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Final Report

**A PILOT LEVEL DECISION ANALYSIS OF
THERMIONIC REACTOR DEVELOPMENT STRATEGY
FOR NUCLEAR ELECTRIC PROPULSION**

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Prepared for:

PROPULSION RESEARCH AND ADVANCED CONCEPTS SECTION
JET PROPULSION LABORATORY
PASADENA, CALIFORNIA



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May 1973

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FOR NUCLEAR ELECTRIC PROPULSION
THERMONIC REACTOR DEVELOPMENT STRATEGY
A PILOT LEVEL DECISION ANALYSIS OF

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I SUMMARY

1.1 Description of the Study

This report describes an analysis of the development policy for thermionic reactors to provide electric propulsion and power for space exploration. It was conducted for the Jet Propulsion Lab (JPL), under a NASA master contract, and was performed by the Decision Analysis Group of Stanford Research Institute (SRI), with the assistance of JPL, NASA, and Gulf General Atomic (GGA) personnel.

The initial aim of the analysis was to evaluate alternatives for developing a thermionic reactor. The decision to develop such a reactor for nuclear electric propulsion should be made within the policy for future space exploration. Consequently, methods were needed for characterizing and assessing space exploration strategies, but only to the level of detail required to provide an appropriate background for the thermionic reactor decision.

The study was performed using decision analysis, a discipline that comprises the philosophy, methodology, and professional practice necessary to formalize the analysis of decisions. The contribution of the Decision Analysis Group was to characterize the logical structure of the decision through formal models and provide a language for describing pertinent information. The contribution of JPL, NASA, and GGA representatives was to provide technological expertise, obtain necessary data, and gather judgments regarding NASA preferences.

The resulting decision model provides a unique approach to advanced propulsion planning by determining the long-term effects of various propulsion alternatives, technological developments, planetary exploration strategies, mission model sizes, and time preference judgments on the thermionic development policy. The models account not only for the direct costs incurred with various development policies, but also for the social benefits, for example from scientific accomplishments, and social costs, such as time delay of accomplishments.

The model is implemented by a computer program that (1) determines the cost (within the concept of a planetary exploration strategy) of accomplishing missions with all available propulsion systems (including effects of flight time and spacecraft power availability); (2) selects

the most effective propulsion system available to fly each mission; and (3) evaluates the benefits received in terms of missions accomplished and the timing of benefits. These effects are economically balanced to determine the desirability of any development policy. An important feature of the model is its ability to rate any development policy in terms of the present value of national profit. This measure of system value allows the effect of changes in both the development policy and the project environment to be determined quantitatively.

It should be noted at this point that during the course of this analysis, the U.S. thermionic project was terminated because of budgetary considerations. SRI's work, which was supported by a subcontract, was terminated at the same time. Therefore, only about two-thirds of the work originally proposed was completed.

The termination has had three principal effects on this project. First, the data and the model structure have not been carefully reviewed with JPL and NASA personnel. Second, since we did not have the necessary value judgments from NASA, many cases under various sets of value assumptions are presented. Thus, more data are presented than would be the case for a more thoroughly digested final report on a completed project. Third, the analysis never proceeded beyond the deterministic stage. Much of the benefits to NASA decision-makers from using decision analysis would derive from more powerful ways to treat uncertainty and to quantify risk.* It is unfortunate therefore that the decision analysis was terminated before the probabilistic phase was undertaken.

These problems restrict the absolute validity of our findings, but probably do not alter the basic insights and tendencies observed. This report also illustrates an approach to the modeling needed for decision-making that should be useful to JPL and NASA personnel. The simplicity of the models developed and the small amount of data required should make the decision analysis a useful, complementary tool to the very detailed Advanced Propulsion Comparison (APC) study conducted concurrently by NASA, JPL, Mathematica, and Lockheed.

1.2 Findings and Insights

Even at our incomplete level of analysis, it appears that the development of a thermionic reactor for nuclear electric propulsion can be economically justified under many reasonable sets of assumptions. The basic assumptions that strongly affect whether NASA should be developing

* See Appendix A for an introduction to risk preference theory.

a nuclear electric propulsion system are the value assigned to planetary exploration and NASA's time preference.

Both are judgments that must come from NASA's top management. The value assigned to planetary exploration may be measured in terms of an annual budget, a specific mission set over a fixed time period, or an appropriate annual number of missions. For example, the APC extended mission set (21 missions over 12 years - see Table 3.1) averages about 2 missions a year, whereas the von Braun mission set (9 missions over 8 years - see Table 3.1) averages about one mission per year. NASA's time preference is based on the future benefits that the agency must realize to justify a current investment. This is most easily represented by a discount rate, which reduces the value of payments received in the future.* A true constant dollar time preference can be expressed by an effective discount rate: the discount rate less the inflation rate.

In terms of these basic value measures, if NASA either desires to perform a planetary exploration program at least as ambitious as the APC base model or accepts an effective discount rate no higher than 5%, then nuclear electric propulsion appears to increase the present value of national profit by more than its development cost (compare Tables 5.4 and 5.5 with Table 5.3). If, however, the von Braun mission model more closely represents the value of planetary exploration to the nation and a 10% effective discount rate represents NASA's time preference, then the developments cost of nuclear electric propulsion cannot be justified. Moreover, under the assumptions that nuclear electric propulsion is economically justified, a 240 kWe spiral escape system is superior to a 120 kWe system which uses Centaur as a direct escape stage (see Table 5.2). In short, the same conditions that favor nuclear electric propulsion at all tend to favor a higher power level than the reference design, within the limitations of this analysis (see footnote on page 4).

Another important finding of this analysis is the critical role of mission values and time preference in design trade-offs. In economic models that consider only the cost of missions without quantifying their values, the main cost resulting from the longer flight times of less capable propulsion systems represents a very small operating cost during the added trip time. A much larger conceptual cost results from the delay in achieving the mission goals and the discount rate. The value of a mission (which must be larger than its cost for logical procedures to

* For example, a 10% discount rate means that one needs to receive a minimum of \$1.10 per year in the future to warrant investing \$1.00 today. With inflation, however, the \$1.10 next year actually has less purchasing power than \$1.10 would today, so the discount rate is effectively reduced by inflation.

apply) is many hundreds of millions of dollars. Such a value, discounted for even a modest time delay, may be substantially reduced in absolute terms. This effect greatly influences the importance of the specific weight of the reactor relative to its unit cost (see Section 3.7). The APC study embodies the same general effect by assuming equal target arrival dates for the various available propulsion systems. Delaying a launch allows the mission costs of more capable propulsion systems to be postponed, which effectively reduces these costs because of discounting.

1.3 Recommendations

The following recommendations are made within the context of our incomplete analysis and regarding a currently defunct program:

- (1) Retain nuclear electric propulsion as an option in all current and future economic analyses of advanced propulsion, such as the APC study, but at a low level of detail.
- (2) (a) Seek a clear statement of the size of mission set-- APC extended (2 per year), APC base (1-1/2 per year), or von Braun (1 per year)--that appears most appropriate to describe our planetary exploration program in the time period 1983-2000.
(b) Seek a judgment on the effective discount rate that should be used for NASA planning.
- (3) If the size of mission set (2a) is larger than the von Braun mission set, or if the effective discount rate (2b) is less than 5%, NASA should try to reinstate a thermionic reactor development program leading to an operational nuclear electric propulsion system.
- (4) Since the same conditions under which nuclear electric propulsion is economically justified also favor the higher power level reactor (240 kWe), any resumption of thermionic reactor development should probably focus on a larger reactor.*

* Multiple tug direct escape combinations with a 120 kWe NEP system may be even more attractive (see Figure 3.4 and Section 5.1).

- (5) NASA should perform a decision analysis on problem areas where uncertainty and risk are the crucial program difficulties. The potential for cost savings through a uniform and consistent risk attitude in space program management is extremely great.*

* See Appendix A for a discussion of how probabilities, values, and costs can be integrated to provide a comprehensive treatment of risk attitude in space program planning.

II INTRODUCTION AND PROBLEM STRUCTURING

2.1 Decision Analysis

Decision analysis^{1,2} has been primarily applied to problems characterized by uniqueness, complexity, and uncertainty. Space program planning faces all of these elements in an environment where the results are usually achieved far in the future and are difficult to evaluate. Nevertheless, significant expenditures continue to be allocated in pursuit of these objectives. In times of tight budgets, when a number of potentially desirable technologies or missions or both are competing for shares of diminishing total resources, it becomes increasingly important to manage the resources of organizations like NASA in a logical and consistent way. Decision analysis facilitates effective resource management, aiding the intuitive procedures of decision-makers by logically combining their value and preference judgments with information and alternatives from the organization's experts.

This synthesis is graphically depicted in Figure 2.1. Note that the aim of decision analysis is not to supplant the decision-maker, but to amplify his insight into numerous complicated and uncertain alternatives, to increase his ability to explain the basis for decisions to others in the management hierarchy, and to improve the organization's total portfolio of projects by providing a comprehensive discipline for management decision-making.

A decision analysis is usually carried out in three phases--deterministic, probabilistic, and informational--as shown in Figure 2.2. The deterministic phase consists of structural modeling and value modeling to formulate criteria for selecting the most appropriate decision if the ultimate value of all the relevant system variables were known. In this phase, sensitivity analysis is used extensively to measure the importance of the system variables. In the probabilistic phase, expert judgment on the uncertainty in the value of the most important system variables is encoded and the most appropriate decision is reexamined in light of the risks present in the project, given management's attitude toward risk. Finally, in the informational phase, the economic value of eliminating the uncertainty in these crucial variables is measured and compared with the costs of realistic information-gathering programs like construction of pilot facilities or prototypes. One benefit of

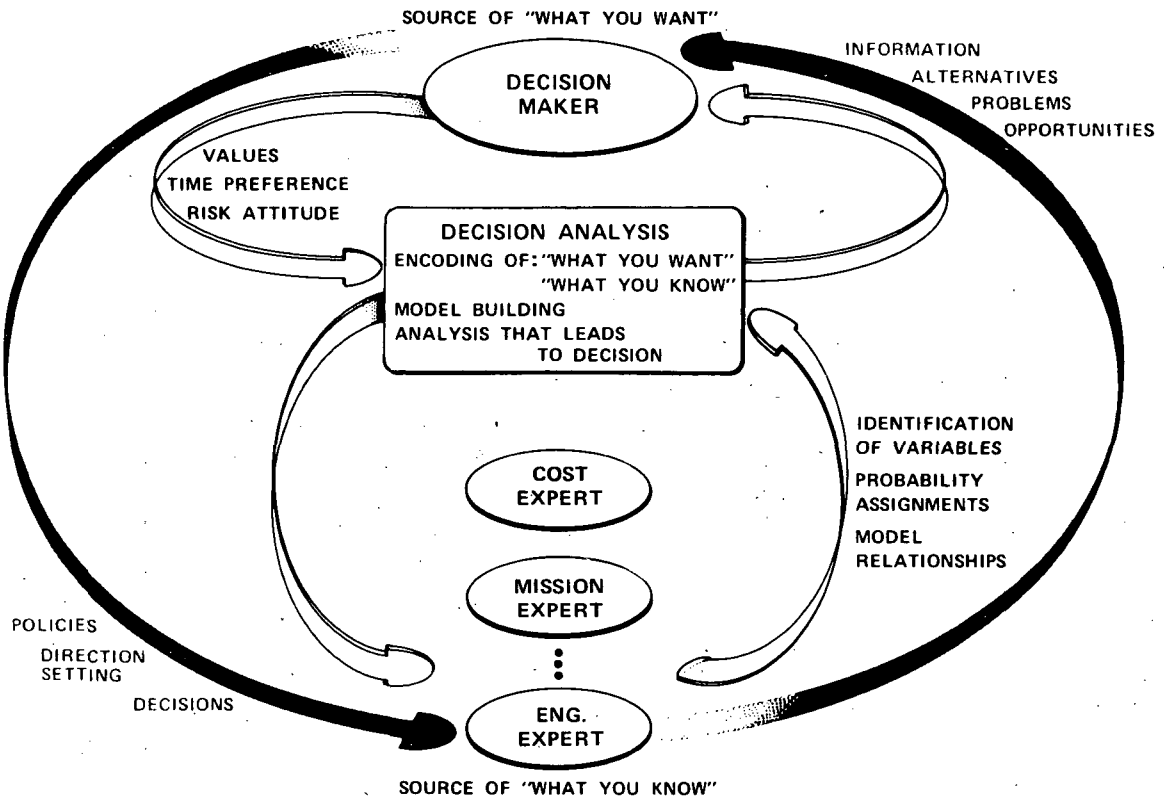


FIGURE 2.1 DECISION ANALYSIS SYNTHESIS

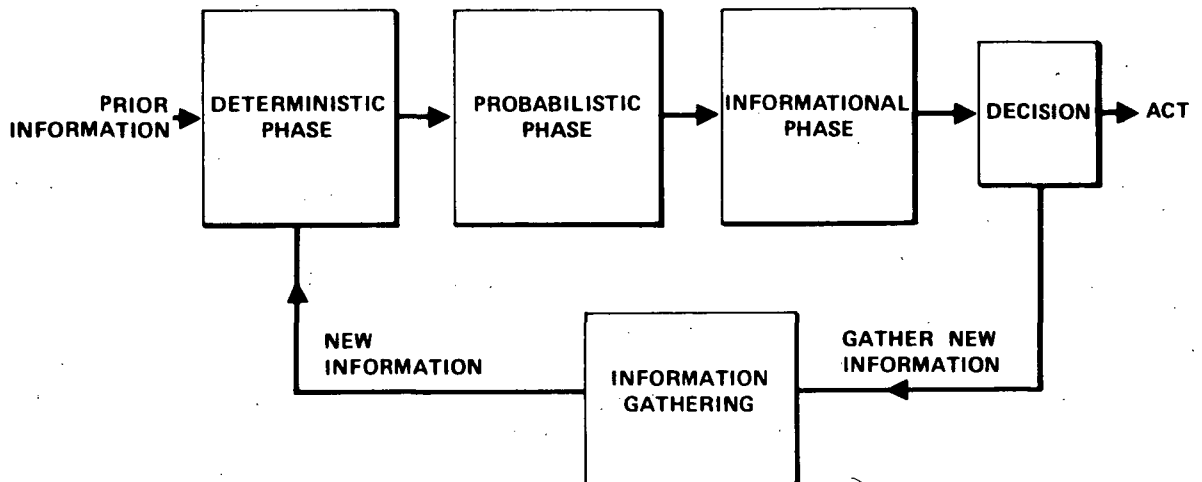


FIGURE 2.2 THE DECISION ANALYSIS CYCLE

this sequential approach is that the analyst is continually monitoring the value of additional modeling³ before proceeding to a new phase of the analysis.

The first application of decision analysis to space program planning evaluated various strategies for the unmanned exploration of Mars. This work, carried out by SRI in the mid-1960s under contract to General Electric, analyzed the highly sequential problem of which experimental configurations to launch at successive launch opportunities and explicitly incorporated the uncertainty and value aspects of the problem into a decision-tree format. The analysis was conducted first at the pilot level⁴ to prove the value of techniques and to gain insight into a simplified version of the problem. It was then expanded to a much more detailed and realistic full-scale analysis.⁵ Since that time, decision analysis has been applied to a number of other difficult public policy problems, including the nuclear expansion of Mexico's electrical power system,⁶ hurricane seeding policy,⁷ and wildland fire protection.⁸ A knowledge of this background of the SRI Decision Analysis Group led to the preliminary discussions from which this project evolved.

2.2 Problem Definition

In our earliest meetings with JPL personnel from the Propulsion Division, a decision problem emerged that was truly difficult. The problem was unique, concerning a type of propulsion that had never been used.⁹ It was important in terms of both the resources currently required for research and development and the ambitious missions and advanced exploration strategies that it would facilitate. The development process was complex, including a new process for generating electricity inside a nuclear reactor, and the development results were highly uncertain. The payoff--an operational nuclear electric propulsion (NEP) system--was at least ten years away, but would be one of the most highly capable advanced propulsion systems available during the last 15 years of this century and perhaps longer. Finally, as in many government problems, the decision-maker (or decision-making body) was difficult to identify; the values of achieving and successfully using an NEP system were unclear; and the preferences of the decision-maker regarding the timing of outcomes, the risks in the project, and the priority of space exploration vis à vis other pressing public problems were not clearly defined.

One of the most effective ways to proceed in such a complicated and unstructured situation is to focus on a specific decision and then establish boundaries for the problem by simplifying or eliminating aspects of the actual situation that do not affect the decision. For this purpose,

a decision is defined as an essentially irrevocable allocation of resources. The resources may be money, facilities, or manpower, but a decision implies a specific choice among alternative allocations. Thus, the identification of feasible alternatives is essential at this stage of the problem.

The Propulsion Research and Advanced Concepts group at JPL originally viewed their "decision" as defining propulsion system requirements that would control, albeit indirectly, the development of the thermionic reactor.¹⁰⁻¹³ The reactor was considered to be the critical technology element of the NEP system. The decision analysis team countered that the problem should be approached at the pilot level and oriented toward a single rational decision-maker considering a well-defined decision among specific alternatives.¹⁴ It was argued that the insights gained would adequately compensate for whatever simplifying assumptions had to be made.

To allocate resources in a rational and consistent manner, real alternatives must be identified. Identification of actual decisions and alternatives allows a careful separation of those factors that are under our control (decision variables) from those factors that are determined by the external environment (state variables). It further allows us to model the logical relationships connecting the decision and state variables of the problem to the subsequent events (outcomes) that determine the ultimate desirability of selecting various alternatives.

The hierarchy of decisions in the development of thermionic reactors for nuclear electric propulsion is illustrated in Figure 2.3. Early in the project, the client team at JPL specified that the focus of analysis should be at the level of thermionic reactor development decisions. Such decisions might include alternative thermionic fuel elements (TFE) designs as well as power level decisions for the overall reactor. Among other things, this specification reflected the fact that a very large study* (APC) was already under way to compare the various advanced propulsion

* The APC study combined the economic analysis capabilities of Mathematica with the planetary mission analysis work of JPL and the geocentric mission analysis of Lockheed Missiles and Space Company. This study began before the decision analysis, proceeded concurrently, and is still continuing. The overlap is less than might be imagined. The APC study has undertaken a very detailed equal capability economic analysis, trying to determine whether future cost savings are sufficient to justify the development of advanced propulsion systems, and, if so, which ones. The decision analysis in the study reported here used APC data--at the

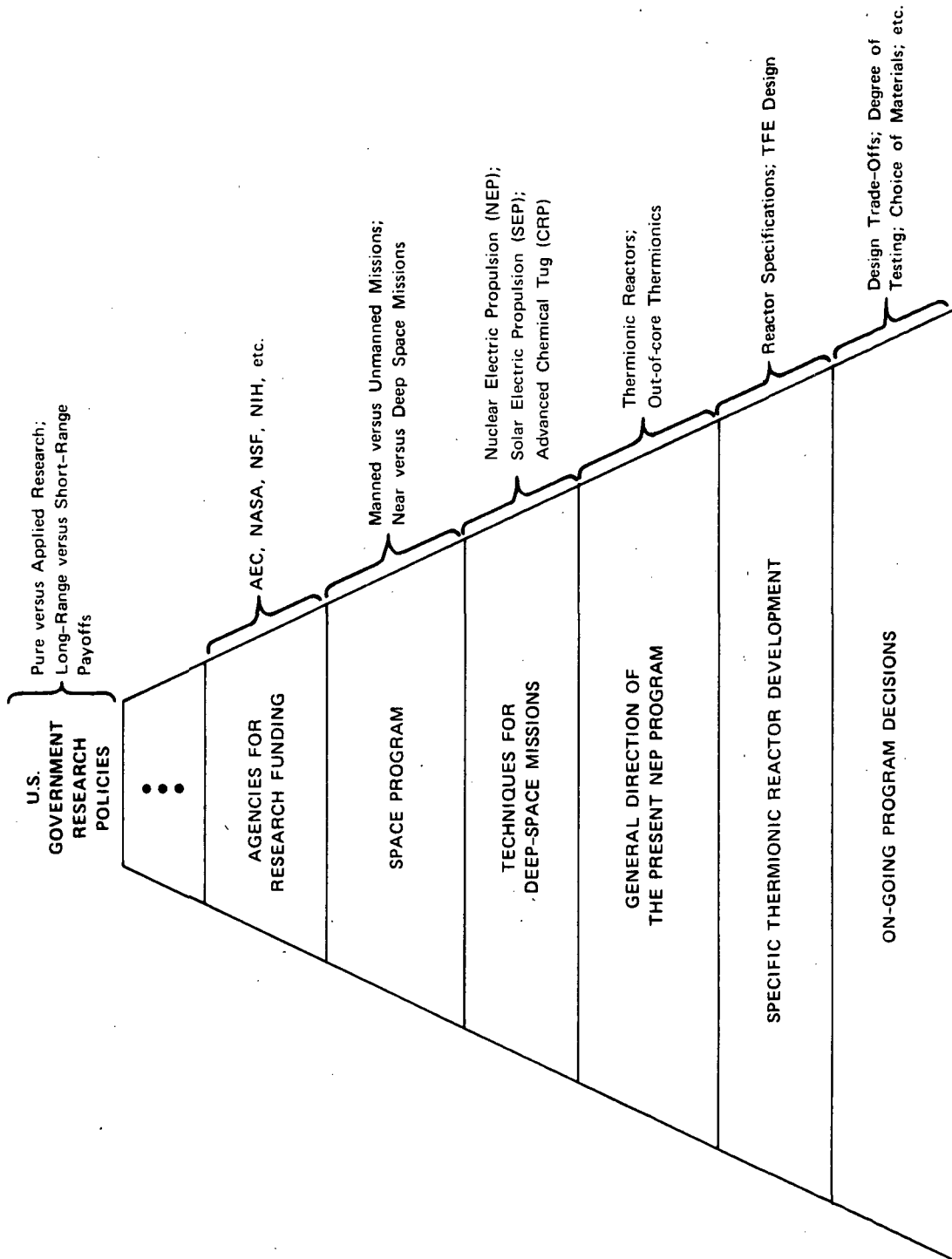


FIGURE 2.3 HIERARCHY OF THE NEP DECISION

systems--chemical tug, nuclear rocket, solar electric, and nuclear electric. With our analysis focused on thermionic reactor decisions, problems at other levels of the hierarchy had only to be treated with regard to their impact on the primary decision.

Decisions on thermionic reactor development influence the course, and hence the outcomes, of the thermionic R&D program, as shown in Figure 2.4. The R&D outcomes--TFE lifetime and reactor specific weight, power, and cost--influence the subsequent uses of the thermionic reactor for NEP missions and other applications.¹⁶ Furthermore, the date that an operational NEP flight system becomes available affects certain NEP specific missions like a Halley's comet rendezvous. The choice of mission strategy for the time period 1980-2000 is reflected in various mission models. NEP will then be selected for missions if it is competitive in cost and performance with other propulsion systems given the requirements of the various missions and alternative ways to accomplish them. This then generates mission accomplishments, which are transformed in the value model into mission values. Mission values combined with mission costs emerge from the model as an equivalent profit flow over time. Finally, the time preference model reduces this flow to a single measure of worth, the net present equivalent profit. (These concepts are explored in detail in Section 3.1)

The present equivalent profit is more valuable as a measure of the differential value due to changes in TFE specifications or thermionic reactor design than it is as an absolute measure of "national profit." This is because at the pilot level only representative mission sets and value scales have been used, which, while probably adequate to evaluate R&D decisions, may be inadequate for other decisions. Although the pilot value model is an explicit structure that allows a rational and consistent comparison of R&D alternatives, it is not necessarily proposed as appropriate for other space exploration questions. Section 3.5 discusses the need for a "national profit" measure and Chapter 4 makes a thorough examination of the value models needed to obtain such a measure.

To obtain information on the thermionic program, the decision analysis team participated in the Thermionic Specialists Conference held at Gulf Energy and Environmental Systems (GEES), September 18-22, 1972.

lowest useful level of detail--to analyze the relative merit of specific NEP development alternatives, but incorporated an explicit value structure and other logical features which the APC study did not employ. Reference 15 is the standard source for APC data.

