JPL Publication 85-5

Spaceborne Power Systems Preference Analyses

Volume II: Decision Analysis

J.H. Smith
A. Feinberg
R.F. Miles, Jr.

January 15, 1985

Prepared for
Defense Advanced Research Projects Agency
Through an Agreement with
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The research described in this publication was carried out by the Jet Propulsion Laboratory, California Institute of Technology and was sponsored by the Defense Advanced Research-Project Agency through an agreement with the National Aeronautics and Space Administration (NASA Task RE-182, Amendment 268; DARPA Order No. 9043).

ABSTRACT

Sixteen alternative spaceborne nuclear power system concepts were ranked using multiattribute decision analysis. The purpose of the ranking was to identify promising concepts for further technology development and the issues associated with such development.

Eleven individuals representing four groups were successfully interviewed to obtain their preferences. The four groups were: safety, systems definition and design, technology assessment, and mission analysis.

The ranking results were consistent from group to group and for different utility function models for individuals. The highest ranked systems were the heat-pipe thermoelectric systems, heat-pipe Stirling, in-core thermionic, and liquid-metal thermoelectric systems. The next group contained the liquid-metal Stirling, heat-pipe AMTEC (Alkali Metal Thermoelectric Converter), heat-pipe Brayton, liquid-metal out-of-core thermionic, and heat-pipe Rankine systems. The least preferred systems were the liquid-metal AMTEC, heat-pipe thermo-photovoltaic, liquid-metal Brayton and Rankine, and gas-cooled Brayton. Although the R&D community subsequently discounted the heat-pipe reactor systems, the three non-heat-pipe technologies selected matched the top three non-heat-pipe systems ranked by this study (liquid-metal thermo-electric, in-core thermionic, and liquid-metal Stirling).

The multiattribute decision analysis process was viewed as a useful exercise for identifying options which needed further development. The analysis highlighted the need for additional and higher quality technical data as well as a need to provide an on-line capability to display source calculations interactively. An approach was suggested for displaying such traceability.

FOREWORD

The Defense Advanced Projects Research Agency, together with the U.S. Department of Energy and NASA, established the Space Power-100 Development Project to assess the potential and demonstrate the feasibility of developing a nuclear power system for operation in space. The SP-100 R&D Project Office was given the responsibility to assess the state of the required technologies and make recommendations for research in support of such a development from a systems perspective. Therefore, the objectives of the assessment were to characterize and give priority to the various subsystem technologies and system concepts through the use of simulation, based on projections of the subsystem capabilities.

This report describes the multiattribute decision analysis that ranked 16 power system concepts using the preferences of 11 individuals, all knowledgeable in advanced nuclear reactor and power-conversion technologies. The advanced system concepts were designed to meet a 100-kW power requirement, 3000-kg mass requirement, and 7-year lifetime.

The report is divided into two volumes. Volume I is a summary of the multiattribute decision analysis. Volume II describes the multiattribute decision analysis and provides detailed technical information on the methodology and system concepts.

ACKNOWLEDGMENTS

This work could not have been completed without the support of many individuals who gave generously of their time. At the Jet Propulsion Laboratory, the authors wish to thank Vince Truscello, Jim French, Jack Mondt, and Tosh Fujita. Considerable thanks are due to those individuals who were interviewed as to their preferences for the attributes of the systems that were evaluated. Those organizations whose representatives participated are:

Organization	Location
Air Force Weapons Laboratory	Albuquerque, New Mexico
Jet Propulsion Laboratory	Pasadena, California
Los Alamos National Laboratories	Albuquerque, New Mexico
NASA Lewis Research Center	Cleveland, Ohio

A very special thanks is owed to Fran Mulvehill who patiently and cheerfully typed this manuscript with its many difficult tables. Notwithstanding the help of these individuals above, the responsibility for this report rests with the authors.

This work was conducted by the Jet Propulsion Laboratory's SP-100 Project, which is a tri-agency agreement under the Defense Advanced Projects Research Agency, U.S. Department of Energy, and NASA.

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SECTION I

INTRODUCTION AND SUMMARY

A. INTRODUCTION

Sixteen alternative spaceborne nuclear power concepts were studied and ranked using a multiattribute decision analysis. The system concepts were all designed to meet a 100-kW power level and 3000-kg mass limit and to operate in the space environment for a 7-year lifetime. The systems included seven heat-pipe cooled and seven liquid-metal cooled systems with a variety of dynamic and static power conversion systems. One gas-cooled system and an in-core system were also examined. The conversion systems included Brayton, Stirling, Rankine, thermoelectric, thermophotovoltaic, thermionic, and AMTEC technologies.

Ten attributes were intended to be used in the ranking, but two were not included because it was believed they would not have affected the rankings significantly--estimated development cost and production cost in 1983 dollars. Thus, only eight attributes impacted the rankings: safety, radiator area, design reliability, technical maturity, estimated cost to reach technical feasibility, survivability, dormancy capability, and producibility.

The methodology used to rank the system concepts was multiattribute decision analysis with the base case model using a multiplicative multi-attribute utility function (Reference 1). A linear multiattribute utility function was also used to compare with rankings derived from the base case model. The methodology combines an individual's preferences with analytical estimates of the attribute states to produce a ranking for that individual. A flow diagram for the method is shown in Figure 1-1.

Because several individuals are involved in a major decision such as the ranking of technical concepts, the rankings had to be determined for groups as well as for individuals. Thus, the Methodology Section includes discussion of group-decision rules. Three group-decision rules were used to aggregate individual rankings because there is no definitive rule for groups: rank sum rule, additive utility rule, and Nash bargaining rule.

B. INTERVIEWS

Eleven individuals, knowledgeable in spaceborne power system technologies, were successfully interviewed to obtain their preferences with regard to the eight attributes selected. These individuals were drawn from organizations with:

(1) Ongoing research and development programs in advanced power conversion systems.

(2) A proven record of achievement in the research and development of nuclear power systems.

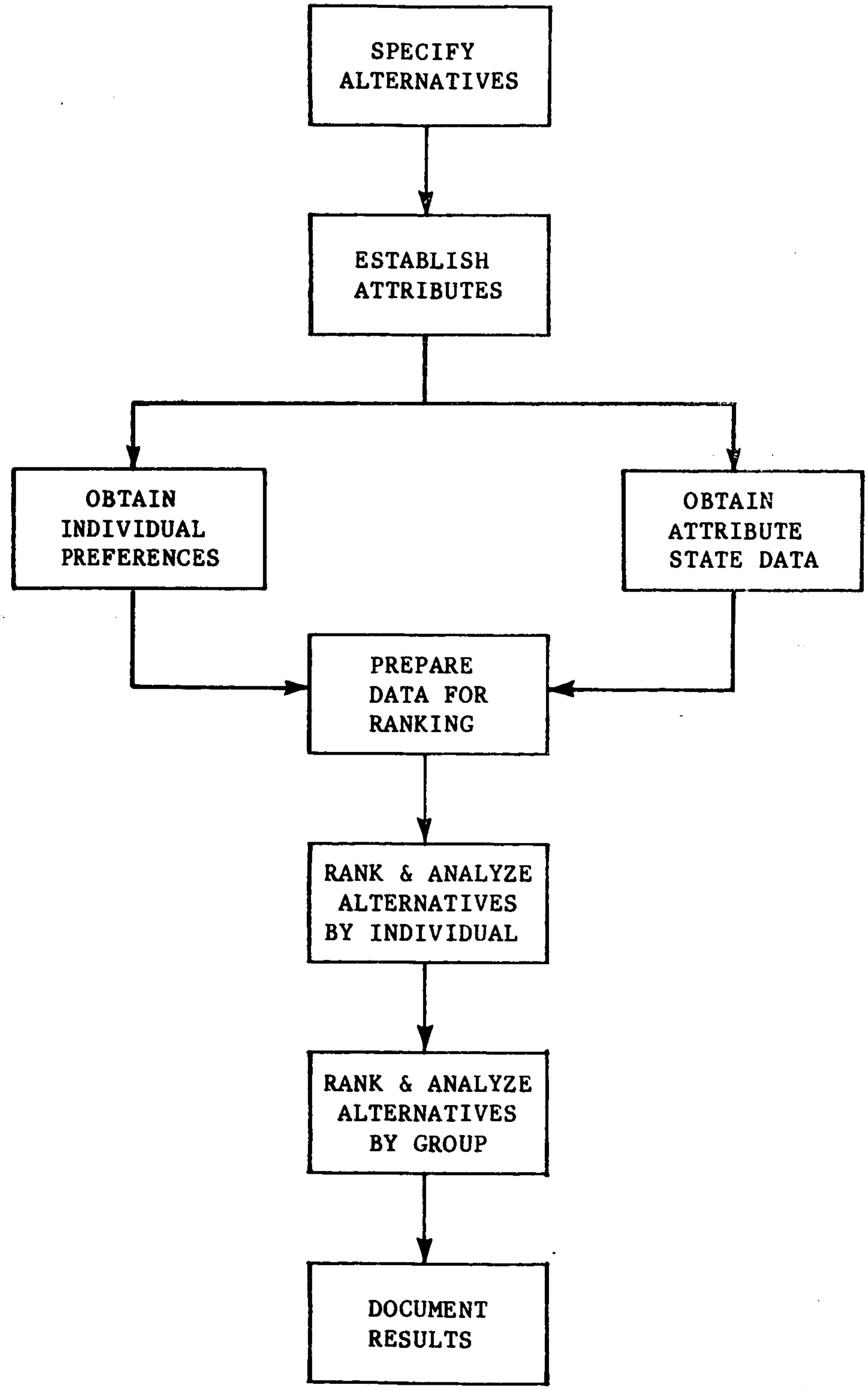


Figure 1-1. Ranking Methodology Flow Diagram

(3) An understanding of space environment issues which have direct impact on developing nuclear power technologies for space applications.

These individuals represented four distinct groups:

(1) Safety Group. This group was concerned with a range of safety issues from ground development through launch, on-orbit operation, and re-entry.

(2) Systems Definition and Design Group. This group was concerned with the design issues and options involved in the development and deployment of the technology.

(3) Technology Assessment Working Group. This group was involved in assessing the technical issues facing the demonstration of technical feasibility for such power systems.

(4) Mission Analysis Group. This area involved the concerns of possible mission users who would utilize the system concepts.

C. RANKINGS

Rankings were calculated for the 11 individuals successfully interviewed and for the four groups that they represented. Rankings for the individuals were calculated using several different multiattribute utility models and with each of the attributes removed. Rankings for the groups were calculated using three different group decision rules.

The ranking results were quite consistent from group to group and for different utility function models for individuals. Generally, the rankings fell into four areas: most preferred concepts (those high-ranking systems whose rankings were unchanged by various assumptions about the multiattribute decision model), preferred (those systems whose (high) rankings varied with changes in the multiattribute decision model assumptions but remained clustered together near the high end of the rankings), intermediate (those systems whose rankings varied with changes in the multiattribute decision model assumptions but remained clustered together near the low end of the rankings), and least preferred (those low-ranking systems whose rankings were virtually unchanged by various assumptions about the multiattribute decision model). The most preferred systems were the heat-pipe thermoelectrics (HTEP, HTEPa). The preferred systems were the heat-pipe Stirling (HSH), in-core thermionic (ICT), and liquid-metal thermoelectric (LTEP). The intermediate systems were the liquid-metal Stirling (LSH), heat-pipe AMTEC (HAP), heat-pipe Brayton (HBO), liquid-metal out-of-core thermionic (LOCTP), and heat-pipe Rankine (HRL). The least preferred concepts were the liquid-metal AMTEC (LAP), heat-pipe thermophotovoltaic (HTPVP), liquid-metal Brayton (LBO), liquid-metal Rankine (LRL), and gas-cooled Brayton (GBH).

The above rankings were used to initiate planning for the technical development of promising options within the project time frame. In particular, the rankings were used to identify technology areas for more comprehensive research. A subsequent technology downscoping evaluation eliminated almost all of the heat-pipe concepts as being riskier than previously thought with a limited operational database. The results of the present analysis had a direct impact on the list of systems which were candidates for this downscoping effort. It should be noted that the rank ordering of the remaining systems (after removing the heat-pipe systems) was substantially the same with the preliminary results obtained herein.

D. CONCORDANCE AMONG RANKINGS

The concordance or agreement among the rankings was calculated for individuals within groups, different group decision rules, and different multiattribute utility models. The concordance calculations were carried out to ascertain how robust the rankings were. In general, the rankings were highly concordant across individuals, different group decision rules, and different multiattribute utility models, implying that the rankings were indeed robust.

The robustness of the rankings was due to (1) a general consensus regarding the importance of the safety and technical maturity attributes; and (2) the dominance of the system data in pre-determining the high and low end rankings.

E. REPORT

This Volume consists of seven sections: an introduction (Section I); methodology (Section II); description of the attributes (Section III); listing of the alternatives and state data (Section IV); summary of the interviews and preference data (Section V); presentation and analysis of the rankings and results (Section VI); and summary of the concordance of rankings (Section VII).

SECTION II

METHODOLOGY

This section describes and illustrates the methodology used to evaluate and compare alternative spaceborne power concepts. The methodology consists of a number of steps which, in short, characterize the alternative approaches under different design options and operating environments, assign utility values to the alternatives, and rank the alternatives based on these utilities. Tests of concordance of the rankings for different individuals, groups, methodologies, and attribute sets were carried out and are discussed in Section VII.

The evaluation methodology may be summarized as follows. The process begins with the selection of a set of descriptive but quantifiable attributes designed to characterize each system. Values for this set of attributes are then generated for each alternate approach that specify its response (e.g., performance or cost) under different design options and operating environments. (The attributes are discussed in Section III.) A decision tree can be constructed to relate economic, technological, and environmental uncertainties (i.e., the operating environment) to the cost and performance outcomes (i.e., attribute values) of the alternative power concepts. Multiattribute utility functions that reflect the preferences and perceptions of knowledgeable individuals are generated, based on interviews with selected personnel. The functions are then employed to generate a multiattribute utility value for each system, based on its characteristics under the scenarios reflected within the decision tree. The decision tree is used to compute an expected multiattribute utility value for each alternative, the expected value being taken over the scenario probability distribution. Alternative systems are ranked according to this expected multiattribute utility value.

A. MULTIATTRIBUTE DECISION ANALYSIS

1. Overview

Multiattribute decision analysis is a methodology for providing information to decision-makers for comparing and selecting from among complex alternative systems in the presence of uncertainty. The methodology of multiattribute decision analysis is derived from the techniques of operations research, statistics, economics, mathematics, and psychology. Thus, researchers from a wide range of disciplines have participated in the development of multiattribute decision analysis. The first books and papers on the subject appeared in the late 1960s (References 2 through 5). The most practical, extensive, and complete presentation of an approach to multiattribute decision analysis is given in the 1976 work of Keeney and Raiffa (see Reference 1). Although several approaches to multiattribute decision analysis have been developed (References 6 through 19), the method used in this report corresponds to an abbreviated form of that of Keeney and Raiffa. A brief introduction to multiattribute decision analysis, discussing primarily the Keeney and Raiffa methodology, is given in Feinberg and Miles (Reference 20). The assumptions needed for the abbreviated form used here are discussed at the end of subsection A-4.

Every systems analysis involving the preference ranking of alternative systems, whatever the specific methodology, requires two kinds of models. One is a "system model" and is representative of the alternative systems (including any uncertainties) under consideration. The other is a "value model" and is representative of the preference structure of the decision-makers whose preferences are being assessed.

The system model describes the alternative systems available to the decision-makers in terms of the risk and possible outcomes that could result from each system. Risk arises from the technological and economic uncertainty associated with each alternative system and from the uncertain environment in which the systems would be required to perform. The outcomes describe the possible consequences of the alternative systems. Because of the element of risk, the selection of a specific system does not in general guarantee a specific outcome, but rather results in a probabilistic situation in which only one of several outcomes may occur. These outcomes, with their measurable attributes, then form the input to the value model. The value model assesses the outcomes in terms of the preferences of the decision-makers for the various outcomes. The measurable attributes of the outcomes are aggregated algebraically in a formula (called a multiattribute utility function) whose functional form and parameters are determined by the preference structure of the decision-makers. The output of the value model is a multiattribute utility function value for each outcome (outcome utility). These outcome utilities are entered back into the system model where an alternative system utility can be calculated for each alternative system simply by taking the expected utility value of the outcomes associated with each alternative system. These alternative system utilities then define a preference ranking over the alternative systems, with greater alternative system utilities being more preferred.

The relationship between the system model and the value model is illustrated in Figure 2-1, which shows that the combination of a selected system and a realized state of uncertainty results in the output from the system model to the value model of a specific outcome. The output of the value model is an outcome utility. The probabilistic combination of the outcome utilities of the outcomes associated with a specific alternative system determine an alternative system utility in the system model. Comparison of the alternative system utilities for all the alternative systems under consideration results in an alternative system ranking as the output from the system model.

2. Decision Trees

Decision trees are used to represent the system model and the inputs to the system model at the gross level required for the decision analysis. Decision trees are graphically depicted by decision nodes (represented by squares), with alternative paths emanating from them; and by chance nodes (represented by circles), with probabilistic paths emanating from them. All paths either terminate at another node or terminate at an outcome, which is a description of the consequence of traversing a specific set of paths and nodes through the decison tree from beginning to end. There can be only one originating node (either a decision node or a chance node). There can be many outcomes terminating the decision tree, depending on the complexity of the decision tree.

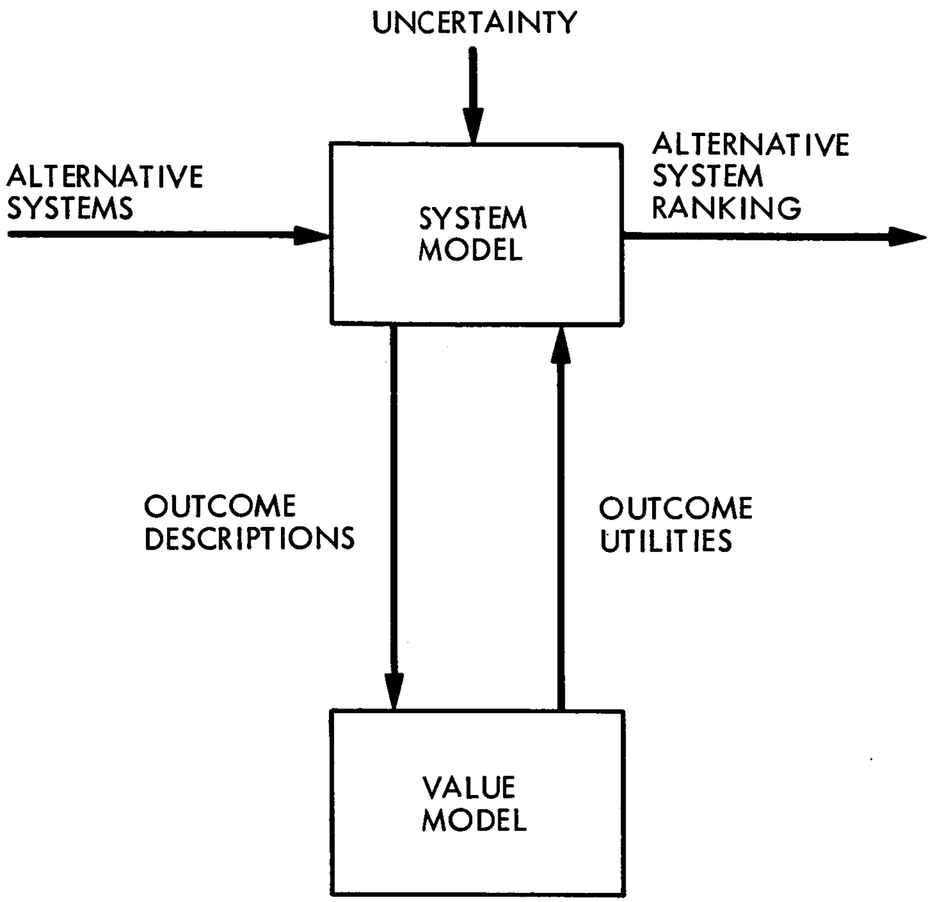


Figure 2-1. Relationship Between System Value Models

Figure 2-2 shows a typical decision tree, terminating in 10 outcomes. The symbols "D_i" stand for the ith decision node ("D" for decision). The symbols "P_j" stand for the jth chance node ("P" for probabilistic). The symbols "C_k" stand for the kth outcome ("C" for consequence). Every path emanating from a decision node corresponds to an alternative that the decisionmakers can select, where "$A_{i\ell}$" stands for the ℓth alternative selected at the ith decision node. The decision-makers can select one and only one path at each decision node. Every path P_{jm} emanating from a chance node corresponds to one of the uncertain and uncontrollable chance states that can occur at that node, where p_{jm} is the probability that the mth chance state will be realized at the jth chance node. The p_{jm}s must obey the laws of probability theory. Thus, one and only one chance path can be realized from a chance node, and the p_{jm}s must sum to 1.0.

The chance nodes and their associated chance paths and probabilities are called "gambles" or "lotteries" in the literature. This report shall refer to them as gambles. An example of a gamble would be a flip of a coin, which could be expected to come up heads 50% of the time and tails 50% of the time. Graphically, such a gamble would be displayed as:

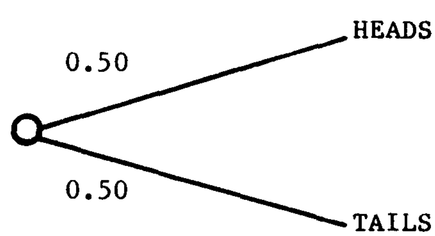


Figure 2-2 has an example of every kind of node-path-outcome relationship. There are examples of decision-node to decision-node paths, decision-node to chance-node paths, decision-node to outcome paths, chance-node to decision-node paths, chance-node to chance-node paths, and chance-node to outcome paths.

As an example of how the decision tree might be traversed, imagine that the decision-maker selects Alternative Path A_{12} at Decision Node D_1, where he must start. This leads to Chance Node P_1 where Chance Path P_{13} is realized, leading to Chance Node P_3, where Chance Path P_{32} is realized, and terminates with Outcome C_{10}.

3. Objectives Hierarchy

The outcomes that terminate the decision tree are to be described in terms of an objectives hierarchy that (1) expresses the preference structure of the decision-makers, and (2) is constructed in a manner compatible with the quantification and mathematical conditions required by a multiattribute utility function of the value model. The objectives hierarchy expresses the preference structure of the decision-makers in ever increasing detail as one proceeds down through the hierarchy from overall objective to a lower-level hierarchy of subobjectives. Below the subobjectives are "criteria." The criteria must permit

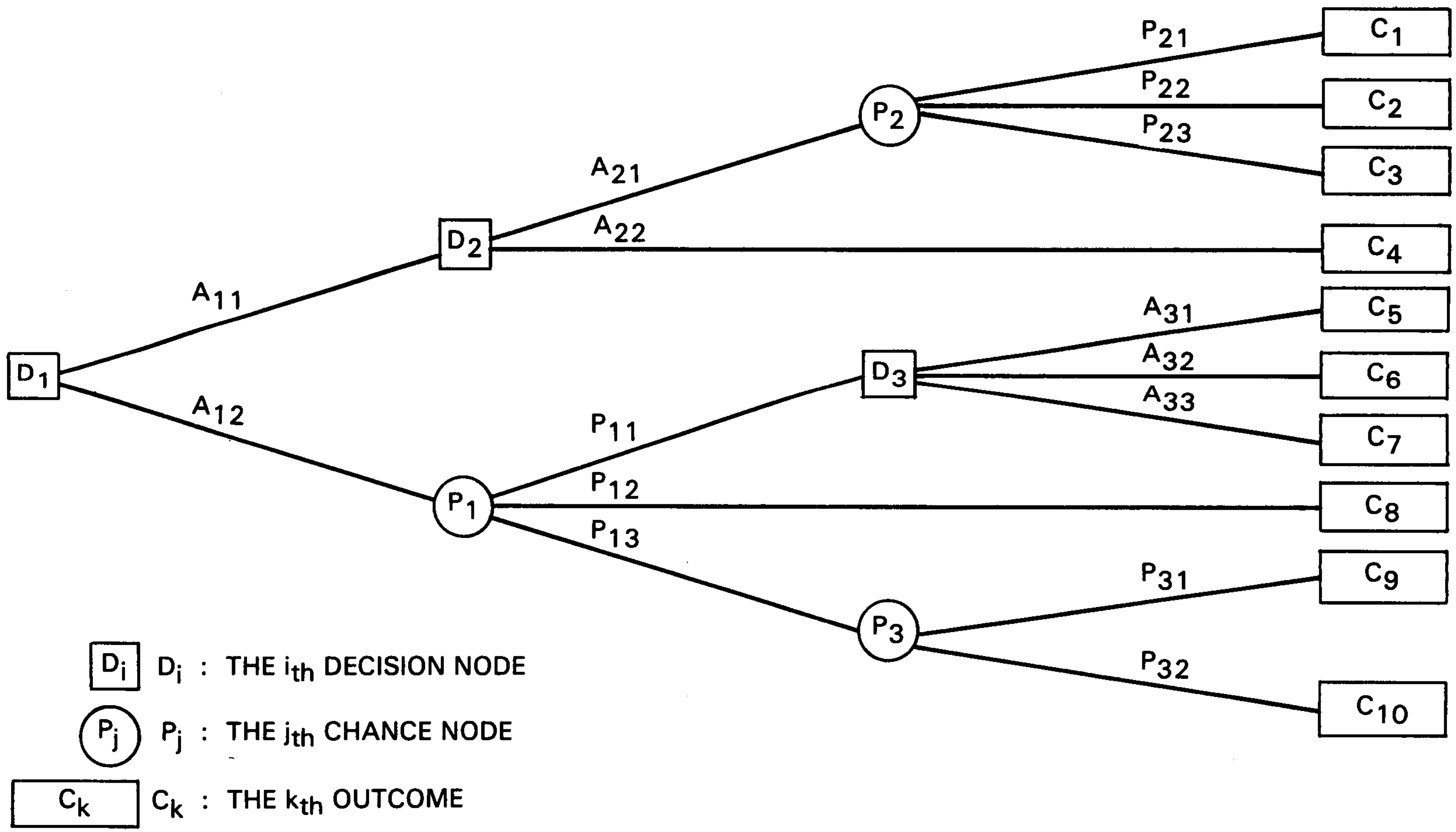


Figure 2-2. Typical Decision Tree

the quantification of performance of the alternatives with respect to the subobjectives. Associated with each criterion is an "attribute," a quantity that can be measured and for which the decision-makers can express preferences for its various states. Figure 2-3 shows an objectives hierarchy with the associated attributes.

The set of attributes must satisfy the following requirements for the value model to be a valid representative of the preference structure of the decision-makers:

(1) Completeness: The set of attributes should characterize all of the factors to be considered in the decision-making process.

(2) Comprehensiveness: Each attribute should adequately characterize its associated criterion.

(3) Importance: Each attribute should represent a significant criterion in the decision-making process, at least in the sense that the attribute has the potential for affecting the preference ordering of the alternatives under consideration.

(4) Measurability: Each attribute should be capable of being objectively or subjectively quantified; technically, this requires that it be possible to establish an attribute utility function for each attribute.

(5) Familiarity: Each attribute should be understandable to the decision-makers in the sense that they should be able to identify preferences for different states of the attribute for gambles over the states of the attribute.

(6) Nonredundancy: Two attributes should not measure the same criterion, thus resulting in double counting.

(7) Independence: The value model should be so structured that changes within certain limits in the state of one attribute should not affect the preference ordering for states of another attribute or the preference ordering for gambles over the states of another attribute.

4. Attribute Utility Functions and the Multiattribute Utility Function

The set of attributes associated with the objectives' hierarchy must satisfy the aforementioned measurability and mathematical requirements. If it satisfies these requirements, then it is possible to formulate a mathematical function (called a multiattribute utility function) that will assign numbers (called outcome utilities) to the set of attribute states characterizing an outcome. The multiattribute utility function that was used is that of Keeney and Raiffa (Reference 1). The outcome utilities generated by the Keeney and Raiffa multiattribute utility function have the properties of Von Neumann and Morgenstern utilities (Reference 23), that is:

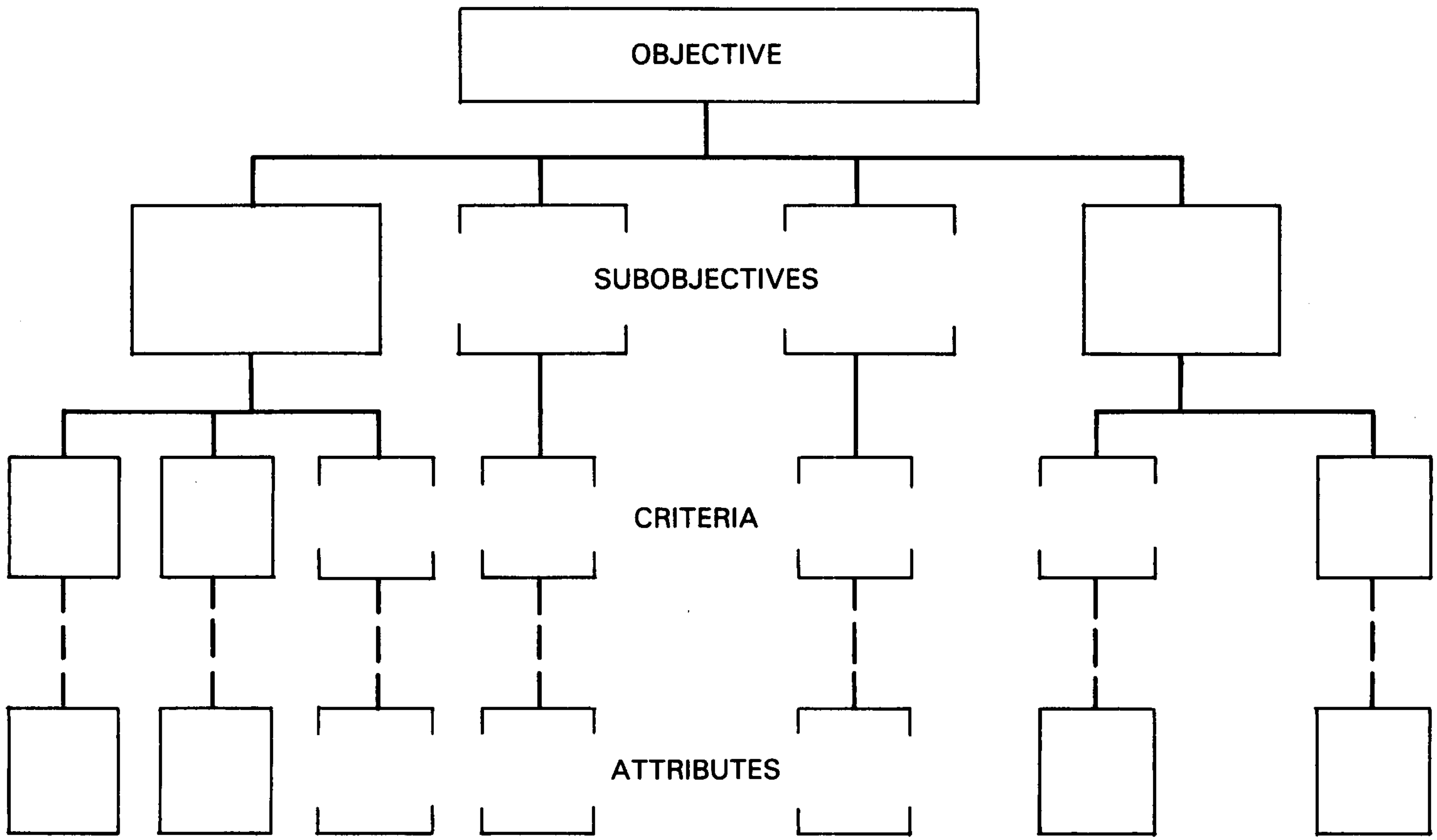


Figure 2-3. Hierarchy of Objectives, Criteria, and Attributes

(1) Greater outcome utility values correspond to more preferred outcomes.

(2) The utility value to be assigned to a gamble is the expected value of the outcome utilities of the gamble.

The mathematical axioms that must be valid for these two properties to hold were first derived by Von Neumann and Morgenstern (see Reference 23). Elementary expositions of these axioms are given in Hadley (Reference 24) and Luce and Raiffa (Reference 25). An intermediate exposition is given in DeGroot (Reference 26). An advanced exposition is given in Fishburn (Reference 27).

To every outcome "C," an N-dimensional vector of attributes $x = (x_1, \ldots, x_N)$ will be associated, the set of which satisfy the attribute requirements presented in the preceding subsection. Most of the attribute requirements are self-evident. The seventh requirement, that of attribute independence, is a condition that makes it possible to consider preferences between states of a specific attribute, without consideration of the states of the other N-1 attributes. It is thus possible to construct an attribute utility function that is independent of the other attribute states, and which, like the outcome utility function, satisfies the Von Neumann and Morgenstern properties for utility functions. This condition of independence, or some equivalent mathematical condition (see Reference 1 for alternative formulations), is necessary for the Keeney and Raiffa methodology. It is necessary to verify that this condition is valid in practice, or more correctly, to test and identify the bounds of its validity.

To continue the discussion from this point on, it is necessary to introduce some mathematical notation:

x_n = The state of the nth attribute.

x_n^o = The least-preferred state to be considered for the nth attribute.

x_n^* = The most-preferred state to be considered for the nth attribute.

x = The vector $(x_1, \ldots, x_N)$ of attribute states characterizing a specific outcome.

x^o = An outcome constructed from the least preferred states of all the attributes. $x^o = (x_1^o, \ldots, x_N^o)$.

x^* = An outcome constructed from the most preferred states of all attributes. $x^* = (x_1^*, \ldots, x_N^*)$.

$(x_n, \bar{x}_n^o)$ = An outcome in which all attributes except the nth attribute are at their least-preferred state.

$u_n(x_n)$ = The attribute utility of the $\underline{nth}$ attribute.

$u(x)$ = The outcome utility of the outcome x.

k_n = The attribute scaling constant for the $\underline{nth}$ attribute. $k_n = u(x_n^*, \bar{x}_n^o)$.

k = The master scaling constant for the multiattribute utility equation. It is an algebraic function of the k_ns.

