systems. The literature review for this thesis revealed no known, formal studies or research on the topic of unmanned payload escape systems.

This chapter discusses whether the research objective and subobjectives have been answered by this thesis. The general methodology will be summarized and conclusions made. Finally, recommendations for future research on this topic are made.

### Research Objective

The main objective was to develop a methodology that defines a mathematical cost relation that would demonstrate the economic feasibility of a payload escape system. This methodology was developed in Chapter III using a subset of the decision analysis method. A decision tree model was developed and then, in Chapter IV, solved for the escape system cost. Eqs (4.15) and (4.17) define the upper limit on payload escape system cost for one to be economically feasible.

First Subobjective. The first subobjective was to demonstrate the use of the mathematical cost relation. This was done in two ways. First, a series of graphs were

developed showing the feasible region over a wide range of satellite costs. Second, the costs of three satellites were used to determine a maximum escape system cost for each satellite.

Second Subobjective. The second subobjective was to identify pertinent background information that could be useful in unmanned payload escape system applications. This was accomplished in the Chapter II literature review. Some of this information hints at technical feasibility although an engineering analysis was beyond the scope of this thesis.

Third Subobjective. The third subobjective was to identify specific unmanned escape system topics for future research. This was accomplished in the recommendation section of this chapter.

### Methodology

The problem for this thesis was approached by first formulating the problem as a decision to be made. The decision was to choose between using a payload escape system and not using a payload escape system. A subset of decision analysis was used to build the model and provide the theoretical background for solving the problem.

Decision analysis is a methodology that is especially adept at handling uncertainty. To perform a classical decision analysis requires a decision maker so that particular preferences and attitudes toward risk can be

incorporated into the model framework. A decision maker was not consulted for this thesis. The assumption was made that this model would be for an expected value (risk neutral) decision maker. Even with no decision maker, it was still decided to use at least a subset of decision analysis for this problem. The reason was to allow the model the flexibility to deal with uncertainty. Therefore, similar problems, even if they are more complex, should be solvable using the methodology of this thesis.

Once the appropriate variables and values were incorporated into this decision tree model, the decision tree could be solved. The tree was solved by taking successive minimum expected values and then solving for the payload escape system cost. The resulting mathematical relations could then be used to define when it was economically feasible to use a payload escape system.

### Recommendations

As is usually the case, time became a constraining factor for this thesis. There are more questions that need answering about payload escape systems and when they should be used. To help answer some of the unanswered questions that were raised during the course of this thesis, the following topics are recommended for further study:

- 1) A study to determine an estimated cost for a payload escape system. This thesis defines the maximum a

payload escape system could cost and still be economically feasible. Perhaps the cost could be broken out by different weight categories the escape system would be capable of lifting.

2) Another study similar to this one but, using utility theory instead of the expected value criteria.

3) A study that performs a classical decision analysis on this problem. Perhaps a NASA or Air Force space program manager would be interested in serving as the decision maker.

4) A study to look at possible alternative payload escape system configurations. The Apollo Launch Escape System could be a possible model. Another possibility would be to cluster solid rocket motors about the circumference of the payload module.

5) A trade off study to examine the merits of taking away payload capacity to add a payload escape system. Many in the space community expressed doubt about the value of such a trade off.

6) A study of blast effects on satellites. Would a satellite survive a booster explosion? Would it be economical to design for blast effects?

7) A parametric study of the stresses that would be placed on a satellite by an operating payload escape system. Are satellites sturdy enough to be "wisked" away from a failing booster?

8) A study on the best method of recovering a satellite. Is there any way it could be recovered on land? What are the effects of salt water exposure on the satellite that lands in the ocean? Could there be an aerial recovery?

9) A study to determine how much damage a satellite could sustain and then be fully refurbished. Would it be cost effective to refurbish damaged satellites? The space shuttle has recovered two communication satellites for refurbishment and reuse.

10) A study of fault detection systems. Could a system be designed to sense catastrophic failures? Could a system be designed that would use the payload escape system to abort a mission to orbit if it was close enough to orbit?

11) A study of launch abort criteria. Should a range safety officer give an escape system time to operate before ordering a booster destroyed?

### Chapter Summary

This chapter discussed the research objective and subobjectives that were answered by this thesis. The general methodology was reviewed and some conclusions made. Finally, recommendations were made for future research.

There is still a trend toward more expensive satellites with even more capability than older versions. In a fiscal atmosphere where budget cuts are becoming the norm, the space community needs to consider alternatives to

tossing away, in some cases, hundreds of millions of dollars on launch failures. With the historical launch loss rates as high as 12-15 percent (13:22), one alternative may be to try and save payloads with some kind of an escape system.

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## VITA

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