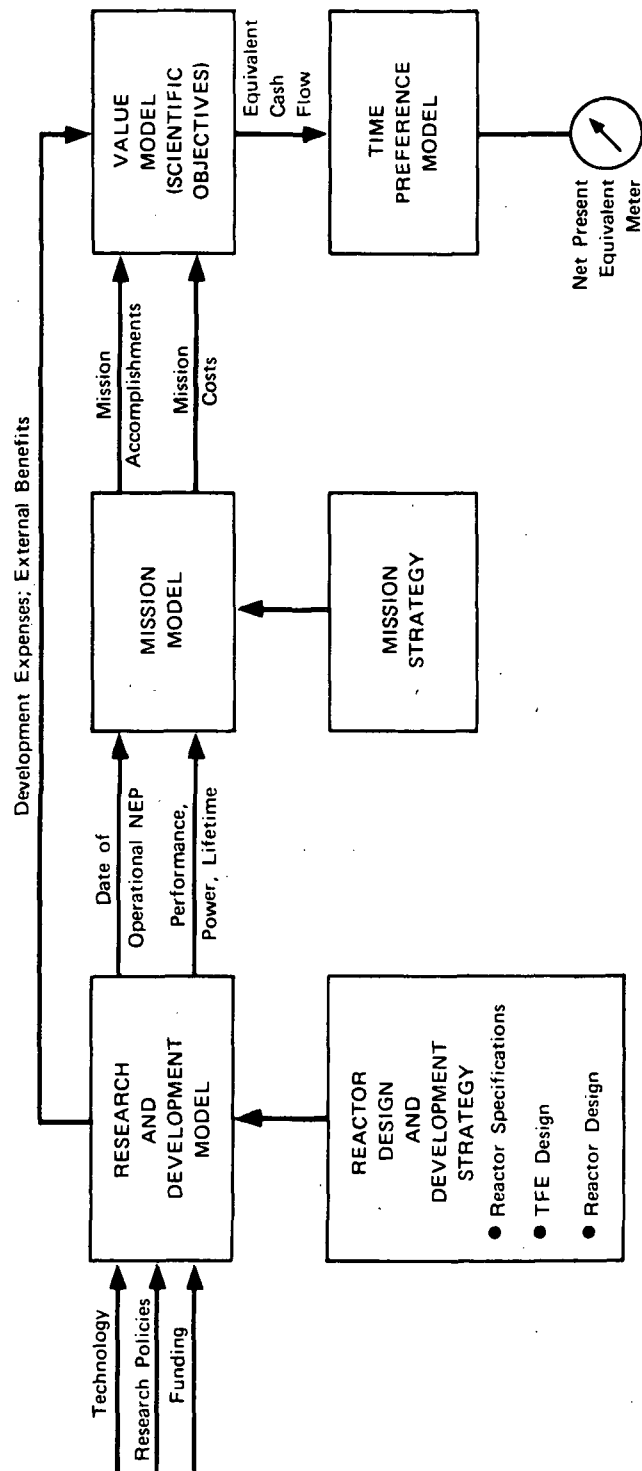


FIGURE 2.4 CONCEPTUAL OVERVIEW OF NEP DEVELOPMENT DECISION MODEL

During this week, experts from eight different laboratories were interviewed to obtain their opinions on TFE development, future TFE lifetimes, thermionic reactor applications, and crucial thermionic program decisions.* Although these discussions yielded valuable information about the technical aspects of TFE development, it became clear that different laboratories had very different views about crucial program decisions.

Decision analysis seeks to evaluate and choose among specific alternatives--whether they are alternative TFE designs, alternative NEP power levels, or alternative space exploration strategies. Figure 2.5 shows a wide range of research and technology development alternatives that were mentioned in our discussions with various thermionic specialists. Those concerned with TFE production and testing saw all the decision points shown in Figure 2.5 as behind them and looked forward to such decisions as whether to proceed with the thermionic reactor experiment (TREX). Others working in thermionic research felt that the ultimate decision would be to move from in-core thermionics to out-of-core thermionics. Still others in program management did not see any real alternatives within the jurisdiction of the Space Nuclear Systems Office (SNSO), presaging the type of higher level decision that eventually curtailed the U.S. thermionic program. But from the vantage point of the thermionic reactor systems project team at JPL, the decision of greatest concern was to select the reactor with "optimal" power level and performance characteristics for planetary exploration.

Thus, one of the initial goals proposed for the decision analysis was to establish specifications for the optimal TFE. These specifications, however, were generally divorced from the inseparable considerations of cost and feasible engineering design. To evaluate a TFE design, the expected TFE performance parameters--mass, power, and lifetime--must exist, as well as an engineering design considered capable of producing a TFE with that performance at some associated cost. These TFE parameters must then be translated into a specific mass, lifetime, and cost for the thermionic reactor and nuclear electric propulsion system. Finally, the effects of performance improvement or degradation measured in terms of missions achievable and trip time can be compared with the increased or decreased unit and development cost of the propulsion system.

* It should be reiterated that a decision is a choice among different feasible alternative allocations of program resources.

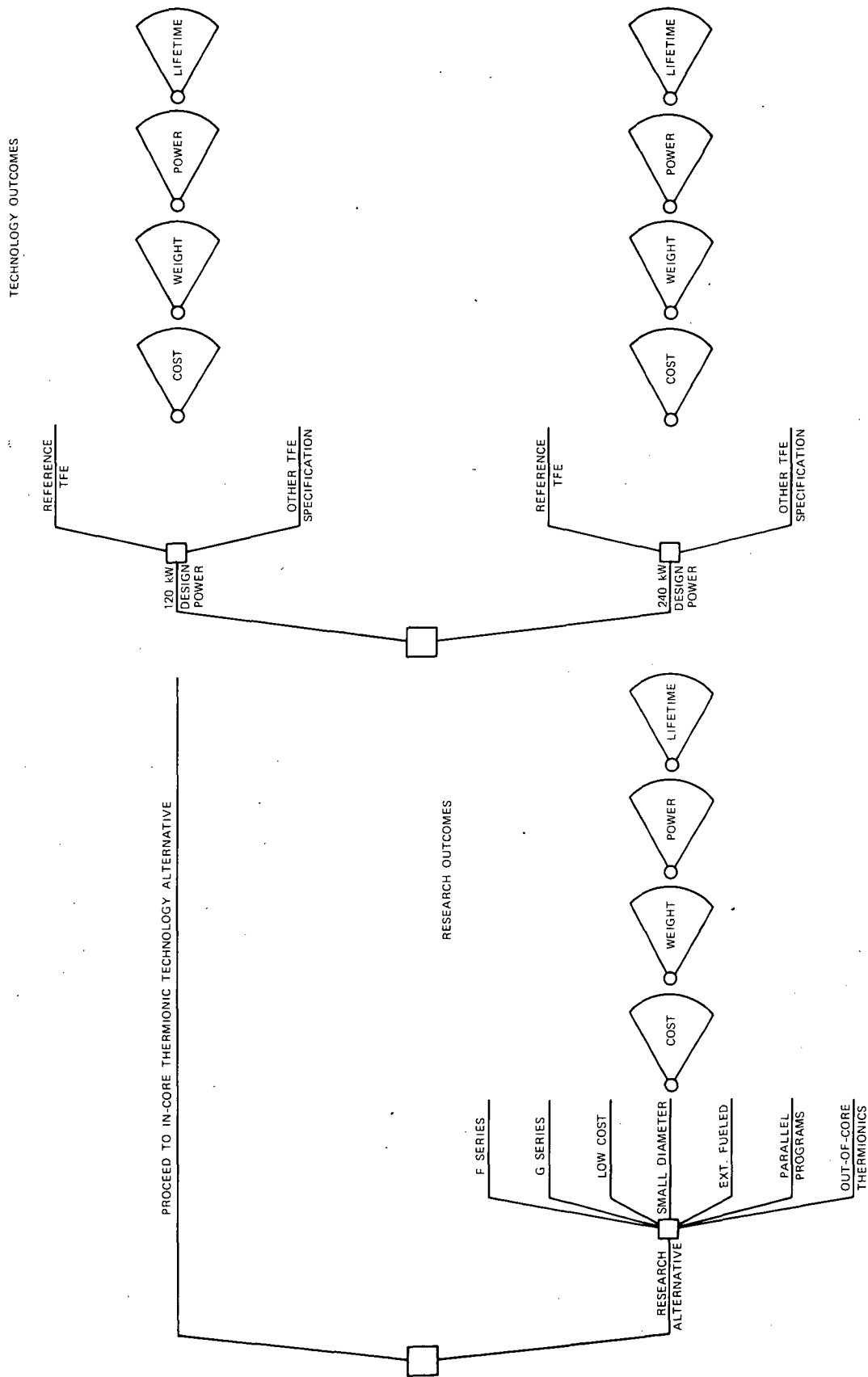


FIGURE 2.5 DIFFERENT POSSIBLE THERMIONIC PROGRAM DECISIONS

In our discussions with thermionic specialists, it became clear that few alternative TFE designs were under serious consideration. In addition to the reference design (F series), there were the advanced design (G series) being studied at Thermo Electron Corporation and various vague "hunches" regarding specifications that approached the Russian design (small diameter) or the French design (low cost). Engineers at JPL had also examined a design for an externally fueled TFE, but the great proportion of the program resources were devoted to the internally fueled reference design TFE. Hence it was natural to examine this design as a first case. The reference TFE was considered suitable for either the 120 kWe or 240 kWe power level reactors. Furthermore, the interaction of power level with mission capabilities was a primary concern of the user-oriented community at JPL. The initial analysis was focused therefore, on the power level decision in the context of the reference TFE design.

2.3 Pilot Level Problem Structure

Figure 2.6 shows the conceptual structure needed to evaluate NEP development alternatives. This diagram emphasizes the sequential nature of the intermediate decisions and outcomes that must be considered to connect current NEP development decisions with the ultimate program outcomes. Thus, although Figure 2.6 is a companion to Figure 2.4, it displays the sequence of program decisions and resolutions of uncertainty that are implicit in Figure 2.4.

The squares in Figure 2.6 represent NASA decisions and the circles represent the resolution of uncertainty. Each of the fan-shaped forms represents the range of possible outcomes that is thought to encompass the ultimate actual outcome which will occur at some point in the future. Another way to view the "fans" is as representing the data required to evaluate the initial development decision. In the deterministic phase analysis discussed in Chapter III, a best-guess estimate (or expected value) has replaced the probability distribution implied by each fan, with the majority of data coming from experts at JPL, GEES, and NASA Ames. Wherever possible, data consistent with the concurrent APC study have been used.

The first decision to be made is the level of power that the NEP system should have; this decision would lead to a determination of the cost, specific weight, and operating lifetime of the system. Depending on these results and the capabilities of other advanced propulsion systems, a planetary exploration strategy will be adopted that determines such factors as modularity, compatibility, and inheritance for

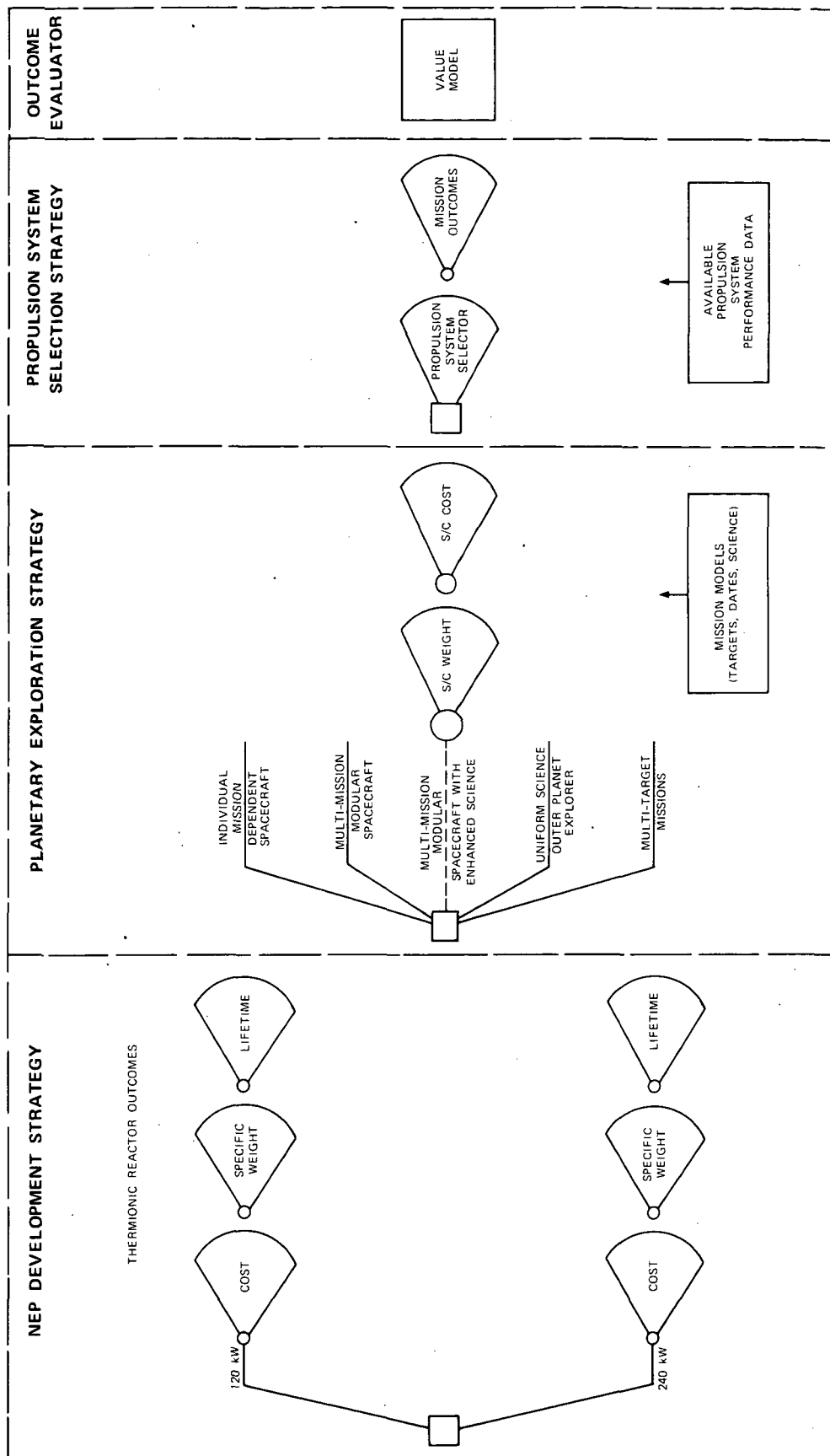


FIGURE 2.6 CONCEPTUAL DECISION TREE FOR ADVANCED PROPULSION DEVELOPMENT DECISIONS

the overall planetary exploration program. Its goals are significantly reduced cost and enhanced accomplishments. Different exploration strategies will result in different spacecraft (S/C) weight and costs. Finally, on a mission-by-mission basis, the most effective propulsion system available will be selected to perform that mission. The outcomes of these missions enter a valuation model that converts scientific findings at various targets to a dollar value (under several sets of assumptions) and subtracts mission cost to produce a total program profit. This structure is generally used for evaluating the NEP development strategy that yields the highest total program profit.

Preliminary findings from the APC study had indicated that the differential benefits from different propulsion technologies used to perform identical missions were very small compared with the total mission costs and, thus, were not very conclusive for the development strategy decisions shown in the leftmost box of Figure 2.6. A much clearer picture in terms of differential program cost and thus, profit, emerges from considering the role of advanced propulsion systems in the development of new, more effective planetary exploration strategies. The current design concept of individual mission-dependent spacecraft places great emphasis on minimum weight and maximum reliability. In this report, this traditional spacecraft design philosophy is referred to interchangeably as "the individual mission dependent" or "the nominal" exploration strategy.

This strategy can be modified in several ways, but most of these modifications require higher mission payloads or mission energies. Among these strategies requiring higher payloads are the multimission modular spacecraft philosophy¹⁷--shown in Figure 2.7--and the uniform science outer planet explorer.* Among those strategies requiring higher energies are those utilized for multitarget missions.† These alternatives are represented in Figure 2.6 by the box labeled "planetary exploration strategy." Such advanced mission concepts were under study at JPL

* The APC study dismissed a "standardized spacecraft" as not currently possible for planetary missions, but this dismissal may have resulted from the mandate of that study to compare four different propulsion systems. For chemical tug and solar electric propulsion, this concept would indeed have been too demanding, whereas many thermionic experts felt that the power and propulsion capabilities of nuclear electric propulsion would enable the development of such a spacecraft.

† Private communication, J. W. Stearns and R. W. Schaupp. See also the APC Phase II Reports, April 1973.

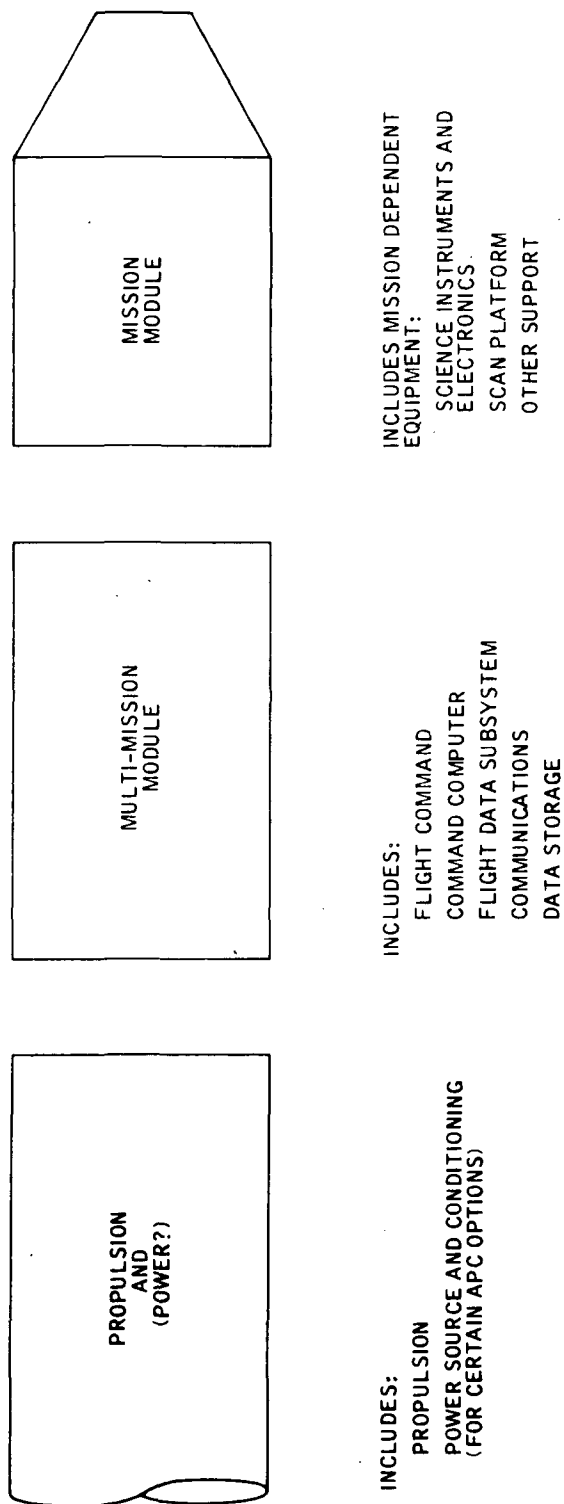


FIGURE 2.7 PLANETARY SPACECRAFT DESIGN USING 'MULTI-MISSION MODULE' CONCEPT (SEE REFERENCE 17)

during the course of the decision analysis, and our analysis was designed to incorporate them as they became available. However, only data for the nominal and the multimission modular spacecraft concept illustrated in Figure 2.7 were available at the time of this analysis. This alternative spacecraft design concept is designated as either "multimission modular" or "low-cost" in this report.

Finally, the box labeled "propulsion system selection strategy" represents the last principal decision of the program--namely which of the various available propulsion systems should be selected to fly each mission. A propulsion system selector has been designed to consider any savings in spacecraft power, target capture propulsion, shuttle launches, and flight time, as well as any reduced risk of failure or enhanced science capability, which could be attributed to various propulsion systems.* This procedure, which is explained in detail in Chapter III, is more comprehensive in its selection criteria than other algorithms that we have seen and furthermore applies equally well to all of the advanced propulsion technologies considered in the APC study.

* The two latter items--reduced risk and enhanced science--have not been implemented at this stage of the analysis.

III DETERMINISTIC ANALYSIS

3.1 Deterministic Phase Model Sequence

Before describing the specific deterministic model developed for this analysis, it will be helpful to review the process of modeling in a very general context, as illustrated in Figure 3.1. Modeling is the process of representing the various relationships of a problem in formal, mathematical terms. The first step in modeling is to establish limits for the decision: that is, to specify precisely just what decision must be made. This step requires listing in detail the perceived alternatives.

The next step is to specify the various outcomes that each alternative could produce. These outcomes are the subsequent events that will determine the ultimate desirability of having chosen an alternative. In a new product introduction, for example, the outcomes might be specified by sales levels and costs of production or, more simply, by yearly profits. Thus, there is a certain amount of arbitrariness in defining an outcome. For decision analysis, an outcome is whatever the decision-maker would like to know in retrospect to evaluate how the problem evolved. In a space exploration problem, the outcome could be a complicated list of missions, achievements, and expenditures; in a medical problem, it could be as simple as whether or not the patient recovered.

Once the outcomes are specified, the system variables for the analysis must be selected--that is, all the variables on which the outcomes depend. Typically, outcome variables are difficult to predict. Some insight can be gained, however, by relating the outcome variables to other factors that are easier to comprehend. For example, a manufacturer might wish to project the sales level of a new product or, in lieu of this, to relate sales to his own price and quality and the competitors' price and quality--factors that might be regarded as more accessible. These factors would then become system variables in the analysis.

The selection of system variables is therefore a process of successive refinement, wherein the generation of new system variables is curtailed by considering the importance of the problem and the contributions of the variables. Clearly, the allocation of the total NASA budget can economically justify the use of many system variables.

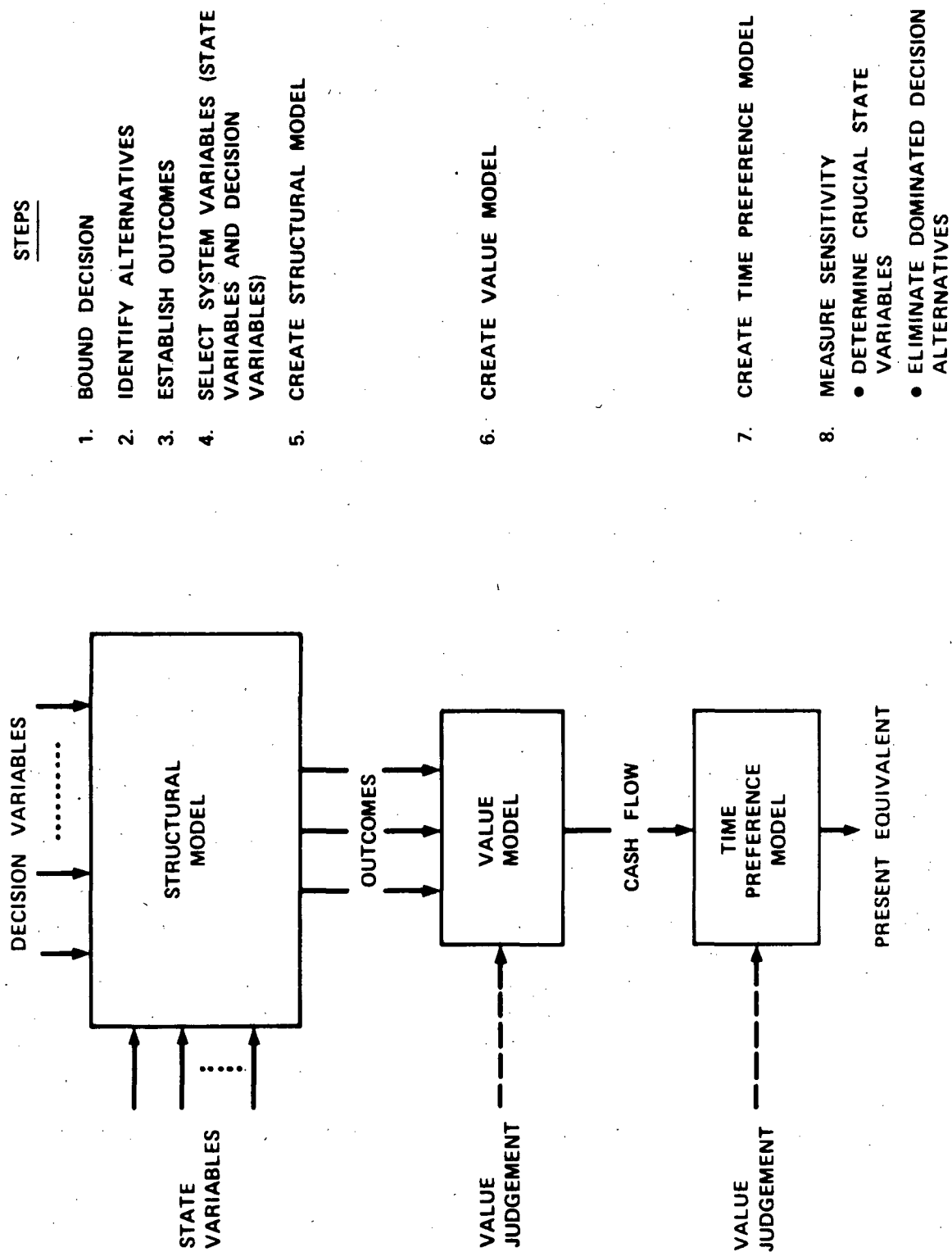


FIGURE 3.1 DETERMINISTIC PHASE MODEL SEQUENCE

Once the system variables of the problem have been established, each must be identified either as a variable under the decision-maker's control or as a variable determined by the environment of the problem. System variables that are under the decision-maker's control are called decision variables. The selection of an alternative in a decision problem is really the specification of the setting of the decision variables. System variables that are determined by the environment are known as state variables. Although state variables may have a distinct effect on the outcomes, they are autonomous, beyond the control of the decision-maker. For example, in a new product introduction, the cost of a crucial raw material or the competitor's advertising level might be state variables.

Modeling will be used to examine the effect of fluctuations in all system variables--whether decision variables or state variables. To aid in this task, the decision-maker or his representative must specify a nominal value and a range of values for each system variable. In the case of a decision variable, the nominal value and range are determined by the decision-maker's preconceptions regarding the interesting alternatives. In the case of state variables, the nominal value and range reflect the uncertainty assigned to the variables. For convenience, the nominal value of a state variable can be considered as its expected value in the mathematical sense and the range as the 10th percentile and 90th percentile points of its probability distribution.