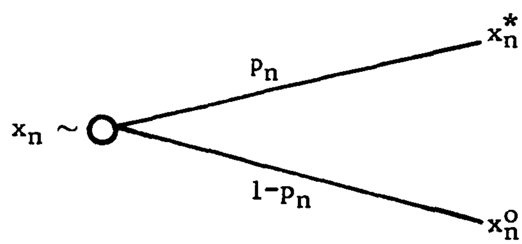
With this mathematical notation, the discussion can proceed to how attribute utility functions and the attribute scaling functions are assessed. The mathematics permit the arbitrary assignments:

$$u_n(x_n^o) = 0.0$$

and

$$u_n(x_n^*) = 1.0$$

Thus, the attribute utility function values will range from 0.0 to 1.0. Attribute utility function values for attribute states x_n intermediate between x_n^o and x_n^* are assessed by determining a value of p_n such that the decision makers or their designated experts are indifferent between receiving x_n for sure $\underline{or}$ a gamble that yields x_n^o with probability p_n or x_n^* with probability $1-p_n$. Graphically, assess p_n, so that:



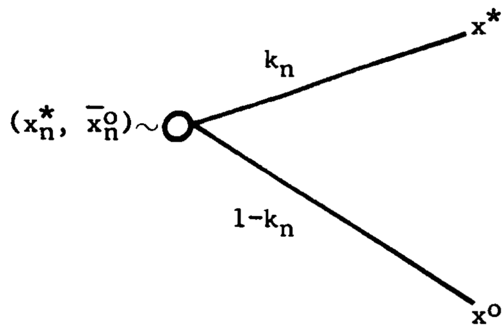
where "~" means indifference.

It follows from the mathematics that:

$$u_n(x_n) = p_n$$

This indifference relation is repeated for various attribute states until either a continuous utility function can be approximated or enough discrete points have been assessed for the attribute states under consideration in the analysis.

A similar approach is used to assess the scaling constants k_n. A value for k_n is assessed such that the following indifference relationship holds:



With this assessed information, the multiattribute utility equation can be solved to yield an outcome utility value for any outcome under consideration. The multiattribute utility function can now be stated:

If

$$\sum_{n=1}^{N} k_n \neq 1.0$$

then

$$u(x) = \frac{1}{k}\left\{\prod_{n=1}^{N}\left[1 + k\, k_n\, u_n(x_n)\right] - 1\right\}$$

where the master scaling constant k is solved for from the equation:

$$1 + k = \prod_{n=1}^{N} (1 + k\, k_n)$$

If

$$\sum_{n=1}^{N} k_n = 1.0$$

then there is an additive utility function,

$$u(x) = \sum_{n=1}^{N} k_n\, u_n(x_n)$$

The outcome utility function values, like the attribute utility function values, will all range from 0.0 to 1.0 with $u(x^o) = 0.0$ and $u(x^*) = 1.0$. Although the mathematical equations appear complex, they can be easily solved, and the information required in the interviews with the decision-makers can be minimized. An extended discussion of these equations, their solution, and the assessment of the required data, together with examples taken from actual applications, is given in Keeney and Raiffa (see Reference 1).

In this study, an abbreviated form of Keeney and Raiffa's methodology was used to reduce the interview time for the interviewee. An assumption was made that utility independence of each attribute implies pair-wise utility independence (i.e., the attributes exhibit utility independence when taken two at a time). This assumption allows the use of Formulation (4) of Theorem 6.2 of Keeney and Raiffa (see Reference 1). Given single-attribute utility independence, the authors could not construct a realistic example where pair-wise utility independence would be violated.

The abbreviated form satisfies the multilinear model shown in Theorem 6.3 of Keeney and Raiffa. However, the multilinear form requires the assessment of 2^n-2 scaling constants, where n is the number of attributes. With n = 8 attributes, 254 scaling constants would be needed, requiring extensive time for both the interviewer and interviewee.

5. Ranking the Alternative Systems

The steps needed prior to ranking the alternatives are: the development of a decision tree, the determination of probabilities for the decision of an objectives hierarchy, the quantification of the criteria in terms of measurable attributes, and the determination of a multiattribute utility function with attribute utility functions and attribute scaling constants corresponding to the preference structure of the decision makers. The ranking of the alternative systems proceeds as follows (see Figure 2-2):

(1) Use the multiattribute utility function to calculate outcome utilities for all of the outcomes of the decision tree.

(2) Calculate a utility value to be assigned to all chance nodes by taking the expected utility value of the utilities assigned to the termination of the chance paths of the chance nodes. The chance paths may terminate at outcomes, other chance nodes, decision nodes, or a combination of these.

(3) Calculate a utility value for all decision nodes by selecting the decision path that terminates in an outcome, chance node, or decision node with the highest utility value. The utility value of that path shall be the utility value assigned to the decision node.

The decision tree for this study has an originating decision node whose decision paths correspond to the alternative systems under consideration. Steps (1) through (3) are performed by starting with the outcomes as shown in Figure 2-2 and assigning utility values to these outcomes. Then Steps (2) and (3) are performed by a "folding back" process, proceeding from right to left, and assigning utility values to the chance nodes and the decision nodes. Finally, utility values are assigned to the decision paths emanating from the orginating decision node on the left. These utility values are the ones assigned to the alternative systems. Because greater utility values correspond to more preferred systems, a rank order in preference for the alternative system can be assigned in correspondence with the utility values. A quantifiable and tangible measure of the strength of preference between the alternative systems can be obtained by referencing each alternative system to a set of systems where only one attribute, such as initial cost, is varied (References 30 and 31). The differences in the attribute states of this one attribute varied in order to obtain indifference to each of the alterative systems will provide a tangible measure of the strength of preference between the alternative systems.

6. Group Decision Models

Throughout this section, "decision-makers" has been consistently discussed in the plural. It is true that in American society, corporate and government (executive branch) decisions are ultimately the responsibility of one person, though the same cannot be said for either the legislative branch of government or the voting public. Thus, depending upon the context, it may be more appropriate to speak of decision-maker in the singular. Nevertheless, when one person holds the ultimate responsibility for the decision, this person may elect to delegate the decision-making responsibility to a group, or at least consider the preferences of several others prior to making the decision.

Unfortunately, there presently exist no analytical models for group decision making that do not violate some intuitively desirable conditions. Arrow (Reference 30) was the first to demonstrate this fact. Extensive discussions of group decision making can be found in Fishburn (Reference 31), Luce and Raiffa (see Reference 25), and Sen (Reference 32). The best that can be done is to look at a range of group decision models, and where consensus of the/models is found, define that as the consensus of the group (References 33 and 34).

The three group decision rules that will be considered in this report are the Rank Sum Rule, the Nash Bargaining Rule, and the Additive Utility Rule. (The Majority Decision Rule, which originally was considered for use in this analysis, was not employed because of unsolved theoretical problems that arise when more than two alternatives are involved).

The Rank Sum Rule (References 30 and 35) in the slightly modified form proposed here, requires the calculation of the sum of the ordinal ranks for each alternative, with the alternative receiving the lowest rank sum being most preferred. Young (Reference 36) has stated four axioms that are necessary and sufficient for any collective choice rule to be equivalent to the Borda Rule.

The Nash Bargaining Rule calculates the product of the utilities assigned by all the individuals to an alternative. The alternatives with greater utility product are more preferred, and from this a group preference order can be established. The Nash Bargaining Rule satisfies Nash's four axioms of "fairness" (Reference 37). As the number of decision-makers increase, the Nash utilities decrease because the individual utilities equal 1.0. Hence, for even ten decision-makers, the Nash utilities are small. Without loss of generality, the Nash utilities can be re-scaled by taking the nth root of the product of the individual utilities, where n is the number of decision-makers in the group.

The modern formulation of the Additive Utility Rule is that of Harsanyi (Reference 38). The Additive Utility Rule averages the utility values assigned by the individuals to each alternative, with higher average utility values being more preferred.

It should be re-emphasized that there is no theoretically compelling reason to use the results of any of these group decision rules, but they do provide information concerning the collective preferences of the decision-makers.

B. RISK ANALYSIS

1. Introduction

Another element of the sensitivity analysis effort is that of risk analysis. Risk is defined as the possibility of loss or injury. This subsection explains and illustrates the elements of risk analysis and describes how risk analysis is incorporated into the multiattribute decision model and into the sensitivity analysis.

2. Risk-Analysis Elements

Often the concept of risk analysis is introduced in the context of comparing two alternatives that have equal expected dollar value. An example is the following pair of alternatives:

Option A: $1000 for sure.

Option B: A 50-50 chance of zero dollars or of $2000.

Although both options A and B have equal expected dollar values of $1000, they may not have equal expected utilities for some individuals. An individual's preferences between options A and B reveal his attitude toward risk in the range $0 to $2000:

(1) An individual preferring A to B is characterized as risk-averse.

(2) An individual preferring B to A is characterized as risk-prone.

(3) An individual indifferent between A and B is characterized as risk-neutral.

In the context of spaceborne power concepts, risk is apparent in the following hypothetical situation:

Option C: Radiator area of 68 m^2 with a technical development cost of $114 million.

Option D: 50-50 chance of 108 or of 27 m^2 of radiator area with a technical development cost of $114 million.

Although both options C and D have equal expected radiator area and equal development costs, individuals may exhibit different preferences, as with the previous dollar example. An individual preferring Option C to Option D is characterized as risk-averse, etc.

Risk attitude implies a certain shape of the individual's utility function and vice versa (see References 1 and 3). A risk-averse attitude for an attribute is equivalent to a concave utility function for that attribute. Also, risk-proneness is equivalent to a convex utility function; and finally, risk-neutrality is equivalent to a linear utility function. All three of these shapes are illustrated in Figure 2-4 for an increasing utility function. An increasing utility function exists for an attribute for which the decision-maker prefers higher values to lower values.

The attitude of an individual toward risk varies with the range of outcomes. For example, few of us who would prefer Option B above would give $1,000,000 for sure for a 50-50 chance at zero or $2,000,000. Nevertheless, variation in individual attitude toward risk is evidenced by many motorists who drive from Los Angeles to Las Vegas to gamble (risk-prone), yet carry insurance on their automobiles (risk-averse).

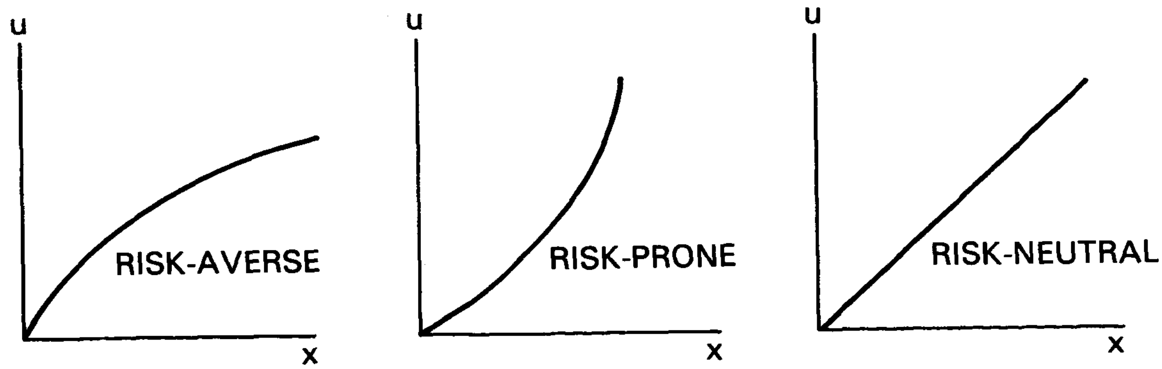
3. Incorporation of Risk in Multiattribute Decision-Making

Risk has usually been incorporated in multiattribute decision making by taking the individual decision-maker's utility functions and probabilities of various outcomes and combining them to obtain an expected multiattribute utility for each decision alternative. Alternatives can then be ranked in order of expected multiattribute utility with the higher expected utility being the more preferred. The incorporation of risk in such a ranking occurs because the individual's attitude toward risk is embodied in the utility functions used to calculate expected utility. If he is risk-averse, then his multiattribute utility function will yield lower utility values for riskier alternatives. Similarly, if he is risk-prone, riskier alternatives will have higher utility values.

C. CONCORDANCE

It is important to determine the extent of agreement among interviewees as to the ranking of the alternative systems. To this end a statistic known as Kendall's Coefficient of Concordance was employed. This statistic varies between zero and one, with one corresponding to exact agreement among the judges and lower values indicating a greater degree of disagreement. The statistic has a known probability distribution. Thus, tests of significance can be performed.

In the current analysis, the hypothesis that the set of rankings produced by a number of judges are independent was tested. The null hypothesis, if accepted, would imply disagreement among judges. The more decisively one rejects this null hypothesis, the greater is the agreement, or concordance, among the judges.



(x = Technical Maturity of Development)

Figure 2-4. Examples of Increasing Utility Functions for Different Risk Attitudes

Kendall's Coefficient of Concordance, W, is given by the following equations:

$$W = \frac{S}{\frac{1}{12} k^2(N^3 - N) - k \sum_{i=1}^{k} T_i}$$

where

$$S = \sum_{j=1}^{N} (R_j - \bar{R})^2$$

$$\bar{R} = \frac{1}{N} \sum_{j=1}^{N} R_j = k(N + 1)/2$$

$$T_i = \sum_{j=1}^{N} \left(t_{ij}^3 - t_{ij}\right) /12$$

and N = Number of alternatives.

k = Number of judges.

R_j = The sum of the ranks assigned to alternative j.

t_{ij} = Number of tied observations for rank j and judge i.

The ranks, R_j, of tied observations are taken as equal to the average of the ranks they would have been assigned had no ties occurred. For example, suppose five alternatives, a through e, are ranked (from best to worst) d, a, c, e, b, with c and e tied. Ranks would be assigned as follows: d-1, a-2, c-3.5, e-3.5, b-5.

Table 2-1 gives the 5% and 1% significance points for S (the unnormalized statistic) and various values of k and N. When $N \geq 7$ one can use the fact that $k(N - 1)W$ has, approximately, a chi-square distribution with $N - 1$ degrees-of-freedom. When $k(N - 1)W$ exceeds the critical significance point, the null hypothesis of independence of rankings, or lack of concordance among the judges is rejected.

Table 2-1. Table of Critical Values of "S" in the Kendall Coefficient of Concordance[a]

	N					Additional values for N = 3	
k	3	4	5	6	7	k	S
Values at the 0.05 Level of Significance							
3			64.4	130.9	157.3	9	54.0
4		49.5	88.4	143.3	217.0	12	71.9
5		62.6	112.3	182.4	276.2	14	83.8
6		75.7	136.1	221.4	335.2	16	95.8
8	48.1	101.7	183.7	299.0	453.1	18	107.7
10	60.0	127.8	231.2	376.7	571.0		
15	89.8	192.9	349.8	570.5	864.9		
20	119.7	258.0	468.5	764.4	1158.7		
Values at the 0.01 Level of Significance							
3			75.6	122.8	185.6	9	75.9
4		61.4	109.3	176.2	265.0	12	103.5
5		80.5	142.8	229.4	343.8	14	121.9
6		99.5	176.1	282.4	422.6	16	140.2
8	66.8	137.4	242.7	388.3	579.9	18	158.6
10	85.1	175.3	309.1	494.0	737.0		
15	131.0	269.8	475.2	758.2	1129.5		
20	177.0	364.2	641.2	1022.2	1521.9		

[a]Source: Sidney Siegel, Nonparametric Statistics, McGraw-Hill, 1956; p. 286 (Reference 39).

SECTION III

OBJECTIVES, CRITERIA, AND ATTRIBUTES

A. INTRODUCTION

In this section, the hierarchy of objectives, criteria, and attributes for evaluating and ranking alternative spaceborne power system concepts is presented. Desirable properties of attributes are described, followed by a statement of the original objectives to be used in evaluating alternative spaceborne power system concepts. Candidates for the objectives, criteria, and attributes are given. Some comments on steps toward a choice of the final attribute set and toward determination of scales for the selected attributed set conclude this section.

There are several purposes to which this section is directed. The first is to explain the concept of a hierarchy of objectives, criteria, and attributes, and what properties are desired of this hierarchy. A second purpose is to provide background information in the form of the original SP-100 Project statement of objectives for the advanced concept alternatives. A final purpose is to detail the necessary steps to select the attribute set and its scales for use in the decision model.

B. HIERARCHY OF OBJECTIVES, CRITERIA, AND ATTRIBUTES

There is a structure that permits the transition from a broad statement of objectives to specific, measurable attributes that meet the needs of the decision model used to rank the alternatives (see Figure 2-3). Included in the hierarchy are an overall objective, subobjectives, criteria and attributes.

Several properties are desired of this hierarchy. First, and most important, the hierarchy should lead to an appropriate ranking of alternatives, which is one that accurately reflects the preferences of the decision-maker. Second, the hierarchy should be reasonably easy to use. Ease of use is critical in order for the ranking to be achieved within time and cost limitations. Some aspects of ease of use include:

(1) Ease of response for those required to provide preferences for the decision model.

(2) Ease of obtaining performance data for alternatives with regard to the attributes.

(3) Ease of carrying out the sensitivity analysis.

The top level in the hierarchy is an overall statement of the objective for the power system concept alternatives (primarily in terms of basic requirements). The overall objective for the project was to assess the potential of developing a nuclear powered source of energy for space applications.

The subobjectives provide distinct categories for the components of the overall objective. These components are chosen to facilitate further refinement of the hierarchy. Suggested categories for the subobjectives include economic, operational and technical objectives.

The level below subobjectives contains criteria. The criteria must permit the quantification of performance of the alternatives with respect to the subobjectives. In other words, the criteria are the highest level elements in the hierarchy that are designed to be, or intended to be, quantifiable. For example, cost is a logical candidate for the criterion related to the economic subobjective.

At the lowest level in the hierarchy are the attributes, which measure the extent to which each of the criteria are satisfied. To give an example, technical maturity may be an attribute to measure technical development requirements with respect to a risk criterion.

The set of attributes to be employed when ranking advanced system alternatives must meet several technical requirements. It must be complete enough to include all of the factors that could significantly influence the decision, yet not so large as to overburden those who must provide preferences. Attributes should be carefully selected to avoid redundancy or double counting of the system characteristics. The attributes selected should differentiate between systems by measuring only important advantages and disadvantages inherent in the different types of technologies being considered. For instance, many of the cost factors may be represented by initial cost and life-cycle cost. Other attributes should measure major indicators such as technical, operational and organizational factors that impinge on the choice of advanced system alternatives.

C. OBJECTIVES FOR ASSESSING SYSTEM CONCEPT ALTERNATIVES

Four specific objectives of the MDA (Multiattribute Decision Analysis) are listed below. They are:

(1) Determination of the spaceborne power system attribute values and relative weightings that reflect the preferences of decision makers in the public and private sectors relative to the nuclear industry (e.g., safety, cost).

(2) Rank the system alternatives with respect to the overall objectives and attributes, based on the system and subsystem assessments.

(3) Perform a sensitivity analysis on the rankings with regard to the system concept attribute values and the relative weightings.

(4) Provide insights about possible combinations of nuclear technologies toward construction of a proof-of-technology plan to carry out development of most promising technologies.

As a guideline for developing the attributes for the first objective, a list of requirements have been developed. Because many power system configurations and subsystem alternatives were being considered to overcome deficiencies of the baseline concepts, a comparison of system candidates on any meaningful basis requires equalizing as many of the external variables as possible. Thus the SP-100 Requirements were developed, which specify the system capabilities in terms of its size, power levels, mass, lifetime, and a number of other criteria. These requirements were used as design goals to synthesize, with the aid of models, the alternative system concepts evaluated. The final configurations are a result of the system requirements, subsystem characteristics, and control strategy trade-offs. The general SP-100 requirements are shown in Table 3-1.

Perhaps the most critical parameters, in terms of the system design, were mass, temperature, and power level. Various parametric relationships between mass, power level, and temperature were used to define the various materials used and identify the feasible combinations of reactors, heat exchangers, and power conversion subsystems. Mass is obviously critical because of its sensitivity to a variety of design variables. Changes in temperature or materials can imply dramatic differences in mass. Because the power level was so interrelated with the other parameters, the assumption of a 100-kW level was made to provide a design baseline for the comparisons. By fixing the mass, and thus fixing a key dimension of the system, the synthesis of the systems was greatly simplified. On the other hand, issues such as growth capability were not included due to the lack of mission definition coupled with the assumption that a number of these 100-kW units could possibly be linked together to obtain higher power levels. Temperature was a key parameter since changes in hot-side temperatures define not only the mass, but the technology development. Increasing the operating temperatures for whatever benefits, in general, requires increasingly complex and longer-range technology development efforts to prove the concept.

The design lifetime was also assumed to be 7 years in the analysis. However, in evaluating the choices among the alternative system concepts, the values associated with each alternative were in some cases related to the probable impact on lifetime. For example, in considering multiple start-up capabilities, some of the technical systems are more amenable to this capability than other due to coolant freezing. In this sense, the alternative concepts were measured against their ability to meet the requirement.

The safety requirements are a key concern and are stated in reference to a more detailed analysis of safety than presented here. Safety in this analysis was defined as a multiple range of scenarios which at one extreme exceed the safety levels of current launch preparation, on-orbit operation, and at the other end are below these safety levels.

A number of additional requirements were also considered but are not detailed here. These included load following capability, start-up, autonomy, reliability, survivability, dormancy, interfaces, reactor-induced and power-system-induced radiation, and size.

Table 3-1. Primary System Concept Requirements

Requirements	Value
(1) System Mass	3000 kilograms
(2) Design Lifetime	7 years
(3) Safety	Shall meet all defined requirements
(4) Power Output	100 kilowatts
Additional Requirements	
(5) Power Distribution	
(6) Load Following Capability	
(7) Start-up Characteristics	
(8) Autonomy of System	
(9) Reliability	
(10) Survivability	
(11) Dormancy	
(12) Interfaces (Electrical, Command/ Data/Telecommunications)	
(13) Reactor-Induced Radiation to Payload	
(14) Power-System-Induced Thermal Radiation	
(15) Size	

The SP-100 requirements list was used to begin to define the heirarchy of objectives, criteria, and attributes for ranking alternatives. The first task was to separate the objectives to be used in the ranking methodology for alternatives from those objectives that are fixed requirements or constraints.

Good candidates for constraints included requirements (1), (2), (4), (15), and (12) through (14). They could be treated as constraints by requiring any system concept to meet them before being accepted for ranking with regard to the remaining objectives. Good candidates for attributes included requirements (3) and (6) through (11) because they can be used effectively to differentiate between alternative systems.

The objectives of cost minimization, high technical maturity, safety, and performance were also candidates to aid in the definition of the hierarchy. Objectives, criteria, and attribute sets are discussed below.

D. OBJECTIVES, CRITERIA, AND ATTRIBUTE SETS

Several sets of candidates for use as objectives, criteria, and attributes were developed. While reviewing these sets, it was noted that there were two possibly conflicting objectives for the set chosen for use with the decision model. The criteria and attribute set had to be complete enough to capture the reality of the problem, yet not so large that it overburdened those people who had to provide their preferences nor those who exercised the decision model and carried out the sensitivity analysis.

The candidate sets of objectives, criteria, and attributes were reviewed by Project staff at JPL and representatives from Los Alamos National Laboratories and NASA Lewis Research Center. After several iterations, a set for use in the ranking was chosen.

The hierarchy chosen is shown in Figure 3-1. This set includes a single overall objective, eight subobjectives (safety, payload, survivability, operational, technical, schedule, and economic), eight criteria, and eight attributes. With eight attributes, the ranking and sensitivity analysis proved manageable. Also, after the interviews, no significant attribute was found to be missing from the set chosen, based on the information available at that time. Estimated development cost and production cost were deemed to be desirable, but insufficient information was available for estimating these elements and so they were not included in the formal analysis.

E. DISCUSSION OF ATTRIBUTES

Safety was characterized in terms of a scenario scale that ranged from 0 - 10 where each point on the scale is described by a brief statement regarding that safety level. In the best case, the safety level would exceed that of present launch vehicles. The scale itself was divided into a number of subdimensions including pre-launch, launch, on-orbit operation, and re-entry.

Survivability was characterized in terms of a scenario scale attribute called estimated likelihood of surviving threats at required levels. The primary concern here was for man-made threats as opposed to those in the natural environment, such as meteorites. It was assumed that all the systems were comparable in terms of armor to protect against meteorites.

The operational aspects of the system concepts were captured with three attributes: dormancy capability, radiator area, and likelihood of meeting the reliability requirements. Again, both dormancy capability and likelihood of meeting the reliability requirements were measured, using a scenario scale from 0 - 10. The radiator area was measured in terms of square meters.

The technical elements of the comparison were characterized by another descriptive measure called producibility. Producibility measures the modularity, fabricability, and level of interfacing involved in the construction of the system. The producibility was measured on a 1 - 10 scale in a similar manner to technical maturity with points on the scale described with brief statements.

The schedule elements of the evaluation were characterized using a descriptive measure called technical maturity. The technical maturity was characterized in terms of a 0 - 10 scale where points on the scale are represented by brief statements describing each level.

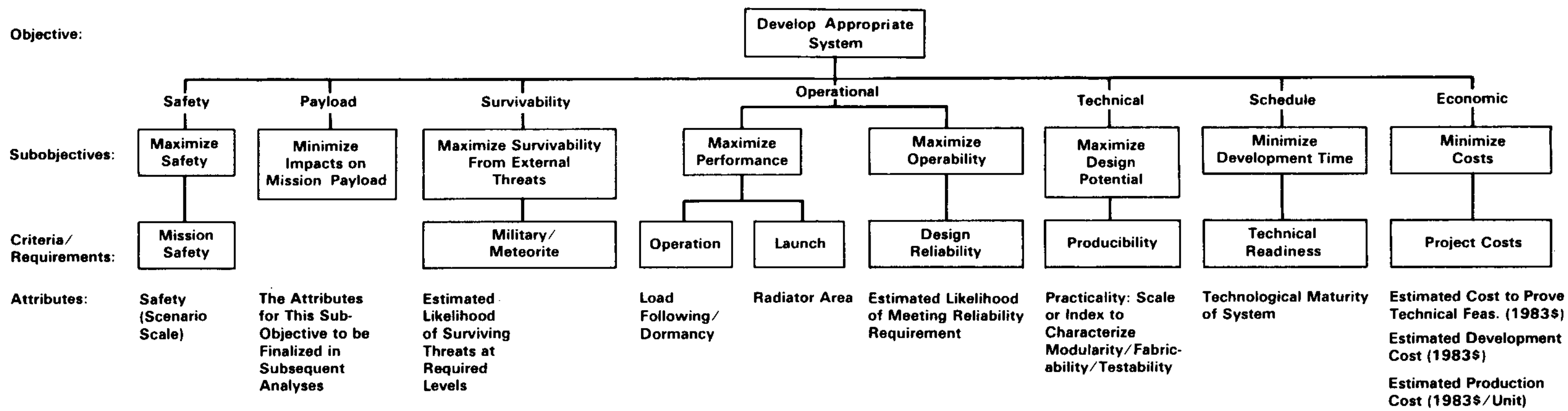


Figure 3-1. Hierarchy of Objectives, Subobjectives, Criteria, and Attributes for Spaceborne Power System Concepts

Three cost measures were identified: estimated cost to prove technical feasibility (at a pre-defined level), development cost, and production cost. Development cost was desired because it tends to scope the overall project cost. Production cost was of interest due to the economies of scale possible with the production of large numbers of power systems and the fact that large development costs could possibly be outweighed by low unit costs. As mentioned earlier, development cost and production cost were not believed to be significant in affecting the overall rankings and thus were not included. The key cost attribute used was the estimated cost to prove technical feasibility. This value was more appropriate because the overall scope of this effort was to provide input into the development of a plan to demonstrate technical feasibility. The costs were measured in 1983 dollars because all of the interviews were conducted in 1983. This cost attribute was considered most directly related to the ranking of a system concept.

F. DETERMINATION OF ATTRIBUTE SCALES

In order for the decision model to be applied in the ranking effort, a scale for each attribute used had to be developed. Each scale required a unit measure and upper and lower bounds. For example, the attribute estimated cost to prove technical feasibility, 1983 dollars was the unit of measure, and $114 million and $240 million dollars were the lower and upper bounds. Because the nature of the task involved technology assessment and the synthesis of conceptual representations of these systems, only subsystem parametric data were available for the most part. As a result, the majority of attributes were characterized, using descriptive scenario scales to develop the ranges necessary to discriminate between systems. The list of attributes chosen with the ranges for cost and performance is given in Table 3-2.

The upper and lower bounds for each attribute had to be determined so that all alternatives had performance levels that fit within these bounds. If a performance level had fallen outside one of these bounds, the utility of that performance level could not have been calculated.

Table 3-2. Attributes with Their Ranges

	Attribute[a]	Range
(1)	Safety	Level 3 to 8 (scenario)
(2)	Radiator Area[b]	27 to 108 m^2
(3)	Design Reliability	Level 2 to 10 (scenario)
(4)	Technical Maturity	Level 3.8 to 7.8 (scenario)
(5)	Estimated Cost to Reach Technical Feasibility	$114 to 240 million (1983 dollars)
(6)	Survivability	Level 5 to 10 (scenario)
(7)	Dormancy Capability[c]	Level 2 to 10 (scenario)
(8)	Producibility	Level 3 to 8 (scenario)

[a]See Appendix A for the scale definitions for attributes (1), (3), (4), and (6) through (8).

[b]Assumes larger radiators deployable.

[c]Load following comparable for all systems via shunt.

SECTION IV

ALTERNATIVES AND STATE DATA

A. INTRODUCTION

This section briefly lists the sixteen alternative system concepts ranked by this study and gives the state data for each concept for the eight attributes. The attributes are described in Section III.

B. ALTERNATIVE SYSTEM CONCEPTS

The systems included seven heat-pipe cooled and seven liquid-metal cooled systems with a variety of dynamic and static power conversion systems. One gas-cooled system and an in-core system were also examined. The conversion systems included Brayton, Stirling, Rankine, thermoelectric, thermophotovoltaic, thermionic, and AMTEC technologies. The sixteen system concepts are listed in Table 4-1 along with their acronyms used to identify the systems in the interview process questionnaire (Appendix A) and in the tables of ranking results (Section VI), respectively. Performance requirements for all sixteen systems are given in Table 3-1.

Table 4-1. Alternative System Concepts with Abbreviations

	System Concept	System Concept Abbreviation
1.	Liquid-metal cooled/out-of-core thermionic	LOCTP
2.	Liquid-metal cooled/Brayton	LBO
3.	Liquid-metal cooled/Stirling	LSH
4.	Liquid-metal cooled/Rankine	LRL
5.	Liquid-metal cooled/AMTEC	LAP
6.	Liquid-metal cooled/Thermoelectric	LTEP
7.	Gas-cooled/Brayton	GBH
8.	Heat-pipe cooled/out-of-core thermionic	HOCTP
9.	Heat-pipe cooled/Brayton	HBO
10.	Heat-pipe cooled/Stirling	HSH
11.	Heat-pipe cooled/Rankine	HRL
12.	Heat-pipe cooled/AMTEC	HAP
13.	Heat-pipe cooled/thermophotovoltaic	HTPVP
14.	Heat-pipe cooled/thermoelectric (1380K)	HTEP
15.	Heat-pipe cooled/thermoelectric (1250K)	HTEPa
16.	In-core-thermionic	ICT

C. SYSTEM CONCEPT ATTRIBUTE STATE DATA

The attribute state data for the sixteen concepts were developed in June and July 1983. The data are presented in Table 4-2. The details of the subjective scales for safety, technical maturity, design reliability, dormancy, survivability, and producibility are given in Section III. To illustrate those concepts that perform well irrespective of the relative importance of the attributes, consider Table 4-3. The attributes within 10% (of the range) of the best state of each attribute are marked. If all the attributes were equally important, the systems with the most checkmarks would be the preferred concepts. Table 4-3 shows, independent of the value model, that the heat-pipe thermoelectrics (HTEP, HTEPa) and Stirling concepts (HSH, LSH) rate highly on a number of attributes. This table is helpful in explaining the results of the ranking procedure.

These data were the culmination of effort by the SP-100 Technology Assessment Working Group of the SP-100 Project and reflect a detailed analysis of each of the major subsystems and their components. As mentioned earlier, much of the data collected were of a parametric form that were used with models and the requirements to synthesize the sixteen systems presented here. It should be noted that these values reflect a great deal of technical judgment because the majority of scales were subjective. However, the relative values among the system concepts are believed to be valuable information. The major difficulties occurred with the assessments of cost and technical maturity. There were a large number of uncertainties in the cost estimates because the totals were dominated by the reactor development costs. The technical maturity of each system was determined by assigning weights to each of the major components within each subsystem and then each subsystem. Each component and subsystem was then assigned a technical maturity value from the scale in Appendix A and a linear weighting was performed to calculate an overall technical maturity value assigned to the system as a whole.

Alternative System Concept [a]	Attribute							
	Safety	Radiator Area	Design Reliab.	Technical Maturity	Est. Cost/ Tech. Feas. $M	Survivability	Dormancy	Producibility
LOCTP	7	42	8	6.0	193	7	4	6
LBO	7	100	6	7.0	198	6	4	4
LSH	7	31	7	7.8	124	7	4	5
LRL	7	27	4	6.9	140	5	2	3
LAP	7	60	4	6.9	114	6	2	5
LTEP	7	80	9	7.2	143	8	5	8
GBH	3	50	2	3.8	213	5	9	4
HOCTP	8	42	8	6.0	200	8	8	6
HBO	8	107	7	7.0	190	7	8	4
HSH	8	31	8	7.8	124	8	8	5
HRL	8	27	5	6.9	160	6	4	3
HAP	8	60	5	6.7	114	7	4	5
HTPVP	8	108	5	3.9	240	5	9	7
HTEP	8	67	10	6.3	135	10	10	8
HTEPa	8	80	10	7.4	135	10	10	8
ICT	6	38	7	7.6	170	9	10	7

[a]LOCTP = Liquid-metal cooled/out-of-core thermionic
LBO = Liquid-metal cooled/Brayton
LSH = Liquid-metal cooled/Stirling
LRL = Liquid-metal cooled/Rankine
LAP = Liquid-metal cooled/AMTEC
LTEP = Liquid-metal cooled/thermoelectric
GBH = Gas-cooled/Brayton
HOCTP = Heat-pipe cooled/out-of-core thermionic
HBO = Heat-pipe cooled/Brayton
HSH = Heat-pipe cooled/Stirling
HRL = Heat-pipe cooled/Rankine
HAP = Heat-pipe cooled/AMTEC
HTPVP = Heat-pipe cooled/thermophotovoltaic
HTEP = Heat-pipe cooled/thermoelectric (1380K)
HTEPa = Heat-pipe cooled/thermoelectric (1250K)
ICT = In-core thermionic

Table 4-2. System Database for Sixteen System Concepts

Table 4-3. Attributes within Range x 10% of Most Preferred State

System	Safety	Radiator Area	Design Reliability	Technical Maturity	Feasibility Cost	Survivability	Dormancy	Producibility
LOCTP								
LBO								
LSH		X		X	X			
LRL		X						
LAP					X			
LTEP								X
GBH								
HOCTP	X							
HBO	X							
HSH	X	X		X	X			
HRL	X	X						
HAP	X				X			
HTPVP	X							
HTEP	X		X			X	X	X
HTEPa	X		X	X		X	X	X
ICT				X			X	

[a]Range x 10% defined as |Best State - Worst State| x 0.10

SECTION V

INTERVIEWS

A. INTRODUCTION

The methodology described in Section II requires preference information from individuals as well as attribute state data to produce a ranking of systems. The preference information required for each individual interviewed includes a scaling constant and a utility function for each attribute. Interviewees were sought who had significant knowledge of, and interest in, spaceborne nuclear power system concepts and who were regarded as decision makers within their organizations.

