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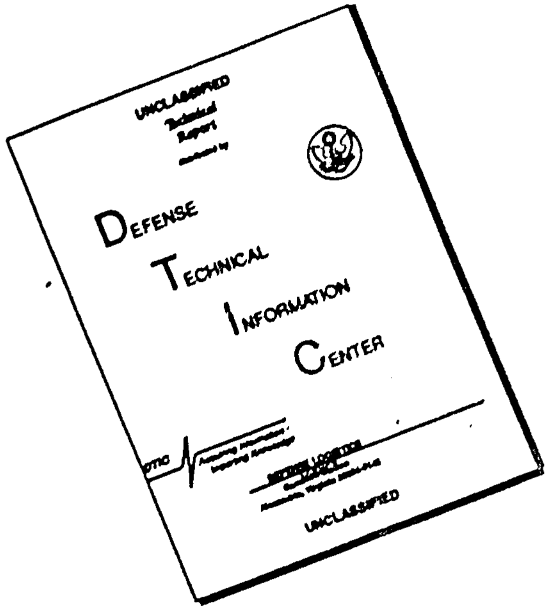

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WEAPON SYSTEM EFFECTIVENESS
INDUSTRY ADVISORY COMMITTEE (WSEIAC)

20

FINAL REPORT OF TASK GROUP IV

COST—EFFECTIVENESS OPTIMIZATION
(TASKS AND ANALYSIS METHODOLOGY)

AFSC-TR-65—4 VOLUME II

JANUARY 1965

HEADQUARTERS, AIR FORCE SYSTEMS COMMAND
ANDREWS AIR FORCE BASE MARYLAND

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FINAL REPORT
of
TASK GROUP IV

COST-EFFECTIVENESS OPTIMIZATION
(TASKS AND ANALYSIS METHODOLOGY)

FOREWORD

This is Volume II of the final report of Task Group IV of the Weapon System Effectiveness Industry Advisory Committee (WSEIAC). It is submitted to the Commander, AFSC in partial fulfillment of Task Group IV objectives cited in the committee Charter. The final report is contained in three separate volumes:

> Volume I presents a summary of the principles of cost-effectiveness analysis, conclusions and recommendations.
>
> Volume II contains a discussion of the specific tasks required to conduct a cost-effectiveness analysis, emphasizing procedural and analytical techniques.
>
> Volume III consists of a technical supplement illustrating some of the methodology appropriate to cost-effectiveness analysis.

The membership of Task Group IV was as follows:

Mr. H. S. Balaban	ARINC Research Corporation
Mr. C. Davenport	Rocketdyne - Division of North American Aviation, Inc.
Mr. B. W. Davis	Battelle Memorial Institute
Dr. A. S. Goldman	GE TEMPO
Dr. G. R. Herd (Technical Director)	Booz-Allen Applied Research, Inc. (Now with Kaman Aircraft Corporation)
Mr. T. K. Jones	The Boeing Company
Mr. M. Kamins	The RAND Corporation
Mr. R. E. Kuehn	IBM - Space Guidance Center
Dr. G. W. Morgenthaler	The Martin Company
Maj Frank H. Moxley, Jr. (Government Chairman)	Headquarters, AF Systems Command
Mr. J. J. Naresky	Rome Air Development Center

Other task group reports submitted in fulfillment of the committee's objectives are

AFSC-TR-65-1	Final Report of Task Group I "Requirements Methodology"
AFSC-TR-65-2	Final Report of Task Group II "Prediction - Measurement"

AFSC-TR-65-3	Final Report of Task Group III "Data Collection and Management Reports"
AFSC-TR-65-5	Final Report of Task Group V "Management Systems"
AFSC-TR-65-6	Final Summary Report "Chairman's Final Report"

Publication of this report does not constitute Air Force approval of the report's findings or conclusions. It is published only for the exchange and stimulation of ideas.

APPROVED

William F. Stevens

William F. Stevens, Colonel, USAF
Chief, Systems Effectiveness Division
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WSEIAC CHARTER

In order that this report of Task Group IV may be studied in context with the entire committee effort, the purpose and task group objectives as stated in the WSEIAC Charter are listed below:

Purpose

The purpose of the Weapon System Effectiveness Industry Advisory Committee is to provide technical guidance and assistance to AFSC in the development of a technique to apprise management of current and predicted weapon system effectiveness at all phases of weapon system life.

Task Group Objectives

Task Group I - Review present procedures being used to establish system effectiveness requirements and recommend a method for arriving at requirements that are mission responsive.

Task Group II - Review existing documents and recommend uniform methods and procedures to be applied in predicting and measuring systems effectiveness during all phases of a weapon system program.