The analyst must next specify the relationships among the system variables. That is the heart of the modeling process: creating a structural model that captures the essential interdependencies of the problem. This model should be expressed in the language of logic--mathematics--typically by a set of equations relating the system variables to the outcomes. In most decisions, these equations will form the basis for a computer program to represent the model. An ability to make pragmatic engineering judgments is helpful at this stage.

The decision-maker must next assign values to outcomes. Just as it is difficult to define outcomes, there may be questions about the distinction between an outcome and its value. For example, in a business problem, the decision-maker may think of his future profit as both the outcome and the value associated with it. However, a distinction must be made between the two. In a public policy evaluation program, the outcome may consist of a diverse set of attributes such as cost, safety, reliability, and pollution. These attributes must then be integrated in the value model into a single value measure that reflects the worth of the particular outcome to the nation.

Although in some cases the decision can be reached as a result of simply ordering outcomes in terms of desirability, most problems of practical interest require a numerical (cardinal) ranking system. Therefore, assigning a value means assigning a numerical value to an outcome. Although there may be many components of value in the outcome, the final value assignment is a single number associated with that outcome.

In commercial situations, the net value assigned to an outcome will typically be some form of profit. In social and space problems, however, the value problem is more complex because of the difficulty in assigning a dollar value to their less tangible outcomes. Often, however, as in the Voyager analysis,^{4,5} a simple model may prove to be sufficient through sensitivity analysis. Although these questions of evaluation may be difficult, logic demands that they be approached directly, and in monetary terms if monetary resources are to be allocated.

The final step in creating the deterministic model is to specify the time preference of the decision-maker. Time preference is the term used to describe the human phenomenon of impatience. Everyone wants good things to happen to him sooner rather than later. This impatience is reflected in a willingness to consume less now rather than to invest in the future and postpone the consumption.¹⁸ The payment of interest on savings accounts and the collection of interest on loans are reflections of this phenomenon. Consequently, representing the desires of a decision-maker requires a realistic mechanism for describing his time preference, a mechanism that reduces any time stream of value to a single number called present equivalent worth. Present equivalent worth will often be simply the discounted difference between future income and expenditures using an interest rate that depends on the relationship of the organization to its financial environment.¹⁹

The modeling part of the deterministic phase thus progresses from the original statement of the decision problem to a formal description suitable for detailed examination by logical and computational analysis. The decision-maker's value assignments and his time preference permit transforming any time stream of outcomes first to a set of values in time and then to a present equivalent worth.

3.2 Deterministic Model

The deterministic model constructed in this analysis exists in the form of a computer program.* Its basic structural relationships are

* This program has been given to JPL. Contact Alan Nakashima for information.

shown in Figure 3.2. It should be emphasized that because of the termination of the analysis in mid-course, the data and, to a lesser degree, the program structure should be considered as preliminary. Chapter VI discusses some of the modifications and improvements that would have been carried out if the decision analysis had been completed; these modifications and improvements can be implemented by JPL.

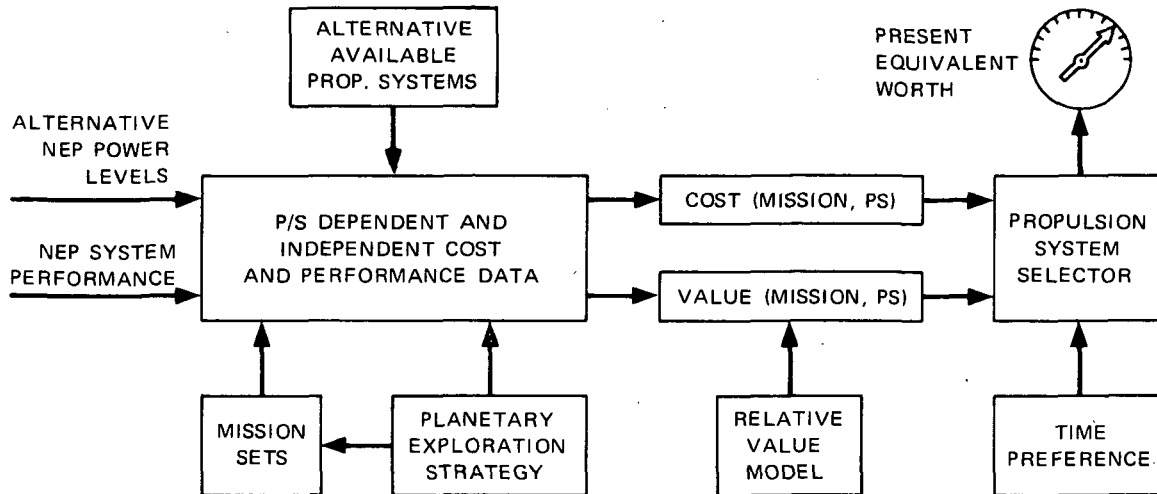


FIGURE 3.2 LOGICAL STRUCTURE OF DETERMINISTIC MODEL

The logical relationships contained in the structural model include the capability: (1) to change NEP flight times as a function of changes in NEP specific weight, (2) to run with discounting, (3) to modify the strategy and mission set, and (4) to select (in a very general way) the optimal propulsion system for each mission. Thus, the program allows analysis of various alternatives at each of the decision levels shown in Figure 2.6.

The alternatives available to the model are (1) the NEP power level, (2) the available competitive propulsion options, and (3) the choice of individual mission-dependent or multimission modular spacecraft designs, as specified in Section 2.3. Data are stored in the program for missions 2-22 in Table 3.1 for each of these spacecraft design philosophies. Additional data that must be supplied include the exact missions to launch, launch dates, discount and inflation rates, any annual development funding constraint, and the space shuttle flight cost. For ease of performing sensitivity analysis, the ability to modify reactor cost or specific

Table 3.1

REPRESENTATIVE PLANETARY EXPLORATION MISSION SETS

	<u>APC</u> <u>EXT</u>	<u>APC</u> <u>Base</u>	<u>Von</u> <u>Braun</u>
1. (Geocentric Payload Placement)	--	--	--
2. Encke Rendezvous	83	83	84
3. Venus Radar Mapper	83	83	84
4. Mars Semi-Autonomous Rover	84	84	86
5. Mercury Orbiter	84	84	87
6. Saturn Orbiter/Probe	84	84	90
7. Asteroid Rendezvous (VESTA)	85	85	89
8. Halley Flyby	85	85	--
9. Jupiter Orbiter	85	85	87
10. U/N (Uranus Probe)	86	86	86
11. Uranus Orbiter/Probe	87	87	*
12. Venus Large Lander	89	89	89
13. Neptune Orbiter/Probe	89	89	*
14. Jupiter/Pluto Flyby	90	90	*
15. Ganymede Orbiter/Lander	90	90	*
16. Mars Surface Sample Return	90	90	*
17. Halley Rendezvous	83		--
18. S/U/N (Uranus Probe)	84		--
19. 0.1 AU Solar Probe	85		*
20. Saturn Rings Probe	88		*
21. Ceres Surface Sample Return	93		*
22. Phobos/Deimos Surface Sample Return	94		*

* The von Braun Model does not identify missions beyond 1990; missions noted by an asterisk are not necessarily excluded, but would not be performed before 1991.

weight is incorporated explicitly. Finally, all missions can be assigned equal value,* or any relative value scale can be assigned.

At the present stage of deterministic model development, flight times are stored directly for each propulsion system and each mission. Separate flight times are stored corresponding to the payloads required to perform the missions in the individual mission-dependent and multimission modular exploration strategies. These flight times have been computed from payload versus flight time curves such as that shown in Figure 3.3. Assume, for the purpose of illustration, that the payload required to perform this mission with an individual mission-dependent design is 1000 kg (for science, guidance, and spacecraft support). Typically, for missions studied (not employing rovers or landers), the payload required in the multimission modular design strategy is double that for the mission-dependent design or 2000 kg. Using the curves in Figure 3.3 to translate payloads into flight times for NEP systems of different power levels and maximum NEP thrust times (i.e., reactor lifetimes), the data in Table 3.2 have been derived. It appears that for the lower payload level the difference in trip time resulting from different power levels or lifetime constraints is very small. For the higher payload, both the power level and reactor lifetime constraints can be important. They would be even more so if the risk reduction implications of reduced trip time were incorporated.

Table 3.2

EFFECTS OF NEP POWER LEVEL AND THRUST TIME CONSTRAINT
ON FLIGHT TIME AT DIFFERENT PAYLOAD LEVELS

	1000 kg <u>(years)</u>	2000 kg <u>(years)</u>
Cent/100 kw (200,000 hours)	4.1	7.0
Cent/100 kw (unconstrained)	4.0	5.6
250 kw (20,000 hours)	3.7	4.3
250 kw (unconstrained)	3.7	4.2

Source: Figure 3.3.

* Thus, the model can be run as a pure cost model by setting all mission values at zero.

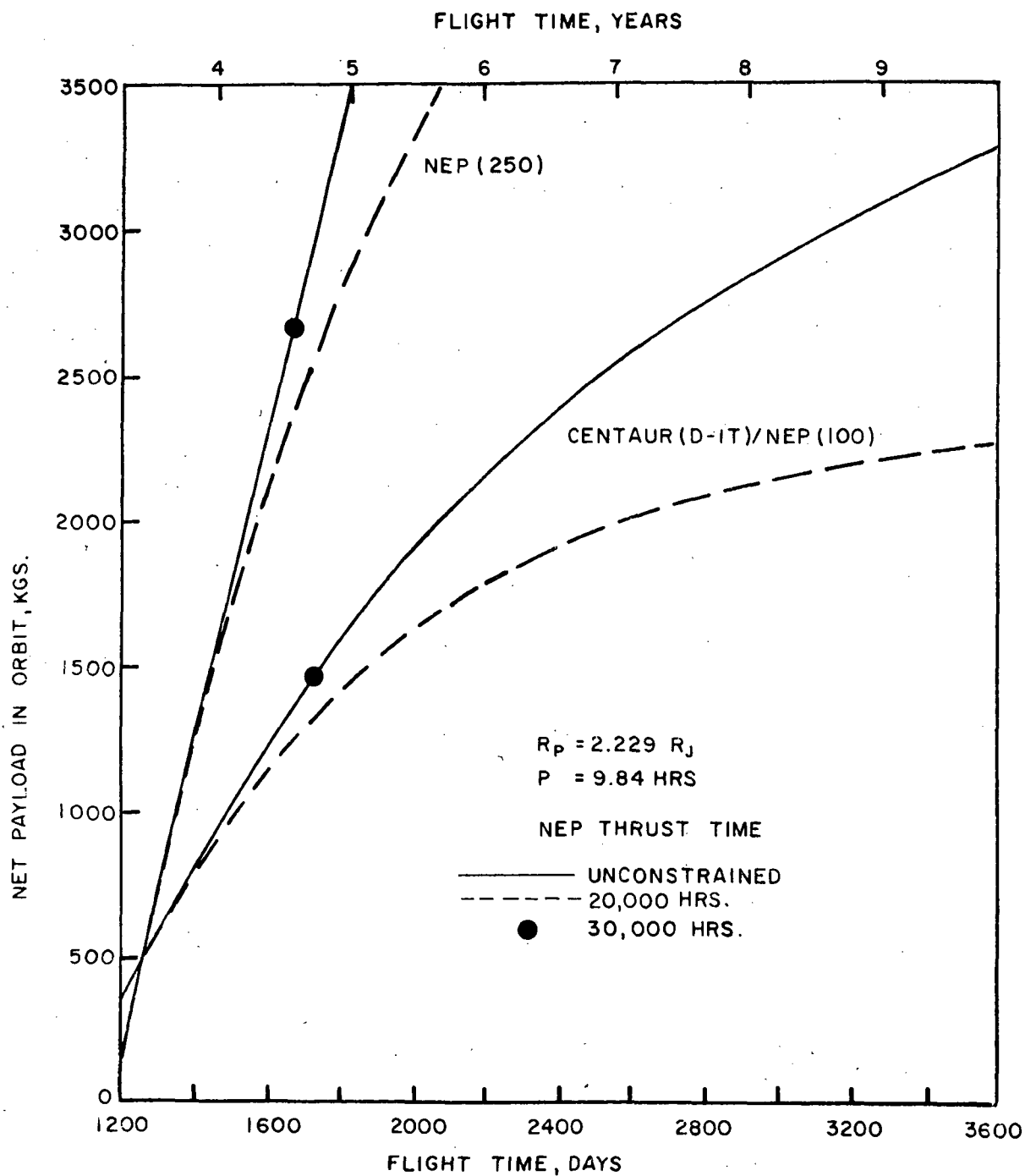


FIGURE 3.3 SAMPLE PERFORMANCE CURVES FOR JUPITER ORBITER MISSION (FROM REFERENCE 16)

The program data have been obtained in this way for missions 2-22 using the nominal and the low-cost design science payloads and the payload versus trip time curves from the APC study. The payload amounts, especially as they relate to NEP, were obtained from the JPL thermionic project team, and the performance curves for various propulsion systems were taken from the APC study.²⁰ The effects of changes in reactor specific weight, α , have been computed using the slopes of these curves, dm/dt , at the appropriate payload amounts. So four data elements are stored at present for each mission to describe the performance of each NEP power level: the flight time and the slope for each of the two payload levels representing the two design strategies.

A more flexible format, especially for NEP, would be to represent the performance curves shown in Figure 3.3 by a function of the form:

$$M(t) = \text{MAX} \left[1 - \left(\frac{T_{\text{MAX}} - t}{T_{\text{MAX}} - T_0} \right)^N \right]$$

where MAX represents the maximum deliverable payload, TMAX is the trip time needed to deliver MAX, and T0 is the trip time needed to deliver zero net payload (i.e., engines and structure only). M(t) and t then represent the payload and flight time, respectively, and N is a parameter that determines the degree of curvature. In this form, it would be practical to simulate the change in MAX resulting from lifetime constraints, as shown in Figure 3.3, or from different escape stages, as shown in Figure 3.4.* Although the TFE lifetime constraint is unique to NEP, the effect of different escape stages modeled in this way could be useful for chemical tug and solar electric propulsion.

Finally, the missions used for the analysis should be described very briefly. Data are loaded for all missions in the APC extended mission set shown in Table 3.1. These missions are discussed in detail in Appendix 1, Part 7, of the APC study, where scientific instruments, trajectories, and propulsion performances are all tabulated for each mission. Two subsets of this mission set, called the APC base case model and the von Braun mission model, have also been designated by NASA for planning purposes. The eventual goal of our deterministic analysis was to use mission 1 as a code to incorporate geocentric payload placement missions. As a first

* Although no such analytic solution exists, low-thrust trajectory experts expressed guarded optimism that such a functional representation could be achieved empirically. We are indebted to R. W. Schaupp, J. F. Ingber, and D. J. Spadoni for discussions of this matter.

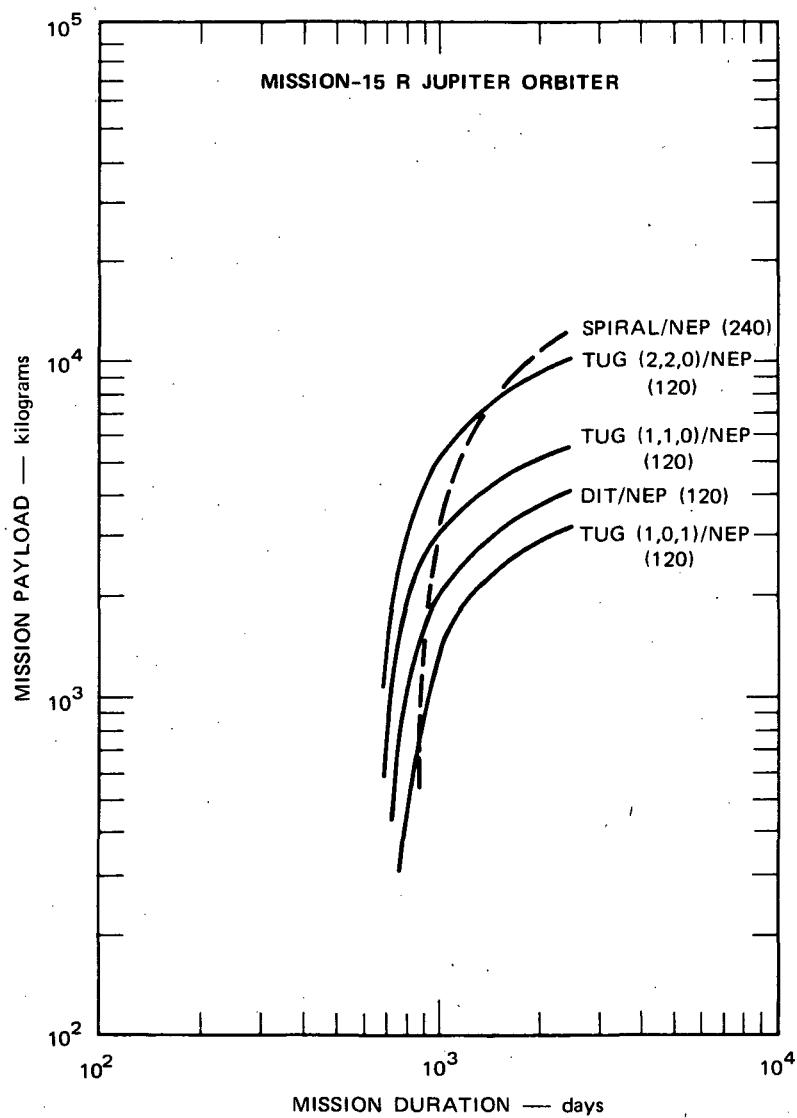


FIGURE 3.4 NEP PERFORMANCE WITH VARIOUS SHUTTLE INJECTION STAGES (FROM REFERENCE 13)

approximation, geocentric missions were omitted because they appeared not to influence the 120/240 kW NEP power level decision.*.

The deterministic model shown in Figure 3.2 has been modified slightly by incorporating the propulsion system selection logic after the value model. This was done because many people working in the electric propulsion field felt that an ample supply of power (in the kilowatt range) should be of benefit to the science experiments and communication requirements at the target. Indeed, the RTG power levels discussed in the APC study for five representative missions are insufficient for the spacecraft demands²¹ of several missions using TUG or nuclear rocket. On the other hand, no concrete benefits for the high power supplies have been agreed upon; thus this potential feature of the propulsion system selector has not been implemented. Furthermore, the selector can operate, using discounting to compare propulsion systems. Thus, if a high discount rate is used, the impact of reduced trip time will be enhanced. A detailed explanation of the propulsion system selection logic follows in the next section.

3.3 Propulsion System Selector

Table 3.3 shows how the cost of a mission can be broken down into factors that are independent of both propulsion system and flight time, independent of flight time but dependent on propulsion system, and finally dependent on both flight time and propulsion system. These groupings, as well as the specific categories shown, emerged from a careful study of JPL's detailed cost estimates for five representative planetary missions.^{†22} The significance of these groupings can be seen in Table 3.4.

Note in particular that for these five missions the additional spacecraft cost when using a chemical tug instead of nuclear electric propulsion is \$93.0 million, \$23.2 million, \$46.9 million, \$85.4 million, and \$77.5 million, respectively. All except the second mission, the Mars semiautonomous rover, are planned to launch two spacecraft. Note that for each of these five missions the NEP spacecraft cost is less than the

* After the conclusion of our work, Dr. E. J. Greenblat of Mathematica mentioned that the APC study had essentially proved this result (private communication, March 1973).

† We are indebted to Mr. R. L. Whitcomb for discussion of this work.

Table 3.3

MISSION COST BREAKDOWN

Mission Cost

= Propulsion System Cost + Spacecraft Cost

Spacecraft Cost

= Trip Time Independent, P/S Independent Costs:

- Systems integration
- Prelaunch project management
- Probes
- Orbiter science
- Landers and lander science
- Rovers and rover science
- Ascent vehicles

+ Trip Time Independent, P/S Dependent Costs:

- RTG power
- Dual propulsion
- Retro propulsion
- (Spacecraft/orbiter development and recurring)

+ Trip Time Dependent (and thus P/S Dependent) Costs:

- Deep space net flight support
- Mission operations in flight
- Science instruments and support in flight
- Postlaunch project management

corresponding cost for any other propulsion system (except SEP for Encke, where an extraordinary inheritance from a previous SEP mission has been assumed) and that in general the costs of SEP, TUG, and NRP are approximately equal. Furthermore, the differences in spacecraft cost for SEP, TUG, and NRP are almost exactly accounted for by the difference in flight time for the different propulsion systems. This situation is illustrated in Table 3.5, where it is clear that for the TUG, NRP, and SEP the RDT&E,

Table 3.4

DETAILED COST ESTIMATES FOR FIVE REPRESENTATIVE MISSIONS*
(Millions of Dollars)

	<u>NEP</u>	<u>SEP</u>	<u>TUG</u>	<u>NRP</u>	<u>Δ</u>
Encke Rendezvous	\$182.0	\$156.6†	\$275.0	\$275.0	93.0
Mars Semi-Autonomous Rover	828.3	852.5	851.5	860.8	23.2
Mars Surface Sample Return	657.0	690.3	703.9	703.9	46.9
Ganymede Orbiter/Lander	441.8	520.8	527.2	519.1	85.4
Uranus/Neptune Flyby/Probe					
Probe	49.0	50.0	50.0	49.0	1.0
Spacecraft	156.0	162.0	161.3	160.3	5.3
RTG power	0	46.0	46.0	46.0	46.0
Science and support	68.0	70.2	70.2	68.3	2.2
Project management	8.5	9.5	9.5	8.7	1.0
Mission operations	30.5	37.0	41.5	32.5	11.0
DSN flight support	26.0	33.0	37.0	28.0	11.0
Total	\$338.0	\$407.7	\$415.5	\$392.8	77.5

* Individual mission dependent spacecraft exploration strategy.

† High degree of inheritance assumed.

The Δ column shows the difference between the TUG column and the NEP column; thus these figures represent the spacecraft savings which can be achieved by using NEP. The detailed breakdown of the Uranus/Neptune Flyby/Probe shows that most of the differences are due to either RTG power or reduced flight time (mission operations and DSN support). These observations led to our propulsion system selection logic as illustrated in Figure 3.5.

Table 3.5

YEARLY COSTS FOR URANUS-NEPTUNE FLYBY/PROBE MISSION

TUG						NRP					
Spacecraft and Operations Costs (FY 70 dollars $\times 10^6$)						Spacecraft and Operations Costs (FY 70 dollars $\times 10^6$)					
Fiscal Year	RDT&E	NRI	RI	ALDO	Total	Fiscal Year	RDT&E	NRI	RI	ALDO	Total
1981	11.7			4.1	15.8	1981	11.7			3.9	15.6
1982	23.6	10.7		7.5	41.8	1982	22.6	10.7		7.3	40.6
1983	41.0	23.0		7.2	71.2	1983	41.0	23.0		7.1	71.1
1984	40.8	16.5	23.0	8.1	88.4	1984	39.9	15.3	23.0	8.1	86.3
1985	34.3		23.6	11.1	69.0	1985	32.5		23.6	12.8	68.9
1986	31.6			13.5	45.1	1986	31.6			13.5	45.1
1987	4.0			11.7	15.7	1987	4.0			11.8	15.8
1988				6.1	6.1	1988				6.1	6.1
1989				4.8	4.8	1989				5.0	5.0
1990				4.7	4.7	1990				7.1	7.1
1991				5.2	5.2	1991				7.2	7.2
1992				7.2	7.2	1992				5.0	5.0
1993				7.2	7.2	1993				7.2	7.2
1994				5.4	5.4	1994				7.2	7.2
1995				5.5	5.5	1995				4.6	4.6
1996				7.1	7.1						
1997				7.2	7.2						
1998				5.1	5.1						
1999				3.0	3.0						
Total	187.0	50.2	46.6	131.7	415.5	Total	183.3	49.0	46.6	113.9	392.8

NEP						SEP					
Spacecraft and Operations Costs (FY 70 dollars $\times 10^6$)						Spacecraft and Operations Costs (FY 70 dollars $\times 10^6$)					
Fiscal Year	RDT&E	NRI	RI	ALDO	Total	Fiscal Year	RDT&E	NRI	RI	ALDO	Total
1981	10.5			4.1	14.6	1981	12.7			4.1	16.8
1982	20.6	7.8		4.0	32.4	1982	25.6	10.7		7.5	43.8
1983	41.0	17.2		7.9	66.1	1983	41.0	23.0		7.2	71.2
1984	38.0	13.1	15.0	9.0	75.1	1984	40.8	16.5	23.7	8.1	89.1
1985	27.4		17.0	13.4	57.8	1985	34.3		23.6	11.1	69.0
1986	19.5			15.6	35.1	1986	29.6			13.5	43.1
1987	3.0			10.8	13.8	1987	3.0			11.7	14.7
1988				5.7	5.7	1988				6.1	6.1
1989				5.8	5.8	1989				4.8	4.8
1990				6.6	6.6	1990				4.7	4.7
1991				6.6	6.6	1991				7.2	7.2
1992				5.3	5.3	1992				7.2	7.2
1993				6.6	6.6	1993				5.2	5.2
1994				6.5	6.5	1994				5.4	5.4
						1995				7.2	7.2
						1996				7.1	7.1
						1997				5.1	5.1
Total	160.0	38.1	32.0	107.9	338.0	Total	187.0	50.2	47.3	123.2	407.7

NRI, and RI* are almost identical, whereas ALDO (Activity Level Dependent Operation) varies in a way essentially proportional to time-of-flight.