This section lists the organizations interviewed to obtain preference data and gives examples of the questions posed to them. (The full set of questions is contained in Appendix A) A summary of the interview results is also given in this section.

B. INTERVIEWEES

The desired interviewees were persons who would either have a direct role in the ultimate development of the concepts or who acted as advisors in the decision-making process. Representatives were sought from a variety of organizations with:

(1) Ongoing research and development programs in advanced power conversion systems.

(2) A proven record of achievement in the research and development of nuclear power systems.

(3) An understanding of space environment issues that have direct impact on developing nuclear power technologies for space applications.

These individuals represented four distinct areas:

(1) Safety. This group was concerned with a range of safety issues from ground development through launch, on-orbit operation, and re-entry.

(2) Systems Definition and Design. This group was concerned with the design issues and options involved in the development and deployment of the technology.

(3) Technology Assessment. This group was involved in assessing the technical issues facing the demonstration of technical feasibility for such power systems.

(4) Mission Analysis. This area involved the concerns of possible mission users who would utilize the system concepts.

Altogether, 11 people were interviewed between July 7, 1983, and July 22, 1983. The organizations represented included the Air Force Weapons Laboratory, Jet Propulsion Laboratory, Los Alamos National Laboratories, and NASA-Lewis Research Center. They included four individuals from the safety area, three from the systems definition and design category, three from the technology assessment working group, and one from the mission analysis category. Accordingly, 11 complete interviews form the corpus of the analysis.

The representation of members in the sample was constituted from an initial survey of representatives derived from conference agendas, personal contacts, and referrals. This "snowball" sampling approach was further refined during the interviews as additional recommendations were made. These recommendations were then reviewed for inclusion in the study. While this sample is not a random one, there were numerous individuals who simply had to be included because they had played a key role in some aspect of the advanced research. Using a random sampling design and possibly omitting them from the survey would have left serious gaps in the results of the study. Furthermore, a larger, random sample would tend to move the results toward some "average" set of responses. The aim of this study was to survey those at the leading edge of the advanced concepts development to obtain an informed, critical response as opposed to an average or typical response. Although more interviews might have been desirable, the time and resources to accomplish them were not available.

C. INTERVIEW PROCESS

The selected personnel were asked to provide their inputs to the rankings during one-hour interviews although, in fact, the interviews ranged from 60 to 100 min with an average of 75 min and a median of 75 min. These sessions were structured to acquire the interviewee's utility functions and scaling constants with regard to the attributes chosen for the purpose of ranking alternative advanced vehicle systems.

There were five steps in the decision-analysis interview, as shown in Figure 5-1. The first step provided an introduction to the interview and afforded the opportunity to have the interviewee's questions about the process answered. Next, the interviewee's utility function for each attribute was obtained by asking a series of preference questions. Following that, independence was checked by asking if the responses to those questions would vary with changes in the levels of the other attributes (i.e., attributes other than the one whose utility function was being assessed). The fourth step in the interview involved having the interviewee rank the attributes in order of importance. This provided a consistency check to aid with the final step, the acquisition of the interviewee's scaling constant for each attribute. The ranking of attributes helped guide the responses to the questions on scaling constants.

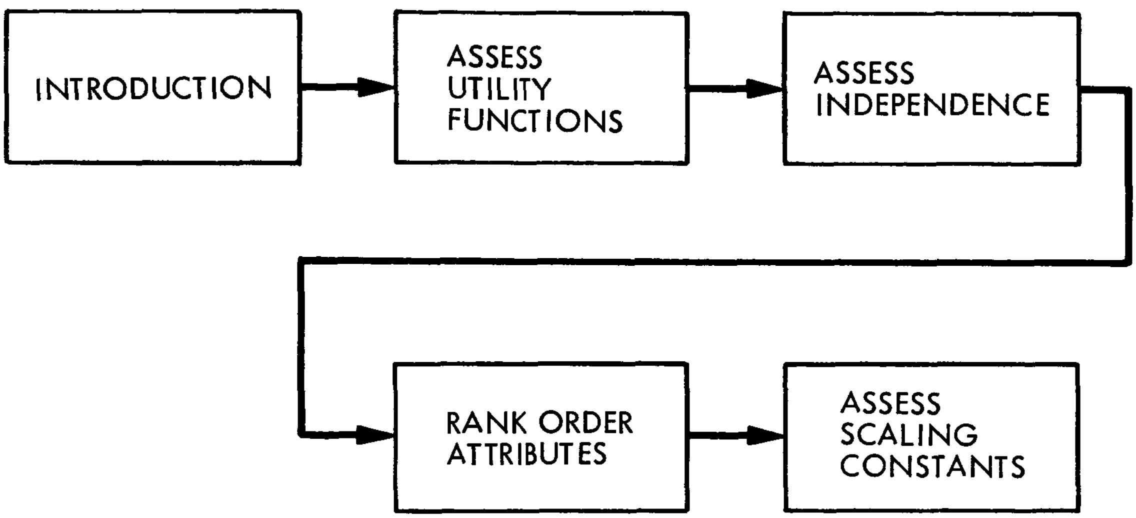


Figure 5-1. Decision-Analysis Interview Flow Chart

D. SAMPLE QUESTIONS

Sample questions for the interviews are illustrated by Figures 5-2, 5-3, and 5-4. Figure 5-2 contains a sample question used to obtain information that enabled the construction of the individual's utility function for the attribute "radiator area." Figure 5-3 contains a sample question for the ranking of attributes in order of importance, while Figure 5-4 shows a sample question for obtaining the scaling constant for an attribute. The full questionnaire used is contained in Appendix A in of this report.

E. INTERVIEW PROCESS REFERENCES

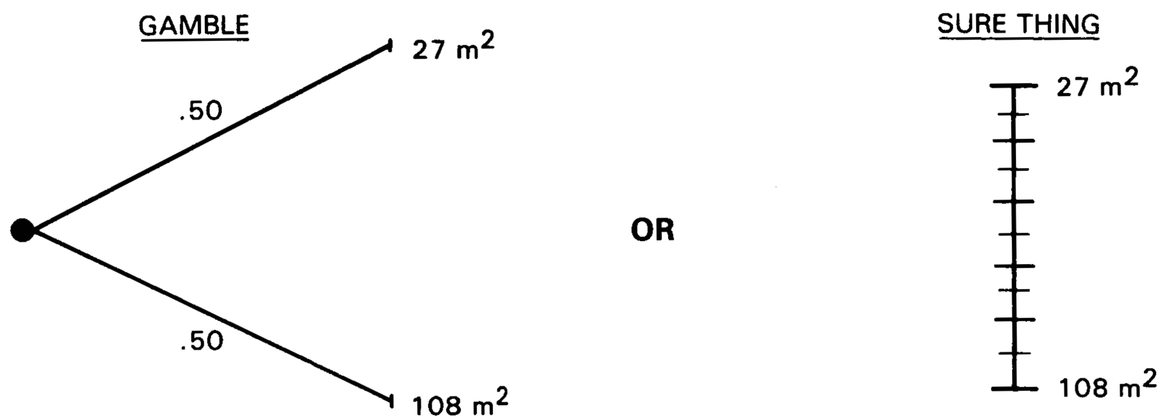
The use of interviews in the decision analysis process is well established and documented. Excellent descriptions of decision analysis with interviews are provided by Raiffa, Schlaifer, and Winkler (see References 3, 5, and 24). References on decision-analysis interviews particulary well-suited to the manager include Brown, Kahr, and Peterson (see Reference 21) and Huber (Reference 42). Chapter 4 of Huber's recent book (Reference 42) contains two case studies involving multiattribute decision-making. The authoritative book by Keeney and Raiffa (see Reference 1) contains a variety of case studies in multiattribute decision-making. Most of these cases are in Chapter 7, but one, involving airport development, described in detail in Chapter 8, includes responses to interview questions on utilities, independence, and scaling constants. Additional cases can be found in Feinberg, et al. (References 40 and 41).

F. INTERVIEW RESULTS

On the whole, the interviews went rather smoothly. All interviewees were able to provide the information needed to form their attribute utility functions and scaling constants. The average length of the interview was 75 min with the longest session completed in 100 min and the shortest in 60 min. There were five interviews (46%) that took 70 min or less; four interviews (36%) between 70 and 85 min; and two interviews (18%) that took 100 min. All 11 interviews were completed within 100 min, with nine (82%) less than 90 min.

The responses for the interviewees to the questions designed to elicit information needed to determine their attribute utility functions are summarized in Table 5-1 for the entire sample. Table 5-2 (a through c) shows the results by group (the mission analysis results are not shown because one person represented that area). As shown, there was a willingness in many cases to take a risk to obtain good (rather than average) technical maturity and safety levels. The safety group tended to be risk-averse to large radiator areas, poor technical maturity, and survivability. The systems area was risk-averse to low technical maturity and low survivability. The technology assessment area was generally neutral about cost, safety, and radiator area with different risk attitudes for survivability, dormancy, and producibility.

ATTRIBUTE: RADIATOR AREA



- FOR WHICH VALUE OF THE "SURE THING" ARE YOU INDIFFERENT BETWEEN THE "SURE THING" AND THE "GAMBLE"?

  INDIFFERENCE POINT _____

- IF YOU KNEW THAT ALL OTHER ATTRIBUTES WERE AT THEIR WORST STATES?

  INDIFFERENCE POINT _____

- IF YOU KNEW THAT ALL OTHER ATTRIBUTES WERE AT THEIR BEST STATES?

  INDIFFERENCE POINT _____

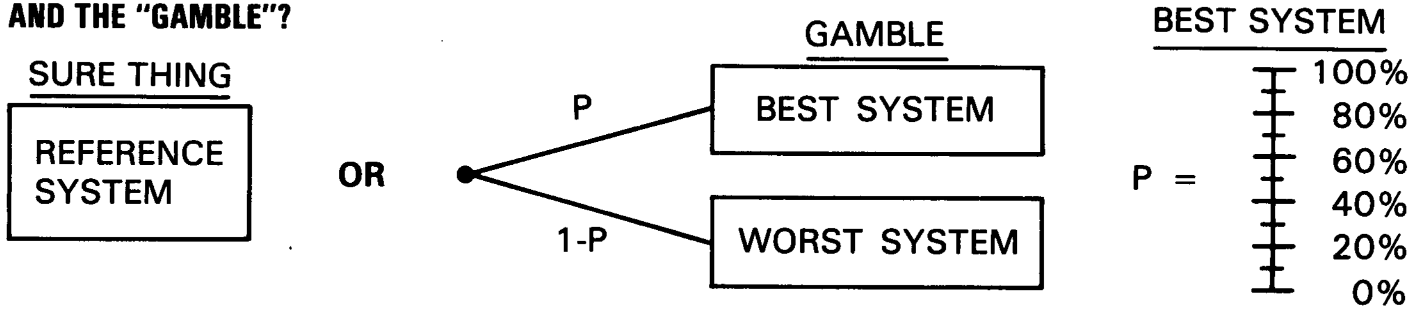
Figure 5-2. Sample Interview Question, Radiator Area

ATTRIBUTE	SAFETY	AREA, m^2	RELI-ABILITY	TECHNI-CAL MATURITY	EST. COST--TECH. FEASIBIL-ITY, $M	SURVIV-ABILITY	DORMANCY	PRODUC-IBILITY	EST. DEVEL. COST, 1983$	EST. PROD. COST, 1983$
Best State	8	27	10	7.8	114	10	10	8	NA	NA
Worst State	3	108	2	3.8	240	5	2	3	NA	NA

Order of Importance									NA	NA

Figure 5-3. Sample of Interview Question, Order of Attribute Importance

FOR WHAT VALUE OF P ARE YOU INDIFFERENT BETWEEN THE "SURE THING" AND THE "GAMBLE"?



	SAFETY	AREA	RELIAB.	MATUR.	FEAS. COST	SURVIV.	DORMANCY	PROD.	DEVEL. COST	PROD. COST
REFERENCE:		27 m^2								
	3		2	3.8	$240M	5	2	3	NA	NA
BEST:	8	27 m^2	10	7.8	$114M	10	10	8	NA	NA
WORST:										
	3	108 m^2	2	3.8	$240M	5	2	3	NA	NA

Figure 5-4. Sample Interview Question, Importance of Radiator Area

Table 5-1. Preference Data for all Interviews

	Attribute Question Range	Response Range	Median Certainty Equivalent	Risk Averse	Risk Neutral	Risk Prone
Safety	3-8	3-7.8	5.5	3	3	5
Radiator Area	27-108m^2	27-95	68.5	3	4	4
Design Reliability	2-10	3-8.5	6	4	4	2
Technical Maturity	3.8-7.8	3.8-7.0	5.75	2	4	5
Est. Cost to Reach Tech. Feasibility	$114-240M	$114-240M	$176M	5	4	2
Survivability	5-10	5-9	6.75	8	2	1
Dormancy	2-10	3-9	5.9	3	5	3
Producibility	3-8	3.5-7.8	5.5	3	3	5

Table 5-2. Preference Data for Interviews
(a) Safety Area

	Attribute Question Range	Response Range	Median Certainty Equivalent	Risk Averse	Risk Neutral	Risk Prone
Safety	3-8	3-7	5.8	1	1	2
Radiator Area	27-108m^2	40-95m^2	72.5m^2	3	1	0
Design Reliability	2-10	4-8	6	1	3	0
Technical Maturity	3.8-7.8	4.4-7.4	5.8	3	0	1
Est. Cost to Reach Tech. Feasibility	$114-240M	$123-230M	$172.5M	1	0	3
Survivability	5-10	5.5-9	6.5	3	1	0
Dormancy	2-10	3-8.5	5.8	2	1	1
Producibility	3-8	4-7	5.8	1	1	2

Table 5-2. Preference Data for Interviews
(b) System Definition and Design Area

	Attribute Question Range	Response Range	Median Certainty Equivalent	Risk Averse	Risk Neutral	Risk Prone
Safety	3-8	5-7.5	6.8	1	0	2
Radiator Area	27-108m^2	50-80m^2	65m^2	1	0	2
Design Reliability	2-10	3-7	5	2	1	0
Technical Maturity	3.8-7.8	3.8-7.8	4	3	0	0
Est. Cost to Reach Tech. Feasibility	$114-240M	$114-240M	$175.M	1	0	2
Survivability	5-10	5.8	6	3	0	0
Dormancy	2-10	4.8-8.5	6	1	1	1
Producibility	3-8	4-7.8	5.5	1	1	1

Table 5-2. Preference Data for Interviews
(c) Technology Assessment Area

	Attribute Question Range	Response Range	Median Certainty Equivalent	Risk Averse	Risk Neutral	Risk Prone
Safety	3-8	4-7.5	5.5	1	2	0
Radiator Area	27-108m^2	27-92m^2	67m^2	1	2	0
Design Reliability	2-10	4-8.5	7	1	0	2
Technical Maturity	3.8-7.8	4-7.4	6.5	1	0	2
Est. Cost to Reach Tech. Feasibility	$114-240M	$120-208M	$177	0	3	0
Survivability	5-10	6.8	7.5	1	1	1
Dormancy	2-10	3-9	6	1	1	1
Producibility	3-8	3.5-7.5	5.5	1	1	1

Responses to the questions asking interviewees to rank the importance of each of the attributes are summarized for each group and the entire sample in Table 5-3. The ranking for each group was determined by taking the sum of the individual rankings within that group and placing the lowest sum as first in rank, the next lowest sum second, and so on.

Overall, initial safety and technical maturity were most important, and radiator area and cost least important (see also Table 5-4). It is interesting to note that some individuals ranked safety much lower than other attributes. This was due (primarily) to the perception that safety is a secondary issue (or non-issue) until it can be shown that the system is technically feasible. The mission analysis area (representing users to some extent) was less interested in cost and technical maturity than the more operational attributes like reliability, survivability, and producibility.

Table 5-3. Preference Data from Interviews, Importance of Attributes

	Rank Sum Rule Rankings			
Attribute	Safety Area	Systems Definition and Design Area	Technology Assessment	Mission Analysis
Safety	1	1	2-3	1
Radiator Area	7-8	8	6-8	4-6
Design Reliability	3	3	2-3	2-3
Technical Maturity	2	2	1	7-8
Estimated Cost to Reach Technical Feasibility	7-8	6-7	6-8	7-8
Survivability	5	4-5	5	4-6
Dormancy	6	6-7	6-8	4-6
Producibility	4	4-5	4	2-3

Table 5-4. Ranking of Attribute Importance

Attribute	Number of Times Rated: Most Important	Number of Times Rated: Least Important
Safety	7	1
Radiator Area	0	4
Design Reliability	0	0
Technical Maturity	4	0
Estimated Cost to Prove Technical Feasibility	0	5
Survivability	0	0
Dormancy	0	2
Producibility	0	1

SECTION VI

RANKING ANALYSIS AND DISCUSSION

A. OVERVIEW OF THE DECISION ANALYSIS RESULTS

The results of 11 successfully conducted interviews were analyzed by several different methods. Preference data were elicited from the interviewees on eight attributes for use in a multiattribute decision-analysis model.

The 11 interviews were classified into four areas, with three to four interviews in a group. The mission analysis area was represented by one individual. The four areas were generically classified as:

Group 1: Safety

Group 2: Systems Definition and Design

Group 3: Technology Assessment

Group 4: Mission Analysis

The rankings were developed by interviewee and by group. Three group decision rules were used for the groups: (1) The Additive Rule, (2) The Nash Bargaining Rule, and (3) The Rank Sum Rule.

B. MATEUS COMPUTER RUNS

A total of 40 MATEUS (MultiATtribute Evaluation of UtilitieS) runs were made to calculate preferences from the data of the multiattribute decision analysis interviews. The MATEUS Computer Program is given in Appendix B. The runs calculated both individual and group preferences. A single run calculated the preferences for a single group and for each of the interviewees of that group. The 40 MATEUS runs were composed of four runs of the nominal data and twelve variations (three runs each) on the nominal data. Comparable runs for the fourth group were not made because only one individual represented that group. However, a fourth run was included using the baseline nominal data (see Set 1 below).

The 40 runs, in sets of three for the three groups, are identified as follows:

(1) Set 1 is the set of runs with the nominal data and are referred to as the NOM/5/MULT Set. The attribute scaling constants are determined with the other attributes set at nominal states, 5 points are used for the piece-wise linear fit to the attribute utility functions, and the multiplicative form of the Keeney-Raiffa methodology is used.

(2) Set 2 is identified as the NOM/5/LIN Set. Set 2 is identical to the NOM/5/MULT Set (Set 1), except that the attribute scaling constants are normalized so that their sum is 1.0, and the Linear Form of the Keeney-Raiffa methodology is used.

(3) Set 3 is identified as the NOM/3/MULT Set. Set 3 is identical to the NOM/5/MULT Set (Set 1), except that a 3-point fit rather than a 5-point fit is used for the piece-wise linear fit to the attribute utility functions.

(4) Set 4 is identified as the WORST/3/MULT Set. Set 4 is identical to the NOM/3/MULT Set (Set 3), except that the attribute utility functions were elicited with the other attributes set at their worst states.

(5) Set 5 is identified as the BEST/3/MULT Set. Set 5 is identical to the NOM/3/MULT Set (Set 3), except that the attribute utility functions were elicited with the other attributes set at their best states.

(6) Set 6 is identified as the SAFETY Set. Set 6 is identical to the NOM/5/MULT Set (Set 1), except that the attribute state for safety (Attribute #1) is fixed at 3 for all systems. The effect of fixing an attribute at its worst state is to remove it, and its contribution, from the analysis. This reveals the sensitivity of the rankings to the attribute.

(7) Set 7 is identified as the RADAREA Set. Set 7 is identical to the NOM/5/MULT Set (Set 1), except that the attribute state for radiator area (Attribute #2) is fixed at $108 m^2$ for all systems.

(8) Set 8 is identified as the DESREL Set. Set 8 is identical to the NOM/5/MULT Set (Set 1), except that the attribute state for design reliability (Attribute #3) is fixed at 2 for all systems.

(9) Set 9 is identified as the TECHMAT Set. Set 9 is identical to the NOM/5/MULT Set (Set 1), except that the attribute state for technical maturity (Attribute #4) is fixed at 3.8 for all systems.

(10) Set 10 is identified as the FEASCOST Set. Set 10 is identical to the NOM/5/MULT Set (Set 1), except that the attribute state for estimated cost to prove technical feasibility (Attribute #5) is fixed at $240 million for all systems.

(11) Set 11 is identified as the SURV Set. Set 11 is identical to the NOM/5/MULT Set (Set 1), except that the attribute state for survivability (Attribute #6) is at 5 for all systems.

(12) Set 12 is identified as the DORMANCY Set. Set 12 is identical to the NOM/5/MULT Set (Set 1), except that the attribute state for dormancy (Attribute 7) is fixed at 2 for all systems.

(13) Set 13 is identified as the PRODUC Set. Set 13 is identical to the NOM/5/MULT Set (Set 1), except that the attribute state for producibility (Attribute 8) is fixed at 3 for all systems.

C. MULTIATTRIBUTE RESULTS FOR NOMINAL ATTRIBUTE DATA

Preference data was elicited from the interviewees on eight attributes for use in a multiattribute decision analysis, with twelve variations on the nominal data to examine the robustness of the multiattribute states on the rankings. The methodology for the multiattribute decision analysis model is the Keeney-Raiffa Methodology, which is discussed in Section II. Section VI discusses the multiattribute results specifically for the nominal data. The nominal data is defined to be the data gathered in the interviews with the 5-point piece-wise linear fit to the interviewee utility functions, the scaling constants determined with the other attributes at nominal states, and the alternative system data unmodified (Set 1: NOM/5/MULT).

Table 6-1 gives the rankings for the system concepts for all 11 interviewees for Set 1 (NOM/5/MULT). Table 6-1 shows that the heat-pipe thermoelectric reactor systems (HTEP, HTEPa) were preferred followed by the heat-pipe Stirling (HSH) system and then a split over the in-core thermionic (ICT) versus the heat-pipe out-of-core thermophotovoltaic (HOCTP) for fourth place. The liquid-metal thermoelectric (LTEP) and Stirling (LSH) are next followed by the heat-pipe AMTEC (HAP). The least preferred systems are the liquid-metal Brayton (LBO), liquid-metal Rankine (LRL), and gas-cooled Brayton (GBH) system.

When the individual rankings are aggregated into group rankings, the rank order becomes somewhat more apparent. See Table 6-2, which was constructed from the results of the three group decision rules. The heat-pipe thermoelectrics (HTEP, HTEPa) still rank first followed by the heat-pipe Stirling (HSH), the in-core thermionic (ICT) and heat-pipe out-of-core thermionic (HOCTP). The least preferred systems are still the liquid-metal Brayton (LBO), liquid-metal Rankine (LRL), and gas-cooled Brayton (GBH).

Table 6-3 gives the rank ordering for the alternative systems according to each of the eight attributes. Each of the attributes was varied in developing the designs that determined the attribute states of the sixteen alternative systems. It is not apparent from Table 6-3 that any one of the attributes can account for the multiattribute results with the nominal data. design reliability, survivability, dormancy, and producibility appear to have the greatest effect in the contributions to the upper-level rankings.

D. RESULTS OF VARIATIONS ON MULTIATTRIBUTE NOMINAL DATA

Runs with thirteen variations on the multiattribute nominal data (Sets 2 through 13) were made to examine the variations of the results to the multiplicative model form, to the preferences of the interviewees, and to the specified states of the alternative systems. Only the group decision results will be discussed because the variations are all of second order, and the group decision rules best summarize the variations in the rankings. The comparisons are summarized in Tables 6-4a, b, and c.

Table 6-1. Rankings for All Individuals for Set 1 (NOM/5/MULT)

	Area 1[a]				Area 2			Area 3			Area 4
Interview No. System Concept[b]	5	10	2	1	8	6	9	4	7	3	11
LOCTP	10	11	10	9	12	10	13	11	8	12	12
LBO	14	13	14	14	14	13	14	14	14	14	15
LSH	7	8	8	5	8	5	7	8	6	6	11
LRL	13	15	15	13	15	14	15	13	13	15	14
LAP	12	14	13	11	13	12	12	12	12	13	13
LTEP	5	4	5	6	10	6	4	6	4	8	9
GBH	16	16	16	16	16	16	16	16	16	16	16
HOCTP	4	5	6	7	4	7	6	4	7	5	4
HBO	9	9	7	10	6	8	9	9	10	9	5
HSH	2	2	3	3	3	2	3	3	5	3	3
HRL	11	11	11	12	9	11	10	7	11	11	6
HAP	8	8	9	8	7	9	5	5	9	7	7
HTPVP	15	15	12	15	11	15	11	15	15	10	8
HTEP	3	3	2	2	2	3	2	2	2	2	2
HTEPa	1	1	1	1	1	1	1	1	1	1	1
ICT	6	6	4	4	5	4	8	10	3	4	10

[a]See page 6-1 for group names.
[b]See Table 4-1 on page 4-2 for system names.

Table 6-2. Multiattribute Decision Analysis: Summary of System Concept Ranking Using Nominal States, Multiplicative Model, 5-pt Utilities

SYSTEM RANKINGS

	Liquid Metal							Heat Pipe								
Group	LOCTP	LBO	LSH	LRL	LAP	LTEP	GBH	HOCTP	HBO	HSH	HRL	HAP	HTPVP	HTEP	HTEPa	ICT
Safety	10	14	7	15	12-13	4	16	6	8	3	11	9	12-13	2	1	5
Systems Definition/Design	11	13-14	6	14-15	12	5-6	16	4-7	9	3	10	8	12-15	2	1	4
Technology Assessment	11	14-15	6-7	13-14	12	4-7	16	4-8	9	3	10	8	13-15	2	1	5
Mission Analysis*	12	15	11	14	13	9	16	4	5	3	6	7	8	2	1	10

*Individual ranking (one member interviewed)

Table 6-3. Rankings by Each of Eight Attributes

System	Safety	Rad. Area	Design Reliab.	Tech. Maturity	Feas. Cost	Surviv.	Dorman.	Prod.
LOCTP	9-14	6-7	4-6	13-14	12	7-10	10-14	6-7
LBO	9-14	14	10	6-7	13	11-13	10-14	12-14
LSH	9-14	3-4	7-9	1-2	3-4	7-10	10-14	8-11
LRL	9-14	1-2	14-15	8-10	7	14-16	15-16	15-16
LAP	9-14	9-10	14-15	8-10	1-2	11-13	15-16	8-11
LTEP	9-14	12-13	3	5	8	4-6	9	1-3
GBH	16	8	16	16	15	14-16	4-5	12-14
HOCTP	1-8	6-7	4-6	13-14	14	4-6	6-8	6-7
HBO	1-8	15	7-9	6-7	11	7-10	6-8	12-14
HSH	1-8	3-4	4-6	1-2	3-4	4-6	6-8	8-11
HRL	1-8	1-2	11-13	8-10	9	11-13	10-14	15-16
HAP	1-8	9-10	11-13	11	1-2	7-10	10-14	8-11
HTPVP	1-8	16	11-13	15	16	14-16	4-5	4-5
HTEP	1-8	11	1-2	12	5-6	1-2	1-3	1-3
HTEPa	1-8	12-13	1-2	4	5-6	1-2	1-3	1-3
ICT	15	5	7-9	3	10	3	1-3	4-5

Table 6-4. Multiattribute Decision Analysis: Summary of System Concept Rankings
(a) Results for Safety Group

SYSTEM RANKINGS

Set	Ranking Method	(------ Liquid Metal					------)		(------ Heat Pipe								------)	
		LOCTP	LBO	LSH	LRL	LAP	LTEP	GBH	HOCTP	HBO	HSH	HRL	HAP	HTPVP	HTEP	HTEPa	ICT
(1)	NOM/5/MULT	10	14	7	15	12-13	4	16	5-6	9-8	3	11	8	12-13	2	1	5
(2)	NOM/5/LINEAR	9-10	13	7	15	12	4	16	6	9-10	3	11	8	14	2	1	5
(3)	NOM/3/MULT	11	14	8	15	13	4-5	16	4-5	9	3	10	7	12	2	1	6
(4)	WORST/3/MULT	12	14	8-9	15	13	4-5	16	4-6	8-9	3	10	6-7	11	2	1	5-7
(5)	BEST/3/MULT	11	14	8-9	15	13	4-5	16	4-5	8	3	10	6-7	12	2	1	6
(6)	NOM/5/MULT/ SAFETY @ 3	8	13	6	14	11-12	5	16	7	10	3-4	11-12	9	15	2	1	3-4
(7)	NOM/5MULT/ RAD AREA @ 108	10	13	7-8	15	14	4	16	5-6	7	3	11	9	12	2	1	5-6
(8)	NOM/5/MULT/ DES REL @ 2	12	15	8	14	11	5-7	16	5-7	9	2-3	10	5-7	13	2	1	4
(9)	NOM/5/MULT/ TECH MT @ 3.8	9	14	10-11	15	13	5	16	4	8	3	12	7	10-11	1	2	6
(10)	NOM/5/MULT/ COST @ $240M	10	13-14	7-8	15	13-14	4-6	16	4-5	7-8	3	11	9	12	2	1	5-6
(11)	NOM/5/MULT/ SURV. @ 5	10-11	14-15	6-7	14-15	12-13	16	5	9	2-3	2-3	10-11	8	12-13	2-3	1	6
(12)	NOM/5/MULT/ DORM @ 2	9-10	13	5-6	13-14	12	4	16	5-6	9-10	3	11	7-8	15	2	1	7
(13)	NOM/5/MULT/ PROD @ 3	11	13	5	14	12	7	16	4	7-8	2	10	7-9	15	3	1	6

Table 6-4. Multiattribute Decision Analysis: Summary of System Concept Rankings
(b) Results for Systems Definition and Design Group

SYSTEM RANKINGS

		(------ Liquid Metal ------)							(------ Heat Pipe ------)								
Set	Ranking Method	LOCTP	LBO	LSH	LRL	LAP	LTEP	GBH	HOCTP	HBO	HSH	HRL	HAP	HTPVP	HTEP	HTEPa	ICT
(1)	NOM/5/MULT	11	13-14	6	14-15	12	5-6	16	4-7	9	3	10	6-8	12-15	2	1	4
(2)	NOM/5/LINEAR	10	13-14	8	15	12	4-6	16	4-6	9	3	11	7	13-14	1-2	1	4
(3)	NOM/3/MULT	11	13-14	6-8	14-15	12	4-5	16	5-7	9	2-3	10	7-8	13-15	2	1	4-5
(4)	WORST/3MULT	11	14	6-9	15	11-12	4-6	16	4-7	7-9	3	10	5-8	13	2	1	5-7
(5)	BEST/3/MULT	11	13-14	6-8	14-15	12	4-7	16	5-6	9	2-3	10	6-8	13-15 .	2-3	1	4-5
(6)	NOM/5/MULT/ SAFETY @ 3	9-10	13	5-6	14-15	11	5	16	7	9-10	4	12	8	14-15	2	1	3
(7)	NOM/5/MULT/ RAD AREA @ 108	11	13	8-9	15	12-13	4	16	5-6	7	3	18	7-9	11-14	2	1	5
(8)	NOM/5/MULT/ DES REL @ 2	12-13	15	7-8	13-14	11	7	16	6	9-10	2-3	9-10	4	12-14	2	1	5
(9)	NOM/5/MULT/ TECH MT @ 3.8	10	14	9	15	13	6	16	4	8	3	10-11	7	12	1	2	5
(10)	NOM/5/MULT/ COST @ $140M	10-11	12-13	9	15	14	6	16	4	6-7	3	10-11	8	12-13	2	1	4
(11)	NOM/5/MULT/ SURV. @ 5	11-12	15	6-8	13-14	12-13	5-7	16	4-7	9	2	10	5-8	11-14	3	1	4-6
(12)	NOM/5/MULT/ DORM @ 2	11	13-14	5	14-15	12	4-5	16	5-8	9-10	2-3	9-10	4-6	13-15	2-3	1	7-8
(13)	NOM/5/MULT/ PROD @ 3	11	13-14	4-7	14-15	12	9-10	16	4-7	6-8	1	9-10	5	13-15	3	1-2	6-8

Table 6-4. Multiattribute Decision Analysis: Summary of System Concept Rankings (c) Results for Technology Assessment Group

SYSTEM RANKINGS

Set	Ranking Method	Liquid Metal							Heat Pipe								
		LOCTP	LBO	LSH	LRL	LAP	LTEP	GBH	HOCTP	HBO	HSH	HRL	HAP	HTPVP	HTEP	HTEPa	ICT
(1)	NOM/5/MULT	11	14-15	6-8	13-14	12	4-6	16	4-8	9	3	10	7	13-15	2	1	4-5
(2)	NOM/5/LINEAR	9-10	13-14	6	13-14	12	5	16	6-7	9-10	3	11	8	15	2	1	4
(3)	NOM/3/MULT	10-11	14	6-7	13	12	4-6	16	4-7	9	3	9-11	7-8	14-15	2	1	4-5
(4)	WORST/3/MULT	9-11	15	4-6	13-14	12	4	16	6-7	9	3	9-11	8	13-14	2	1	5-6
(5)	BEST/3/MULT	9-11	14	5	13	12	4-5	16	4-7	9-11	3	10	5-8	15	2	1	5-6
(6)	NOM/5/MULT/ SAFETY @ 3	9	13-14	6	13-14	11	5	16	7	10	3-4	12	8	14-15	2	1	3-4
(7)	NOM/5/MULT/ RAD AREA @ 108	10	13-14	6-8	15	12	4	16	7-9	7-9	3	10-11	5-8	13-14	2	1	5
(8)	NOM/5/MULT/ DES REL @ 2	12	14-15	5-6	12-13	11	6-8	16	6-8	10	2	9	4-7	12-15	3	1	4
(9)	NOM/5/MULT/ TECH MT @ 3.8	7-10	15	8-9	14	13	4-5	16	4-5	8-10	3	11	6-8	12	1	2	6-7
(10)	NOM/5/MULT/ COST @ $240M	10-11	13-14	6-8	14-15	12-13	5-6	16	4-7	9	3	10-11	7-8	12-15	2	1	4-5
(11)	NOM/5/MULT/ SURV. @ 5	11	14-15	6-7	13-14	12	4-5	16	4-8	9	2-3	10	5-7	13-15	2	1	5-8
(12)	NOM/5/MULT/ DORM @ 2	11	14	5-6	13	12	4	16	7-8	9-10	2-3	9	4-7	15	2	1	6-8
(13)	NOM/5/MULT/ PROD @ 3	11	14-15	4-5	13	12	6-9	16	7-8	8-9	2	9-10	4-7	14-15	3	1	4

The data for Set 2 (NOM/5/LIN) were derived from the data of Set 1 (NOM/5/MULT) by normalizing the sum of the attribute scaling constants to 1.0 for all interviewees. This reduces the Keeney Multiplicative Form to the Linear Form, where the attributed scaling constants are simple weighting factors, and the multiattribute model is just the weighted sum of the attribute utilities. Linearizing the model makes a significant difference in the form of the model because the sum of the attribute scaling constants for the nominal data for the 11 interviewees range from a low of 2.70 (master scaling constant = -0.965791) to a high of 4.80 (master scaling constant = -0.999696) with a mean value of 3.516. Even with this significant change in the scaling constants, the results prove to be very robust, with very little change in ranking as shown in Table 6-4.

