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ALO-67
SAI-102-80-AM

A SELECTION METHODOLOGY
FOR LWR SAFETY R&D
PROGRAMS AND PROPOSALS

MASTER

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Printed in the United States of America

Available from
National Technical Information Service
U. S. Department of Commerce
5285 Port Royal Road
Springfield, VA 22161

Price: Printed Copy \$9.50; Microfiche \$3.00

DRAFT REPORT
A SELECTION METHODOLOGY
FOR LWR SAFETY R&D
PROGRAMS AND PROPOSALS

A. A. Husseiny
R. L. Ritzman

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Prepared by

Science Applications, Inc.
507 Main Street
Ames, Iowa 50010

Prepared for

U. S. Department of Energy
Light Water Reactor Safety Technology Management Center
Sandia National Laboratories
Albuquerque, New Mexico 87185

Sponsored by

U. S. Department of Energy
Division of Nuclear Power Development
Washington, D. C. 20545

Work performed under Sandia Contract No. 13-6458

Submitted: September 1979
Printed: March 1980

DISTRIBUTION OF THIS DOCUMENT IS UNLIMITED

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ABSTRACT

The results of work done to develop a methodology for selecting LWR safety R&D programs and proposals is described. A critical survey of relevant decision analysis methods is provided including the specifics of multiattribute utility theory. This latter method forms the basis of the developed selection methodology. Details of the methodology and its use are provided along with a sample illustration of its application.

ACKNOWLEDGEMENT

Many SAI staff members and consultants, too numerous to mention, provided technical input to this work. These contributions are gratefully acknowledged. However, special recognition belongs to a few who made major contributions to the project. These include Dr. Z. A. Sabri, who was a key contributor to the review of decision methodologies and a knowledgeable user of MAU techniques. In addition, the considerable efforts of Andrew McClymont and Michael Hale spent on constructing computerized assessment modules and on implementing the interactive features into a workable system are especially acknowledged.

1.0. INTRODUCTION

The Department of Energy (DOE) recently organized and initiated a Light Water Reactor (LWR) Safety R&D Program. Sandia Laboratories was selected to manage the program which was envisioned as a multi-year effort involving numerous individual and/or team contractors. Each contractor would engage in R&D work aimed at enhancing the overall level of safety of commercial LWR power plants.

Currently, the program is in its first year, during which numerous studies have been initiated to review information for the purpose of identifying specific areas and items needing Safety R&D effort. In addition, the recent accident at the Three Mile Island Nuclear Power Station has produced many recommendations for a broad range of safety oriented programs. The Sandia Program Office thus faces the task of evaluating a very large collection of potential R&D activities and selecting a set which should yield the greatest return within the budget constraints of the program.

As part of the first year effort on the LWR Safety R&D Program, Science Applications, Inc. was contracted to develop, and later test, a methodology which could be used to rank and select R&D programs or proposals for funding commitment. The present report constitutes a description of the work that has been performed to define and develop the required selection methodology. In the next section of the report, a compilation and critical survey of appropriate decision methods is presented. This is followed by a section which describes the elements of the technique which form the basis for the R&D selection methodology used here; namely, multiattribute utility (MAU) theory. The section also describes the specific adaptation of MAU to the unique requirements of the LWR Safety R&D Program criteria and scope, including the special computerized assessment modules which were developed

to facilitate application of the procedure. The final section presents an illustration of the use of the methodology on a sample selection problem. References are included at the end of the main report and further details regarding certain aspects of decision analysis methods are contained in Appendices to the report.

2.0 SURVEY OF RELEVANT METHODOLOGIES

2.1 CRITICAL SURVEY OF AVAILABLE R&D DECISION METHODS

Several methods have been proposed for development of R&D strategies. Most of those were developed in the field of econometrics and operation research to improve government efficiency and reduce unwarranted spending.¹ Thus, the presentation is often sketchy and falls more or less in the realm of politicizing rather than planning and policy-making. In a business-like manner, many of the quantitative approaches are concerned with minimizing a cost function of one type or the other; such as $C(M,T)$ where M refers to R&D monetary expenditures on a given project and T refers to the time required to execute that project.² The cost function may be expressed as a linear combination,

$$C(M,T) = SM + h(T)$$

where S is a non-negative constant and $h(T)$ is some non-decreasing function of T .

2.1.1 The Deterministic Approach

A deterministic approach which has been frequently applied in R&D planning is simply to ignore uncertainty or risk.³ This approach stems from the fact that both in the theoretical analysis and operation of actual systems, it is often expedient to act as if consequences of various decisions could be predicted accurately. The approach has considerably evolved from being a traditional method to one that is being applied to contemporary R&D problems. In the traditional sense, the term 'uncertainty' has been used to describe situations whose outcomes are based on unknown probability distributions. If a probability distribution, based on objective probabilities or relative frequencies of the outcomes is known, the situation is a 'risky' one.³ In modern decision analysis, personal (or subjective) probabilities are acceptable and hence there is no distinction between risk and uncertainty. In the application of the deterministic method, the planner uses 'best estimates' (or 'most likely

values') of the projects' variables (such as cost and return) in formulating a 'measure of merit' which is envisioned as an approximation of the 'most likely' outcome of a given design alternative. Measures of merit are, for example, benefit-cost ratio, net benefit or other performance criterion. The approach is clearly less tedious than the more advanced quantitative methods used in investment analysis. However, there is only a small likelihood that the single-valued estimates utilized in the analysis will prove accurate and there is no provision to accommodate for the likely variation about an expected outcome of a given project. Nevertheless, there are some conditions under which assumed certainty can provide the correct approach.⁴⁻⁶ Those conditions follow from the 'certainty equivalence theorem'.⁶ The deterministic approach fails to explicitly consider factors; such as supply and demand uncertainties which surround each project alternative.⁷

2.1.2 Benefit-Cost Approaches

2.1.2.1 Benefit-Cost Ratio

The benefit-cost ratio is widely employed in selection of R&D programs.¹ In this method, the ratio must exceed unity for a project or design to be justified. To select between alternate strategies, the one with the highest ratio is the best. In some situations this approach may lead to false conclusions. For example, two projects may have the same benefit-cost ratio based on the most likely values of each component, but one project may be more 'risky' in the sense that it is much more vulnerable to possible adverse conditions. Thus, additional information must be incorporated in the decision process before rational choices can be made.

2.1.2.2 Benefit-Cost Difference

A method which can be shown to be logically erroneous; if no risk is included, is the benefit-cost difference. The major practical difficulties in using any of the benefit-cost methods or a combination of both lie in the tendency toward optimistic inflation of the benefit and the underestimation of cost.

2.1.2.3 Two-Valued Preference

Another approach which is based on the use of two-valued preferences can be employed when certainty is assumed for expediency. Once a world of complete certainty is assumed, the developer's task is well defined, since a prior knowledge exists about in what region of the performance space the developed items lie for a given approach of pursuing the development. Obviously, if one defines an ordinal cost function $C(M,T)$ for all non-negative values of M and T , then the alternative of the smaller cost function is the most preferred, since

$$C(m_1, t_1) < C(m_2, t_2)$$

if (m_1, t_1) is preferred to (m_2, t_2) ,

where m and t are specific values or outcomes of variables or events M and T , respectively. In the presence of a number of alternative approaches, the developer can rank the alternative combinations of time and money (or any other two variables) that suffice to attain a satisfactory version of the item of interest.

Since the developer knows the time and money each approach would require if it were pursued to completion, the cost function $C(M,T)$ can compactly represent the preferences for a given item and a given satisfactory region of its performance space. Actually, the developer prefers less money to more and less time to more, but is willing to trade time and money against each other. Consequently, the approach having the smallest value of completion cost $C(m,t)$, is the one to be picked and pursued by itself.² Such certainty method can be expanded to encompass a host of variables, by defining a cost function $C(M,T,\Pi)$ where Π is a vector that implicitly includes an arbitrary number of variables. In this case, the analysis can only be expedited if a form of C is depicted based on experience or on some empirical roles. The validity of the approach depends on whether or not the developer accepts the axiom a world of complete certainty for expediency.

2.1.2.4 Cost-Effectiveness

In this approach, multivalued benefits could be used and budget constraints may be introduced. For parallel programs, the sum of proposed expenditures has to be less or equal to the ceiling on the budget. An aspiration level of benefits is set a priori to program selection. Then, each program is evaluated to find whether the benefits gained would be less than or equal to the aspiration levels. Meeting those multi-benefit levels can be used as criteria for program/proposal ranking. The difficulties in applying this approach is in determining aspiration levels, accommodating for uncertainties, conducting tradeoffs, and allowing for group decisions.

2.1.2.5 Value-Impact

The primary objective for a value-impact analysis of a research program is to compare the technical merits as well as to address the politico-social aspects of the regulatory process. An integral part of the value-impact analysis is the identification of qualitative values associated with a research program. Quantitative values in terms of program costs can be derived from the criteria established for a program. The overall impact assessment allows a decision-maker to make a balanced value judgment which is meaningful.

2.1.2.6 Accommodation for Uncertainties

Uncertainty is explicitly recognized typically by such deterministic methods as conservative estimation of the variables involved; for example (a) returns and costs, (b) the addition of a premium to the discount rate, and (c) the economic life of a project. Conservative estimation approaches have been specifically employed by Federal agencies.⁸

a. Adjustment of Returns and Costs

In the technique of adjusting returns and costs, a benefit-cost ratio may be employed to rank alternate R&D strategies. Conservative adjustments are used in such a way that benefit estimates are to be reduced and cost estimates increased in some proportion. This is due to the lack of confidence in the expected or most likely values. The main drawback in the conservative method is

the fact that there is a small likelihood that all estimates will be in error adversely. Consequently, this method of compensating for uncertainties obscures important information. For example, in examining a benefit-cost ratio based on conservative estimates, there is no indication of the degree of conservatism and there is no assurance that a higher benefit-cost ratio will result. Moreover, conservatism displays an aversion to uncertainty which is not necessarily the best attitude of a decision-maker. Generally, conservatism in benefit and cost estimates is not regarded as an appropriate means of counteracting uncertainty in 'expected values.'⁹ However, conservatism may be often used as an appropriate countermeasure for the invariably optimistic bias of the decision-maker in estimating benefits and costs. Nevertheless, biased estimates is an issue separate from the underlying uncertainty of such estimates.

b. Discount Rate

The technique of adjusting the 'discount rate' is a more sophisticated approach to allow for uncertainty. The discount rate is a method formally used in development planning and is based on the economic evaluation of alternate projects to select the item with the lowest present value. The method implicitly takes into account the time necessary for completion of the projects.¹⁰ The discount rate, i , may be adjusted to allow for uncertainty by breaking it into two components, that is

$$i = i_t + i_r$$

where subscript t and r refer to time and risk components of the discount rate, respectively. The less certain the outcome of a given R&D strategy, the higher the value of i_r and hence i for a given i_t . Thus

$$i_r \approx r$$

where r is an index of riskiness. Consequently, the higher the risk discount rate associated with a given strategy, the more risky the strategy is.¹¹⁻¹⁵ The main disadvantages of adjusting the discount rate are:

- It represents an ordinate aversion to uncertainty as the technique of adjusting cost and benefit estimates.
- Variation in the discount rate has very little effect on the outcome of a project having a short life.
- When a particular design is being evaluated from the standpoint of cost alone to meet more specified demand,

increasing the discount rate to reflect cost uncertainty will have an effect opposite to what is intended, that is a higher discount rate will lower the present value of cost, with the result that higher risk alternatives are favored.⁹

- Two risk premiums must be considered; one is the 'expected-value adjustment' premium which is equivalent (in the case of government R&D projects) to assigning a higher discount rate than the government borrowing rate. The second is 'risk-aversion' premium. The government is also capable of pooling risks and hence the technique could lead to favoring more risky strategies.¹⁶⁻¹⁸

c. Economic Life

The conservative technique of adjusting the economic life of projects under examination also fails to provide a reasonable approach to uncertainty accommodation. This is especially true in situations where a large number of mutually independent alternate strategies contribute to aggregated objectives.⁹

2.1.2.7 Other Cost-Benefit Techniques

Several other techniques, not necessarily conservative, have been developed in cost-benefit analysis (CBA) which has practically evolved as a discipline by itself.¹⁹⁻²⁵ Application of the CBA to evaluation of public projects dates back to the work of Dupuit in 1844 wherein the concept of net social benefits of projects has been initiated.²⁶ The ideas presented in this early work on CBA have been generalized and developed further in specific applications.^{27,28} The CBA field gained momentum after the US Flood Control Act of 1936 which declares that 'benefits to whomsoever they may accrue of Federal projects should exceed costs.' Consequently, several government documents have been issued in an attempt to standardize the CBA methodology.^{8,30,33} Most of the documents were released in the context of water resources developments. This is why many of the methods developed at that time were a variation of the riskless conservative approach. While Federal efforts were directed toward revisions of that approach in practice, a firm theoretical base of CBA was being constructed in various fields.³⁴⁻⁷²

2.1.2.8 Intangibles and Incommensurables

In order to accommodate for non-monetary factors in the CBA of alternate projects, several provisions have been made. For example, market prices do not always accurately reflect social value and hence 'shadow pricing' is used. A shadow price may be defined as a value associated with a unit of some good which indicates how much some specified index of performance can be increased or decreased by the use or loss of the marginal unit of that commodity. The use of such factor is promoted by the attempt to present all factors and outcomes in terms of a monetary value. Nevertheless, there are still some incommensurables and intangibles which are not measurable in even their own terms.⁴⁹ To overcome that difficulty, balance sheets have been developed for cost-benefit analysis which are divided into two parts: monetized effects and non-monetized effects. In the latter part incommensurables and intangibles, which are not susceptible to quantification or monetization are displayed.¹⁹ However, there is an argument against considering incommensurables without assigning a shadow price to them since in principle every outcome has a social opportunity cost.²⁰

2.1.3 Sensitivity Analysis

Sensitivity analysis is another traditional approach which is devised to help recognizing explicitly some of the uncertainties in decision-making. In its typical form, sensitivity analysis is employed to supplement certainty approaches. The sensitivity of outcomes is measured by varying the values of individual elements one at a time and noting the effect on the performance criteria (measure of merit). This method isolates the outcome effect of overestimating or underestimating an element's value and thus suggests the relative importance of accurately estimating each element. However, consideration of each single element alone disregards the fact that all elements will vary somewhat from their estimated values: the actual outcome(s) will be the result of a combination of estimating errors, not the error of just one element.

A natural extension of this approach is to alter the values of several elements (rather than a single element) simultaneously. This extension

is frequently referred to as the multiple-case approach and typically takes the form of determining the effect of optimistic, most likely, and pessimistic estimates of all relevant elements of factors such as supply and demand. The method results in the establishment of limits on the probable outcomes and the most likely outcome for each possible decision.

These two forms of sensitivity analysis, although they are more effective tools in the face of uncertainty than the assumed certainty approach or the adjustment approaches, they lack both conciseness and comprehensiveness. Knowledge of how much variation is required in a particular element in order to reverse a decision based on best-estimate values, or knowledge of the range of possible outcomes for a given decision, is of limited value to decision makers if they do not take the next step of estimating the relative frequencies (probabilities) with which these outcomes occur.

2.1.4 R&D Strategy

The traditional methods have features which are useful for dealing with some aspects of uncertainty, all are inadequate in several respects. Decision-making can be improved by a more systematic, complete, and explicit treatment of uncertainty, using certain aspects of the decision theory and what has come to be known as research and development (R&D) strategy.^{68,73-79}

2.1.4.1 Probability Theory and Computer Simulation

In recent years, considerable effort in the fields of management, econometry, and operational research has been devoted to developing improved techniques of analysis under conditions of uncertainty.⁸⁰⁻⁹⁰ Most of these techniques involve the direct utilization of probability theory and computer analysis.

As previously noted, the likelihood that all 'best estimates' in an analysis will prove to be exactly accurate is extremely small. Since it is the joint effect of variation in all attributes that will determine a decision's outcome, an analysis technique is required that can allow for this more complex variation. Such a technique must explicitly employ probability

theory. Operationally, this involves not only estimating a range of values for each of the most important factors affecting a decision's outcome, but establishing probabilities of occurrence for each of the intervals within that range. The question of dependence or correlation among factors must also be recognized.

Seldom is there sufficient evidence to estimate probability distributions entirely from historical records, experiments, econometric analysis, or other frequency evidence. In some situations, frequency evidence providing the likelihood of occurrence for some factors does exist and is readily available. More often, objective data must be supplemented with expert judgment in order to determine the desired probability distributions. When subjective elements enter the analysis, we obtain 'subjective' rather than 'objective' probability distributions for the various factors. These probability distributions may be based, of course, on 'more' or 'less' frequency evidence and in this sense might be labeled 'more' or 'less' subjective. The amount of frequency evidence that ought to be collated and utilized in the analysis is itself a decision problem.⁹¹ For decision purposes, however, it makes little difference whether an outcome is 'known' in terms of a more subjective or a more objective probability distribution.⁹²

This approach differs from the traditional approach in that judgmental elements explicitly enter the underlying assumptions rather than being applied to the final results of the analysis. The subjective probabilities reflect the degree of confidence which an investigator has in the estimates that fall in his area of expertise. No matter how 'objective' or 'subjective' these probability distributions might be, they illustrate precisely what is unknown, as well as what is known regarding a factor's future value. Further, based on the best information available, the degree of imperfect knowledge is quantified in the form of probability statements. Such probabilities are introduced in an attempt to 'represent ignorance.' In contrast to those approaches which consider only the 'best estimates,' the use of these probability distributions allows a more complete analysis of each decision alternative. In conjunction with the computer, which is employed to enumerate the probable performance outcomes resulting from the combinations of the relevant factors, this approach gives the decision makers a more precise assessment of the risk that may be associated with each decision alternative.

2.1.4.2 Utility Theory

Studies on R&D strategy² have clarified the implication of ideas such as learning, flexibility, and parallel developments. The fact that information can be gained through time and that 'better' decisions can be made on the basis of the additional knowledge gained are recognized. Thus, the appropriate conceptual framework for most long-term development problems is sequential or multi-stage decision making under uncertainty. The use of utility as a dimensionless measure of preferences is introduced to replace cost functions.⁹³ This is done to accommodate for risk aversion. By deriving von Neumann-Morgenstern utility functions⁹⁴ for all attributes that are relevant to the decision problems, the utilities of the levels of those attributes specific to the given R&D program can be used to select the most preferred R&D program. The criterion employed in this case is maximization of expected utility.⁹⁵

2.1.4.3 Group/Individual Preferences

The derivation of indifference curves or preference functions can be easily done at the level of the individual decision-maker. At a community level, the preference functions can be approximated by the legislative process.²¹ At a level of groups of decision-makers, some prescribed processes have been developed.⁹⁷⁻⁹⁹ The preference functions can be easily synthesized over multiple attributes, including both tangible and intangible factors. An alternative approach, which avoids explicit derivation of preference functions (utility functions or indifference curves), is simply to present the 'efficiency frontier' to the relevant decision-making group and let it make a direct choice. By making the risks explicit, the risk preferences of the decision-makers are called into play and they 'reveal' their preferences by their decisions.

2.1.4.4 Safety First Principle

It may also be practical to derive special forms of preference functions for problems of this sort. For example, the decision makers may be willing to employ some variant of the 'safety-first' principle,¹⁰⁰ which is

closely related to the idea of 'satisfying' (achieving 'satisfactory' levels of goals) in a multiple-goal framework. One form of the 'safety-first' principle is to specify a maximum variance that is permissible ('satisfactory') and then proceed to maximize expected value subject to that maximum permissible variance. The main deficiency of past practice in development of R&D strategies with regard to preference functions is that a multiple goal framework has not been used. Decisions regarding LWR safety technology programs are expected to include a number of broad objectives. Those broad goals may be classified into four categories: (1) national income objectives, (2) national energy development objectives, (3) environmental and public safety objectives, and (4) 'well-being' objectives. Broad goals of this sort are often competitive in the sense that a higher level of attainment of one goal can be reached only by reducing the level of attainment of other goals. Thus, decision makers have a preference function by which they implicitly weight the relative importance of the various goals when making choices.

2.1.4.5 Sequential Decisions

R&D program planners recognize that current decisions are likely to have consequences that extend over a considerable period of time. The consequences of such decisions are not a single outcome, but rather a sequence of outcomes. While sequential aspects of decision-making are recognized,¹⁰¹ for example when the construction of a system is spread over a considerable period of time, the question of timing is usually treated within an environment of certainty.

Marglin,^{9,10} has treated the case of sequential decision-making under certainty rather completely, with several important results. He demonstrates analytically, for example, that the economic merit of a project can be improved by postponing construction and that the postponement may change the measure of merit for a particular project from an undesirable figure for construction today to a desirable value for construction at some future date. Arrow¹⁰² in a generalization of some of Marglin's work, has demonstrated that in some cases optimal timing of each project or component increment can be achieved by scheduling construction the first time the project reveals a

positive present value. Manne¹⁰³ in still a more general framework, has shown that optimal construction time is determined by balancing interest costs, loss of benefits, and economies of scale. In fact, if substantial economies of scale exist, it may be optimal to build ahead of benefits.

The literature mentioned recognized the possibility of accumulating additional information through time so that decisions can be revised sequentially. However, it does not explicitly introduce uncertainty in the form of probability distributions by which decision strategies could be formulated. Moreover, it does not explicitly introduce the possibility of allocating available resources in such a way as to reduce or resolve uncertainties. To partially resolve uncertainty, decision-makers may revise probabilities on the basis of new information by utilizing Bayesian analysis.¹⁰² Formally, this involves converting prior probabilities to posterior probabilities.

2.1.4.6 Parallel Programs

The R&D strategy approach⁷⁶ suggests the use of parallel and loosely related approaches to develop R&D programs. The decision to invest in a particular program need not be viewed as a 'once-and-for-all' decision. Rather, the decision to work with some intensity on a program may be viewed as the exploration of a possibility aimed at finding out more about the chances of success and the costs and benefits of the particular program, if it were completed.

2.1.4.7 Normative Theory

Marschak, Glennan, and Summers,⁷⁶ have formally extended these ideas to the pursuit of approaches with different intensities, isolating the peculiar way such different approaches relate to each other; to the case of many review points and multicomponent parallel developments; and to the case of many-valued preferences.^{76,77} As Hirschman argues quite convincingly, development projects are essentially "voyages of technological and administrative discovery" and as such, require an R&D approach; such as the normative theory developed by Marschak.²

A fairly complete normative theory makes it possible to test reasonable conjectures about what good development strategy and organization look like. That is to say, it would be possible to find a variety of assumptions that yield models simple enough to analyze and for which the conjectures could be demonstrated to be true, if, in fact, they are true. This requires a precise statement of the tested conjectures. If under certain assumptions a tested conjecture is invalid (the development strategy it describes is not good) the developer would have to decide whether or not such assumptions are met before he could accept the tested conjecture in formulating his own development strategy. Among the conjectures to be tested in this manner are that the more one learns in each approach to a development task the more approaches it pays to pursue; and that successive increments in the scale of a development project yield smaller and smaller improvements in the project's pay-off, suitably defined. In addition, the theory is a step in finding out what the production function of the knowledge-producing industry looks like. In particular, the theory would shed light on the critical question of returns to scale in the conduct of research and development, first with respect to individual projects--the most disaggregated research and development efforts--and ultimately by aggregation with respect to the national research and development effort. Furthermore, the theory helps in identification of various areas of ignorance about development in which intensive and critical inquiry would particularly pay off. If certain properties of good development are particularly sensitive to assumptions about how knowledge is acquired, then it is particularly fruitful to make an empirical study of which assumptions are in fact satisfied. Such assumptions might have to do, for example, with the shape of the curve that relates the amount of money spent on development in a particular stage to the decrease in uncertainty (suitably measured) that this spending can bring about.

2.1.5 Logic Trees

Conceptually, the decision tree approach can be used to solve R and D problems of the more complex type described above. However, as Raiffa⁹³ points out, the decision tree in such a case is likely to become

a "bushy mess." Unfortunately, some of the more powerful mathematical tools for solving multistage problems, such as linear and nonlinear programming, are severely limited in handling cases that involve uncertainty^{105,106}. The most viable approaches under uncertainty are probably dynamic programming^{107,108} and stochastic simulation^{109,110}.

2.1.6 Dynamic Programming

Dynamic programming under uncertainty is a formal solution procedure which, at least for some decision problems, allows the derivation of optimal decision strategies.¹¹¹ Essentially, the procedure involves restating the complex multistage decision problem as a number of subproblems (one representing each stage within the planning horizon), each of which contains a few controllable or decision variables. The solution procedure is analogous to the "backward" solution employed in decision-tree analysis.¹¹²⁻¹¹³

2.1.7 Simulation and Monte Carlo Approaches

Unfortunately, generally applicable analytical solution procedures do not exist for certain classes of more complex problems. Thus, stochastic computer simulation is often regarded as the most realistic approach to tracing out the implications of alternative decision strategies. The simulation model can be as complex as a realistic statement of the decision problem requires. Interdependencies among actions and probability distributions can be specified in the model. The probability distribution of the overall performance criterion can be obtained for a given decision strategy by Monte Carlo sampling methods, that is, by sampling from the relevant probability distributions for each state of nature to obtain the value of the criterion function for a specific computer run. Successive runs with other samples allow approximation of the probability distribution of the particular strategy. Probability distributions for other strategies can be obtained in similar fashion. There is no guarantee that an "optimal" strategy can always be obtained with these methods, but "better" strategies can be derived.^{114,115}

2.1.8 Ranking and Weighing

In some of the aforementioned techniques a combination of several parameters has been used to describe the consequences of a given strategy. This approach has been shown inadequate in many cases since it does not reflect the preferences of the decision maker and hence it does not provide a guide to rational decisions.

One approach presently employed to remedy the problems created by the reliance on a single attribute, is to minimize or maximize the weighted sum of the expected values of all the relevant attributes. Besides the previously mentioned deficiencies of using an expected value of an attribute, this approach assumes only that the amounts of the individual attributes are important and the various ways they can be combined are unimportant. That is, evaluation is dependent only on the marginal probability distributions of the various attributes and not on their joint probability distribution. In many problems this assumption is unreasonable.

2.1.9 Target Rate Approach

Still another technique used by decision makers to determine which course of action to follow is the target rate. In this approach, acceptable levels of certain attributes are specified and, subject to attaining these levels, the expected value of another attribute is minimized or maximized. The acceptable level may have a specified probability associated with it. That is, for example, based on the decision maker's state of knowledge, only alternative courses of action which have a 0.99 probability of achieving the acceptance level are considered. This is similar to the value-impact approach.

2.1.10 Multiattribute Utility Approach

An R&D selection methodology may be based on the exploitation of utility theory and related decision analysis techniques. In some of the approaches mentioned earlier a utility function has been used in place of the single attribute since the expected utility can be used as a guide to rational decision.¹¹⁶⁻¹²² The utility theory provides a mathematical model

in which an attempt is made to measure preferences towards multiple objectives by means of numerical "utility functions" ¹²³. The concept of utility has been borrowed in decision analysis to establish a scale of expected monetary values of lotteries or business ventures ⁹³. Assessment of numerical utilities can be used for nonmonetary as well as monetary attributes ¹²⁴. Many techniques have been suggested and used to assess utility functions of a single attribute ¹²¹, 125-128.

Obviously, applications of mathematical decision-making models have, in the past, tended to use unidimensional and easily measurable objective functions. However, almost all decisions involve multiple criteria which are often subjective in nature, eluding easy qualification. The essence of good decision-making in such circumstances lies in trading off one goal properly applied in such situations only if these trade-offs can be expressed in quantitative form. Therein lies the value of multiattribute utility (MAU) models which provide a practical tool for the development of multi-dimensional objective functions.

Multiattribute utility theory provides a formal basis for describing or prescribing choices between alternatives whose consequences are characterized by multiple values of relevant attributes ¹²⁹. Thus, analytic work on such problems requires that one obtains an objective function involving multiple measures of effectiveness to indicate the degree to which these objectives are met. Such an objective function specifies a preference ranking of consequences, and allows one to identify the trade-offs between various combinations of levels of the different attributes. In a risk-free environment, one should choose the alternative course of action that maximizes (or minimizes) the objective function ¹³⁰.

However, most decision problems; such as selection of LWR safety technology proposals and programs, involve uncertainties--and these uncertainties need to be either considered formally or informally in analyzing the problem. If one chooses to do this formally, it is necessary to specify an objective function with special characteristics in order to make the analysis for solving the problem tractable. For this reason, it would be

convenient to be able to use the expected value of the objective function as a guide to identify the best alternatives. This is appropriate, given that one accepts the axioms of utility theory specified by Von Neumann and Morgenstern⁹⁴. The objective function is then a utility function. This utility function not only provides one with the necessary information to rank consequences and identify trade-offs between attributes, but it also follows the aforementioned axioms that one should choose the alternative that maximizes the expected utility.

The utility concept is theoretically sound, and the mathematical details are not involved. However, as mentioned earlier, the difficulty comes when one tries to specify reasonable procedures for obtaining multi-attributed utility functions. The general approach followed by many people has been to make assumptions about preferences and then derive the functional form(s) of the utility function satisfying these assumptions. If the assumptions are verified, the functional form can be used to simplify the requisite assessments needed to specify the utility function. Often these assumptions are so involved that it is unreasonable to expect a decision-maker to ascertain whether or not they might be appropriate for a specific problem.

2.1.10.1 Isopreference maps

This limitation can be removed by proper exploitation of the general properties of the multidimensional utility function in assessing it. One of the techniques used in evaluation multidimensional preferences is to use indifference maps or iso-preference curves in absence of uncertainty to transform the multivariable function into a function of one variable via the employment of specific substitution rates¹³¹. The technique has been tested¹³² and was found to be limited to situations in which the substitution rates are independent of the levels of the attributes.

2.1.10.2 Lexicography

A lexicographic ordering is another procedure for evaluating multidimensional consequences under certainty. With this type of ordering,

that is, one attribute dominates preferences, and only when there is indifference involving comparisons of this attribute is the second attribute considered. Hausner¹³³ presented in axiomatic structure providing this type of ordering.

The lexicographic formulation seems unreasonable for most decision problems, since the substitution rate between attributes is implied to be zero. However, in cases where both attributes can take on only a few discrete values and there is not uncertainty involved in the problem, a lexicographic ordering may be useful. Thrall¹³⁴ and Mellon¹³⁵ each suggests specific military examples for application of such preferences.

2.1.10.3 Additive Approach

The classical and most common approach for evaluating multidimensional consequences under certainty is the additive representation. If a set of attributes $\{X_1, X_2, \dots, X_i, \dots, X_n\}$ having consequences $(x_1, x_2, \dots, x_n)$, then the additive formulation, a real value v is assigned to each consequence $(x_1, x_2, \dots, x_n)$ by

$$v(x_1, x_2, \dots, x_n) = v_1(x_1) + v_2(x_2) + \dots + v_n(x_n),$$

where $v_i(x_i) > v_i(x'_i)$ if and only if x_i is preferred to x'_i .

Debreu¹³⁶ proved for $n > 3$ that if the substitution rate between attributes X_i and X_j is independent of all other attributes for all i and j , there exists a set of functions v_i , $i = 1, 2, \dots, n$, such that v in (1.5) is larger for more preferable consequences. Luce and Tukey¹³⁷ gave an alternate proof of this proposition for $n = 2$, and Krantz¹³⁸ extended their work for arbitrary n . Miller¹³⁹ developed a similar assessment procedure and applied his work in choosing among various employment opportunities and in computer acquisition.

One major shortcoming of the additive approach is that the function v is not necessarily a utility function in the probabilistic sense.

That is, the expected value of v cannot be used as an appropriate guide to decision making under uncertainty. Raiffa¹³¹ suggests one approach to obtain a probabilistic index from the v function. This additive representation has been suggested by Hammond¹⁴⁰ in the choice of a college and Aumann and Kruskal¹⁴¹ for solving the assignment problem.

2.1.10.4 Additive Utility Approach

In problems involving uncertainty, the usual approach for evaluating multidimensional consequences is the additive utility function. In n dimensions, this function may be written as

$$u(x_1, x_2, \dots, x_n) = u_1(x_1) + u_2(x_2) + \dots + u_n(x_n) ,$$

where $u_i(x_i)$ is a utility function defined over the X_i attribute.

For whole product sets, $X_1 \times X_2 \times \dots \times X_n$, Fishburn¹⁴² has proven that $u(x_1, x_2, \dots, x_n)$ may be evaluated by an additive utility function if the desirability of any lottery, which is represented by $(\bar{x}_1, \bar{x}_2, \dots, \bar{x}_n)$ where "-" indicates a random variable, depends only on the marginal probability distributions of the X_i 's and not on their joint probability distribution. He has extended this idea using the same premise to include denumerable product sets,¹⁴³ incomplete product sets,¹⁴⁴ and interdependencies among some attributes.¹⁴⁵ Pollak¹⁴⁶ also derives necessary and sufficient conditions for additive utility functions.