These observations lead to the concept of an effective propulsion system cost that incorporates all factors that depend on propulsion system or flight time and a corresponding spacecraft cost that is completely independent of propulsion system and flight time. This concept is illustrated in Figure 3.5. For a simple approximate model, it has been assumed that only NEP can generate spacecraft savings, that the magnitude of these savings is \$24 million for each mission-dependent spacecraft launched and \$8 million for each multimission modular spacecraft launched† and that all other propulsion systems have equal spacecraft cost and no spacecraft savings. A typical average annual operating cost of \$6 million per year (see ALDO numbers from 1988 onward in Table 3.5) has been assumed for this analysis.

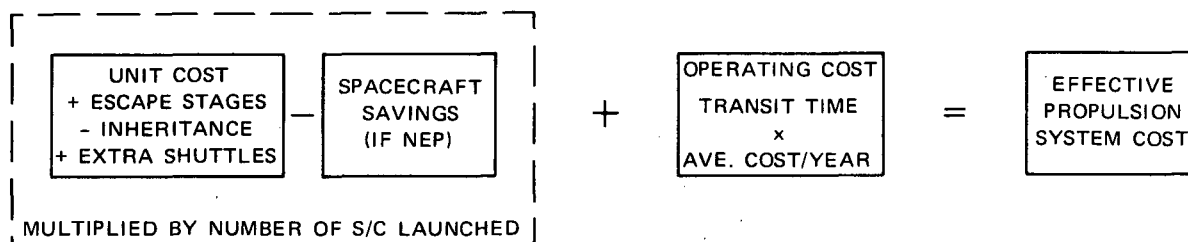


FIGURE 3.5 PROPULSION SYSTEM SELECTION OPERATION: MINIMIZE EFFECTIVE PROPULSION SYSTEM COST TO MAXIMIZE MISSION NET PRESENT EQUIVALENT PROFIT

* RDT&E = research, development, testing and evaluation;
 NRI = nonrecurring investment;
 RI = recurring investment.

† The figure of \$24 million per spacecraft is essentially 1/2 of the \$46 million for RTG power shown in Table 3.4 (for a two spacecraft mission). The \$8 million amount for the multimission modular spacecraft is the approximate recurring investment for an individual RTG power supply with no development. We are indebted to Mr. R. L. Whitcomb of JPL for clarification of these matters.

A sample calculation of the selector in comparing the effective cost of NEP and Centaur as propulsion systems for the Uranus-Neptune Flyby/Probe mission is shown in Table 3.6(a). Even though NEP entails the purchase of two \$31 million thermionic reactor propulsion systems, the savings generated by providing spacecraft power and reducing trip time make NEP less costly by more than \$34 million.

The selector logic can also penalize (or reward) NEP for a change in specific mass α . An increase in α will either increase flight time or make a mission impossible (with the desired payload). The calculations are simple since the extra propulsion system mass can be treated like additional payload. Thus, small changes about the nominal α will be directly proportional to changes in operating cost resulting from changes in flight time. This calculation is shown in Table 3.6(b). Since the actual performance curves are convex, as shown in Figures 3.3 and 3.4, a linear approximation overemphasizes the importance of changes in α . Therefore, the analyst must be careful not to use the linear approximation for changes so large that the tangent will differ significantly from the actual curves on changes that would make the mission impossible.

Discounting introduces another very subtle effect into the selection process. It has been stated, and will be discussed at length in Chapter IV, that the selection of alternatives must be based on optimizing the net present equivalent profit and not merely on minimizing costs. Once values have been assigned to outcomes, we naturally desire to obtain these values earlier rather than later. Discounting is a mathematical expression of our desire to defer expenditures and to accelerate receipts. If we wish to express this attitude by discounting costs, we must simultaneously discount values as well. A failure to do this can generate anomalies and even incorrect decisions, as discussed in Chapter IV:

To demonstrate how the selector deals with this effect, consider two propulsion systems which, if they are launched simultaneously, will arrive at their target after times T_1 and T_2 . Further, let us assume that a discount factor $DF = (1+D)^{-1}$ is being used (in an inflation free economy). Then if $V(>0)$ is the value of accomplishing this mission, the present values achieved by the two arrival times are:

$$V_1 = V * DF^{T_1} \text{ and } V_2 = V * DF^{T_2}.$$

It follows that:

Table 3.6

SAMPLE PROPULSION SYSTEM SELECTOR CALCULATIONS

(A)

PS	$\frac{\#S/C \times (\text{Unit Cost})}{}$	$\frac{+ \text{Escape}}{}$	$\frac{- \text{Inheritance}}{}$	$\frac{- S/C \text{ Savings}^*)}{}$	$\frac{+ \text{Operations}}{}$	$\frac{(\alpha) = \text{Eff. Cost}}{}$
CENT/KICK	2 × (6.0 .	+	1.0 -	0	-	11.7 × 6 = 84.2
					14.0	
CENT/NEP	2 × (31.1	+	6.0 -	3.11 -	24)	+ 5.0 × 6 = 49.98
					19.98	

(B)

EFFECT OF ALPHA MODIFICATION

$$\begin{array}{rcl} \text{Percent Change in } \alpha \times \alpha \times \text{Power} \times 1/\text{Slope} \times \text{Average In-Flight Cost} & = & \text{Change in Cost} \\ (+0.20 \times 30 \text{ kg/kW} \times 120 \text{ kW} \times 1/300 \text{ yr/kg}) \times 6 \text{ \$/yr} & = & \\ 2.4 \text{ yr} & & + 14.4 \\ & & \hline & & 64.38 \end{array}$$

* Individual mission dependent spacecraft exploration strategy.

$$\begin{aligned}
\Delta V &= V_2 - V_1 = -V_1 * \left(1 - \frac{V_2}{V_1} \right) \\
&= -V_1 * (1 - DF^{T_2 - T_1}) \\
&= -V * DF^{T_1} * (1 - DF^{T_2 - T_1})
\end{aligned}$$

When DF is less than unity, the usual case for discounting, $T_2 < T_1$ implies $1 - DF^{T_2 - T_1} < 0$, while $T_2 > T_1$ implies $1 - DF^{T_2 - T_1} > 0$. Thus, for decreased trip times ($T_2 < T_1$), that value is increased ($V_2 > V_1$), whereas for increased trip time ($T_2 > T_1$) that value is decreased, $V_2 < V_1$. The equation above has been used to incorporate the value reduction resulting from slower trip times into the propulsion system selector logic. In all cases, the flight time for each propulsion system is compared with that for a "reference" propulsion system to measure the value effects of timing. In this way, the model selects the propulsion system yielding the highest net present equivalent profit.

This effect vanishes when $DF = 1$ --that is, if no discounting is being used. It also vanishes if the launch times are changed so that the target arrivals, and hence the values, come at the same time for either propulsion system or if all mission values are set at zero. In any other case, the values and the costs must be discounted in an identical fashion.

3.4 Deterministic Phase Analysis

In the deterministic phase, the analysis centers on observing how changes in the system variables affect worth. Experimentation of this type is known as sensitivity analysis. It is highly effective in refining the formulation of the problem and simplifying the deterministic model structure; see the last step in the deterministic phase shown in Figure 3.1.

The first sensitivity analysis performed is associated with the decision variables. First, the analyst fixes all the state variables in the problem at their nominal values, then allows one of the decision variables to traverse its assigned range and observes how worth changes. These observations are usually carried out by computer program. If a particular decision variable has a major effect, then it was correct to include it in the original formulation. But if a decision variable has little or no effect, the analyst is justified in considering removing it as a decision variable. For example, the time of introducing a new product might seem to be a decision variable of major importance, but

because of the combined effects of competitive reaction and the gaining of production experience, it might have very little effect. The timing of entry would then be an impotent variable.

Next, sensitivity analyses are performed on the state variables, which are uncertain and over which the decision-maker has no control. With all other system variables at their nominal values, the change in worth is observed while sweeping one state variable over its range. If a state variable has a major effect, then the uncertainty in the variable deserves special attention. Such variables are called crucial variables to emphasize their importance. If, however, varying a state variable over its range produces only a minor change in worth, then that variable might well be fixed at its nominal value.

Although sensitivity analysis has been described as if it concerns only changes in one variable at a time, some of the most interesting sensitivity results are often observed when there are simultaneous changes in state variables. Since the possibilities of changing state variables jointly increase rapidly with the number of state variables, it is important for the decision analyst to determine the amount of simultaneous sensitivity analysis that is economic. This judgment requires a careful consideration of the dependencies among the crucial variables.

3.5 Definition of Base Case for Nuclear Electric Propulsion

To establish nominal data for a NEP base case, the decision analysis team worked very closely with specialists from the thermionic projects at JPL and GGA. The base case development program specifies a 120 kWe NEP developed for a 1983 launch, according to the development cost estimate from JPL.²³ Alternative development cost streams were provided in the same document for 120 kW NEP that will be ready in 1986 and 240 kW NEP that will be ready in either 1983 or 1986. The base case development outcomes were a power of 120 kW, a specific mass of 30 kg/kW, a lifetime of 20,000 hours, and a unit cost of \$31.1 million including the avionics necessary for geocentric guidance and control, with a cost reduction of 10% for all units after the first.

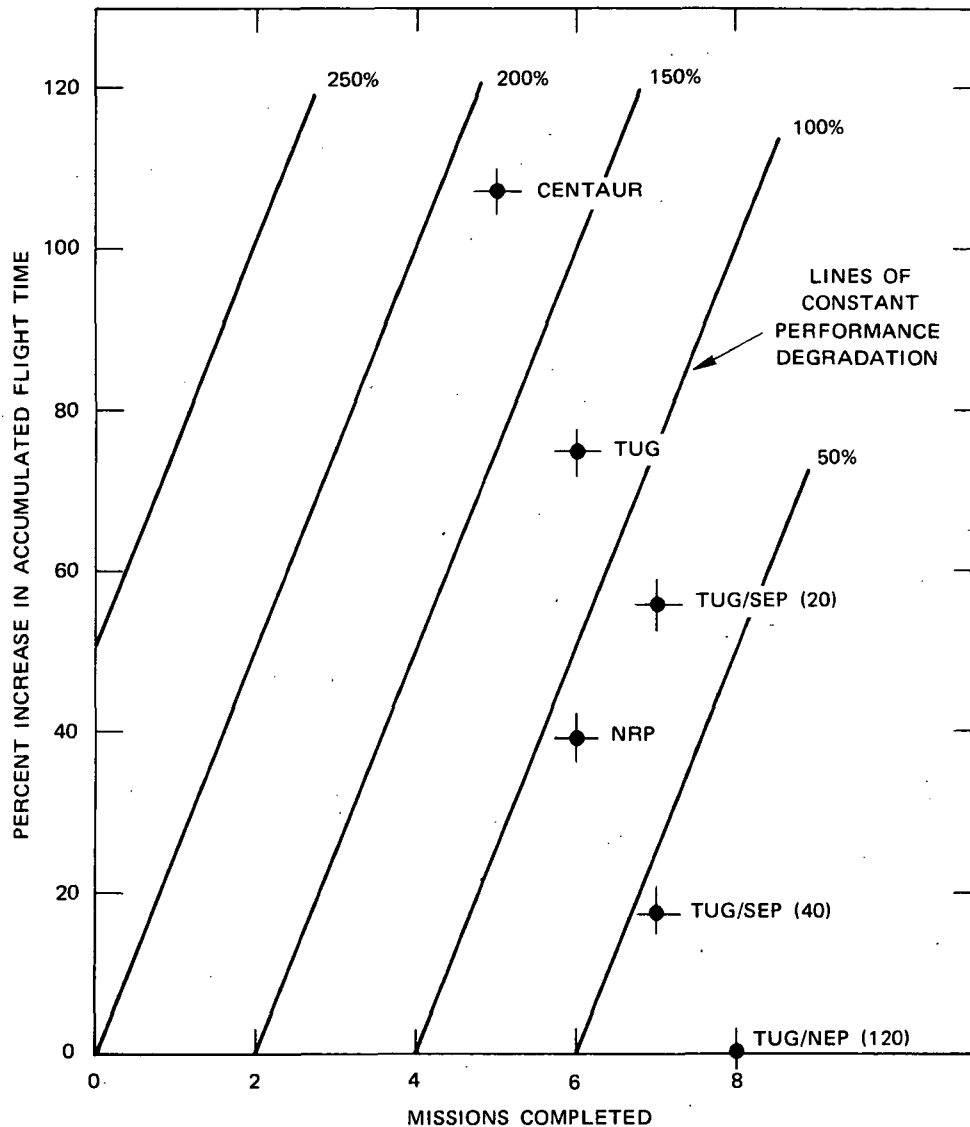
For the 120 kWe NEP base case, the Centaur (CENT) was used as a direct escape stage with a unit cost of \$6.0 million, and the cost of one shuttle flight--considered sufficient for a CENT/NEP(120) launch--was taken to be \$10.5 million. For a first simple development decision situation the alternatives were to develop 120 kWe NEP or to develop

nothing using only the Centaur whenever possible.* The planetary exploration strategy for the base case was individual mission-dependent, dictating high cost, high reliability, and minimal weight spacecraft. To examine the full potential of NEP, the entire APC extended mission set was run for the base case, but in every instance parallel runs have been made for the APC base missions and the von Braun mission set. Finally, for base case runs, the discount rates and inflation rates have been assumed to be equal, thereby eliminating time preference effects, but again parallel runs have been made with 10% and 15% discounting and 5% inflation.

For the base case value model, every mission has been assigned an equal value of \$950 million, a value just large enough so that even the most costly mission (Mars rover) is profitable. Such a value model is the most simple extension of a pure cost model, which after all is an equal value model in which all missions are assigned a value of zero. Thus, each cost reduction is reflected directly as a profit increase. But, furthermore, when a mission cannot be accomplished by a particular propulsion system in some planetary exploration strategy, a model with values shows both a cost reduction and a profit reduction. Profit is a more formal and more useful way to represent the "performance degradation parameter" discussed in the APC study²⁴ and shown here in Figure 3.6. Note that if the APC extended missions are assumed to accomplish most of the scientific and political components of value currently assigned to planetary exploration, then the equal values of \$950 million and the size of this mission set imply a total assigned value of at least \$20 billion for the entire solar system (exclusive of the moon). Again, this value is not proposed, but only used to demonstrate the operation and usefulness of a value model. Value models are discussed in great detail in Chapter IV.

Table 3.7 shows the deterministic model output for the base case defined above. Shuttle costs, propulsion system costs, spacecraft costs, and operating costs are summed separately over all missions and then combined into a total mission cost. The NEP development cost (reduced by the cost of the first NEP flight system) is added to the mission cost to obtain the program cost. Then on a mission-by-mission basis, the following data are provided: mission number; propulsion system selected to

* It has been assumed for the pilot model that Centaur alone always requires a kick stage at an additional cost of \$1 million. This assumption is very favorable to the Centaur since it often needs several additional retro stages for orbital capture as well.



$\Delta M \equiv$ Number of Missions Not Performed

$\Delta T_f \equiv$ Percent Increase in Accumulated Flight Time

PD $\equiv$ Percent Degradation in Mission Performance

Assumption: Percent Loss in Missions is Twice as Detrimental
as Percent Increase in Accumulated Flight Time

$$PD = 2(1 - \Delta M/8) + \Delta T_f$$

FIGURE 3.6 EXAMPLE OF APC PLANETARY PERFORMANCE EVALUATION (WITHOUT AN EXPLICIT VALUE AND PROFIT STRUCTURE, AND WITH TUG/NEP(120) AS THE REFERENCE PROPULSION OPTION FOR AN EIGHT-MISSION SET – SEE REFERENCE 24.)

Table 3.7

BASE CASE DETERMINISTIC MODEL OUTPUT USING AN EQUAL VALUE MODEL
AND DISCOUNT RATE EQUAL TO THE INFLATION RATE

ALL MISSION SUMS													
SHUTTLES		388.50		PROP. SYS.		912.98		S/C 6652.00		OPNS.		421.29	
TOTAL COSTS													
MISSIONS		8374.77		NEP DEVEL.		504.00		PROGRAM		8878.77			
MISSION	PS	PS COST	DELTA(<#2)	VALUE	-	COST	=	PROFIT					
2	CENT	32.30	6.38	950.00		211.30		738.70					
3	CENT	16.16	12.32	950.00		274.16		675.84					
4	CENT	13.72	7.86	950.00		893.22		56.78					
5	NEP	35.44	*****	950.00		244.44		705.56					
6	NEP	39.18	3.32	950.00		520.18		429.82					
7	CENT	21.20	4.99	950.00		233.20		716.80					
8	CENT	15.80	6.58	950.00		251.80		698.20					
9	NEP	31.68	1.67	950.00		355.68		594.32					
10	NEP	49.98	34.22	950.00		507.98		442.02					
11	NEP	53.58	*****	950.00		480.58		469.42					
12	CENT	16.76	6.70	950.00		337.76		612.24					
13	NEP	63.18	*****	950.00		469.18		480.82					
14	CENT	54.50	1.48	950.00		315.50		634.50					
15	NEP	64.98	*****	950.00		575.98		374.02					
16	NEP	35.91	*****	950.00		560.41		389.59					
17	NEP	34.80	*****	950.00		250.80		699.20					
18	NEP	55.98	18.02	950.00		576.98		373.02					
19	NEP	26.55	*****	950.00		217.55		732.45					
20	NEP	54.18	*****	950.00		495.18		454.82					
21	NEP	42.39	*****	950.00		602.89		347.11					
MISSIONS FLOWN 20		NEP MISSIONS 13		TOTAL PROFIT		10625.23							

perform the mission; the effective propulsion system cost (including spacecraft savings and value effects when discounting); the difference between the lowest and the second lowest effective propulsion system cost (in the table ***** indicates that only one propulsion system can accomplish the mission); and finally the value, cost, and profit for each mission. The bottom line of Table 3.7 shows the total number of missions accomplished, the number for which NEP was selected, and the total mission profit. The sensitivity results reported in Section 3.7 summarize a large number of such cases.

3.6 Variations from the Base Case

The design of the base case for the decision analysis has been strongly influenced by the focus of the pilot analysis--namely on the power level decision. The principal variation from the base case discussed above therefore has been the addition of the 240 kWe GNEP system for comparison. For the decision of whether to orient the thermionic program toward a 120 kWe or a 240 kWe reactor, it has proved important to consider alternative planetary exploration strategies. These strategies can utilize the capabilities of advanced propulsion systems to explore the solar system more effectively. Since the 240 kWe reactor would be somewhat more expensive to develop and produce, any savings resulting from reduced flight time are likely to be insufficient to offset the increased reactor costs. The real economic and technical advantages of more capable systems result from the implementation of lower cost or higher capability exploration strategies such as those shown in Figure 2.6 and discussed in Section 2.3.

Thermionic reactor specialists contend that the reference TFE design is suitable for both power levels, so lifetime constraints have been assumed to be the same for either power level. On the other hand, the specific weight of the reactor is expected to decrease slightly as a function of power level. Finally, the cost differential between the 120 kWe and 240 kWe propulsion system (thermionic reactor, radiator, power conditioners, and thrusters) is very close to \$10 million. The deterministic lifetime constraint has been set at 20,000 hours. The nominal specific weights used have been $\alpha(120\text{kWe}) = 30 \text{ kg/kWe}$ and $\alpha(240 \text{ kWe}) = 25 \text{ kg/kWe}$. The nominal costs for the two propulsion systems used are \$31.1 million for the 120 kWe system and \$41.0 million for the 240 kWe. These costs each include \$6.4 million for avionics. Since avionics is not obviously necessary for planetary missions, a provision has been made to run cases with or without it. All of these numbers have been obtained from JPL, reviewed with GGA, and to the best of our knowledge are the same numbers that have been submitted to the APC study.

In addition to the runs for 240 kWe GNEP, sensitivities to percentage variations in NEP specific weight and unit cost have also been examined at both power levels. Similar variations could not be made for lifetime, since only performance curves for the 20,000 hour assumption had been provided. If performance data similar to that shown in Figure 3.3 were available for all APC missions corresponding to TFE lifetimes of 10,000, 15,000, 20,000 and 25,000 hours, then sensitivity runs could be made similar to those made for specific weight.*

Our impressions from a number of discussions at JPL and GGA were that NEP specific weight variation of $\pm 20\%$ and unit cost variations of $\pm 10\%$ were reasonable for deterministic sensitivities. It can be seen that these variations have some significance, which will be examined in the next section. Opinions among thermionic specialists were divided as to whether the 20,000-hour lifetime could be achieved, as shown in Figure 3.7. However, it seemed possible to achieve in light of the opinions expressed regarding the lifetime of a typical Ground Prototype Reactor TFE about 1980. Furthermore, for most missions where thrust times greater than 15,000 hours are desirable, there is a sizable performance margin that could probably be used to reoptimize trajectories with reduced thrust time at the cost of increased trip time.

3.7 Deterministic Sensitivity Analysis of NEP

This section examines the results of a sensitivity analysis to variations in discount rate, mission set, NEP specific weight, NEP unit cost, planetary exploration strategy, and NEP power level, all within the context of an equal mission value model. The results from a relative model value are discussed briefly in Chapter IV, but even without detailed analysis it is clear that the profit differentials in the undiscounted sensitivity tables, which reflect changes in mission costs and values will be entirely a reflection of cost changes unless missions are lost because of the changed conditions. That is because none of the variations examined can influence the deterministic, undiscounted mission values unless they eliminate the mission entirely. So undiscounted sensitivities to unit cost and specific weight changes will be identical in either an equal or a relative value model.

* Low thrust trajectory experts expressed some optimism that, as with the effects of specific weight and direct escape stages change discussed in Section 3.2, there might be a simple way to express such TFE lifetime effects by their effect on the maximum deliverable payload in an analytic form.

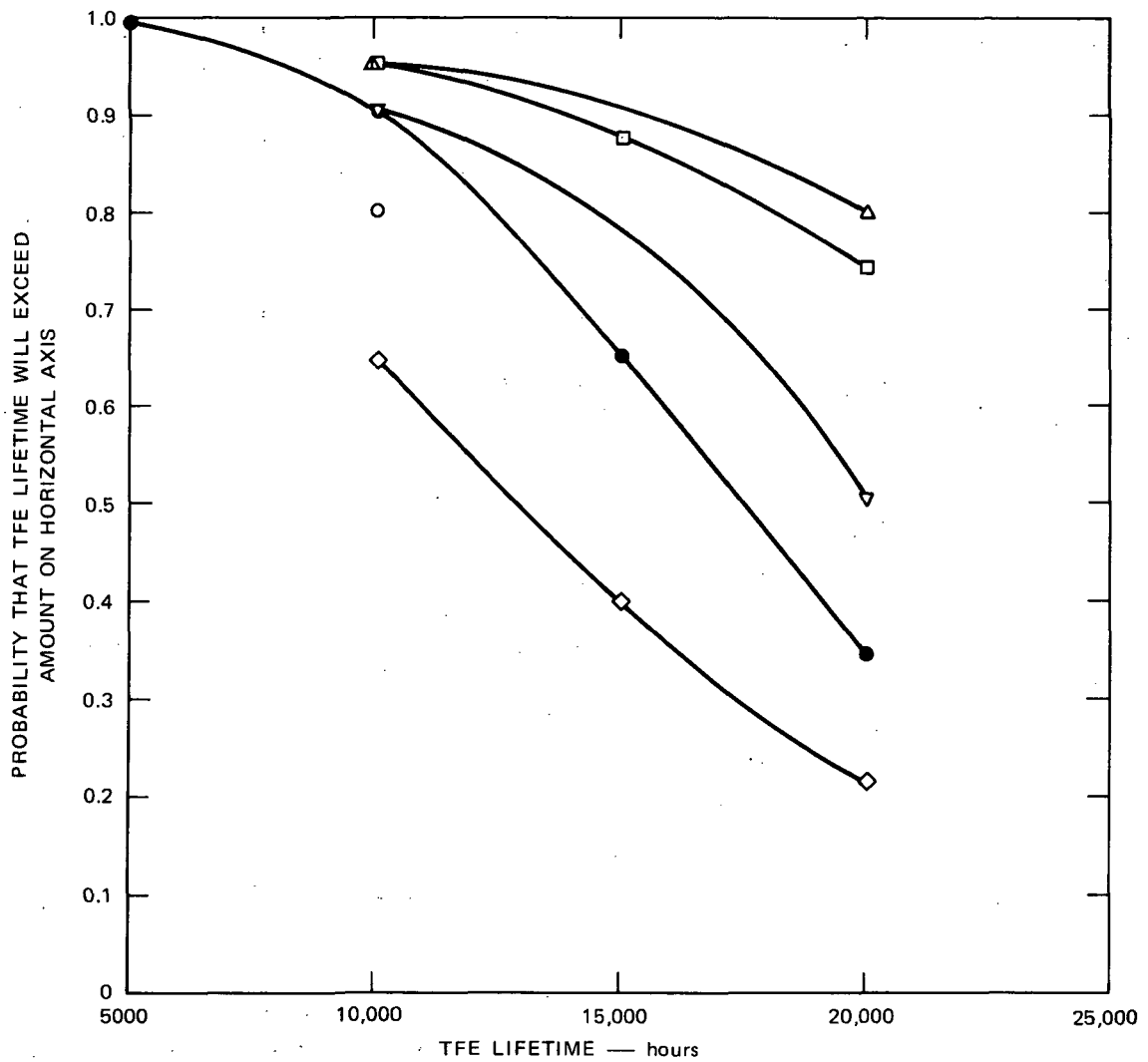


FIGURE 3.7 PRELIMINARY OPINIONS ON LIFETIME OF TYPICAL GROUND
PROTOTYPE REACTOR TFE (CIRCA 1980) FROM PARTICIPANTS
AT THERMIONIC SPECIALISTS CONFERENCE, SEPTEMBER 1972

In any program whose benefits will not be realized for ten years or more in the future, the choice of discount rate is bound to influence significantly the outputs from any evaluation procedure. It does not necessarily follow, however, that any decisions should change or even that the relative importance of any state variables will be altered. These answers must result from careful analysis. However, it should be noted that for effective discount rates of 5% to 10%, a delay of 11 years (i.e., from 1972 to 1983) produces discount factors of about 60% and 35%, respectively. These factors differ to such a degree that sensitivity tables will be given separately for different discount rates. The present curtailment of space thermionic reactor research certainly reflects these severe reductions of future benefits that will not be achieved for at least ten years.