The data for Set 3 (NOM/3/MULT) were derived from the data of Set 1 (NOM/5/MULT) by using only the end points and the midpoint of the attribute utility functions. The results of using Set 3 serve two purposes: (1) to examine the sensitivity of the results to the coarseness of the piece-wise linear approximation to what is almost certainly a smooth function, and (2) to use as a reference for examining the results from using the data of Set 4 and Set 5. The results of using the data for Set 3 are shown in Table 6-4. The results of using the data for Set 3 are virtually identical to the results of using the data for Set 1, with only small changes in ranking for a few applications of the group decision rules.

The data for Set 4 (WORST/3/MULT) were derived from the interview data, using the attribute utility functions obtained when the interviewees were asked to assume that all other attributes were at their worst states. Placing the other attributes at their worst states made some of the alternative systems so undesirable that some interviewees were unable to respond with answers that could be translated into attribute utility functions. Where runs could be made to determine rankings with the group decision rules, once again only minor changes in ranking for a few applications of the group decision rules occurred (Table 6-4).

The data for Set 5 (BEST/3/MULT) were derived from the interview data, using the attribute scaling constants obtained when the interviewees were asked to assume that all other attributes were at their best (most-preferred) states. Where runs could be made to determine rankings with the group decision rules, once again only as much as a one-place change in ranking for a few applications of the group decision rules occurred (Table 6-4). Thus the results for Set 4 (WORST/3/MULT) and Set 5 (BEST/3/MULT) indicate that the assumptions made by the interviewees about other attribute states when assessing a utility function for an attribute did not significantly affect the rankings, at least at the group decision level of aggregation.

Several variations on the nominal data were made to examine the effects of specific attributes on the rankings. The data for Set 6 (SAFETY) were derived from Set 1 (NOM/5/MULT) by fixing the attribute state for safety (Attribute #1) at 3 for all systems. The results are shown in Table 6-4. The results are essentially identical to the results for Set 1, thus eliminating the difference in safety as a sole factor in determining the rankings. The in-core thermionic (ICT) rises 2 places because it is no longer penalized for a (highly weighted) safety rating of 6. The liquid cooled out-of-core thermionic (LOCTP) drops 2 places because its higher safety rating supported its somewhat lower score on the other attributes. With safety removed, it dropped in the rankings.

The data for Set 7 (RADAREA) were derived from Set 1 (NOM/5/MULT) by fixing the attribute state for radiator area (Attribute #2) at 108m^2 for all systems. The results are shown in Table 6-4. The heat-pipe Brayton (HBO) and heat-pipe thermophotovoltaic (HTPVP) rise 2 places since their large radiator areas no longer penalize them. The results are essentially identical to the results for Set 1, thus eliminating the difference in radiator area as the sole factor in determining the rankings.

The data for Set 8 DESREL were derived from Set 1 (NOM/5/ MULT) by fixing the attribute state for design reliability (Attribute #3) at 2 for all systems. The results are shown in Table 6-4. The results are essentially identical to the results for Set 1, thus eliminating the difference in design reliability as the sole factor in determining the rankings.

The data for Set 9 (TECHMAT) were derived from Set 1 (NOM/5/MULT) by fixing the attribute state for technical maturity (Attribute #4) at 3.8 for all systems. The results are shown in Table 6-4. The results are essentially identical to the results for Set 1, except the heat-pipe thermoelectrics (HTEP, HTEPa) reverse order and the liquid-metal cooled Stirling (LSH) drops 3 positions because it loses its high advantage in technical maturity contribution.

The data for Set 10 (FEASCOST) were derived from Set 1 (NOM/5/MULT) by fixing the attribute state for cost (Attribute #5) at $240 million for all systems. The results are shown in Table 6-4. The results are essentially identical to the results for Set 1, except for the liquid-metal Stirling (LSH) which drops three places because it loses its advantage of having a relatively low cost while the heat-pipe Brayton (HBO) rises in the rankings due to its penalty for a somewhat high cost.

The data for Set 11 (SURVIV) were derived from Set 1 (NOM/5/MULT) by fixing the attribute state for survivability (Attribute #6) at 5 for all systems. The results are shown in Table 6-4. Little change is observed, even for the low survivability systems because they tend to have other low attribute values holding them down in the rankings.

The data for Set 12 (DORMAN) were derived from Set 1 (NOM/5/MULT) by fixing the attribute state for dormancy (Attribute #7) at two for all systems. The results are shown in Table 6-4. The in-core thermionic (ICT) drops in position when dormancy is removed because its high score (a 10) is removed.

The data for Set 13 (PRODUC) were derived from Set 1 (NOM/5/MULT) by fixing the attribute state for producibility (Attribute #8) at three for all systems. The results are essentially identical to the results for Set 1, except for the liquid-metal cooled thermoelectric (LTEP), which drops three positions in the ranking because it relies heavily on its high producibility for its position.

E. GENERAL CONCLUSIONS

The general conclusions can be made from Table 6-4, which summarizes the results from the application of the group decision rules to the baseline data of Set 1 (NOM/5/MULT). All other runs resulted in only minor variations on the rankings of Table 6-4. First and second rankings always went to heat-pipe thermoelectrics (HTEP, HTEPa). The third place ranking usually went to the heat-pipe Stirling (HSH), followed by fourth and fifth place with the in-core thermionic (ICT) and heat-pipe out-of-core thermionic (HOCTP). Sixth through tenth place went to the liquid-metal thermoelectric (LTEP) and Stirling (LSH), followed by the heat-pipe AMTEC (HAP), Brayton (HBO), and Rankine (HRL). The least preferred systems were the liquid-metal out-of-core thermionic (LOCTP) liquid-metal AMTEC (LAP), heat-pipe thermophotovoltaic (HTPVP), liquid-metal Brayton (LBO) and Rankine (LRL), and the gas-cooled Brayton (GBH).

Variations on the baseline data of Set 1 (NOM/5/MULT), as made in data Set 2 through Set 5, made at most a two-place change in the rankings as determined by the group decision rules, with typically no change. Data Set 6 and Set 13 fixed each of the attribute states and made changes in the ranking as compared to the baseline data of Set 1 (NOM/5/MULT) of as much as three places in ranking. Data Set 6 improved the preference for the in-core thermionic (ICT) by 2 places because of a lower safety rating on that system, which was not counted against it in Set 11. Data Set 7, where radiator area is dropped as an attribute, improved the heat-pipe Brayton and heat-pipe thermophotovoltaic (HTPVP) by two places due to their large radiator areas. Data Set 9, where technical maturity is dropped, causes the liquid-metal Stirling (LSH) to drop three places due to its high reliance on technical maturity. The liquid-metal Stirling (LSH) also relies on low cost for a high ranking. When cost is eliminated as an attribute, as in data Set 10, the liquid-metal Stirling drops three places in the rankings. In data Set 13, where producibility is dropped, the liquid-metal cooled thermoelectric (LTEP) drops three places due to its reliance on high producibility in the scoring.

It was not possible to rank the alternative systems on the basis of any one attribute.

In summary, the top three rated systems were virtually unchanged with all twelve variations in assumptions across groups. The heat-pipe thermoelectrics (HTEP, HTEPa) and heat-pipe Stirling (HSH) were the top three systems. Some shifting occurred in the fourth place although the in-core thermionic (ICT) tended to come up most often.

The decision analysis process was viewed as useful for (1) reducing the large number of subsystem combinations to a manageable number; (2) characterizing and communicating the alternatives; and (3) providing the rationale and support for R&D planning to carry forward with the more promising technologies.

F. CRITIQUE OF MULTIATTRIBUTE DECISION ANALYSIS METHODOLOGY

The multiattribute decision analysis methodology was successful in all of the 11 interviews in ranking all the alternative system concepts. The group decision rules were capable of aggregating preferences by groups, and, in general, the three group decision rules were in agreement.

The multiattribute decision analysis was a deterministic analysis, as contrasted with a probabilistic analysis, and so did not completely reveal the technical experts' opinion as to the attribute states of the alternative systems. A better analysis could have been undertaken if the attribute states had been estimated probabilistically. Either a discrete probability tree or a Monte Carlo simulation model, using subjectively estimated cumulative probability distributions for the attribute states of the alternative systems, would have been sufficient data for a probabilistic analysis. The present analysis does not incorporate the uncertainties in the attribute state estimates. As a result, the process highlighted the need for more technical information about the systems and the degree of confidence to be placed on such information.

The interview times could have been shortened if only three-point rather than five-point estimates had been made of the attribute utility functions. With the worst-state and the best-state used for two of the three points, questions for only one-attribute utility value need be asked in the interviews. Comparison of Tables 6-1 and Table 6-4 show that only minor differences in the rankings would have resulted in the group decision rules. Because continuity and monotonicity of preferences can be assumed for the attribute states, an attribute utility function of the "constant risk aversion" form:

$$u(x) = a + be^{cx}$$

would have sufficed. Given the high premium for short interview times, it is recommended that in the future, unless there is strong reason to believe that the utility function is not represented by such a function with sufficient accuracy, the attribute utility functions be derived from three-point estimates.

It was difficult for some, and impossible for others, of the interviewees to assess gambles with respect to the set of attributes at their worst states. Had the system concepts been determined further in advance, the attribute worst states could have been made more desirable. It is highly recommended, in future multiattribute decision analyses, that the system states be determined before the interviews are conducted. This will also preclude the unfortunate situation in which the system states are ultimately determined to lie outside the range of the assessed attribute states.

During the course of the process, the need for displaying the source calculations of the rankings was identified. Forays into piles of computer listings, no matter how comprehensive, were deemed insufficient. Although such transparency can be shown to some extent with summary graphics, an interactive version of the model to allow display of both intermediate and summary calculations is needed.

SECTION VII

CONCORDANCE OF RANKINGS

A. INTRODUCTION

This section presents and discusses the results of concordance calculations for the rankings presented in Section VI (see subsection C in Section II for a discussion of concordance statistics). Two different types of concordances were calculated and analyzed:

(1) Individual rankings within groups.

(2) Group rankings with different group decision rules.

The purpose of these concordance calculations and analyses was to ascertain how robust, or conversely, how sensitive the rankings were to: differences among individuals within groups and differences in group decision rules. In general, the rankings were highly concordant across individuals within groups and across different group decision rules, implying that the rankings presented in Section VI were indeed robust.

The concordance of the rankings given to the sixteen alternative system concepts by individuals within the three groups was examined in two ways: (1) by comparing the individual rankings within groups (Table 7-1) for each of the 40 runs previously described in Section VI; and (2) by comparing the group rankings according to the additive, Nash, and rank sum rules (Table 7-2). The following observations can be made:

(1) There is not, of course, perfect agreement throughout the ranking.

(2) There are several instances in which the ranks assigned to several alternatives by one interviewee in a group seem to be at variance from those given by the other interviewees in the group.

(3) The concordance measures in every instance, however, are highly significant. Each of them is significant well below the 1% level; many are significant below the 0.1% level.

(4) Accordingly, by each of the comparison methods, there is substantial agreement as to the rankings of the sixteen alternative systems within each of the three groups of interviewees.

The chi-square values corresponding to the coefficients of concordance indicate no instances in which there is no significance at a minimum 1% level. The other 78 chi-square values are significant well beyond the 5% level. This indicates excellent agreement among interviewees and among group decision rules. Although it is possible to examine concordance among different methods, this was not done, due to time constraints. The majority of lower concordance values occurred within Group 2 - Systems Definition due to different weightings of certain attributes which have moderate impacts (cost, design reliability, survivability, producibility) on ranking.

Table 7-1. Summary of Kendall's Coefficient of Concordance (W) and the Associated Chi-Square Values (χ^2) for all Runs: Individuals Within Groups

		1		2		3	
RUNS	METHOD	W	χ^2	W	χ^2	W	χ^2
1-3	NOM/5/MULT	0.9596	57.57	0.9314	41.91	0.9072	40.82
5-7	NOM/5/LIN	0.9750	58.50	0.9366	42.15	0.9784	44.03
9-11	NOM/3/MULT	0.9647	57.88	0.9294	41.82	0.9327	41.97
17-19	WORST/3/MULT	0.9588	43.15	0.8725	39.26	0.9046	40.71
21-23	BEST/3/MULT	0.9647	57.88	0.9268	41.71	0.9242	41.59
25-27	NOM/5/MULT SAFETY @ 3	0.9665	57.99	0.9647	43.41	0.9784	44.03
29-31	NOM/5/MULT RAD AREA @ 108	0.9732	58.39	0.9163	41.24	0.9092	40.91
33-35	NOM/5/MULT DES REL @ 2	0.9449	56.69	0.8556	38.50	0.8908	40.09
37-39	NOM/5/MULT TECH MT @ 3.8	0.9246	55.48	0.9144	41.15	0.8974	40.38
41-43	NOM/5/MULT COST @ $240M	0.9621	57.73	0.8791	39.56	0.9131	41.09
45-47	NOM/5/MULT SURV @ 5	0.9441	56.65	0.8693	39.12	0.9137	41.12
49-51	NOM/5/MULT DORM @ 2	0.9511	57.07	0.9346	42.06	0.9399	42.29
53-55	NOM/5/MULT PROD @ 3	0.9408	56.45	0.8876	39.94	0.9229	41.53

Table 7-2. Summary of Kendall's Coefficient of Concordance (W) and the Associated Chi-Square Values (χ^2) for all Runs: Group Decision Rules

		1		2		3	
RUNS	METHOD	W	χ^2	W	χ^2	W	χ^2
1-3	NOM/5/MULT	0.9987	44.94	0.9902	44.56	0.9869	44.41
5-7	NOM/5/LIN	0.9984	44.93	0.9964	44.84	0.9971	44.87
9-11	NOM/3/MULT	0.9987	44.94	0.9895	44.53	0.9889	44.50
17-19	WORST/3/MULT	0.9922	44.65	0.9738	43.82	0.9926	44.67
21-23	BEST/3/MULT	0.9980	44.91	0.9833	44.25	0.9816	44.17
25-27	NOM/5/MULT SAFETY @ 3	0.9974	44.88	0.9971	44.87	0.9969	44.86
29-31	NOM/5/MULT RAD AREA @ 108	0.9984	44.93	0.9915	44.62	0.9863	44.38
33-35	NOM/5/MULT DES REL @ 1	0.9948	44.76	0.9948	44.76	0.9862	44.38
41-43	NOM/5/MULT COSTS @ $240M	0.9935	44.71	0.9971	44.87	0.9817	44.18
45-47	NOM/5/MULT SURV @ 5	0.9944	44.75	0.9739	43.82	0.9758	43.91
49-51	NOM/5/MULT DORM @ 2	0.9967	44.85	0.9843	44.29	0.9912	44.60
53-55	NOM/5/MULT PROD @ 3	0.9987	44.94	0.9774	43.98	0.9859	44.37

SECTION VIII

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APPENDIX A

QUESTIONNAIRE USED FOR INTERVIEWS

S P A C E P O W E R S Y S T E M S T U D Y

QUESTIONNAIRE FOR OBTAINING PREFERENCE INFORMATION FOR USE IN RANKING SPACEBORNE NUCLEAR POWER SYSTEMS

INTERVIEWEE ______________________

AFFILIATION ______________________

LOCATION ______________________

DATE ______________________

INTERVIEW NUMBER ______________________

QUESTIONNAIRE
PREPARED BY
JEFFREY H. SMITH
PASADENA, CALIFORNIA
JULY 1983

PURPOSE OF THE INTERVIEW

THE PURPOSE OF THE INTERVIEW IN WHICH YOU ARE BEING ASKED TO PARTICIPATE IS TO ASSIST DARPA/DOE/NASA WITH THE COMPARISON OF ALTERNATIVE SYSTEM CONCEPTS FOR SPACEBORNE NUCLEAR POWER SYSTEMS. THE ALTERNATIVE CONCEPTS BEING CONSIDERED EMBODY VARYING FORMS OF REACTORS, COOLING SYSTEMS, AND POWER CONVERSION SYSTEMS. THE QUESTIONS THAT YOU WOULD BE ASKED ARE AIMED AT OBTAINING YOUR PREFERENCES FOR SEVERAL FACTORS (E.G. SAFETY, COST) PERTINENT TO THE SELECTION OF PROMISING CONCEPTS FOR EXTENDED RESEARCH. THE RESPONSE OF ALL PERSONS INTERVIEWED WILL BE INCORPORATED IN THE RANKING OF THE CANDIDATE SYSTEMS. THE INTERVIEW IS DESIGNED TO TAKE ABOUT 60 MINUTES.

SPACE POWER SYSTEM REQUIREMENTS

SAFETY (GROUND, NUCLEAR, SPACE TRANSPORTATION SYSTEM, EARTH ORBIT & DISPOS.)
POWER OUTPUT
POWER DISTRIBUTION
DESIGN LIFETIME
LOAD FOLLOWING CAPABILITY
START - UP
AUTONOMY
RELIABILITY
SURVIVABILITY
DORMANCY
INTERFACES (ELECTRICAL, COMMAND/DATA/TELECOMMUNICATIONS)
REACTOR INDUCED RADIATION TO PAYLOAD
POWER SYSTEM INDUCED THERMAL RADIATION
MASS
SIZE

SAFETY

		Ground/Pre-flight	Launch/flight	Post-mission
Best Case	10	safety level exceeds normal pre-flight precautions due to nature of power system	safety exceeds current launch/ flight standards --remains subcrit. if immersed in water	safety exceeds current disposal practices/core will disperse safely in event of reentry
	7	low risk of exposure in event of pre-flight accident; safety level comparable to current practice	low risk of problems in event of abort--remains subcritical if immersed in water	low risk of large objects reaching the ground
	3	some risk of radiation exposure in event of pre-flight accident	some risk of problems in event of abort	some risk of large objects reaching the ground
Worst Case	0	pre-flight accident could lead to criticality and/or radiation dosage to personnel	plausible scenarios for criticality/ explosion in event of water immersion ,very large objects reaching the ground, or loss of coolant after deployment	large radioactive objects reach the ground

DESIGN RELIABILITY

Best Case	10	Very high--tolerant to single point and multiple failures with graceful degradation in performance.
	8	High--tolerant to single point failures with graceful degradation in performance. Tolerant within certain limits to multiple-point failures.
	6	Moderate-A: tolerant to single point failures with graceful degradation in performance--low risk of system failure. Moderate tolerance to multiple failures.
	4	Moderate-B: more limited tolerance to single point failures with more dramatic degradation in system performance over time--some risk of system failure. Low tolerance to multiple failures
	2	Moderate-C: lower tolerance to single point failures and very low tolerance to multiple failures with moderate risk of system failure.
Worst Case	0	Low--susceptable to single point failures which propagate into overall system failure (through loss of coolant or damage to control system). Similarly, multiple failures result in system failure.

TECHNOLOGICAL MATURITY

Best Case	10	Maximum technological maturity requiring a minimum of new developments.
	8	Advanced technological maturity requiring some minor developments in particular subsystems.
	6	Moderate technological maturity requiring some major developments in minor subsystems.
	4	Some technological maturity requiring significant developments in minor subsystems.
	2	Low technological maturity requiring significant developments in major subsystems.
Worst Case	0	Virtually no technological maturity requiring full scale technology developments in major subsystems.

SURVIVABILITY

Best	10	Very high likelihood of surviving military threats at required levels and higher without loss of performance. Also a high likelihood of surviving meteorite impacts without loss of performance.
	7	Likely that system will survive designed levels of military threat and meteorite hazard without loss of performance.
	3	Moderate likelihood of surviving designed levels of military threat and meteorite hazard without loss of performance.
Worst	0	Low likelihood of surviving military threats at design levels. High risk of system failure in event of meteorite impact or military induced damage.

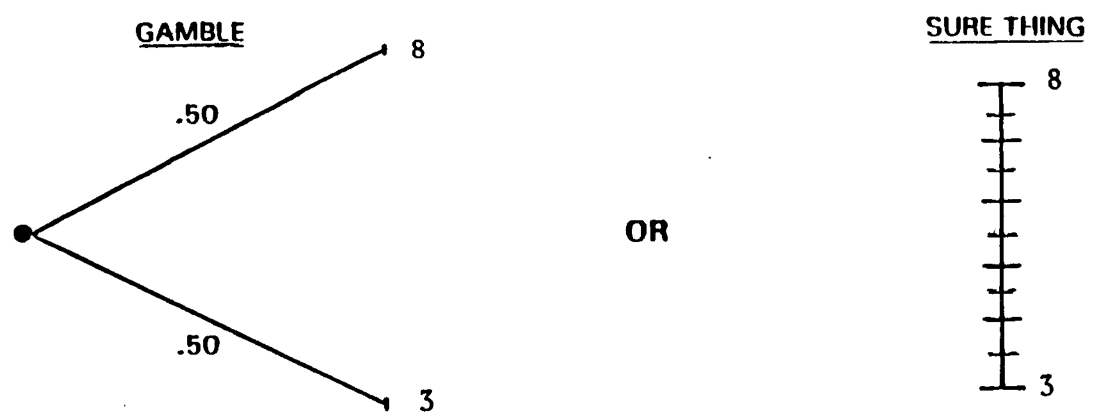
LOAD-FOLLOWING/DORMANCY CAPABILITY

Best	10	Multiple restart capability throughout mission lifetime with high degree of load following capability using electrical switching to follow load closely in steps and responding quickly to rapid drops in load. Minimal power storage requirements for startup enabling long periods of dormancy.
	7	Multiple restart capability throughout mission lifetime. Moderate power storage required for restarts due to power requirements thus dormancy period is shorter than in best case. Moderate load following capability due to gas valving system for dumping excess energy.
	3	Multiple restart capability throughout mission life. High power requirements for startup. Reduced load following capability due to vapor valving for dumping excess energy.
Worst Case	0	Poor load following capability--system runs at full power and vents excess heat using an unvalved system or one with electric shunt. No dormancy capability other than launch period prior to initial start and no ability to shutdown after startup.

PRODUCIBILITY/PRACTICALITY

Best Case	10	Highly modularized independent subsystems with simple interfaces. Easily manufactured materials, parts, and assemblies and no extraordinary tooling/facilities required. All components can be pre-flight tested independently without assembling the whole system.
	7	System is somewhat modular with some complex interfaces. The fabricability is similar to other spaceborne systems with comparable fabrication problems. The subsystems are, for the most part, testable independently.
	3	Minimal modularity with complex interfaces between most of the subsystems. The fabricability is more difficult than comparable spaceborne systems requiring some special materials. Some of the subsystems are difficult to test without a vacuum environment.
Worst Case	0	Virtually no modularity--system is an integrated whole with complex interfaces. It is very difficult to manufacture since special materials, tooling, and facilities are required. Major subsystems are not testable and may require space testing to determine flight worthiness.

ATTRIBUTE: SAFETY



- FOR WHICH VALUE OF THE "SURE THING" ARE YOU INDIFFERENT BETWEEN THE "SURE THING" AND THE "GAMBLE"?

  INDIFFERENCE POINT ______

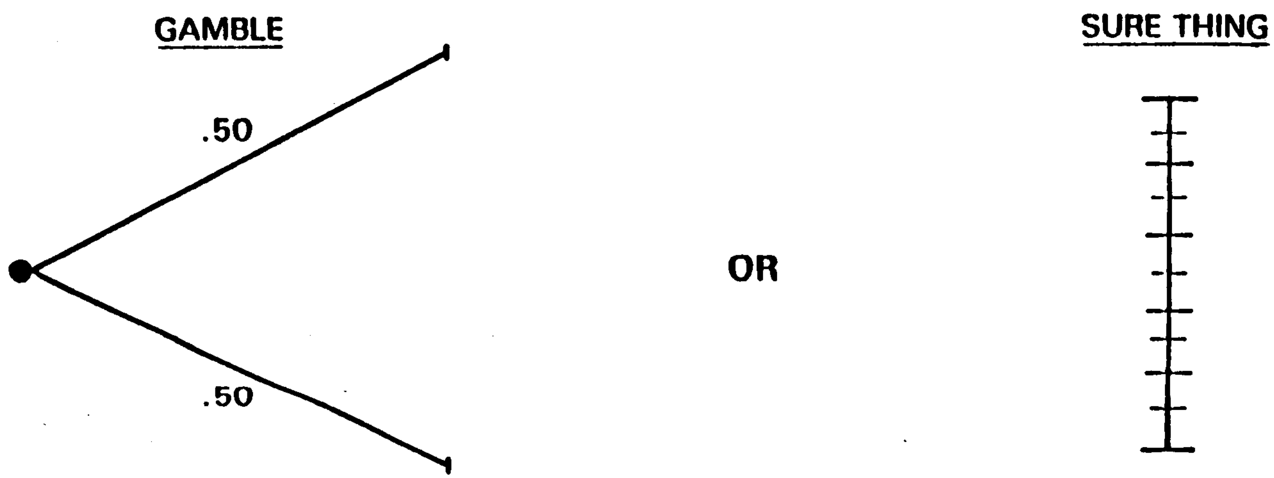
- IF YOU KNEW THAT ALL OTHER ATTRIBUTES WERE AT THEIR WORST STATES?

  INDIFFERENCE POINT ______

- IF YOU KNEW THAT ALL OTHER ATTRIBUTES WERE AT THEIR BEST STATES?

  INDIFFERENCE POINT ______

ATTRIBUTE: SAFETY

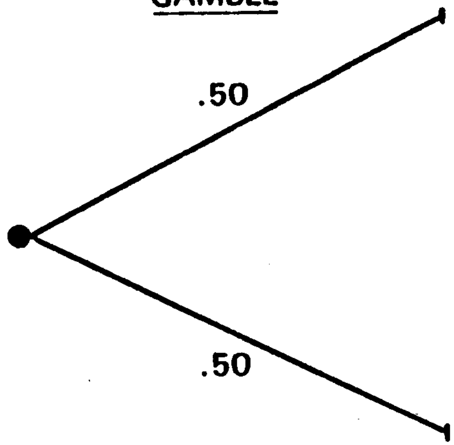


- FOR WHICH VALUE OF THE "SURE THING" ARE YOU INDIFFERENT BETWEEN THE "SURE THING" AND THE "GAMBLE"?

INDIFFERENCE POINT ______

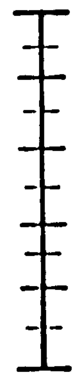
ATTRIBUTE: SAFETY

GAMBLE



OR

SURE THING



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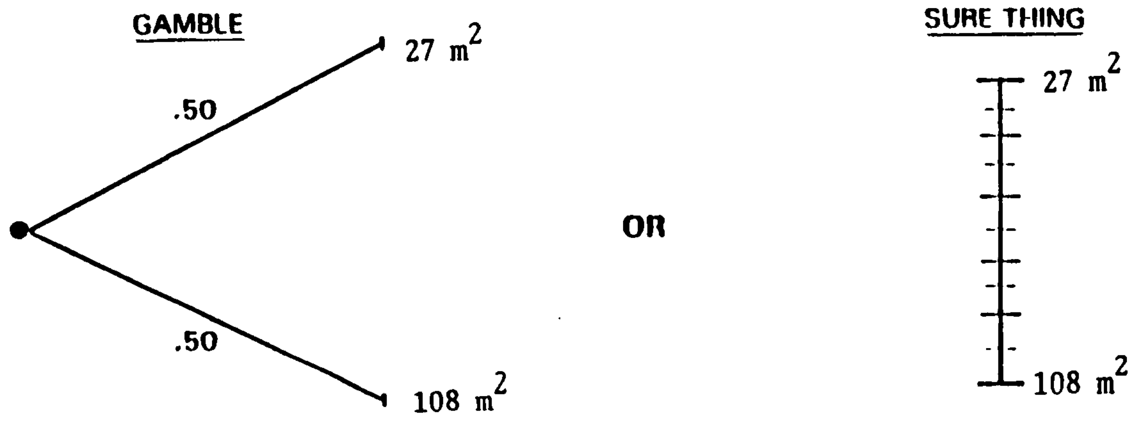
INDIFFERENCE POINT ______

ATTRIBUTE: RADIATOR AREA



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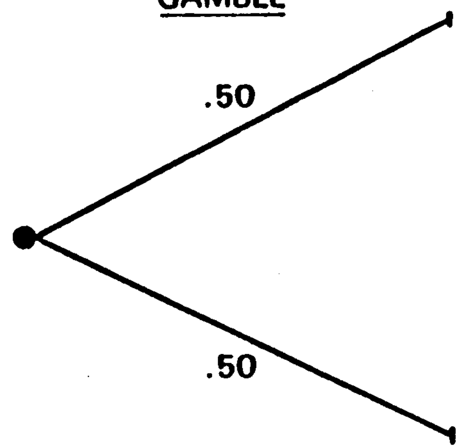
  INDIFFERENCE POINT ______

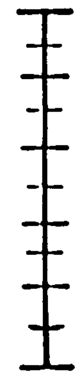
ATTRIBUTE: RADIATOR AREA

GAMBLE



OR

SURE THING



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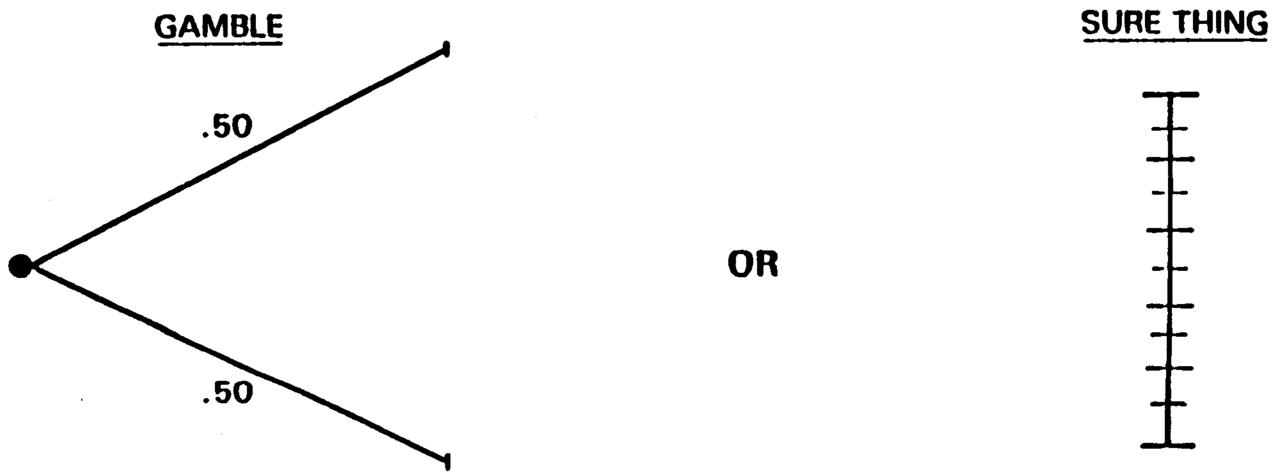
INDIFFERENCE POINT ______