In all these cases, the resulting utility function differs from the v function discussed above in that it is valid in the probabilistic sense; that is, expected utility should be used as a guide to rational behavior.

The main advantage to the additive utility function is its relative simplicity. The assessment of the n -dimensional utility function is reduced to the assessment of n one-dimensional utility functions, and - as previously mentioned - adequate systematic procedures do exist for assessing one-dimensional utility functions. A major shortcoming of this approach is the

restrictiveness of the necessary assumptions. One would often expect the utility of a lottery to be dependent not only on the marginal distributions of the respective attributes, but also on their joint probability distribution. It is also difficult to determine whether or not the requisite assumptions would be reasonable in a specific real-world problem. This difficulty arises because the assumptions are stated in terms of the decision maker's preferences for probability distributions over consequences, rather than directly in terms of his preferences for consequences. Assumptions of the latter type have more operational significance. Often, the multidimensional utility function is assumed to be additive for convenience, rather than justified by testing the validity of the requisite assumptions. Many potential applications of additive utility functions, including cost-effectiveness problems, are suggested by Fishburn¹⁴⁷.

2.1.10.5 The Decision-Maker Preference Approach

An alternate approach to assessing multidimensional utility functions involves assumptions about the decision maker's qualitative preferences for consequences. Based on these assumptions, it was shown in Keeney¹⁴⁸ how the two-dimensional utility function in certain cases could be evaluated from

$$u(x,y) = u_x(x) + u_y(y) + k u_x(x)u_y(y),$$

where k was an empirically evaluated constant.

This method has been further developed for n -dimensional utility functions.¹³⁰

Sufficient conditions have to be met in order to determine whether a multiattribute utility function is of the above form. The number of conditions required increase linearly with the number of attributes. None of the conditions, however, requires the decision-maker to consider trade-offs between more than two attributes simultaneously or to consider lotteries over more than one attribute. In order to determine the single utilities for each attribute several schemes have been developed, for individual^{93, 149} and for a group of decision-makers.^{96-98,150}

In summary, the MAU R&D selection methodology involves the following steps:

1. Consider the LWR safety R&D program areas and identify all possible measures of effectiveness or attributes; especially those pertinent to the program goals such as improved safety, public acceptance, etc;
2. Rank attributes and evaluate scaling factors and the multiplicative weight using appropriate methods;
3. Synthesize utility curves or preference patterns of all attributes by decision-makers and/or expert participation and then provide analytical expression for the utility functions;
4. Check utility and preferential independence;
5. Identify alternative programs or proposals (options) in a specific study area, and
6. Maximize the MAU function to rank order the identified proposals.

2.1.10.6 Merits of the MAU Approach

From the review of the existing selection methodologies it is apparent that existing methods suffer from many deficiencies especially in dealing with practical selection of R&D programs of many attributes. Where intangibles tend to affect selection decisions, shadow pricing and social discount rates are only superficially used but subject to controversy. Among the points which are in favor of an MAU approach are:

1. Consideration of tangibles, monetized factors and intangibles,
2. Ability to reduce multidimensional factors into one function useful for ranking order,
3. Accommodation for decision-makers (program managers, legislators, public groups) preferences,
4. Amenability to analytic solutions and computer programming,

5. Flexibility in iterative applications and in applying to all study areas of the LWR safety R&D program,
6. Applicability to various problems similar in nature to the R&D selection program considered here,
7. Simplicity of input information and directness of the output results.

2.1.10.7 Prospective Applications of MAU

Prospective applications of the MAU methodology to the selection of LWR safety technology programs and proposals may be seen by enumerating some of the decision areas in which the MAU approach has been used. Throughout those applications, the methodology has been refined and techniques for its implementation have been developed. Most notably, the developments by members of the SAI team in programming of a generalized approach and in assessment of preference patterns using Delphi approach.

The MAU method has been applied in the assessment of preferences concern providing equitable service to two groups of telephone customers, surveying a controlled waterway, and in assessing inventory ordering policy by the manager of a hospital blood bank.¹⁵⁴ Yntema and Klem¹⁵² have assessed the safety of landing aircraft in various weather conditions. Other decision problems of multiobjectives and many attributes which have been analyzed by the MAU method to select appropriate and optimal programs include: a forest pest problem¹⁵³, energy policy¹⁵⁴, salmon management policies¹⁵⁵ and ecosystem management¹¹⁸.

Group preferences curves have been assessed in the selection of alternative strategies for the Mexico Airport⁹⁷. A sketchy approach is proposed for the use of multiattribute utility theory by Keeney and Nair⁽⁹⁹⁾ in decision analysis for the siting of nuclear power plants. In the same context the utility theory has been used earlier by Gros⁹⁶ who employed a Paretian environmental approach to power plant siting in New England. In this approach the decision-makers have been partitioned in groups of special interests. The preferences of each group have been assessed and combined in an overall utility function which is maximized to yield the choice site. The method has been also employed in water resources developments by Wood¹⁵⁶ in a descriptive fashion.

The multiattribute theory has been recently applied by Bushnak¹⁵⁷ in problems of transportation under extreme conditions; by Abdul-Fattah¹⁵⁸ and by Abdul-Fattah and Hussein¹⁵⁹ in selection of management approaches for dual purpose nuclear desalination plants and for large engineering projects, respectively; by Ahmed¹⁶⁰ in selection of energy systems; by Ahmed, Cho and Abdul-Fattah¹⁶¹ in selection of water resources development alternatives; and by Kusayer¹⁶² in selection of strategies for transfer of nuclear technology.

To facilitate the calculations of the expected utility, a computer program has been developed by SAI personnel to synthesize utility functions and provide the various scaling factors for a general situation. The program has been tested in several problems including: selection of energy systems¹⁶³⁻¹⁶⁵, selection of nuclear power plant sites⁹⁸, solar energy planning¹⁶⁶, comparison between hard and soft energy paths¹⁶⁸ and bid evaluation^{169,170}. The computer package may be developed further to provide high degree of flexibility. Some features which may be considered include a Monte Carlo routine for sampling of values of attribute levels, a Bayes probability distribution module, and a facility to use Delphi input to synthesize preference curves and proper scaling functions.

The Delphi approach has been employed in site selection by Ahmed, Hussein and Cho⁹⁸. A set of questionnaires was sent to solicit preferences of expertise regarding siting issues. The variance in the responses was reduced by reformulating the questions in the second round of the survey and informing the respondents of the statistics of the first survey. Anonymity of the respondents was guaranteed all through the process. The Delphi technique is currently being employed by the Chase Manhattan Bank to assess the viability of fusion as an energy option.

In this siting study the multiattribute theory has been applied to verify the site selection for a nuclear power plant in John Redmond Reservoir region, Kansas. Seventeen attributes have been considered. Due to the complexity of the problem those attributes have been divided into 75 factors each of which impact the decision of varying intensity.

2.1.11 Verbal Rating

To overcome the difficulty of selecting exact numbers for attribute levels or weights or the use of absolute numbers for ranking, one may assign a set of numbers each having a different level of possibility. Such fuzzy set accommodates for imprecision in values of attributes or utilities. The use of the fuzzy set theory in ranking, weighing or evaluation of utility or probability can add new information to the preferability among options. The relative degree of preference can be evaluated and the range of values in which a given option is preferred over others can be determined. A detailed exposé of the fuzzy set analysis is given in Appendix B.

2.1.12 Simple Ranking & Scoring Approaches

There are a variety of simple approaches which are based on pure subjective judgement. The simplest is providing simple score from 0 to 10; say for each program/proposal. A ranking of programs and proposal using various criteria of evaluation may be used with weights being assigned to each criterion. The weighted averages of each option can be then used for selection.

Another approach is the Q-sort method which can involve group decision-makers. The programs/proposals are ordered in groups of low, medium or high preference. The process is repeated several times after rounds of open discussions.

Pair comparison of evaluation criteria may be used to assign relative ranks and weights to criteria of evaluation and to measures of how a given program meets the criteria requirement. These methods are illustrated in Appendix A.

2.1.13 Bayes Decision Approach

The traditional Bayesian decision approach involves the use of the payoff matrices, logic diagrams and maximin and minimax techniques. An additional dimension is the use of value of information to assess the feasibility of postponing the decision until more precise information is obtained.

2.2 FEATURES OF AVAILABLE METHODS

2.2.1 Specific R&D Approaches

A summary of some of the methods which can be applied in the selection of R&D programs/proposals is given in Table 2.2-1. The methods are classified according to the discipline wherein they have been developed and/or applied, namely

- A. Decision Theory Approaches (DT)
- B. Operation Research Approaches (OR)
- C. Economic Analysis Approaches (EA)
- D. Combination of EA and OR Approaches
- E. Combination of EA and DT Approaches
- F. Combination of DT and OR Approaches
- G. Other Approaches

In evaluation of R&D selection methodologies specific factors have to be considered; such as those listed in Table 2.2-2. A comparison of some of the techniques is given in Table 2.2-3. The optimization techniques and constraints are also shown along with the features of each method. Ease of use is assessed in Table 2.2-4 and R&D areas of applicability are given in Table 2.2-5¹⁷¹.

The approaches listed in Table 2.2-1 and compared in Tables 2.2-3 through 2.2-5 have been proposed for R&D in military applications and have been considered for application in several industries, such as the petroleum and chemical industries. Due to the fact that some of the techniques are based on the exploration of complex mathematical tools, industrial managements have been reluctant in directly employing those approaches. Occasionally, the approaches have been used by the technical staff to evaluate decisions a posteriori to examine their validity. Also, some of the techniques are used in extensive feasibility studies. For management decisions, methods such as those reviewed in Section 2.1, Appendix A and Section 2.2-2 are preferred.

Table 2.2-1 Miscellaneous Methods

A. Decision Theory Approaches

#	Method	Date	Description	Reference
1	Mottley-Newton	1959	Project proposals are rated with respect to a number of evaluation criteria. An overall score is computed and used to rank the alternatives. Selection criteria are considered with respect to constraints including research budget, risk, and overall program balance.	172
2	Gargiulo et. al.	1961	Project proposals are rated with respect to a number of evaluation criteria. An overall score is computed and used to rank the alternatives. Constraints such as research budget, skills available, facilities available, and competitor efforts in the area are considered.	173
3	Pound	1964	Project proposals are rated with respect to a number of weighted selection objectives. An overall score is computed and used to rank the alternatives. The budget constraint is considered.	174
4	Cetron, "PROFILE"	1965	Designed to aid in exploring (a) the total structure of project selection decision problems in the context of the R&D manager, and (b) R&D processes which are relevant to the design and implementation of management systems for planning, appraising, and controlling resource allocation among various projects.	175

Table 2.2-1 Miscellaneous Methods (con't)

A. Decision Theory Approaches (con't)

#	Method	Date	Description	Reference
4 (con't)			PROFILE's nine quantified criteria (value to warfare, task responsiveness, timeliness, long range plan, probability of success, technological transfer, manpower, facilities, and funding) are used in developing a task "Profile" as well as in determining the military utility, the technical feasibility, and the application of resources for each project.	
5	Wells	1966	Approach to store, track, and properly relate judgements concerning systems; to show the impact of these judgements; to permit real-time iterations of planning problems to facilitate the assessment and selection of system candidates for development. Criteria are: threat, types of war, policy objectives, functions, systems contributions, force structure, technical feasibility, schedule and cost, and budget.	176
6	Belt	1966	Based on quantified subjective judgements on the predicted value of a successful laboratory project outcome, the likelihood of success of the project in terms of its technological achievability, the specific plan of attack and the suitability of the proposed performers of the work, and the predicted cost. This technique stops short of producing a single numerical rating of project value,	177

Table 2.2-1 Miscellaneous Methods (con't)

A. Decision Theory Approaches (con't)

#	Method	Date	Description	Reference
6 (con't)			but gives the decision maker the opportunity to select from a group of alternative projects.	
7	De L'Estoile	1966	This refined rating scheme uses a formula including four factors: military utility, probability of technical success, possibility of realization in France, and direct and indirect economic impact (including the cross support to the civilian sector of the economy). This total system, because of the large number of projects involved, was computerized in 1967.	178
8	Caulfield-Freshman	1967	Development project proposals are rated with respect to a number of weighted selection categories. These six categories consist of progress of program, military utility, technical risk, resources, management environment, and technological transfer; an overall score is computed and used to rank the alternatives. This technique is used to develop a task "Profile" which serves as an aid in the allocation of resources.	179

Table 2.2-1 Miscellaneous Methods (con't)

B. Operation Research Approaches

#	Method	Date	Description	Reference
1	Sobelman	1958	For each alternative project, estimates are made of average value per year, economic life, average development cost per year and development time. Selection is accomplished by maximizing discounted net value, perhaps subject to constraints.	180
2	Freeman	1960	For each alternative project, an estimate is made of the probability distribution of net value. Selection is accomplished by maximizing expected discounted net value subject to constraints on the total budget, facilities, and personnel. A linear programming formulation is used.	181
3	Asher	1962	For each alternative project, estimates are made of the discounted net value of the project and probability of success. Selection is accomplished by maximizing expected discounted net value subject to constraints on the man hours available and on the raw materials available. The optimal manpower allocation is indicated by the result. A linear programming formulation is used.	182

Table 2.2-1 Miscellaneous Methods (con't)

B. Operation Research Approaches (con't)

#	Method	Date	Description	Reference
4	Hess	1962	For each alternative project, estimates are made of the discounted gross value as of several points in time. Probabilities of success are also estimated. Selection is accomplished by maximizing expected discounted net value subject to a budget constraint for the first period. The optimal allocation to each project is indicated for each period. A dynamic programming formulation is used.	183
5	Dean	1964	Mathematical models consider the relevant resource variables, noncontrollable variables, parameters, and constraints that are responsive to corporate goals and yield solutions for allocating technical resources to projects. The scoring model permits determination of important factors in a profitability model.	184, 185
6	Hill - Roepck	1961	A mathematical model considering the military value of the objective for technology. The technical probability of success, the expected value of the individual efforts, and a method to select the optimum program from many such efforts.	186

Table 2.2-1 Miscellaneous Methods (con't)

B. Operation Research Approaches (con't)

#	Method	Date	Description	Reference
7	Nutt	1965	A deterministic model which quantifies the value or technical payoff of each research task. The model developed considers the world environment; the Air Force missions; future weapons systems configurations; laboratory technical objectives; and the timeliness, complexity, and scope of each research effort. The result consists of recommended funding levels of efficient tasks along with suggested tasks for close scrutiny or possible elimination. A modified linear program.	187
8	Rosen & Saunder	1965	A modification of Hess' dynamic programming approach by discussing it in the context of different optimization criteria for obtaining optimum expenditure patterns. The optimization criteria are: expected profit; total expected output; life expected output; and a minimum fixed percent return on nondiscounted expenditure.	188
9	Sacco	1965	A refinement to the Hill-Roepcke model that permitted dynamic programming to be used and thus achieving a more nearly optimum R&D program.	189

Table 2.2-1 Miscellaneous Methods (con't)

B. Operation Research Approaches (con't)

#	Method	Date	Description	Reference
10	Albertini	1965	A methodology for the evaluation and selection of research and development tasks directed toward the determination of material development objectives. A mathematical choice model to assist management in the synthesis of pertinent information for the purpose of selection, within applicable constraints, of a maximum expected value program of research and development effort. Specifications, in the form of flow charts, are included for the computerization of the model.	190
11	Albertini	1965	To synthesize information pertinent to the planning process for the purpose of determining which long-range technical plan tasks to recommend for funding. This technique begins with given major barrier problem areas (MBPA's), operations on these MBPA's using the following criteria: expected technical value, annual cost of a configuration, annual monetary quota cost of a configuration. A computer program helps formulate the recommended R&D program.	191, 192

Table 2.2-1 Miscellaneous Methods (con't)

B. Operation Research Approaches (con't)

#	Method	Date	Description	Reference
12	Cetron, "QUEST"	1966	QUEST utilizes a double set of matrices, consisting of the sciences, technologies, and missions, developed with the "technology" parameter common to both. By having "Figures of Utility" assigned to each mission and by determining the value of the contribution of each technological area to each mission, a cumulative quantified value for each technological area is then related to each scientific area and the relevant impact of each of the scientific disciplines is identified with each technological area.	193, 194
13	Martino et al.	1967	Factors taken into account are importance of military missions, criticality of technological effort to mission, and level of technology required. Funds are allocated among technical projects on the basis of maximum marginal payoff per dollar, within a budget total.	195

C. Economic Analysis Approaches

1	Disman	1962	For each alternative project, an estimate is made of the discounted net value (not including R&D costs). This estimate, perhaps modified by a probability of technical and/or commercial success is considered to be the maximum expenditure justified. The ratio of the maximum expenditure justified to estimated project cost is an index of the desirability of the project.	196
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Table 2.2-1 Miscellaneous Methods (con't)

D. Combination Economic Analysis and Operation Research Approaches :

#	Method	Date	Description	Reference
1	Dean-Sengupto	1962	The optimal research budget is first determined. Then for each alternative project, estimates are made of the discounted net value and the probability of technical and commercial success. Selection is accomplished by maximizing expected discounted net value subject to a budget constraint. A linear programming formulation is suggested.	197
2	Cramer - Smith	1964	An application of portfolio selection and utility theory to the problem of research project selection. For each alternative project, estimates are made of net values and probabilities of occurrence. Utility curves are also obtained. Projects may be ranked on the basis of expected value or expected utility. Lack of project independence is also mentioned.	198
3	Dean - Hauser	1966	An economic analysis and operations research approach. An application of project selection under constrained resource conditions. By using mathematical models, computer programs, and available information concerning costs, uncertainties and military values, it is possible to obtain optimum solutions. The case study has developed a mathematical model for handling the large number of alternatives through the use of a series of simpler computerized methods, where the results of one stage are used in the succeeding stage. A dynamic programming formulation is used.	199

Table 2.2-1 Miscellaneous Methods (con't)

E. Combination Economic Analysis and Decision Theory Approaches

#	Method	Date	Description	Reference
1	Berman	1965	The approach considers the incremental cost of the project in R&D resources; the incremental production and operating and manning costs of introducing the new technology, and the incremental military value of the technology.	200

F. Combination Decision Theory and Operation Research Approaches

1	Esch, "PATTERN"	1963	Project PATTERN is a continuing large scale, corporate effort to assign quantitative, relative values to the importance of conducting R&D on the various technology deficiencies which now stand in the way of the achievement of the national security objectives for the decade from 1968-1978. The model considers national survival, threat force structure, capability, prestige, cost effectiveness, requirements, scientific implications, feasibility, effort, risk, capability improvement, and operational advantages. this technique is the first full-scale application of the heuristic "relevance tree" concept development in 1958 by H. Wells in his Ohio State University Master's thesis.	201
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Table 2.2-1 Miscellaneous Methods (con't)

G. Other Approaches

#	Method	Date	Description	Reference
1	Blum	1963	A mathematical treatment leading to a methodology of ranking R&D events in the project by their cost, risk, time, and value. The methodology sequences the efforts by a version of the DOD and NASA Pert-cost technique.	202
2	Bakanas	1964	A model to aid in the selection of applied research and development tasks for inclusion in a long-range R&D program. The model consists of a structure relating the conceptional elements of the R&D program; formats for delineating the characteristics of the conceptional elements; mathematical relations between the expected program value and military priority probability of task success, task cost, and program cost; and a rank-ordering procedure to select a program of maximum expected value. A computer program aids in formulating the R&D program.	203

Table 2.2-1 Miscellaneous Methods (con't)

G. Other Approaches (con't)

#	Method	Date	Description	Reference
3	Sobin - Gordon	1965	A comparative method which will analyze alternative applications of resource allocation techniques and attempt to evaluate the value of these techniques against various frames of reference. The analytical method thus developed (basically using ordinal values converted to relative values made up of interdependence of different proposals, definiteness of applications, capability values, probability of success, and military utility) will be used to optimize the selected principles of resource allocation in the dynamic multiple project environment. Linear programming will be used. Principal application to laboratory selection of efforts.	204, 205

Table 2.2-2 Factors to be Considered in Evaluation of
Methodologies of Selection of R&D Programs

1. Utility measure.
2. Probability of success.
3. Orthogonality of criteria.
(Mutually exclusive criteria)
4. Sensitivity.
5. Rejected alternatives retention.
6. Classification structure.
(Structural relationship between R&D project and
a hierarchy of higher level goals)
7. Time.
8. Strategies.
(Provides for scenarios)
9. Program cross support.
(Credit)
10. Technology cross support.
(Credit)
11. Graphical display.
12. Flagging.
13. Optimization criteria.
(Score, maximum)
14. Constraints.
15. Computerized.

Table 2.2-3 Features

	Utility Measure	Prob. of Success	Orthog. Criteria	Semi-tivity	Retain Rej. Alt.	Class Struc.	Time	Strategies	Sys. Cross Support	Tech. Cross Support	Graph. Displ.	Flag.	Optimize* Criteria	Constraints**	Computerized
1 Mottley-Newton, 1959	X	X	X	X			X	X					1	1, 6, 7	X
2 Gargiulo et al., 1961	X	X	X				X		X	X			1	1, 2, 3, 4	
3 Pound, 1964	X	X				X							7	1	
4 Sobelman, 1958	X	X					X						7		
5 Freeman, 1960	X	X	X					X					7	1, 2, 3	X
6 Asher, 1962	X	X	X										7	2, 5	X
7 Hess, 1932	X	X					X						7	1	X
8 Dean-Sengupta, 1962	X	X			X	X							7	1	X
9 Disman, 1962	X	X	X										7		
10 Cramer-Smith, 1964	X	X			X	X							7	1	
11 Eash, "PATTERN," 1963	X	X	X	X	X	X	X	X	X				1, 2		X
12 Blum, 1963	X	X	X		X	X							6	6	
13 Bakannas, 1964	X	X	X	X	X	X							3	1, 6	X
14 Dean, 1964	X	X	X	X	X	X							4		
15 Hill-Roepecke, 1964	X	X	X	X	X	X							2	1, 6, 7	
16 Nutt, 1965	X	X	X	X	X	X	X	X		X	X		1, 2, 3	1, 2, 3	X
17 Cetron, "PROFILE," 1965	X	X	X	X	X	X	X	X		X	X	X	1, 2	1, 2	
18 Rosen-Saunders, 1965	X	X											3, 3, 4, 7	1	X
19 Sacco, 1965	X	X	X			X			X				3		
20 Albertini, 1965	X	X				X			X	X			2	1, 6, 7	X
21 Berman, 1965	X	X				X	X	X					5		
22 Sobin-Gordon, 1965	X	X		X	X								1	1, 2, 3, 7	X
23 Albertini, 1965	X	X	X			X								1, 6, 7	
24 Wells, 1966	X	X	X	X	X	X		X			X		2	1, 7	X
25 Cetron, "QUEST," 1966	X	X			X	X	X	X		X		X	1, 2	1, 7	
26 Dean-Hauser, 1966	X	X	X	X	X	X		X				X	2, 3	1, 6	X
27 Bell, 1966	X	X			X					X		X			
28 De l'Estuile, 1966	X	X								X			3		X
29 Martino et al., 1967	X		X		X	X	X	X					3	1, 7	
30 Caulfield-Freshman, 1967	X	X			X	X	X	X	X	X	X	X	1, 2, 3	1, 7	

* Optimization Criteria

1. Ordinal Ranking
2. Expected Value
3. Cost-Benefit
4. Profitability
5. Incremental Costs
6. Composite Score
7. Discounted Net Value

** Constraints

1. Budget
2. Skills Available
3. Facilities Available
4. Competitor Efforts
5. Raw Materials Available
6. Risk
7. Program Balance

Table 2.2-4 Ease of Use

	Data Req'ts	Manual Oper'n Posa.	Comp. Prog. Avail.	Comp. Run Time	Diffic. of Updating	Operator Profic. Level	Need for Outside Help
1. Mottley-Newton, 1959	L	X	X		L	T	L
2. Gargiulo et al., 1961	M	X				T	L
3. Pound, 1964	C	X				T	L
4. Sobelman, 1958	M	X					
5. Freeman, 1960	C	X	X			T	
6. Asher, 1962	C		X			T	
7. Hess, 1962	C		X			T	
8. Dean-Sengupta, 1962	C					T	
9. Disman, 1962	C						M
10. Cramer-Smith, 1964	M	X					M
11. Esch, "PATTERN," 1963	C		X	C	C	P	C
12. Blum, 1963	M	X			L	T	
13. Bakanas, 1964	C		X	M	L	P	
14. Dean, 1964	M	X			L	P	L
15. Hill, Roepcke, 1964	C			M	L	P	L
16. Nutt, 1965	C		X	L	L	P	C
17. Cetron, "PROFILE," 1965	L	X			L	P	M
18. Rosen-Saunders, 1965	C		X			T	
19. Sacco, 1965	C				L	P	L
20. Albertini, 1965	C		X	L	L	T	
21. Berman, 1965	C			C	L	T	
22. Sobin-Gordon, 1965	M		X	M	L	P	L
23. Albertini, 1965	C		X	M	L	P	L
24. Wells, 1966	M		X	L	L	P	L
25. Cetron, "QUEST," 1966	C	X			M	P	C
26. Dunn-Hausser, 1966	C		X	L	L	P	L
27. Bolt, 1966	M	X			M	P	L
28. Du P'Estoile, 1966	C		X	C	C	P	C
29. Martino et al., 1967	C	X			M	P	C
30. Caulfield-Freshman, 1967	C	X			M	P	C

Symbol Keys

Computer Running Time	Need for outside help
L—little	L—little or none
M—moderate	M—moderate
C—considerable	C—considerable
Difficulty of Updating	Operator Proficiency
L—low	C—clerk
M—moderate	T—technician
C—considerable	P—degreed professional

Table 2.2-5 R&D Areas of Applicability

	Rsch.	Expl. Devel.	Adv. Devel.	Engr. Devel.
1. Mottley-Newton, 1959	X	X	X	
2. Gargiulo et al., 1961		X	X	X
3. Pound, 1964		X	X	
4. Sobelman, 1958			X	
5. Freeman, 1960				X
6. Asher, 1962			X	X
7. Hless, 1962				X
8. Dean-Sengupta, 1962				X
9. Disman, 1962		X	X	X
10. Cramer-Smith, 1964	X			
11. Esch. "PATTERN," 1963		X	X	X
12. Blum, 1963		X	X	X
13. Bakanas, 1964		X	X	
14. Dean, 1964		X	X	X
15. Hill-Roepcke, 1964		X	X	
16. Nutt, 1965		X	X	
17. Cetron, "PROFILE," 1965		X	X	
18. Rosen-Saunders, 1965				X
19. Sacco, 1965		X	X	
20. Albertini, 1965		X	X	
21. Berman, 1965		X	X	X
22. Sobin-Gordon, 1965	X	X	X	
23. Albertini, 1965	X			
24. Wells, 1966			X	X
25. Cetron, "QUEST," 1966	X	X		
26. Donn-Hamner, 1966		X	X	X
27. Belt, 1966		X	X	
28. De l'Estoile, 1966		X	X	X
29. Martino et al., 1967	X	X		
30. Caulfield-Freshman, 1967			X	

2.2.2 Management Approaches

Considering available R&D selection methods and their applicability to LWR safety technology program evaluation, the methods can be classified into the following major categories.

- ordinal utility
- cardinal utility
- fuzzy set theory
- logic trees
- rating and weighing
- payoff matrices
- scoring charts and techniques
- simulation
- sensitivity
- cost-benefit
- dynamic programming
- pair-wise comparison
- normative method

The simplest are the scoring and pair-wise comparison methods while the most complex are the sensitivity and programming techniques. The most flexible and adaptable to R&D program selection and strategy are the cardinal utility, fuzzy set and normative methods payoff matrices, logic trees and simulation can be used with other techniques to display the decision process as it evolves.

2.3 APPROACH

Selection methodology can be developed for the evaluation of programs/ proposals which possesses the following features

- formal, systematic and structured
- user-oriented and simple
- accommodate for uncertainty and imprecision

- allows for quantification of intangibles
- reflects decision-maker's preferences
- flexible in including inputs from public, industrial and governmental groups
- suitable for group decisions
- modular and adaptable to various situations

The selected methodology which has those features is the MAU approach providing that other aspects of the decision methods are incorporated in the application of the approach. Those aspects include

- realistic attribute levels and ranges and emphasizing the pragmatic approach;
- handling multi-objectives;
- ability to use fuzzy sets to represent verbal judgement;
- adaptation of probability distribution and Monte Carlo simulation;
- simplification of use and ability to use simple computer programs and displays;
- allowance for reconciliation and updating; and
- optimization of outcomes;

3.0 DESCRIPTION OF THE SELECTION METHODOLOGY

3.1 ELEMENTS OF THE MULTIATTRIBUTE UTILITY THEORY METHOD

Decision making is, even at its best, not an easy matter. One can seldom adopt a course of action resulting in maximum benefits in every possible respect. Multiattribute utility (MAU) theory attempts to resolve the problems of benefit trade-offs by utilizing the decision maker's own set of preferences and his own feelings toward different outcomes which may result from his decision.

Ideally, the MAU method should accurately reflect the decision maker's true feelings, helping him to better understand what he really wants. This proves most useful when the number of objectives confronting the decision maker is so large that the trade-off synthesis is too difficult to accomplish without computational aid.

Early in the process, objectives must be identified and clearly defined. An objective should specify an area of concern to the decision maker, indicating the direction of improvement that he is seeking. If a specific level of achievement is desired, then this would properly be called a goal instead of an objective. What is really wanted here is a direction of desired improvement rather than some specific goal.

Broad objectives should be divided into sub-objectives for which attributes may easily be defined. An attribute is a measurement that refers to what degree an objective is met. An attribute may be either scalar or vector valued. Any attribute which does not directly measure an objective is called a proxy attribute.

Keeney and Raiffa ²⁰⁶ suggest that a set of attributes should have the following desirable properties.

1. Completeness. All important aspects of the problem should be covered. If the decision maker knew the value of every attribute, he should be able to tell how well the overall objective is met.
2. Operational. The attributes should be such that they can be meaningfully used in the analysis. This implies that the attributes should be meaningful to the decision maker and should aid in explanations to others.
3. Decomposable. To make the problem tractable, it is usually necessary to break the utility assessments into smaller parts, each part containing only a few attributes. One needs to be able to group some attributes together in order to reduce dimensionality of the problem.
4. Nonredundancy. Attributes should be defined so that different attributes aren't measuring the same thing. One needs to be especially careful for two situations. One is when one attribute measures part of what another attribute measures. The other is when some attributes deal with input and some with output.
5. Minimum size. The set of attributes should be kept as small as possible since the complexity of the problem increases vastly as the number of attributes increases.

Great care must be taken in choosing the attributes which will be considered. All of the subsequent analysis depends on this vital step. A poorly chosen set can easily make the problem intractable or lead to problems of inconsistency.

Once the attributes have been carefully chosen, one needs to evaluate the multiattribute utility function. The proposed method is to break the set of attributes into smaller sets which may be more easily assessed. To successfully break up the set of attributes, one needs the concepts of

preferential independence and utility independence. This will be explained later in this report. Once the smaller sets are obtained, it is necessary to be able to assess a one-dimensional utility function. Hence, some definitions and results follow with the basic ideas of unidimensional utility theory.

A decision maker must select some action α from a set of actions A . He is interested in an attribute X which has possible values of $X_1, X_2, \dots, X_n$. He prefers X_n to X_{n-1} to X_{n-2} ...to X_1 . This is denoted by $X_1 < X_2 < X_3 < \dots < X_n$. (If he were indifferent between X_i and X_j this would be denoted as $X_i \sim X_j$.)

The action a' will result in consequence X_i with probability p_i' for $i=1, 2, \dots, n$ where $0 < p_i' < 1$, $\sum_{i=1}^n p_i' = 1$. Likewise action a'' results in consequence X_i with probability p_i'' . Now let the decision maker be presented with the following choice.

I. Receive X_i for sure

II. Receive X_n with probability π_i or receive X_1 with probability $1-\pi_i$

(Option II is written as $\langle X_n, \pi_i, X_1 \rangle$ and is called a lottery.)