Another factor that strongly affects the total profit magnitude, but that may or may not strongly affect decisions, is the size and nature of the mission set that is judged to represent most closely the way the nation wants its resources for space exploration allocated. To represent this effect, data will be presented in a parallel way for the three mission sets defined in Table 3.1. For each of these, Table 3.8 shows the effect of variations in NEP availability, NEP specific weight, NEP unit cost, and planetary exploration strategy. The cases are described by their total program profit, their difference from the base case of nominal spacecraft with Centaur and 120 kWe NEP, and the number of NEP and total missions flown. In all cases, the undiscounted* total program profit is considerably more sensitive to a 10% cost reduction in unit cost than to a 20% reduction in specific weight. The 10% cost reduction also causes a dramatic increase in the number of missions (all except one) that employ NEP as their optimal propulsion system.

When only Centaur is available, the total program profit is reduced in a manner approximately proportional to the fraction of the mission set that can be accomplished by the Centaur alone. In these equal value cases (with the discount rate equal to the inflation rate), the reduction in profit because of missions not accomplished when NEP is not available is sufficient to justify the \$500 million cost of the NEP development program. This same comparison will be examined below for more realistic combinations of discount and inflation rates.

A final observation related to Table 3.8 is the apparent difference between mission sets in the multimission modular (low cost) planetary

* Effective discount rate is zero, i.e., discount rate equals inflation rate.

Table 3.8

DETERMINISTIC SENSITIVITIES FOR 120 kW NEP BASE CASE
FOR VARIOUS MISSION SETS (UNDISCOUNTED)
(Millions of Dollars)

Case	20 APC Ext. Missions			15 APC Base Missions			9 von Braun Missions		
	Profit	Δ	# NEP/ # Flown	Profit	Δ	# NEP/ # Flown	Profit	Δ	# NEP/ # Flown
CENT only	\$ 5,915	\$	0/11	\$5,560	\$	0/10	\$4,227	\$	0/8
BASE	10,625	0	13/20	8,019	0	8/15	4,972	0	4/9
$\Delta\alpha = +20\%$	10,565	-60	11/20	7,976	-43	6/15	4,952	-20	2/9
$\Delta\alpha = -20\%$	10,687	+62	14/20	8,064	+45	9/15	4,993	+21	4/9
$\Delta C = +11\%$	10,546	-79	11/20	7,973	-46	6/15	4,952	-20	2/9
$\Delta C = -10\%$	10,733	+108	19/20	8,093	+74	14/15	5,013	+41	8/9
Low cost S/C	10,827	+202	15/19	7,813	-205	10/14	4,583	-389	6/8

exploration strategy. For the 20-mission set, this strategy increases total program profit by more than \$200 million, whereas for the 9-mission set it reduces the profit by nearly \$400 million. The reason for this drastic change follows:

In all three mission sets there is one mission, the Venus large lander, for which 120 kW NEP is incapable of delivering the heavier, low cost payload (with a Centaur escape stage). The spacecraft savings resulting from the modularity of the 19 other APC extended missions compensate for the loss of the profit on the Venus mission, but the savings from the other 8 missions in the von Braun set cannot do so. In this way, the profit model trades off spacecraft savings against lost missions and points the way to optimal strategies.

Table 3.9 displays the analogous data for the 240 kW system (GNEP). In this table, the base case is for the reference design GNEP system with the multimission modular spacecraft planetary exploration strategy. For GNEP, the effect of a 20% change in specific weight has decreased slightly because of the much steeper slopes of the appropriate performance curves (see Figure 3.4), whereas the effect of a 10% change in cost has increased since the cost itself is larger. In fact, because of the decreased number of missions which Centaur can perform, these variations cause no change in the number of missions that would utilize GNEP. Furthermore, GNEP used in the individual mission-dependent spacecraft strategy is clearly less profitable than the 120 kW NEP in the same strategy and considerably less profitable than the GNEP base case.

Table 3.10 is the analog of Table 3.8, but utilizes an inflation rate of 5% and a discount rate of 10%, or an effective discount rate of 5% on constant dollars.* It can be seen that discounting increases the number of missions for which NEP is selected in the base case because of the ability of NEP to save approximately one year of flight time on missions 2 and 14. This change in selection would not occur if the mission values were set at zero. Furthermore, in the discounted cases, NEP retains all but one of its missions for a 20% increase in specific weight and all of its missions for a 10% unit cost increase, because of the significance of delaying accomplishments. By the same reasoning, an NEP 10% cost reduction gains one less mission than it did without discounting because it is slower than the Centaur for that mission.

* See Reference 19, page 3-49.

Table 3.9

DETERMINISTIC SENSITIVITIES FOR 240 kW GNEP (LOW-COST)
 BASE CASE FOR VARIOUS MISSION SETS (UNDISCOUNTED)
 (Millions of Dollars)

Case	20 APC Ext. Missions			15 APC Base Missions			9 von Braun Missions		
	Profit	Δ	# NEP/ # Flown	Profit	Δ	# NEP/ # Flown	Profit	Δ	# NEP/ # Flown
CENT only	\$ 2,610	\$	0/4	\$2,610	\$	0/4	\$1,039	\$	0/2
BASE	11,437		16/20	8,434		11/15	5,168		7/9
$\Delta\alpha = + 20$	11,383	-54	16/20	8,399	-35	11/15	5,154	-14	7/9
$\Delta\alpha = - 20$	11,491	+54	16/20	8,468	+34	11/15	5,182	+14	7/9
$\Delta C = + 10$	11,314	-123	16/20	8,348	-86	11/15	5,111	-57	7/9
$\Delta C = - 10$	11,560	+123	16/20	8,520	+86	11/15	5,226	+58	7/9
NOM S/C	10,566	-871	11/20	7,975	-459	6/15	4,951	-217	2/9

Table 3.10

DETERMINISTIC SENSITIVITIES FOR 120 kW NEP BASE CASE
FOR VARIOUS MISSION SETS (10% DISCOUNT RATE, 5% INFLATION)
(Millions of Dollars)

Case	2 APC Ext. Missions			15 APC Base Missions			9 von Braun Missions		
	Profit	Δ	# Flown	Profit	Δ	# Flown	Profit	Δ	# Flown
CENT only	\$2,413	\$	0/11	\$2,405	\$	0/10	\$1,706	\$	0/8
BASE	4,460		15/20	3,445		10/15	2,220		5/9
$\Delta\alpha = + 20\%$	4,273	-187	14/20	3,311	-134	10/15	2,155	- 65	5/9
$\Delta\alpha = - 20\%$	4,660	+200	16/20	3,588	+143	11/15	2,292	+ 72	6/9
$\Delta C = + 10\%$	4,406	- 54	15/20	3,409	- 36	10/15	2,201	- 19	5/9
$\Delta C = - 10\%$	4,518	+ 58	17/20	3,485	+ 40	12/15	2,243	+ 23	7/9
Low cost S/C	4,452	- 8	16/19	3,259	-186	11/14	2,027	-193	6/8
Low cost, GNEP	4,798	+338	17/20	3,567	+122	12/15	2,260	+ 40	7/9

In this table, the relative importance of a 20% change in specific weight compared with a 10% change in cost has changed drastically. As stated before, values and costs must be discounted in identical ways to avoid contradictory, and even incorrect, results. Thus, a change in trip time resulting from a change in NEP specific weight will change the timing of the mission accomplishments, and thus modify their present value.* This dramatic change in sensitivities illustrates the importance of understanding the values and time preference issues that underlie our space exploration activities.

Table 3.10 shows that discounting also emphasizes the inability of NEP to take full advantage of the low-cost, multimission modular exploration strategy, which GNEP can. This occurs because the Venus large lander, even with a 1989 launch, has a relatively early payoff (1989) with relatively late costs (1989). Thus, its profit contribution is emphasized by discounting. Note that all of our spacecraft costs are assumed to occur in the launch year.

By performing careful sensitivity analysis, it is possible to evaluate the effect of reduced unit cost on the present equivalent worth, the effect of reduced specific weight, and so forth. Since the analysis was not focused on making specific design decisions, the results from this type of evaluation will probably not be highly accurate for design purposes. The assumptions that were made in the pilot level analysis were justified on the basis that they would not affect the general direction of the NEP program, particularly the power level decision. These same assumptions may affect design trade-off decisions to a much greater degree. Thus, caution should be employed if applying the deterministic model to determine specific design trade-offs.

*The APC economic analysis incorporates the same effect by stipulating that launch dates will be adjusted to equalize the target arrival times of all propulsion candidates. This effectively reduces the mission costs of more capable propulsion systems through discounting.

IV VALUE MODELING IN SPACE PROGRAM PLANNING

A great number of studies have examined the problem of explicit value models for space program planning.^{5,25,26} Although these studies were interesting, imaginative, and logically sound, they have apparently never been applied by top NASA management to the basic planning process. A quotation from Reference 25 shows the usual attitude with which such models are regarded: "These values ... should be regarded only as illustrative, however, since we had been requested by NASA not to attempt to obtain a 'final' set of values by interviewing a large number of experts or scientists not associated with the study."²⁷ There is a widespread uneasiness among decision-makers in the government concerning the use and misuse of explicit value models.

In discussions with NASA management regarding this issue, the standard reply has been that the Scientific Advisory Boards do make cost-effective decisions when there is not enough money to pursue optimal programs. They do so implicitly, however, in a manner that cannot be checked and cannot be clearly communicated to other parts of the organization, where related decisions on coordinated programs are being made by others. Several recent reports of the Space Science Board^{28,29} giving recommendations for high-level, intermediate-level, and low-level programs provide a good example of such implicit value judgments.

In this chapter we will explore explicit value systems in detail to see exactly what advantages they offer, how they may be obtained, and how they might be applied in the evaluation of advanced propulsion alternatives. One of the primary problems with explicit value systems should be mentioned at the onset--namely, that value judgments are hierarchical, just as decisions are (see Figure 2.3). A common objection to explicit value models is that "... you can never get an expert on Jupiter and an expert on Mars to agree on the relative value of Jupiter and Mars." This statement no doubt is true, but a panel of broadly-based exobiologists, planetary astronomers, and planetary geologists probably could make such judgments, at least with regard to their special areas. If these various groups disagreed, then a higher level judgment would be needed to establish relative priorities among exobiology, planetary astronomy, and extra-terrestrial geology in the context of our total space program. In this way, many of the objections to explicit value assignment translate into requests for a well-defined management decision-making hierarchy.

In summary, an explicit value system provides rules for resource allocation that are easy to communicate and can be applied consistently at all stages of a project, as well as among projects. An explicit value system is not a set of moral or theological judgments on intrinsic merit. It is an expression of how we desire to allocate limited resources. Thus, it will, and should, change in response to changes in the technical, economic, and political climate of the larger system that it represents.

4.1 Nature of Value

The application of logic to the decisions involved in space program planning requires, as one of its fundamental steps, the construction of a value function on possible program outcomes. That is, it is necessary to construct a scale of values that specifies the preferences of the decision-maker for one outcome as opposed to another. The problem is analogous to the one we face if we delegate someone to buy a car for us: we must tell him which features of a car are important to us and to what extent. How do we value performance relative to comfort, appearance relative to economy of operation, and so forth? The need for specifying the value function grows out of the desire to utilize the potential of analytical and logical methods to extend and improve our more intuitive concepts, as well as the desire to delegate many of the detailed decisions to lower-level decision-makers. Analytical and logical methods allow us to take direct account of many more factors, including the dimension of uncertainty, to make better decisions. To obtain maximum benefit from these methods, however, we must be willing to specify a value function, especially in a complex sequential decision situation such as planetary exploration.

4.2 Derived and Assigned Values

In constructing the value function, careful distinction must be drawn between derived and assigned components of value.* The assigned component of value is obtained as an explicit benefit of the project. For example, conducting a life experiment on Mars has an assigned scientific value that is very high. Similarly, placing a spacecraft in orbit around Mars has an assigned value as an engineering accomplishment. However, placing the spacecraft in orbit also has a derived value because

* These will be illustrated using examples of Martian exploration drawn from the Voyager analysis.

of its importance in achieving later assigned values, like the conduct of life detection experiments. A derived value component therefore is one that accrues to an accomplishment because of its contribution to achieving future assigned values. If a project is terminated at some date, it will be credited with all of the assigned values it had achieved prior to that date, but not with any derived values that had not yet been realized in assigned form. These values could only be realized by continuation of the project.

The same accomplishment may have both assigned and derived values. The assigned values are determined by factors outside the project; the derived values stem from the assigned values and the probabilistic structure of the problem. Assigned values must be determined directly, as their name implies. The derived contributions are incorporated by increasing the probability of success in future missions, thus increasing the probability of eventually achieving future assigned values.

4.3 Direct and Indirect Values

The assigned value function has both direct and indirect contributions. The direct values of exploring Mars arise from the various kinds of knowledge that the explorations will produce: visual records of Mars, significant data on both the biological and physical environment, engineering capability, and operational experience. From these direct contributions, the nation derives indirect contributions such as national prestige and favorable world opinion. Thus, the indirect value is the value of obtaining and possessing the knowledge. The existence of the indirect components can be demonstrated by observing that if a race of galactic explorers were to offer us solid information of the type we have listed under direct contributions (such as a Martian atlas or a guide to the Martian flora and fauna), the price we would offer would probably be considerably less than the cost of the Mariner and Viking projects. Part of the satisfaction comes from having done it ourselves, and the value function must include this indirect value, which is characteristic of the project.

4.4 Construction of a Value Scale

The first step in constructing the value function is to establish an ordinal scale of values that states, for each pair of outcomes, the outcome that is preferred. The next step is the construction of a cardinal scale that allows us to compare the strength of preference. One way to develop such a scale is to assign points to the different outcomes

and adjust values until decision-makers are satisfied with the results. The final step is to construct an absolute dollar scale that interprets points directly in terms of dollar benefits. The ordinal and cardinal point scales can be established by intuitive comparisons within the project scope; the absolute dollar scale requires that the project under consideration be compared with other space projects in light of NASA's overall priorities and budget.

The use of cardinal and absolute value scales can be illustrated by returning to the car purchase example of Section 4.1. We could tell our agent, who will buy the car for us, the dollar value we assign to each component of a car's value. We might say, for example, that given our use characteristics, a car that runs 18 miles to a gallon of gas is worth \$40 a year more to us than a car that runs only 15 miles and that foam rubber seats are worth \$50 more to us than ordinary seats. When we had similarly specified the dollar value of all possible features, including those whose values might not be additive, then our agent would be able to go into the marketplace, determine the value and price of every car offered, and return with the most acceptable car for us (which might, of course, be no car at all). Notice, in following this philosophy that we do not care whether, in fact, there are any cars for sale that have all or any part of the features that we have valued. The establishment of the value function depends remotely, if at all, on the spectrum of cars available. One of the weaknesses prevalent in the literature on explicit value is that technical feasibility has been incorporated in the value function.

The point value (cardinal) approach is similar except that points are assigned to each of the components of value, individually and jointly. In this case, we would fix a purchase budget for our agent and send him out to find the best car (highest points) within the budget. Of course, we might be very sorry if we learned that he could have purchased a much better car for a little more money or if he paid very dearly for the last few points he obtained. However, since we can often convert point value scales to absolute dollar value scales by assigning a dollar value to each point, the essential difference in the two schemes lies in whether we want to find the most profitable course of action with or without budgetary constraints.

It should be emphasized that the main role of the value function is to serve as a framework for discussion of preferences. The value function encodes preferences consistently; it does not create them. Consequently, the decision-maker can insert alternative value specifications to determine the sensitivity of decisions to changes in the value function. The process of assigning the value is naturally an iterative one, with components of value being added and eliminated as understanding of the problem grows.

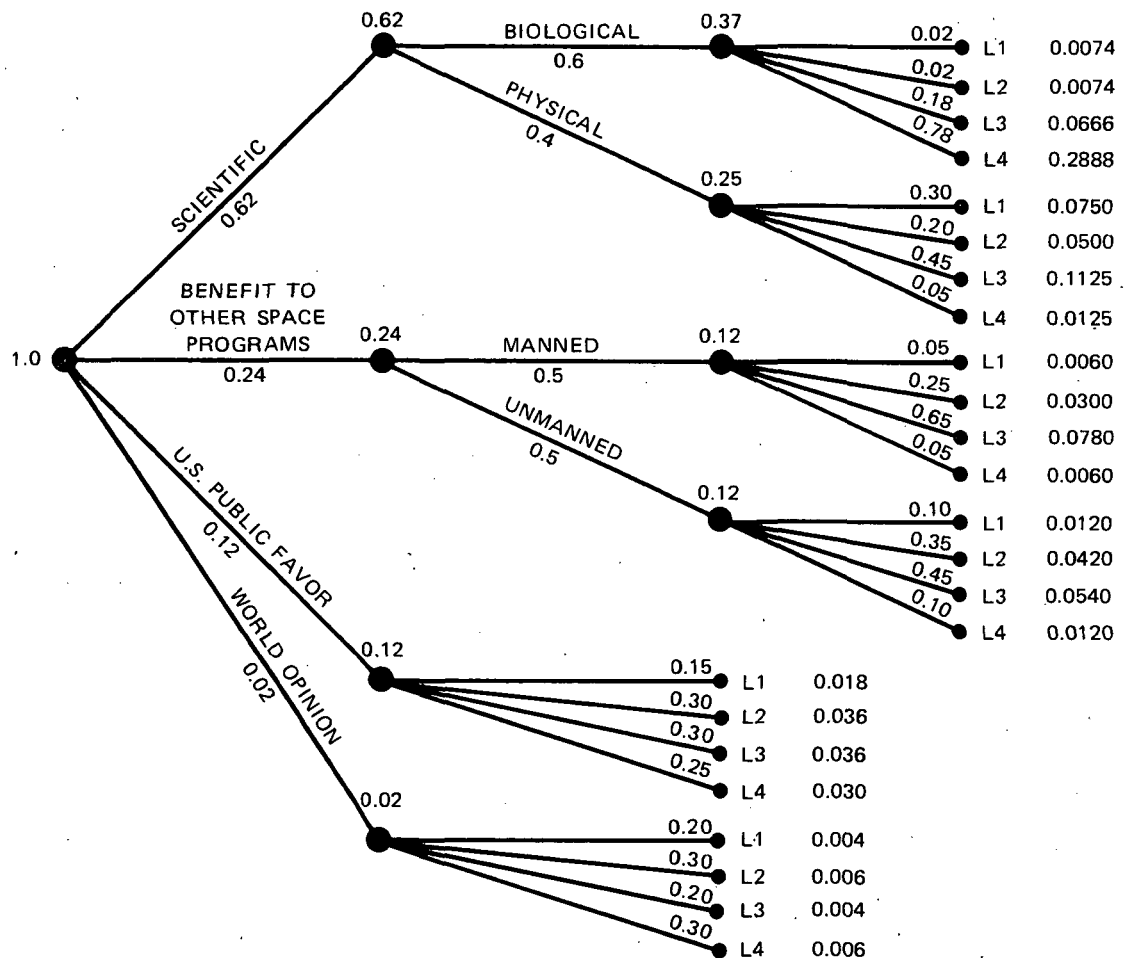
4.5 Value Tree

To aid in constructing the value function appropriate to a given target in the solar system, the problem can be visualized as one of constructing a value tree. This tree is drawn by considering first the major assigned components of value, both direct and indirect, then the subcategories of each type, identified in more and more detail, until no further distinction is necessary. Then, each tip of the tree is finally subdivided into achievement categories, each corresponding to the contribution of one of the achievements to the value subcategory represented by that tip.

Specifically, the value tree that served as the value function in the Voyager pilot analysis is pictured in Figure 4.1. The number 1.0 attached to the node at the extreme left represents the total value of all the objectives of the pilot Voyager project (thus, the value of achieving the four outcomes L1, L2, L3, and L4). The four branches emanating from this node represent the four major categories of value recognized by the pilot model. The number 0.62 attached to the upper branch represents the fraction of total value assigned to science. Two branches emanate from the science node, and 60 percent of the science value falls into the category of biological science. The 0.37 attached to the biological science node represents the fraction of total value attached to biological science and is obtained by taking 60 percent of 0.62 (the fraction of total value attached to all science). Finally, the bottom branch following the biological science node indicates that 78 percent of the biological science value is achieved by jumping from L3 to L4.

The final step in value modeling is to obtain the fraction of total value to be attached to achieving each of the four levels. If we add all the contributions to achieving L1 (coming from world opinion, U.S. public favor, physical science, etc.), the result is the fraction of value that should be attached to achieving L1. The same process is followed for reaching L4 from L1, L3 from L2, and L4 from L3. The results of such a calculation are shown in the lower-lefthand corner of Figure 4.1.

The complete value tree allows us to assign values to any proposed project. If a project is certain to achieve some of the total values, then it would be credited with those values. If it has a probability of less than one of achieving some total value, then it is credited with its expected contribution. The evaluation of projects can be performed at any vertical cross-section of the tree. As the components of value are more carefully broken down and the evaluation is performed to the right of the tree, the value computation becomes more precise. Of course, no plan for the project is expected to have a perfect value score.



RESULTS

L1 0.1224 - Perform atmospheric experiments

L2 0.1714 - Return descent TV

L3 0.3511 - Return landed TV and do surface property experiments

L4 0.3551 - Perform life detection experiments

TA-6152-10R

FIGURE 4.1 THE VALUE TREE USED IN THE VOYAGER PILOT ANALYSIS

4.6 The Need for Explicit Value Systems and National Profit Measures

Given a value scale and function such as those discussed in the preceding two sections, the cost of accomplishing our objectives can be subtracted from their value to yield a "national profit." This quantity provides a figure of merit by which the worth of alternative actions can be measured. Maximizing profit allows us to minimize cost--but only in such a way that we do not forego our basic program objectives. This is especially important if the analysis is examining advanced R&D projects, for which the restrictions of an "equal capability analysis" do not make sense. Advanced systems are generally developed to provide new capabilities that were previously unavailable; an equal capability cost analysis will almost surely underestimate what such systems have to offer.

It is possible to examine the sources of national profit which are attributable to the development of advanced propulsion systems. The first, and most readily accepted, component of profit is cost reduction resulting from the development. Such savings could come from either a less expensive propulsion system that could perform a mission in the same way or a more capable propulsion system (of equal cost) that could perform the mission in a less expensive way. An example of the latter is an electric propulsion system that could replace radioisotope thermal generators as a spacecraft power source.

A second component of profit is the set of additional accomplishments that can be achieved at no extra cost. Additional useful capabilities, if they are available with a propulsion system of equal cost, make the more capable system more valuable. Examples might be: (1) the availability of surplus power for enhanced science capability; (2) the capability to reduce flight times either (a) to achieve earlier results or (b) to postpone mission expenditures for results achieved at the same time (this capability produces an effective cost reduction when discounting); and (3) the possibility of reducing risk either via reduced flight times or with intrinsically more reliable systems. The problem here arises when we must choose between two systems of equal cost--for example, one of higher reliability and another offering shorter flight times.

The third, and very difficult, component of profit is the ability to perform desirable additional accomplishments at "reasonable" extra cost. The NEP program exhibited a classic example of this effect, because developing NEP is the only possible way to rendezvous with the famous Halley Comet when it next arrives in the 1985-86 time period. This comet, which reappears only once every 75 years, not only has great direct scientific value because of its newness and visible activity, but also possesses high indirect value because of widespread public knowledge

of its spectacular past visits. With any discount rate greater than inflation, the value of this achievement can be considered lost to our generation if NEP is not developed for a 1983 launch. A less dramatic example would be NEP's ability to perform multitarget missions that would be virtually impossible with ballistic propulsion systems.

Thus, the following situations obtain. Cost reductions, all other factors being equal, are both universally accepted as profitable and easily ordered for preferences: the more money that is saved, the more profitable the outcome. Equal cost capability enhancements are readily accepted as profitable, but are not easily ordered for preference when a difficult choice is offered: for example, shorter trip time versus higher intrinsic reliability. Finally, the ability to perform unique and desirable missions, like the Halley rendezvous, which can only be achieved by purchasing and launching an additional \$200 million spacecraft, taxes our power to judge intuitively whether this ability is profitable or not. In all but the first of these situations, logical and consistent decisions in complex, uncertain problems are difficult, if not impossible, to obtain intuitively.

An explicit value model is therefore necessary to deal with any (or all) of the following circumstances:

- (1) Propulsion alternatives that make possible additional missions not achievable by other systems.
- (2) Propulsion alternatives that enhance the capability of some mission through special features (like surplus available power).
- (3) Propulsion alternatives that significantly reduce the risk of mission failure.
- (4) Propulsion alternatives that allow earlier mission accomplishments.