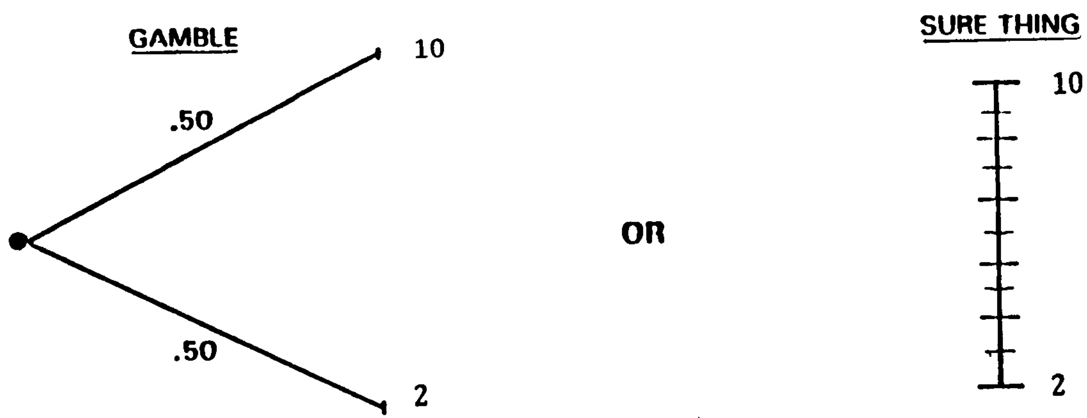
ATTRIBUTE: RADIATOR AREA



- **FOR WHICH VALUE OF THE "SURE THING" ARE YOU INDIFFERENT BETWEEN THE "SURE THING" AND THE "GAMBLE"?**

INDIFFERENCE POINT ______

ATTRIBUTE: DESIGN RELIABILITY



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  INDIFFERENCE POINT ______

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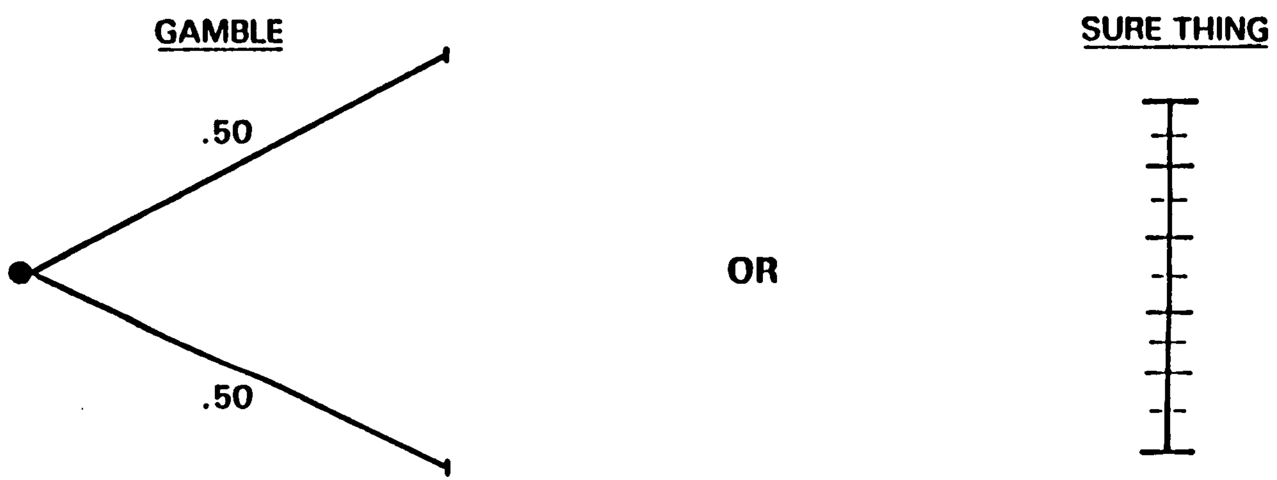
  INDIFFERENCE POINT ______

ATTRIBUTE: DESIGN RELIABILITY



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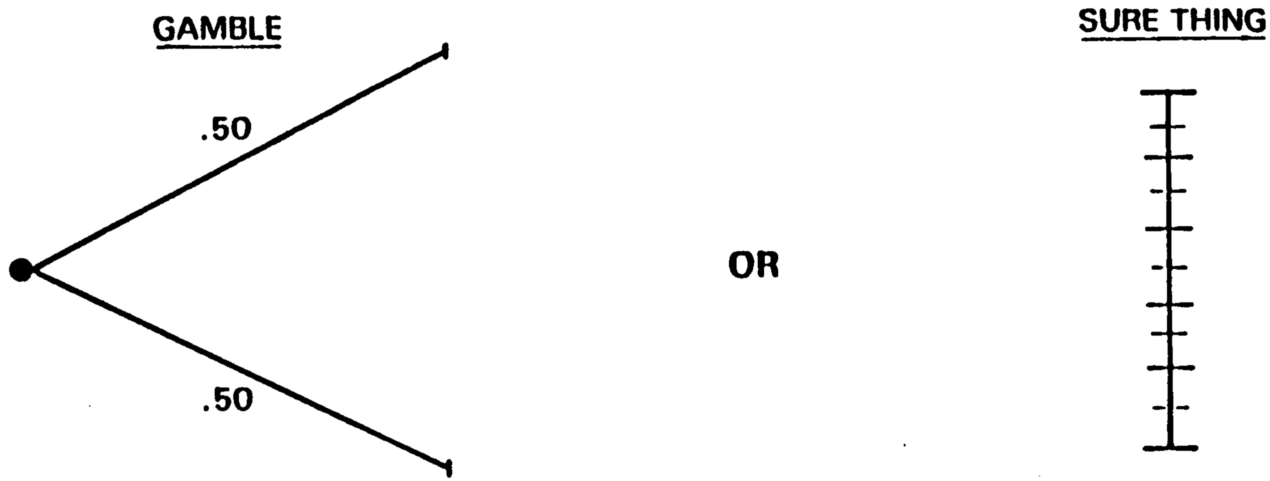
INDIFFERENCE POINT ______

ATTRIBUTE: DESIGN RELIABILITY



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INDIFFERENCE POINT ______

ATTRIBUTE: TECHNICAL MATURITY

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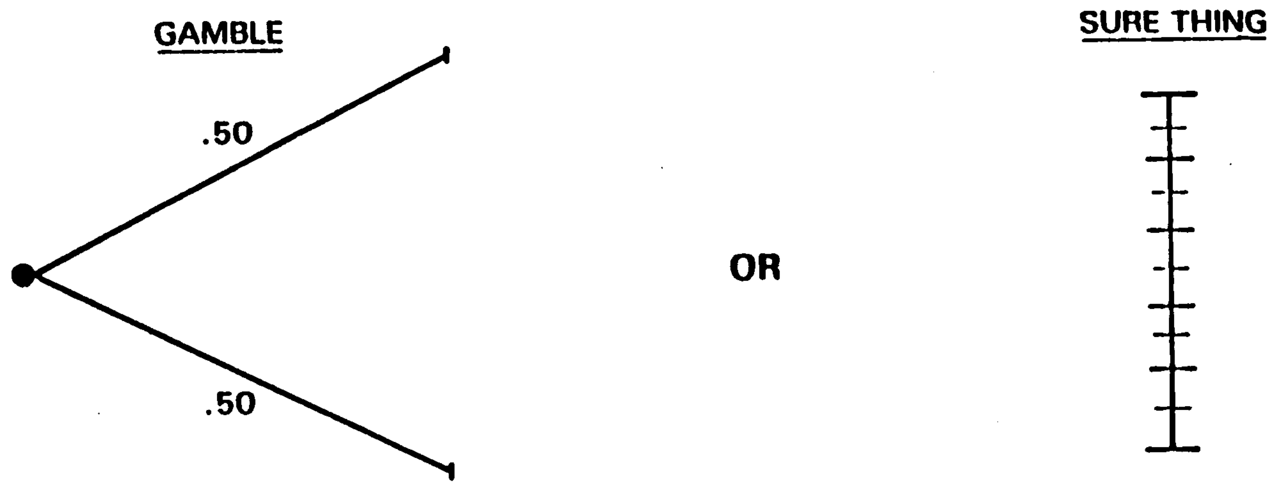
  INDIFFERENCE POINT _____

ATTRIBUTE: TECHNICAL MATURITY



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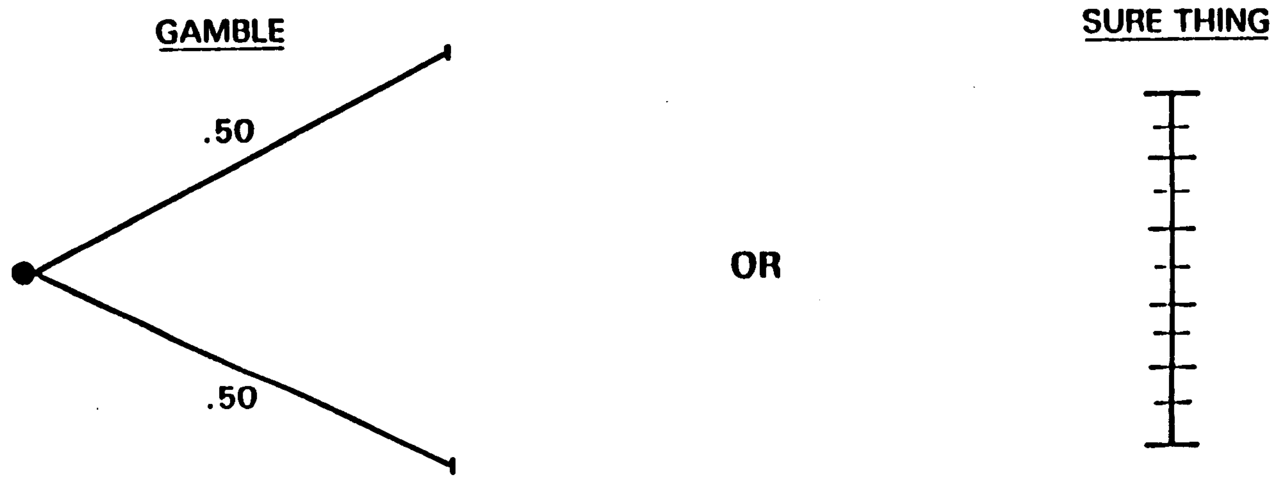
INDIFFERENCE POINT ______

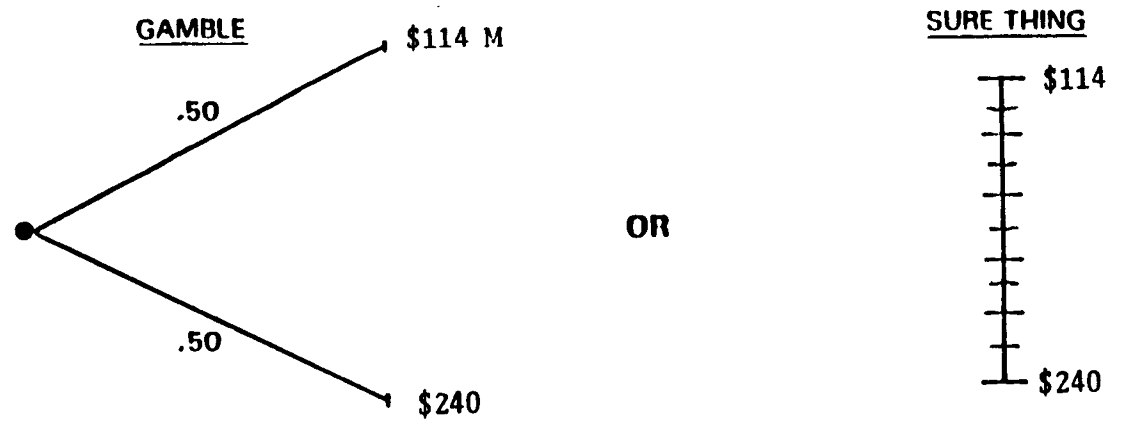
ATTRIBUTE: TECHNICAL MATURITY



- **FOR WHICH VALUE OF THE "SURE THING" ARE YOU INDIFFERENT BETWEEN THE "SURE THING" AND THE "GAMBLE"?**

INDIFFERENCE POINT ______

ATTRIBUTE: ESTIMATED COST TO REACH TECHNICAL FEASIBILITY



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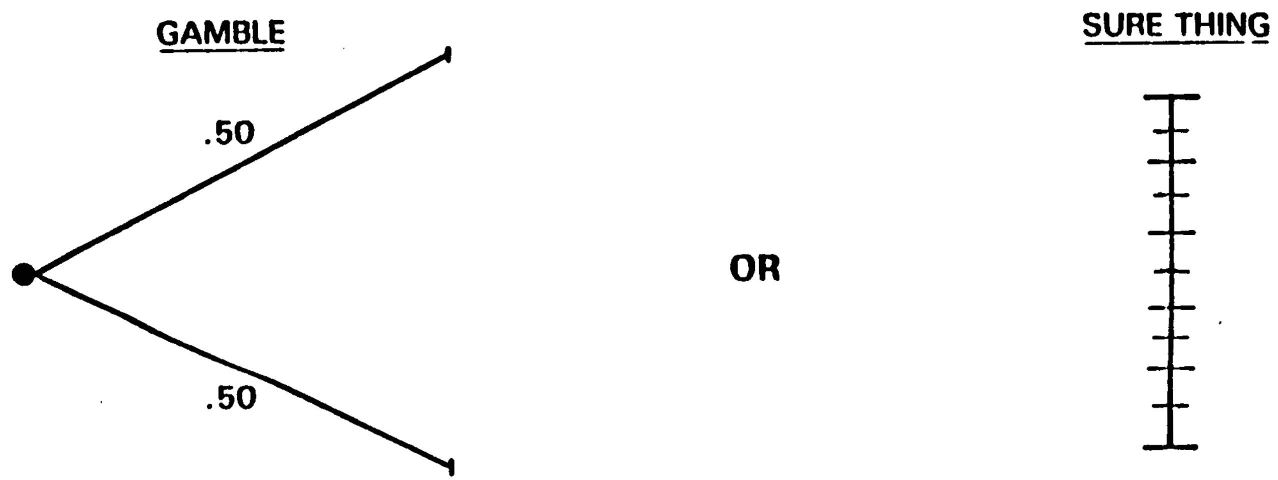
ATTRIBUTE: ESTIMATED COST TO REACH TECHNICAL FEASIBILITY



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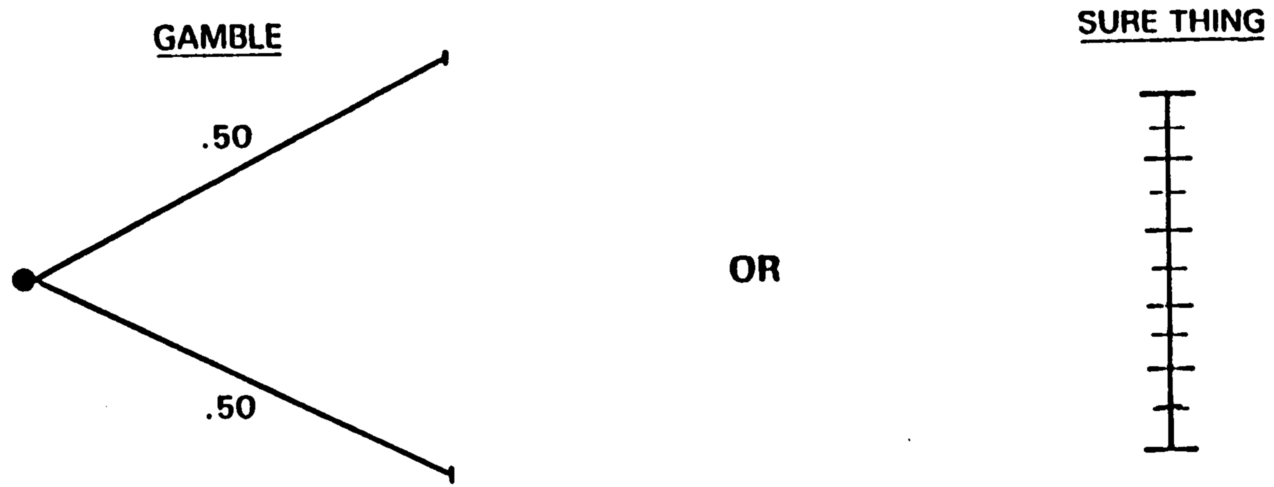
INDIFFERENCE POINT ______

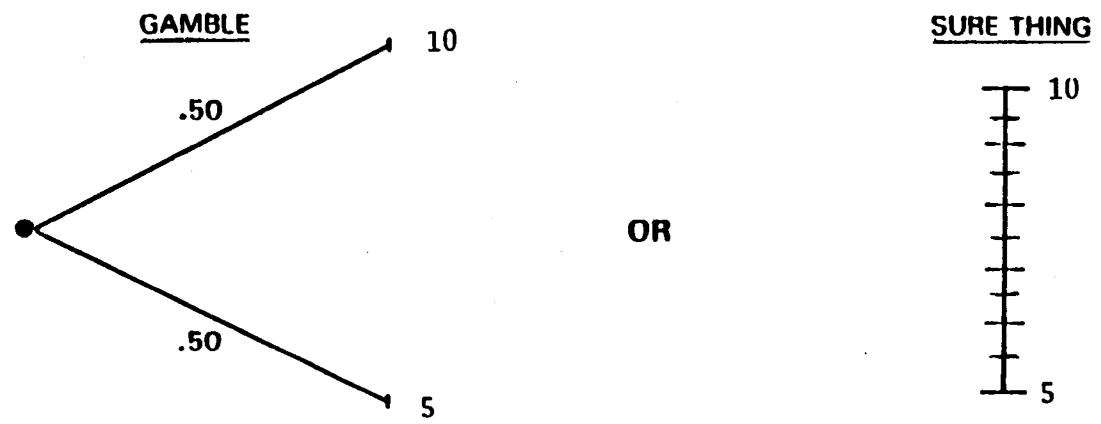
ATTRIBUTE: ESTIMATED COST TO REACH TECHNICAL FEASIBILITY



- FOR WHICH VALUE OF THE "SURE THING" ARE YOU INDIFFERENT BETWEEN THE "SURE THING" AND THE "GAMBLE"?

INDIFFERENCE POINT ______

ATTRIBUTE: SURVIVABILITY



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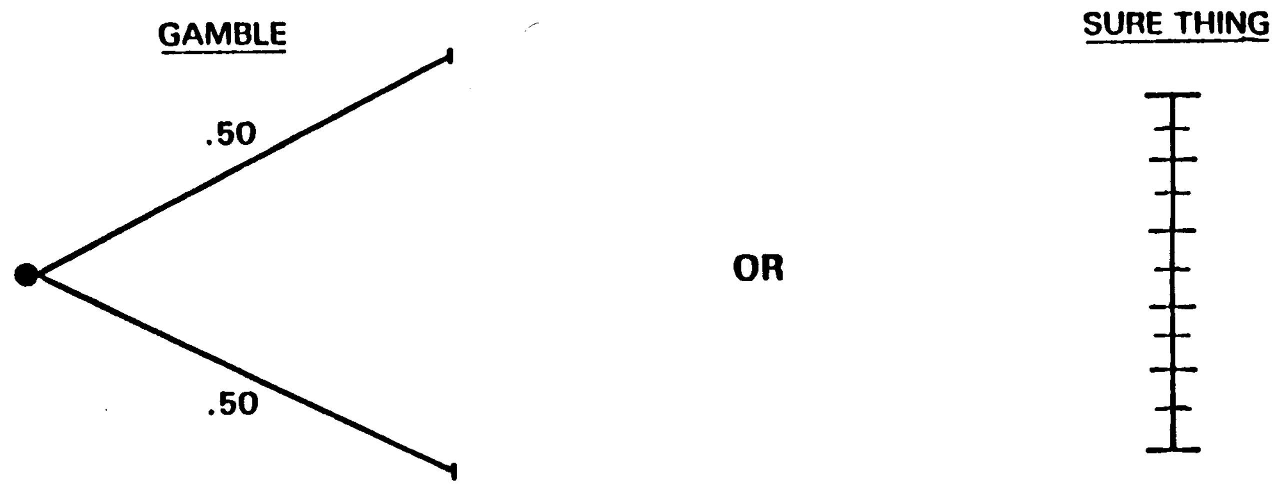
  INDIFFERENCE POINT _____

ATTRIBUTE: SURVIVABILITY



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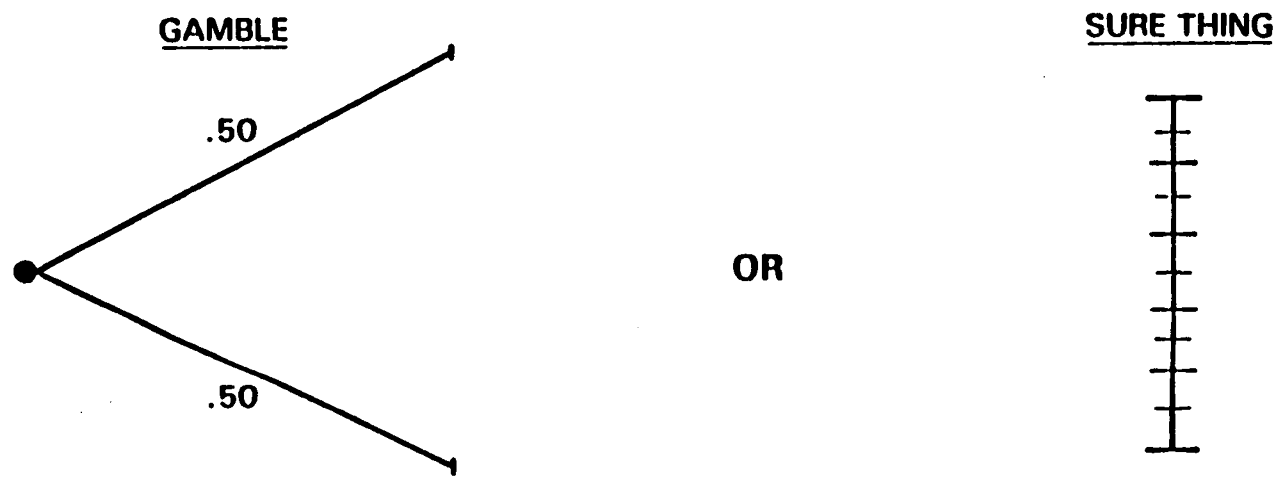
INDIFFERENCE POINT ______

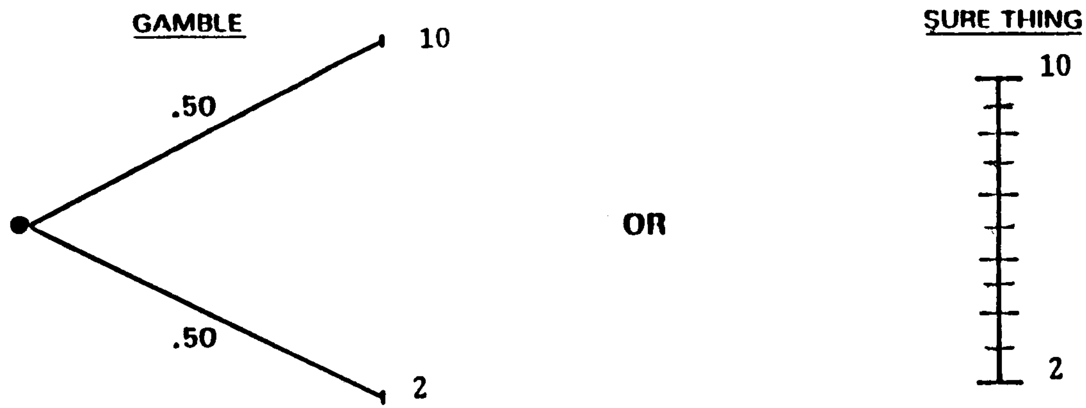
ATTRIBUTE: SURVIVABILITY



- **FOR WHICH VALUE OF THE "SURE THING" ARE YOU INDIFFERENT BETWEEN THE "SURE THING" AND THE "GAMBLE"?**

INDIFFERENCE POINT ______

ATTRIBUTE: LOAD-FOLLOWING/DORMANCY CAPABILITY



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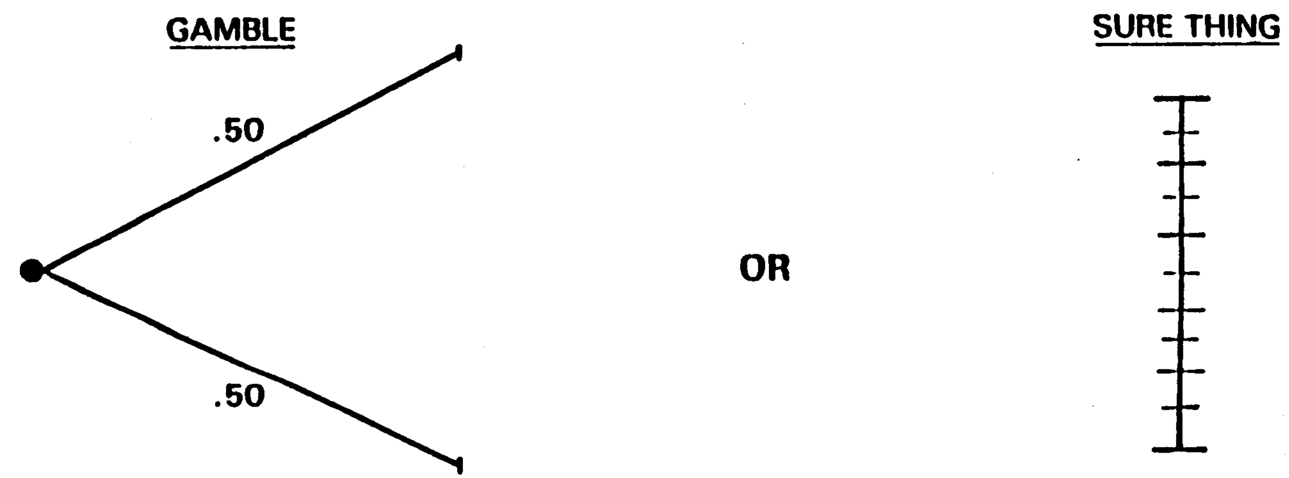
  INDIFFERENCE POINT ______

ATTRIBUTE: ~~LOAD-FOLLOWING~~/DORMANCY CAPABILITY



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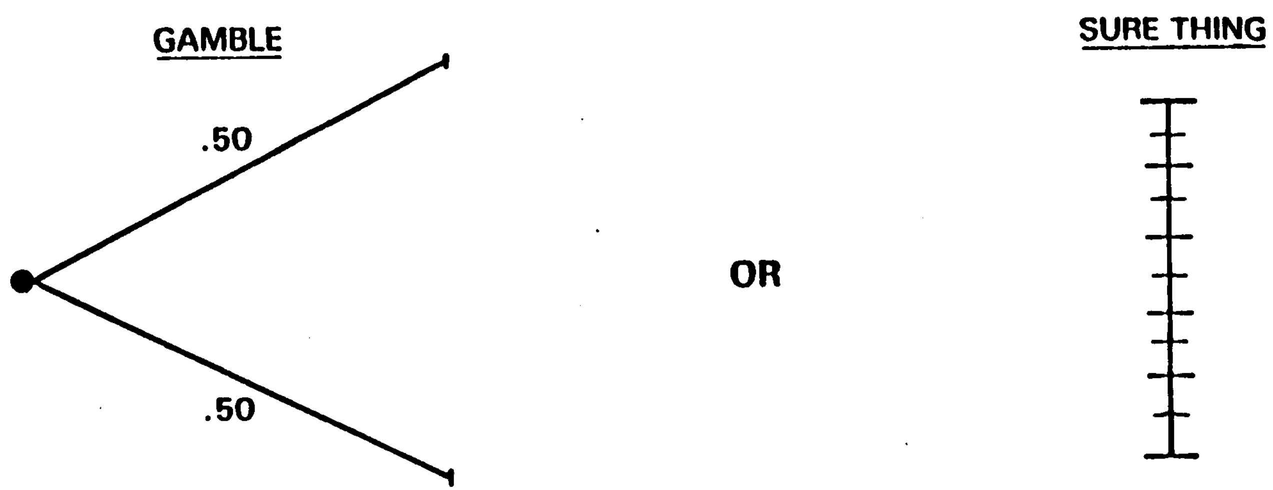
INDIFFERENCE POINT ______

ATTRIBUTE: LOAD-FOLLOWING/DORMANCY CAPABILITY



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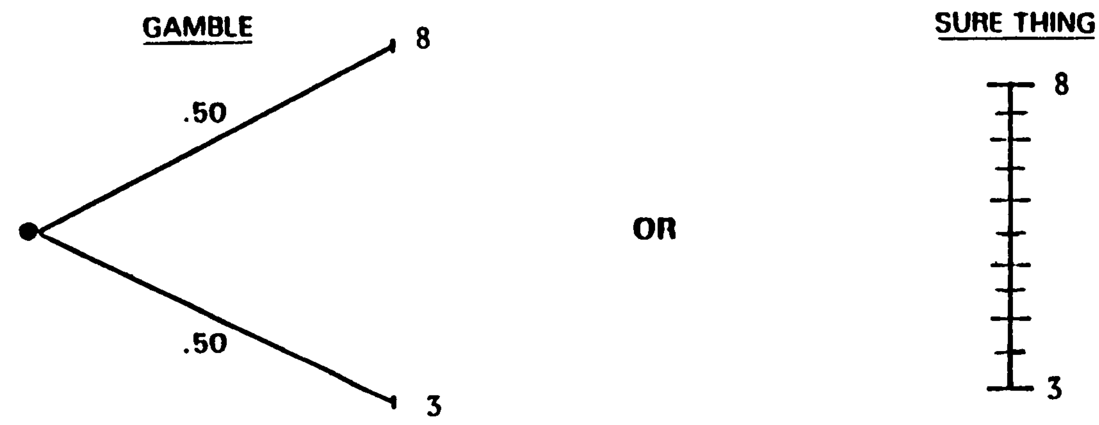
  INDIFFERENCE POINT ______

ATTRIBUTE: PRODUCIBILITY



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  INDIFFERENCE POINT ______

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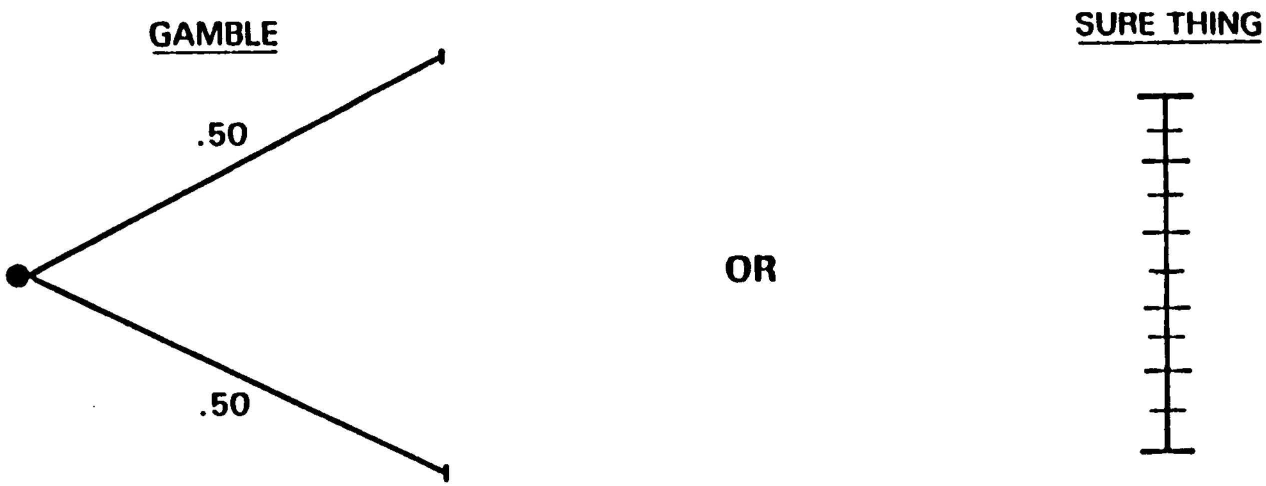
  INDIFFERENCE POINT ______

ATTRIBUTE: PRODUCIBILITY



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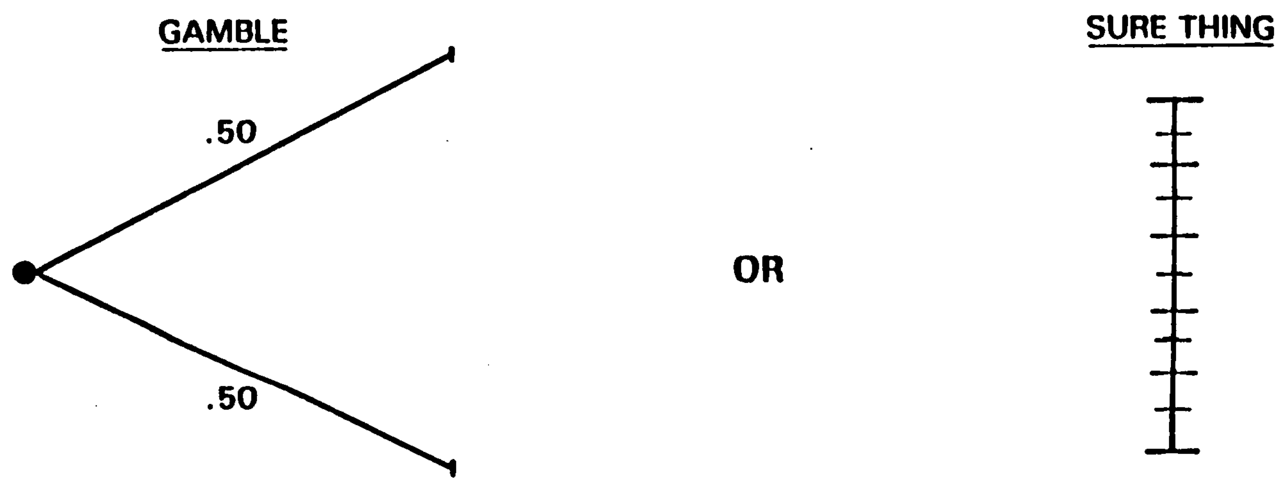
INDIFFERENCE POINT ______

ATTRIBUTE: PRODUCIBILITY



- FOR WHICH VALUE OF THE "SURE THING" ARE YOU INDIFFERENT BETWEEN THE "SURE THING" AND THE "GAMBLE"?

INDIFFERENCE POINT ______

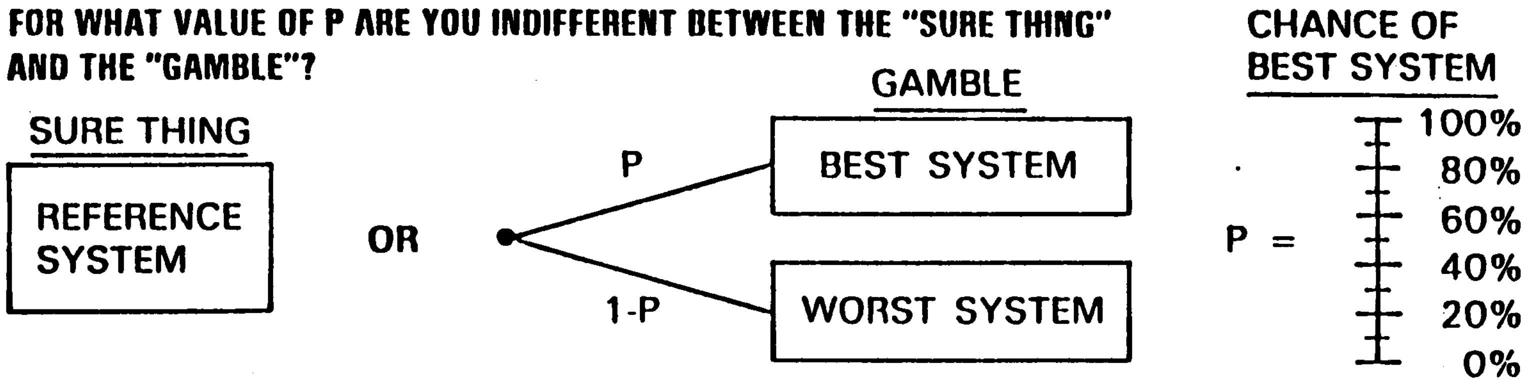
ORDER OF IMPORTANCE OF ATTRIBUTES. WHICH ATTRIBUTE WOULD YOU CHANGE FROM ITS WORST STATE TO ITS BEST STATE?