If the decision maker is indifferent between I and II, then π_i is called his indifference probability for X_i . Because $X_1 < X_2 < \dots < X_n$, the rational decision maker will have $\pi_1 < \pi_2 < \pi_3 < \dots < \pi_n$ with $\pi_1 = 0$ and $\pi_n = 1$. Thus, the consequences have been numerically scaled by the π_i 's. Now the quantities $\bar{\pi}' = \sum_{i=1}^n p_i' \pi_i$ and $\bar{\pi}'' = \sum_{i=1}^n p_i'' \pi_i$ are used to rank acts a' and a'' . Since for act a' , X_i occurs with probability p_i' and X_i is indifferent to $\langle X_n, \pi_i, X_1 \rangle$, a' is, to the decision maker, equivalent to $\langle X_n, \bar{\pi}', X_1 \rangle$. So act a' is preferred to act a'' if $\bar{\pi}' > \bar{\pi}''$.

and is indifferent to a'' if $\bar{\pi}' = \bar{\pi}''$.

It should be noted that a positive linear transformation of the π_i 's doesn't change the ordering of the acts a' and a'' since

$$\begin{aligned} U_i &= a + b\pi_i, \quad b > 0 \\ \rightarrow U_1 &< U_2 < \dots < U_n \\ \text{and } \bar{U}' &= a + b\bar{\pi}' \end{aligned}$$

However, a nonlinear monotone transformation of the π_i 's, while still preserving the preferences over the X_i 's by $U_1 < U_2 < \dots < U_n$, may no longer correctly order a' and a'' .

In the above, a utility function was actually used, e.g. $U_X(X_i) = \pi_i$, so $U(a') = \bar{\pi}'$. One of the general characteristics of a utility function is monotonicity. That is, $X_2 < X_1 \leftrightarrow U(X_2) < U(X_1)$. This may not be a monotone function of X , however. If preferences are monotone in X , then U will be a monotone function of X .

Define $\bar{X} = E(X) = \sum_{i=1}^n p_i X_i$ to be the expected value of a lottery over $X_1, X_2, \dots, X_n$ with probabilities $p_1, p_2, \dots, p_n$. The expected utility of the lottery is

$$E[U(X)] = \sum_{i=1}^n p_i U(X_i)$$

This value is used to rank order lotteries.

A certainty equivalent of a lottery L is the value $\hat{X}$ such that the decision maker is indifferent between the lottery and the amount $\hat{X}$ for certain. Therefore

$$\begin{aligned} U(\hat{X}) &= E[U(X)] \quad \text{and} \\ \hat{X} &= U^{-1}E[U(X)]. \end{aligned}$$

The certainty equivalent is very useful for restricting the form that the utility function can take. A decision maker is said to be risk averse if

$$U[E(X)] > E[U(X)]$$

or equivalently if

$$U(\bar{X}) > U(\hat{X}).$$

That is, he prefers the expected outcome of any lottery to the lottery itself. It indicates the decision maker's desire to avoid risk. This implies a concave utility function. This narrows the choice of utility functions under consideration and may indicate a starting point in the search for a utility function.

Alternately, if $U(\hat{X}) > U(\bar{X})$ the decision maker is said to be risk prone and the utility function is then convex.

Two utility functions U_1 and U_2 are said to be strategically equivalent, $U_1 \sim U_2$, if and only if they imply the same preference rankings for any two lotteries. If $U_1 \sim U_2$, then there exists constants $a, b \neq 0$ such that

$$U_1(X) = a + bU_2(X) \text{ for all } X.$$

Because of this property, changes in location or scale present no particular problem. Therefore the utility function is usually scaled so that

$$U(X^*) = 1 \text{ and } U(X^0) = 0$$

where X^* , X^0 are the most and least preferred consequences respectively.

This property also allows for the synthesis of a utility function for several people if they have basically similar preferences.

A measure used to check for the strategic equivalence of two utility functions is the risk aversion function

$$r(X) = - \frac{U''(X)}{U'(X)} = \frac{d}{dX} [\log_e U'(X)]$$

Two utility functions are strategically equivalent if and only if they have the same risk aversion function.

The risk aversion function also provides information concerning the decision maker's attitude toward risk, both overall and at specific levels of the attribute. If $r > 0$ (< 0) for all X , then the utility function is concave (convex) and the decision maker is risk averse (prone).

A particularly useful utility function displaying risk aversion is

$$U(X) = -e^{-cX}, \quad c > 0.$$

This utility function has the property that if $\hat{X}$ is the certainty equivalent of a lottery L over X , then $\hat{X} + X_0$ is the certainty equivalent of the same lottery over $X + X_0$.

To assess a utility function, one must do several things. The range of values an attribute X may attain is needed. It must be determined if U is monotone in X . Is the decision maker risk averse?

A "splitting" technique may be useful. Now X_1 is taken as the best consequence and X_0 is taken as the worst consequence. Set

$$U(X_1) = 1 \text{ and } U(X_0) = 0.$$

Define $\langle X_i, X_j \rangle = \langle X_1, .5, X_j \rangle$. The decision maker is asked for a value of X such that he is indifferent between this value and $\langle X_1, X_0 \rangle$. This value is called $X_{.5}$ and

$$U(X_{.5}) = \frac{1}{2}U(X_1) + \frac{1}{2}U(X_0) = .5.$$

Likewise obtain $X_{.25}$ and $X_{.75}$ such that

$$X_{.25} \sim \langle X_{.5}, X_0 \rangle \quad U(X_{.25}) = .25$$

and
$$X_{.75} \sim \langle X_1, X_{.5} \rangle \quad U(X_{.75}) = .75$$

One now has the points $(X_0, 0)$, $(X_{.25}, .25)$, $(X_{.5}, .5)$, $(X_{.75}, .75)$, and $(X_1, 1)$ which may be plotted and checked against the assumptions. As a consistency check, questions may be asked such as: is the decision maker indifferent between $X_{.5}$ and $\langle X_{.75}, X_{.25} \rangle$?

Assuming that the consistency checks are okay, one might next find a parametric family of utility functions which satisfies the assumptions. Using the certainty equivalents (points), one tries to find a member of the family which "fits". If U is not monotone in X , it will probably be necessary to find two utility functions U_1 and U_2 so that U

$$U(X) = \begin{cases} U_1(X) & \text{for } X \leq X_m \\ U_2(X) & \text{for } X \geq X_m \end{cases}$$

where U is increasing to X_m and decreasing after X_m .

Finally, a sensitivity analysis is often in order at this point. The fitted parameters are perturbed so that one can observe what effect this has on the expected utility. This indicates the sensitivity of the decision to parameters of the utility function. It is essential that the utility function accurately reflect the true preferences of the decision maker since this is one of the features that strongly recommends the method.

In the multiattribute setting it is desirable to try to express the utility function as a function of the individual conditional utility functions (i.e. say $U(X_1, X_2, \dots, X_n) = f[f_1(X_1), f_2(X_2), \dots, f_n(X_n)]$ where f_i is a function of attribute X_i only and where f is preferably in an additive or multiplicative form.) To accomplish this end, it is necessary to break the set of attributes into smaller sets of one, two, or three attributes, which may be more easily handled. The concept of utility independence is needed.

The attribute X is said to be utility independent of the attribute Y if the conditional preferences for lotteries on X given y do not depend on the particular level of y. This implies the functional form

$$U(x,y) = g(y) + h(y) U(x,y'), h(\cdot) > 0.$$

Notice that y is not necessarily utility independent of X. There is a single utility function structure over X when X is utility independent of Y.

Finding this simplifies the assessment of $U(x,y)$.

One simple form is the additive form

$$U(x,y) = K_X U_X(x) + K_Y U_Y(y)$$

where

1. $U_X(x)$ is a conditional utility function on X with $U_X(x^0) = 0$ and $U_X(x^1) = 1$
2. $U_Y(y)$ is a conditional utility function on Y with $U_Y(y^0) = 0$ and $U_Y(y^1) = 1$.
3. $K_X = U(x^1, y^0)$
4. $K_Y = U(x^0, y^1)$
5. $U(x^0, y^0) = 0, U(x^1, y^1) = 1$

An additive utility function is not implied by mutual utility independence, but an additive form does imply mutual utility independence. Mutual utility independence does imply a multilinear representation, however, such as

$$U(x,y) = K_X U_X(x) + K_Y U_Y(y) + K_{XY} U_X(x) U_Y(y)$$

with

$$K_X > 0, K_Y > 0$$

or

$$U(x,y) = U(x, y_0) + U(x_0, y) + KU(x, y_0)U(x_0, y)$$

where

1. $U(x,y)$ is scaled so $U(x_0, y_0) = 0$ and $U(x_1, y_1) = 1$ for

arbitrary x_1 and y_1 such that $(x_1, y_0) > (x_0, y_0)$ and $(x_0, y_1) > (x_0, y_0)$.

2. $U_X(x)$ is a conditional utility function on X with $U_X(x_0) = 0$ and $U_X(x_1) = 1$
3. $U_Y(y)$ is a conditional utility function on Y with $U_Y(y_0) = 0$ and $U_Y(y_1) = 1$.
4. $K_X = U(x_1, y_0)$
5. $K_Y = U(x_0, y_1)$
6. $K_{XY} = 1 - K_Y - K_X$ and $K = K_{XY}/K_X K_Y$

Notice that this may be rewritten in a multiplicative form if

$K \neq 0$ as

$$\begin{aligned} U'(x, y) &= 1 + KU(x, y) = 1 + KU(x, y_0) + KU(x_0, y) + K^2 U(x, y_0) U(x_0, y) \\ &= (1 + KU(x, y_0))(1 + KU(x_0, y)) \\ &\triangleq U'(x, y_0) U'(x_0, y) \end{aligned}$$

where U' denotes $1 + KU$.

If $K = 0$, the additive form

$$U(x, y) = U(x, y_0) + U(x_0, y)$$

is appropriate. Sufficient conditions for $K = 0$ are

1. X and Y are mutually utility independent
2. $\langle (x_3, y_3), (x_4, y_4) \rangle \sim \langle (x_3, y_4), (x_4, y_3) \rangle$ for some x_3, x_4, y_3, y_4 such that (x_3, y_3) is not indifferent to (x_3, y_4) or (x_4, y_3) .

If conditional utility functions are difficult to obtain, sometimes isopreference curves may be substituted. This is particularly useful when only one attribute is utility independent. An isopreference curve is a set of consequences which are all equally desirable.

If neither of two attributes is utility independent, the assessment procedure is much more difficult. The attributes might be transformed so that utility independence is appropriate. Or direct

assessment may be possible by finding several points $[(x, y), U(x, y)]$ and using interpolation, extrapolation, and curve-fitting. One might look at smaller ranges of the attributes over which independence is approximately valid. More assumptions may be needed.

A weaker assumption that may be appropriate is that of preferential independence. (x', y') is conditionally preferred to (x'', y'') given z' if and only if $(x', y', z') > (x'', y'', z')$.

The attributes X and Y are said to be preferentially independent of Z if the conditional preferences in the (x, y) space given z' do not depend on z' . That is, if $(x_1, y_1, z') \succeq (x_2, y_2, z')$ for some z' then $(x_1, y_1, z) \succeq (x_2, y_2, z)$ for all z . If each pair of attributes is preferentially independent of its complement (that is, all other attributes considered as one vector attribute), the attributes are said to be pairwise preferentially independent.

More generally, the set of attributes X is preferentially independent of the complementary set Y if and only if the conditional preference structure in the X space given y' does not depend on y' .

If every subset Y of the attributes $X_1, X_2, \dots, X_n$ is preferentially independent of its complementary set, then the attributes $X_1, X_2, \dots, X_n$ are said to be mutually preferentially independent. Pairwise preferential independence implies mutual preferential independence.

These ideas are used mostly for value functions, but they prove useful for assessing MAU functions. A value function is similar to a utility function in that it indicates the decision maker's preferences. Thus, if V is a value function

$$x' \sim x'' \leftrightarrow V(x') = V(x'')$$

and

$$x' > x'' \leftrightarrow V(x') > V(x'')$$

Value functions are used for cases of certainty, however, and only aid, instead of replace, utility functions under uncertainty.

The additive value function proves useful quite often. For the two attribute, X and Y , case, the value function (which implies a preference structure) is additive, $V(x,y) = V_x(x) + V_y(y)$, if and only if the corresponding tradeoffs condition is satisfied.

The corresponding tradeoffs condition is this: If

1. $(x_1, y_1) \sim (x_1 - a, y_1 + b)$
2. $(x_1, y_2) \sim (x_1 - a, y_2 + c)$
3. $(x_2, y_1) \sim (x_2 - d, y_1 + b)$
4. $(x_2, y_2) \sim (x_2 - z, y_2 + c)$

then the corresponding tradeoffs condition is said to be satisfied if

$z = d$ for all x_1, x_2, y_1 , and y_2 .

Theorem: Given attributes $X_1, X_2, \dots, X_n$, $n \geq 3$, an additive value function $V(X_1, X_2, \dots, X_n) = \sum_{i=1}^n V_i(X_i)$, V_i is a value function for x_i , exists if and only if the attributes are mutually preferentially independent.

This proves useful to the following theorem. If there is an additive value function V for attributes $X_1, X_2, \dots, X_n$ for $n \geq 3$ and at least one of the X_i 's is utility independent (of its complement) then the utility function U must have one of the following forms.

1. $U(X) \sim e^{-cV(X)}$, $c > 0$

2. $U(X) \sim V(X)$

3. $U(X) \sim e^{cV(X)}$, $c > 0$

This can greatly simplify the assessment of a MAU function or even be useful as a check against some other assessment procedure. If the utility function is additive, one must have 2. If the utility function is multiplicative, one has either 1. or 3. If V is known, one uses the certainty equivalent $\hat{x}$ for the lottery $\langle x_1^*, x_1^0 \rangle$ where x_1 is (one of) the utility independent attribute(s), x_1^* is the best consequence for X_1 , and x_1^0 the worst.

Then

$$V_1(\hat{X}_1) = \frac{1}{2}V_1(X_1^*) + \frac{1}{2}V_1(X_1^0) \rightarrow 2.$$

$$V_1(\hat{X}_1) < \frac{1}{2}V_1(X_1^*) + \frac{1}{2}V_1(X_1^0) \rightarrow 1.$$

$$V_1(\hat{X}_1) > \frac{1}{2}V_1(X_1^*) + \frac{1}{2}V_1(X_1^0) + 3.$$

The constant C is evaluated by setting $U(\hat{X}_1) = \frac{1}{2}[U(X_1^*) + U(X_1^0)]$.

Preferential independence plays a key role in another theorem. The attributes $X_1, X_2, \dots, X_n$ $n \geq 3$ are mutually utility independent if and only if X_1 is utility independent and $\{X_1, X_i\}$ is preferentially independent for $i = 2, 3, \dots, n$; $n \geq 3$. This greatly reduces the number of assumptions which must be checked for mutual utility independence.

If $X_1, X_2, \dots, X_n$ are mutually utility independence then

$$U(X) = \sum_{i=1}^n K_i U_i(x_i) + K \sum_{\substack{j=1 \\ j>i}}^n K_i K_j U_i(x_i) U_j(x_j) \\ + K^2 \sum_{\substack{j=1 \\ j>i}}^n K_i K_j K_l U_i(x_i) U_j(x_j) U_l(x_l) \\ + \dots + K^{n-1} K_1 K_2 \dots K_n U_1(x_1) U_2(x_2) \dots U_n(x_n)$$

where

1. $U(x_1^0, x_2^0, \dots, x_n^0) = 0$ and $U(x_1^*, x_2^*, \dots, x_n^*) = 1$
2. $U_i(x_i)$ is a conditional utility function on X_i with $U_i(x_i^0) = 0$ and $U_i(x_i^*) = 1$ for $i = 1, 2, \dots, n$.
3. $K_i = U(x_i^*, \bar{x}_i^0)$, where $\bar{x}_i^0$ indicates $(x_1^0, x_2^0, \dots, x_{i-1}^0, x_{i+1}^0, \dots, x_n^0)$
4. K , a scaling constant, is a solution to

$$1 + K = \prod_{i=1}^n (1 + K_i).$$

Note that when $K = 0$, the utility function is additive with

$$U(X) = \sum_{i=1}^n K_i U_i(x_i) \text{ and } \sum_{i=1}^n K_i = 1.$$

When $K \neq 0$, the compact form

$$KU(X) + 1 = \prod_{i=1}^n [KV(X_i) + 1]$$

where $V(x_i)$ is defined to equal $K_i U_i(x_i)$

may be used.

In general, the scaling constants $K_1, K_2, \dots, K_Y$ are obtained by generating a set of γ (gamma) independent equations with the K_j 's as the unknowns. Several iterations may be needed in order to achieve a set of K_j 's which are consistent with the decision maker's preferences and which satisfy the assumptions. Some of this is to be expected since the decision maker is not expected to have hard and fast judgements on every issue and feel confident on the exact amounts involved in tradeoffs.

The method, then, begins with the identification and selection of appropriate attributes. These are subdivided and grouped together into more manageable units so that conditional utility functions may be assessed.

The scaling constants are determined and the resulting implications are carefully checked with the decision maker, reiterating as necessary until a utility function is obtained which accurately reflects his preferences. The utility function is then used to rank order the various alternatives available to the decision maker. The alternative giving the highest value of this function is then viewed as yielding the highest utility for the decision maker.

A problem is that many of the assumptions may not be valid or are only approximately valid. More serious is the problem in probing the decision maker's mind. It is essential that his preference structure and tradeoffs levels between attributes be discovered. There are also indications that any aggregation of preferences of a group will possess some non-optimal properties. The Delphi questionnaire process, however, seems to be a reasonable one that should yield satisfactory results.

Probably the outstanding argument for the MAU method is that it is based on making choices according to the decision maker's own preferences and value tradeoffs. This, together with its operating under conditions of uncertainty, makes it a powerful tool for the decision maker. Its proven ability in successfully solving complex problems make it a strong contender for any decision problem which contains uncertainty with several attributes which may not be conveniently converted to a common scale of measurement otherwise.

Overall, the MAU method appears to be a most reasonable procedure that does not avoid the complex portions of a problem by ignoring them. It recognizes that there are difficult tradeoffs involved and meets them head on in a rational fashion, discovering and exploiting true preference structures.

3.2 DEFINITION OF PROGRAM/PROPOSAL EVALUATION MEASURES, ATTRIBUTES AND SUBATTRIBUTES

3.2.1 Program Selection

The paradigm shown in Figure 3.2-1 illustrates the steps to be followed in the definition of the factors to be used in the program/proposal evaluation process. The general objectives of the LWR safety technology program may be identified as those listed in Table 3.2-1. A measure of effectiveness can be used as a metric of the level of achievement of each objective as in Table 3.2-1. The measure categories carry different importance and hence a tradeoff process may be used to rank order them. The process involves fixing each measure at its worst level and selecting which one would be raised to its best level on the expense of not raising the level of the other measures. The selected measure is then eliminated and the process is repeated until a rank is assigned to all measures. The measure categories are listed in Table 3.2-2 according to their ranks. Here, the number selected for each measure is the same as the rank; however, this is done for simplification of presentation only and need not be the case.

There are several elements which independently attribute to each measure and which provide a measure of achievement of each of the subobjectives constituting one of the general objectives. Those attributes are given in Table 3.2-3 and are listed according to their rank as obtained by the trade-off process described above.

In order to assist the decision-maker in providing quantitative values of the measures of achieving the program objectives, the attributes are divided further to independent subattributes. Table 3.2-4 lists such attributes in descending order of importance. The subattributes have been selected to provide a comprehensive and realistic variable which can be used to measure the attributes.

Figure 3.2-1 MAU Paradigm

Table 3.2-1 General Objectives of the LWR Safety Technology Program and the Corresponding Measures of Effectiveness

OBJECTIVE	MEASURE
Reduce Present Level of Risk	Risk Reduction Potential
Reduce Safety Related Cost	Impact on Power Costs
Increase Public Acceptance	Institutional Issues
Improve LWR Licensability	Programatic Measures

Table 3.2-2 Measure Categories

Rank Order	Symbol (z_i)	Measure Category
1	z_1	Risk Reduction Potential
2	z_2	Power Costs
3	z_3	Institutional Issues
4	z_4	Programatic Measures

Table 3.2-3 Attributes (Ranked in Descending Order of Importance)

1. Risk Reduction Potential z_1	2. Power Costs z_2	3. Institutional Issues z_3	4. Programatic Measures z_4
y_{11} , accident initiators y_{12} , public consequence y_{13} , occupational hazards y_{14} , system response y_{15} , human response	y_{21} , capital costs y_{22} , O&M costs	y_{31} , group perception y_{32} , industrial acceptance y_{33} , licensability	y_{41} , R&D cost y_{42} , schedule y_{43} , resources y_{44} , likelihood of program success y_{45} , urgency

Table 3.2-4 Program Selection Measures

RISK REDUCTION POTENTIAL OF PROGRAM

- Reduction in Accident Initiators Frequency
 - change in personnel error rates
 - change in mechanical failure rates
 - change in resistance to sabotage
- Reduction in Public Consequences of Operation
 - change in population dose from accidents
 - change in routine population dose rates
 - change in non-radiological injury rate
 - change in public psychological risk
- Reduction in Occupation Hazard
 - change in occupational radiation dose rate
 - change in occupational non-radiological injury

Table 3.2-4 Program Selection Measures (cont)

- Improvement in System Response to Emergencies
 - change in safety system reliability/availability
 - change in potential for common-cause failures
 - change in core thermal/mechanical response
 - change in containment response
- Improvement in Human Response to Emergencies
 - change in operator response times
 - change in operator response accuracies

IMPACT ON POWER COSTS

- Capital Costs
 - outage time needed for retrofitting
 - incremental equipment cost of retrofitting or replacement
 - labor costs for retrofitting or replacement
 - change in cost of lead time for licensing
- Operation and Maintenance Costs
 - change in plant availability
 - increase in maintenance, inspection and testing costs
 - increase in costs of operators and maintenance and testing crew

INSTITUTIONAL ISSUES

- Group Perception of Safety
 - anticipated change in public perception of safety
 - change in uncertainty in safety quantification
 - anticipated change in special interest group attitudes
- Industry Acceptance
 - degree of change in system/components reliability
 - availability of finance
 - degree of external interference with company management
 - change in industry established practices
- Licensability
 - probability of standardized design features
 - change in QA effectiveness

Table 3.2-4 Program Selection Measures (cont)

PROGRAMATIC MEASURES

- Projected Continuation Costs
 - costs of fully executed R&D program
 - first phase program costs
 - major capital expenses
 - opportunity cost
 - Time Schedules/Constraints
 - anticipated lead time for industry implementation
 - time required to complete program
 - RFP lead time
 - Availability of Resources
 - manpower requirement for R&D program
 - special facilities/equipment needs
 - potential for continued availability of funds
 - impact on other programs
 - Likelihood of Program Success
 - generic applicability of program results
 - potential of achieving program objectives on time
 - potential of effort duplications in other agencies
 - Urgency of Research Topic
 - power generation lost due to safety problem
 - potential for future availability losses due to problem
 - NRC/ACRS unresolved safety issue
-

In Table 3.2-5 definitions of each measure/attribute/subattribute are given as well as a description of the appropriate units for each attribute. Selection of units will depend on available information and the ease of quantification of such information.

Table 3.2-5 Attribute Definitions

z₁. RISK REDUCTION POTENTIAL - The expected degree of reduction in the probability and/or amount of damage to health as a result of the R&D effort

y₁₁. Accident Initiator Frequency - Rates of failure for plant hardware or operations which can initiate accident sequences.

x₁₁₁. Human Error - Failures of plant operations personnel (operators, maintenance crew, etc.) to perform as needed to prevent accidents.

Ratio of human error rates - the expected error rate for plant personnel without the R&D effort (old value) divided by that expected with the completed and implemented R&D (new value)

Human error rate - the quantitative error rate for a specific operation or a class of operations expected as a result of the completed and implemented R&D effort

x₁₁₂. Mechanical Failure - Failures of plant equipment which is important to the prevention of accidents.

Ratio of failure rates - the expected failure rate for a component, system, or plant without the R&D effort (old value) divided by that expected with the completed and implemented R&D (new value)

Failure rate - the quantitative failure rate for a component, system, or plant expected as a result of the completed and implemented R&D

x₁₁₃. Resistance to Sabotage - The improved resistance of the nuclear plant to sabotage as an accident initiator.

Subjective judgment - the estimated degree of improved sabotage resistance produced by the completed and implemented R&D effort

y₁₂. Public Consequence - Consequences to the general public due to routine operations and accident events at nuclear power plants.

x121. Accidental Population Radiological Risk - the probabilistic radiological risk to the population living within 500 miles of a nuclear plant from potential accidents at the plant

Ratio of dose rates - the expected dose rate (on a individual or population basis) from accidents without the R&D effort divided by that expected with the completed and implemented R&D

Dose rate - the quantitative population dose expected on a probabilistic basis (accident dose and accident frequency) over all accidents following completion and implementation of the R&D program

Latent fatality rate - the predicted latent fatalities, based on probabilistic analyses of accident population dose, dose response, and accident frequency, over all accidents following completion and implementation of the R&D effort

x122. Routine Operations - Refers to effects of normal operations

Ratio of dose rates - the expected radiation dose rates (maximum or average individual or population basis) without the R&D effort (old) divided by that expected with the completed and implemented R&D (new)

Dose rate - the quantitative dose rate (individual at the site boundary or population within 50 miles) expected as a result of the completed and implemented R&D program

x123. Nonradiological Injury (evacuation) - the probabilistic estimate of injuries (not due to radiation) to the population living within about 50 miles of a nuclear plant from potential accidents at the plant. The major impact is assumed to be connected with evacuation problems.

Ratio of injury rates - the expected injury rate from evacuation actions resulting from accidents without the R&D effort divided by that expected with the completed and implemented R&D

Injury rate - the predicted injury rate, based on probabilistic analyses of accident frequency, evacuation probability, and injury likelihood, over all accidents following completion and implementation of the R&D effort

- x₁₂₄· Psychological Risk - The potential for observable negative psychological effects in the population living near a nuclear plant

Psychological impact - a subjective judgment of the extent of negative psychological behavior as a result of concern about nuclear accidents

- y₁₃· Occupational Hazards - Routine and accidental hazards to workers at nuclear power plants

- x₁₃₁· Occupational Radiation - Refers to routine and emergency radiation doses experienced by workers

Ratio of dose rates - the expected dose rate (individual or worker population basis) without the R&D effort (old value) divided by that expected with the completed and implemented R&D (new value).

Dose rate - the quantitative dose rate (individual or worker population basis) expected as a result of the completed and implemented R&D program.

- x₁₃₂· Occupational Nonradiological Injury - Refers to all injuries, from minor occurrences to fatality, not involving exposure to nuclear radiation, that cause some loss of job time.

Ratio of injury rates - the expected injury rate without the R&D effort (old value) divided by that expected with the completed and implemented R&D (new value)

Severity rate - the quantitative rate on a time lost per time worked basis expected as a result of the completed and implemented R&D program

Frequency rate - the quantitative rate on a number per time worked basis expected as a result of the completed and implemented R&D program

Economic loss - the dollar value of worker injuries (lost time + insurance fees) expected as a result of the completed and implemented R&D

y₁₄· Improved System Response to Emergencies - Systems and plant equipment that are involved with accident control and mitigation

x₁₄₁· Safety Systems Performance - The performance of systems that respond after accident initiation to mitigate accident effects in the plant.

Reliability - the expected reliability of operation of key safety features on demand as a result of the completed and implemented R&D effort

Unavailability - the expected failure of safety equipment to be available when demanded (i.e., any outage cause such as scheduled test or unscheduled repair) as a result of completion and implementation of the R&D

x₁₄₂· Common-Cause Failure - Multiple or sequential failures of equipment or systems as a result of a single (common) cause.

Change in potential failure rate - the expected common cause failure rate for plant systems or components without the R&D effort (old value) divided by that expected with the completed and implemented R&D (new value)

Failure rate - the quantitative failure rate expected as a result of completion and implementation of the R&D effort

x₁₄₃· Core Thermal/Mechanical Response - The physical response of the reactor core under accident conditions, i.e., the potential for radioactivity release.

Change in response - the expected core response without the R&D effort (old value) divided by that expected with the completed and implemented R&D (new value)

Clad failures during events - the estimated amount of cladding failures (ruptures) expected during an accident as a result of the completed and implemented R&D program

Probability of core melt - the estimated probability of accidental core meltdown expected as a result of the completed and implemented R&D

x₁₄₄ · Containment Response - The response of an important aspect of containment behavior, such as leak rate, under accident conditions; i.e., the potential for radioactivity escape

Change in response - the estimated response without the R&D effort (old value) divided by the estimated response with the completed and implemented R&D (new value)

Leakage rate - the quantitative estimate of containment leak rate as a result of the completed and implemented R&D effort

y₁₅ Improved Human Response to Emergencies - Key personnel at the plant who are initially and directly involved with accident diagnosis and control

x₁₅₁ · Operator Response Time - The time required by the operator(s) to diagnose and response to the emergency

Change in response time - the time required without the R&D effort (old value) divided by the time expected after completion and implementation of the R&D (new value)

Response time - the quantitative estimate of the response time as a result of the completed and implemented R&D effort

Actual response time/standard response time - the expected value of this ratio after the R&D effort is completed and implemented

x₁₅₂ · Operator Response Accuracy - The accuracy with which the operator(s) diagnose and respond to an emergency

Change in accuracy - the estimated successful action rate without the R&D effort (old value) divided by the expected rate with the completed and implemented R&D effort (new value)

Performance - the quantitative estimated successful action rate as a result of the completed and implemented R&D effort

z₂. POWER COSTS - The cost to an electric utility to implement the results of an R&D program.

y₂₁. Capital Cost - All capital costs associated with retrofitting existing plants or replacing features in future plants. Included are equipment costs, labor costs for installation, added licensing costs, and outage costs for retrofitting.

x₂₁₁ Outage Time for Retrofitting - The time an existing plant would be out of service in order to accomplish the retrofit task

Time - the estimated actual time of plant outage needed for the retrofit

Cost - the dollar value of the outage time in terms of interest payments, cost of maintaining an otherwise ready plant, and the cost penalty for purchased power

x₂₁₂ Safety Equipment for Retrofitting/Replacement - The cost of the hardware and materials for the retrofitted (existing plants) or replaced (future plants) safety features

Relative change - the estimated equipment and materials cost without the retrofit/replacement action divided by the expected equipment and materials cost with the retrofit/replacement action

Cost - the expected actual additional cost of the retrofit/replacement hardware and materials

x₂₁₃ Labor Costs for Retrofitting/Replacement - The cost of labor for plant changes and equipment installation for retrofitted (existing plants) or replaced (future plants) safety features

Relative change - the estimated labor costs without the retrofit/replacement action divided by the expected labor costs with the retrofit/replacement action

Cost - the expected actual additional cost of labor connected with installation of retrofit/replacement features

x₂₁₄. Lead Time for Licensing - The additional time needed for licensing of the retrofit/replacement safety features

Change in lead time - the estimated lead time without the retrofit/replacement features divided by that expected with the retrofit/replacement features

Lead time - the estimated actual additional time that would be needed for license approval because of the retrofit/replacement features

Cost of lead time - the estimated cost of the additional lead time in terms of interest payments, cost of maintaining a ready plant, and the cost penalty for purchased power

y₂₂. Operation and Maintenance Cost - The economic effect that the implementation of the results of an R&D program has on an utility.

x₂₂₁. Plant Availability - The portion of the time the nuclear plant is available for power production

Change - the estimated plant availability without the implemented results of the R&D divided by the estimated plant availability after implementation

Availability - the expected actual plant availability after the implementation of the R&D results

x₂₂₂. Maintenance, Inspection, and Testing Cost - The additional cost associated with the implementation of the results of the R&D program

Change - the estimated M, I, & T cost without the implemented results of the R&D divided by the estimated M, I, & T cost after implementation

Cost - the expected actual cost of M, I, & T associated with the implemented results of the R&D effort

- x₃₂₃ Degree of External Interference With Management - A measure of industrial acceptance is the degree of external interference in the affairs of the management of the industry which would result as a consequence of planning to implement a certain R&D program. Examples of programs which may cause a high degree of interference is increasing the demand on plant inspections; imposing rules and regulations on utility decision makers and administration. This can be measured in subjective units as represented by attitude of industrial managers.
- x₃₂₄ Change in Established Practices in Operation or Management - The program may result in requiring changes in operation procedures or personnel and/or management organization. Such changes may or may not be acceptable to the industry. The level of acceptability is subjective and can be evaluated by Delphi or interviewing a representative sample of industrial personnel.
- y₃₃ Licensability - The impact of any LWR safety R&D program on the licensing process is of importance to the public, the industry; and the planners. A program that accelerates the licensing of new plants through procedural or design changes will be desirable. A program which would cause delay or changes in licensability would not be accepted.
- x₃₃₁ Standardization Potential - The probability that the program will enhance the potential of standardization of plants.
- x₃₃₂ QA Effectiveness - A subjective measure of the role of the R&D program on increasing the effectiveness of the QA or in rendering it more complex and inadequate.
- z₄ Programmatic Measures - This category deals with the specific measures of effectiveness of the program.
- y₄₁ R&D Cost - The cost of an R&D program is an attribute which affects the decision on whether the program is worthwhile pursuing or not compared to other programs.
- x₄₁₁ Follow-up Cost - To evaluate a given program from the point of view of cost it is necessary not only to consider present cost, but also future costs of the follow-up effort required to achieve the program objective. This may amount to several million dollars.