The third point deserves further elaboration. Although everyone desires undiminished opportunities for gain at lower "risk," realistic opportunities usually require that larger risks be undertaken to achieve larger rewards.³⁰ This condition is definitely true in the space program, especially when the rewards are defined as net national profit--that is, value less cost. It is entirely possible that in NASA today excessive expenditures are being made to reduce or eliminate the risk (probability) of failure, thereby greatly diminishing or even negating the expected net profit of some programs. Appendix A gives some simple examples that illustrate the concepts of risk and shows why a logical treatment of risk

requires explicit values as well as costs. In particular, one definition of risk as an expected loss:

$$\text{Risk} = (\text{Probability of Failing}) \times (\text{Cost of Failing})$$

which was adopted for the APC Risk Comparison Study³¹ is demonstrated to be inadequate to deal with issues as important as space program planning.

The fourth point also deserves further elaboration. In the Voyager analysis, it was shown³² that if values and costs are discounted with different discount rates in a sequential decision problem, logical contradictions will arise and inferior alternatives may be selected. The same difficulty appears in the operation of the propulsion system selector. When values are set equal to zero, the model operates as a cost minimizer and selects NEP for 13 missions. When the values are larger than the costs, NEP is selected for 15 missions to achieve the values of 2 missions more rapidly.

Finally, it is worth reiterating that a pure cost minimizer presents us with a paradox, since the ultimate cost reduction is to eliminate, or seriously degrade, missions. Only with a value and profit structure can we economize efficiently without impairing mission effectiveness. These results illustrate the importance of developing a value model: that is, a rational structure for making the value assignment by breaking down value into more fundamental quantities that may be determined more easily and precisely. The following sections discuss how a value model can be applied to decisions regarding advanced propulsion development.

4.7 Establishment of a Relative Value Scale

The Voyager example discussed in the preceding sections has examined the problem of establishing the relative value of various types of missions to a single target (e.g., flyby, orbiter, orbiter/lander, surface sample return). These judgments should be made by panels of specialists in each of the targets in the solar system. Then, a higher level question arises--namely, what are our relative priorities for exploration of the various solar system features in light of our basic goals for planetary exploration. A simple priority ranking was established as early as 1965 by the Space Science Board³³ and is shown in Table 4.1. Note that if 100 total points are to be divided among the target objects, such a priority rank ordering already imposes strong constraints on how these points can be assigned.

Table 4.1

RELATIVE PRIORITIES OF TARGETS IN SOLAR SYSTEM

"After considering these reports the Working Group attempted to assign overall priorities to the various groups of objects on the basis of current scientific interest and on the bases of their relevance to the questions of the origin of the solar system, the origin of life, and the understanding of the Earth. A surprising degree of unanimity was evident. It should be emphasized, however, that these priorities are preliminary in the sense that they should be modified both by further debate among scientists in general and by the application of new data acquired."

Object	Rank
Mars	1
Moon }	2,3
Venus }	
Major planets	4
Comets and asteroids	5
Mercury	6
Pluto	7
Dust	8

Source: Reference 33.

A very comprehensive format for determining such relative priorities from basic objectives, developed in a RAND study,²⁵ is illustrated in Figure 4.2. For the purposes of propulsion development decisions, the structure of the RAND model is far more detailed than necessary. A structure much closer to that of the Space Science Board is suitable, but should incorporate a cardinal (numerical) scale of relative preference rankings. The scale used here is shown in Table 4.2. Although this table is by no means a survey or consensus of planetary experts, its formulation resulted from discussion with a number of JPL and NASA personnel and incorporates a number of their constructive suggestions.

In constructing this scale, a judgmental separation was made between the inner and outer solar system. Thus, whereas the RAND study of 1968 favored the inner solar system over the outer by 2:1, it appeared that today, with much more data available on Mars and with a growing interest in the role of the giant planets in establishing the origins of the solar system, a 1:1 relative value would be more appropriate. Since this ratio can be easily changed, more attention was given to the relative value scales of the objects within the inner and outer solar system categories. These scales reflect a number of other recent studies on space exploration objectives and values.^{26, 28, 29}

Because of time limitations and incomplete status of the current work, we were unable to model the value of specific missions to each target as was done for the Voyager analysis (see Figure 4.1). Instead, some very rough estimates were made, without the benefit of models and calculations, as to the fractional value of each target object in the solar system that would be attained by the successful completion of each mission in the extended APC mission set. This effort produced the scale shown in Table 4.3, where the most valuable missions (Mars rover and Mars sample return) are about 22 times more valuable than the least valuable mission (Halley flyby). Some model runs were made using these values to determine whether they differed substantially from runs made assuming equal values for all missions. For illustration, the relative values assigned in Table 4.2 to the solar system targets and the fraction of these values assumed to be accomplished by the APC missions are shown in Table 4.3. For the calculations of the next section, it is useful to note that since the relative mission value is the product of two percentages, its scale is $100 \times 100 = 10000$ times a true fractional mission accomplishment.

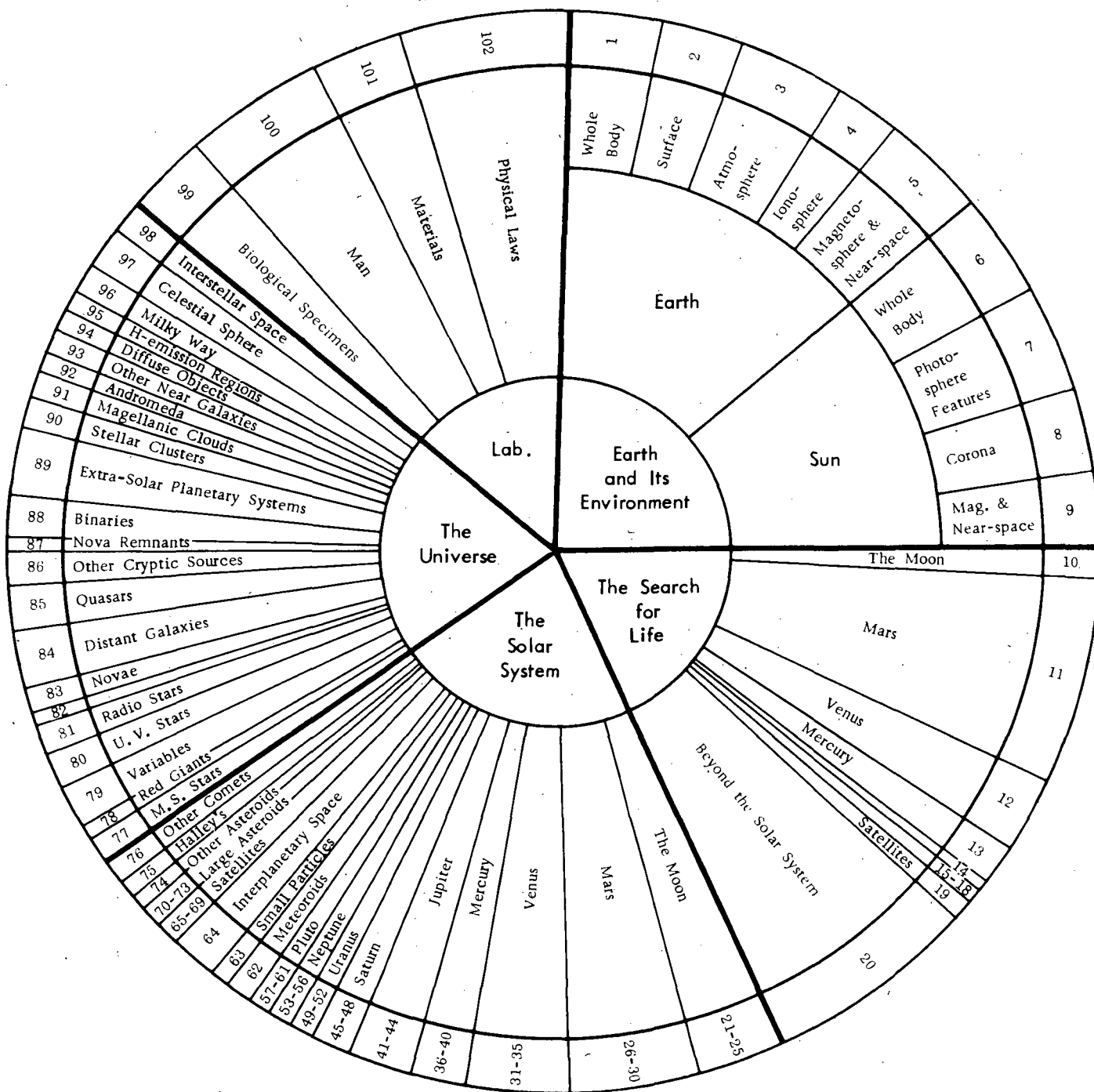


Table 4.2

A RELATIVE VALUE SCALE FOR SPACE EXPLORATION

<u>Inner Solar System</u>	<u>50.0%</u>	
Mars	30.0	
Venus	12.0	
Mercury	8.0	
<u>Outer Solar System</u>	<u>50.0%</u>	
Jupiter	17.0	(34.0%)
Saturn and Rings	12.0	(24.0)
Uranus	2.5	(5.0)
Neptune	2.5	(5.0)
Pluto	2.0	(4.0)
Meteorites	1.1	(2.2)
Small Particles	1.1	(2.2)
Large Asteroids	2.0	(4.0)
Other Asteroids	1.0	(2.0)
Halley's Comet	1.8	(3.6)
Other Comets	3.6	(7.2)
Interplanetary Space	3.4	<u>(6.8)</u>
		100.0%

Table 4.3

SAMPLE RELATIVE VALUES FOR PLANETARY EXPLORATION MISSIONS

	Relative Target % Value	Mission % Value	Relative Mission Value
Encke Rendezvous	3.6	30	108
Venus Radar Mapper	12.0	25	300
Mars Semiautonomous Rover	30.0	40	1200
Mercury Orbiter	8.0	30	240
Saturn Orbiter/Probe	12.0	40	480
Asteroid Rendezvous (Vesta) (large ast.)	1.0	60	60
Halley Flyby	1.8	30	54
Jupiter Orbiter	17.0	40	680
U/N (Uranus Probe)	2.5,2.5	40,30	175
Uranus Orbiter/Probe	2.5	40	100
Venus Large Lander	12.0	40	480
Neptune Orbiter/Probe	2.5	40	100
Jupiter/Pluto Flyby	17.0,2.0	10,40	250
Ganymede Orbiter/Lander	17.0	20	340
Mars Surface Sample Return	30.0	40	1200
Halley Rendezvous	1.8	70	126
S/U/N (Uranus Probe)	12.0,2.5,2.5	10,10,10	170
0.1 AU Solar Probe	3.4	50	170
Saturn Rings Probe	12.0	20	240
Ceres Surface Sample Return	20.0	75	150
Phobos/Deimos Surface Sample Return	30.0	10	300

4.8 Assignment of Total Value to Program

To decide whether a given mission should be performed, we must compare its value to its cost and reject those missions whose values do not exceed their costs in a given planetary exploration strategy. This undertaking requires a step beyond the assignment of relative values to proposed missions--namely, the translation of these relative values to a dollar scale. There are at least two approaches, which can be described as "top-down" and "bottom-up." The top-down approach requires establishing the total value of space exploration. It can be compared to establishing a space exploration endowment fund, the interest and appreciation from which can be used to perform missions. Missions can only be pursued that are feasible within the income stream of the endowment. The overall size of the fund is the total value of all of our objectives in space, as they are viewed at the time the fund is established. The relative values of various space targets such as those shown in Table 4.2 correspond to percentage shares of the initial principal of the fund.

It is clear that in reality both the total value and relative values of space exploration change in response to the political, economic, and technological climate of the times. Thus, the value of sending additional Apollo missions to the moon after the first moon landing changed not only because the political impact of being first to the moon was past, but also because the economy had turned down and because the technical impact was no longer unique. We mean to imply here a total value assignment that incorporates all of these realities--both direct and indirect value.

One way of assessing total program value is to assign an average annual value (such as is represented by budgetary constraints) and to determine the present value of that amount received every year for the foreseeable future. Using several discount rates, various present values corresponding to a constant annual amount will be obtained, so this method places high emphasis on determining the proper discount rate for NASA planning. Although this issue has been examined,¹⁹ it has certainly not been settled.

For a discount rate D , the present value of receiving a constant annual amount, V , forever is:

$$V + \frac{V}{(1 + D)} + \frac{V}{(1 + D)^2} + \dots = V \left(\frac{1 + D}{D} \right)$$

so that discount rates of 5% and 10% correspond to present values of 2100% and 1100%, respectively, of the annual amount. The total present value implications of several annual budget levels^{28, 29} at different conceivable discount rates are shown in Table 4.4.

Table 4.4

PRESENT VALUES CORRESPONDING TO VARIOUS
ANNUAL BUDGET LEVELS AND DISCOUNT RATES
(Millions of Dollars)

Annual Budgets	Effective Discount Rates			
	2%	3%	5%	10%
\$400	\$20400	\$13720	\$8400	\$4400
250	12750	8600	5250	2750
100	5100	3430	2100	1100
50	2550	1720	1050	550

It is evident that the relationship between annual budgets, discount rates, and present value is fairly sensitive to the choice of rate--so sensitive in fact that this method is best used as a consistency check on the values implied by the indirect method defined below.

Since most people find it difficult to think in terms of such quantities as the total value of space exploration, an indirect conceptual procedure has been devised to deduce the total value from the relative value scale and projected mission costs. This approach is the bottom-up approach. Value is defined as the maximum cost one would be willing to spend to accomplish a mission successfully. Note that if a less expensive way to accomplish the same mission becomes available, it should not reduce the value of the mission, but only increase our desire to accomplish it--as measured by the mission profit. Thus, the approval of missions by NASA management and Congress is taken as a statement that their value exceeds their cost. In fact, since all missions have a finite chance of failing, approval should imply that their value exceeds their cost by enough of a margin (profit) so that the expected profit of the mission exceeds zero (see Appendix A). Therefore, this indirect procedure begins by assuming that together NASA management and Congress reflect national values implicitly through their approval cycle.

Next, this procedure assumes that relative values, or relative effectiveness ratings, can be explicitly assigned to a set of planetary mission outcomes as was done in the previous section. Then, the cost of the least cost-effective mission in an approved set of missions defines a lower bound of the values of missions in that set. At this point an assumption is made that should be generally acceptable to NASA planners,

namely that mission designers and planners are striving to design optimal missions in the sense of achieving the highest value for the lowest cost. Effectively, this assumption says that NASA hires talented people who are doing a conscientious job. Given this condition, it follows that for an optimally designed and maximal approvable mission set, the least cost-effective mission is the last mission that is "socially profitable." Therefore the Value (last included mission) less the Cost (last included mission) must be approximately zero.

In this way, the difficult overall total value judgment is avoided and replaced by a judgment on how large a planetary exploration program with a known cost structure is "approvable." The total value then follows from mission costs and relative values. This procedure would appear to tie the values strongly to the costs. A more careful consideration, however, shows that this is not so, because if the total cost could be reduced by 25%, some additional missions would probably be flown. The total value of planetary exploration is most closely reflected by the budget constraints placed on that part of the space program; the job of mission planners is to accomplish the largest number of valued objectives within the overall total value constraint.

Figure 4.3 shows the missions of Table 4.3 plotted in a mission benefit versus mission cost plane. The costs used are those corresponding to the individual mission-dependent spacecraft design concept (exclusive of propulsion system costs). To evaluate the total program profit implied by different approvable mission sets (here for illustration APC extended, APC base, or von Braun), we shall use the right triangle construction shown in Figure 4.4. Let λ be the dollar value assigned to the accomplishment of one point on the scale of Table 4.3 (10,000 points equal total accomplishment of our planetary exploration objectives). Furthermore, let B be the expected benefit of the mission and C be its total cost. Then λB is the dollar value of accomplishing the mission under consideration, and hence $\lambda B - C$ is the profit of that mission.

Since B is the height of the right triangle shown and λB the base, it follows that the slope of the hypotenuse is given by $B/\lambda B = \lambda^{-1}$ (opposite side divided by adjacent side). This result can be visualized geometrically as shining a light beam across the figure from the direction of the upper right-hand corner, so that the rays of the beam have the slope λ^{-1} . The expected profit for the mission is determined by the shadow of the mission point on the expected cost axis, with profit increasing to the left.

If we shine the light beam on all of the mission points simultaneously, as in Figure 4.5, the shadows of the points on the expected cost axis give the expected profit for each mission. The mission with the

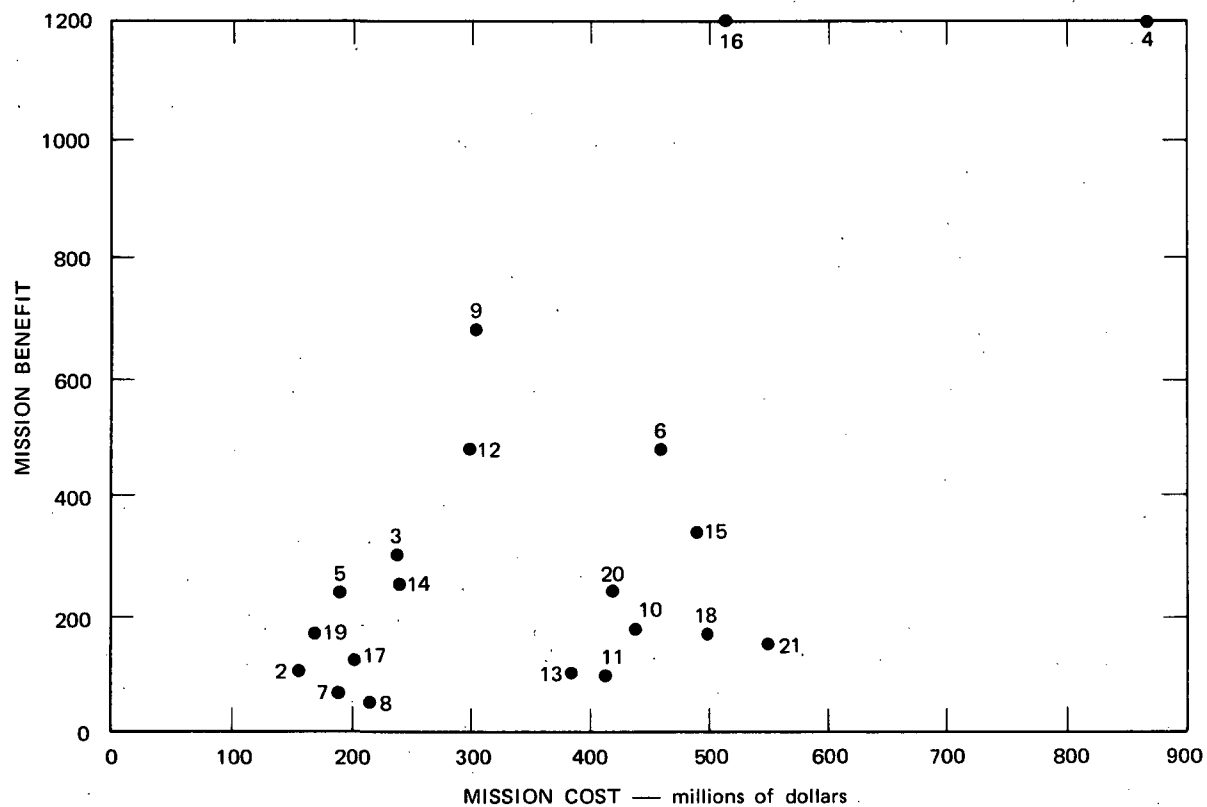


FIGURE 4.3 BENEFIT-COST PLOT FOR APC EXTENDED MISSIONS

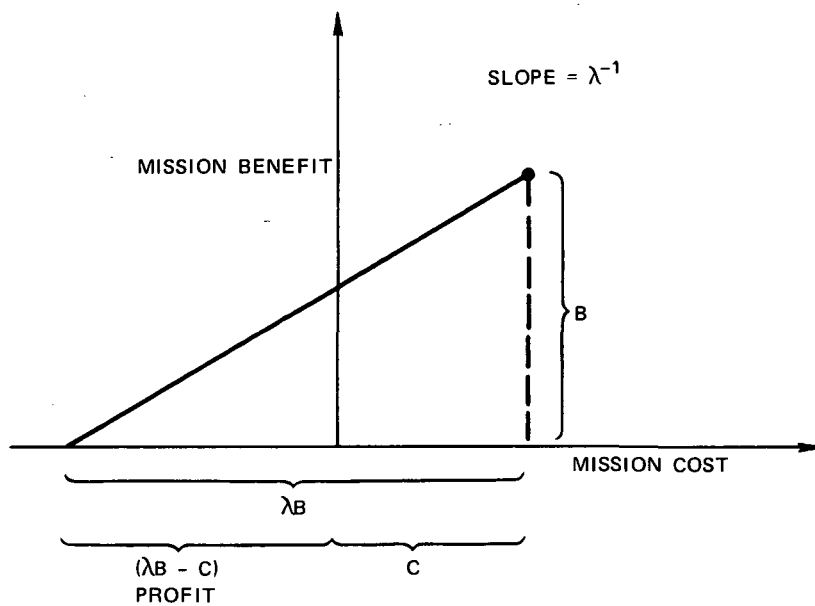


FIGURE 4.4 CONSTRUCTION OF MISSION PROFIT

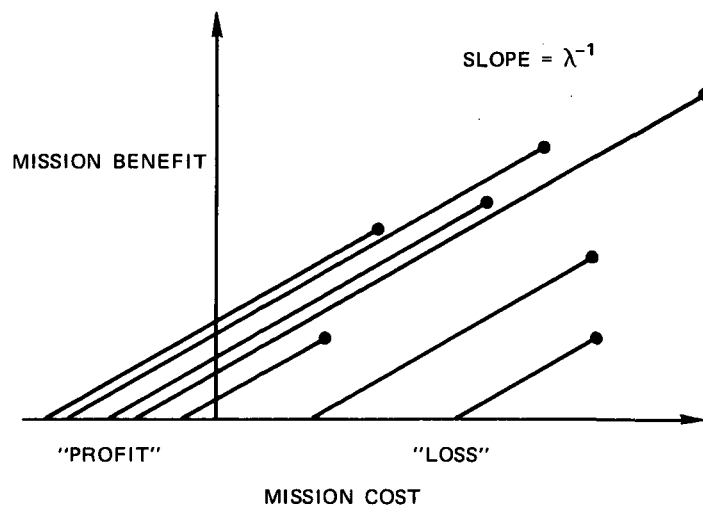


FIGURE 4.5 SHADOWS OF MISSION POINTS

leftmost shadow is the mission of maximum profit. As the slope λ^{-1} of the light beam increases, lower cost missions will have the leftmost expected profit shadow; as the slope of the light beam decreases the higher benefit, higher cost missions will have the leftmost expected profit shadow. The geometry of this problem shows that sweeping the slope of the light beam from vertical to horizontal is equivalent to sweeping λ from zero to infinity.

If a mission belongs to an approvable set, then we assume that it is profitable. Only missions whose shadows fall to the left of the origin have positive values of profit. Thus for an entire set to be approvable, the slope λ^{-1} must be so small that the shadows of all the mission points in their benefit-cost plane lie in the "negative cost" (i.e., positive profit) region of the cost axis. For λ^{-1} to be small, the total dollar value measure λ must be large.

A simple algorithm to identify the maximum slope λ^{-1} --and hence the minimum total value--which will allow all missions to be profitable is to look for the mission with the smallest ratio of benefit to cost. Geometrically, the lowest benefit to cost ratio belongs to the first mission point intercepted by a radial line through the origin making an angular sweep beginning from the positive cost axis. If missions 8 and 11 (which have the lowest benefit to cost ratio) are profitable, then the slope λ^{-1} must be less than the ratio of their benefit points to their mission costs, e.g., 100/\$0.406 billion. Thus the total value, $10,000\lambda$, must be larger than \$40.6 billion if mission 11 is to be profitable under these crude assumptions.

The dollar value scale that emerges from this procedure is shown in Table 4.5, which exhibits a run of the base case for Centaur and NEP, using the relative value of Table 4.3 with missions 8 and 11 just barely profitable. With this value structure, the missions of highest profit are 16, 4, 9, 12, and 6, which means that any strategy option incapable of performing one of these missions will show a severely reduced profit. This case also shows most of the extended APC missions, namely 17-21, to be more profitable than missions 7, 8, 11, and 13 of the APC base mission set. So either the relative target values and percentage mission accomplishments at target should be revised, or certain of the extended missions should be interchanged with less profitable missions in the base set. Likewise missions 14-16 of the APC base mission model appear more profitable than missions 2, 7, and 10 of the von Braun model. A similar inconsistency obtains here.