ATTRIBUTE	SAFETY	AREA, m^2	RELI-ABILITY	TECHNI-CAL MATURITY	EST. COST--TECH. FEASIBIL-ITY $M	SURVIV-ABILITY	DORMANCY	PRODUC-IBILITY	EST. DEVEL. COST, (1983$)	EST. PROD. COST, (1983$)
Best State	8	27	10	7.8	114	10	10	8	NA	NA
Worst State	3	108	2	3.8	240	5	2	3	NA	NA

Order of Importance									NA	NA

IMPORTANCE OF SAFETY

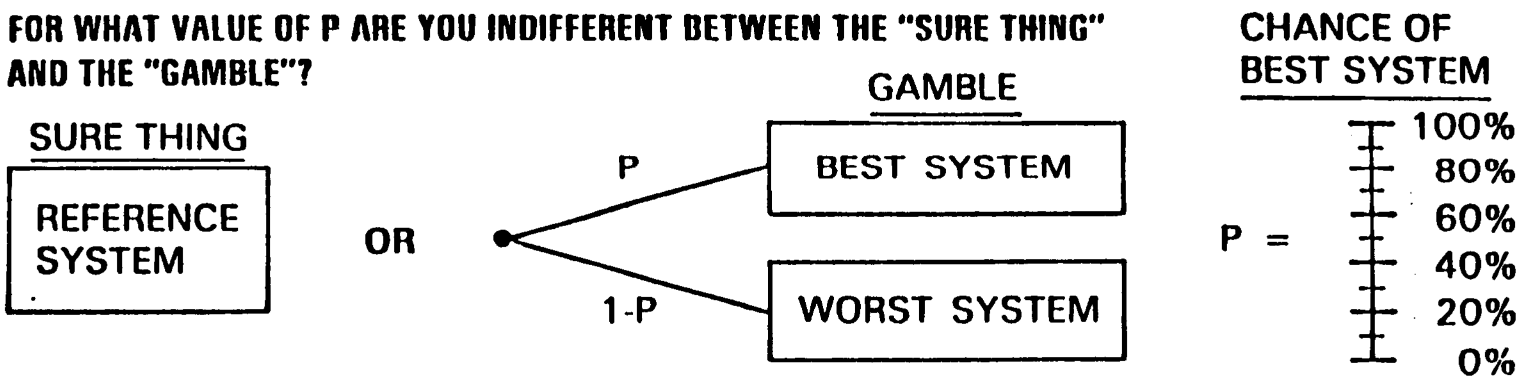
FOR WHAT VALUE OF P ARE YOU INDIFFERENT BETWEEN THE "SURE THING" AND THE "GAMBLE"?



	SAFETY	AREA	RELIAB.	MATUR.	FEAS. COST	SURVIV.	DORMANCY	PROD.	DEVEL. COST	PROD. COST
REFERENCE:	8									
		108 m^2	2	3.8	$240M	5	2	3	NA	NA
BEST:	8	27 m^2	10	7.8	$114M	10	10	8	NA	NA
WORST:										
	3	108 m^2	2	3.8	$240M	5	2	3	NA	NA

IMPORTANCE OF RADIATOR AREA

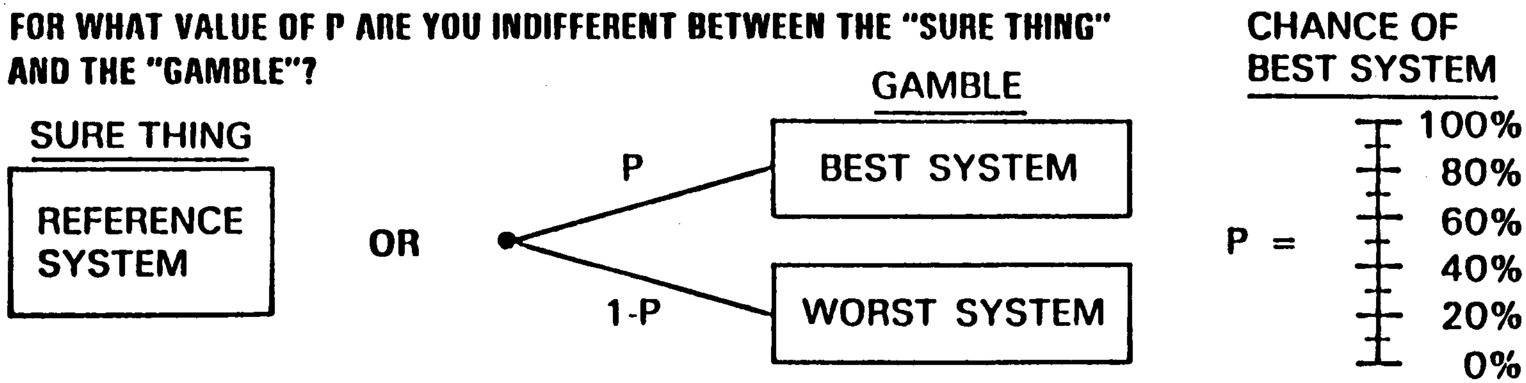
FOR WHAT VALUE OF P ARE YOU INDIFFERENT BETWEEN THE "SURE THING" AND THE "GAMBLE"?



	SAFETY	AREA	RELIAB.	MATUR.	FEAS. COST	SURVIV.	DORMANCY	PROD.	DEVEL. COST	PROD. COST
REFERENCE:		27 m^2								
	3		2	3.8	$240M	5	2	3	NA	NA
BEST:	8	27 m^2	10	7.8	$114M	10	10	8	NA	NA
WORST:										
	3	108 m^2	2	3.8	$240M	5	2	3	NA	NA

IMPORTANCE OF DESIGN RELIABILITY

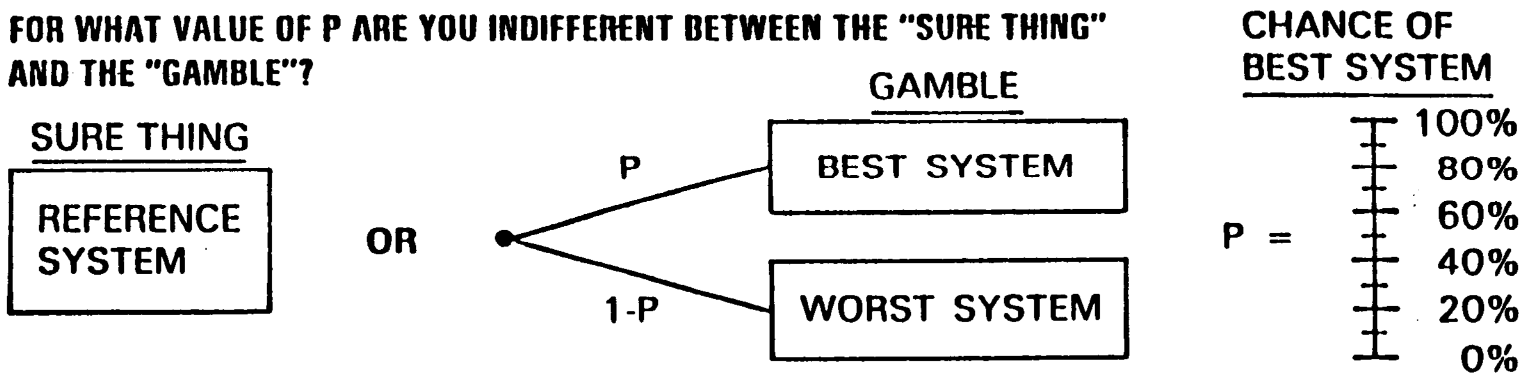
FOR WHAT VALUE OF P ARE YOU INDIFFERENT BETWEEN THE "SURE THING" AND THE "GAMBLE"?



	SAFETY	AREA	RELIAB.	MATUR.	FEAS. COST	SURVIV.	DORMANCY	PROD.	DEVEL. COST	PROD. COST
REFERENCE:			10							
	3	108 m^2		3.8	$240M	5	2	3	NA	NA
BEST:	8	27 m^2	10	7.8	$114M	10	10	8	NA	NA
WORST:										
	3	108 m^2	2	3.8	$240M	5	2	3	NA	NA

IMPORTANCE OF TECHNICAL MATURITY

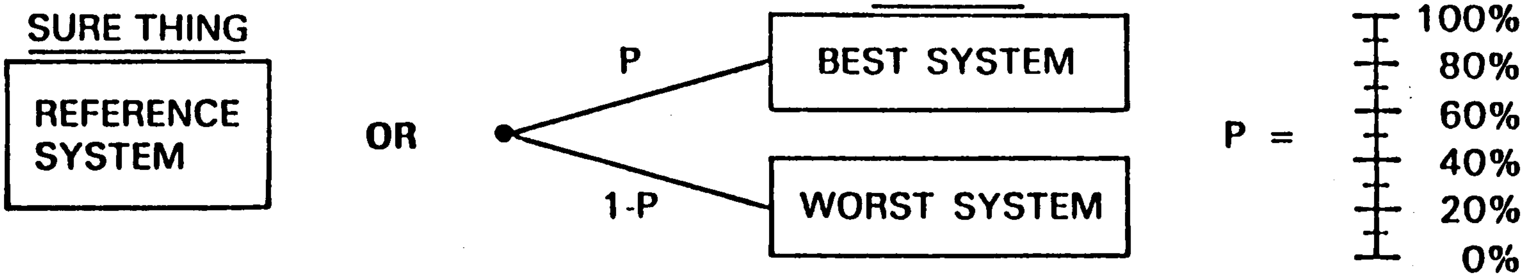
FOR WHAT VALUE OF P ARE YOU INDIFFERENT BETWEEN THE "SURE THING" AND THE "GAMBLE"?



	SAFETY	AREA	RELIAB.	MATUR.	FEAS. COST	SURVIV.	DORMANCY	PROD.	DEVEL. COST	PROD. COST
REFERENCE:				7.8						
	3	108 m^2	2		$240M	5	2	3	NA	NA
BEST:	8	27 m^2	10	7.8	$114M	10	10	8	NA	NA
WORST:										
	3	108 m^2	2	3.8	$240M	5	2	3	NA	NA

IMPORTANCE OF ESTIMATED COST TO REACH TECHNICAL FEASIBILITY

FOR WHAT VALUE OF P ARE YOU INDIFFERENT BETWEEN THE "SURE THING" AND THE "GAMBLE"?



	SAFETY	AREA	RELIAB.	MATUR.	FEAS. COST	SURVIV.	DORMANCY	PROD.	DEVEL. COST	PROD. COST
REFERENCE:					$114M					
	3	108 m^2	2	3.8		5	2	3	NA	NA
BEST:	8	27 m^2	10	7.8	$114M	10	10	8	NA	NA
WORST:										
	3	108 m^2	2	3.8	$240M	5	2	3	NA	NA

IMPORTANCE OF SURVIVABILITY

FOR WHAT VALUE OF P ARE YOU INDIFFERENT BETWEEN THE "SURE THING" AND THE "GAMBLE"?

SURE THING		GAMBLE
REFERENCE SYSTEM	OR	P: BEST SYSTEM
		1-P: WORST SYSTEM

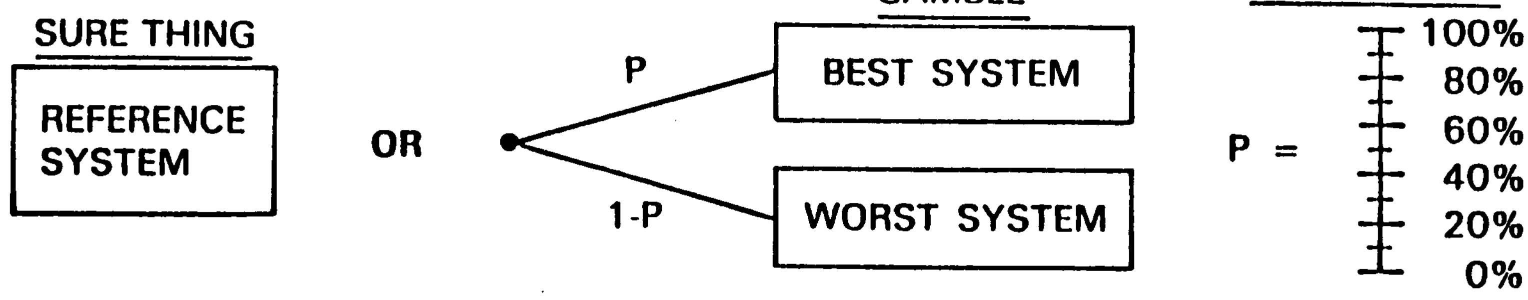
CHANCE OF BEST SYSTEM

P = 100% / 80% / 60% / 40% / 20% / 0%

	SAFETY	AREA	RELIAB.	MATUR.	FEAS. COST	SURVIV.	DORMANCY	PROD.	DEVEL. COST	PROD. COST
REFERENCE:						10				
	3 .	108 m^2	2	3.8	\$240M		2	3	NA	NA
BEST:	8	27 m^2	10	7.8	\$114M	10	10	8	NA	NA
WORST:										
	3	108 m^2	2	3.8	\$240M	5	2	3	NA	NA

IMPORTANCE OF ~~LOAD-FOLLOWING~~/DORMANCY CAPABILITY

FOR WHAT VALUE OF P ARE YOU INDIFFERENT BETWEEN THE "SURE THING" AND THE "GAMBLE"?



REFERENCE:

SAFETY	AREA	RELIAB.	MATUR.	FEAS. COST	SURVIV.	DORMANCY	PROD.	DEVEL. COST	PROD. COST
						10			
3	108 m^2	2	3.8	$240M	5		3	NA	NA

BEST:

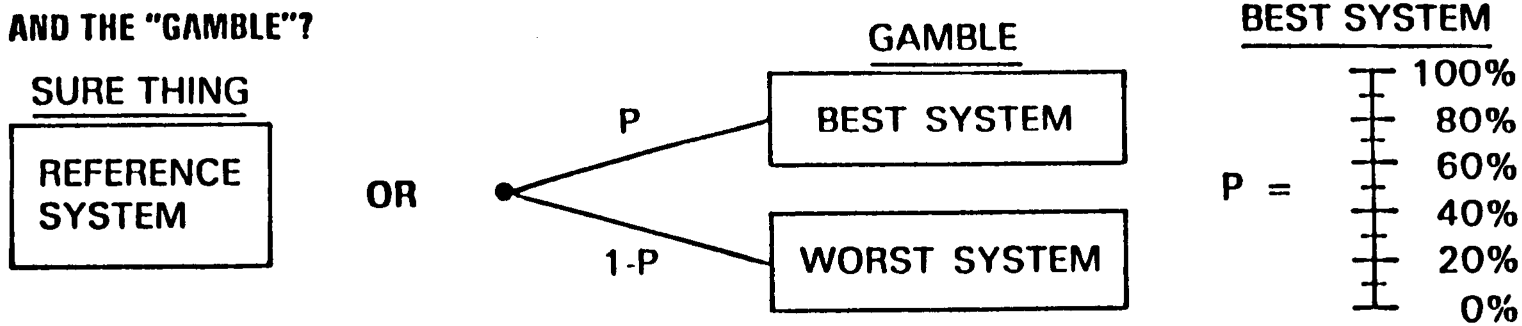
SAFETY	AREA	RELIAB.	MATUR.	FEAS. COST	SURVIV.	DORMANCY	PROD.	DEVEL. COST	PROD. COST
8	27 m^2	10	7.8	$114M	10	10	8	NA	NA

WORST:

SAFETY	AREA	RELIAB.	MATUR.	FEAS. COST	SURVIV.	DORMANCY	PROD.	DEVEL. COST	PROD. COST
3	108 m^2	2	3.8	$240M	5	2	3	NA	NA

IMPORTANCE OF PRODUCIBILITY

FOR WHAT VALUE OF P ARE YOU INDIFFERENT BETWEEN THE "SURE THING" AND THE "GAMBLE"?



	SAFETY	AREA	RELIAB.	MATUR.	FEAS. COST	SURVIV.	DORMANCY	PROD.	DEVEL. COST	PROD. COST
REFERENCE:								8		
	3	108 m^2	2	3.8	$240M	5	2		NA	NA
BEST:	8	27 m^2	10	7.8	$114M	10	10	8	NA	NA
WORST:										
	3	108 m^2	2	3.8	$240M	5	2	3	NA	NA

APPENDIX B

FLOW CHART OF INFORMATION FLOWS AND MATEUS PROGRAM USED TO CALCULATE RANKINGS WITH SAMPLE RUNS

The MATEUS Computer Program

I. MATEUS Computer Program Overview

The Computer Program MATEUS: MultiATtribute Evalution of UtilitieS was used to process the interview data and to determine ordinal and cardinal rankings of the alternative systems for individual and group preferences. MATEUS is presently written in MicroSoft FORTRAN-80, Release 3.4, December 1980, and will run on any MicroSoft FORTRAN-80 compatible microcomputers (with 8080, 8085, Z80, 8086, and 8088 microprocessors). MicroSoft FORTRAN-80 is essentially equivalent to FORTRAN IV, and with only minor modification (principally in the READ and WRITE statements) should run on any computer with a FORTRAN processor. (See also Figure B-1.)

MATEUS does three major computations: (1) It calculates the multiattribute utilities of outcomes based on the Keeney Multiplicative Model for multiattribute decision analysis, (2) it calculates utilities and rankings of alternative systems based on the the multiattribute utilities of outcomes and a discrete probability tree, and (3) it calculates group preferences corresponding to three group decision rules.

MATEUS comprises ten modules, each module partitioned into lower-level modules. Figure B-2 is a Program Tier Chart for MATEUS. The number above the upper right corner of a module gives the calling module. A number preceded by an "S" above the upper left corner of a module indicates that the module is a subroutine called at more than one place in the Program. Module S1 is called by Module 1.8 and Module 1.11. Figure B-3 is a Top-Level Program Flowchart for MATEUS. The top-level flowchart has a DO-loop that processes the data for each individual. Table B-1 gives the principal variable, array, and array index definitions for MATEUS.

A. Module MAIN

Module "MAIN" is the Main Routine for MATEUS and is the calling routine for all other routines. It initializes the dimensions of all arrays, and contains the structure of the DO-loop that processes the data for each individual.

B. Module DATA1

Module "DATA1" is called by the MAIN Module. It inputs the data for the probabilities of the decision tree and the attribute states for all outcomes. In the application of MATEUS to the evaluation and ranking of Electric and Hybrid Vehicles, no probabilistic analysis was undertaken, so that all probability nodes had only one path emanating from them, each with an associated probability of 1.0.

C. Module DATA2

Module "DATA2" is called by the MAIN Module. It inputs the data for the calculations for each individual. The data comprises the attribute scaling constants and (x,y) pairs of data points for piece-wise linear fits to the attribute utility functions. In the application of MATEUS to the evaluation and ranking of Electric and Hybrid Vehicles, both three-point and five-point fits to the attribute utility functions were used.

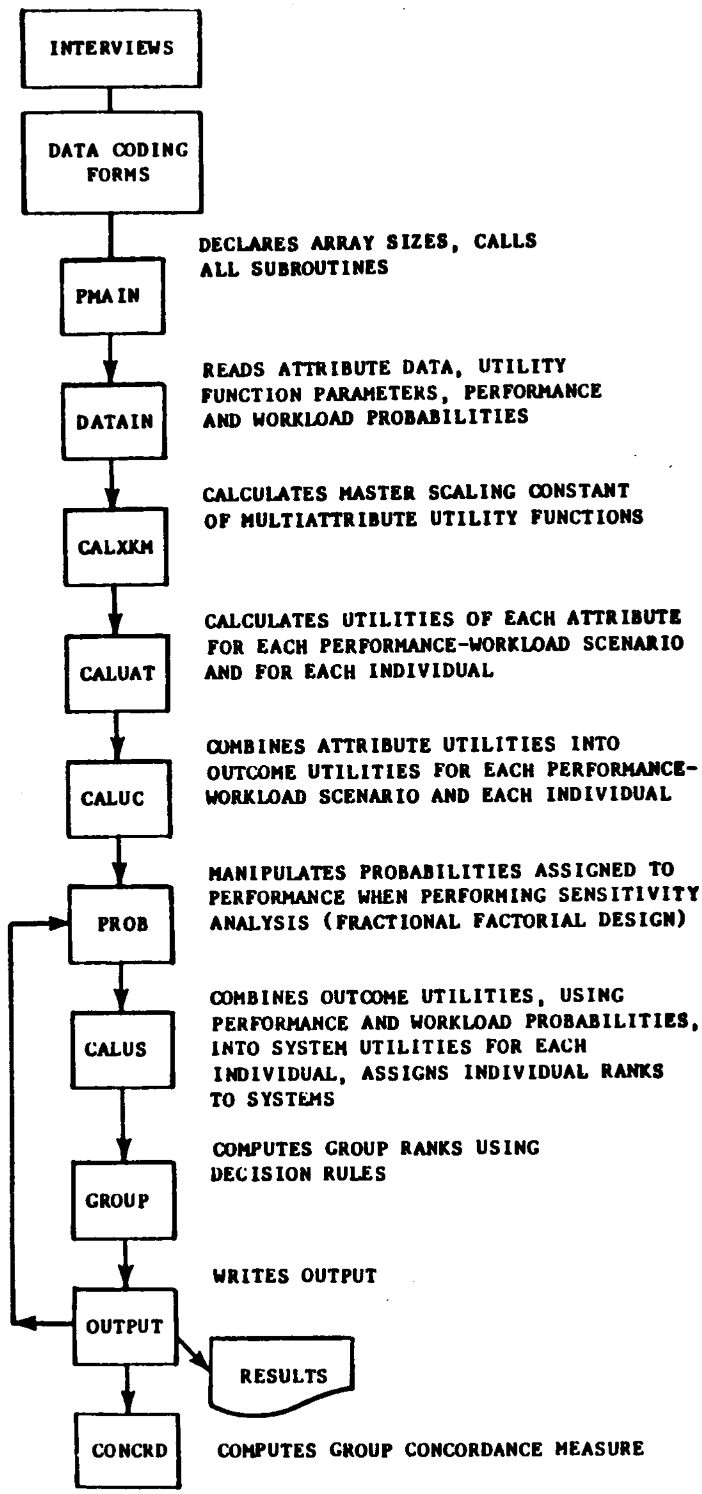


Figure B-1. Information Flows and Relevant Computer Programs Used to Rank Alternatives

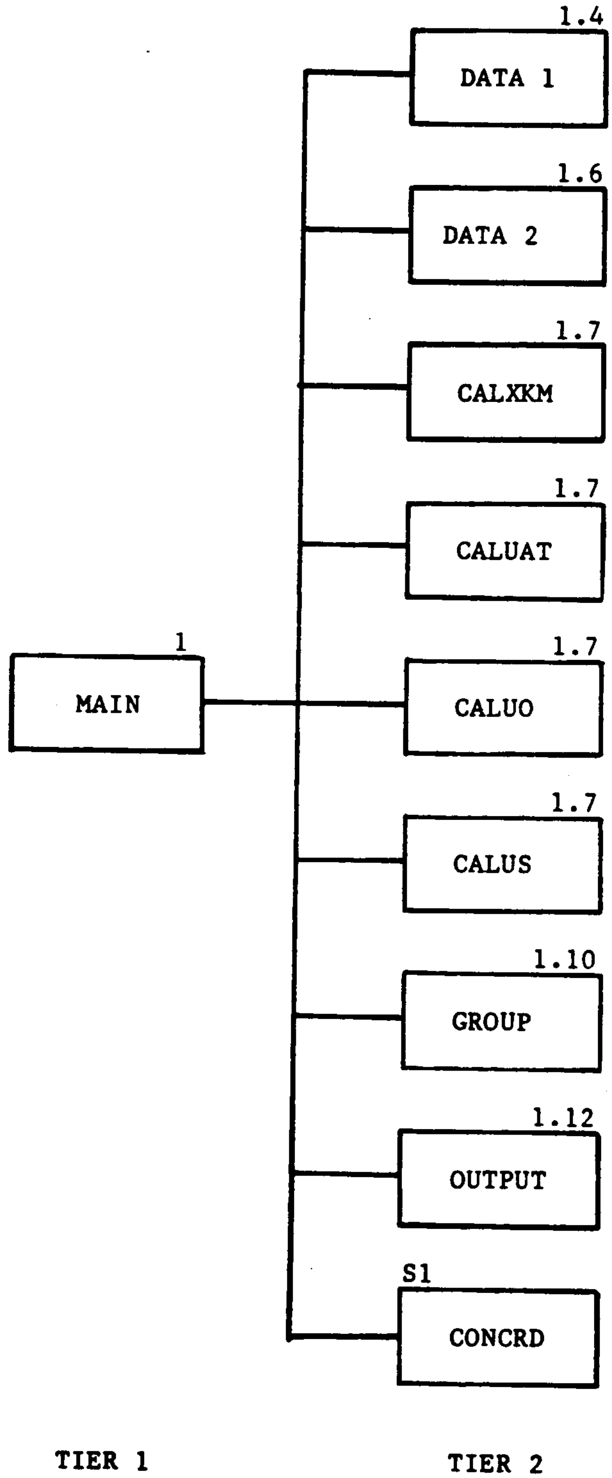


Figure B-2. MATEUS Program Tier Chart

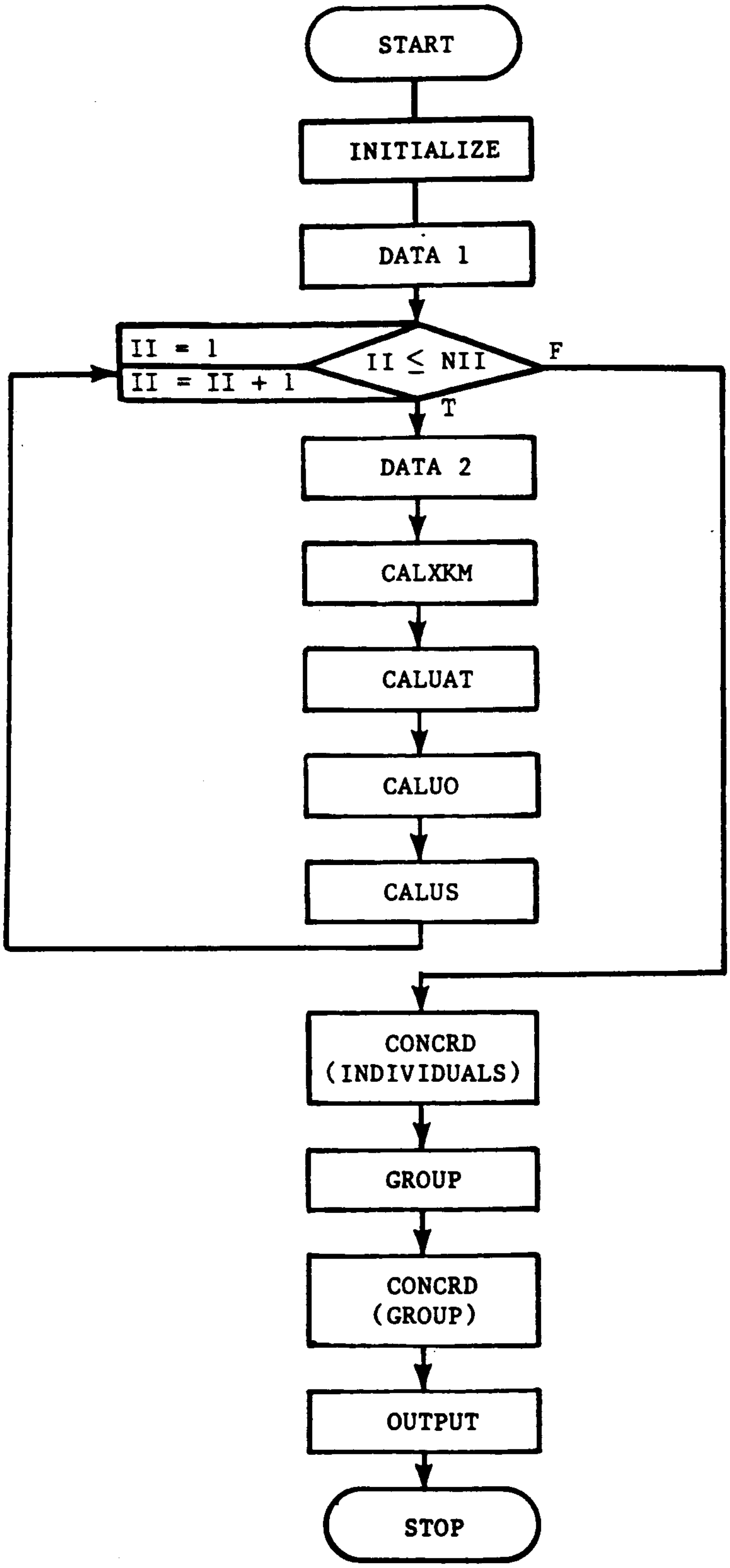


Figure B-3. MATEUS Top-Level Program Flowchart

D. Module CALXKM

Module "CALXKM" is called by the MAIN module. It calculates the master scaling constant for the Keeney Multiplicative Formulation of the multiattribute decision analysis model, given the attribute scaling constants of an individual. It has been proven by Keeney that the master scaling constant must be greater than -1.0, and that for the sum of the scaling constants less than 1.0, the master scaling constant must be greater than 0.0, for the sum of the scaling constants equal to one the Multiplicative Formulation is replaced by a Linear Formulation, and that for the sum of the scaling constants greater than 1.0, the master scaling constant must be less than 0.0. This information is used to determine a starting point for a Newton-Raphson iteration for the master scaling constant.

E. Module CALUAT

Module CALUAT is called by the MAIN Module. It calculates the attribute utility function values for the attributes of each outcome given the outcome states and the individual utility functions.

F. Module CALUO

Module CALUO is called by the MAIN Module. It calculates the outcome utility function values for an individual for the outcomes, given the outcome attribute utility function values, and the individual master and attribute scaling constants.

G. Module CALUS

Module CALUS is called by the MAIN Module. It calculates the alternative (system) utility function value for each alternative given the outcome utility function values and the probabilities of the decision tree. In the application of MATEUS to the evaluation and ranking of Electric and Hybrid Vehicles, the analysis was deterministic and the decision tree defaulted to probability nodes with one path emanating with probability 1.0.

F. Module GROUP

Module GROUP is called by the MAIN Module. It calculates the group decision rule values for three group decision rules: (1) The Additive Rule, (2) the Nash Bargaining Rule, and (3) the Rank Sum Rule.

G. Module CONCRD

Module CONCRD is called twice by the MAIN Module--once for the individual rankings and once for the three group decision rules. It calculates Kendall's Coefficient of Concordance.

H. File ARRAY.FOR

File ARRAY.FOR is "INCLUDE"d at compile time for the MAIN Routine. It allocates memory space for all arrays with FORTRAN "DIMENSION" AND "DOUBLE

PRECISION" statements. It is the only file that has to be modified to change the maximum size of arrays.

//

IA	Index for Attributes. IA = 1,...,NIA.
IC	Index for Coefficients of piece-wise linear fit to Attribute Utility Data. IC = 1,...,NIC.
ID	Index for Attribute Utility Data. ID = 1,...,NID.
IG	Index for Group Decision Rules. IG = 1,...,3.
IP	Index for Probability Node Paths. IP = 1,...,NIP.
IS	Index for Systems or Alternatives. IS = 1,...,NIS.
IW	Index for Kendall's Coefficient of Concordance Group. IW =1,2
JRUNID	Integer Identifier for the Input and Output Data of the MATEUS run.
JDIAG	Integer Level of Diagnostic display during run. (Not implemented in Version 1.1.)
NIA	Number of Attributes.
NIC	Number of Coefficients. NIC = NID - 2.
NID	Number of Attribute Data Values.
NIP	Number of Probability Paths.
NIS	Number of Systems or Alternatives.
AT(IS,IP,IA)	Attribute State for Attribute IA of the Outcome of Probability Path IP for System IS.
CHISQR(IW)	CHI-Square Statistic for Group IW.
IRS(II,IS)	Array RS(II,IS) converted from real to integer data type.
IRG(IG,IS)	Array RG(II,IS) converted from real to integer data type.
JDF(IW)	Degrees of Freedom for Group IW.
PROB(IS,IP)	Probability assigned to Probability Path IP for System IS.
RG(IG,IS)	Preference Rank assigned to System IS by Group Decision Rule IG .
RS(II,IS)	Preference Rank assigned to System IS by Individual II.
UAT(IS,IP,IA)	Utility assigned to Attribute IA for Outcome of Probability Path IP (by some Individual II).
UATC(IA,IC)	Utility Coefficent IC of piece-wise linear fit to Utility of Attribute IA (for some Individual II).
UATD(IA,ID)	Utility Data ID for Attribute IA (assessed by some Individual II).
UO(II,IS,IP)	Utility assigned to Outcome of Probability Path IP for System IS by Individual II.
US(II,IS)	Utility assigned to System IS by Individual II.
VG(IG,IS)	Value assigned to System IS by Group Decision Rule IG.
XK(II,IA)	Scaling Constant assigned to Attribute IA by Individual II.
XKM(II)	Master Scaling Constant for Individual II.