- x₄₁₂ Program Cost - This is the actual cost of the program in thousands of dollars.
- x₄₁₃ Capital Outlay - The capital cost of test facilities, and capital equipment and future capital spending in implementing the program.
- x₄₁₄ Opportunity Cost - This is the cost of what could be done in lieu of the program to draw similar benefits. It represents the regret factor if the program did not achieve its objectives.
- y₄₂ Schedule - The program schedule is an attribute that measures the time value of a program. If the results of the R&D effort would not be produced when needed or will not be available in the proper time, the worth of the program is then questionable.
 - x₄₂₁ Implementation Time - This is the time required to commercially realize the outcome of an R&D program measured in years.
 - x₄₂₂ Time-to-Completion - This is the calendar time required to achieve the specific objectives of a program.
 - x₄₃₃ RFP Lead Time - Some programs may require a long time and probably a considerable research effort prior to issuing the RFP.
- y₄₃ Resources - The availability of resources is a major factor in assessing the viability of a program.
 - x₄₃₁ Manpower Availability - The adequacy of resources is measured by the availability of readily trained and qualified manpower to carry out the program.
 - x₄₃₂ Facilities/Equipment Needs - Among the resources is the availability of facilities/equipment needed. The cost of nonexistent facilities/equipment or the cost of use of existing facilities. This can be alternatively measured as:
 - The Percentage of Existing/Required Facilities/Equipment - This gives a measure of the degree of preparation needed to affectively start the program.
 - Cost - This is the cost in millions of dollars of facilities/equipment needed.

- x₄₃₃ Continuity to Achieve Objectives - A subjective sub-attribute to measure the probability of continuity of the program to achieve objectives.
- x₄₃₄ Impact on Other Programs - A selected program would draw on the resources of the overall LWR Safety Technology Program including budget allocations, manpower, and facilities. Since such resources are limited, a major undertaking in a single R&D area would drain the efforts in other areas and thus result in a negative effect or it may assist other programs and hence result in a positive effect.
- y₄₄ Likelihood of Success - Some programs have an undefined or objectives which may not be achieved successfully in time or may be a duplication of already existing efforts. This attribute would provide an apriori measure of the expected success of the program.
- x₄₄₁ Generic Applicability - The results of the program under consideration may apply to all or a fraction of the plants. It is desirable to have results which are generic to available plants.
- x₄₄₂ Timely Achievement of Objectives - It is a crucial measure for a program to a priori know the probability of achieving the objectives in time to assure the success of the whole plan and availability of the results when needed.
- x₄₄₃ Effort Duplication - The probability of effort duplication in other agencies in case of uncertainty and in case of high cost of getting such information.
- y₅ Urgency - The need for a program may be judged according to the urgency to acquire the program results.
- x₄₅₁ Power Lost Due to Safety Problems - A measure of the urgency of carrying out the program is the estimation of the penalty in terms of power generation loss which may result if the program is not carried out. Examples are R&D component design to replace failing components which increase plant outage.

Percent - Amount of kWh lost due to safety problems relative to expected power generation at a given period of time.

Cost - Cost of power loss due to safety problems in millions of dollars.

x₄₅₂ Future Unavailability of Power - This attribute indicates the urgency of an R&D program in terms of whether it does not or does influence projection of the lack of electric power in future years.

x₄₅₃ NRC/ACRS Unresolved Safety Issues - The program will or will not result in resolving regulatory issues.

3.2.2 Proposal Evaluation

Evaluation of proposals is a complex process that involves a myriad of issues which need to be considered in order to assure successful implementation of programs. The factors which must be considered in the evaluation processes depend on the type of the proposal and the program for which the proposal is submitted. Proposals may be classified in three categories:

- Unsolicited
- Sole source
- Competitive

Unsolicited proposals are evaluated according to common criteria which may be listed in order of their importance in the decision process:

- Availability of funds
- Compatibility of the proposal scope with general program objectives
- Need for proposed services
- Ability of proposer to provide services
- Cost effectiveness of buying proposed services

In case of sole source proposals many of the factors which are needed for evaluation are usually predetermined, such as capability of proposer and need for services. Hence, other factors may be considered, such as

- Scheduling
- Specificity of scope of work and milestones
- Cost of service

In competitive bids, an RFP lists several criteria which are often stated in general terms. However, it may be difficult to extract the relevant information for each criterion from a proposal. Although, in some RFP's the criteria are rank ordered or are associated with specific weights the evaluator may find difficulty in simultaneously considering all the criteria in a consistent manner. In order to permit a quantitative evaluation and ensure that

the evaluator seeks information for each proposal on all the criteria, well-defined measures for each criterion must be explicitly developed.

It is unlikely that any proposal will be distinctively superior to all other proposals in all the criteria. Once inferior proposals are screened out, close similarities between proposals may be hard to distinguish. Therefore, the evaluator has to make tradeoffs between different levels of attaining the various criteria.

The evaluator has to use his/her judgment in estimating how well a proposal meets given criteria. This is due to uncertainty caused by inadequacy of information or unvarified proposer data. The cost and time to make a precise varification of information would be extensive.

Furthermore, the evaluation technique has to be specified in the RFP and the results of the screening process have to be justified. Thus, the use of quantifiable attributes and tradeoffs would facilitate the communications with the management and the proposers.

The attributes which can be used to measure the preference between proposals be categorized into three categories:

- Program specific
- General merits
- Proposal specific

The program specific attributes are identified by considering the objectives of the program and structuring those objectives. The attributes are then defined as measures of effectiveness of how well the subobjectives are met. The list of attributes should be comprehensive and non-redundant and the attributes could be evaluated using easily obtainable data. Some of the attributes may be represented by subjective scales if they cannot lend themselves to common units of measure. However, it is necessary to describe the conditions associated with each discrete numerical index of the subjective scale.

The general merits used to judge proposals are independent of the specific program objectives although they may be tailored to satisfying the goals of a general mission; such as schedule adherence and implementation potential.

Proposal specific attributes are related to items identified in the RFP which require special emphasis such as preliminary design or technical approach. However, the presence of proposal specific attributes does not affect the general nature of the approach proposed here. In Table 3.2-6 a list is given of the attributes and subattributes.

Table 3.2-6 Proposal Evaluation Measures

z_1	GENERAL ATTRIBUTES
y_{11}	<u>Cost Merit</u>
x_{111}	Cost of project (\$)
x_{112}	Direct/indirect cost (ratio)
x_{113}	Cost effectiveness (adequacy of cost breakdown) (cost/milestone)
x_{114}	Cost of implementation of proposed results. (M\$)
y_{12}	<u>Overall Merit</u>
x_{121}	Past experience (years)
x_{122}	East of communication between SANDIA & contractor (subjective)
x_{123}	Proposer company size (M\$)
x_{124}	Interest in other programs and/or follow up work (subjective)
x_{125}	Credibility of company (subjective)
x_{126}	Soundness in selection of subcontractors and/or consultants (subjective)
x_{127}	Awareness of RFP objectives (subjective)
x_{128}	Company stability (average dividend/share over a year)
y_{13}	<u>Socio-Political Merit</u>
x_{131}	Abiding to buy-American act (subjective)
x_{132}	Compliance with government rules and regulations (subjective)
x_{133}	Willingness of exchange of know-how (subjective)

y_{14} Logistics Merit

- x_{141} Priority of exceptions from RFP (subjective)
- x_{142} Guarantees of completion time (subjective)
- x_{143} Responsiveness to Sandia requests (subjective)

y_{15} Management Merit

- x_{151} Adequacy of scheduling (subjective)
- x_{152} Balance of workloads (subjective)
- x_{153} Ease of procedures (subjective)
- x_{154} Ease of communication among different management levels (subjective)
- x_{155} Details on manpower allocation (subjective)
- x_{156} Prioritization of execution phases (subjective)

y_{16} Technical Merit

- x_{161} Completeness/comprehensiveness (%)
- x_{162} Ease of execution plan (subjective)
- x_{163} Soundness of approach (subjective)
- x_{164} Clarity of technical specifications (subjective)
- x_{165} Estimated execution time (months)
- x_{166} Expected work quality (subjective)
- x_{167} Flexibility in utilization of results (subjective)
- x_{168} Viability of expected results
- x_{169} Qualification of labor (subjective)
- x_{170} Number of qualified labor allocated for the project. (ratio of qualified/total labor)

z_2 PROGRAM SPECIFIC

y_{21} Risk Reduction Potential

- x_{211} Elimination of accident initiators (subjective)
- x_{212} Reduction in public consequences (fatality (including latent fatalities) 1 year)
- x_{213} Reduction in occupational hazards (days lost/year)
- x_{214} Safety systems availability (probability)
- x_{215} Human response (probability)

y_{22} Implementation Costs

- x_{221} Capital costs (M\$)
- x_{222} O&M costs (\$/kW)

y_{23} Public/Industrial Perception

- x_{231} Group acceptability (subjective)
- x_{232} Industrial acceptability (subjective)
- x_{233} Licensability (subjective)

y_{24} Programatic Measures

- x_{241} Ratio of project cost to program funds (ratio)
- x_{242} Urgency (subjective)
- x_{243} Genericalness of anticipated results (subjective)

z_3

PROPOSAL SPECIFIC

y_{31}

Commercial Viability of Design (subjective)

y_{32}

Applicability of Methodology (subjective)

y_{33}

Degree of Interaction with Users and Concerned Parties (subjective)

3.3 UNITS AND RANGES OF VALUES FOR THE INDIVIDUAL ATTRIBUTES AND SUBATTRIBUTES

3.3.1 Ranges and Units

In Tables 3.3-1 through 4 the units and ranges for subattributes are listed for each measure category. Optional units are provided to facilitate information acquisition and to assure the use of precise data. The range for each subattribute is selected in a way to include the worst and best possible levels. The limits are intended to be realistic to facilitate the synthesis of the utility functions via the use of lotteries.

Table 3.3-1 RISK REDUCTION POTENTIAL (z_1)

Attribute		Subattribute		Units	R a n g e		
					Worst	Best	
y ₁₁	Accident Initiators Frequency	x ₁₁₁	Human error:				
			● ratio of human error rate	Ratio (old/new)	0.5	10	
			● human error rate	Error/plant-year	10	1	
			Error/year	1000	100		
		x ₁₁₂	Mechanical failure:				
			● ratio of failure rates	Ratio (old/new)	0.5	10	
● failure rate	Failure/plant-year		100	1			
	Failure/year	10,000	100				
x ₁₁₃	Resistance to sabotage						
	● Subjective	%	0	100			
y ₁₂	Public Consequence	x ₁₂₁	Accidental population radiological risk:				
			● ratio of dose rates	Ratio (old/new)	0.5	10	
			● dose rate	Man-rem/plant-year	1000	1	
		● latent fatalities	Fatality/plant-year	0.1	0.0001		
		x ₁₂₂	Routine population radiological risk:				
			● ratio of dose rates	Ratio (old/new)	0.5	3	
● dose rate	Man-rem/plant-year (50 miles)		100	0.01			
	Man-rem/man-year (Siteboundary)	5	0.01				

Table 3.3-1 RISK REDUCTION POTENTIAL (z_1) - cont.

Attribute		Subattribute		Units	Range	
					Worst	Best
		x_{123}	Non-radiological public injury (evacuation)			
			<ul style="list-style-type: none"> ratio of injury rate injury rate 	Ratio (old/new) Injuries/plant-year	1 0.01	10 0.0001
		x_{124}	Psychological public risk:			
			<ul style="list-style-type: none"> psychological impact (subjective) 	%	100	0
	y ₁₃	x_{131}	Occupational radiation:			
			<ul style="list-style-type: none"> ratio of dose rates dose rate 	Ratio (old/new) Man-rem/plant-year Man-rem/man-year	0.5 5000 5	10 10 0.1
		x_{132}	Occupational non-radiological injury:			
			<ul style="list-style-type: none"> ratio of injury rates severity rate frequency rate economic loss 	Ratio (old/new) Day/million-person-hour Injury/million-person-hour M\$/year	0.5 1000 100 0.5	10 50 10 0.005

Table 3.3-1 RISK REDUCTION POTENTIAL (z_i) - cont.

Attribute		Subattribute		Units	Range	
					Worst	Best
y ₁₄	Improvement to System Response to Emergencies	x ₁₄₁	Safety system performance ● reliability ● Unavailability	Probability : Failure/demand	0.99 10 ⁻²	0.9999 10 ⁻⁷
		x ₁₄₂	Common-cause failure: ● ratio of common-cause failure rates ● Unavailability	Ratio (old/new) Failure/demand	0.5 10 ⁻²	10 10 ⁻⁴
		x ₁₄₃	Core thermal/mechanical response: ● ratio of degradation rates ● clad failure/event ● probability of core melt	Ratio (old/new) % Probability	0.5 100 10 ⁻⁴	10 0 5x10 ⁻⁶
		x ₁₄₄	Containment response: ● ratio of leakage rates ● leakage rate	Ratio (old/new) Volume %/day per event	0.5 100	10 0.1

Table 3.3-1 RISK REDUCTION POTENTIAL (z_1) - cont.

Attribute		Subattribute		Units	Range	
					Worst	Best
y ₁₅	Improvement in Human Response to Emergencies	x ₁₅₁	Operator response time:			
			• ratio of response times	Ratio (old/new)	0.5	10
			• response time	Secs/demand	60	1
			• actual to standard response times	Ratio	2	0.2
		x ₁₅₂	Operator response accuracy:			
			• ratio of accuracies	Ratio (old/new)	0.5	2
			• performance	Success/action	0.33	1

TABLE 3.3-2 POWER COSTS (z_2)

Attribute		Subattribute		Units	Range	
					Worst	Best
y ₂₁	Capital Cost	x ₂₁₁	Outage for retrofitting:			
			• time	Months/plant	6	0
			• cost	\$/kW	100	0
		x ₂₁₂	Safety equipment for retrofitting replacement:			
			• relative increase	Ratio (old/new)	0.1	1
			• cost	\$/kW	75	1
		x ₂₁₃	Labor costs for retrofitting/replacement:			
			• relative increase	Ratio (old/new)	0.1	1
			• cost	\$/kW	75	1
		x ₂₁₄	Lead time for licensing:			
			• ratio of lead times	Ratio (old/new)	0.5	2
			• lead time	Months	24	0
			• cost	\$/kW	400	0
y ₂₂	Operation and Maintenance Costs	x ₂₂₁	Plant availability			
			• ratio of availabilities	Ratio (old/new)	1.3	0.7
			• availability	%	50	95

TABLE 3.3-2 POWER COSTS (z_2) - cont.

Attribute		Subattribute		Units	R a n g e	
					Worst	Best
		x ₂₂₂	Increase in maintenance/ inspection and testing cost: <ul style="list-style-type: none"> ● ratio of cost increases ● cost 	Ratio (old/new) M\$/plant-year	0.3 10	3 1
		x ₂₂₃	Operators or maintenance and testing crew costs: <ul style="list-style-type: none"> ● incremental increase 	M\$/plant-year	1	0.1

TABLE 3.3-3 INSTITUTIONAL ISSUES (z_3)

Attribute		Subattribute		Units	R a n g e	
					Worst	Best
y_{31}	Group perception	x_{311}	Change in public perception	Subjective	-1	1
		x_{312}	Reduction of uncertainty in safety quantification: • ratio of uncertainty values	Ratio (old/new)	1	5
		x_{314}	Change in special interest groups attitude	Subjective	-1	1
y_{32}	Industrial acceptance	x_{321}	Degree of change in system/components	Probability	1	0
		x_{322}	Availability of finance	Subjective	0	1
		x_{323}	Degree of external interference with management	Subjective	1	0
		x_{324}	Change in established practices in operation or management	Subjective	1	0
y_{33}	Licensability	x_{331}	Standardization potential	Probability	0	1
		x_{332}	QA effectiveness	Subjective	0	1

TABLE 3.3-4 PROGRAMATIC MEASURES (z_4)

Attribute		Subattribute		Units	R a n g e	
					Worst	Best
y ₄₁	R&D cost	x ₄₁₁	Follow-up cost	M \$	100	0.5
		x ₄₁₂	Program cost	k \$	2000	20
		x ₄₁₃	Capital outlay	M \$	100	0
		x ₄₁₄	Opportunity cost	%	100	0
y ₄₂	Schedule	x ₄₂₁	Implementation time	years	10	0.5
		x ₄₂₂	Time-to-completion	months	36	3
		x ₄₂₃	FFP lead time	months	6	0.5
y ₄₃	Resources	x ₄₃₁	Manpower availability			
			● Existing/required	%	0	100
			● Actual	person-years	1	100
		x ₄₃₂	Facilities/equipment needs			
			● Existing/required	%	0	100
			● Cost	M \$	100	0.1
		x ₄₃₃	Continuity to achieve objectives (subjective)	probability	0	1

TABLE 3.3-4 PROGRAMATIC MEASURES (z_4) - cont.

Attribute		Subattribute		Units	Range	
					Worst	Best
		x_{434}	Impact on other programs	subjective	-1	1
y_{44}	Likelihood of Program Success	x_{441}	Generic applicability of results (fraction of plants affected)	ratio	0	1
		x_{442}	Timely achievement of objectives	probability	0	1
		x_{443}	Effort duplication in other agencies	probability	1	0
y_{45}	Urgency	x_{451}	Power lost due to safety problems ● Percent ● Cost	%	100	0
				M \$	1000	0
		x_{452}	Future unavailability of power	probability	1	0
		x_{453}	NRC/ACRS unresolved safety issues	binary logic	1 (yes)	0 (no)

3.3.2 Summary of Rationale for Assigning Ranges to the Attribute Units

The various technical specialists on the project participated in selecting appropriate range limits for the many attribute units. Individual recommendations were generated on the basis of technical data or expert judgment. The responses were reviewed for consistency and extent of supporting data in order to select a representative set of range limits. The central ground rule applied throughout the process was that the two limits (the worst value and the best value) should reflect realistic experience and/or objectives rather than very infrequent maximum or minimum values that might occur for the various units. The following text provides a brief rationale for the worst and best values selected for each unit at this point of the R&D selection methodology development.

y₁₁ · Accident Initiator Frequency

x₁₁₁ · Human Error

Ratio of human error rates - the same rationale as used for the ratio of mechanical failure rates in x₁₁₂ applies here also.

Human error rate - the range (10 to 1 errors/plant-year) is the average result of several judgment values by members of the project technical team.

- the range (1000 to 100 errors/year) applies to the entire industry which is assumed to consist of 100 plants.

x₁₁₂ · Mechanical Failure

Ratio of failure rates - the worst value (0.5) reflects the opinion that any R&D program should not cause a worse effect on equipment failure rates and still have utility, while the best value (10) reflects the judgment that this much improvement is feasible.

Failure rate - the wide range (100 to 1 failures/plant-year) is because this unit applies to a component, a system, or an entire plant, depending on the nature of the R&D effort.

- the range (10,000 to 100 failures/year) applies to the entire industry, which is assumed to consist of 100 nuclear plants.

x₁₁₃ · Resistance to Sabotage

Subjective judgment - the range (100 to 0 percent) represents an arbitrary assignment of the degree improvement that could be expected from further R&D effort.

y₁₂ · Public Consequence

x₁₂₁ · Accidental Population Radiological Risk

Ratio of dose rates - the same rationale as used for the ratio of dose rates in attribute x₁₂₂ applies here

Dose rate - the range (1000 to 1 man-rem/plant-year) was estimated from reference 210 and from preliminary predictions of TMI-2 impact which indicate a risk expectation of 100-200 man-rem/plant-year. Considering uncertainties in risk assessment and in R&D program effectiveness, a judgment was made to increase the expectation by approximately an order of magnitude to produce the worst estimate and to decrease the expectation by about two orders of magnitude to produce a best estimate.

Latent fatality rate - the range (0.1 to 0.0001 latent fatality/plant-year) was derived from the dose rate range using the approximate conversion factor of one latent fatality per 10,000 man-rem.

x₁₂₂ · Routine Operations Radiological Impact

Ratio of dose rates - the worst value (0.5) reflects the opinion that any R&D program should not cause a worse effect on dose rates and still have utility while the best value (3) reflects the judgment that this much improvement is feasible.

Dose rate - the range (100 to 0.01 man-rem/plant-year) is consistent with general experience as published in reference 209

- the range (5 to 0.01/mrem/man-year) is also consistent with general experience as published in reference 209

x₁₂₃. Nonradiological Injury (Evacuation)

Ratio of injury rates - the worst value (1) reflects the opinion that rates probably could not be worse than under present circumstances, while the best value (10) indicates the opinion that significant improvements are feasible.

Injury rate - the range is crudely estimated by assuming that up to 2 million persons might require evacuation with a frequency of about 10^{-5} per plant-year at an average travel distance of 50 miles in vehicles containing an average of 4 persons per vehicle. Using statistical data on vehicle injury rates (reference (2)), multiplied by 10 for stressful conditions, an upper limit (worst) injury rate of 0.01 injuries/plant-year is estimated. Milder conditions or improved safety might lead to a lower limit (best) rate of 0.0001 injuries/plant-year.

x₁₂₄. Psychological Risk

Psychological impact - the range for this subjective unit was arbitrarily set at 100 units with 100 signifying the worst impact and 0 signifying the best impact.

y₁₃. Occupational Hazards

x₁₃₁. Occupational Radiation

Ratio of dose rates - the worst value (0.5) reflects the opinion that any R&D program should not cause a worse effect on dose rates and still have utility, while the best value (10) reflects the judgment that this much improvement is feasible.

Dose rate - the range (5000 to 10 man-rem/plant-year) is consistent with experience as published in reference (1)

- the range (5 to 0.1 mrem/man-year) is consistent with experience as published in reference.²⁰⁷

x₁₃₂· Occupational Nonradiological Injury

Ratio of injury rate - the same rationale as used for the ratio of dose rates in attribute x₁₃₁ applies here.

Severity rate - the range (1000 to 50 days lost/million person-hours) is consistent with general experience as published in reference.²⁰⁸

Frequency rate - the range (100 to 10 injuries/million person-hours) is consistent with general experience as published in reference.²⁰⁸

Economic loss - the lower (best = \$5000) value corresponds to 50 days/million person-hours x 0.4 million person-hours/plant-year x \$250/day. The upper (worst = \$0.5 M) value corresponds to the worst value for the severity and the same multiplies as above except an additional factor of 5 for possible medical costs.

y₁₄· Improved System Response to Emergencies

x₁₄₁· Safety System Performance

Reliability - the probability of proper performance of a safety feature is judged to range from about 0.99 (worst value) to 0.9999 (best value).

Unavailability - the lack of availability of a safety feature when called upon to operate is judged to cover a wide range with 10⁻² failure/demand being about the worst value and 10⁻⁷ failure/demand being about the best that could be expected.

x₁₄₂· Common-Cause Failure

Change in potential failure rates - the worst value (0.5) of the ratio reflects the opinion that an R&D program would have no utility at a lower value, and the best value (10) reflects a judgment of the degree of improvement that might be realized.

Failure rate - the worst value (10^{-2} failure/demand) reflects existing experience regarding common mode influences such as human failures, while the best value (10^{-4} /failure/demand) is a judgment concerning the realistic limit that could be achieved in eliminating "designed in" common mode dependencies.

^x₁₄₃. Core Thermal/Mechanical Response

Change in response - the same rationale as used for the change in potential failure rates in ^x₁₄₂ applies here also.

Clad failure/event - the percentage of fuel rod cladding failures could reach 100% (worst value) as the result of a natural catastrophe causing extensive plant damage, while no failures (best value) seems to be a realizable objective for accidents that originate within a nuclear plant.

Probability of core melt - the probability of core melt estimated in WASH-1400 was about 5×10^{-5} per reactor-year. The range here (10^{-4} to 5×10^{-6} /plant-year) reflects a judgment that an R&D effort should not increase the probability very much but such effort might be able to reduce the probability by an order of magnitude.

^x₁₄₄. Containment Response

Change in response - the same rationale as used for the change in potential failure rates in ^x₁₄₂ applies here also.

Leakage rate - the worst value (100 volume percent/day) reflects the opinion that any R&D program would be of no utility if it should lead to a leakage rate of this magnitude or greater, while the best value (0.1 volume percent/day) is indicative of present design leakage rates.

^y₁₅. Improved Human Response to Emergencies

^x₁₅₁. Operator Response Time

Change in response time - the worst value (0.5) reflects the opinion that an R&D program which would cause such a degradation in response time would have no utility, while the best value (10) indicates the degree of improvement that is considered feasible.

Response time - the rather wide range in actual response times (60 to 1 seconds/demand) is because some emergency situations do not require very rapid operator response, while other situations do require quick response.

Actual response time/standard response time - the range (2 to 0.2) reflects judgment regarding the potential negative effect of an R&D program on actual response time and the possible positive effect a program might have.

^x₁₅₂ · Operator Response Accuracy

Change in accuracy - the same rationale as used for assigning the range for the change in response time in ^x₁₅₁ applies here also, except the range is smaller because of the opinion that wide variations in response accuracy cannot be tolerated and in reality do not exist.

Performance - the best value (1 success/act) is obviously the ultimate, while the worst value (0.33 success/act) is judged to be an unacceptable level of performance.

^y₂₁ · Capital Costs

^x₂₁₁ · Outage Time for Retrofitting

Time - the range (6 to 0 months) represents a consensus estimate of the technical specialists on the project team.

Cost - the range (100 to 0 \$/Kw) corresponds to the time range, using the same cost estimate procedure as outlined for the cost of lead time in ^x₂₁₅.

^x₂₁₂ · Safety Equipment for Retrofitting/Replacement

Relative change - the worst value (0.1) represents a judgment that an R&D effort which results in multiplying retrofitting or replacement equipment costs by an order of magnitude or more would have essentially no utility, and the best value (1.0) reflects the judgment that retrofitting or replacement would, at best, not increase equipment costs.

Cost - the range (75 to 1 \$/Kw) reflects a consensus judgment of the realistic spread in such capital cost items. See reference (211)

- the range (75,000 to 1000 K\$/plant) is referenced to a 1000 MWe sized plant and the opinion that additional equipment for such a plant would cost at least 1 million dollars (best value), but should not exceed 75 million dollars (worst value) in order to have practical utility.

x₂₁₄ · Labor Cost for Retrofitting/Replacement

Relative change - the same rationale as used for the relative change in equipment costs in x₂₁₂ applies here also.

Cost - the range (75 to 1 \$/Kw) represents the judgment that labor costs are roughly equivalent to materials costs for installed equipment. See reference (211).

- the range (75,000 to 1000 K\$/plant) is also referenced to a 1000 MWe sized plant.

x₂₁₅ · Lead Time for Licensing

Change in lead time - the range of the ratio of lead time connected with the licensing of the particular safety features is judged to extend from about 0.5 (worst value) to 2.0 (best value); that is, a doubling of the lead time would have no utility, while a halving of the lead time would have a unit utility.

Lead time - an average technical judgment is that additional time for licensing could range from about zero up to about 24 months.

Cost of lead time - the cost of lead time is estimated at 200 million dollars per plant per year; this includes about 100 million dollars for 10% annual interest on the plant investment, plus another 100 million dollars for the net cost of purchased power and the cost of keeping a plant in ready condition during the time delay. The range in possible cost then extends from about 400 \$/Kw (worst value) to 0 \$/Kw (best value).

- the cost in terms of K\$/plant (for a 1000 MWe plant) ranges from 400,000 K\$/plant (worst value) to 0 K\$/plant (best value).

y₂₂ · Operating & Maintenance Costs

x₂₂₁ · Plant Availability

Change in availability - the range (1.3 to 0.7) reflects a technical judgment that plant availability could be influenced by about 30%, either worse or better, by R&D effort.

Availability - the consensus estimate of the technical specialists indicated a realistic range of from 50% (worst value) to 95% (best value).

x₂₂₂ · Maintenance, Inspection, and Testing Cost

Change in costs - it is estimated that a factor of about 3 increase or decrease in M, I, and T costs could occur if R&D should cause or eliminate major maintenance tasks.

Cost - the actual cost range (10 to 1 M\$/plant-year) corresponds to the above ratio and a rough estimate of 3 million dollars for current plant annual M, I, and T costs.

x₂₂₃ · Operator or Maintenance Crew Retaining Cost

Incremental increase - the cost of retaining is assumed to be a fraction of the basic training costs. As a recurring expense the range is estimated to extend from 1 M\$/plant-year (worst value) to about 0.1 M\$/plant-year (best value).

y₃₁ · Group Perceptions of Safety

x₃₁₁ · Change in Public Perceptions

Subjective evaluation - provision is made for both negative and positive attitudes.

x₃₁₂ · Uncertainty in Safety Quantification

Ratio of uncertainty values - present uncertainty is considered the worst and it is judged that any specific R&D effort could reduce uncertainties by a most a factor of 5.

x₃₁₄ · Change in Special Group Perceptions

Subjective evaluation - provision is made for both negative and positive attitudes

y₃₂ · Industrial Acceptance

x₃₂₁ · Degree of Change in Operations

Probability of change - values ranging from 1 (worst) to 0 (best) are possible.

x₃₂₂ · Availability of Finances

Subjective - a probabilistic basis is used which can range from zero chance (worst) to certainty (best).

x₃₂₃· External Interference with Management

Subjective - a probabilistic basis is used which can range from from certainty (worst) to no chance (best).

x₃₂₄· Change in Established Practice

Subjective - the same rationale as used for x₃₂₃.

y₃₃· Licensability

x₃₃₁· Standardization Potential

Probability - a probabilistic basis which can range from 0 (worst effect on ability to license) to 1 (best effect on ability to license).

x₃₃₂· QAE Effectiveness

Subjective - a probabilistic basis is used which can range from no impact on QA effectiveness (worst = 0) to very strong positive impact (best = 1).

y₄₁· R&D Cost

x₄₁₁· Follow-on Cost Requirement

Cost - the range is very wide (100 to 0.5 million dollars) since follow-on R&D efforts can vary in duration as well as complexity.

x₄₁₂· Initial Phase R&D Cost

Cost - the range (2 M\$ to 20 K\$) is only a judgment estimate.

x₄₁₃· Capital Outlay

Cost - the range (100 to 0 M\$) is very wide because some programs require no capital equipment while others require elaborate experimental or testing facilities.

x₄₁₄· Opportunity Cost

Subjective - the range is simply the limits for a relative effect which is measured in percentage units.

y₄₂ · Schedule

x₄₂₁ · Implementation Time

Time - the wide range reflects technical judgment regarding realistic limits.

x₄₂₂ · Time to Completion

Time - the range indicates the general opinion that projects of less than 3 months or greater than 3 years are unlikely.

x₄₂₃ · RFP Lead Time

Time - the range is based on an estimate of needs for a complex and costly project versus the needs for a very simple and clearly defined study.

y₄₃ · Resources

x₄₃₁ · Manpower Availability

Existing/Required - realistically the available manpower to perform a program can range from a worst case of none (0%) to complete staffing (100%).

x₄₃₂ · Facilities/Equipment Needs

Existing/Required - the same rationale as used for x₄₃₁ applies.

Cost - the wide range of cost values is due to the possibility of the need for elaborate experimental or test facilities for some R&D programs.

x₄₃₃ · Continuity to Achieve Objectives

Probability - the range is due to the normal limits of probability values.

x₄₃₄ · Impact on Other Programs

Subjective - the range allows for both negative and positive impacts.

y₄₄ · Likelihood of Program Success

x₄₄₁ · Generic Applicability of Results

Fraction of plants affected - fractional values must range from 0 to 1.

x₄₄₂ · Timely Achieving of Goals

Probability - normal limits of probability values set the range.

x₄₄₃ · Duplication of Effort

Probability - normal limits of probability values set the range.

y₄₅ · Urgency

x₄₅₁ · Power Losses Due to Safety Problems

Percentage - values ranging from zero to complete loss are considered possible.

Cost - complete loss of power production could produce financial losses of one billion dollars if the time period is long or many plants are involved.

x₄₅₂ · Future Unavailability of Power

Probability - normal limits of probability values set the range.

x₄₅₃ · NRC/ACRS Unresolved Issue

Choice - this simply requires either a yes or a no reply.

3.4 TOOLS AND PROCEDURES

3.4.1 MAUP

A computer package is developed for program selection or proposal evaluation. The package comprises several modules, subroutines and options which provide a flexibility in the selection methodology application. The Multiattribute Utility Package (MAUP) is a collection of interactive computer programs. The package consists of several programs to assist the user in performing a utility analysis. Following is a brief description of the major programs.