Task Group III - Review format and engineering data content of existing system effectiveness reports and recommend uniform procedures for periodically reporting weapon system status to assist all levels of management in arriving at program decisions.

Task Group IV - Develop a basic set of instructions and procedures for conducting an analysis for system optimization considering effectiveness, time schedules, and funding.

Task Group V - Review current policies and procedures of other Air Force commands and develop a framework for standardizing management visibility procedures throughout all Air Force commands.

ABSTRACT

This report discusses the philosophy of cost-effectiveness and techniques for trade-off and optimization studies. It lists and discusses twelve tasks necessary to perform a cost-effectiveness analysis. A methodology is outlined for identifying and standardizing cost and effectiveness factors. Descriptive analytical models for cost-effectiveness are provided, including discussion of their sensitivity and validity. One section defines and discusses risk and uncertainty and their effect on the decision making process. Included is an extensive bibliography on cost-effectiveness. Examples of some of the techniques are covered in detail in a "Technical Supplement," which is Volume III of this final report of Task Group IV. Abstracts of these examples will be found in Appendix I of this report. Appendix II of this report illustrates a technique for cost-effectiveness optimization in the Definition Phase when there is a relative dearth of data, program objectives are fixed, and system effectiveness is unconstrained.

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SECTION I

INTRODUCTION

A major management goal throughout the life cycle of a system -- from the Conceptual Phase through the Operational Phase -- is to exercise management control for the purposes of selecting, developing, and using systems in an optimum manner. The process by which management is provided inputs for these types of decisions has been commonly called cost-effectiveness analysis.

Effectiveness is a measure of the capability of the system to accomplish the mission objectives. Cost-effectiveness studies are concerned with achieving a combination of resource-use and attained effectiveness that is best according to a selected criterion. Resource-use represents the expenditure of dollars, manpower, material, time, etc., required for the development, operation, and support of a system. We shall interpret such studies as an attempt to quantify how much it costs to achieve a certain effectiveness in order to select among a set of alternatives.

There is a recognized need for such studies. The enormous responsibility of the Department of Defense and the military services for maintaining a strong posture involves considerable expenditure of national resources. This is clearly evidenced by the proportion of the federal budget now allocated to defense. It is thus mandatory that the military authorities exercise maximum control in their planning, procurement, and operational activities in order to minimize the burden placed on the economy without any sacrifice in over-all defense goals.

Cost-effectiveness analysis is not new. It has been a part of military planning for some time, but the complexity of the military tasks now require a multidisciplinary approach. The major utility of cost-effectiveness analysis is to provide management with the necessary information for decision making purposes utilizing all the available knowledge and data in as efficient and complete a manner as is possible. Consequently, a demand has been created for improved analytical methods, better and more complete data, expanded computational capacity, etc., which has improved and will continue to improve management's capability for making good decisions.

A. LEVELS OF COST-EFFECTIVENESS ANALYSES

There are several decision making levels at which a cost-effectiveness analysis can be meaningfully applied, and these roughly correspond to the phases during system development. One level for application is at the Required Operational Capability (ROC) level, formerly called the General Operational Requirement (GOR) phase. The ROC establishes a spectrum of objectives or missions. By considering over-all defense goals, the geo-political and environmental factors, and the economic and technological capabilities, a particular mission or objective is selected. This level of application is generally coordinated at the DOD level.

After mission requirements are set at the Specific Operational Requirements (SOR) phase, there exists the need for selecting alternate or competing systems. Application of cost-effectiveness analysis at this level is primarily the responsibility of the military or procuring agencies.

A third level of application occurs during the development and operation of the weapon system. This level of application furnishes information for optimal use of resources within the constraints of mission and system requirements.

As a simple example of these levels, the first would be concerned with such problems as optimum force mix; e.g., expanded bomber-force size versus expanded missile-force size. The second level would be concerned with such combinatorial choices as pertain within a class of systems; e.g., within missile systems we may examine liquid versus solid fuel, tandem versus parallel stages, or soft versus hardened sites. The third level would be concerned with more detailed decisions within a given system configuration; e.g., for a missile one might evaluate pressurized or pump-fed propellant loading systems, various stage diameters, various area ratios of engine nozzles, checkout and monitoring procedures, and the like.

This report is concerned primarily with the third level of analysis, and to a lesser extent with the second level, in presenting and illustrating the concepts, methods, and procedures of cost-effectiveness analysis.