Table B-1. Principal Variable, Array, and Array Index Definitions for MATEUS.

```
C***********************************************************************C
C                               PROGRAM MATEUS
C
C THIS IS THE PROGRAM MATEUS: MULTIATTRIBUTE EVALUATION OF UTILITIES.
C IT IS WRITTEN IN MICROSOFT FORTRAN-80, RELEASE 3.4, DECEMBER 1980.
C IN GENERAL, FORTRAN PROCESSORS WILL REQUIRE THAT MINOR MODIFICATIONS
C BE MADE TO THE PROGRAM.
C
C PROGRAMMER: R. F. MILES, JR.
C             JET PROPULSION LABORATORY
C             PASADENA, CALIFORNIA 91009
C
C VERSION:    1.1x1  7/21/83.
C***********************************************************************C
C THIS IS THE MAIN ROUTINE OF THE PROGRAM MATEUS.
C***********************************************************************C
C THIS IS THE MAIN ROUTINE.  IT DECLARES THE SIZES OF THE ARRAYS.  IT
C IS THE MAIN CALLING ROUTINE FOR ALL SUBROUTINES.  IT CONTAINS THE DO
C LOOP FOR INDIVIDUALS, II = 1,...,NII.  IT ENDS THE PROGRAM.
C-----------------------------------------------------------------------C
C***C DIMENSION THE ARRAYS.  {MODULE 1}
      INCLUDE B:ARRAY.FOR
C-----------------------------------------------------------------------C
C***C INITIALIZATION.  {MODULE 2}
C
      WRITE  (5,100)
100   FORMAT (' START MAIN ROUTINE')
C
      READ   (7,110) JRUNID,JDIAG,NII,NIS,NIP,NIA,NID
110   FORMAT (//1X,7I10)
C
      NIC = NID - 2
C-----------------------------------------------------------------------C
C***C WRITE TITLE TO TERMINAL AND DISK.  {MODULE 3}
C
C     TERMINAL (JUNIT = 5) AND DISK (JUNIT = 8 FOR FILE FORT08.DAT).
C
      DO 150 IU=1,2
C       INSERT "20H" FOR PRINTER AND "0AH" FOR FILE.
        IF (IU .EQ. 1)    LF = Z'20'
        IF (IU .EQ. 1) JUNIT = 5
        IF (IU .EQ. 2)    LF = Z'0A'
        IF (IU .EQ. 2) JUNIT = 8
C
C       *** PROGRAM TITLE ***
        WRITE  (JUNIT,120)
120     FORMAT (1X,35X,'MATEUS')
        WRITE  (JUNIT,130) LF,LF
130     FORMAT (A1,20X,'MULTIATTRIBUTE EVALUATION OF UTILITIES'/A1)
C
C       *** PROGRAM INITIALIZATION PARAMETERS ***
        WRITE  (JUNIT,140) LF,LF,JRUNID,LF,JDIAG,LF,NII,LF,NIS,LF,NIP,
     1          LF,NIA,LF,NID,LF
140     FORMAT (A1/A1,'RUN IDENTIFICATION NUMBER:     ',I5,/
     1          A1,'DIAGNOSTIC DISPLAY LEVEL:      ',I5/
```

```
     2          A1,'NUMBER OF INDIVIDUALS:        ',I5/
     3          A1,'NUMBER OF SYSTEMS:            ',I5/
     4          A1,'NUMBER OF PROBABILITY PATHS:  ',I5/
     5          A1,'NUMBER OF ATTRIBUTES:         ',I5/
     6          A1,'NUMBER OF ATTRIBUTE DATA:     ',I5/A1)
150   CONTINUE
C
C     *** DELAY TO READ TERMINAL ***
      DO 160 I=1,5000
        DELAY = DELAY + 1.0
160   CONTINUE
C-------------------------------------------------------------------C
C***C INPUT DATA FOR PROBABILITIES AND ATTRIBUTE STATES.  {MODULE 4}
C
      CALL DATA1(PROB,AT,NIS,NIP,NIA)
C-------------------------------------------------------------------C
C***C DO LOOP FOR INDIVIDUAL CALCULATIONS.  {MODULE 5}
C
      DO 180 II=1,NII
        WRITE  (5,170) II
170     FORMAT (/1X,'CALCULATIONS FOR INDIVIDUAL ',I3)
C-------------------------------------------------------------------C
C***C   INPUT DATA FOR SCALING CONSTANTS AND ATTRIBUTE UTILITY
C***C   FUNCTIONS FOR INDIVIDUAL II.  {MODULE 6}
C
        CALL DATA2(XK,UATD,II,NII,NIA,NID)
C-------------------------------------------------------------------C
C***C   CALL SUBROUTINES FOR INDIVIDUAL II CALCULATIONS.  {MODULE 7}
C
        CALL CALXKM(XK,XKM,II,NII,NIA)
        CALL CALUAT(AT,UATD,UATC,UAT,II,NIS,NIP,NIA,NID,NIC)
        CALL CALUO(XK,XKM,UAT,UO,II,NII,NIS,NIP,NIA)
        CALL CALUS(PROB,UO,US,RS,IRS,II,NII,NIS,NIP)
C-------------------------------------------------------------------C
C***C   END DO LOOP FOR INDIVIDUAL CALCULATIONS.  {MODULE 5}
C
180   CONTINUE
C-------------------------------------------------------------------C
C***C CALCULATE INDIVIDUAL CONCORDANCE.  {MODULE 8}
C
      CALL CONCRD(RS,SRX,TIES,STIES,W,CHISQR,JDF,1,NII,NIS)
C-------------------------------------------------------------------C
C***C END CALCULATIONS FOR INDIVIDUALS.  {MODULE 9}
C
      WRITE  (5,200)
200   FORMAT (/1X,'END CALCULATIONS FOR INDIVIDUALS'/)
C-------------------------------------------------------------------C
C***C CALCULATIONS FOR GROUP RULES.  {MODULE 10}
C
      CALL GROUP(US,RS,IRS,VG,RG,IRG,NII,NIS)
C-------------------------------------------------------------------C
C***C CALCULATE GROUP CONCORDANCE.  {MODULE 11}
C
      CALL CONCRD(RG,SRX,TIES,STIES,W,CHISQR,JDF,2,3,NIS)
C-------------------------------------------------------------------C
```

```
C***C WRITE OUTPUT TO TERMINAL AND DISK.  {MODULE 12}
C
      CALL OUTPUT(US,IRS,VG,IRG,W,CHISQR,JDF,NII,NIS)
C---------------------------------------------------------------------C
C***C END PROGRAM MATEUS.  {MODULE 13}
C
      WRITE  (5,999)
999   FORMAT (///1X,' EXIT  MAIN PROGRAM'/)
C
      STOP MATEUS
C
      END
C*********************************************************************C
```

```
C**********************************************************************C
C                           SUBROUTINE DATA1                    9/5/82
C**********************************************************************C
C SUBROUTINE DATA1 INPUTS THE DATA FOR PROBABILITIES AND ATTRIBUTE
C STATES.
C**********************************************************************C
      SUBROUTINE DATA1(PROB,AT,NIS,NIP,NIA)
C**********************************************************************C
C***C INITIALIZE.  {MODULE 1}
C
      DIMENSION PROB(NIS,NIP),AT(NIS,NIP,NIA)
      WRITE  (5,100)
100   FORMAT (/' ENTER SUBROUTINE DATA1')
C----------------------------------------------------------------------C
C***C  READ & WRITE PROBABILITY DATA PROB(NIS,NIP).  {MODULE 2}
C
      DO 150 IS=1,NIS
        READ   (7,110)
110     FORMAT (1X)
        READ   (7,120) (PROB(IS,IP),IP=1,NIP)
120     FORMAT (1X,10F7.4)
        WRITE  (5,130) IS
130     FORMAT (/1X,'PROBABILITY DATA FOR OUTCOMES (IS,IP) OF SYSTEM',
     1          ' (IS =',I3,')')
        WRITE  (5,140) (PROB(IS,IP),IP=1,NIP)
140     FORMAT (1X,10F7.4)
150   CONTINUE
C----------------------------------------------------------------------C
C***C READ & WRITE ATTRIBUTE DATA AT(IS,IP,IA) FOR OUTCOMES (IS,IP).
C     {MODULE 3}
C
      DO 200 IS=1,NIS
        DO 200 IP=1,NIP
          READ   (7,160)
160       FORMAT (1X)
          READ   (7,170) (AT(IS,IP,IA),IA=1,NIA)
170       FORMAT (5(1X,E14.4))
          WRITE  (5,180) IS,IP
180       FORMAT (1X,'ATTRIBUTE DATA FOR OUTCOME ',
     1            '(IS =',I3,', IP =',I3,')')
          WRITE  (5,190) (AT(IS,IP,IA),IA=1,NIA)
190       FORMAT (5(1X,1PE14.4))
200   CONTINUE
C----------------------------------------------------------------------C
C***C EXIT SUBROUTINE DATA1.  {MODULE 4}
C
      WRITE  (5,999)
999   FORMAT (' EXIT  SUBROUTINE DATA1')
C
      RETURN
C
      END
C**********************************************************************C
```

```
C***********************************************************************C
C                          SUBROUTINE DATA2                      8/28/82
C***********************************************************************C
C SUBROUTINE DATA2 INPUTS THE DATA FOR THE CALCULATIONS FOR EACH
C INDIVIDUAL II.
C***********************************************************************C
      SUBROUTINE DATA2(XK,UATD,II,NII,NIA,NID)
C***********************************************************************C
C***C INITIALIZE.  {MODULE 1}
      DIMENSION XK(NII,NIA),UATD(NIA,NID)
      WRITE  (5,100)
100   FORMAT (/' ENTER SUBROUTINE DATA2')
C-----------------------------------------------------------------------C
C***C READ DATA FOR INDIVIDUAL (II).  {MODULE 2}
C     READ SCALING CONSTANTS XK(II,IA)
      READ   (7,105)
105   FORMAT (/1X)
      READ   (7,110) (XK(II,IA),IA=1,NIA)
110   FORMAT (1X,10F7.4)
      WRITE  (5,120) (XK(II,IA),IA=1,NIA)
120   FORMAT (1X,'SCALING CONSTANTS XK(II,IA)'
     1       /(1X,10F7.4))
C     READ ATTRIBUTE UTILITY DATA UATD(IA,ID) FOR INDIVIDUAL (II).
      READ   (7,130)
130   FORMAT (1X)
      WRITE  (5,140)
140   FORMAT (1X,'ATTRIBUTE UTILITY DATA UATD(IA,ID)')
      DO 180 IA=1,NIA
        READ   (7,145)
145     FORMAT (1X)
        READ   (7,150) (UATD(IA,ID),ID=1,NID)
150     FORMAT (3(1X,E16.4,F7.4))
        WRITE  (5,160) IA
160     FORMAT (1X,'ATTRIBUTE ',I3)
        WRITE  (5,170) (UATD(IA,ID),ID=1,NID)
170     FORMAT (3(1X,1PE16.4,0PF7.4))
180   CONTINUE
C-----------------------------------------------------------------------C
C***C EXIT SUBROUTINE DATA2.  {MODULE 99}
      WRITE  (5,999)
999   FORMAT (' EXIT  SUBROUTINE DATA2')
C
      RETURN
C
      END
C***********************************************************************C
```

```
C***********************************************************************C
C                            SUBROUTINE CALXKM                    2/6/83
C***********************************************************************C
C SUBROUTINE CALXKM CALCULATES THE MASTER SCALING CONSTANT XKM(II).
C***********************************************************************C
      SUBROUTINE CALXKM(XK,XKM,II,NII,NIA)
C***********************************************************************C
C***C INITIALIZE.  {MODULE 1}
C
      DOUBLE PRECISION XKM(NII),FG,G,DG,XKML
      DIMENSION XK(NII,NIA)
      WRITE  (5,100)
100   FORMAT (/' ENTER SUBROUTINE CALXKM')
C
C     *** WRITE SCALING CONSTANTS XK(NII,NIA) ***
      WRITE  (5,110) II
110   FORMAT (/1X,'SCALING CONSTANTS XK(II,IA) FOR INDIVIDUAL (II=',
     1        I3,')')
      WRITE  (5,120) (XK(II,IA),IA=1,NIA)
120   FORMAT (1X,10F7.4)
C----------------------------------------------------------------------C
C***C TEST FOR SIGN OF XKM(II).  {MODULE 2}
C
      SXK = 0.0
      DO 130 IA=1,NIA
        SXK = SXK+XK(II,IA)
130   CONTINUE
C
      WRITE  (5,140) II,SXK
140   FORMAT (1X,'SUM OF ATTRIBUTE SCALING CONSTANTS FOR INDIVIDUAL ',
     1        '(II=',I3,') IS:',F8.4)
C
      IF (ABS(SXK-1.0) .LT. 1.0E-3) GO TO 160
      IF (SXK .GT. 1.0) GO TO 150
      IF (SXK .LT. 1.0) GO TO 170
C----------------------------------------------------------------------C
C***C INITIALIZE XKM(II).  {MODULE 3}
C
C     *** INITIAL XKM < 0 ***
150   XKM(II) = -1.0
      GO TO 200
C
C     *** INITIAL XKM = 0 ***
160   XKM(II) = 0.0
      GO TO 230
C
C     *** DETERMINE INITIAL XKM > 0.  ITERATION REQUIRED ***
170   CONTINUE
      XKM(II) = 1.0
      FG = 0.0
180   CONTINUE
      XKM(II) = 2*XKM(II)
      WRITE  (5,185) II,XKM(II),FG
185   FORMAT (1X,'ITERATE FOR XKM(II=',I3,') > 0.0.    XKM =',F11.8,
     1        '    FG =',1PE16.8)
```

```
      G = 1.0
      DO 190 IA=1,NIA
        G = G*(1.0+XKM(II)*XK(II,IA))
190   CONTINUE
      FG = 1.0+XKM(II)-G
      IF (FG .GT. 0.0) GO TO 180
      GO TO 200
C-----------------------------------------------------------------------C
C***C NEWTON-RAPHSON ITERATION FOR XKM.  {MODULE 4}
C
200   CONTINUE
C
      G = 1.0
      DO 210 IA=1,NIA
        G = G*(1.0+XKM(II)*XK(II,IA))
210   CONTINUE
      FG = 1.0+XKM(II)-G
      DG = 0.0
      DO 220 IA=1,NIA
        DG = DG+(XK(II,IA)/(1.0+XKM(II)*XK(II,IA)))*G
220   CONTINUE
      DG = 1.0-DG
      XKML = XKM(II)
      XKM(II) = XKM(II)-FG/DG
      WRITE  (5,225) II,XKM(II)
225   FORMAT (1X,'NEWTON-RAPHSON ITERATION.   XKM(II=',I3,') =',F11.8)
      IF (DABS(XKM(II)-XKML) .GT. 1.0E-8) GO TO 200
      GO TO 230
C-----------------------------------------------------------------------C
C***C WRITE XKM(II) FOR INDIVIDUAL (II).  {MODULE 5}
C
230   CONTINUE
C
      WRITE  (5,240) II,XKM(II)
240   FORMAT (1X,'MASTER SCALING CONSTANT FOR INDIVIDUAL (II=',I3,
     1        ') IS:',F11.8)
C-----------------------------------------------------------------------C
C***C WRITE XK(II,IA),SXK, AND XKM(II) TO DISK.  {MODULE 6}
C
      LF = Z'0A'
C
C     *** WRITE ATTRIBUTE SCALING CONSTANTS XK(NII,NIA) ***
      WRITE  (8,250) LF,LF,II
250   FORMAT (A1/A1,'ATTRIBUTE SCALING CONSTANTS XK(II,IA) FOR ',
     1        'INDIVIDUAL (II=',I3,')')
C
      DO 270 IAM=1,NIA,10
        IAN = IAM + 9
        IF (IAN .GE. NIA) IAN = NIA
        WRITE  (8,260) LF,(XK(II,IA),IA=IAM,IAN)
260     FORMAT (A1,10F7.4)
        IF (IAN .EQ. NIA) GO TO 280
270   CONTINUE
280   CONTINUE
C
```

```
C     *** WRITE SUM OF ATTRIBUTE SCALING CONSTANTS SXK ***
      WRITE  (8,290) LF,II,SXK
290   FORMAT (A1,'SUM OF ATTRIBUTE SCALING CONSTANTS FOR INDIVIDUAL ',
     1        '(II=',I3,') IS:',F8.4)
C
C     *** WRITE MASTER SCALING CONSTANT XK(II) ***
      WRITE  (8,300) LF,II,XKM(II)
300   FORMAT (A1,'MASTER SCALING CONSTANT FOR INDIVIDUAL (II=',I3,')',
     1        ' IS:',F11.8)
C--------------------------------------------------------------------C
C***C EXIT SUBROUTINE CALXKM.  {MODULE 7}
C
      WRITE  (5,999)
999   FORMAT (/' EXIT  SUBROUTINE CALXKM')
C
      RETURN
C
      END
C********************************************************************C
```

```
C*********************************************************************C
C                           SUBROUTINE CALUAT                   2/7/83
C*********************************************************************C
C SUBROUTINE CALUAT CALCULATES THE ATTRIBUTE UTILTITY FUNCION VALUES
C UAT(IS,IP,IA) FOR THE ATTRIBUTES IA OF EACH OUTCOME (IS,IP) FOR EACH
C INDIVIDUAL II.
C*********************************************************************C
      SUBROUTINE CALUAT(AT,UATD,UATC,UAT,II,NIS,NIP,NIA,NID,NIC)
C*********************************************************************C
C***C INITIALIZE.  {MODULE 1}
      DIMENSION
     1  AT(NIS,NIP,NIA),
     2  UATD(NIA,NID),UATC(NIA,NIC),UAT(NIS,NIP,NIA)
      WRITE  (5,100)
100   FORMAT (/' ENTER SUBROUTINE CALUAT')
C-------------------------------------------------------------------C
C***C WRITE ATTRIBUTE UTILITY DATA FOR INDIVIDUAL (II).  {MODULE 2}
      WRITE  (5,110) II
110   FORMAT (/1X,'ATTRIBUTE UTILITY DATA UATD(IA,ID) FOR INDIVIDUAL',
     1         ' (II=',I3,')')
      DO 140 IA=1,NIA
        WRITE  (5,120) IA
120     FORMAT (1X,'ATTRIBUTE ',I3)
        WRITE  (5,130) (UATD(IA,ID),ID=1,NID)
130     FORMAT (3(1X,1PE16.4,0PF7.4))
140   CONTINUE
C-------------------------------------------------------------------C
C***C CALCULATE ATTRIBUTE UTILITY FUNCTION COEFFICIENTS UATC(IA,IC)
C     FOR INDIVIDUAL (II).  {MODULE 3}
      NICC = NIC - 1
      DO 170 IA=1,NIA
        DO 170 IC=1,NICC,2
          AT1 = UATD(IA,IC)
          AT2 = UATD(IA,IC+2)
          UTIL1 = UATD(IA,IC+1)
          UTIL2 = UATD(IA,IC+3)
          IF (AT2 .NE. AT1) GO TO 150
          A = 0.0
          B = 0.0
          GO TO 160
150       CONTINUE
          A = (UTIL2 - UTIL1)/(AT2 - AT1)
          B = UTIL1 - AT1*A
160       CONTINUE
          UATC(IA,IC)   = A
          UATC(IA,IC+1) = B
170   CONTINUE
C-------------------------------------------------------------------C
C***C WRITE ATTRIBUTE UTILITY FUNCTION COEFFICIENTS UATC(IA,IC)
C     FOR INDIVIDUAL (II).  {MODULE 4}
      WRITE  (5,180) II
180   FORMAT (/1X,'ATTRIBUTE UTILITY FUNCTION COEFFICIENTS ',
     1         'UATC(IA,IC) FOR INDIVIDUAL (II=',I3,')')
      DO 210 IA=1,NIA
        WRITE  (5,190) IA
```

```
190      FORMAT (1X,'ATTRIBUTE ',I3)
         WRITE  (5,200) (UATC(IA,IC),IC=1,NIC)
200      FORMAT (5(1X,1PE14.4))
210    CONTINUE
C-----------------------------------------------------------------C
C***C WRITE ATTRIBUTE DATA AT(IS,IP,IA) FOR OUTCOMES (IS,IP).
C      {MODULE 5}
       WRITE  (5,220)
220    FORMAT (1X/1X,'ATTRIBUTE DATA AT(IS,IP,IA)')
       DO 250 IS=1,NIS
         DO 250 IP=1,NIP
           WRITE  (5,230) IS,IP
230        FORMAT (1X,'ATTRIBUTE DATA FOR OUTCOME ',
     1             '(IS=',I3,',IP=',I3,')')
           WRITE  (5,240) (AT(IS,IP,IA),IA=1,NIA)
240        FORMAT (5(1X,1PE14.4))
250    CONTINUE
C-----------------------------------------------------------------C
C***C CALCULATE ATTRIBUTE UTILITIES UAT(IS,IP,IA).  {MODULE 6}
       DO 260 IS=1,NIS
         DO 260 IP=1,NIP
           DO 260 IA=1,NIA
             DO 258 ID=3,NID,2
               IF ((UATD(IA,1) .LT. UATD(IA,3))
     1           .AND. (AT(IS,IP,IA) .GT. UATD(IA,ID)))
     2           GO TO 258
               IF ((UATD(IA,1) .GT. UATD(IA,3))
     1           .AND. (AT(IS,IP,IA) .LT. UATD(IA,ID)))
     2           GO TO 258
               IC = ID - 2
               UAT(IS,IP,IA) = UATC(IA,IC)*AT(IS,IP,IA)
     1                         + UATC(IA,IC+1)
               GO TO 260
258          CONTINUE

260    CONTINUE
C-----------------------------------------------------------------C
C***C WRITE ATTRIBUTE UTILITIES UAT(IS,IP,IA) FOR ALL OUTCOMES
C      (IS,IP).  {MODULE 7}
       WRITE  (5,265) II
265    FORMAT (/1X,'ATTRIBUTE UTILITIES FOR INDIVIDUAL (II=',I3,')')
       DO 290 IS=1,NIS
         DO 290 IP=1,NIP
           WRITE  (5,270) IS,IP
270        FORMAT (1X,'ATTRIBUTE UTILITIES UAT(IS,IP,IA) FOR ',
     1             'OUTCOME (IS=',I3,',IP=',I3,')')
           WRITE  (5,280) (UAT(IS,IP,IA),IA=1,NIA)
280        FORMAT (1X,10F7.4)
290    CONTINUE
C-----------------------------------------------------------------C
C***C EXIT SUBROUTINE CALUAT.  {MODULE 99}
       WRITE  (5,999)
999    FORMAT (/' EXIT  SUBROUTINE CALUAT')
C
       RETURN
```

```
C
      END
C***************************************************************************C
```