- UTILITY1 is a program to assist the user in constructing utility functions for subattributes. A simple five point assessment technique is used to obtain some certainty equivalents for simple lotteries. A least squares procedure is used to fit a utility function to these points. The results may be easily filed for use by other programs.
- REVIEW allows the user to examine the certainty equivalents, scalar utility functions, and scaling constants presently on file. The user may also examine the evaluation of any proposal on file, along with its expected utility (if previously computed).
- KVALUE is a program to assess the scaling constants needed to construct a multiattribute utility function. The program helps the user answer complex trade-off questions. The results may be filed for program/proposal evaluation.
- PROPIN is used to input facts concerning a proposal. The inputs may be either fixed or stochastic. If needed, the program will help the user specify a probability distribution.
- UPDATE allows measure categories, attributes, and subattributes to be added or deleted. Also provided is a means for changing the range of a subattribute and for changing the units of measurement.
- EVALU calculates the expected utility of specified programs/proposals. The user may specify Monte Carlo sampling (to find the variability of the estimates) or simple mean inputs for quick estimates.
- MAFDA is an optional module which utilizes verbal rating, ranking and weights for each attribute and subattribute as input. The program is based on fuzzy set theory wherein each rating is represented by a membership function. The output gives a final rating for each program/proposal. Also, it gives the fuzzy membership function and the degree of preferability of each program/proposal.

A flow diagram is shown in Figure 3.4-1 which displays the elements of the package. A flow chart of the MAFDA program is given in Figure 3.4-2.

3.4.2 Special Features and Program Development

MAUP was developed by the Ames, Iowa office of SAI using the facilities of the Iowa State University Computation Center (ISUCC). The programs were tested on an IBM 370 using an ITTEL AS/6 control processor. The ISUCC currently runs under HASP.

All of the modules are written in the standard ANSI FORTRAN IV and were compiled using an IBM G compiler. In order to run interactive programs at the ISUCC, it was necessary to operate through ORVYL, a package distributed by Stanford University. ORVYL simplifies many programming problems and has extensive file handling capabilities.

MAUP was designed for a user with a cathode ray tube (CRT) type terminal having a scrolling feature. Minor modifications would allow for its use on a CRT without scrolling. The program was developed using a Datamedia Elite 2500 and should work nicely on any comparable terminal.

Most of the modules may be run successfully on a non-CRT type terminal, but some of the graphic features would be lost unless the plotting routines were modified. For example, in UTILITY1 when a utility function is fit, it is plotted over a graph of the certainty equivalents. This is accomplished by using direct control of the cursor for X-Y addressing, and this would not work on most non-CRT type terminals.

Highly desirable is immediate graphical feedback since the user can get a better "feel for the numbers". This is one of the strong features of MAUP.

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Figure 3.4.1 MAUP Flow Chart

Figure 3.4-2 MAFDA Flow Chart

Also included are some of the latest and best computational algorithms. This ensures not only accuracy and efficiency, but also that the package will not be quickly outdated. One example of this is the function fitting routine. Employed here is the Fletcher-Reeves method of conjugate gradients, using Davidon cubic interpolation for the linear searches. By using this powerful method, the program may easily be modified to fit a wide variety of complicated functions.

The user of MAUP will find that it is designed to make for an easier job. No knowledge of computer programming is required and the user is prompted in clear language for all of the inputs which the computer requires.

All programs are designed for user ease and simplicity. Simple graphic displays are included wherever they may be helpful. Error recovery is accomplished with little difficulty. Most intermediate results are easily filed so that the user may employ the programs at his own convenience.

The keystone throughout the development of MAUP was usefulness and the product is a package which is useful for anyone doing a multiattribute utility analysis. While still maintaining power and sophistication, MAUP is well-suited for use, even for one not well acquainted with the terminology and theory of multiattribute utility.

3.4.3 Details of User-Oriented Computer Module

The subroutine CELOT is the basic component of the program UTILITY1 in which the subattribute utility functions are assessed. In the module, this routine is called four times, three times to obtain points on the user's utility function, and once to check the consistency of these points with the axioms of utility theory.

The purpose of CELOT is to obtain the user's certain equivalent for a particular fifty-fifty lottery. The input parameters RHI and RLO are the possible outcomes of the lottery (each with probability one-half), and the output parameter CE is the certain equivalent of the lottery. The input parameters XNAME, UNAME, and UNITS are character string giving, respectively, the subattribute units. The final input parameter, TOL, provides a criterion for terminating the assessment process. Its use will be illustrated later.

The subroutine begins by asking the user whether he/she wishes to (1) input the certain equivalent directly, (2) go through a series of questions in which the program helps the user find the certain equivalent. If the user chooses (1), he/she is then asked for the value of the certain equivalent (which is assigned to CE), and the subroutine returns. If the user chooses (2), an assessment process is begun in which the program narrows the possible interval of values in which the certain equivalent lies until the interval is less than or equal to the value of TOL in length. An intermediate value of the interval is then chosen for the certain equivalent, and the user is asked whether this value is satisfactory. If so, the subroutine assigns the value to CE and returns. If not, the user supplies his/her own value for CE, and the subroutine returns.

The process under option (2) consists of questions asking the user whether he/she prefers the lottery or some certain value between the two lottery outcomes. If the user prefers the lottery, then his/her certain equivalent for the lottery must lie between the certain value and the better outcome of the lottery. If the user prefers the certain value, his/her certain equivalent for the lottery must lie between the certain value and the worse outcome of the lottery. A new certain value is chosen that is in the new narrowed interval and the user is asked about his/her preference between this new value and the lottery. His/her response again defines the new narrowed interval in which the certain equivalent lies. The questions continue until the interval is sufficiently small (according to TOL) or until the user responds that he/she is indifferent between the lottery and the certain value supplied for comparison.

Throughout the routine, there are checks for invalid input which the user may supply accidentally. A message is printed pointing out the error and asking the user to try again. The attribute name, units description, and units are printed with every question to the user so that he/she is constantly reminded of the meaning of her responses. In addition, subroutine LINEPL is called to give the user a graphical aid in making choices between lotteries and certain outcomes. A flow-chart of subroutine CELOT is given in Figure 3.4-3, and a sample run through it are given in Appendix C.

3.4.4 Algorithm For Obtaining Scaling Constants of Multiplicative and Additive Utility Functions (Used in Program KVALUE)

Suppose we have n attributes: $x_1, \dots, x_n$.

CELOT
 Input: RHI, RLO
 Output: CE

Figure 3.4-3 CELOT Flowchart

and two results:

$$x' = (x_1', x_2', \bar{x}_3, \dots, \bar{x}_n)$$

$$x'' = (x_1'', x_2'', \bar{x}_3, \dots, \bar{x}_n)$$

such that $x' \sim x''$

then utilities of the two results must be equal $u(x') = u(x'')$.

Similarly, suppose we have two more results

$$x''' = (x_1''', x_2''', \bar{x}_3, \dots, \bar{x}_n)$$

$$x^{IV} = (x_1^{IV}, x_2^{IV}, \bar{x}_3, \dots, \bar{x}_n)$$

such that $x''' \sim x^{IV}$

then, since only x_1 and x_2 vary, this implies the system of equations

$$1) k k_1 k_2 u_1(x_1') u_2(x_2') + k_1 u_1(x_1') + k_2 u_2(x_2') =$$

$$k k_1 k_2 u_1(x_1'') u_2(x_2'') + k_1 u_1(x_1'') + k_2 u_2(x_2'')$$

$$2) k k_1 k_2 u_1(x_1''') u_2(x_2''') + k_1 u_1(x_1''') + k_2 u_2(x_2''') =$$

$$k k_1 k_2 u_1(x_1^{IV}) u_2(x_2^{IV}) + k_1 u_1(x_1^{IV}) + k_2 u_2(x_2^{IV})$$

$$\text{Now let } A = u_1(x_1') u_2(x_2') - u_1(x_1'') u_2(x_2'')$$

$$B = u_1(x_2''') u_2(x_2''') - u_1(x_1^{IV}) u_2(x_2^{IV})$$

$$C = u_1(x_1') - u_1(x_1'')$$

$$D = u_1(x_1''') - u_1(x_1^{IV})$$

$$E = u_2(x_2''') - u_2(x_2^{IV})$$

$$F = u_2(x_2''') - u_2(x_2^{IV})$$

Regrouping, the above system becomes

$$A k k_1 k_2 + C k_1 + E k_2 = 0$$

$$B k k_1 k_2 + D k_1 + F k_2 = 0$$

Solving this system, we get

$$\frac{k_2}{k_1} = \frac{BC-AD}{AF-BE} \quad k k_1 = \frac{CF-DE}{BC-AD}$$

Now, given results of the form

$$\begin{aligned} x' &= (x'_1, x'_j, \bar{x}_{1j}) \\ x'' &= (x''_1, x''_j, \bar{x}_{1j}) \end{aligned} \quad j = 3, \dots, n$$

such that $x' \sim x''$

We can set up equation of the form

$$P k k_1 k_j + Q k_1 + R_{kj} = 0$$

where $P = u_1(x'_1) u_j(x'_j) - u_1(x''_1) u_j(x''_j)$

$$Q = u_1(x'_1) - u_1(x''_1)$$

$$R = u_j(x'_j) - u_j(x''_j)$$

Since we previously calculated $k k_1$, we can solve for $\frac{k_j}{k_1} = Q/(R + P k k_1)$

Once we have obtained $k k_1$ and the ratios k_j/k_1 for all j , we can solve for the absolute values of the scaling k_j 's and k .

First, if $k k_1 = 0$, then $k = 0$. In this case, $k_j = \frac{k_j}{k_1} / \left(\sum_{j=1}^n \frac{k_j}{k_1} \right)$ since $\sum_{j=1}^n k_j = 1$.

If $k k_1 \neq 0$ and hence $k \neq 0$, then the utility function is of multiplicative form and

$$k = \frac{n}{\pi} (1 + k k_1 \frac{k_j}{k_1}) - 1.$$

Once k is calculated, it is trivial to solve for k_1 the k_j 's.

Program KVALUE, the computer module which calculates the scaling constants of the multiattribute utility functions used to evaluate proposals, employs this method. Results varying only in the values of two attributes that are required to make the above calculations are given by the user. Several traps occur in the module to catch inconsistent values that the user may supply. the following subroutines are called in this module:

1. TRADE 2 - Performs calculation of first part of above algorithm. Its inputs are, in the terminology above, the eight utility values

$u_1(x_1'), u_2(x_2'), u_1(x_1''), u_2(x_2''), \dots, u_2(x_2^{IV})$ stored in the array u . It returns the ratio k_2/k_1 and the product kk_1 , stored in RAT and $BKK1$, respectively. The output parameter $IERR$ is set if bad input is detected.

2. **TRADE1** - Once kk_1 and k_{j_0}/k_1 , for some j_0 , have been obtained by **TRADE2**, the remaining ratios k_j/k_1 can be calculated by successive calls of this subroutine. Besides kk_1 (stored in $BKK1$), the inputs required are four utility values $u_1(x_1')$, $u_j(x_j')$, $u_1(x_1'')$, $u_j(x_j'')$, stored in u . The output is the ratio k_j/k_1 stored in RAT . If bad input is detected, $IERR$ is set.
3. **LOADU** - Obtains the attribute values and the array of utilities to be processed by **TRADE1** or **TRADE2**. The attribute values of the indifference pairs $(x_1', x_2', \bar{x}_{12})$ and $(x_1'', x_2'', \bar{x}_{12})$ are obtained by presenting the user with x_1', x_2' , and x_1'' , and asking at what value for x_2'' would she be indifferent. The single-attribute utilities of x_1 at x_1' and x_1'' and x_2 at x_2' and x_2'' are loaded into the array for input to **TRADE1** or **TRADE2**. **LOADU** can be used to obtain up to five indifference pairs. This feature is useful for generating indifference curves between two attributes, so that the user can view the implications of the answers she gives to question about tradeoffs among attributes. Graphical display of indifference curves will be programmed in this module in the future.
4. **GETRK** - Handles the interface between **LOADU** and **TRADE1** and **TRADE2**, and takes corrective action if a value of $IERR$ is returned that indicates an error condition. Input parameter $ITASK = 1$ indicates that **TRADE 1** is to be called and $ITASK = 2$ indicates **TRADE 2** is to be called.
5. **GETAK** - Calculates absolute values of scaling constants from relative values. The array RAT , containing the ratios $k_j/k_1, j=1, \dots, n$, is input along with the product kk_1 in $BKK1$. Output parameters are the absolute k_j 's stored in RAT and k stored in BK .

In the main program in this module, GETAK is first called with ITASK = 1, and two indifference pairs are obtained by LOADU for input into TRADE 2. TRADE 2 uses this input to calculate k_2/k_1 and kk_1 . GETRK is then repeatedly called with ITASK = 1. In each call a single indifference pair is obtained by LOADU for input into TRADE 1, and k_j/k_1 is calculated, for $j = 3, \dots, n$. After all these ratios have been computed. GETAK is called to calculate the absolute values of the k_j 's and k . The user can file the constants or reassess them if he/she is dissatisfied with the results. In the context of the attribute structure for proposal evaluation, this process must be repeated for each attribute (y), each measure category (z), and the overall multivariate utility function. In order for this module to run successfully, the user must have previously calculated the scalar utility functions of all subattributes of the attribute for which the k_j 's and k are desired.

Flow charts for TRADE 1 and TRADE 2 are given in Figures 3.4-4 and 3.4-5.

Trade 1 (ifind = 1)
 inputs: u, BKK1
 outputs: RAT

Trade 1 (ifind = 2)
 inputs: u, RAT
 output: BKK1

Figure 3.4-4 TRADE 1 Flowchart

Trade 2
 inputs: U(2,2,2)
 outputs: RAT, BKK1

Figure 3.4-5 TRADE 2 Flowchart

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Trade 2 (cont'd)

3.5 FURTHER DISCUSSION OF METHODOLOGY

3.5.1 Consistency Smoothing of Utility Assignments

The following is an observation on scalar utility, presumably of relevance as well for the vector case. The starting point is the criticism, in Davidson, Suppes and Siegel (DSS 1957),²¹² of utility function deductions in Mosteller and Nogee²¹² (MN 1951).

Consider a finite monotonically favored set of alternative $R_0, R_1, \dots, R_m$. MN, it appears, limited the task of deducing utilities $u(R_j)$ (the abbreviation U_j is used below) to that (essentially) of eliciting $(m-1)$ probabilities p_j such that

$$R_j \approx < R_0, R_m, p_j >; \quad j: 1, 2, \dots, m-1,$$

i.e., such that

$$u(R_j) = (1 - p_j)u(R_0) + p_j u(R_m),$$

or, under the usual standardization $R_0 = 0, R_m = 1$,

$$(1) \quad u(R_j) = p_j.$$

The actual indifference sought was of the essentially equivalent form $R_\phi \approx < R_0, R_j, p_j >$

DSS criticize this approach on the grounds that the uniqueness of the assignment (1) was not checked. This criticism of MN is interpreted as apprehension about the consistency (the word as well as concern over the problem involved) in fact appears on page 82 of DSS, but leads to a rather different compromise.) of the assignments (1), vis-à-vis other assignments that might have been elicited on the basis of other possible declarations of indifference regarding other possible preferred choices.

A practical compromise may be suggested between MN's alleged neglect of, and DSS's presumed insistence on, consistency. This compromise involves eliciting declarations of indifference for an expanded set of proffered choices, together with the quantification of whatever inconsistencies arise from these declarations and the computation of a set of "compromise" utility assignments. These latter are the "consistency-smoothed" utility assignments of the title, and are in fact best estimates of the person's actual utilities if one postulates an appropriate statistical error structure for the process of declaring indifference.

The idea simply is not just to elicit the $(m-1)$ probabilities p_j (call them p_j^{om} in the present context) of (1), but rather all $\binom{m+1}{3}$ probabilities p_j^{ik} such that

$$R_j \approx \langle R_i, R_k, p_j^{ik} \rangle, \quad 0 \leq i < j < k \leq m,$$

i.e., such that, presumably,

$$(2) \quad U_j = (1 - p_j^{ik})U_i + p_j^{ik}U_k, \quad 0 < i < j < k \leq m.$$

Presumably the $\binom{m+1}{3}$ choices involved should be presented in an order minimizing the person's tendency to artificially force consistency at the expense of genuine introspection.

The p_j^{ik} once elicited, we can expect that they will not be consistent, in the sense that there typically will not exist $m-1$ numbers U_j , $0 \leq U_1 \leq \dots \leq U_{m-1} \leq 1$, satisfying all $\binom{m+1}{3}$ relations (2).

It is however possible to solve for a set of numbers $\hat{U}_j$ will necessarily inherit the ordering implicit in (2), say in the sense of least squares. We do not know whether such $\hat{U}_j$ will necessarily inherit the ordering implicit in (2), so that perhaps constrained least squares would be appropriate. At any rate the $\hat{U}_j$ should serve, depending on the extent of formalism introduced, as approximations or estimates of the person's actual utilities $\hat{U}_j$.

Lastly, a measure of lack of fit such as the residual mean square

$$\sum_{(i,j,k)} \left[\hat{U}_j - \{ (1 - p_j^{ik}) \hat{U}_i + p_j^{ik} \hat{U}_k \} \right]^2 / \binom{m+1}{3}$$

should provide a reasonable measure of internal ("within") consistency, hence credibility, and might thus serve to weigh individual persons' contributions to aggregated utility estimates.

Here is an example: Suppose $m = 3$. Then there are four relations (2):

$$U_1 = p_1^{03}; U_2 = p_2^{03}; U_1 = p_1^{02} U_2; U_2 = (1 - p_2^{13}) U_1 + p_2^{13},$$

with least-squares objective function

$$(U_1 - p_1^{03})^2 + \dots + (U_2 - (1 - p_2^{13}) U_1 - p_2^{13})^2.$$

Taking partials w.r.t. U_1 and U_2 , and setting these equal to zero, we find the normal equations

$$\begin{aligned} \hat{U}_1 [2 + (1 - p_2^{13})^2] - \hat{U}_2 [p_1^{02} + 1 - p_2^{13}] &= p_1^{03} - p_2^{13}(1 - p_2^{13}) \\ \hat{U}_2 [2 + (p_1^{02})^2] - \hat{U}_1 [p_1^{02} + 1 - p_2^{13}] &= p_2^{03} + p_2^{13} \end{aligned} \quad (3)$$

Now consider the (consistent) assignment (4) below of indifference probabilities p_j^{ik} :

$$(4) \quad p_1^{03} = 1/3, p_2^{03} = 2/3, p_1^{02} = p_2^{13} = 1/2.$$

Then the equations (3) have as their solution

$$\hat{U}_1 = 1/3, \hat{U}_2 = 2/3,$$

with zero residual squares, verifying the individual's complete consistency.

3.5.2 Objective vs. Subjective Probability

Davidson, Suppes and Siegel²¹² lay great stress on deducing a person's utility from observing that person's actual behavior, in actual choice situations, and hence are led naturally to formulating that person's choice mechanism in terms of that person's perceived (i.e., subjective) probabilities. In other words, DSS trust the "moral expectation hypothesis" (that a person acts according to expected utility only in the context of subjective probability.

von Neumann and Morgenstern;⁹⁴ Mosteller and Nogee;²¹³ or Keeney and Raiffa,²⁰⁶ on the other hand, content themselves with noting the person's professed preferences for hypothetical "what if" sorts of alternatives. Hence, they allow themselves to confront the person with hypothetical lotteries involving "probabilities" of unspecified pedigree, which the person might as well accept at face value, and as his own, since there is in fact nothing to lose.

Let us call the above two views the purist and the pragmatic. The distinction between the two seems compelling in the light of Section 3.5-1 Relationship.202, written from the pragmatic point of view, drew attention to the possibility of the person's artificially slanting his utility appraisals with the aim of appearing consistent. It would seem that if the game involved actual bagatelles, to win or to loose, as in DSS's study,²¹² introspection would stand a better chance vis-à-vis wishing to appear consistent, at least in the case of persons prizing their purse above their good name.

It may be noted that the purist and pragmatic views of utility largely reflect a parallel controversy in Bayesian statistics. There, L. J. Savage and H. Rubin (the latter cited by DSS for assistance) espoused the purist view that only those subjective probabilities deserve the name that have been elicited from the person through exhaustive questioning of a highly stylized sort, similar to the sort of questioning that elicits the person's

utility. Other Bayesians, on the other hand, J. Cornfield for example, are willing to do with much less, and will accept as the genuine article any prior distribution that the person may be willing to advance as reflecting his current opinion.

3.5.3 Explicit Incorporation of Time Considerations into R&D Selection Methodology

The following pursues some thoughts on the explicit incorporation of time consideration in R&D selection methodologies, with respect, in particular, to the real cost of future uniform real expenditures, and related issues.

It is now 1/1/80. If one is going to purchase goods and services, currently worth M dollars, uniformly from 1/1/80+n to 1/1/80+N, how much need we have in the bank today?

Let f be the estimated instantaneous rate of inflation, computed from the estimated yearly rate F of inflation in accordance with

$$f = \ln (1 + F) . \quad (1)$$

Similarly, let b be the estimated instantaneous rate of interest, computed from the yearly interest rate B by

$$b = \ln (1 + B) \quad (2)$$

Also let

$$p \quad (3)$$

be the unit price of goods and services, as of today.

Suppose now that we wished to purchase an amount dQ of goods and services during an interval of time dt at some future point t in time somewhere between 1/1/80+n and 1/1/80+N.

Whereas today these goods and services would cost us

$$p \cdot dQ, \quad (4)$$

at that future time t they will in fact cost us

$$p \cdot dQ \cdot e^{tf} \quad (5)$$

which we shall be able to cover with a deposit today of

$$p \cdot dQ \cdot e^{tf} \cdot e^{-tb} \quad (6)$$

But we intend in fact a total purchase worth M dollars today; i.e., a total quantity

$$Q = M/p \quad (7)$$

so that, given one uniform intent, we mean to purchase an amount

$$\begin{aligned} dQ &= Q \cdot dt/(N-n) \\ &= M \cdot dt/(p)(N-n) \end{aligned} \quad (8)$$

during the time interval dt .

Substituting (8) in (6) yields the amount

$$M \cdot e^{(f-b)t} \cdot dt/(N-n) \quad (9)$$

required in deposit today, to cover future purchases in the time interval dt .

Integrating (9) from n to N yields a total amount of

$$\frac{M}{(f-b)(N-n)} \cdot e^{(f-b)N} - e^{(f-b)n} \quad (10)$$

required on deposit today.

What then, for example, is the current real cost of P-1? For the research part of the program we have

$$M = 4S, N = 1, n = 0 \quad (11)$$

where S is one year's salary for the requisite human factors research, and for implementation we have

$$M = 65\mu, N = 6, n = 1 \quad (12)$$

The total current real cost will be the sum of (10) with substitutions (11), plus (10) with substitutions (12).

It should be said that the above computations are really not primarily intended to fix by edict the manner of computing the effective current cost of contemplated programs. After all, the economics of large scale government spending may perhaps be better reflected by some other model. Or the future discount of other than monetary dimensions may again have a different flavor of its own.

What is primarily intended is to express the thought that, in many selection methodologies with a delphi component, in which dimensions appear that are related to time, it may be possible to compress such dimensions in order to simplify and standardize the delphi task. Thus, rather than confronting the delphi participants with the four dimensions of research; time, research cost, implementation time, and implementation cost, perhaps one should confront them just with effective current implementation cost (with perhaps a preliminary delphi round on the best way to compute it).

4.0 PROSPECTIVE APPLICATION OF THE METHODOLOGY

4.1 ILLUSTRATIVE EXAMPLE

To illustrate the use of the methodology, three programs were selected from the Preliminary LWR Safety Technology Program Plan prepared by Sandia for the DOE; namely

1. Improved Safety Systems
2. Utility Training Program
3. Siting

The improved safety systems program encompasses the following subprograms:

- Component
- Systems
- Plant Design

The utility training program involves:

- Upgraded training and certification
- Human factors and human engineering
- Improved operating procedures and diagnostics
- Human error rate quantification
- Improved quality assurance

The attribute trade-off factors and levels of subattributes are listed in 4.1-1. Using the utility curves obtained by the UTILITY 1, the utility values corresponding to each of the attribute levels for each program were obtained. The expected overall utility for each program was then computed via application of EVALU.

Two different persons selected the appropriate subattribute levels for each of the three programs and assigned the proper weight for each measure/attribute/subattribute. The results are shown for each individual in Tables 4. 1-1 and 4. 1-2. The rank of the three programs and the expected utilities are listed in Table 4. 1-3. Although the subattribute levels and weights are significantly different for each evaluator, the rank ordering of the programs is similar. Also, evaluator #1, did not include all the attributes. The agreement is based on the fact that the same preference patterns were used. Those were obtained by 4 other investigators. In addition, the difference in subattribute levels chosen by the two evaluators mostly followed a similar trend in judgment of options in ordering of attributes measures, and selection of weights.

To see how the methodology handles attributes that take values according to probability distributions, consider the following variation of the sample application.

As can be seen in Table 4.1-1, evaluator #1 made the following assignments to subattribute x_{111} :

Program 1 : 1
 Program 2 : 5
 Program 3 : 1

Suppose that instead of deterministic values, evaluator #1 made his assignments in the form of probability distributions:

Program 1: .5 with probability .3
 .9 with probability .5
 2 with probability .2

Program 2: normal distribution with mean 5 and variance 4.

Program 3; exponential distribution with mean 1.

Each of these three distributions has mean equal to the deterministic levels assigned to each program originally. The introduction of uncertainty, into the subattribute level assignments, however, can be seen to alter the utilities implied by each level.

The utility function for subattributes x_{111} is given by

$$u(x'_{111}) = 4.5226 (1 - e^{-0.24989x'_{111}}),$$

$$\text{where } x'_{111} = x \frac{x_{111} - .5}{9.5}$$

(i.e., $x'_{111} = x_{111}$)

scaled to lie between 0 and 1.

For Program 1, the expected utility of x_{111} is given by (the sum of the utilities) at the three values weighted by their probabilities, and is equal to .0587.

For Program 2, the expected utility is calculated using the Laplace transform of the normal distribution, and is equal to .4993.

For Program 3, the expected utility is also calculated using the Laplace transform, and equals .0576.

In each case, the expected utility of the subattributes when their levels are described by probability distributions is less than that obtained by the original (deterministic) levels as shown in Table 4.1-1. This behavior is expected, since the utility function for the subattribute represents a risk averse attitude.

Table 4. 1-1 Results for Evaluator #1

Attribute	Subattribute	Weight	Scaling Constant	P R O G R A M					
				1 Level	Utility	2 Level	Utility	3 Level	Utility
Y ₁₁	-	.4	0	-	.309	-	.363	-	.151
	X ₁₁₁	.5	-	1	.059	5	.505	1	.059
	X ₁₁₂	.4	-	5	.474	1	.053	1	.053
	X ₁₁₃	.1	-	90	.9	90	.9	100	1
Y ₁₂	-	.3	-.281	-	.254	-	.322	-	.424
	X ₁₂₁	.6	-	5	.392	6	.497	7	.610
	X ₁₂₂	.3	-	1	.004	1	.004	2	.172
	X ₁₂₃	.14	-	1	.007	1	.007	3	.051
	X ₁₂₄	.06	-	70	.3	60	.4	90	.1
Y ₁₃	-	.15	0	-	.597	-	.788	-	.147
	X ₁₃₁	.84	-	4	.637	6	.819	1	.127
	X ₁₃₂	.16	-	3	.390	5	.623	2	.249
Y ₁₄	-	.1	-.842	-	.843	-	.402	-	.402
	X ₁₄₁	.45	-	10 ⁻⁷	1	10 ⁻⁶	.732	10 ⁻⁶	.732
	X ₁₄₂	.32	-	8	.863	1	.132	1	.132
	X ₁₄₃	.53	-	7	.697	1	.091	1	.091
	X ₁₄₄	.44	-	5	.313	1	.029	1	.029
Y ₁₅	-	.05	0	-	.053	-	.789	-	.053
	X ₁₅₁	1	-	1	.053	1	.789	1	.053
Z ₁		.8	0	-	.376	-	.440	-	.253

Table 4. 1-1 Results for Evaluator #1 (cont'd)

Attribute	Subattribute	Weight	Scaling Constant	P R O G R A M					
				1 Level	Utility	2 Level	Utility	3 Level	Utility
Y ₂₁	-	.6	0	-	.210	-	.701	-	.730
	X ₂₁₁	.35	-	6	0	.5	1	.5	1
	X ₂₁₂	.30	-	8	.202	.1	1	.1	1
	X ₂₁₃	.25	-	6	.596	2	.192	3	.293
	X ₂₁₄	.10	-	.1	0	1	.032	2	.072
Y ₂₂	-	.4	0	-	.574	-	.401	-	.450
	X ₂₂₁	.55	-	1	.5	.8	0	1	.5
	X ₂₂₂	.34	-	1.5	.556	.3	1	2	.37
	X ₂₂₃	.11	-	.1	1	.5	.556	.6	.444
Z ₂	-	.6	0	-	.355	-	.581	-	.618

Table 4. 1-1 Results for Evaluator #1 (cont'd)

Attribute	Subattribute	Weight	Scaling Constant	P R O G R A M					
				1 Level	Utility	2 Level	Utility	3 Level	Utility
Y ₃₂	-	.35	0	-	.145	-	.34	-	.79
	X ₃₂₁	.55	-	.9	.1	.8	.2	0	.1
	X ₃₂₂	.25	-	.2	.2	.6	.6	.3	.3
	X ₃₂₃	.15	-	1	0	.5	.5	.2	.8
	X ₃₂₄	.05	-	.2	.8	.9	.1	.1	.9
Y ₃₃	-	.2	0	-	.5	-	.9	-	.1
	X ₃₃₁	.1	-	.5	.5	.9	.9	.1	.1
Z ₃	-	.5	6.429	-	.184	-	.437	-	.332

Table 4. 1-1 Results for Evaluator #1 (cont'd)

Attribute	Subattribute	Weight	Scaling Constant	P R O G R A M					
				1 Level	Utility	2 Level	Utility	3 Level	Utility
Y ₄₁	-	.42	0	-	.122	-	.717	-	.700
	X ₄₁₁	.45	-	80	.089	2.5	1	4	.967
	X ₄₁₂	.35	-	2000	0	1500	.351	1500	.351
	X ₄₁₃	.14	-	50	.5	10	.9	20	.8
	X ₄₁₄	.06	-	80	.2	70	.3	50	.5
Y ₄₂	-	.36	0	-	.007	-	.61	-	.745
	X ₄₂₁	.82	-	10	0	5	.526	3	.737
	X ₄₂₂	.16	-	36	0	3	1	10	.788
	X ₄₂₃	.02	-	4	.364	1	.909	2	.727
Y ₄₃	-	.12	0	-	.740	-	.811	-	.665
	X ₄₃₁	.47	-	80	.8	70	.7	100	1
	X ₄₃₂	.34	-	70	.7	90	.9	10	.1
	X ₄₃₃	.14	-	.9	.9	.9	.9	.9	.9
	X ₄₃₄	.05	-	-1	0	1	1	0	.703
Y ₄₄	-	.06	0	-	.326	-	.972	-	.098
	X ₄₄₁	.54	-	.5	.285	1	1	.25	.123
	X ₄₄₂	.32	-	.1	.1	1	1	.1	.1
	X ₄₄₃	.14	-	0	1	.2	.8	.1	0
Y ₄₅	-	.04	0	-	.853	-	.610	-	.591
	X ₄₅₁	.63	-	10	.766	20	.582	30	.437
	X ₄₅₂	.27	-	0	1	1	0	.4	.8
	X ₄₅₃	.10	-	0	1	.2	.9	0	1
Z ₄	-	.2	0	-	.196	-	.701	-	.672