Table 4.5

DETERMINISTIC MODEL OUTPUT USING RELATIVE VALUE SCALE OF TABLE 4.3
(WITH LEAST COST EFFECTIVE MISSION DEFINING TOTAL VALUE OF SPACE EXPLORATION)

ALL MISSION SUMS			PROP. SYS.	912.98	S/C	6652.00	OPNS.	421.29
SHUTTLES	388.50							
TOTAL COSTS								
MISSIONS	8374.77	NEP DEVEL.	504.00	PROGRAM	8878.77			
MISSION	PS	PS COST	DELTA(<#2)	VALUE	- COST	=	PROFIT	
2	CENT	32.30	6.38	538.12	211.30		326.82	
3	CENT	16.16	12.32	1494.79	274.16		1220.63	
4	CENT	13.72	7.86	5979.16	893.22		5085.94	
5	NEP	35.44	*****	1195.83	244.44		951.39	
6	NEP	39.18	3.32	2391.67	520.18		1871.49	
7	CENT	21.20	4.99	298.96	233.20		65.76	
8	CENT	15.80	6.58	269.06	251.80		17.26	
9	NEP	31.68	1.67	3388.19	355.68		3032.51	
10	NEP	49.98	34.22	871.96	507.98		363.98	
11	NEP	53.58	*****	498.26	480.58		17.68	
12	CENT	16.76	6.70	2391.67	337.76		2053.91	
13	NEP	63.18	*****	498.26	469.18		29.08	
14	CENT	54.50	1.48	1245.66	315.50		930.16	
15	NEP	64.98	*****	1694.10	575.98		1118.12	
16	NEP	35.91	*****	5979.16	560.41		5418.75	
17	NEP	34.80	*****	627.81	250.80		377.01	
18	NEP	55.98	18.02	847.05	576.98		270.07	
19	NEP	26.55	*****	847.05	217.55		629.50	
20	NEP	54.18	*****	1195.83	495.18		700.65	
21	NEP	42.39	*****	747.40	602.89		144.51	
MISSIONS FLOWN	20	NEP	MISSIONS 13	TOTAL PROFIT			24625.23	

One explanation for this apparent inconsistency might be that technical feasibility has been intermingled with actual value in determining these mission sets. These observations highlight the most useful role of an explicit value model, namely uncovering apparent inconsistencies in our proposed allocation of resources. Subsequent examination of the issues may lead to a better value model, or even to a better set of missions. In any case, the explicit value model plays an important role in simplifying communication and identifying difficulties in an otherwise very complex area.

The sensitivities to NEP specific weight and unit cost resulting from this relative value model would be exactly the same in Tables 3.8-3.10, unless certain missions could not be performed. In such cases, this value model would produce a larger or smaller sensitivity according to whether the total profit of the missions eliminated were larger in Table 4.5 or in Table 3.7. For example, since 120 kW NEP cannot accomplish mission 12 using multimission modular spacecraft design, this combination of alternatives would show a \$2 billion profit reduction with this relative value structure because of the loss of mission 12. The very interesting results of how this relative value structure affects the profitability of NEP as opposed to other advanced propulsion alternatives are explored in Chapter V.

V DETERMINISTIC DECISION ANALYSIS

5.1 Examination of NEP Alternatives

This chapter is devoted to illustrating how the deterministic model and value structure described in the previous chapters can be applied to propulsion decision situations. Because of the incomplete status of this analysis and the very detailed parallel APC work of JPL and Mathematica most of the situations examined in this chapter are oversimplified. Nonetheless, they highlight important trends, give a quantitative expression to many previously qualitative opinions, and demonstrate the ability of our deterministic model to deal with such questions.

Table 5.1 compares the total program profit less NEP development, when both NEP and Centaur are available, to the total program profit if only the latter is available. Comparisons are made for three mission sets and three combinations of discount and inflation rate, all within the context of the equal value model used in Chapter III. Thus each entry in Tables 5.1-5.5 represents a separate model run like the NEP base case shown in Table 3.7. Note that the total program profit with NEP, less the cost of NEP development, is always greater than the total program profit without NEP, even for the highest discount rate and the smallest mission set examined. Therefore, the performance degradation encountered if only the Centaur were available for space exploration in the 1980s and 1990s is so severe that the development cost of NEP is always justified--in the absence of other advanced propulsion alternatives. Obviously, for the relative value model of Chapter IV, according to which many missions have significantly higher profits, NEP would have an even more compelling advantage. Thus, if the country had only two alternatives, to live with the Centaur only or to develop NEP (and use it whenever advantageous), we should develop NEP.

A second simple decision situation that can be examined in this way is the NEP power level decision, toward which this pilot analysis has been focused. This comparison assumes for the 120 kW NEP case that the mission-dependent spacecraft design would be used. Naturally, the 240 kW GNEP case will always be more attractive with the multimission modular design, so that is always used here. Table 5.2 shows that the higher power level appears preferable to the reference 120 kW reactor for nearly all combinations of mission sets and discount rates. Only for the highest discount rate and the two less ambitious mission sets examined does NEP

Table 5.1

TOTAL PROGRAM PROFITS WITH CENTAUR ONLY AND
WITH CENTAUR/NEP (LESS NEP DEVELOPMENT COST)
(Millions of Dollars)

		Mission Sets			Prop. Systems
		20 APC Ext.	15 APC Base	9 von Braun	
Time Preference	Discount Rate (D) Equal to Inflation Rate (I)	\$10121 5915	\$7515 5560	\$4468 4227	CENT/NEP CENT alone
	D = 10% I = 5%	\$ 4079 2393	\$3064 2384	\$1838 1706	CENT/NEP CENT alone
	D = 15% I = 5%	\$ 1723 1059	\$1304 1123*	\$ 747 741	CENT/NEP CENT alone

* The smaller mission set is more profitable since the Centaur performs one of the APC extended missions so slowly that its discounted value is significantly less than its discounted cost.

Table 5.2

TOTAL PROGRAM PROFITS WITH CENTAUR/NEP AND
WITH CENTAUR/GNEP (LESS NEP OR GNEP DEVELOPMENT COST)
(Millions of Dollars)

Time Preference	Mission Sets				
	20 APC Ext.	15 APC Base	9 von Braun	Prop. Systems	
	Discount Rate (D) Equal to Inflation Rate (I)	\$10121 10881	\$7515 7878	\$4468 4612	CENT/NEP CENT/GNEP
	D = 10% I = 5%	\$ 4079 4376	\$3064 3146	\$1838 1838	CENT/GNEP CENT/GNEP
	D = 15% I = 5%	\$ 1723 1841	\$1304 1303	\$ 747 707	CENT/GNEP CENT/GNEP

show a very small advantage over GNEP. Although such results are hardly conclusive, being based on preliminary data without any consideration of uncertainty, this table strongly suggests that a GNEP-type system should be given serious consideration if the United States resumes a program of thermonuclear reactor research.

The preceding observation may prove incorrect, however, since a two-stage tug direct escape combination with the 120 kW NEP system could probably accomplish the Venus large-lander mission and thus would make the 120 kW multimission modular combination even more attractive. The main reason why NEP does not gain full advantage of the spacecraft savings associated with the multimission modular exploration strategy is that the Venus large-lander mission is a highly profitable mission that carries a strong penalty in the form of reduced profit if it cannot be accomplished. An extension of the program logic to add the capabilities and costs of additional direct escape stages to the 120 kW NEP, when necessary, would be a significant model improvement that would facilitate a more careful examination of the relative merits of NEP and GNEP. The basis for such an extension would be calculations such as those supporting Figure 3.4 for the entire APC extended mission set.

These tables provide a quantitative expression for many of the qualitative opinions that have been expressed by engineers and managers in the NEP development program. They show clearly how the advantage of the CENT/NEP combination over Centaur alone depends on the nation's time preference for money (desire for early returns on expenditure) and on the size and structure of the planetary exploration program that is assumed to represent national goals in space. Both are value judgments that must be set by higher level decision-makers outside of the NEP program. Tables 5.1 and 5.2 show in a simple way the sensitivity of NEP program decisions to NASA preferences and values.

5.2 Comparison of NEP and GNEP with Other Advanced Propulsion Alternatives

The observations of the preceding section are limited in impact because of the recent curtailment of the U.S. Thermionic program. This limitation suggests an additional application of the deterministic model--namely, to compare the NEP and GNEP cases to other advanced propulsion alternatives such as chemical tug (TUG), 20 kW solar electric (SEP), and 40 kW solar electric (GSEP). Several points need to be made, however, before presenting any such results. First, it should be emphasized that the decision analysis was not focused on the comparison of all advanced propulsion options; that was the subject of the APC study conducted by Mathematica and JPL. However, the decision analysis model is not restricted to NEP alternatives, since the selector logic has been built

to pick out the most effective propulsion system from any available types. Therefore, it is possible to examine NEP in comparison with these other alternatives simply by inserting their flight times into the model data.

One restriction of these results on TUG, SEP, and GSEP is that no detailed study of their unit costs has been made (the unit costs used in the APC study have been taken without question) and no development costs have been incorporated into the program for systems other than NEP and GNEP. If, however, the total program profit obtained by the CENT/NEP (or CENT/GNEP) combination minus the NEP (GNEP) development cost already exceeds the total program profit of some other combination of advanced propulsion alternatives--without any allowance for the development cost of these other alternatives--then the NEP (GNEP) alternative should be clearly preferable. Another limitation of these results is that they have only considered planetary exploration missions, because the geocentric missions appeared not to influence the NEP power level decision which was the focus of this analysis. These geocentric missions, however, could be very important in comparing CENT/NEP with alternatives like CENT/TUG or CENT/SEP. This problem should be the subject of further analysis.

Table 5.3 shows the total program profits--without any development expenses--for CENT/TUG, CENT/SEP/GSEP, and CENT/TUG/SEP/GSEP. It has been assumed in these tabulations that, if SEP is available, GSEP will also be available for an additional unit cost of \$2.3 million, but with little or no additional development necessary. This situation is to be contrasted with that of the NEP; in the latter situation the thermionic community believes that even if a 120 kW NEP system were available, it would require a significant additional development and testing program to obtain a 240 kW system.

Table 5.3 shows that the CENT/NEP or CENT/GNEP alternatives are superior to CENT/TUG, CENT/SEP/GSEP and CENT/TUG/SEP/GSEP for all cases involving the assumption that the APC extended mission set reflects national planetary exploration values. For the cases in which this assumption does not hold, however, one or more of the alternatives in Table 5.3 is more profitable than the corresponding NEP alternatives in Table 5.2. Of course, if the proper development costs for the other propulsion systems in Table 5.3 were subtracted from their true operating profits, they might no longer exceed the NEP alternatives in total profit. On the other hand, there is not a situation of clear NEP dominance. Thus, a careful refinement of the total value assumptions--as reflected in the size of the mission model--is especially important in comparing the NEP alternatives with other advanced propulsion candidates.

Table 5.3

TOTAL PROGRAM PROFITS FOR CENT/TUG,
CENT/SEP/GSEP, AND CENT/TUG/SEP/GSEP
(WITHOUT ANY DEVELOPMENT COSTS SUBTRACTED)
(Millions of Dollars)

Time Preference		Mission Sets			
		APC Ext.	APC Base	von Braun	Prop. Systems
	Discount Rate (D) Equal to Inflation Rate (I)	\$8900	\$7323	\$4260	C/T
		7798	7443	4909	C/S/GS
		9582	8005	4942	C/T/S/GS
	D = 10% I = 5%	\$3531	\$2948	\$1798	C/T
		2990	2946	2037	C/S/GS
		3907	3323	2125	C/T/S/GS
	D = 15% I = 5%	\$1512	\$1290	\$805	C/T
		1278	1312	913	C/S/GS
1724		1503	966	C/T/S/GS	

To remove the problem presented by the absence of TUG and SEP development costs in our analysis, another approach is possible. We can compare CENT/TUG to CENT/TUG/NEP, and so forth, to determine whether the additional profit generated by having NEP (GNEP) available will justify its development cost. Table 5.4 is the analog of Table 5.3 adding NEP to each alternative, and Table 5.5 does the same for GNEP. All entries in these tables marked with an asterisk (*) gain enough profit from the availability of NEP or GNEP to justify the development costs shown.

These results are extremely powerful since they do not depend on the non-NEP development costs and already take NEP (GNEP) development costs into account. The tables show that if our space exploration value system is best represented by the APC extended mission set, the development of NEP (or GNEP) is profitable for any of the time preference parameters used. If the von Braun mission set is the best representative of our national space exploration goals and values, then NEP (or GNEP) should only be developed if (1) solar electric is not developed and (2) the national time preference is not as strong as that expressed by a discount rate of 15% and an inflation rate of 5%. For the APC base mission set, NEP and GNEP are generally justifiable, but not always.

To test these results, analogous model cases were examined using the relative value model discussed in sections 4.7 and 4.8. Even with this value model, NEP cannot be justified for a 10% effective discount rate using the von Braun mission model. Since the equal value model and the relative value model span a wide range of value models, this conclusion may be independent of the exact value model employed. A conclusion such as this one, which holds for a wide range of assumptions, is said to be robust. This robustness emphasizes again the importance of NASA's time preference and total planetary exploration value for the NEP development decision.

Additional comparisons of the type shown in this chapter, together with further refinement of the model logic and the deterministic data used, should be extremely rewarding in developing a quantitative intuition among JPL and NASA program managers. They can also gain a much deeper understanding of the interaction between time preference and value assumptions, on the one hand, and propulsion system development decisions in the other. The use of a simple interactive model such as the one delivered to JPL in the course of the decision analysis should complement the very detailed work of the APC study. This model allows insight to be developed via rapid feedback on the implications of many different model assumptions.

Table 5.4

TOTAL PROGRAM PROFITS WITH NEP ADDED
TO EACH PROPULSION COMBINATION OF TABLE 5.3
(Millions of Dollars)

	NEP Dev.	Mission Sets			9 von Braun	Prop. Systems
		20 APC Ext.	15 APC Base			
Discount Rate (D) Equal to Inflation Rate (I)	504	* \$10682 * 10625 * 10682	* \$8055 * 8017 8055	* \$4980 4972 4980	C/T/N C/S/GS/N C/T/S/GS/N	
		* \$4530 * 4460 * 4530	* \$3481 * 3445 3481	* \$2226 2220 2226	C/T/N C/S/GS/N C/T/S/GS/N	
					C/T/N C/S/GS/N C/T/S/GS/N	
D = 15% I = 5%	294	* \$ 2069 * 2017 * 2069	* \$1623 1598 1623	\$1046 1042 1046	C/T/N C/S/GS/N C/T/S/GS/N	

* An asterisk means that the profit increase over Table 5.3 is larger than the NEP development cost.

Time Preference

Table 5.5

TOTAL PROGRAM PROFITS WITH GNEP ADDED
TO EACH PROPULSION COMBINATION OF TABLE 5.3
(Millions of Dollars)

	NEP Dev.	Mission Sets			9 von Braun	Prop. Systems
		20 APC Ext.	15 APC Base			
Discount Rate (D) Equal to Inflation Rate (I)	\$556	\$11642 * 11467 * 11660	\$8634 * 8464 * 8652	\$5289 * 5198 5306	C/T/GN C/S/GS/GN C/T/S/GS/GN	
D = 10% I = 5%	\$422	\$4873 * 4828 * 4894	\$3643 * 3598 3664	\$2318 * 2287 2337	C/T/GN C/S/GS/GN C/T/S/GS/GN	
D = 15% I = 5%	\$328	\$2215 * 2193 * 2235	\$1677 * 1655 1697	\$1071 1056 1085	C/T/GN C/S/GS/GN C/T/S/GS/GN	

* An asterisk means that the profit increase over Table 5.3 is larger than the NEP development cost.

5.3 The Timing Decision for NEP Development

Our analysis has not focused on the optimal timing for the NEP development program. This section discusses how the deterministic model can be used to gain insight into this question. Both model revisions and data refinements would be necessary to make a definitive study of whether a development program for a 1983 launch or a slower program, such as for a 1986 launch, would be more consistent with our space exploration preferences.

A NEP development program geared for a 1983 launch has been used as our reference case since a great deal of thought has been given to using NEP for a Halley's comet rendezvous. Many NASA studies and pronouncements have acknowledged high scientific interest in such a mission. NEP is the only propulsion system under consideration that could accomplish a rendezvous--as opposed to a short-encounter flyby--with this comet, which only enters our environment every 75 years. Thus, if we do not accomplish a rendezvous with Halley's comet during its next visit in 1986, the value of this accomplishment can be considered lost to our generation for any realistic choice of discount rate (e.g., a 5% discount rate over 75 years reduces the present value of a delayed accomplishment to about 3% of the value that it could achieve today).

For both NEP and GNEP, the deterministic model currently has development cost streams for 1983 and 1986 launch years. In each case, the preliminary opinion of thermionic experts was that the longer development program would be about \$50 million less expensive. Whereas this projection has not been examined in detail, it implies that 10 years is too short a time in which to develop a reliable NEP system with minimal resources and that 13 years allows more flexibility to overcome potential program problems without being faced with large unforeseen expenditures.

The existing deterministic model logic does not check the development program against the mission set to see whether NEP would be available between 1983 and 1986. It is simple, however, to make these adjustments to the model outputs, such as that shown in Table 3.7. There are three types of adjustments to be made. First, if NEP is not available by 1983, then the profit of the Halley rendezvous is lost, so the total profit must be reduced by the profit of that mission, number 17. For all other missions with launches scheduled between 83 and 86, the launch can either be delayed until NEP is available or the second best propulsion system--if any--can be used in the originally scheduled launch year. Using equal discount and inflation rate, there is no penalty for delayed achievements, so we would always prefer to wait for a less expensive propulsion system. In the more realistic case where the discount rate exceeds the inflation

rate, the profit reduction resulting from a delayed launch because of discounting must be compared with the profit reduction resulting from employing a propulsion system with a higher effective cost.

For the APC extended mission set using a 10% discount rate and 5% inflation rate, the changes to the base case run are as follows. If NEP is not available until 1986, the Halley rendezvous mission is lost, reducing profit by \$358 million. Six other missions scheduled to be launched before 1986 need to be postponed or launched with Centaur instead of NEP. The profit impact is minimized by launching mission 2 with Centaur instead of NEP, at a loss of \$18.5 million, and delaying the launch of missions 5, 6, 9, 18, and 19 until 1986 when NEP is available, at a loss of \$88 million. Thus, the total profit reduction under these conditions resulting from a three-year NEP development time increase to 1986 is \$465 million. This reduction should be compared with the cost savings of the slower development program which has a present value of \$78 million.

If the discount rate is assumed to equal the inflation rate, no penalty is assigned to delayed accomplishments, so the loss of the profit from the Halley's comet mission should be the only penalty for delaying the development of NEP. This case alone amounts to \$699 million, using the equal value model (and \$377 million using the relative value model of Chapter IV), which would dominate the \$50 million development cost savings of the slower development program. If there is no penalty for delaying accomplishments, however, we should be indifferent to performing the Halley's rendezvous in 1986 or in 2061 when it will next return. The absurdity of this statement indicates that we do have a preference for earlier accomplishments. Therefore, we should be using some discount rate, however small. Furthermore, without an expression of time preference, the entire issue of faster versus slower development programs is meaningless and impossible to address.

For the two smaller mission sets, a slower development program appears to be appropriate, but for any mission set including the Halley's comet rendezvous, the cost savings are negligible compared with the profit lost. In this way, the model can be used to provide a quantitative expression to the value of a Halley's rendezvous mission in terms of potential development savings that could be obtained only by foregoing this mission. Such a study should begin by a careful comparison of the two development cost streams.

VI CONCLUSIONS

The objective of this effort was to develop a logical procedure for selecting NEP development alternatives that reflect technical feasibility, JPL/NASA project objectives, and the economic environment of the project. This report has presented the partial evolution of a decision model from the underlying philosophy of decision analysis to a deterministic pilot phase which is responsive to these requirements. The general manner in which this decision model can be employed to examine propulsion development alternatives, as well as the way in which it can be used to answer more specific questions, such as which propulsion systems to use on which missions, has been illustrated in the previous sections.

6.1 Steps Necessary To Complete This Analysis

The decision analysis project was terminated close to the conclusion of the deterministic phase, but prior to a critical aspect of it--namely, presentation of the deterministic analysis to JPL and NASA management. Such a presentation would stimulate their review of the data used, the model structure, and the pilot level assumptions. The data, logic, and assumptions pertaining to NEP development should be reviewed by thermionic specialists, whereas appropriate choices for JPL/NASA time preference and value structure need to be reviewed at a higher level. Exercising the deterministic model so far has given insight into which types of decisions might change in response to different assumptions.

After presenting tentative results of the deterministic analysis, some improvements in data, model structure, and assumptions would no doubt be forthcoming and should be incorporated in the analysis. Some capability for analyzing the effect of TFE lifetime should also be added to the model. At this stage, final sensitivities should be run, simplifications made in the model wherever possible, and crucial variables selected for the probabilistic analysis, in conjunction with JPL/NASA experts. This effort would complete the deterministic phase.

The deterministic analysis undertaken thus far indicates that the size of mission set chosen, the discount rate used, and other factors can change the relative attractiveness of NEP versus GNEP, as well as alter the attractiveness of NEP or GNEP relative to nonnuclear advanced propulsion alternatives. Thus, in all likelihood, the analysis would continue

into a probabilistic phase in which the uncertainty in crucial variables would be explicitly considered. The steps are described in Task III of SRI's proposal to JPL.¹⁴

Some modifications of the model would be needed at this stage, specifically to incorporate the probability of failure for various propulsion system and stage combinations. It is likely that the SRI decision tree programs would be used to extend the analysis to accommodate these probabilistic features. This approach would allow us to choose the best alternative with the various failure modes taken into account.

After encoding the uncertainty in the crucial variables, a probability distribution on the net present worth of the various alternatives will be derived. To evaluate the certain equivalent of a probability distribution on worth, techniques to include risk aversion may be needed if JPL/NASA decision-makers do not want to be expected value decision-makers, i.e., to play the averages. If not, the appropriate risk attitude must be determined and incorporated in the analysis. The concept of risk attitude and its consistent application throughout space program planning should be of great importance to NASA. Risk attitude as it pertains to space applications has been discussed in Appendix A.

Having expressed the data in probabilistic form, extended the model to a probabilistic structure, and encoded JPL/NASA risk attitude, the probabilistic analysis would recommend the superior development alternatives. Furthermore, value of information calculations, which are made possible by the probabilistic form of the data, would be performed to provide insight into whether to proceed immediately with a development alternative or to gather additional information through research before being committed to a particular NEP design.

A possible refinement to this model would be to include more of the advanced propulsion alternatives at a greater level of detail. This step might require models of propulsion system performance, such as the payload versus flight time curves shown for NEP in Figures 3.3 and 3.4. A rapid turnaround or even interactive model would be provided to complement the detailed runs of the APC study. The work could also be reoriented toward determining whether we should reconsider nuclear electric propulsion in the future by extending the analysis of Section V.

Of course, there is no such thing as a "final analysis" (in the sense of ultimate refinement); there are only decisions that the analysis supports. The degree of refinement of the analysis must be economic in terms of the resources to be allocated by the decision. The analysis presented here has not yet reached that level. Its purpose is to show

the feasibility of the approach. The amount of resources already spent in examining advanced propulsion concepts provides an idea of a reasonable amount that could be devoted to a decision analysis of the entire project.

6.2 Future Use of Decision Analysis by NASA and Other Agencies

Decision analysis in principle is applicable to any decision-making problem. It is economic to apply it only to problems concerning the allocation of significant amounts of resources. Thus, its use is especially appropriate for NASA and other governmental agencies. The potential for application at NASA is especially high because, by the nature of NASA's work, its staff has high analytical capability, and therefore should be receptive to the decision analysis approach and capable of putting it into practice.

The principles of decision analysis bear reiteration in this context. The discipline of decision analysis provides a language and philosophy for approaching any decision problem, as well as logical and quantitative procedures for implementing this philosophy. Both of these aspects are important in their own right, and together they provide a powerful aid to the decision-making process.

The existence of the language allows us to be precise in specifying the many factors that influence a decision. The most important features of the language are its ability to represent the uncertainties that inevitably infest a decision problem, as well as the values and preferences being used by decision-makers.

In representing uncertainty, the language of probability is used, which allows specification of our initial information regarding the uncertainties and the incorporation of new information as it is produced. There is no need for vagueness in the language that describes uncertainty--admitting our ignorance is the first step to new knowledge.

Placing values and preferences in unambiguous terms is equally important in describing a decision problem. By values, we mean the desirability of each outcome; by preferences, we mean the attitudes of the decision-maker toward temporal postponement or uncertainty in the outcomes he receives.

Decision analysis provides both philosophical and operational guidelines for the delegation of responsibility and transmittal of information in an organization. If we wish someone to make an effective decision, we

must provide him not only with a description of the problem, but also with the values and preferences that are relevant to the decision. If these quantities can be stated explicitly, we can ensure that everyone in the organization is acting consistently with them. For example, we can ensure that everyone is acting consistently (i.e., with the same state of information) regarding the probability of life in the solar system, or the probability that a given device will operate properly, as well as in assigning value to such things as scientific knowledge, national prestige, and the loss of human life.

Many sources of confusion and differences can be resolved, or at least focused, when we are able to use unambiguous terms. People who differ over the best alternative to follow may find that their disagreements lie in the areas of probability assignments, values, or preferences. Thus, two persons who are equally willing to take a risk may disagree because they assign different probabilities to various outcomes; or two persons who assign the same probability to the outcomes may differ in their aversion to risk. The formal language of decision analysis provides the means by which the real nature of disagreement can be uncovered.

Since decision analysis encodes information, values, and preferences in terms of hard numbers, it allows the use of logical and quantitative procedures as an analytical aid to the decision-making process. Many techniques have been developed to implement these analyses, such as the decision tree programs discussed in the Voyager report.⁵ Of course, the accurate formulation of problems in quantitative terms permits and stimulates the development of new techniques for solution. The decision analysis procedure provides documentation of the state of information at any stage of the problem and determines whether the gathering of further information is economically justifiable.

In new applications, aspects of decision analysis not utilized in this work may become important. The planning of other space projects is likely to be similar in concepts and techniques to the problem of advanced propulsion for planetary exploration presented here. The move to the next higher level--that is, the allocation of resources between different NASA divisions--is likely to require additional considerations. Ultimately, we hope to see the application of decision analysis to the problem of allocation among various governmental programs. This of course will require an understanding and acceptance of this new discipline on a broad scale.