File: B:CALUO.FOR

```
C*********************************************************************C
C                             SUBROUTINE CALUO                  2/6/83
C*********************************************************************C
C SUBROUTINE CALUO CALCULATES THE OUTCOME UTILITY FUNCTION VALUE
C UO(IS,IP) FOR EACH OUTCOME (IS,IP) FOR EACH INDIVIDUAL (II).
C*********************************************************************C
      SUBROUTINE CALUO(XK,XKM,UAT,UO,II,NII,NIS,NIP,NIA)
C*********************************************************************C
C***C INITIALIZE.  {MODULE 1}
      DOUBLE PRECISION XKM(NII), PROD
      DIMENSION XK(NII,NIA),UAT(NIS,NIP,NIA),UO(NIS,NIP)
      WRITE  (5,100)
100   FORMAT (/' ENTER SUBROUTINE CALUO')
C---------------------------------------------------------------------C
C***C WRITE SUBROUTINE INPUT ARRAYS.  {MODULE 2}
      WRITE  (5,110) II
110   FORMAT (/1X,'ATTRIBUTE SCALING CONSTANTS FOR INDIVIDUAL (II=',
     1        I3,')')
      WRITE  (5,120) (XK(II,IA),IA=1,NIA)
120   FORMAT (10(1X,F7.4))
      WRITE  (5,130) II,XKM(II)
130   FORMAT (1X,'MASTER SCALING CONSTANT FOR INDIVIDUAL (II=',I3,')',
     1        ' IS:',F11.8)
      WRITE  (5,140) II
140   FORMAT (/1X,'ATTRIBUTE UTILITIES FOR INDIVIDUAL (II=',I3,')')
      DO 170 IS=1,NIS
        DO 170 IP=1,NIP
          WRITE  (5,150) IS,IP
150       FORMAT (1X,'ATTRIBUTE UTILITIES UAT(IS,IP) FOR ',
     1              'OUTCOME (IS=',I3,',IP=',I3,')')
          WRITE  (5,160) (UAT(IS,IP,IA),IA=1,NIA)
160       FORMAT (1X,10F7.4)
170   CONTINUE
C---------------------------------------------------------------------C
C***C TEST FOR ADDITIVE OR MULTIPLICATIVE UTILITY FUNCTION.
C***C {MODULE 3}
      IF (XKM(II) .EQ. 0.0) GO TO 180
      IF (XKM(II) .NE. 0.0) GO TO 210
C---------------------------------------------------------------------C
C***C CALCULATE ADDITIVE UTILITIES UO(IS,IP) FOR OUTCOMES (IS,IP).
C***C {MODULE 4}
180   CONTINUE
      DO 200 IS=1,NIS
        DO 200 IP=1,NIP
          UO(IS,IP) = 0.0
          DO 190 IA=1,NIA
            UO(IS,IP) = UO(IS,IP) + XK(II,IA)*UAT(IS,IP,IA)
190       CONTINUE
200   CONTINUE
      GO TO 235
C---------------------------------------------------------------------C
C***C CALCULATE MULTIPLICATIVE UTILITIES UO(IS,IP) FOR OUTCOMES
C***C (IS,IP).  {MODULE 5}
210   CONTINUE
      DO 230 IS=1,NIS
```

```
        DO 230 IP=1,NIP
          PROD = 1.0
          DO 220 IA=1,NIA
            PROD = PROD*(1.0+XKM(II)*XK(II,IA)*UAT(IS,IP,IA))
220       CONTINUE
          UO(IS,IP) = (PROD-1.0)/XKM(II)
230   CONTINUE
C-------------------------------------------------------------------C
C***C WRITE UTILITIES UO(IS,IP) FOR OUTCOMES (IS,IP).  {MODULE 6}
235   CONTINUE
      WRITE  (5,240) II
240   FORMAT (/1X,'OUTCOME UTILITIES (IS,IP) FOR INDIVIDUAL (II=',I3,
     1        ')')
      DO 270 IS=1,NIS
        WRITE  (5,250) IS
250     FORMAT (1X,'OUTCOME UTILITIES (IS,IP) FOR SYSTEM (IS=',I3,')')
        WRITE  (5,260) (UO(IS,IP),IP=1,NIP)
260     FORMAT (1X,10F7.4)
270   CONTINUE
C-------------------------------------------------------------------C
C***C EXIT SUBROUTINE CALUO.  {MODULE 99}
      WRITE  (5,999)
999   FORMAT (/' EXIT  SUBROUTINE CALUO')
C
      RETURN
C
      END
C*******************************************************************C
```

```
C*********************************************************************C
C                          SUBROUTINE CALUS                      9/8/82
C*********************************************************************C
C SUBROUTINE CALUS CALCULATES THE SYSTEM UTILITY FUNCTION VALUE
C US(II,IS) FOR EACH SYSTEM (IS) FOR EACH INDIVIDUAL (II).
C*********************************************************************C
      SUBROUTINE CALUS(PROB,UO,US,RS,IRS,II,NII,NIS,NIP)
C*********************************************************************C
C***C INITIALIZE.  {MODULE 1}
C
      DIMENSION
     1  PROB(NIS,NIP),UO(NIS,NIP),
     2  US(NII,NIS),RS(NII,NIS),IRS(NII,NIS)
      WRITE  (5,100)
100   FORMAT (/' ENTER SUBROUTINE CALUS')
C---------------------------------------------------------------------C
C***C WRITE SUBROUTINE INPUT ARRAYS.  {MODULE 2}
C
      WRITE  (5,110)
110   FORMAT (/1X,'PROBABILITIES PROB(IS,IP) FOR OUTCOMES (IS,IP)')
      DO 140 IS=1,NIS
        WRITE  (5,120) IS
120     FORMAT (1X,'PROBABILITIES PROB(IS,IP) FOR OUTCOMES (IS,IP) ',
     1          'FOR SYSTEM (IS=',I3,')')
        WRITE  (5,130) (PROB(IS,IP),IP=1,NIP)
130     FORMAT (1X,10F7.4)
140   CONTINUE
C
      WRITE  (5,150) II
150   FORMAT (/1X,'OUTCOME UTILITIES (IS,IP) FOR INDIVIDUAL (II=',I3,
     1        ')')
      DO 180 IS=1,NIS
        WRITE  (5,160) IS
160     FORMAT (1X,'OUTCOME UTILITIES (IS,IP) FOR SYSTEM (IS=',I3,')')
        WRITE  (5,170) (UO(IS,IP),IP=1,NIP)
170     FORMAT (1X,10F7.4)
180   CONTINUE
C---------------------------------------------------------------------C
C***C CALCULATE UTILITIES US(II,IS) FOR  SYSTEMS (IS).  {MODULE 3}
C
      DO 200 IS=1,NIS
        US(II,IS) = 0.0
        DO 190 IP=1,NIP
          US(II,IS) = US(II,IS) + PROB(IS,IP)*UO(IS,IP)
190     CONTINUE
200   CONTINUE
C---------------------------------------------------------------------C
C***C WRITE UTILITIES US(II,IS) FOR SYSTEMS (IS) FOR INDIVIDUAL (II).
C***C {MODULE 4}
C
      WRITE  (5,210) II
210   FORMAT (/1X,'UTILITIES US(II,IS) FOR INDIVIDUAL (II=',I3,')')
      WRITE  (5,220) (US(II,IS),IS=1,NIS)
220   FORMAT (1X,10F7.4)
C---------------------------------------------------------------------C
```

```
C***C CALCULATE RANKS RS(II,IS) OF ALTERNATIVE SYSTEMS (IS).
C***C {MODULE 5}
C
      DO 240 IS=1,NIS
        RS(II,IS) = 0.5
        DO 230 IIS=1,NIS
          IF (US(II,IS) .EQ. US(II,IIS)) RS(II,IS) = RS(II,IS) + 0.5
          IF (US(II,IS) .LT. US(II,IIS)) RS(II,IS) = RS(II,IS) + 1.0
230     CONTINUE
240   CONTINUE
C---------------------------------------------------------------------C
C***C WRITE RANKS RS(II,IS) FOR SYSTEMS (IS) FOR INDIVIDUAL (II).
C***C {MODULE 6}
C
      WRITE  (5,250) II
250   FORMAT (/1X,'SYSTEM RANKS RS(II,IS) FOR INDIVIDUAL (II=',I3,')')
      WRITE  (5,260) (RS(II,IS),IS=1,NIS)
260   FORMAT (1X,10F7.4)
C---------------------------------------------------------------------C
C***C CALCULATE INTEGER RANKS IRS(II,IS) OF ALTERNATIVE SYSTEMS (IS).
C***C {MODULE 7}
C
      DO 280 IS=1,NIS
        IRS(II,IS) = 1
        DO 270 IIS=1,NIS
          IF (US(II,IS) .LT. US(II,IIS)) IRS(II,IS) = IRS(II,IS) + 1
270     CONTINUE
280   CONTINUE
C---------------------------------------------------------------------C
C***C WRITE INTEGER RANKS IRS(II,IS) FOR SYSTEMS (IS) FOR INDIVIDUAL
C***C (II).  {MODULE 8}
C
      WRITE  (5,290) II
290   FORMAT (/1X,'SYSTEM INTEGER RANKS IRS(II,IS) FOR INDIVIDUAL ',
     1        '(II=',I3,')')
      WRITE  (5,300) (IRS(II,IS),IS=1,NIS)
300   FORMAT (1X,10I7)
C---------------------------------------------------------------------C
C***C EXIT SUBROUTINE CALUS.  {MODULE 9}
C
      WRITE  (5,999)
999   FORMAT (/' EXIT  SUBROUTINE CALUS')
C
      RETURN
C
      END
C*********************************************************************C
```

```
C***********************************************************************C
C                          SUBROUTINE GROUP                      1/29/83
C***********************************************************************C
C SUBROUTINE GROUP CALCULATES THE GROUP DECISION RULE VALUES VG(IG,IS)
C AND THE RANKINGS RG(IG,IS) AND IRG(IG,IS) FOR THE SYSTEMS
C (IS=1,...,NIS) FOR EACH GROUP DECISION RULE (IG=1,..,3).
C***********************************************************************C
      SUBROUTINE GROUP(US,RS,IRS,VG,RG,IRG,NII,NIS)
C***********************************************************************C
C***C INITIALIZE.  {MODULE 1}
C
      DIMENSION
     1  US(NII,NIS),RS(NII,NIS),IRS(NII,NIS),
     2  VG(3,NIS),RG(3,NIS),IRG(3,NIS)
C
      WRITE  (5,100)
100   FORMAT (/' ENTER SUBROUTINE GROUP')
C-----------------------------------------------------------------------C
C***C WRITE SUBROUTINE INPUT ARRAYS.  {MODULE 2}
C
C     WRITE UTILITIES US(II,IS) FOR SYSTEMS (IS) FOR INDIVIDUALS (II).
      WRITE  (5,110)
110   FORMAT (/1X,'SYSTEM UTILITIES US(II,IS) FOR INDIVIDUALS (II)')
      DO 140 II=1,NII
        WRITE  (5,120) II
120     FORMAT (1X,'UTILITIES US(II,IS) FOR INDIVIDUAL (II=',I3,')')
        WRITE  (5,130) (US(II,IS),IS=1,NIS)
130     FORMAT (1X,10F7.4)
140   CONTINUE
C
C     WRITE SYSTEM RANKS RS(II,IS) FOR INDIVIDUALS (II).
      WRITE  (5,150)
150   FORMAT (/1X,'SYSTEM RANKS RS(II,IS) FOR INDIVIDUALS (II)')
      DO 180 II=1,NII
        WRITE  (5,160) II
160     FORMAT (1X,'SYSTEM RANKS RS(II,IS) FOR INDIVIDUAL (II=',I3,
     1              ')')
        WRITE  (5,170) (RS(II,IS),IS=1,NIS)
170     FORMAT (1X,10F7.4)
180   CONTINUE
C
C     WRITE SYSTEM INTEGER RANKS IRS(II,IS) FOR INDIVIDUALS (II).
      WRITE  (5,190)
190   FORMAT (1X,'SYSTEM INTEGER RANKS IRS(II,IS) FOR INDIVIDUALS ',
     1          '(II)')
      DO 220 II=1,NII
        WRITE  (5,200) II
200     FORMAT (1X,'SYSTEM INTEGER RANKS IRS(II,IS) FOR INDIVIDUAL ',
     1              '(II=',I3,')')
        WRITE  (5,210) (IRS(II,IS),IS=1,NIS)
210     FORMAT (1X,10I7)
220   CONTINUE
C-----------------------------------------------------------------------C
C***C CALCULATION FOR ADDITIVE UTILITY RULE (IG = 1).  {MODULE 3}
C
```

```
C     CALCULATE GROUP VALUES VG(1,IS).
      DO 240 IS=1,NIS
        SUM = 0.0
        DO 230 II=1,NII
          SUM = SUM + US(II,IS)
230     CONTINUE
        VG(1,IS) = SUM/NII
240   CONTINUE
C
C     CALCULATE GROUP RANKS RG(1,IS).
      DO 260 IS=1,NIS
        RG(1,IS) = 0.5
        DO 250 IIS =1,NIS
          IF (ABS(VG(1,IS) - VG(1,IIS)) .LE. 0.5E-4)
     1      RG(1,IS) = RG(1,IS) + 0.5
          IF (ABS(VG(1,IS) - VG(1,IIS)) .LE. 0.5E-4) GO TO 250
          IF (VG(1,IS) .LT. VG(1,IIS)) RG(1,IS) = RG(1,IS) + 1.0
250     CONTINUE
260   CONTINUE
C
C     CALCULATE GROUP INTEGER RANKS IRG(1,IS).
      DO 280 IS=1,NIS
        IRG(1,IS) = 1
        DO 270 IIS =1,NIS
          IF (ABS(VG(1,IS) - VG(1,IIS)) .LE. 0.5E-4) GO TO 270
          IF (VG(1,IS) .LT. VG(1,IIS)) IRG(1,IS) = IRG(1,IS) + 1
270     CONTINUE
280   CONTINUE
C------------------------------------------------------------------C
C***C CALCULATION FOR NASH BARGAINING RULE (IG = 2).  {MODULE 4}
C
C     CALCULATE GROUP VALUES VG(2,IS).
      DO 300 IS=1,NIS
        PROD = 1.0
        DO 290 II=1,NII
          PROD = PROD*US(II,IS)
290       CONTINUE
        PROD = ABS(PROD)
        VG(2,IS) = PROD**(1.0/NII)
300   CONTINUE
C
C     CALCULATE GROUP RANKS RG(2,IS).
      DO 320 IS=1,NIS
        RG(2,IS) = 0.5
        DO 310 IIS =1,NIS
          IF (ABS(VG(2,IS) - VG(2,IIS)) .LE. 0.5E-4)
     1      RG(2,IS) = RG(2,IS) + 0.5
          IF (ABS(VG(2,IS) - VG(2,IIS)) .LE. 0.5E-4) GO TO 310
          IF (VG(2,IS) .LT. VG(2,IIS)) RG(2,IS) = RG(2,IS) + 1.0
310     CONTINUE
320   CONTINUE
C
C     CALCULATE GROUP INTEGER RANKS IRG(2,IS).
      DO 340 IS=1,NIS
        IRG(2,IS) = 1
```

```
        DO 330 IIS =1,NIS
          IF (ABS(VG(2,IS) - VG(2,IIS)) .LE. 0.5E-4) GO TO 330
          IF (VG(2,IS) .LT. VG(2,IIS)) IRG(2,IS) = IRG(2,IS) + 1
330     CONTINUE
340   CONTINUE
C-----------------------------------------------------------------------C
C***C CALCULATION FOR RANK SUM RULE (IG = 3).  {MODULE 5}
C
C     CALCULATE GROUP VALUES VG(3,IS)
      DO 350 IS=1,NIS
        VG(3,IS) = 0.0
        DO 350 II=1,NII
          VG(3,IS) = VG(3,IS) + RS(II,IS)
350   CONTINUE
      DO 360 IS=1,NIS
        VG(3,IS) = 1.0 - ((VG(3,IS) - NII)/(NIS*NII - NII))
360   CONTINUE
C
C     CALCULATE GROUP RANKS RG(3,IS).
      DO 380 IS=1,NIS
        RG(3,IS) = 0.5
        DO 370 IIS=1,NIS
          IF (ABS(VG(3,IS) - VG(3,IIS)) .LE. 0.5E-4)
     1      RG(3,IS) = RG(3,IS) + 0.5
          IF (ABS(VG(3,IS) - VG(3,IIS)) .LE. 0.5E-4) GO TO 370
          IF (VG(3,IS) .LT. VG(3,IIS)) RG(3,IS) = RG(3,IS) + 1.0
370     CONTINUE
380   CONTINUE
C
C     CALCULATE GROUP INTEGER RANKS IRG(3,IS).
      DO 400 IS=1,NIS
        IRG(3,IS) = 1
        DO 390 IIS=1,NIS
          IF (ABS(VG(3,IS) - VG(3,IIS)) .LE. 0.5E-4) GO TO 390
          IF (VG(3,IS) .LT. VG(3,IIS)) IRG(3,IS) = IRG(3,IS) + 1
390     CONTINUE
400   CONTINUE
C-----------------------------------------------------------------------C
C***C WRITE GROUP CALCULATION RESULTS.  {MODULE 7}
C
      WRITE  (5,410)
410   FORMAT (//1X,'SYSTEM    ADDITIVE RULE            NASH RULE       ',
     1        '       RANK SUM RULE'/1X,' (IS)    VALUE   RANK   IRANK   ',
     2        '  VALUE   RANK   IRANK    VALUE   RANK   IRANK '/
     3        1X,'------------------------------------------------------',
     4        '--------------------')
      DO 430 IS=1,NIS
        WRITE  (5,420) IS,VG(1,IS),RG(1,IS),IRG(1,IS),VG(2,IS),
     1                 RG(2,IS),IRG(2,IS),VG(3,IS),RG(3,IS),IRG(3,IS)
420     FORMAT (1X,I3,3(F10.4,F7.4,I5))
430   CONTINUE
C-----------------------------------------------------------------------C
C***C EXIT SUBROUTINE GROUP.  {MODULE 8}
C
      WRITE  (5,999)
```

```
999   FORMAT (/' EXIT  SUBROUTINE GROUP')
C
      RETURN
C
      END
C********************************************************************C
```

```
C**********************************************************************C
C                              SUBROUTINE CONCRD                 7/21/83
C**********************************************************************C
C SUBROUTINE CONCRD CALCULATES THE CONCORDANCE STATISTICS FOR
C RANKINGS BY INDIVIDUALS OR BY GROUP DECISION RULES.
C**********************************************************************C
      SUBROUTINE CONCRD(RX,SRX,TIES,STIES,W,CHISQR,JDF,IW,NIIX,NIS)
C**********************************************************************C
C***C INITIALIZE.  {MODULE 1}
C
      DIMENSION
     1  RX(NIIX,NIS),
     2  SRX(NIS),TIES(NIIX,NIS),STIES(NIIX),
     3  W(2),CHISQR(2),JDF(2)
C
      WRITE  (5,100)
100   FORMAT (/' ENTER SUBROUTINE CONCRD')
C
      WRITE  (5,110) IW,NIIX,NIS
110   FORMAT (/1X,'IW = ',I1,5X,'NIIX = ',I3,5X,'NIS = ',I3)
C
      DO 140 II=1,NIIX
        WRITE  (5,120) II
120     FORMAT (1X,'RX(II,IS) FOR II =',I3)
        WRITE  (5,130) (RX(II,IS),IS=1,NIS)
130     FORMAT (1X,5F10.4)
140   CONTINUE
C----------------------------------------------------------------------C
C***C CALCULATE SUMSQR = SUM OF SQUARES.  {MODULE 2}
C
C     *** SUM OF RANKINGS BY SYSTEM (IS) ***
      DO 145 IS=1,NIS
        SRX(IS) = 0.0
145   CONTINUE
      DO 150 IS=1,NIS
        DO 150 II=1,NIIX
          SRX(IS) = SRX(IS) + RX(II,IS)
150   CONTINUE
C
      WRITE  (5,155)
155   FORMAT (/1X,'SRX(IS)')
      WRITE  (5,160) (SRX(IS),IS=1,NIS)
160   FORMAT (1X,5F10.4)
C
C     *** MEAN OF SUM OF RANKINGS ***
      SRXM = 0.0
      DO 170  IS=1,NIS
        SRXM = SRXM + SRX(IS)/NIS
170   CONTINUE
C
      WRITE  (5,180) SRXM
180   FORMAT (/1X,'SRXM = ',3X,F10.4)
C
C     *** SUM OF SQUARES ***
      SUMSQR = 0.0
```

```
      DO 190 IS=1,NIS
        SUMSQR = SUMSQR + (SRX(IS) - SRXM)**2
190   CONTINUE

      WRITE  (5,200) SUMSQR
200   FORMAT (1X,'SUMSQR =   ',F10.4)
C
C---------------------------------------------------------------------C
C***C CALCULATE TIES CORRECTION.  {MODULE 3}
C
      DO 204 II=1,NIIX
        DO 204 IS =1,NIS
          TIES(II,IS) = 0.0
204   CONTINUE
      DO 206 II=1,NIIX
        STIES(II) = 0.0
206   CONTINUE
C
      DO 260 II=1,NIIX
        DO 250 IS=1,NIS
          DO 220 IIS=1,NIS
            IF (IIS .EQ. IS) GO TO 220
C
            IF ((ABS(RX(II,IIS) - RX(II,IS)) .LE. 0.5E-4)
     1        .AND. (IIS .LT. IS)) GO TO 250
C
            IF (TIES(II,IS) .GT.  0.0) GO TO 210
C
            IF (ABS(RX(II,IIS) - RX(II,IS)) .LE. 0.5E-4)
     1        TIES(II,IS) = 2.0
            GO TO 220
C
210         CONTINUE
            IF (ABS(RX(II,IIS) - RX(II,IS)) .LE. 0.5E-4)
     1        TIES(II,IS) = TIES(II,IS) + 1.0
C
220       CONTINUE
C
          WRITE  (5,230) II,IS,TIES(II,IS)
230       FORMAT (1X,'II = ',I3,5X,'IS = ',I3,10X,
     1             'TIES(II,IS) = ',F10.4)
C
          STIES(II)    = STIES(II)
     1                     + (1.0/12.0)*(TIES(II,IS)**3 - TIES(II,IS))
          WRITE  (5,240) II,STIES(II)
240       FORMAT (1X,'II = ',I3,5X,'STIES(II) = ',F10.4)
250     CONTINUE
260   CONTINUE
C
      TTIES = 0.0
      DO 270 II=1,NIIX
        TTIES = TTIES + STIES(II)
270   CONTINUE
      WRITE  (5,280) TTIES
280   FORMAT (1X,'TTIES = ',F10.5)
```

```
C-----------------------------------------------------------------------C
C***C CALCULATE W(IW) = CONCORDANCE, JDF(IW) = DEGREES OF FREEDOM, AND
C***C CHISQR(IW) = CHI SQUARE VALUE.  {MODULE 4}
C
      W(IW) = SUMSQR/((1.0/12.0)*(NIIX**2)*(NIS**3 - NIS) - NIIX*TTIES)
C
      JDF(IW) = NIS - 1
C
      CHISQR(IW) = NIIX*(NIS - 1)*W(IW)
C
      WRITE  (5,290) IW,W(IW),IW,CHISQR(IW),IW,JDF(IW)
290   FORMAT (1X,'W(',I1,') = ',F10.4,10X,'CHISQR(',I1,') = ',F10.4,
     1        10X,'JDF(',I1,') = ',I5)
C-----------------------------------------------------------------------C
C***C EXIT SUBROUTINE CONCRD.  {MODULE 5}
C
      WRITE  (5,999)
999   FORMAT (/' EXIT  SUBROUTINE CONCRD')
C
      RETURN
C
      END
C***********************************************************************C
```

```
C*********************************************************************C
C                          SUBROUTINE OUTPUT                    9/8/82
C*********************************************************************C
C SUBROUTINE OUTPUT FORMATS AND OUTPUTS THE RESULTS OF THE
C CALCULATIONS.
C*********************************************************************C
      SUBROUTINE OUTPUT(US,IRS,VG,IRG,W,CHISQR,JDF,NII,NIS)
C*********************************************************************C
C***C INITIALIZE.  {MODULE 1}
      DIMENSION
     1  US(NII,NIS),IRS(NII,NIS),VG(3,NIS),IRG(3,NIS),
     2  W(2),CHISQR(2),JDF(2)
      WRITE  (5,100)
100   FORMAT (/' ENTER SUBROUTINE OUTPUT')
C---------------------------------------------------------------------C
C***C DO LOOP FOR OUTPUT UNIT.  {MODULE 2}
      DO 280 IU=1,2
        IF (IU .EQ. 1)    LF = Z'20'
        IF (IU .EQ. 1) JUNIT = 5
        IF (IU .EQ. 2)    LF = Z'0A'
        IF (IU .EQ. 2) JUNIT = 8
        WRITE  (5,110) JUNIT
110     FORMAT (/1X,'JUNIT = ',I3/1X)
C---------------------------------------------------------------------C
C***C   OUTPUT PREFERENCE PAGES BY INDIVIDUALS (II).  {MODULE 3}
C
        ISM  =  1
        ISN = 20
        IF (ISN .GT. NIS) ISN = NIS
        IIM  =  1
        IIN  =  5
        IF (IIN .GT. NII) IIN = NII
C
C       **** PAGE HEADER ***
C
120     CONTINUE
        WRITE  (JUNIT,130) LF,LF,LF,LF
130     FORMAT (A1/A1,29X,'MULTIATTRIBUTE DECISION ANALYSIS'/
     1          A1,27X,'RANKING OF ALTERNATIVE SYSTEMS (IS)'/
     2          A1,35X,'BY INDIVIDUALS (II)')
        WRITE  (JUNIT,140) LF,LF,(II,II=IIM,IIN)
140     FORMAT (A1/A1,6X,'IS',5X,'II=',I3,4(8X,'II=',I3))
        WRITE  (JUNIT,150) LF
150     FORMAT (A1,8X,5('  UTILITY RANK'))
C
C       *** INDIVIDUAL PREFERENCES (US AND IRS) ***
C
        DO 170 IS=ISM,ISN
          WRITE  (JUNIT,160) LF,LF,IS,(US(II,IS),IRS(II,IS),II=IIM,IIN)
160       FORMAT (A1/A1,5X,I3,2X,5(F6.4,2X,I3,3X))
170     CONTINUE
C
C       *** PAGE LOGIC ***
C
        IF (IIN .EQ. NII .AND. ISN .EQ. NIS) GO TO 190
```

```
      IF (IIN .EQ. NII) GO TO 180
      IIM = IIM+5
      IIN = IIN+5
      IF (IIN .GT. NII) IIN = NII
      GO TO 120
180   CONTINUE
      ISM  = ISM +20
      ISN = ISN+20
      IF (ISN .GT. NIS) ISN = NIS
      IIM  =  1
      IIN  =  5
      IF (IIN .GT. NII) IIN = NII
      GO TO 120
190   CONTINUE
C
C     *** CONCORDANCE FOR INDIVIDUALS ***
C
      WRITE  (JUNIT,200) LF,LF,W(1),CHISQR(1),JDF(1)
200   FORMAT (A1/A1,'W = ',F6.4,10X,'CHI SQUARE = ',F10.2,10X,
     1        'DF =',I3)
C-----------------------------------------------------------------------C
C***C  OUTPUT PREFERENCE PAGES BY GROUP DECISION RULES (IG).
C     {MODULE 4}
C
      ISM  =  1
      ISN = 20
      IF (ISN .GT. NIS) ISN = NIS
C
C     *** PAGE HEADER ***
C
210   CONTINUE
      WRITE  (JUNIT,220) LF,LF,LF,LF
220   FORMAT (A1/A1,19X,'MULTIATTRIBUTE DECISION ANALYSIS'/
     1        A1,17X,'RANKING OF ALTERNATIVE SYSTEMS (IS)'/
     2        A1,21X,'BY GROUP DECISION RULES (IG)')
      WRITE  (JUNIT,230) LF,LF,LF,LF
230   FORMAT (A1/A1,6X,'IS',7X,'IG = 1',10X,'IG = 2',10X,'IG = 3'/
     1        A1,14X,'ADDITIVE',10X,'NASH',10X,'RANK SUM'/
     2        A1,7X,3(6X,'VALUE RANK'))
C
C     *** GROUP PREFERENCES (VG AND RG) ***
C
      DO 250 IS=ISM,ISN
        WRITE  (JUNIT,240) LF,LF,IS,(VG(IG,IS),IRG(IG,IS),IG=1,3)
240     FORMAT (A1/A1,6X,I2,4X,3(F6.4,2X,I2,6X))
250   CONTINUE
C
C     *** PAGE LOGIC ***
C
      IF (ISN .EQ. NIS) GO TO 260
      ISM  = ISM +20
      ISN = ISN+20
      IF (ISN .GT. NIS) ISN = NIS
      GO TO 210
260   CONTINUE
```

```
C
C       *** CONCORDANCE FOR GROUPS ***
C
        WRITE  (JUNIT,270) LF,LF,W(2),CHISQR(2),JDF(2)
270     FORMAT (A1/A1,'W = ',F6.4,10X,'CHI SQUARE = ',F10.2,10X,
     1          'DF =',I3)
C---------------------------------------------------------------------C
C***C END DO LOOP FOR JUNIT.  {MODULE 5}
C
280   CONTINUE
C---------------------------------------------------------------------C
C***C EXIT SUBROUTINE OUTPUT.  {MODULE 6}
C
      WRITE  (5,999)
999   FORMAT (/' EXIT  SUBROUTINE OUTPUT')
C
      RETURN
C
      END
C*********************************************************************C
```

```
C*********************************************************************C
C                             ARRAY.FOR                        6/25/83
C*********************************************************************C
C THIS ROUTINE IS TO BE "INCLUDED" IN THE MAIN ROUTINE AT COMPILE
C TIME.  IT DIMENSIONS ALL THE ARRAYS.
C*********************************************************************C

C***C FORMAT FOR DIMENSIONING THE ARRAYS.  ALL THE ARRAY DIMENSIONS
C     MUST BE REPLACED WITH NUMBERS.
C
C     WHERE A "/" IS PRESENT, ENTER THE LARGER OF THE TWO VALUES ON
C     EITHER SIDE.
C
C     DOUBLE PRECISION XKM(NII)
C     DIMENSION
C    1  PROB(NIS,NIP), AT(NIS,NIP,NAT),
C    2  UATD(NAT,NID), UATC(NAT,NIC), UAT(NIS,NIP,NAT),
C    3  XK(NII,NAT),
C    4  UO(NIS,NIP), US(NII,NIS), RS(NII,NIS),
C    5  VG(3,NIS), RG(3,NIS),
C    6  IRS(NII,NIS), IRG(3,NIS),
C    7  RX(NII/3,NIS),SRX(NIS),TIES(NII/3,NIS),STIES(NII/3),
C    8  W(2),CHISQR(2),JDF(2)
C---------------------------------------------------------------------C
C***C DIMENSION THESE ARRAYS WITH NUMBERS.
C
      DOUBLE PRECISION XKM(10)
      DIMENSION
     1  PROB(18,1), AT(18,1,10),
     2  UATD(10,10), UATC(10,8), UAT(18,1,10),
     3  XK(5,10),
     4  UO(18,1), US(5,18), RS(5,18),
     5  VG(3,18), RG(3,18),
     6  IRS(5,18), IRG(3,18),
     7  RX(5,18),SRX(18),TIES(5,18),STIES(5),
     8  W(2),CHISQR(2),JDF(2)
C***************************** ARRAY.FOR *****************************C
```

MATEUS RUN PARAMETERS

JRUNID	JDIAG	NII	NIS	NIP	NIA	NID
53	0	4	16	1	8	10

PROBABILITY DATA FOR OUTCOMES (IS,IP) OF SYSTEM (IS=1)
1.000
PROBABILITY DATA FOR OUTCOMES (IS,IP) OF SYSTEM (IS=2)
1.000
PROBABILITY DATA FOR OUTCOMES (IS,IP) OF SYSTEM (IS=3)
1.000
PROBABILITY DATA FOR OUTCOMES (IS,IP) OF SYSTEM (IS=4)
1.000
PROBABILITY DATA FOR OUTCOMES (IS,IP) OF SYSTEM (IS=5)
1.000
PROBABILITY DATA FOR OUTCOMES (IS,IP) OF SYSTEM (IS=6)
1.000
PROBABILITY DATA FOR OUTCOMES (IS,IP) OF SYSTEM (IS=7)
1.000
PROBABILITY DATA FOR OUTCOMES (IS,IP) OF SYSTEM (IS=8)
1.000
PROBABILITY DATA FOR OUTCOMES (IS,IP) OF SYSTEM (IS=9)
1.000
PROBABILITY DATA FOR OUTCOMES (IS,IP) OF SYSTEM (IS=10)
1.000
PROBABILITY DATA FOR OUTCOMES (IS,IP) OF SYSTEM (IS=11)
1.000
PROBABILITY DATA FOR OUTCOMES (IS,IP) OF SYSTEM (IS=12)
1.000
PROBABILITY DATA FOR OUTCOMES (IS,IP) OF SYSTEM (IS=13)
1.000
PROBABILITY DATA FOR OUTCOMES (IS,IP) OF SYSTEM (IS=14)
1.000
PROBABILITY DATA FOR OUTCOMES (IS,IP) OF SYSTEM (IS=15)
1.000
PROBABILITY DATA FOR OUTCOMES (IS,IP) OF SYSTEM (IS=16)
1.000

ATTRIBUTE DATA AT(IS,IP,IA) FOR OUTCOME (IS=1,IP=1)

7.0	42.0	8.0	6.0	193.0E6
7.0	4.0	3.0		

ATTRIBUTE DATA AT(IS,IP,IA) FOR OUTCOME (IS=2,IP=1)

7.0	100.0	6.0	7.0	198.0E6
6.0	4.0	3.0		

ATTRIBUTE DATA AT(IS,IP,IA) FOR OUTCOME (IS=3,IP=1)

7.0	31.0	7.0	7.8	124.0E6
7.0	4.0	3.0		

ATTRIBUTE DATA AT(IS,IP,IA) FOR OUTCOME (IS=4,IP=1)

7.0	27.0	4.0	6.9	140.0E6
5.0	2.0	3.0		

ATTRIBUTE DATA AT(IS,IP,IA) FOR OUTCOME (IS=5,IP=1)

7.0	60.0	4.0	6.9	114.0E6
6.0	2.0	3.0		

ATTRIBUTE DATA AT(IS,IP,IA) FOR OUTCOME (IS=6,IP=1)

7.0	80.0	9.0	7.2	143.0E6
8.0	5.0	3.0		

```
ATTRIBUTE DATA AT(IS,IP,IA) FOR OUTCOME (IS=7,IP=1)
    3.0          50.0          2.0          3.8          213.0E6
    5.0           9.0          3.0
ATTRIBUTE DATA AT(IS,IP,IA) FOR OUTCOME (IS=8,IP=1)
    8.0          42.0          8.0          6.0          200.0E6
    8.0           8.0          3.0
ATTRIBUTE DATA AT(IS,IP,IA) FOR OUTCOME (IS=9,IP=1)
    8.0         100.0          7.0          7.0          190.0E6
    7.0           8.0          3.0
ATTRIBUTE DATA AT(IS,IP,IA) FOR OUTCOME (IS=10,IP=1)
    8.0          31.0          8.0          7.8          124.0E6
    8.0           8.0          3.0
ATTRIBUTE DATA AT(IS,IP,IA) FOR OUTCOME (IS=11,IP=1)
    8.0          27.0          5.0          6.9          160.0E6
    6.0           4.0          3.0
ATTRIBUTE DATA AT(IS,IP,IA) FOR OUTCOME (IS=12,IP=1)
    8.0          45.0          5.0          7.1          114.0E6
    7.0           4.0          3.0
ATTRIBUTE DATA AT(IS,IP,IA) FOR OUTCOME (IS=13,IP=1)
    8.0         108.0          5.0          3.9          240.0E6
    5.0           9.0          3.0
ATTRIBUTE DATA AT(IS,IP,IA) FOR OUTCOME (IS=14,IP=1)
    8.0          67.0         10.0          6.3          135.0E6
   10.0          10.0          3.0
ATTRIBUTE DATA AT(IS,IP,IA) FOR OUTCOME (IS=15,IP=1)
    8.0          80.0         10.0          7.4          135.0E6
   10.0          10.0          3.0
ATTRIBUTE DATA AT(IS,IP,IA) FOR OUTCOME (IS=16,IP=1)
    6.0          38.0          7.0          7.6          170.0E6
    9.0          10.0          3.0

SCALING CONSTANTS XK(II,IA) FOR INTERVIEW #5.  II=1
 0.670  0.500  0.620  0.700  0.200  0.300  0.450  0.500
ATTRIBUTE UTILITY DATA UATD(IA,ID) FOR INTERVIEW #5.  II=1
ATTRIBUTE 1
      3.0        0.00        5.5        0.25        6.5        0.50
      6.8        0.75        8.0        1.00
ATTRIBUTE 2
    108.0        0.00       95.0        0.25       85.0        0.50
     72.5        0.75       27.0        1.00
ATTRIBUTE 3
      2.0        0.00        4.5        0.25        5.0        0.50
      6.5        0.75       10.0        1.00
ATTRIBUTE 4
      3.8        0.00        4.8        0.25        5.5        0.50
      6.8        0.75        7.8        1.00
ATTRIBUTE 5
          240.0E6  0.00         195.0E6  0.25         170.0E6  0.50
          140.0E6  0.75         114.0E6  1.00
ATTRIBUTE 6
      5.0        0.00        5.8        0.25        6.5        0.50
      7.3        0.75       10.0        1.00
```

```
ATTRIBUTE 7
     2.0        0.00       4.2        0.25       5.5        0.50
     6.0        0.75      10.0        1.00
ATTRIBUTE 8
     3.0        0.00       4.79       0.25       4.8        0.50
     7.0        0.75       8.0        1.00

SCALING CONSTANTS XK(II,IA) FOR INTERVIEW #10.  II=2
 0.800  0.100  0.500  0.700  0.100  0.300  0.200  0.600
ATTRIBUTE UTILITY DATA UATD(IA,ID) FOR INTERVIEW #10.  II=2
ATTRIBUTE 1
     3.0        0.00       5.0        0.25       6.0        0.50
     7.0        0.75       8.0        1.00
ATTRIBUTE 2
   108.0        0.00      90.0        0.25      75.0        0.50
    40.0        0.75      27.0        1.00
ATTRIBUTE 3
     2.0        0.00       5.0        0.25       7.0        0.50
     8.0        0.75      10.0        1.00
ATTRIBUTE 4
     3.8        0.00       5.0        0.25       6.0        0.50
     7.0        0.75       7.8        1.00
ATTRIBUTE 5
         240.0E6  0.00          230.0E6  0.25          200.0E6  0.50
         180.0E6  0.75          114.0E6  1.00
ATTRIBUTE 6
     5.0        0.00       5.5        0.25       6.0        0.50
     7.0        0.75      10.0        1.00
ATTRIBUTE 7
     2.0        0.00       3.0        0.25       4.0        0.50
     5.0        0.75      10.0        1.00
ATTRIBUTE 8
     3.0        0.00       5.0        0.25       6.0        0.50
     7.0        0.75       8.0        1.00

SCALING CONSTANTS XK(II,IA) FOR INTERVIEW #2.  II=3
 0.600  0.100  0.500  0.400  0.200  0.200  0.400  0.300
ATTRIBUTE UTILITY DATA UATD(IA,ID) FOR INTERVIEW #2.  II=3
ATTRIBUTE 1
     3.0        0.00       3.5        0.25       5.5        0.50
     6.0        0.75       8.0        1.00
ATTRIBUTE 2
   108.0        0.00      85.0        0.25      67.0        0.50
    47.0        0.75      27.0        1.00
ATTRIBUTE 3
     2.0        0.00       4.0        0.25       6.0        0.50
     8.0        0.75      10.0        1.00
ATTRIBUTE 4
     3.8        0.00       4.4        0.25       5.0        0.50
     6.5        0.75       7.8        1.00
ATTRIBUTE 5
         240.0E6  0.00          190.0E6  0.25          175.0E6  0.50
         145.0E6  0.75          114.0E6  1.00
```

```
ATTRIBUTE 6
      5.0         0.00         6.7         0.25         7.5         0.50
      8.5         0.75        10.0         1.00
ATTRIBUTE 7
      2.0         0.00         4.0         0.25         6.0         0.50
      8.0         0.75        10.0         1.00
ATTRIBUTE 8
      3.0         0.00         4.2         0.25         5.5         0.50
      6.5         0.75         8.0         1.00

SCALING CONSTANTS XK(II,IA) FOR INTERVIEW #1.  II=4
 0.850  0.400  0.550  0.450  0.450  0.550  0.250  0.350
ATTRIBUTE UTILITY DATA UATD(IA,ID) FOR INTERVIEW #1.  II=4
ATTRIBUTE 1
      3.0         0.00         3.01        0.25         3.02        0.50
      3.03        0.75         8.0         1.00
ATTRIBUTE 2
    108.0         0.00        85.0         0.25        70.0         0.50
     60.0         0.75        27.0         1.00
ATTRIBUTE 3
      2.0         0.00         5.0         0.25         6.0         0.50
      7.0         0.75        10.0         1.00
ATTRIBUTE 4
      3.8         0.00         6.0         0.25         7.0         0.50
      7.4         0.75         7.8         1.00
ATTRIBUTE 5
          240.0E6  0.00           180.0E6  0.25           140.0E6  0.50
          122.5E6  0.75           114.0E6  1.00
ATTRIBUTE 6
      5.0         0.00         5.75        0.25         6.5         0.50
      9.0         0.75        10.0         1.00
ATTRIBUTE 7
      2.0         0.00         4.0         0.25         6.5         0.50
      8.5         0.75        10.0         1.00
ATTRIBUTE 8
      3.0         0.00         4.0         0.25         6.5         0.50
      6.75        0.75         8.0         1.00
```

MATEUS

MULTIATTRIBUTE EVALUATION OF UTILITIES

RUN IDENTIFICATION NUMBER: 53
DIAGNOSTIC DISPLAY LEVEL: 0
NUMBER OF INDIVIDUALS: 4
NUMBER OF SYSTEMS: 16
NUMBER OF PROBABILITY PATHS: 1
NUMBER OF ATTRIBUTES: 8
NUMBER OF ATTRIBUTE DATA: 10

ATTRIBUTE SCALING CONSTANTS XK(II,IB) FOR INDIVIDUAL (II= 1)
.6700 .5000 .6200 .7000 .2000 .3000 .4500 .5000
SUM OF ATTRIBUTE SCALING CONSTANTS FOR INDIVIDUAL (II= 1) IS: 3.9400
MASTER SCALING CONSTANT FOR INDIVIDUAL (II= 1) IS: -.99702036
ATTRIBUTE SCALING CONSTANTS XK(II,IB) FOR INDIVIDUAL (II= 2)
.8000 .1000 .5000 .7000 .1000 .3000 .2000 .6000
SUM OF ATTRIBUTE SCALING CONSTANTS FOR INDIVIDUAL (II= 2) IS: 3.3000
MASTER SCALING CONSTANT FOR INDIVIDUAL (II= 2) IS: -.99424555
ATTRIBUTE SCALING CONSTANTS XK(II,IB) FOR INDIVIDUAL (II= 3)
.6000 .1000 .5000 .4000 .2000 .2000 .4000 .3000
SUM OF ATTRIBUTE SCALING CONSTANTS FOR INDIVIDUAL (II= 3) IS: 2.7000
MASTER SCALING CONSTANT FOR INDIVIDUAL (II= 3) IS: -.96579052
ATTRIBUTE SCALING CONSTANTS XK(II,IB) FOR INDIVIDUAL (II= 4)
.8500 .4000 .5500 .4500 .4500 .5500 .2500 .3500
SUM OF ATTRIBUTE SCALING CONSTANTS FOR INDIVIDUAL (II= 4) IS: 3.8500
MASTER SCALING CONSTANT FOR INDIVIDUAL (II= 4) IS: -.99722735

MULTIATTRIBUTE DECISION ANALYSIS
RANKING OF ALTERNATIVE SYSTEMS (IS)
BY INDIVIDUALS (II)

IS	II= 1		II= 2		II= 3		II= 4		II=	
	UTILITY	RANK	UTILITY	RANK	UTILITY	RANK	UTILITY	RANK	UTILITY	RANK
1	.9549	11	.9045	11	.8561	11	.9664	10		
2	.9153	14	.8924	12	.8178	12	.9278	14		
3	.9807	5	.9526	7	.8976	8	.9856	4		
4	.9219	12	.8546	15	.8016	15	.9376	13		
5	.9216	13	.8730	13	.8096	13	.9586	12		
6	.9726	7	.9501	8	.9150	6	.9748	8		
7	.6848	16	.2747	16	.4138	16	.4969	16		
8	.9812	4	.9601	5	.9213	5	.9793	7		

9	.9709	9	.9621	4	.9074	7	.9675	9
10	.9939	1	.9859	2	.9559	3	.9927	2
11	.9650	10	.9492	9	.8662	10	.9630	11
12	.9719	8	.9577	6	.8860	9	.9795	6
13	.8720	15	.8617	14	.8032	14	.8989	15
14	.9893	3	.9758	3	.9710	2	.9913	3
15	.9922	2	.9860	1	.9771	1	.9928	1
16	.9779	6	.9276	10	.9268	4	.9822	5

W = .9408   CHI SQUARE = 56.45   DF = 15

MULTIATTRIBUTE DECISION ANALYSIS
RANKING OF ALTERNATIVE SYSTEMS (IS)
BY GROUP DECISION RULES (IG)

IS	IG = 1 ADDITIVE		IG = 2 NASH		IG = 3 RANK SUM	
	VALUE	RANK	VALUE	RANK	VALUE	RANK
1	.9205	11	.9194	11	.3500	11
2	.8883	13	.8873	13	.2000	13
3	.9541	5	.9535	5	.6667	5
4	.8789	14	.8772	14	.1500	14
5	.8907	12	.8889	12	.2167	12
6	.9531	7	.9528	7	.5833	7
7	.4675	16	.4435	16	.0000	16
8	.9605	4	.9602	4	.7167	4
9	.9520	8	.9516	8	.5833	7
10	.9821	2	.9820	2	.9333	2
11	.9359	10	.9350	10	.4000	10
12	.9488	9	.9480	9	.5833	7
13	.8590	15	.8582	15	.1000	15
14	.9819	3	.9818	3	.8833	3

15	.9870	1	.9870	1	.9833	1
16	.9537	6	.9533	6	.6500	6

W = .9987 CHI SQUARE = 44.94 DF = 15