Table 4. 1-2 Results for Evaluator #2

Attribute	Subattribute	Weight	Scaling Constant	P R O G R A M					
				1 Level	Utility	2 Level	Utility	3 Level	Utility
Y ₁₁	-	.3	0	-	.076	-	.425	-	.101
	X ₁₁₁	.6	-	1	.059	5	.505	1	.059
	X ₁₁₂	.3	-	1	.053	2	.158	1	.053
	X ₁₁₃	.1	-	25	.25	75	.750	50	.5
Y ₁₂	-	.2	0	-	.256	-	.212	-	.294
	X ₁₂₁	.5	-	4	.294	2	.117	5	.392
	X ₁₂₂	.2	-	1	.004	1	.004	2	.172
	X ₁₂₃	.1	-	4	.087	2	.025	5	.14
	X ₁₂₄	.1	-	50	.5	25	.75	75	.25
Y ₁₃	-	.1	0	-	.303	-	.46	-	.112
	X ₁₃₁	.6	-	2	.34	3	.506	1	.127
	X ₁₃₂	.4	-	2	.249	3	.39	1	.088
Y ₁₄	-	.2	0	-	.548	-	.324	-	.233
	X ₁₄₁	.5	-	10 ⁻⁶	.732	10 ⁻⁵	.546	10 ⁻⁴	.363
	X ₁₄₂	.3	-	3	.390	1	.132	1	.132
	X ₁₄₃	.1	-	5	.495	1	.091	1	.091
	X ₁₄₄	.1	-	3	.156	1	.029	1	.029
Y ₁₅	-	.2	0	-	.158	-	.368	-	.053
	X ₁₅₁	.1	-	2	.158	4	.368	1	.053
Z ₁	-	.4	0	-	.246	-	.354	-	.158

Table 4. 1-2 Results for Evaluator #2 (cont'd)

Attribute	Subattribute	Weight	Scaling Constant	P R O G R A M					
				1 Level	Utility	2 Level	Utility	3 Level	Utility
Y ₂₁	-	.6	0	-	.144	-	.586	-	.627
	X ₂₁₁	.4	-	.6	0	.5	1	.5	1
	X ₂₁₂	.2	-	4	.606	2	.808	1	.909
	X ₂₁₃	.2	-	.5	.04	1	.091	2	.192
	X ₂₁₄	.2	-	2	.072	1	.032	1	.032
Y ₂₂	-	.4	0	-	.606	-	.39	-	.576
	X ₂₂₁	.7	-	1	.5	.9	.25	1	.5
	X ₂₂₂	.2	-	.75	.833	1	.741	1	.741
	X ₂₂₃	.1	-	.2	.889	.4	.667	.3	.778
Z ₂	-	.3	0		.328	-	.508	-	.606

Table 4. 1-2 Results for Evaluator #2 (cont'd)

Attribute	Subattribute	Weight	Scaling Constant	P R O G R A M					
				1 Level	Utility	2 Level	Utility	3 Level	Utility
Y ₃₁	-	.4	0	-	.867	-	.716	-	.629
	X ₃₁₁	.2	-	.1	.55	.1	.55	.5	.75
	X ₃₁₂	.6	-	2	1	1.5	.749	1	.497
	X ₃₁₃	.2	-	.1	.786	.1	.786	.5	.904
Y ₃₂	-	.4	0	-	.650	-	.51	-	.74
	X ₃₂₁	.2	-	.3	.7	.1	.9	0	1
	X ₃₂₂	.3	-	.2	.2	.1	.1	.3	.3
	X ₃₂₃	.3	-	.1	.9	.4	.6	.1	.9
	X ₃₂₄	.2	-	.1	.9	.4	.6	.1	.9
Y ₃₃	-	.2	0	-	.52	-	.56	-	.22
	X ₃₃₁	.6	-	.6	.6	.6	.6	.3	.3
	X ₃₃₂	.4	-	.4	.4	.5	.5	.1	.1
Z ₃	-	.2	0	-	.711	-	.603	-	.592

Table 4. 1-2 Results for Evaluator #2 (cont'd)

Attribute	Subattribute	Weight	Scaling Constant	P R O G R A M					
				1 Level	Utility	2 Level	Utility	3 Level	Utility
Y ₄₁	-	.2	0	-	.408	-	.791	-	.938
	X ₄₁₁	.4	-	50	.302	10	.846	3	.989
	X ₄₁₂	.3	-	1000	.675	400	.876	100	.976
	X ₄₁₃	.1	-	50	.5	10	.9	0	1
	X ₄₁₄	.2	-	75	.25	50	.5	25	.75
Y ₄₂	-	.2	0	-	.516	-	.837	-	.718
	X ₄₂₁	.5	-	4	.632	1	.947	5	.526
	X ₄₂₂	.4	-	24	.364	12	.727	6	.909
	X ₄₂₃	.1	-	3	.545	2	.727	1	.909
Y ₄₃	-	.2	0	-	.579	-	.346	-	.628
	X ₄₃₁	.4	-	75	.75	25	.25	50	.5
	X ₄₃₂	.3	-	50	.5	25	.25	75	.75
	X ₄₃₃	.1	-	.3	.3	.3	.3	.3	.3
	X ₄₃₄	.2	-	.5	.494	0	.703	.5	.864
Y ₄₄	-	.2	0	-	.266	-	.407	-	.378
	X ₄₄₁	.4	-	.4	.214	.6	.368	.2	.096
	X ₄₄₂	.4	-	.2	.2	.4	.4	.6	.6
	X ₄₄₃	.2	-	.5	.5	.5	.5	.5	.5
Y ₄₅	-	.2	0	-	.755	-	.593	-	.733
	X ₄₅₁	.4	-	30	.437	20	.582	20	.582
	X ₄₅₂	.4	-	.1	.95	.2	.9	.5	.75
	X ₄₅₃	.2	-	0	1	1	0	0	1
Z ₄	-	.1	0	-	.505	-	.595	-	.679

Table 4. 1-3 Expected Overall Utility for the Three Programs

Program	Expected Utility		Rank
	Evaluator 1	Evaluator 2	
Improved Safety Systems	0.48867	0.38945	3
Utility Training Program	0.72865	0.47409	1
Siting	0.63287	0.43119	2

4.2 PROCEDURAL STEPS AND FUTURE APPLICATIONS

The package is designed to help the user collect data in an orderly fashion. To accomplish this, there is a natural order in which the computer modules would normally be used. Following is one possible scenario illustrating a typical usage of MAUP.

The user begins by examining the various attributes and their ranges. Attribute will be used generically here to refer to measure category, attribute, and subattribute. This may be done by using the UPDATE module or by referencing the written material supplied with the package. The user may want to change some of the ranges, some of the scales of measurement or possibly insert or delete some attributes. UPDATE allows for all of these to be easily done.

Utility functions are constructed for each subattribute using UTILITY1. The user is afforded a great deal of flexibility at this stage so that the functions accurately represent the user's preferences. UTILITY1 saves important information for use by other modules. The typical user would spend two or three sessions using UTILITY1 until all subattributes have a satisfactory utility function.

At this stage the user finds it helpful to re-examine the scalar utility functions. REVIEW helps in this task, displaying graphs, certainty equivalents, and function parameters on request. Finding some of the earlier assessments inadequate, the user readjusts these easily with UTILITY1.

KVALUE is used next to help decide some difficult tradeoff questions. The user finds that this, too, is a module that may require more than one session. Good answers, however, are important here so that the scaling constants obtained yield a useful multiattribute utility function. Once again, REVIEW aids in examining previous results.

The user next evaluates proposals. PROPIN is used here to collect all of the relevant information concerning each proposal. The user decides that a few attributes are stochastic, so PROPIN helps choose a probability distribution for each stochastic attribute. REVIEW allows the user to

re-examine each proposal evaluation.

Nearing completion, the user now employs EVALU. This module calculates the utility for each proposal. A nice feature is the breakdown by subattributes so that the user can easily see the strengths and weaknesses of each proposal. This also allows for a side-by-side comparison of proposals. All results are saved so that later proposals may also be compared.

The preceding scenario is one way the user might use MAUP. However, MAUP is supplied with subattribute utility functions and scaling constants. This means that if desired, a user may, after looking these over by using REVIEW, start with PROPIN to evaluate proposals.

In its present form, MAUP is nicely suited for evaluating nuclear reactor safety research and development proposals. Its flexibility, however, allows it to be used in more general settings. By using UPDATE to input new attributes and ranges, a user could apply MAUP to practically any kind of multiattribute utility problem.

5.0 REFERENCES

1. McKean, Roland N., Efficiency in Government Through Systems Analysis: With Emphasis on Water Resource Development, (John Wiley, New York, 1958).
2. Marschak, Thomas, "Toward a Normative Theory of Development," in Strategy for R&D, Thomas Marschak; Thomas K. Glennan, Jr.; and R. Summers; eds., (Springer-Verlag, New York, 1967).
3. Knight, F.H., Risk, Uncertainty, and Profit, (Houghton-Mifflin, Boston, 1921).
4. Simon, H., "Dynamic Programming under Uncertainty with Quadratic Criterion Function," Econometrica, 24, 74 (1956).
5. Theil, H., Optimal Decision Rules for Government and Industry (North-Holland, Amsterdam, 1964).
6. Malinvaud, E., "First Order Certainty Equivalence," Econometrica, 37, 706 (1969).
7. Rausser, Gordon C. and Dean, Gerald W., "Uncertainty and Decision-Making in Water Resources," in California Water, A Study in Resource Management, David Seckler, Ed. (University of California Press, Berkeley, California, 1971).
8. U.S. Government, Federal Inter-Agency River Basin Committee, Subcommittee on Benefits and Costs, Proposed for Economic Analysis of River Basin Projects (Washington, DC, 1950 revised 1958) (the Green Book).
9. Marglin, S. A., Public Investment Criteria, (The MIT Press, Cambridge, MA, 1967).
10. Hirshliefer, Jack, DeHaven, James C., and Milliman, Jerome W., Water Supply, Economics, Technology and Policy, (The University of Chicago Press, Chicago, 1960).
11. Marglin, S. A., Approaches to Dynamic Investment Planning (North-Holland, Amsterdam, 1963).
12. Eckstein, Otto, "A Survey of the Theory of Public Expenditure," in Public Finances: Needs, Sources and Utilization, (National Bureau of Economic Research, Princeton, NJ, 1961).

13. Arrow, K. J., "Discounting and Public Investment Criteria," in Water Research, eds. A. V. Kneese and S. C. Smith (Johns Hopkins University Press, Baltimore, 1966).
14. Hirschleifer, J., "Investment Decision Under Uncertainty: Applications of the State-Preference Approach," Quarterly J. of Economics, 80, 252 (1966).
15. Task Force on Water Resources and Power for the Commission on Organization of the Executive Branch of the Government (Hoover Commission), Report on Water Resources and Power, (Washington, DC, 1955).
16. Renshaw, Edward F., Toward Responsible Government (Idyia Press, Chicago, 1957).
17. Krutilla, John V. and Eckstein, Otto, Multiple Purpose River Development, (Johns Hopkins Press, Baltimore, 1958).
18. Eckstein, Water Resource Development (Harvard University Press, Cambridge, MA, 1958).
19. Sassone, Peter G. and Schaffer, William A., Cost-Benefit Analysis, A Handbook (Academic Press, New York, 1978).
20. Dasgupta, A. K. and Pearce, D. W., Cost-Benefit Analysis (Barnes and Noble, New York, 1972).
21. Maass, A., Benefit-Cost Analysis: Its Relevance to Public Investment Decisions, Quarterly Journal of Economics, 80, 208 (May, 1966).
22. Merewitz, L. and Sosnick, S.H., The Budget's New Clothes, (Markham, Chicago, 1971).
23. Mishan, E. J., Cost-Benefit Analysis (Praeger, New York, 1976).
24. Nash, C., Pearce, D., and Stanley, J., "An Evaluation of Cost-Benefit Analysis Criteria," Scottish Journal of Political Economy, 22, 121 (1975).
25. Prest, A. R. and Turvey, R., "Cost-Benefit Analysis: A Survey," Economic Journal, 75, 683 (1965).
26. Dupuit, J., "On the Measurement of Utility of Public Works," International Economic Papers, 2, 83 (1952).
27. Friedman, M., "The Marshallian Demand Curve," Journal of Political Economy, 57, 463 (1949).
28. Schumpeter, J. A., History of Economic Analysis (Oxford Univ. Press, New York, 1954).

29. U.S. Bureau of the Budget. Reports and budget estimates relating to federal programs and projects for conservation, development, and use of water and related land resources, Circular A-47, Washington, DC, 1952.
30. U.S. Water Resources Council. Policies, Standards, and Criteria for Formulation, Evaluation and Review of Plans for Use and Development of Water and Related Land Resources, Senate Document 97, 87th Congress. Washington, DC: U.S. Government Printing Office, 1962.
31. U.S. Office of Management and Budget. Discount rates to be used in evaluating time-distributed costs and benefits, Circular A-94 (revised), Washington, DC, March 27, 1972.
32. U.S. Water Resources Council, Principles, Standards and Procedures for Water and Related Land Resource Planning. Federal Register 38-174 (Sept. 10, 1973), Part III.
33. "National Environmental Policy Act of 1969," U.S. Statutes at Large, 91st Congress, 1st Session, Volume 83, 852-856.
34. Hotelling, H., "The General Welfare in Relation to Problems of Taxation and of Railway and Utility Rates," Econometrica, 6, 242 (1938).
35. Kaldor, N., "Welfare Propositions of Economics and Interpersonal Comparisons of Utility," Economic Journal, 49, 549 (1939).
36. Hicks, J. R., "The Foundations of Welfare Economics," Economic Journal, 49, 696 (1939).
37. Hicks, J. R., "The Four Consumers' Surpluses," Review of Economic Studies, 11, 31 (1941).
38. Henderson, A. M., "Consumer's Surplus and the Compensating Variation," Review of Economic Studies, 8, 117 (1941).
39. Scitovsky, T., "A Note on Welfare Propositions in Economics," Review of Economic Studies, 9, 77 (1941).
40. Friedman, M. and Savage, L. J., "Utility Analysis of Choices Involving Risks," Journal of Political Economy, 56, 279 (1948).
41. Scitovsky, T., "Two Concepts of External Economics," Journal of Political Economy, 67, 143 (1954).
42. Hicks, J. R., "A Revision of Demand Theory," (Clarendon Press, Oxford, 1956).
43. Little, I. M. D., A Critique of Welfare Economics, (Oxford Univ. Press 2nd Edition, New York, 1957).

44. Eckstein, O., "Investment Criteria for Economic Development and the Theory of Intertemporal Welfare Economics," Quarterly Journal of Economics, 71, 56 (1957).
45. Bator, F. M., "The Anatomy of Market Failure," Quarterly Journal of Economics, 72, 351 (1958).
46. Griliches, Z., "Research Costs and Social Returns: Hybrid Corn and Related Innovations," Journal of Political Economy, 66, 419 (1958).
47. Margolis, J., "The Economic Evaluation of Federal Water Resource Development," American Economic Review, 49, 96-111 (1959).
48. Coase, R. H., "The Problems of Social Cost," Journal of Law and Economics, 3, 1 (1960).
49. Hitch, C. J. and McKean, R. N., "Economics of Defense in the Nuclear Age," Cambridge, MA, Harvard Univ. Press, 1960.
50. Steiner, P. O., "Choosing Among Alternative Public Investments in the Water Resource Field," American Economic Review, 49, 1960.
51. Samuelson, P. A., "The Pure Theory of Public Expenditure," Review of Economics and Statistics, 36, 387-389 (1954).
52. Rothenberg, J., "The Measurement of Social Welfare," Englewood Cliffs, NJ: Prentice-Hall (1961).
53. Samuelson, P. A., "Foundations of Economic Analysis," 2nd ed., Cambridge, MA: Harvard University Press (1963).
54. Turvey, R., "On Divergences Between Social Cost and Private Cost," Economica, 30, 309-313 (1963).
55. Turvey, R., Optimal Pricing and Investment in Electricity Supply, (The MIT Press, Cambridge, MA, 1968).
56. Davis, O.A. and Winston, A.B., "Externality, Welfare and the Theory of Games," Journal of Political Economy, 70, 241-262 (1962).
57. Feldstein, M. S., "Net Social Benefit Calculation and the Public Investment Decision," Oxford Economic Papers, 16, 114-131 (1964).
58. Dorfman, R., "Measuring Benefits of Government Investments," Washington, DC: Brookings Inst., 1965.
59. Buchanan, J. M. and Tullock, G., "The Calculus of Consent," Ann Arbor: University of Michigan Press, 1962.

60. Maass, A., et al., "Design of Water Resource Systems: New Techniques for Relating Economic Objectives, Engineering Analysis, and Government Planning," Cambridge, MA: Harvard Univ. Press, 1962.
61. Marglin, S. A., "The Social Rate of Discount and the Optimal Rate of Investment," Quarterly Journal of Economics, 77, 95-111 (1963a).
62. Marglin, S. A., "The Opportunity Costs of Public Investment," Quarterly Journal of Economics, 77, 274-289 (1963b).
63. Mishan, E. J., "The Relationship Between Joint Products, Collective Goods, and External Effects," Journal of Political Economy, 77, 329-348 (1969).
64. Mishan, E. J., "Welfare Economics: An Assessment," Amsterdam: North-Holland Publ., 1969b.
65. Baumol, W. J., "On the Social Rate of Discount," American Economic Review, 58, 788-802 (1968).
66. Arrow, K. J. and Lind, R. C., "Uncertainty and the Evaluation of Public Investment Decisions," American Economic Review, 50, 364-378 (1970).
67. Currie, J. M., Murphy, and A. Schmitz, "The Concept of Economic Surplus and Its Use in Economic Analysis," Economics, 3, 1 (1960).
68. Dasgupta, P., Marglin, S., and Sen, A., "Guidelines for Project Evaluation," New York: United Nations, 1972.
69. Pearce, D., "The Limits of Cost-Benefit Analysis as a Guide to Environmental Policy," Kyklos, 29, 97-112 (1976).
70. Pigou, A. C., "Economics of Welfare," 4th Ed. New York (McMillan, 1946).
71. Little, I. M. D. and Mirrlees, J. A., "Project Appraisal and Planning for Developing Countries," New York: Basic Books, 1974.
72. Gittinger, J. P., "Economic Analysis of Agriculture Projects," Baltimore, MD: Johns Hopkins Univ. Press, 1972.
73. Hirschman, A. O., Development Project Observed, The Brookings Institution, Washington, DC (1967).
74. Klein, B. H., Marschak, T. A., Marshall, A. W., Meckling, W. H., and Nelson, R. R., The Rate and Direction of Inventive Activity, (Princeton University Press, Princeton, 1962).
75. Marschak, T., "Strategy and Organization in a System Development Project," (P-1091) The Rand Corporation, Santa Monica, 1960).
76. Marschak, T., Glennan, T. K., Summers, R., Strategy for R&D, (Springer-Verlag, New York: 1967).

77. Nelson, R., "Uncertainty, Learning, and the Economics of Parallel Research and Development Efforts," Review of Economics and Statistics, 34, 351 (1961).
78. Nelson, R., "The Efficient Achievement of Rapid Technological Progress," American Economic Review, 56, 232 (1966).
79. Nelson, R., Peck, M. J., and Kalachek, E. D., Technology, Economic Growth, and Public Policy (The Brookings Institution, Washington, DC, 1967).
80. Bellman, R., "Adaptive Control Processes," (Princeton, NJ: Princeton Univ. Press, 1961).
81. Farrar, D. E., "The Investment Decision Under Uncertainty," (Englewood Cliffs, NJ: Prentice-Hall, 1962).
82. Fox, K. A., Sengupta, J. K., and Thorbecke, E., "The Theory of Quantitative Economic Policy," Amsterdam: North Holland Publ. Co., 1966.
83. Hertz, D. B., "Risk Analysis in Capital Investment," Harvard Business Review, 42, (January-February, 1964).
84. Holt, C. C., Modigliani, F., Muth, J. F., and Simon, H. A., "Planning Production, Inventories, and Work Force," Prentice-Hall, 1960, Englewood Cliffs, NJ.
85. Good, I. J., The Estimation of the Probabilities - An Essay on Modern Bayesian Methods, (The MIT Press, Cambridge, MA, 1965).
86. Madansky, A., "Linear Programming Under Uncertainty," in Recent Advances in Mathematical Programming, R. L. Graves and P. Wolfe, eds. (New York: McGraw-Hill, 1963).
87. Magee, J. F., "How to Use Decision Trees in Capital Investment," Harvard Business Review, 42 (September-October, 1964).
88. Sengupta, J. K., Tintner, G., and Millham, C., "On Some Theorems of Stochastic Linear Programming with Applications," Management Science, 10 (October 1963), 143-159.
89. Hillier, F. S., "The Derivation of Probabilistic Information for the Evaluation of Risky Investments," Management Science, 9, (1963).
90. Aaker, D. A. and Tyebee, T. T., "A Model for the Selection of Interdependent R&D Projects," IEEE Trans. on Engineering Management, Vol. EM-25, No. 2, May 1978.
91. Modigliani, F. and Cohen, K. F., "The Role of Anticipations and Plans in Economic Behavior and Their Use in Economic Analysis and Forecasting," University of Illinois Bulletin, Urbana, 1961.

92. Reutlinger, S., "Techniques for Project Appraisal Under Uncertainty," International Bank for Reconstruction and Development Report No. EC-169, August 1968.
93. Raiffa, H., Decision Analysis: Introductory Lectures on Choices Under Uncertainty (Addison-Wesley, Reading, MA, 1968).
94. Von Neumann, J. and Morgenstern, O., Theory of Games and Economic Behavior (Princeton University Press, Princeton, NJ, 1947).
95. Halter, A.N. and Dean, G.W., Decisions Under Uncertainty with Research Applications (Southwestern Publishing Co., Cincinnati, 1972).
96. Gros, J., "A Paretian Environmental Approach to Power Plant Siting in New England," doctoral dissertation, Harvard University, Cambridge, MA, 1974.
97. Keeney, R. L., "A Decision Analysis With Multiple Objectives: The Mexico Airport," Bell J. Econ. Management Sci., 4, 101 (1973).
98. Ahmed, S., Husseiny, A. A., and Cho, Hang Youn, "A Formal Methodology for Acceptability Analysis of Alternate Sites for Nuclear Power Stations," Nuclear Engineering and Design, 51, 361 (1979).
99. Keeney, R. L. and Nair, K., "Decision Analysis for the Siting of Nuclear Power Plants - The Relevance of Multi-attribute Theory," Proc. of the IEEE, 63 (3), 494 (1975).
100. Pyle, D. H. and Turnovsky, S. J., "Safety-First and Expected Utility Maximization in Mean-Standard Deviation Portfolio Analysis," Review of Economics and Statistics, 50, 75 (1970).
101. Marschak, Thomas and Yakav, J. A., "The Consequential Selection of Approaches to a Task," Management, May 1966.
102. Arrow, K. J., "Optimal Capital Policy, the Cost of Capital, and Myopic Decision Rules," Annals of the Institute of Statistical Mathematics, 26, 23 (1964).
103. Manne, A. S., "Capacity Expansion and Probabilistic Growth," Econometrica, 29, 632 (1961).
104. Chernoff, H. and Moses, L. E., Elementary Decision Theory (John Wiley, New York, 1959).
105. Charnes, A. J., Dreze, J., and Miller, M., "Decision and Horizon Rules for Stochastic Planning Problems: A Linear Example," Econometrica, 34, 307 (1966).
106. Sengupta, J. K., "The Stability of Truncated Solutions of Stochastic Linear Programming," Econometric, 34, 77 (1966).
107. Blackwell, David, "Discrete Dynamic Programming," Annals of Mathematical Statistics, 33, 719 (1962).

108. Howard, Ronald A., "Dynamic Programming and Markov Processes," (The MIT Press, Cambridge, MA, 1960).
109. Aoki, Massano, Optimization of Stochastic Systems, (Academic Press, New York, 1967).
110. Monko, D. and Robbins, H., "A Stochastic Approximation Model," Annals of Mathematical Statistics, 22, 400 (1951).
111. Wilson, R., "Computation of Optimal Controls," Journal of Mathematical Analysis and Applications, 14, 77 (1957).
112. Bellman, R., "Dynamic Programming," (Princeton University Press, Princeton, NJ, 1957).
113. Hadley, G., Nonlinear and Dynamic Programming (Addison-Wesley, Reading, MA, 1964).
114. Halter, A. N. and Dean, G. W., Decisions Under Uncertainty With Research Applications, (South Western, Cincinnati, 1971).
115. Becker, Gordon M. and McClintock, Charles G., "Value: Behavioral Decision Theory," in Annual Rev. of Psychology, 1967.
116. Halter, A. N. and Beinger, C., "Cardinal Utility Functions and Managerial Behavior," J. Farm Economics, 42, 118 (1960).
117. Keeney, R. L., "A Group Preference Axiomatization with Cardinal Utility," IIASA Report #Rm-75-47, Laxenburg, Austria, 1975.
118. Bell, D. E., "Defining and Quantifying Goals for Measuring the State of an Ecosystem," IIASA Report #Rm-74-26, Laxenburg, Austria, 1974.
119. Howard, R. A., Editor, Special Issue on Decision Analysis, IEEE Trans. System Science and Cybernetics, Vol. SSC-4, No. 3, pp. 119-366.
120. Savage, L. J., The Foundations of Statistics, John Wiley and Sons, New York, 1954.
121. Raiffa, H. and Schlaifer, R. O., Introduction to Statistical Decision Theory, McGraw-Hill, New York, 1965.
122. Fishburn, P. C., Decision and Value Theory, John Wiley and Sons, New York, 1964.
123. Papp, R., McGrath, P. E., Maxim, L. D., and Cook, F. X. Jr., "A New Concept in Risk Analysis for Nuclear Facilities," Nuclear News, 17 (11), (1974).

124. Fishburn, P. C., "Methods of Estimating Additive Utilities," Management Science, 13 (7), (1967).
125. Becker, G. M., De Groot, M. H., and Marschak, J., "Measuring Utility by a Single-Response Sequential Method," Behavioral Science, Vol. 9, No. 3, July, 1964, pp. 226-232.
126. Davidson, D., Suppes, P., and Siegel, S., Decision Making: An Experimental Approach, Stanford University Press, Stanford, CA, 1957.
127. Pratt, J. W., "Risk Aversion in the Small and in the Large," Econometrica, Vol. 32, 1964, pp. 122-136.
128. Analysis of Decisions Under Uncertainty, McGraw-Hill, New York, 1967.
129. Turban, E. and Metasky, M. L., "Utility Theory Applied to Multivariable Systems Effectiveness Evaluation," Management Science, 17 (12), (1971).
130. Keeney, R. L., "Multiple Utility Functions," Operations Research, 22, (1), (1974).
131. "Preferences for Multi-Attributed Alternatives," RM-5868-DOT/RC, The RAND Corporation, April, 1969.
132. MacCrimmon, K. R. and Toda, M., "The Empirical Determination of Indifference Curves," Working Paper No. 124, Western Management Science Institute, University of California, Los Angeles, August 1967.
133. Hausner, M., "Multidimensional Utilities," in R. M. Thrall, C. H. Coombs, and R. L. Davis (Eds.), Decision Processes, John Wiley and Sons, New York, 1954.
134. Thrall, R. M., "Applications of Multidimensional Utility Theory," in R. M. Thrall, C. H. Coombs, and R. L. Davis (Eds.), Decision Processes, John Wiley and Sons, New York, 1954.
135. Mellon, W. G., "Priority Rating in More Than One Dimension," Naval Research Logistics Quarterly, Vol. 7, 1960, pp. 513-527.
136. Debreu, G., "Topological Methods in Cardinal Utility Theory," in K. J. Arrow, S. Karlin, and P. Suppes (Eds.) Mathematical Methods in the Social Sciences, 1959, Stanford Univ. Press, Stanford, CA, 1960.
137. Luce, R. D. and Tukey, J. W., "Simultaneous Conjoint Measurement," Journal of Mathematical Psychology, Vol. 1, 1964, pp. 1-27.
138. Krantz, D. H., "Conjoint Measurement: The Luce-Tukey Axiomatization and Some Extensions," Journal of Mathematical Psychology, Vol. 1, 1964, pp. 248-277.

139. Miller, J. R., III, "The Assessment of Worth: A Systematic Procedure and Its Experimental Validation," Doctoral Dissertation, MIT, June, 1966.
140. Hammond, J. S., "Bringing Order into the Selection of a College," Personnel and Guidance Journal, March, 1965, pp. 654-660.
141. Aumann, R. J. and Kruskal, J. B., "The Coefficients in an Allocation Problem," Naval Research Logistics Quarterly, Vol. 5, 1958, pp. 111-123.
142. "Independence in Utility Theory with Whole Produce Sets," Operations Research, Vol. 13, 1965, pp. 28-45.
143. "Additivity in Utility with Denumerable Product Sets," Econometrica, Vol. 34, 1964, p. 503.
144. "Additive Utilities with Incomplete Product Sets: Application to Priorities and Assignments," Operations Research, Vol. 15, 1967, pp. 537-542.
145. "Interdependence and Additivity in Multivariate, Unidimensional Expected Utility Theory," International Economic Review, Vol. 8, 1967, pp. 335-342.
146. Pollak, Robert A., "Additive Von Neumann-Morgenstern Utility Functions," Econometrica, Vol. 35, 1967, pp. 485-494.
147. "Additive Utilities with Finite Sets: Applications in the Management Sciences," Naval Research Logistics Quarterly, Vol. 14, 1967, pp. 1-13.
148. Keeney, R. L., "Quasi-Separable Utility Functions," Naval Research Logistics Quarterly, Vol. 15, 1968, pp. 551-565.
149. Officer, R. R. and Halter, A. N., "Utility Analysis in a Practical Setting," Am. J. of Ag. Econ., 50, 2 (1968).
150. Officer, R. R., Halter, A. N., and Dillion, John L., "Risk, Utility and the Probability of Extension Advice to Farmer Groups," Aust. J. of Ag. Econ., 11, 2 (1967).
151. Keeney, R. L., "Multidimensional Utility Function: Theory Assessment and Application," Operation Research Center Technical Report #43, Massachusetts Institute of Technology, October, 1969.
152. Yntema, D. B. and Klem, L., "Telling a Computer How to Evaluate Multidimensional Situations," IEEE Trans. on Human Factors in Electronics, Vol. HFE-6, No. 1, September 1965, pp. 3-13.
153. Bell, D. E., "A Decision Analysis of Objectives for a Forest Pest Problem," IIASA Report #RR-75-43, Laxenburg, Austria, 1975.

154. Keeney, R. L., "Energy Policy and Value Tradeoffs," IIASA Report #RM-75-76, Laxenburg, Austria, 1975.
155. Hilborn, R., "Preferences for Salmon Management on the Skeena River," Inst. of Resource Ecology Report #PR-2, Univ. of British Columbia, Vancouver, 1975.
156. Wood, E. F., Applying Multiattribute Utility Theory to Evaluation of Tisza River Basin Development Plans, Vol. 2, IIASA, International Inst. of Applied Systems Analysis Conference, Austria (1976).
157. Bushnak, Adil A., "Planning and Evaluation of Special Event Transportation Systems With Application to the Haji," Ph.D. Dissertation, Civil Engineering, Univ. of Michigan, Ann Arbor, MI, 1977.
158. Abdul-Fattah, A. F., "Engineering and Safety Analysis of Dual-Purpose Desalination Plants: A Case Study of Saudi Arabia," Ph.D. Dissertation, Nuclear Engineering, Iowa State University, Ames, Iowa, 1978.
159. Chiu, L. and Gear, T. E., "An Application and Case History of a Dynamic R&D Portfolio Selection Model," IEEE Trans. Engineering Management, Vol. EM-26, No. 1, Feb. 1979.
160. Ahmed, S., "Comparative Risk Analysis of Different Sources Using Utility Theory," M.S. Thesis, Nuclear Engineering, Iowa State University, Ames, Iowa, 1978.
161. Ahmed, Shahid, Cho, Hang Youn, and Abdul-Fattah, A. F., "Making Decisions on Iceberg Utilization Based Upon Multivariate Utility Theory: A Case Study - Saudi Arabia," in Iceberg Utilization, ed. A. A. Hussein (Pergamon Press, New York, 1978).
162. Kusayer, T. A., "Transfer of Nuclear Technology to Saudi Arabia," M.S. Thesis, Iowa State University, Ames, Iowa, 1978.
163. Ahmed, S. and Hussein, A. A., "Selection of Energy Systems Based on Decision Analysis of Various Attributes," SIMULATION 78, IASTED, Calgary, Alberta, Canada, 1978.
164. Ahmed, S. and Hussein, A. A., "Accommodation of Public Preference in Selection of Energy Alternatives," Trans. Am. Nucl. Soc., 30, 13 (1978).
165. Ahmed, S. and Hussein, A. A., "A Multivariate Utility Approach for Selection of Energy Source," Energy, 3, (1978), pp. 669-700.
166. Elsharkawy, A. I., Hussein, A. A., Nazer, W. O., and Kenarangui, R., "Planning of the Introduction of Solar Energy in Saudi Arabia: A Case Study," Energy Policy, (accepted for publication) (1979).