REFERENCES

1. R. A. Howard, "Decision Analysis: Applied Decision Theory," Proceedings of the Fourth International Conference on Operational Research (1966), D. B. Hertz and J. Melese, eds. (John Wiley and Sons, New York, 1968).
2. J. E. Matheson, "Decision Analysis Practice: Examples and Insights," OR 69: Proceedings of the Fifth International Conference on Operational Research, John Lawrence, ed. (Tavistock Publications, London, 1970).
3. J. E. Matheson, "The Economic Value of Analysis and Computation," IEEE Transactions on Systems Science and Cybernetics, Vol. SSC-4, No. 3, pp. 325-332 (September 1968).
4. J. E. Matheson and W. J. Roths, "Decision Analysis of Space Projects: Voyager Mars," presented at National Symposium: Saturn/Apollo and Beyond, American Astronautical Society (11 June 1967).
5. J. E. Matheson and A. B. Pollard, "A New Approach to Space Project Planning: Decision Analysis of Voyager," Final Report, SRI Project 6152, prepared for General Electric Company Missile and Space Division (December 1967).
6. SRI Decision Analysis Group, "Decision Analysis of Nuclear Plants in Electrical System Expansion," Final Report, SRI Project 6496, prepared for the Comision Federal de Electricidad, Mexico City (December 1968).
7. R. A. Howard, J. E. Matheson, and D. W. North, "The Decision to Seed Hurricanes," Science, Vol. 176, pp. 1191-1202 (1972).
8. D. W. North, "Decision Analysis of Wild Land Fire Protection: A Pilot Study," presented to California State Board of Forestry, Riverside, California (16 January 1973).
9. E. Stuhlinger, Ion Propulsion for Space Flight (McGraw-Hill, New York, 1964).

10. J. F. Ingber and D. T. Higdon, "Reactor Requirements for First Generation Thermionic Nuclear Electric Propulsion," AIAA Paper 69-250, 7th Electric Propulsion Conference, Williamsburg, Virginia (March 1969).
11. J. F. Mondt, C. D. Sawyer, and R. W. Schaupp, "Thermionic Reactor Electric Propulsion System Requirements," JPL TM 33-549 (June 1972).
12. R. W. Schaupp and C. D. Sawyer, "Propulsion System Requirements for a Multi-Mission Nuclear Electric Spacecraft," AIAA Paper 72-503, 9th Electric Propulsion Conference, Bethesda, Maryland (April 1972).
13. R. W. Schaupp, J. F. Mondt, and A. M. Nakashima, "Thermionic Reactor System Application to Electric Propulsion Missions," presented to American Nuclear Society Meeting, Washington, D.C. (November 1972).
14. J. E. Matheson and M. M. Menke, "A Decision Analysis of Thermionic Reactor Development for Nuclear Electric Propulsion," SRI Proposal MSD-72-25, prepared for the Propulsion Division of JPL (2 March 1972).
15. "Advanced Propulsion Comparison Study: Phase I Report, Planetary Mission Sections," JPL (November 8, 1972). SRI has access only to this material. Subsequently in April 1973, Vols. I and II of Phase II were also published by JPL. We have not had the benefit of seeing any Phase II results during the course of our work.
16. D. J. Spadoni, "Advanced Mission Applications of Nuclear Electric Propulsion," IIT Research Institute Report T-31, prepared for Office of Space Sciences, NASA, under contract NASW-2144 (July 1972).
17. See Reference 15, Chapter VII, "Description of Spacecraft and Payload Systems," Part A on Planetary Spacecraft, Section 4.
18. A. B. Pollard, "A Normative Model for Joint Time/Risk Preference Decision Problems," Stanford University Ph.D. Thesis, 1969 (University Microfilms, No. 70-10, 509).
19. K. P. Heiss and O. Morgenstern, "Economic Analysis of the Space Shuttle System," prepared for NASA under contract NASW-2081 (31 January 1972). See especially section 3.3.1.
20. See the payload versus flight time curves in Appendix 2 of Reference 15. See also J. C. Niehoff and A. L. Friedlander, "Planetary Performance Analysis for Advanced Propulsion Comparison (APC) Study," IIT Research Institute Report T-33 (October 1972).

21. See Reference 15, Chapter VII, Table VII.A.2-3.
22. See Reference 15, Appendix 1, Part 14.
23. J. F. Mondt, "Development Program Costs for 120 and 240 kWe NEP Systems," unpublished table dated Nov. 29, 1972.
24. See Reference 15, Chapter IV, "Performance Comparisons," especially Table IV.A.1-1 and Figures IV.A.1-5 and 6.
25. S. H. Dole et al., "Methodologies for Analyzing the Comparative Effectiveness and Costs of Alternative Space Plans," RAND Memorandum RM-5656-NASA (August 1968).
26. J. P. Hennes and C. V. Fulmer, "Identifying Relevant Scientific Goals in Planetary Exploration," *Journal of Spacecraft*, Vol. 9, No. 3, p. 205 (March 1972).
27. See Reference 25, Vol. I, p. 12.
28. Space Science Board, National Research Council, Priorities for Space Research 1971-1980 (National Academy of Sciences, Washington, D.C., 1971).
29. Space Science Board, National Research Council, Outer Planets Exploration 1972-1985 (National Academy of Sciences, Washington, D.C., 1971).
30. R. A. Howard, "Risk Preference," unpublished (1970). Available from SRI.
31. See Reference 15, Chapter IX, Section A on "Risks."
32. See Reference 5, pp. 291-295.
33. Space Science Board, National Research Council, Space Research: Directions for the Future, Vols. I-III (National Academy of Sciences, Washington, D.C., 1965).
34. W. B. Gibson and M. M. Menke, "Meeting the Challenge of an Age of Uncertainty," to be published in 1973 Presidential Issue of Handling and Shipping.
35. J. von Neumann and O. Morgenstern, Theory of Games and Economic Behavior (Princeton University Press, Princeton, N.J., 1953).
36. H. Raiffa, Decision Analysis: Introductory Lectures on Choice Under Uncertainty (Addison-Wesley, Reading, Massachusetts, 1970).

37. C. S. Spetzler, "Establishing a Corporate Risk Policy," AIIE 1968 Proceedings.
38. C. S. Spetzler, "The Development of a Corporate Risk Policy for Capital Investment Decisions," IEEE Transactions on System Science and Cybernetics, Vol. SSC-4, No. 3 (September 1968).

Appendix

MEASURING THE VALUE OF RISK REDUCTION

Appendix

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Decision analysis carefully distinguishes between uncertainty³⁴--which is expressed by the probabilities of future events--and risk--which comprises both the probabilities and the consequences of future events. Thus, uncertainty can be expressed for any important variable of the problem, whereas risk is an appropriate concept only for the uncertainty in the program outcomes. These outcomes are the factors that will determine the ultimate worth of the program and typically take the form of corporate or "national" profit.

For example, consider a planetary exploration mission. If the spacecraft fails to reach its target or reaches its target but returns no information (e.g., because of radio failure), then the cost of the mission is lost and nothing of value is accomplished. In this case, the national profit is negative, specifically the negative of the mission cost. If the spacecraft accomplishes all of its stated objectives, then some value (greater than the mission cost) is achieved and thus produces a positive national profit equal to the value less the cost. Section IV systematically explains how a value function can be developed for space exploration. Of course, intermediate outcomes with partial accomplishments also are obtained; these outcomes may or may not yield positive national profit.

Once a reasonable set of at least representative mission outcomes and the value and cost of each have been established, one would like to know the probability of each outcome. Given a complete set of outcomes (one of which will occur) together with the profit and probability of occurrence corresponding to each outcome, we have a complete description of the uncertain proposition. Such a description is called a lottery. A very general lottery is shown in Figure A.1. The term "reward" will be used in a very general way to describe either the various outcomes of the lottery or the respective profits associated with these outcomes.

Life becomes difficult when we must choose among alternative uncertain propositions, i.e., different lotteries. In order to define clearly an approach to risk, let us for the moment remove complexity from the problem by examining lotteries with only two outcomes and remove the controversial value issues by dealing in simple monetary rewards.

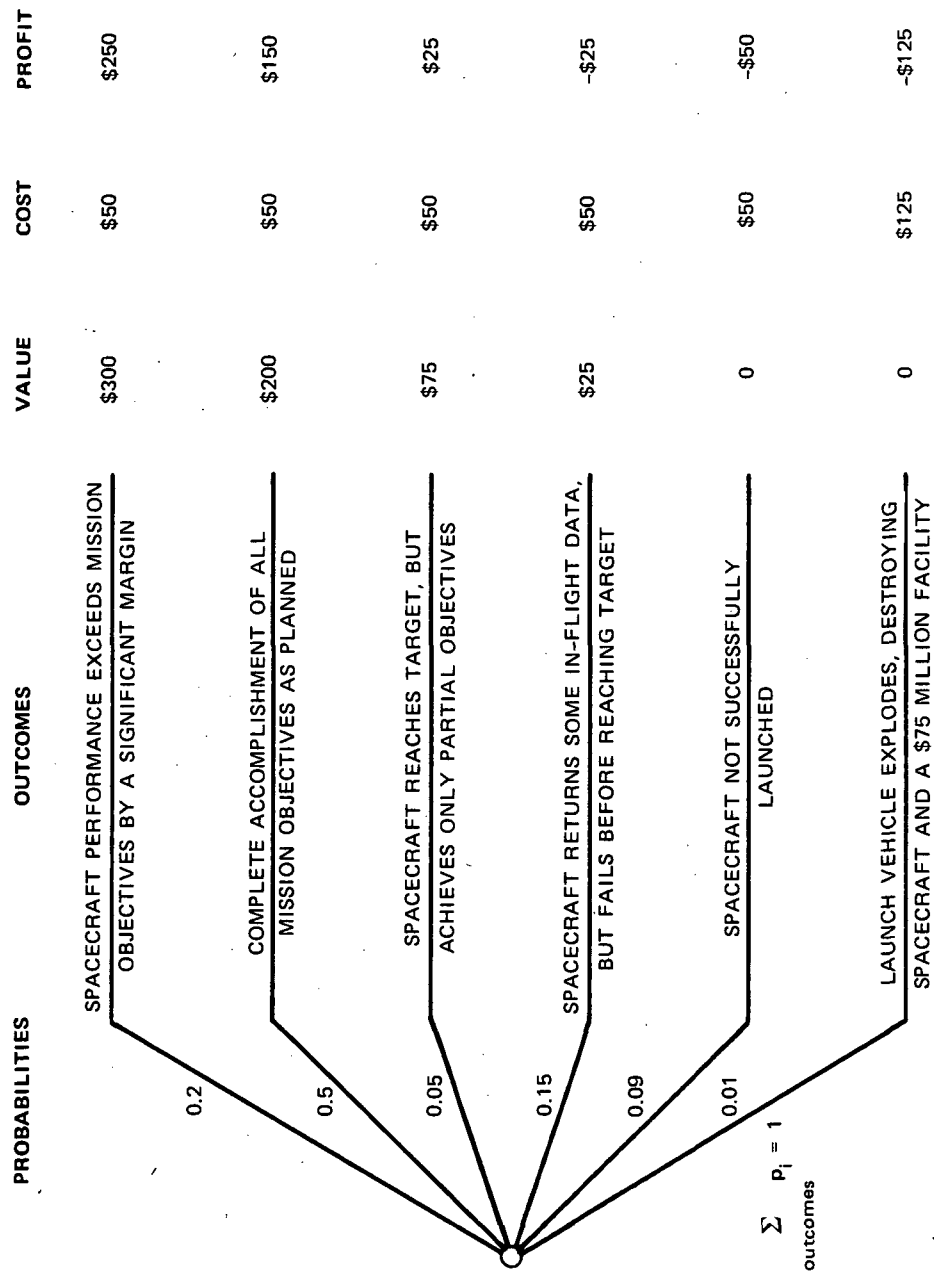


FIGURE A.1 REPRESENTATION OF SPACE EXPLORATION MISSION AS A LOTTERY
(ALL AMOUNTS IN DOLLAR MILLIONS)

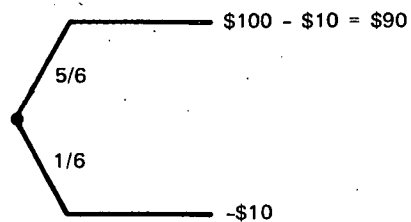
Two-outcome lotteries, where the two states can be thought of as failure and success, are a reasonable first approximation to space exploration missions.

Figure A.2 illustrates two such lotteries. If we are asked to choose one of these propositions, how should we proceed? One measure that might be considered as a basis for selecting between lotteries is the expectation, computed by multiplying the profit of each outcome by its probability and summing over all outcomes. This calculation has been performed for the two lotteries in Figure A.2. Since the rewards for the two lotteries are identical, the lottery with the highest probability of "success" has the highest expected profit. Indeed, no logical reason exists for anyone to prefer the lottery with the lower expected profit; in lotteries with equal rewards, any rational procedure will maximize the probability of success.

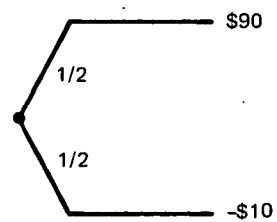
The choice between the two lotteries shown in Figure A.3, however, may be more difficult. Here, the lottery with the highest expectation also has the largest probability of failure. Although few people would hesitate to accept the risk entailed in either of these lotteries, the situation would be quite different if the losses were hundreds, thousands, or even many millions of dollars, as they might be in an unsuccessful space shot. In particular, the lotteries in this figure illustrate very clearly that uncertain propositions cannot be evaluated by their expected losses if the profits involved differ substantially. This simple example shows the problems inherent in the APC proposed definition of risk.³¹

The nature of risk is even more graphically illustrated by the two lotteries shown in Figure A.4. These have equal probabilities of failure and equal expectations, but most people would prefer the lottery with the lesser cost of failure. Here it is clear that the "spread" between the best and worst outcomes (on a meaningful value scale) is an important factor in determining the risk involved in the lottery. Generally, the less the spread, the less the perceived risk in the venture.

Given these intricate ways in which the probabilities and the rewards that define a lottery interact to generate risk, how can one develop logical and consistent procedures for choosing among uncertain propositions? The answer can be found in the theory of risk preference,³⁰ sometimes called utility theory.^{35,36} Given that an individual or an organization such as NASA may not always want to "play the averages," risk preference theory provides both procedures for assessing risk tolerance (a measure of the organization's ability to withstand losses) and ways to predict how the organization should want to choose among uncertain propositions on the basis of this risk tolerance.

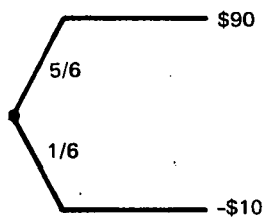


$$\text{EXPECTATION} = 5/6 \$90 - 1/6 \$10 \\ \cong \$73.3$$

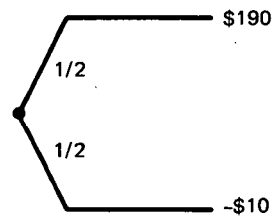


$$\text{EXPECTATION} = 1/2 \$90 - 1/2 \$10 \\ = \$40$$

FIGURE A.2 TWO SAMPLE LOTTERIES WITH EQUAL REWARDS (PROFITS), BUT DIFFERENT PROBABILITIES

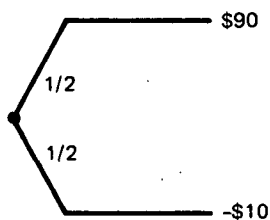


$$\text{EXPECTATION} = 5/6 \$90 - 1/6 \$10 \\ \cong \$73.3$$

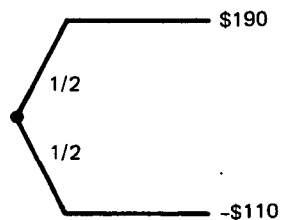


$$\text{EXPECTATION} = 1/2 \$190 - 1/2 \$10 \\ = \$90$$

FIGURE A.3 TWO SAMPLE LOTTERIES WHERE THE LOTTERY WITH THE LARGEST EXPECTED LOSS ALSO HAS THE HIGHEST EXPECTED PROFIT



$$\text{EXPECTATION} = 1/2 \$90 - 1/2 \$10 \\ = \$40$$



$$\text{EXPECTATION} = 1/2 \$190 - 1/2 \$110 \\ = \$40$$

FIGURE A.4 TWO SAMPLE LOTTERIES WITH EQUAL PROBABILITIES, AND EQUAL EXPECTATIONS, BUT WITH UNEQUAL "RISK"

The central concept of the theory of risk preference is the certain equivalent. The certain equivalent profit of a lottery, such as those shown in Figures A.2-4, is just the selling price, a "risk free" amount for which one would exchange the lottery if he owned it. In general, the certain equivalent of a lottery is less than its expectation by an amount that depends on the resources of the organization and its ability to tolerate the losses corresponding to the worst possible outcomes.

The relevance of this concept can be understood when the following question is considered: Should NASA spend an extra \$20 million on a \$50 million spacecraft and launch vehicle to reduce the probability of mission failure from 0.2 to 0.05? Two such lotteries are portrayed in Figure A.5. The mission has been given a value of \$100 million for purpose of illustration. These lotteries typify the choices offered in real life where additional safety and reliability in an already well-engineered system is usually quite expensive. Naturally there is a point of diminishing returns in procuring such refinements. Risk attitude can be an important aspect in determining just where that point is.

In Figure A.5, the additional \$20 million spent to improve mission reliability reduces the expected profit of the mission from \$30 million to \$25 million, in spite of the reduced risk of failure. However, this

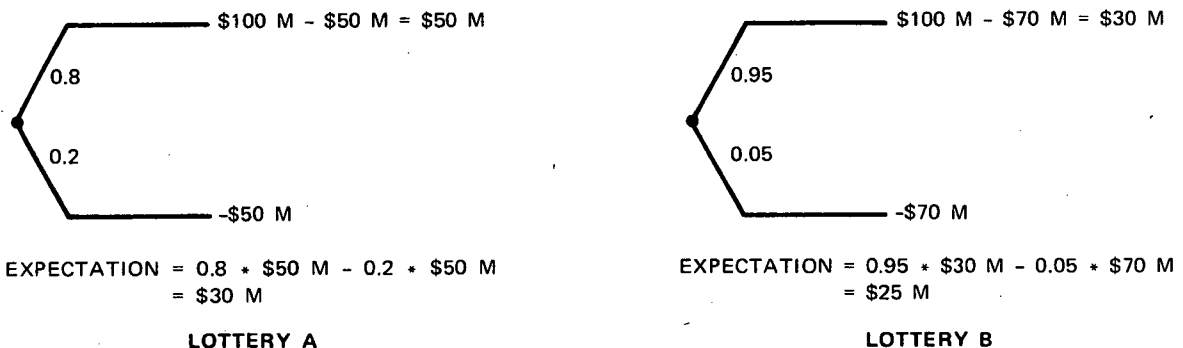


FIGURE A.5 TWO LOTTERIES WHICH REPRESENT TWO ALTERNATIVES DIFFERING THROUGH THE EXPENDITURE OF AN EXTRA \$20 M TO REDUCE THE RISK OF FAILURE FROM 0.2 TO 0.05 (ALL AMOUNTS IN DOLLAR MILLIONS)

does not necessarily imply that the lowest cost configuration is preferable. Which lottery should rationally be preferred depends on the organization's risk tolerance, a purely subjective preference judgment. Figure A.6 shows how the certain equivalent of these two lotteries depends on the risk tolerance under certain simple assumptions* that are likely to be valid for NASA decisions involving these amounts of money. The parameter γ is the reciprocal of the risk tolerance, ρ . The curves representing the certain equivalents of the two lotteries intersect at a γ of about 0.008, whose reciprocal indicates a risk tolerance of approximately \$125 million. Thus, if NASA's risk tolerance is \$125 million, NASA should spend the additional \$20 million for greater reliability. If, however, its tolerance for loss exceeds \$125 million, spending such a large amount for such a reliability gain is probably not justified.

This appendix has not explained how the risk aversion coefficient γ (or equivalently the risk tolerance) should be determined for an organization like NASA. The encoding procedures for risk attitude described in Reference 30 go part of the way, but there are still some practical problems and some research to be done in this area. It must be recognized that the appropriate organizational risk tolerance coefficient is a management value judgment very similar to the choice of a discount rate. An approach to determining a corporate risk attitude is described in References 37 and 38. Even if the encoding procedures needed to determine NASA's risk to tolerance for space exploration were completely clear; it is still not obvious from the explanations presented here why the two curves representing the certain equivalents of lotteries intersect at a ρ of precisely \$125 million. This amount bears little superficial relationship to any of the figures in Figure A.5.

The concepts introduced in this appendix have of necessity been only loosely defined. A more comprehensive treatment of the theory and procedures needed to assess and apply these concepts to decisions in risky situations can be found in References 30, 35, and 36. The purpose of this appendix has been fulfilled if the reader understands the concept of a lottery for representing uncertain propositions; realizes that values, costs, and probabilities are all necessary for the subjective evaluation of such lotteries; and can visualize the analogy between a lottery and a space exploration mission. Then he will understand why our final recommendation is that NASA select a problem in which uncertainty and

* These assumptions, listed and discussed extensively in References 30 and 35, are those that lead to an exponential utility function. Exponential utility functions, which are always characterized by a single "risk aversion coefficient," have been used to develop the curves in Figure A.6.

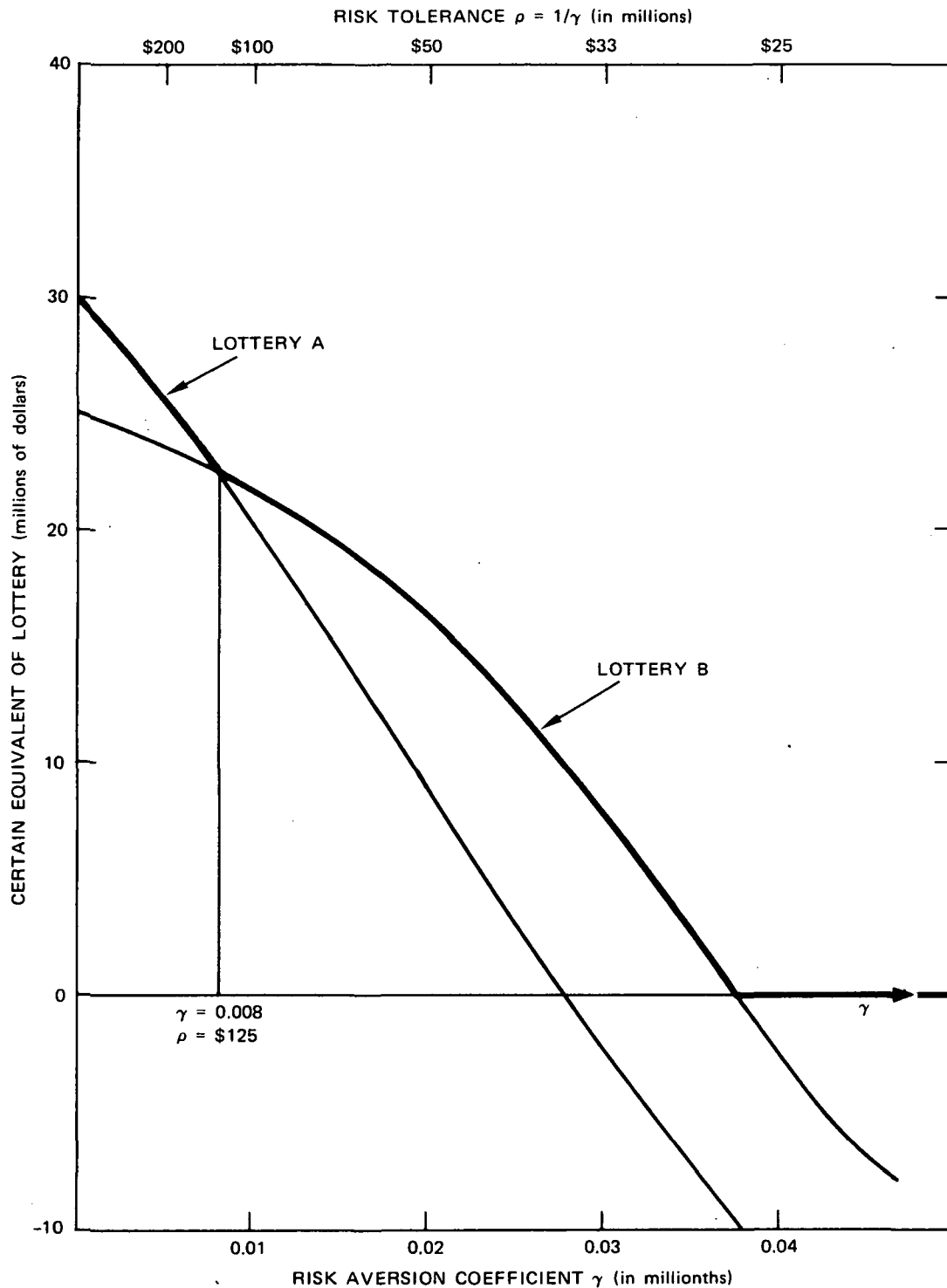


FIGURE A.6 CERTAIN EQUIVALENT OF THE TWO LOTTERIES SHOWN IN FIGURE A.5 AS A FUNCTION OF RISK AVERSION COEFFICIENT γ

risk attitude play a crucial role for a future application of decision analysis. An ability to answer questions like the one discussed above (and illustrated in Figures A.5 and A.6) in a logical and consistent way should be an important step toward a more effective allocation of NASA's diminishing resources for space exploration.