167. Ahmed, S., Hussein, A. A., Wyatt, P., and Poraun, Hower, "A Conservation Assessment of Proliferation Routes," (to be published, 1979).
168. McLagan, G. and Hussein, A. A., "Hard vs. Soft, A Gambler's Choice," Energy Communication, (to be published, 1979).
169. Hussein, A.A., Sabri, Z.A., Bushnak, A.A., Abdul-Fattah, A.F., and Khericha, Soli, "Procurement of Desalination Systems in a Competitive Business Environment," Third International Congress in Water Resources, April 23-27, 1979, Mexico City, Mexico.
170. Bushnak, A. A., Abdul-Fattah, A.F., Hussein, A.A., and Sabri, S. A., "A Comprehensive Systematic Approach to the Evaluation of Bids for Desalination," Desalination (to be published, 1979).
171. Cetron, M.J., Martino, J. and Roepcke, L., "The Selection of R&D Program Content - Survey of Quantitative Models." IEEE Trans Eng. Management EM-14 (1), 4 (1967).
172. Mottley, C. M. and Newton, R. D., "The Selection of Projects for Industrial Research," Operations Research, vol. 7, pp. 740-751, November-December 1959.
173. Garqiulo, G. R. , Hannoeh, J., Hertz, D. B. and Zang, T. "Developing Systematic Procedures for Directing Research Program." IRE Trans. on Engineering Management, vol. EM-8, pp. 24-29, March 1961.
174. Pound, W. H., "Research Project Selection: Testing a Model in the Field," IEEE Trans. on Engineering Management, vol. EM-11, pp. 16-22, March 1964.
175. Cetron, M. J., "Programmed Functional Indices for Laboratory Evaluation, "Profile," presented at the 16th Military Operations Research Symp. (MORS), Seattle, Wash., October 1965.
176. Wells, H. A., "Systems Planner Guide," presented at the 18th Military Operations Research Society Meeting, Fort Bragg, N. C., October 1966.
177. Belt, J. R., "Military applied R&D Project Evaluation" Master's thesis, U.S. Navy Marine Engineering Lab., Annapolis, MD. June 1966 (unpublished).
178. De L'Estoile, "Resource Allocation Model," French Ministere Des Armees, Paris, France.
179. Caufield, P. and Freshman, R., "Technology Evaluation Workbook," HQ Research and Technology Division, AFSC. Bolling AFB, Washington, D. C., January 1967.
180. Sobelman, S. A., "Modern Dynamic Approach to Product Development," Picatinny Arsenal, Dover, N.J., December 1958.

195. Martino, J. P., Caulfield, Cetron, M., Davidson, H., Liebowitz, H. and Rocpske, L., "A Method for balanced Allocation of Resources Among R&D Projects," USAF Office of Scientific Research, Tech. Rept., February 1967.
196. Disman, S., "Selecting R&D Projects for Profit," Chem. Engrg., vol. 69, pp. 87-90, December 1962.
197. Dean, B. V., and Sengupta, S., "On a Method for Determining Corporate Research Development Budgets," Management Sciences, Models and Techniques, vol. 2, C. W. Churchman and M. Verhulst, Eds. New York: Pergamon Press, 1960.
198. Cramer, R. H., and Smith, B. E., "Decision Models for the Selection of Research Projects," The Engineering Economist, vol. 9, pp. 1-20, January-February 1964.
199. Dean, B. V., and Hauser, L.E., "Advanced Materiel Systems Planning," Case Inst. Tech., Cleveland, Ohio, Operations Research Group Tech. Memo. 65, ONR-AMC Project Nonr-1141(19) September 15, 1966.
200. Berman, E. R., Draft: "Theoretical Structure of a Methodology for R&D Resource Allocation," Research Analysis Corp., May 26, 1965.
201. Esch, M. E., "Planning Assistance through Technical Evaluation 'Pattern'" presented at the 17th Nat'l Aerospace Electronics Conf., Dayton, Ohio, May 1965.
202. Blum, S., "Time, Cost, and Risk Analysis in Project Planning," U.S. Army Frankford Arsenal Report, August 22, 1963.
203. Bakanas, V., "An Analytical Method to aid in the Choice of Long Range Study Tasks," Cornell Aeronautical Lab. Rept. VQ-1887-H-1, USAMC Contract DA-49-186 AMC-97 (X) May 19, 1964.
204. Sobin, B. and Proschan, A., "Search and Evaluation Methods in Research and Exploratory Development," presented at the 2nd Conf. on Research Program Effectiveness, Washington, D. C., July 1965.
205. Sobin, B., "Proposal Generation and Evaluation Methods in Research and Exploratory Developments," Research Analysis Corp., Paper RAC-P-11, November 1965.
206. Keeney, R.L. and Raiffa, H., (1976). Decisions with Multiple Objectives, Wiley, New York.
207. Pelletier, C. A., et al., "Compilation and Analysis of Data on Occupational Radiation Exposure Experience at Operating Nuclear Power Plants" report to Atomic Industrial Forum, Inc. (September, 1974).

181. Freeman, R. J., "A Generalized Network Approach to Project Activity Sequencing," IRE Trans. on Engineering Management, vol. EM-7 pp. 103-107, September 1960.
182. Asher, D. T., "A Linear Programming Model for the Allocation of R&D Efforts," IRE Trans. on Engineering Management, vol. EM-9, pp. 154-157, December 1962.
183. Hess, S. W., "A Dynamic Programming Approach to R&D Budgeting and Project Selection," IRE Trans. on Engineering Management, vol. EM-9 pp. 170-179, December 1962.
184. Dean, B. V., Ed., Operations Research in Research and Development (Proc. Conf. at Case Inst. Tech.). New York: Wiley, 1963.
185. Dean, B. V., Ed., "Scoring and Profitability and Profitability Models for Evaluating and Selecting Engineering Projects", Case Inst. Tech., Operation Research Group, 1964.
186. Hill, F. I., and Roepcke, L. A., "An Analytical Method to Aid in the Choice of Long Range Study Tasks," presented at the U. S. Army Operations Research Symp. at Rock Island Arsenal, May 1964.
187. Nutt, A. B., "An Approach to Research and Development Effectiveness." IEEE Trans. on Engineering Management, pp. 103-112, September 1965.
188. Rosen, E. M., and Souder, W. E., "A Method for Allocating R&D Expenditures," IEEE Trans. on Engineering Management, vol. EM-12, pp. 87-93, September 1965.
189. Sacco, W. J., "On the Choice of Long Range Study Tasks," Ballistic Research Lab. Memo Rept. 1963, August 1965.
190. Albertini, J., "The QMDO Planning Process as it Relates to the U. S. Army Materiel Command," Cornell Aeronautical Lab. Rept. VQ-2044-H-1, USAMC Contract DA-49-185 AMC-237 (X), August 31, 1965.
191. Albertini, J., "The LRTP Planning Process as it Related to the U. S. Army Materiel Command," Cornell Aeronautical Lab. Rept. VQ-2044-H-2, USAMC Contract DA-49-186 AMC-237 (X), October 30, 1965.
192. Albertini, J., "LRTP Mathematical Model Brochure," Cornell Aeronautical Lab. Rept. VQ-2044-H-3, USAMC Contract DA-49-186 AMC-237 (X), October 30, 1965.
193. Cetron, M. J., "Quantitative Utility Estimates for Science & Technology 'Quest,'" presented at the 18th Military Operations Research Society, Fort Bragg, N.C., October 1966.
194. Cetron, M. J., and Freshman, R., "Some Results of 'PROFILE,'" presented at the 17th MORS, Monterey, Calif., May 1966.

208. Bureau of the Census, "Statistical Abstract of the United States - 1976", U.S. Department of Commerce, Washington, D. C., 1976.
209. Goldman, M. I., "Radioactive Waste Management and Radiation Exposure," presented at ANS Winter Meeting, Miami Beach, Fla., Oct. 19, 1971.
210. Wall, I. B., et al., "Overview of the Reactor Safety Study Consequence Model," NUREG-0340, (October, 1977).
211. "Capital Cost: Pressurized Water Reactor Plant," United Engineers and Constructors, NUREG-0241 (1976).
212. Davidson, D. P., Suppes, P., and Siegel, S., Decision-Making, an Experimental Approach, Stanford University Press, Stanford, California, 1957.
213. Mosteller, F. and Nozette, P., "An Experimental Verification of Utility," Journal of Political Economy, lix (1951), 371-404.

APPENDIX A

SUMMARY OF SELECTION METHODS FACT SHEETS

1. Cost Benefit Methods
2. Linear Programming
3. Normative Methods
4. Traditional Bayesian Methods
5. Value of Information
6. Value-Impact Analysis
7. Fuzzy Decision
8. Credibility Forecast
9. Pairwise Comparison
10. Delphi
11. Simple Checklist Approach
12. Q-Sort Procedure
13. Q-Sort Tally
14. Achievement Impact Matrix

APPENDIX B
SELECTION OF R&D PROGRAMS AND PROPOSALS EVALUATION
BASED ON VERBAL RATINGS

APPENDIX C
CELOT SAMPLE RUN

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COST-BENEFIT METHODS

1. Cost-Effectiveness

Cost c

Budget constraint c^*

Benefit measures $(b_1, b_2, \dots, b_n)$

Example

Select a set of s projects that yield a desirable portfolio of joint benefits within

$$\sum_{k=1}^s c_k \leq c^*$$

Method

- Define aspiration levels $b_1^*, b_2^*, \dots, b_n^*$.
- Find $b_1, b_2, \dots, b_n$ for the set.
- If $(b_1, b_2, \dots, b_n) \succeq (b_1^*, b_2^*, \dots, b_n^*)$
raise b_1^* if possible.
- If $(b_1, b_2, \dots, b_n) < (b_1^*, b_2^*, \dots, b_n^*)$
change some b_1^* 's.

2. Benefit-Cost Ratio

Method

- Find a set of conversion factors

$$w_1, w_2, \dots, w_n$$

To combine all benefits in terms of commensurable units

$$b = w_1 b_1 + w_2 b_2 + \dots + w_n b_n$$

- Compare projects by the pair (c_k, b_k)

- Define $R_k = b_k/c_k$ benefits to cost ratio
- Selection criterion

$$\max_{\sum_k} c_k \leq c^* (R_k)$$

- A similar approach is maximize benefit-cost difference
- A combination of ratio and difference methods may be used for consistency of results.

3. Modified Cost-Benefit Methods

Define a cost function

$$C(M, T)$$

M R&D monetary expenditures

T Time required to execute program

- Linear combination

$$C(M, T) = SM + h(T)$$

S non-negative constant

h non-decreasing function of T

- Program 1 is preferred to program 2 if

$$C(M_1, T_1) < C(M_2, T_2)$$

- Expanded cost function

$$C(M, T, \Pi)$$

where vector Π implicitly includes any number of variables

ACCOMMODATION FOR UNCERTAINTIES MAY BE DONE BY 3 METHODS:

Adjust returns and costs

- Reduce benefit estimates
- Increase cost (use conservative estimates)
- Drawbacks
 - No indication of degree of conservatism
 - Displays an aversion to uncertainty (not a desirable attitude)
 - Unlikely presence of errors in all estimates and hence may obscure important information

Adjust discount rate

- Used when present values of alternate programs are to be compared
$$I = I_T + I_R$$

T = Time and R = Risk

 - Represents an ordinate aversion to uncertainty
 - Very little effect for short term projects
 - Could lead to more risky strategies since lower present values will result from use of high discount rate

Adjust economic life

- Use shadow pricing

Merits and Limitations

- Conservative
- Deterministic
- Objectivity preserved
- Important benefits are incommensurables and intangibles (aesthetics, psychological comfort,...)
 - Shadow pricing
 - Conversion factors
 - Social discount rate
- Uncertainties are not considered

- Legitimacy of linear transformation
- Discount rate (for time dependent benefits)
- Group decision not possible
- Two projects may have the same ratio but one is more risky
- Tendency to inflate benefits and underestimate costs
- Selection of aspiration levels
- Tradeoffs
- Uncertainty
- Group decisions

LINEAR PROGRAMMING

Method

- Each program or alternative version is represented by a variable:
(not selected) $0 \leq x_{ij} \leq 1$ (fully selected)
i program (n-programs)
j version/proposal (m_i versions)
- Maximize a benefit function

$$\max \sum_{i=1}^n \sum_{j=1}^{m_i} b_{ij} x_{ij}$$

subject to

$$\sum_{j=1}^{m_i} x_{ij} \leq 1 \quad i = 1, 2, \dots, n$$

to ensure that each program appears once at most

$$\sum_{i=1}^n \sum_{j=1}^{m_i} a_{ijkp} x_{ij} \leq A_{kp}$$

$$k = 1, 2, \dots, N$$

$$p = 1, 2, \dots, P$$

b_{ij} expected benefit of version j of program i

a_{ijkp} amount of kth resource type (e.g., man-month)
required by version j of program i in time period p.

A_{kp} resource limit

Merits and Limitations

- Method feasibility tested.
- Assumes once a program is selected it has to continue to completion.
- Assumes the time series of resource requirements is known in advance.
- Assumes a single value benefit.
- Deterministic.
- Linear programming is severely limited in handling uncertainties.

NORMATIVE METHODS

Mathematical Models

- Objective function.
 - Measures benefit given an allocation pattern.
- Constraint function.
 - Represents organizational pattern.

Benefit Measurements Models

- Scoring models.
 - Specify merit of each proposal with respect to each of several program criteria.
 - Aggregate criterion scores to yield an overall program score.
- Comparative models.
 - Compare one proposal either to another or to some subset of alternative proposals.
- Benefit contribution models.
 - Tie the proposals to R&D program objectives.
 - Measure benefit in terms of contributions to the objectives.

Merits and Limitations

- Clarifies the concepts of:
 - Learning.
 - Flexibility.
 - Parallel developments.
- Recognizes that:
 - Information gained through time.
 - Better decisions require additional knowledge.

Merits and Limitations (cont.)

- Treats sequential or multi-stage approaches to select R&D programs.
- Allows possibility of pursuit of alternative R&D programs at different intensity.
- Requires a precise description of R&D programs/proposals to be selected.
- Inadequate treatment of project and parameter interrelations with respect to both benefit contribution and to resource utilization.
- Inadequate treatment of uncertainty as it impacts on benefit measurement and parameter estimation.
- Inadequate treatment of multiple, interrelated decision criteria which have no common, natural underlying measure.
- Inadequate treatment of the time variant property of the parameters and criteria and the associated problem of continuity in the research program and staff.
- A restricted view of the problem which
 - Portrays a once-a-year investment decision rather than in intermittent stream of investment alternatives.
 - Does not include such attributes as timing of the decision, generation of additional alternatives, and recycling.
 - Does not recognize the diversity of projects along the spectrum from basic research to engineering.
 - Views the problem as a decision event rather than as a hierarchial, diffuse decision process.
- No explicit recognition and incorporation of the importance of individual R&D personnel.
- The inability to establish and maintain balance in the R&D program; e.g., balance between basic and applied research, between offensive and defensive research, between breakthrough and improvement orientations, between in-house and contracted projects, between product and process oriented projects, and between high risk/high payoff and low risk/moderate payoff projects.
- Given these limitations, it is clear why few normative models of the R&D project selection/resource allocation decision have been implemented and used by R&D managers.
- As a result of the small number of applications and of the limited types of models which have been applied, most applications are simple scoring models or financial index models, it is nearly impossible to assess the potential utility of the normative R&D project selection/resource allocation models.

TRADITIONAL BAYESIAN METHODS

- Decision Under Uncertainty

The consequence of selection of an alternative depends on the choice and the uncontrolled role of chance which may result in different outcomes at different levels of expectation. (State-of-Nature)

- Decision criteria:

DECISION CRITERIA	ACTION	ATTITUDE
Maximax	Maximize the maximum possible gain	Optimistic
Maximin	Maximize the minimum possible gain	Pessimistic
(Or Minimax)	(Or minimize the maximum possible gain)	Pessimistic
Maximum Probability	Maximize the gain assuming that the most likely outcome prevails	Neutral

- Pay-off Matrix

Example

- Each successful program corresponds to gain \$30K
- Each failure corresponds to lose \$20K

		CHANCE			
		0	1	2	3
ACTION	# OF PROGRAMS CONSIDERED \ # OF SUCCESSES	0	0	0	0
	0	0	0	0	0
	1	-20	30	30	30
	2	-40	0	60	60
	3	-60	-10	40	90
PROBABILITY OF SUCCESS		0.1	0.3	0.5	0.1

CRITERIA	ACTION	HOPED PAYOFF
Maximax	Select 3 programs	Gain \$90K
Maximin	Undertake 0 programs	Lose \$0K only
Maximum Probability	Select 2 programs	\$60K

- Expected (monetary) value EMV
- Moderates are often called EMVER or Baysian

$$EMV = \sum_{i=1}^n P_i V_i \quad n \equiv \# \text{ of chances}$$

P_i probability of occurrence of chance i

V_i outcome of chance i

NUMBER OF PROBLEMS UNDERTAKEN	0	1	2	3
EMV	0	25	<u>35</u> (Best Action)	20

CRITERIA	ACTION	HOPED PAYOFF
Maximax	Select 3 programs	Gain \$90K
Maximin	Undertake 0 programs	Lose \$0K only
Maximum Probability	Select 2 programs	\$60K

- Expected (monetary) value EMV
- Moderates are often called EMVER or Baysain

$$EMV = \sum_{i=1}^n P_i V_i \quad n \equiv \# \text{ of chances}$$

P_i probability of occurrence of chance i

V_i outcome of chance i

NUMBER OF PROBLEMS UNDERTAKEN	0	1	2	3
EMV	0	25	35 (Best Action)	20

VALUE OF INFORMATION

- The decision-maker usually has two strategies at hand in a typical R&D program.
 1. Launch those program/projects that are most likely to achieve objectives of LWR Safety.
 2. Start with pilot programs at lower funding level to gather more information for a more reliable selection at a later date. (This is the action taken by Sandia in Fiscal Year 1979).
- The decision here will depend on the value of information which can be gathered by the pilot programs.
- Define "Expected Profit under Certainty" (EPC) as
 "The profit that can be accrued if no uncertainty of outcomes prevailed"
- Define the "Expected Value of Perfect Information" (EPVI) as
 "The incremental amount that can be justified to remove uncertainty"

$$E V P I = E P C - E M V$$

	PROGRAM A			PROGRAM B		
	HIGH	MODERATE	LOW	HIGH	MODERATE	LOW
1. <u>PROBABILITY OF SUCCESS:</u>	0.2	0.4	0.4	0.2	0.4	0.4
2. <u>EQUIVALENT MONETARY VALUE OF ACHIEVING GOALS (\$M)</u>						
A. REDUCTION OF PRE- SENT LOW LEVEL RISK	100	10	5	50	10	5
B. LICENSABILITY IMPROVEMENT	20	7	2	50	5	10
C. INCREASE PUBLIC ACCEPTANCE	30	8	3	30	5	20
D. REDUCTION OF SAFETY-RELATED COSTS	150	15	-70	70	10	-55
TOTAL	300	40	-60	200	30	-20

PAYOFF MATRIX

<div> <div>PROBABILITY</div> <div>PROGRAM</div> </div>	H	M	L	EMV
	0.2	0.4	0.4	
A	300	40	-60	<u>52</u>
B	200	30	-20	44

- Select A based on High EMV
- EPC Calculations

CHANCE	BEST ACTION	PROFIT \$M	% OF TIME	EPC \$M
H	A	300	0.2	60
M	A	40	0.4	16
L	B	-20	0.4	-8
TOTAL				68

$$EVPI = EPC - EMV = \$16M$$

- To know how successful the R&D programs A and B is likely to be worth up to \$16M investment prior to selection of either one.
- Drawbacks
- Use of one dimensional measure (monetary in the example).
- Does not reflect preferences among objectives.

Use of Utility

- The utility of low success of B is 10 compared to 0 in case of A because decision-maker may prefer to improve licensability and public perception than reduce safety-related cost.
- Utility values can be determined using various measures of effectiveness not necessarily tangibles.

PAYOFF MATRIX

PROGRAM \ PROBABILITY	H	M	L	E U UTILITIES
	0.2	0.4	0.4	
A	85	35	0	31
B	80	40	10	<u>36</u>

VALUE - IMPACT ANALYSIS

Method

- Statement of the objective
- Problem description
- Background of analytical approach and assumptions used
- Identification of alternatives including the status quo
- Estimation of the value and cost alternatives
- Specification of criteria for the alternatives
- Value judgment and recommendations

Objective Function

- Identify the issue and subissues associated with a specific policy action.
- Evaluates the values of alternative for meeting an objective.
- Compares consequences associated with alternative identified to meet some goal.
- Document explicitly any value judgments and assumptions made.

Merits and Limitations

- Addresses both the impact and the value of a proposed action.
- Measures the relative merits of an action.
- Estimates the relative or absolute differences in the effectiveness of the alternatives.
- Measures an alternative's ability to satisfy some stated objective.
- Proper evaluation reduces the time spent on argumentative discussions about attractive but unfeasible options.
- Suitable for unique or generic licensing actions and non-routine, non-recurring regulatory actions.
- Suitable for proposal review by Regulatory Requirements Committee.
- A balanced value judgment is provided.
- Meaningful recommendations can be made.
- Depends on the anticipated magnitude of costs and benefits associated with a proposed action.
- Depends on the dictates of anticipated public interest.
- Require particular methods to cope with special factors.
 - Sensitivity analysis - If conclusions are dependent on particular variables or specific assumptions, the effect of using a range of estimates for the variables, or changing assumptions, should be investigated.
 - Discounting - When comparing resources at different points in time, discounting is applied. This can change substantially the preference ranking of proposed policy actions.
 - Intangibles - Factors which cannot be quantified and may increase the values of a particular alternative must be addressed in the analysis.
 - Inflation - Where assumptions of inflation would significantly alter the analyses, it is preferable to present conclusions in current dollars.

FUZZY DECISION

Method

- Define membership function $\mu_A(a)$
 - $\mu_A(a)$ represents the degree of belonging of an element to a set.
 - $0 \leq \mu_A(a) \leq 1$
 - Can represent statements
 - Subjective

EXAMPLE

CRITERION	WEIGHT	RATINGS	
		PROGRAM A	PROGRAM B
1	Very Important	Good	Fair
2	Rather Unimportant	Fair	Good

The degree of membership of A&B in the set of alternatives

A	1
B	0.7

Membership function of preferability of Program A over Program B

- Ordinal utility

- Alternate projects A_1 ----- A_M
to be evaluated using aspects a_1 ----- a_n
- If weight w_j corresponds to the importance of aspect j
- Given A_i , the relative merit of a_j is assessed by rating r_{ij}
- Alternative A_i receives the average rating

$$\bar{r}_j = \sum_{j=1}^n w_j r_{ij} / \sum_{j=1}^n w_j$$

- Higher rating number $\implies$ higher utility

- Fuzzy-Set

Membership functions

$$\mu_{w_j}^{(w_j)}$$

IMPORTANCE OF a_j

$$\mu_{R_{ij}}^{(r_{ij})}$$

RATING OF a_j for A_i

$$g(z) = \sum_{j=1}^n w_j r_{ij} / \sum_{j=1}^n w_j$$

$$z_i = (w_1, w_2, \dots, w_n, r_{i1}, r_{i2}, r_{i3}, \dots, r_{in})$$

$$\mu_{z_i}^{(z_i)} = \min (\mu_{w_1}(w_1), \dots, \mu_{w_n}(w_n),$$

$$\mu_{R_{i1}}(r_{i1}), \dots, \mu_{R_{in}}(r_{in}))$$

and

$$\mu_{\bar{R}_i}(\bar{r}) = \sup_{\substack{z_i \\ g(z_i) = \bar{r}}} \mu_{z_i}(z_i)$$

Merits and Limitations

- Probabilities and utilities are represented by unique numbers.

If the results are insensitive to the exact values then imprecision of such values is not important.

BUT IF results depend on precision of values then fuzzy set theory may be used.

Bayes
Probability
Uncertainty

Fuzzy
Possibility
Imprecision

CREDIBILITY FORECAST

Method

- Determine the credibility range for benefit in each stage of the program.
- Transform benefit ranges into focus values.
- Construct a benefit diagram for each project.
- Comparison of graphs shows that $A > B$.
- Benefit flow is used as a yardstick.
- Another yardstick is the Equivalent Maximum Investment Period (EMIP).

EMIP = Shaded area/maximum outlay

This can be used to evaluate proposals

Merits and Limitations

- Credibility method is as subjective as probability methods since benefit flow curves are subjective.

PAIRWISE COMPARISON

Method

- Set criteria (valid, operative and real)

OBJECTIVE	CRITERION
1. Reduce present low level of risk	Risk reduction
2. Improve LWR licensability	Licensability improvement
3. Increase public acceptance	Public acceptance
4. Reduce safety related cost	Safety cost reduction

- Rate criteria by assigning values on a ratio scale by pairwise comparison.
(Forced choice among competing alternatives)
 - Risk reduction 5 times as important as licensability improvement.
 - Licensability is 0.5 times as important as public acceptance.
 - Public acceptance is twice as important as safety cost reduction.
 - Nothing to compare cost reduction with.

CRITERION, i	RATING, R_i	K_i	W_i
Risk reduction	5	3.75	.50
Licensability improvement	0.5	0.75	.10
Public acceptance	2.0	2.0	.27
Safety cost reduction	--	1	.13
		<u>7.5</u>	<u>1.00</u>

- Enter $K_4 = 1$ the last criterion.
- Obtain other K_i 's by cross multiplication.
- $W_i = K_i / \sum K_i$
- Order criteria according to weights.

- Compare cumulative weights C_i and weights for consistency check.

ORDER	CRITERIA ORDERED	W_i	C_i^*
1	Risk reduction	0.50	0.43
2	Public acceptance	0.27	0.23
3	Safety cost reduction	0.13	0.10
4	Licensability	0.10	--

- Moved up one position
- Comparison shows that
 - Risk reduction is more important than other criteria combined.
 - Public acceptance is less important than safety cost reduction and licensability improvement combined.
- If the comparison is consistent with a preassessment by decision-maker then proceed.
- Project Evaluation
- Consider 3 projects "A", "B" and "C"
- For each criterion, rate projects pairwise.

1. RISK REDUCTION

PROJECT	R_{1j}	K_{1j}	S_{1j} WEIGHT
A	5.0	30.0	0.81
B	6.0	6.0	0.16
C	--	1.0	0.03
		37.0	1.00

3. SAFETY COST REDUCTION

PROJECT	R_{3j}	K_{3j}	S_{3j}
A	10.0	4.0	0.74
B	0.4	0.4	0.07
C	--	1.0	0.19
		5.4	1.00

2. PUBLIC ACCEPTANCE

PROJECT	R_{2j}	K_{2j}	S_{2j}
A	3.0	1.5	0.50
B	0.5	0.5	0.17
C	--	1.0	0.33
		3	1.00

4. LICENSABILITY IMPROVEMENT

PROJECT	R_{4j}	K_{4j}	S_{4j}
A	0.5	1.0	0.25
B	2.0	2.0	0.50
C	--	1.0	0.25
		4.0	1.00

- Make consistency checks between weight S_{ij} and cumulative weights for each criterion to compare with prior assessment by decision-maker.
- A reference project (standard) may be included for comparison.
- Final score

$$\text{MAX. } \sum_{i=1}^4 W_i S_{ij}, j = A, B, C$$

CRITERION	W_i	A		B		C	
		S_{iA}	$W_i S_{iA}$	S_{iB}	$W_i S_{iB}$	S_{iC}	$W_i S_{iC}$
1. Risk Reduction	0.50	0.81	0.41	0.16	0.08	0.03	0.02
2. Public Acceptance	0.20	0.50	0.10	0.17	0.03	0.33	0.07
3. Safety Cost Reduction	0.13	0.74	0.10	0.07	0.01	0.19	0.03
4. Licensability Improvement	0.10	0.25	0.03	0.50	0.05	0.25	0.03
FINAL SCORE			0.64		0.17		0.15

Merits and Limitations

- A Pragmatic Approach.
- Based on pairwise comparison by forced choice.
- R&D projects/proposals ranked and rated using simple arithmetic.
- Emphasizes measuring quality (utility) rather than measuring quantity.

DELPHI

Method

Collection and analysis of expert opinion utilizing surveys and well-designed questionnaires.

Merits and Limitations

- Anonymity.
 - Reduce effect of dominant individual.
 - Questionnaires.
 - Other formal communication channels.
- Controlled Feedback:
 - Sequence of rounds.
 - A summary of the results given to participants between rounds.
 - Reduces noise.
- Statistical group response.
 - Reduce group pressure for conformity.
 - Final results may exhibit spread in individual opinions.
- Rapid and relatively efficient way to acquire expert's knowledge (compared to conferences and papers).
- Less effort to respond (if questionnaire is well-designed).
- Properly managed DELPHI survey can be highly motivating.
- Lends an air of objectivity to outcomes.
- Response can be novel, informative, and interesting to all participants.
- Releases respondents inhibitions.
- Risk sharing.

SIMPLE CHECKLIST APPROACH

ELEMENT	DESCRIPTOR*				
	A	B	C	D	F
R & D					
PROBABILITY OF TECHNICAL SUCCESS					
TECHNICAL NOVELTY					
RELATED KNOW-HOW					
KNOW-HOW GAIN					
TIME TO DEVELOP					
MANPOWER AVAILABLE					
EQUIPMENT					
COMPETITIVE ACTIVITY					
PATENTABILITY					
SANDIA					
FITS DOE OBJECTIVES					
ACCEPTABLE FUND SIZE					
PRESTIGE VALUE					
EFFECT ON DOE					
EFFECT ON FUTURE PLANS					
• A VERY FAVORABLE					
B FAVORABLE					
C AVERAGE					
D UNFAVORABLE					
F VERY UNFAVORABLE					

QUALITATIVE METHOD

1. Qualitative Method

Method

- List elements of interest
 - Avoid double counting
 - Keep list short
- Check appropriate descriptor for each project
- Select projects with acceptable overall descriptor checkmarks pattern
- Compare selected projects for further screening

Merits and Limitations

- Simple and attractive
- Seemingly convincing
- Commonly used
- Useful for keeping records straight (in case of premeditated decisions)
- Considerable off-list study often required
- Acceptable patterns hard to define
- Deliberate or unconscious favoritism likely
- Superficial

2. Quantified Method

Method

- Form checklist as in the qualitative method
- Weight the elements for importance

W_E = Element Weight

$\sum_{I=1}^M W_{EI}$ = Total Weight of M-Elements

- Weight the descriptors according to increasing favor; W_D ; for example

$W_D = 4.0$	A
$= 3.0$	B
$= 2.0$	C
$= 1.0$	D
$= 0.0$	F

- Project rating, R_p , from 0 to 100,

$$R_p = 100 \frac{\sum_{I=1}^M (W_{EI} W_{DI})}{(4 \sum_{I=1}^M W_{EI})}$$

3. Profile

Method

- The profile of a given element reflects the decision-maker's confidence in the information available at a specific time about a particular project.
- Profiles represent optimum information accumulation patterns.
- Prepare a standard set of profiles; one for each element, for earlier successful projects.
- Construct profiles on the checklist for the new projects.
- Compare new profiles against standard profiles.
- Precision of information is ranked in the profile on a scale of 1 to 5.
- Values 4 are shaded for comparison purposes.

- Visual display
- Useful for project progress evaluation
- Can be computerized
- Profiles of new projects are difficult to predict
- Standard profiles are hard to construct
- Reevaluating past projects in terms of confidence in information requires unusual honesty
- Speculative in nature

A-30

Q-SORT PROCEDURE

Method

- A psychometric method for classifying a set of projects according to individual opinions of a group of persons.

- Assemble decision-making group in one room.
- Prepare a stack of cards for each member.
- Each card bear a title of one of the projects considered.
- Each member will sort the cards using specific criterion; for example, reduction of low risk level, increase of public acceptance, etc.

Merits and Limitations

- Useful when merits of R&D projects defy quantification.
- The semistructured open forum allows parties to articulate and exchange opinions.
- The exchange may assist formulating a self-awareness of their own value structures.

The method is useful in preceding quantification for thought stimulation and conceptual evaluation.

- In general there is a need for effective structured group communication within most project selection processes.
- Too imprecise to yield final decisions.

Steps

1. Give a deck to each member.
2. Divide deck into two piles (not necessarily equal):
 - High level pile
 - Low level pile
3. Select cards from each pile to form a third pile, medium level of criterion.
4. Select cards from H. L. to form a very high level pile.
Select cards from low level to form a very low level pile.
5. Survey the selections and shift any cards that seem out of place until the classification is satisfactory.

Q-SORT TALLY

Method

- Each individual announces his result.
- Records result as tallys in a chart.
- Display chart.
- Discuss findings.
- Repeat Q - Sort to approach organizational consensus.
- In presence of multicriteria situations for the Q-Sort, the process may be done for each criterion in the form of:

Structuring --- Sharing --- Structuring Activity.

Q - SORT TALLY

(# OF PERSONS = 15)

PROJECT #	PRIORITIES				
	V.H.	H.	M.	L.	V.L.
1	1	2	1	3	8
2	11	2	2	0	0
3	1	3	7	2	2
4	9	6	0	0	0
5	0	1	5	4	5
6	1	2	6	2	4
7	11	0	3	1	0
8	0	0	7	2	6

Merits and Limitations

- Useful when merits of R&D projects defy quantification.
- The semistructured open forum allows parties to articulate and exchange opinions.
- The exchange may assist formulating a self-awareness of their own value structures.

The method is useful in preceding quantification for thought stimulation and conceptual evaluation.

- In general there is a need for effective structured group communication within most project selection processes.
- Too imprecise to yield final decisions.

ACHIEVEMENT IMPACT MATRIX

Method

- The matrix illustrates the impact of program tasks on criteria.
- Reordering the matrix to display clusters of impacts.
- Matrix shows that program emphases are $B > A > C \approx D$
- Matrices for various programs may be compared for selection based on criteria such as A, B, C and D.
- Matrix may include numbers and formal reordering algorithms may be used to display clusters of higher-valued ratings.
- Negative values may result for adverse results.

	PROGRAM MILESTONES/PROPOSALS									
	10	9	8	7	6	5	4	3	2	1
1. LOW LEVEL RISK	*								*	*
2. PUBLIC ACCEPTANCE	*				*		*		*	*
3. SAFETY-RELATED COST				*		*				*
4. LICENSABILITY		*			*	*				

	MILESTONES									
	8	9	5	7	6	10	2	3	5	3
A	0	0	0	0	0	10	6	5	5	3
B	0	0	0	0	9	7	7	0	0	0
C	0	0	7	5	0	0	0	0	0	0
D	0	9	8	0	4	0	0	0	0	0

	MILESTONES									
	8	9	5	7	6	4	1	10	2	1
A									*	*
B						*	*	*	*	*
C			*	*	*					
D	*	*			*					

Impact Analysis

- Similar to delphi.
- Experts postulate key effects/results of a given set of programs/proposals.
- In a session a group evokes (say 100 results) to come out of the programs.
- A specialist selects the most significant (say 8).
- Experts (in one session) rate the impact of each of these happenings on the other 7 using a simple numerical scale.
- The key result probabilities are calculated using the resulting IMPACT MATRIX.
- Compare to initial postulate.
- Finally a consensus is reached about the structure of the R&D program.

SELECTION OF R&D PROGRAMS AND PROPOSALS EVALUATION BASED ON VERBAL RATING

Introduction

Decision-makers often prefer verbal ratings over the use of precise numerical values. In this case, the ratings can be expressed by the degree of belonging to a fuzzy set, which allows for numerical representation of ratings over a range of values. This technique is capable of handling imprecision since a range of values is used to describe a level of a given attribute rather than a precise number. However, each value is associated with a degree of possibility representing the given attribute level.

In decision problems where many attributes have to be considered, the imprecision in input values may affect the final decision. Sensitivity analysis may be used with its limitations to detect changes in the results as the input values vary. Changing the attribute levels or the input variables one-at-a-time may show robustness of the decision, and yet the decision may flip when the attributes are changed in combination.

As a way to overcome such difficulty and to accommodate for fuzziness in the decision environment, fuzzy set theory may be used. The theory is flexible enough to be used in conjunction with formal decision methodologies including cost/benefit analysis, decision trees, value impact, rating or multiattribute utility theory. Here,

fuzzy sets are used in the case of weighted-ratings alternatives characterized by a number of attributes for which specific weights can be assigned.

The objective of weighted-ratings is to rank order each alternative under uncertainty. This is done in the context of fuzzy environment by verbal evaluation of the attribute ratings and weights. The verbal statements are fuzzy variables which can be characterized by appropriate membership functions.

Theory

Informally, a fuzzy set is a "class" of "objects" in which there is no sharp boundary that exists between those objects that belong to the class and those which do not belong to that class. Mathematically, if $X = \{x\}$ represents a collection of points or objects denoted generically by x , then a fuzzy set A in X ($A \subseteq X$) is a set of ordered pairs of the form

$$A = \{(x, \mu_A(x))\} , \quad x \in X \quad (1)$$

where $\in$ is a shorthand of "belongs to" and $\subseteq$ refers to "a subset of". The function $\mu_A(x)$ is the grade of membership of x in A and $\mu_A: X \rightarrow M$ is a function mapping from X into a space M called the membership space [1]. The space M may be assumed to occupy the interval $[0,1]$ with 0 being the lowest and 1 the highest grades of membership.

As an example, let $X = \{0, 1, 2, \dots\}$ be the collection non-negative integers, thus a fuzzy set A ($A \subseteq X$) of several objects may be (subjectively) defined as the collection of the order pairs,

$$A = \{(3, 0.6), (4, 0.8), (5, 1), (6, 1), (7, 0.8), (8, 0.6)\} \quad (2)$$

The general properties of decision-making in a fuzzy environment may be assessed by a fuzzy goal G and a fuzzy constraint C . Those are fuzzy sets with membership functions $\mu_G(x)$ and $\mu_C(x)$ of G and C respectively, where $G \subset X$ and $C \subset X$ and the set $X = \{x\}$ is a set of possible alternatives. [1]

A decision is basically a choice or a set of choices selected from available alternatives to achieve a specific goal or objective under given constraints. Thus, a fuzzy decision D is a set of alternatives resulting from the intersection of the goals and constraints, that is $D \subset X$ is formed from a combination of a goal, G , and a constraint C , or

$$D = G \cap C \quad (3)$$

where $\cap$ refers to the intersection between two sets. The corresponding membership function $\mu_D(x)$ of D is given by

$$\mu_D(x) = \mu_G(x) \wedge \mu_C(x) \quad (4)$$

where $\wedge$ refers to intersection of outcomes or functions and it represents a minimum in the fuzzy sense.

In general, if there are n goals and m constraints, the fuzzy decision is given by

$$D = \left(\bigcap_{i=1}^n C_i \right) \cap \left(\bigcap_{j=1}^m C_j \right) \quad (5)$$

and similarly

$$\mu_D = \left(\bigwedge_{i=1}^n \mu_{G_i} \right) \wedge \left(\bigwedge_{j=1}^m \mu_{C_j} \right) \quad (6)$$

An optimal decision is defined as any alternative $x' \in X$ which maximizes μ_D , that is

$$\mu_D(x') = \sup_x \mu_D(x) \quad (7)$$

In some situations, the product of μ_G and μ_C is used to get closer interdependence between the goals and constraints [2], thus a product-fuzzy decision $D_{Pr} \subset X$ has the membership function

$$\mu_{D_{Pr}} = \left(\prod_{i=1}^n \mu_{G_i} \right) \cdot \left(\prod_{j=1}^m \mu_{C_j} \right) \quad (8)$$

Also, it is sometimes useful to assign weights to the goals and constraints in a decision-making process to obtain a convex-fuzzy decision $D_{co} \subset X$ with the membership function

$$\mu_{D_{co}} = \sum_{i=1}^n \alpha_i \mu_{G_i} + \sum_{j=1}^m \beta_j \mu_{C_j} \quad (9)$$

where

$$\{\alpha_i\}_{i=1}^n ; \{\beta_j\}_{j=1}^m ; \alpha_i, \beta_j \geq 0 ;$$

and

$$\sum_{i=1}^n \alpha_i + \sum_{j=1}^m \beta_j = 1 \quad (10)$$

Fuzzy Weighted-Ratings

Consider a decision that involves m multi-aspect alternatives, A_i , $i = 1, 2, \dots, m$ characterized by the aspects (attributes), a_j , $j = 1, 2, \dots, n$. The fuzzy evaluation of A_i based on the fuzzy weights w_j of aspect a_j and the fuzzy rating r_j of A_i from the point of view of aspect a_j is obtained by defining

$$g(z) = \frac{\sum_{j=1}^n w_j r_j}{\sum_{j=1}^n w_j} \quad (11)$$

where the function g maps R^{2n} into R , $z = (w_1, w_2, \dots, w_n, r_1, r_2, \dots, r_n)$ on product space R^{2n} . Thus,

$$\mu_{Z_i} = \left[\bigwedge_{j=1}^m \mu_{W_j}(w_j) \right] \wedge \left[\bigwedge_{k=1}^n \mu_{R_{ik}}(r_k) \right] \quad (12)$$

The fuzzy rating r_{ij} of aspect a_j of alternative A_i is represented by the membership function $\mu_{R_{ij}}(r_{ij})$, where r_{ij} takes its values on the real line R . Similarly, the relative importance of aspect a_j will be a fuzzy variable w_j represented by the membership function $\mu_{W_j}(w_j)$ where w_j also takes its values on R . Through the mapping $g: R^{2n} \rightarrow R$, the fuzzy set $Z = (R^{2n}, \mu_{Z_i})$ induces a fuzzy set $\bar{R}_i = (\bar{R}, \mu_{\bar{R}})$ with membership function

$$\mu_{\bar{R}_i}(\bar{r}) = \sup_{Z: g(r) = \bar{r}} \mu_{Z_i}(z), \quad \bar{r} \in R \quad (13)$$

where $\bar{r}_i$ defines the final rating of alternative A_i .

Ranking

In fuzzy decisions, the optimal decision is not directly that of selecting the alternative of the highest rank as is generally the case. In order to select the most preferred alternative,

a fuzzy set (I, μ_I) is defined where I is the fuzzy rank of alternative i .

Also, one may define a conditional fuzzy set $(I, \mu_{I/\bar{R}})$ with a membership function $\mu_{I/\bar{R}}(i)/\bar{r}_1, \bar{r}_2, \bar{r}_3 \dots \bar{r}_m = \begin{cases} 1, & \text{if } \bar{r}_i > \bar{r}_j \forall j \in I \\ 0, & \text{otherwise.} \end{cases}$ (14)

The final fuzzy rating on R^m define a fuzzy set $\bar{R} = (R^m, \mu_{\bar{R}})$ with

$$\mu_{\bar{R}}(\bar{r}_1, \bar{r}_2 \dots \bar{r}_m) = \bigwedge_{i=1}^m \mu_{\bar{R}_i}(\bar{r}_i) \quad (15)$$

The fuzzy set $(R^m, \mu_{\bar{R}})$ and the conditional fuzzy set $(I, \mu_{I/\bar{R}})$ together induce the fuzzy set (I, μ_I) for which μ_I is now defined as

$$\mu_I(i) = \sup_{\bar{r}_1, \bar{r}_2 \dots \bar{r}_m} \mu_{I/\bar{R}} \wedge \mu_{\bar{R}} \quad (16)$$

The order of preference of alternatives i will be determined by the degree of membership given by μ_I . The best alternative corresponds to unity. However, the order of preference only provides partial information about the preferred alternative and does not indicate how much is the degree of preference of this alternative compared to other alternatives. Furthermore, it is possible that more than one alternative would have a unity membership in the fuzzy set (I, μ_I) .

Preferability

In order to determine the degree of preferability of the preferred alternative, the mapping $h_i: R^m \rightarrow R$ is defined to induce

a fuzzy set $P_i = (R, \mu_{P_i})$ with membership function

$$\mu_{P_i}(p) = \sup_{\substack{\bar{r}_1, \bar{r}_2, \dots, \bar{r}_m: \bar{R}(\bar{r}_1, \bar{r}_2, \dots, \bar{r}_m), \\ h_i(\bar{r}_1, \bar{r}_2, \dots, \bar{r}_m) = p}} \bar{R}(\bar{r}_1, \bar{r}_2, \dots, \bar{r}_m), \quad p \in R \quad (17)$$

where $\mu_{\bar{R}}$ is given by Eq. (15). The function $\mu_{P_i}(p)$ may be used to judge the degree of preferability of alternative A_i over the other options. To evaluate this membership function, assume the general function

$$\mu_Y(y) = \sup_{x \in R^n: f(x)=y} \bigwedge_{i=1}^n \mu_i(x_i), \quad y \in R \quad (18)$$

where $\mu_i(x_i)$ are given membership functions; $i = 1, 2, \dots, n$; f is a function of mapping R^n into R and $x = (x_1, x_2, x_3, \dots, x_n)$. Assume that μ_i are piecewise continuously differentiable functions mapping R^n into R ; each function is bounded, non-negative and with finite support. Also, f is a continuously differential mapping of R^n into R .

Now, consider the following theorem [3]: Suppose that the point $\hat{x} = (\hat{x}_1, \hat{x}_2, \dots, \hat{x}_n) \in R^n$ satisfy the following three conditions:

$$(1) \quad \mu'_i(\hat{x}_i) = \frac{d \mu_i(x_i)}{d x_i} \neq 0$$

and

$$f_i(x) = \frac{df(x_1, x_2, \dots, x_n)}{dx_i} \neq 0$$

$$(2) \mu_1(\hat{x}_1) = \mu_2(\hat{x}_2) = \dots = \mu(\hat{x}_n); \text{ and}$$

$$(3) \mu'_i(\hat{x}_i)/f_i(\hat{x}) \text{ has the same sign for each}$$

$$i \in \{1, 2, \dots, n\}$$

Then $\hat{x}$ is a strict relative maximum point of the mathematical programming problem

$$\max \bigwedge_{i=1}^n \mu_i(x_i) \text{ subject to } f(x) = \hat{y} \quad (19)$$

where $\hat{y} = f(\hat{x})$. Thus, in order to determine the membership function

$\mu_{\bar{r}}$ of

$$\bar{r} = \frac{\sum_{j=1}^n w_j r_j}{\sum_{j=1}^n w_j} \quad (20)$$

the partial derivatives f_{w_j} and f_{r_j} with respect to w_j and r_j respectively need to be evaluated, that is

$$f_{\bar{r}_j}(r, w) = \frac{w_j}{\sum_{i=1}^n w_i} \quad (21)$$

and

$$f_{w_j}(r, w) = \frac{r_j - \bar{r}}{\sum_{i=1}^n w_i} \quad (22)$$

where

$$i = 1, 2, \dots, n$$

$$r = (r_1, r_2, \dots, r_n)$$

and

$$w = (w_1, w_2, \dots, w_n)$$

In order to compute the values of $\bar{r}$ for which $\mu_{\bar{R}}(\bar{r}) = \mu_0$ with μ_0 a given number, the numbers $\hat{r}_1, \hat{r}_2, \dots, \hat{r}_n$ and $\hat{w}_1, \hat{w}_2, \dots, \hat{w}_n$ need to be found such that $\mu_{R_i}(\hat{r}_i) = \mu_{W_i}(\hat{w}_i) = \mu_0$ for $i=1, 2, \dots, n$ and $\mu'_{R_i}(\hat{r}_i)$ and $\mu'_{W_i}(\hat{w}_i)/\hat{r}_i - \bar{r}$ all have the same signs.

To compute the values of p_i for which

$$p_i = x_i - \frac{1}{m-1} \sum_{\substack{j=1 \\ j \neq i}}^m x_j \quad (23)$$

and

$$\mu_{P_i}(p_i) = \mu_0 \quad (24)$$

with μ_0 a given number, the numbers $\hat{x}_1, \hat{x}_2, \dots, \hat{x}_m$ need to be found such that $\mu_1(\hat{x}_1) = \mu_2(\hat{x}_2) = \dots = \mu_m(\hat{x}_m) = \mu_0$ and $\mu'_j(\hat{x}_j)$, $j = 1, 2, \dots, m$ with $j \neq i$, all have the same signs, while $\mu'_i(\hat{x}_i)$ has the opposite sign.

Approach

Decision analysis by fuzzy subset may be used in evaluation of LWR safety R&D programs. The process has five distinct steps, which are as follows:

- A. Goal definition
- B. Criteria (attributes/subattributes)
- C. Criteria weights
- D. Rating
- E. Ranking

A. Goal definition

In the first step of analysis, the goal needs to be defined to make it possible to determine to what extent a particular alternative satisfies the goal. The goal in this study can be characterized as follows.

Three program proposals are to be considered for evaluation as part of the LWR safety R&D program. The objective of the three programs is to investigate the man-machine interactions in the operation of commercial LWR stations and to develop a scheme to improve operator performance and/or to reduce risk in LWR operations in order to (1) reduce the present low-level of risk, (2) improve the licensability of LWR's, (3) increase public acceptance, and (4) reduce safety-related costs. The goal is to rank order the three programs and to select the optimal R&D program. Two programs may be of equal rank.

P-1 Control Room Design Improvement

This program entails redesign of control rooms in LWR's, using state-of-the-art human factor engineering, to reduce operator errors and increase operator performance. The program will involve four man-years of effort for one year. The new design can be adopted by new plants. However, extensive retrofitting of operating plants can be done over a period of five years at a total cost of 65M\$.

P-2 Operator-Error Assessment in Operating Nuclear Power Stations

An assessment is proposed of all accumulated operation data from

1965-1978 for LWR's, such as those documented in the licensee event reports (LER's). The review entails identification of the frequency, causes, and consequences of operator errors during normal operation. The proposed program is expected to provide a list of frequently occurring errors, recommend special modification of operation procedures, improvement of training, or specific design changes to eliminate the causes of those errors and to mitigate their consequences if they should occur. The review will involve four man-years over 18 months. The implementation of the recommendations is estimated to cost about 15M\$ over a period of 2 years.

P-3 Computer Control Development

Based on the state-of-the-art in human factors engineering and experience with computer control of reactors, a computer program and automatic operation system is to be developed to replace the majority of operators during normal operation. The automation functions include most of the operator tasks, such as checks, tests, and calibration tasks. The proposed program would provide an operation scheme more predictable than the human element, presumably not subject to variability under stress or fatigue. The system would be incapable of isolated acts such as sabotage, suicide, or sudden incapacitation. The execution of the program involves three man-years for two years. The realization of the developed system if proven viable, would be over 16 years, including possible retrofitting of operating systems. A cost of 100M\$ is estimated for demonstration,

improvement, and implementation of the developed system.

B. Criteria

Any proposed program must be judged on the basis of how well it satisfies the goal. Each program will be measured with respect to a set of attributes and subattributes, to see how well it satisfies the goal. The attributes and subattributes are presented in table 1.

C. Criteria Weights

Since not all attributes or subattributes carry the same weight in the evaluation process, it is important to put weights for each attribute/subattribute to identify that criterion which is more important than others. This is because often the programs involve a wide variety of aspects. Thus, possibly verbal weights are used to indicate relative importance between attributes or subattributes. The weight may be represented by a fuzzy weighting of criteria, W_j .

$$W_j = \{ (w_j, \mu_{w_j}(w_j)) \} \quad j = 1, 2, \dots, n \quad (24)$$

$$W_j = \text{Very important} = \{ (0.8, 0), (0.875, 0.5), (0.95, 1.0), (0.975, 0.5), 1.0, 0 \} \quad (25)$$

$$W_j = \text{Important} = \{ (0.6, 0), (0.7, 0.5), (0.8, 1.0), (0.9, 0.5), (1.0, 0) \} \quad (26)$$

$$W_j = \text{Moderately important} = \{ (0.3, 0), (0.4, 0.5), (0.5, 1.0), (0.6, 0.5), (0.7, 0) \} \quad (27)$$

$$W_j = \text{Rather unimportant} = \{ (0, 0), (0.1, 0.5), (0.2, 1.0), (0.3, 0.5), (0.4, 0) \} \quad (28)$$

Table 1 Weights and Ratings

Attributes/Subattributes	Weighting	Program 1	Program 2	Program 3
<u>Program Logistics</u>	Important	-	-	-
Funding level	Important	Fair	Fair	Good
Execution time	Important	Very good	Good	Fair
Ease of execution and/or confidence in achieving program objectives	Rather unimportant	Fair	Very good	Fair
State-of-the-art technology and/or information resources adequacy for achieving objectives	Very important	Good	Good	Fair
<u>Practicability of Program Objectives:</u>	Important	-	-	-
Implementation lead time	Moderately important	Good	Very good	Fair
Implementation/retrofitting cost of operating LWR's	Important	Very good	Very good	Good
NRC approval of results	Very important	Good	Very good	Poor
<u>Risk Reduction:</u>	Very important	-	-	-
Operator errors (reduction)	Moderately important	Good	Very good	Good
Operator error consequence mitigation potential (Public risk reduction)	Very important	Poor	Good	Fair
<u>LWR Promotion and Cost Reduction:</u>	Moderately important	-	-	-
Increase in public acceptance	Moderately important	Very poor	Poor	Fair
Utility acceptance of change	Important	Good	Very Good	Fair
Expected improvement on LWR availability/reliability	Very important	Very poor	Poor	Fair
Reduction in O&M/capital cost	Very important	Poor	Poor	Very good
Change in manpower, qualification, and/or number (unionized labor acceptance)	Very important	Very good	Very good	Fair

$$W_j = \text{Very unimportant} = \{(0,0), (0.025), (0.05, 1.0), (0.15, 0.5), (0.2, 0)\} \quad (29)$$

or by membership functions as shown in Fig. 1.

D. Rating

Each program is rated possibly by verbal rates with respect to each subattribute alone, independently of all other programs. The rating of the attributes can then be obtained from final ratings of each program which are obtained using ratings and weights for subattributes. The development of attributes and subattributes and measures is the most important part of the task which needs special care.

The fuzzy rating of an alternative or subattribute R_{ij} is given by

$$R_{ij} = \{(r_{ij}, \mu_{R_{ij}}(r_{ij}))\} \quad \begin{matrix} i = 1, 2, \dots, m \\ j = 1, 2, \dots, n \end{matrix} \quad (30)$$

$$R_{ij} = \text{Very good} = \{(0.8, 0.0), (0.875, 0.5), (0.95, 1.0), (0.975, 0.5), (1.0, 0)\} \quad (31)$$

$$R_{ij} = \text{Good} = \{(0.6, 0.5), (0.8, 1.0), (0.4, 0.5), (1.0, 0.0)\} \quad (32)$$

$$R_{ij} = \text{Fair} = \{(0.4, 0.0), (0.5, 0.5), (0.6, 1.0), (0.7, 0.5), (0.8, 0)\} \quad (33)$$

$$R_{ij} = \text{Poor} = \{(0,0), (0.1, 0.5), (0.2, 1.0), (0.3, 0.5), (0.4, 0)\} \quad (34)$$

Fig. 1 Fuzzy Weights Membership Function

Figure 1 continued

$$R_{ij} = \text{Very poor} = \{(0,0), (0.025, 0.5), (0.05, 1.0), (0.15, 0.5), (0.2, 0)\} \quad (35)$$

or by membership function as shown in Fig. 2.

E. Ranking

The final ratings for the alternate programs at the subattribute level are obtained using this information about weights and ratings for subattribute by using specially developed computer program, and the results are depicted by the membership function of Fig. 3.

Results

The memberships of alternative programs at the subattribute level in the set of alternative program ranking first appear in Table 1. The final rating for attribute 1 (program logistics) is given in Fig. 3. The preference rank is given in Table 2.

The membership function of the preferability of a selected program over other programs just in subattributes can be calculated from

$$\mu_o = 0.25$$

$$P_1 = 0.6 - 1/2(0.9102 + 0.8264) = -0.268$$

$$P_1 = 0.9102 - 1/2(0.5774 + 0.494) = 0.3745$$

$$\mu_o = 0.5$$

$$P_1 = 0.6576 - 1/2(0.859 + 0.7699) = -0.1568$$

$$P_1 = 0.865 - 1/2 (0.6369 + 0.549) = 0.272$$

$$\mu_o = 0.75$$

$$P_1 = 0.7145 - 1/2 (0.807 + 0.714) = -0.046$$

$$P_1 = 0.819 - 1/2 (0.695 + 0.6033) = 0.16985$$

The results are shown in Fig. 4. B-17

Fig. 2 Fuzzy Rating Membership Function

Fig. 3 Final rating for sub-attributes
program logistic logistics

Table 2		program logistics	
		i	$\mu_I(i)$
		1	1.0
		2	0.965
		3	0.747

Fig. 4 Membership function of preferability
of program 1 over other programs
based on programs logistics attribute

The results for the second attribute (Practicability of program objectives) are given in Fig. 5 and Table 3. In this case the program 2 is preferable. The membership function of program 2 over the other two can be calculated from

$$\mu_o = 0.25$$

$$P_2 = 0.8375 - 1/2 (0.967 + 0.69) = 0.009$$

$$P_2 = 0.9875 - 1/2 (0.703 + 0.317) = 0.4775$$

$$\mu_o = 0.5$$

$$P_2 = 0.875 - 1/2 (0.931 + 0.6284) = 0.095$$

$$P_2 = 0.975 - 1/2 (0.753 + 0.3795) = 0.408$$

$$\mu_o = 0.75$$

$$P_2 + 0.9125 - 1/2 (0.893 + 0.566) = 0.183$$

$$P_2 = 0.9624 - 1/2 (0.8038 + 0.4413) = 0.3398$$

The results are shown in Fig. 6

Fig. 5 Final rating for sub-attributes
practicability of objectives

Table 3. Practicability of program objectives

i	$\mu_I(i)$
2	1.0
1	0.69
3	0.0

Fig.6 Membership function of preferability of program 2
over other programs in sub-attributes
practicability of program objectives

The results for risk reduction subattributes are shown in Fig. 7 and Table 4. The preferability function of program 2 is computed from

$$\mu_o = P_2 .25$$

$$P_2 + 0.7 - 1/2(0.612 + .837) + 0.02$$

$$P_2 + 0.97 - 1/2(0.207 + 0.5023) + 0.62$$

$$\mu_o = 0.5$$

$$P_2 = 0.75 - 1/2(0.544 + .781) = 0.04$$

$$P_2 + 0.93 - 1/2(0.274 + .558) = 0.51$$

$$\mu_o + .75$$

$$P_2 + 0.801 - 1/2(0.476 + 0.725) = 0.2$$

$$P_2 + 0.892 - 1/2 (0.34 + .614) = 0.42$$

and the results are given in Fig. 8.

The results for the final attribute are shown in Fig. 9, and Table 5 and the preferability is obtained from

Fig. 7 Final rating for sub-attributes risk reduction

Table 4 Practicability of program objectives

i	$\mu_I(i)$
2	1.0
3	0.57
1	0.069

Fig. 8 Membership function of preferability of program 2 over other programs just in sub-attributes risk reduction

Fig. 9 Final rating for sub-attributes
LWR promotion and cost reduction

Table 5. LWR promotion and cost reduction

2	1.0
3	0.845
1	0.574

$$\mu_o = 0.25$$

$$P_2 + 0.323 - 1/2 (0.494 + .613) + -0.23$$

$$P_2 + 0.680 - 1/2 (0.2977 + 0.153) + 0.46$$

$$\mu_o .50$$

$$P_2 + 0.387 - 1/2 (0.426 + 0.555) = -0.1$$

$$P_2 + 0.63 - 1/2 (0.198 + 0.344) = 0.36$$

$$\mu_o + .73$$

$$P_2 = 0.45 - 1/2 (0.359 + 0.497) = 0.02$$

$$P_2 + 0.5727 - 1/2 (0.244 + 0.3915) = 0.25$$

and the results are shown in Fig. 10.

Now if we use the weights given for attributes in table I ,
and membership function of final rating of subattributes which are
assumed to be a rating for attributes, the overall membership function
of final rating can be depicted as in Fig. 11 and Table 6.
Then the membership function of the preferability of selected program
over other programs can be calculated

$$P_i = \mu_i - \frac{1}{m-1} \sum_{\substack{j=1 \\ i \neq j}}^m \mu_j$$

$$\mu_o = 0.25$$

$$P_2 = 0.6116 - 1/2 (0.7996 + 0.7746) + -0.1755$$

$$P_2 = 0.9274 - 1/2(0.3919 + 0.4) = 0.5314$$

$$\mu_o = 0.5$$

$$P_2 = 0.6748 - 1/2 (0.736+ 0.7115) = -0.049$$

$$P_2 = 0.887 - 1/2 (0.462 + 0.462) = 0.425$$

$$\mu_o = 0.75$$

$$P_2 + 0.737 - 1/2 (0.6707 + 0.648) = 0.0776$$

$$P_2 + 0.844 - 1/2 (0.532 + 0.5236) = 0.3162$$

Fig. 10 Membership function prefers preferability of program 2 over other programs just in sub-attributes LWR promotion and cost reduction

Fig. 11 Membership function of final ratings

Table 6. The membership function μ_I .

i	$\mu_I(i)$
2	1.0
1	0.62
3	0.573

The results are sketched in Fig. 12.

Fig. 12 Membership function of preferability
of program 2 over other programs

REFERENCES

1. R. E. Bellman and L. A. Zudeh, "Decision Making in a Fuzzy Environment," Management Sci, 178, 141 (1970).
2. C. V. Negoita and D. A. Ralescu, "Application of Fuzzy Sets to System Analysis," John Wiley & Sons, New York, 1975.
3. S. M. Baas and H. Kwakernaak, "Rating and Ranking of Multiple-Aspect Alternatives Using Fuzzy Sets," Automatica, 13, 47 (1977).
4. S. R. Watson, J. J. Weiss, and M. L. Donnell, "Fuzzy Decision Analysis," IEEE Trans Systems, Man & Cybernetics, SMC-9, 1 (1979.)

WE WISH TO FIND YOUR CERTAIN EQUIVALENT FOR THE
FOLLOWING LOTTERY:

A 50% CHANCE OF A INCREMENTAL INCREASE OF
0.100000 \$ / KW (BETTER OUTCOME) AND
A 50% CHANCE OF A INCREMENTAL INCREASE OF
1.000000 \$ / KW (WORSE OUTCOME)

IF YOU KNOW YOUR CERTAIN EQUIVALENT FOR THE LOTTERY,
TYPE 1. OTHERWISE, TYPE 2 AND THE COMPUTER WILL HELP
YOU ASSESS IT.

-->2

WHICH OF THE FOLLOWING DO YOU PREFER?

- 1) A SURE OUTCOME OF 0.730000 \$ / KW
OR
2) A 50% CHANCE OF AN OUTCOME OF
0.100000 \$ / KW (BETTER) AND
A 50% CHANCE OF AN OUTCOME OF
1.000000 \$ / KW (WORSE)

0.100 1.000
+-----+-----+
0.730

REMEMBER, OUTCOMES REFER TO OPERATOR/M&T CREW COST
AS MEASURED BY INCREMENTAL INCREASE
ENTER PREFERENCE (1 OR 2 ; TYPE 3 IF YOU ARE INDIFFERENT)

-->1

WHICH OF THE FOLLOWING DO YOU PREFER?

- 1) A SURE OUTCOME OF 0.811000 \$ / KW
OR
2) A 50% CHANCE OF AN OUTCOME OF
0.100000 \$ / KW (BETTER) AND
A 50% CHANCE OF AN OUTCOME OF
1.000000 \$ / KW (WORSE)

0.100 1.000
+-----+-----+
0.811

REMEMBER, OUTCOMES REFER TO OPERATOR/M&T CREW COST
AS MEASURED BY INCREMENTAL INCREASE
ENTER PREFERENCE (1 OR 2 ; TYPE 3 IF YOU ARE INDIFFERENT)

-->2

WHICH OF THE FOLLOWING DO YOU PREFER?

- 1) A SURE OUTCOME OF 0.786700 \$ / KW
OR
2) A 50% CHANCE OF AN OUTCOME OF
0.100000 \$ / KW (BETTER) AND
A 50% CHANCE OF AN OUTCOME OF
1.000000 \$ / KW (WORSE)

0.100 1.000
+-----+-----+
0.787

REMEMBER, OUTCOMES REFER TO OPERATOR/M&T CREW COST
AS MEASURED BY INCREMENTAL INCREASE
ENTER PREFERENCE (1 OR 2 ; TYPE 3 IF YOU ARE INDIFFERENT)

-->2

WHICH OF THE FOLLOWING DO YOU PREFER?

- 1) A SURE OUTCOME OF 0.747010 \$ / KW
OR
2) A 50% CHANCE OF AN OUTCOME OF
0.100000 \$ / KW (BETTER) AND
A 50% CHANCE OF AN OUTCOME OF
1.000000 \$ / KW (WORSE)

0.100 1.000
+-----+-----+
0.747

REMEMBER, OUTCOMES REFER TO OPERATOR/M&T CREW COST
AS MEASURED BY INCREMENTAL INCREASE
ENTER PREFERENCE (1 OR 2 ; TYPE 3 IF YOU ARE INDIFFERENT)

-->1

IT SEEMS THAT YOU ARE INDIFFERENT BETWEEN:

- 1) A SURE OUTCOME OF 0.774793 \$ / KW
AND
2) A 50% CHANCE OF AN OUTCOME OF 0.100000 \$ / KW AND
A 50% CHANCE OF AN OUTCOME OF 1.000000 \$ / KW
IS THAT CORRECT? (YES OR NO)

-->YES