B. GENERAL CONCEPTS

To introduce the general concepts of a cost-effectiveness analysis, we shall interpret such analysis in the simplest of terms -- namely, the attempt to quantify how much it costs to achieve a certain effectiveness in order to select among a set of alternatives. Cost is used to represent the amount of resource expenditure, and effectiveness is a measure of the system ability to accomplish its mission objectives.

The general approach for making such decisions consists of the following steps:

(1) Define criterion for selection

(2) Generate alternatives that satisfy operational requirements and constraints

(3) Compute resultant values of cost and effectiveness for each alternative

(4) Evaluate results with respect to the decision criterion.

Each of these major steps is discussed in detail in the report. It is worthwhile, however, to set the stage for such discussions in this introduction.

The criterion for selection must be one that is mission responsive; that is, it must answer the right question. Essentially, the criterion is based on maximizing effectiveness for a given cost or, conversely, minimizing cost for a given level of effectiveness. The criterion, however, must also define the level of analysis as discussed previously in this introduction and also the scope of the analysis in terms of resource, system, operational and support constraints. Thus, the four basic criteria listed above may evolve into a criterion such as one to maximize effectiveness per dollar, provided effectiveness is greater than E* and cost is less than C* (where E* and C* refer to specific limiting values).

In generating acceptable alternatives, identification of all variable and fixed factors and their costs is required. In addition, the elements of risk and uncertainty as related to these factors and costs and the analysis of effects on other programs must also be considered. Such factors as availability of appropriate data, computational capacity, and restraints in time and effort available for the analysis will play important roles in this phase. A generated alternative is then an acceptable combination of the selected factors with associated risk and uncertainty elements.

Measures of cost and effectiveness for each design alternative must then be computed. The form these measures take is related to the decision criterion. For effectiveness, the measure can range from a simple probability numeric, to an expected value, to the complete distribution of some over-all performance characteristic. The effectiveness model is based on sub-models for reliability, maintainability, and performance. These in turn are based on the variable and fixed factors to be considered such as failure and repair distributions, internal stresses, environment, and design integration.

The cost measure must be one that can treat the major types of resource expenditures on some common basis. Sub-models are required for development costs, operating costs, and support costs both in terms of dollars and schedules. In addition, the burden a particular alternative places on other systems and objectives must be evaluated for a complete cost model.

The integration of the separate cost and effectiveness models into a single cost-effectiveness model provides the basis for decisions. It is at this stage where optimization theory becomes applicable, involving such disciplines as mathematical programming, stochastic process theory, calculus of variations, econometrics, and decision theory.

All of the above models must satisfy characteristics related to adequacy, representativeness, consistency, sensitivity, plausibility, criticality, workability, and suitability. These characteristics are discussed more fully in later sections. In applying the model, it must be emphasized that results of the optimization process can only indicate the best decision within the simplifications, assumptions, restrictions and omission that were required to circumvent such problems as uncertainties, nonquantifiable factors, and inadequate data, time or computational capacity.

Thus, the cost-effectiveness analysis will usually yield only partial analytic solutions. However, the framework for a final decision is provided. The cost-effectiveness analysis has reduced the guess work and intuitive estimates of cost and effectiveness, but the initial results must still be critically evaluated and combined with relevant political and timing factors by a judgment of the decision maker.

SECTION II

DISCUSSION OF TASKS AND FACTORS IN COST-EFFECTIVENESS ANALYSIS

There is no unique approach to performing a cost-effectiveness study just as there is no single detailed model which will be useful in studying all systems. A cost-effectiveness study may be regarded as one form of system analysis. In general, certain tasks and input elements are involved in such analyses. Figure 1 provides a typical example of tasks and their sequential relationship. These tasks and input elements will be briefly described here in order to orient the reader to the over-all cost-effectiveness optimization process. Discussion of methods associated with the tasks will be covered in subsequent sections of this document.

A. TASKS

1. Define Program Objectives and Mission The introduction pointed out that cost-effectiveness studies are conducted at three basic levels; selection of mission, selection of system, and optimization of system. The first or highest level of these studies is not within the scope of this report. However, the results of cost-effectiveness studies at this higher level must provide the initial basis for establishing program objectives and requirements to permit the lower level optimizations. It is fundamental to the basic definition of effectiveness that the end goals and purpose be defined so that a system can be optimized in terms of a specified mission or task to be accomplished.

2. Identify Resources and Constraints In addition to stipulating the program task, it is necessary to define resources and constraints. Resources are those items (i. e., people, technology, dollars, etc.) available to accomplish a task or program. Constraints are limits on resources. The resources and constraints are inherent in, or a direct result of, the statement of a program task or a program definition. Although it is possible to design a system without prior knowledge of the resources which are available, it is not logical or usual to do so. The optimization of a system to

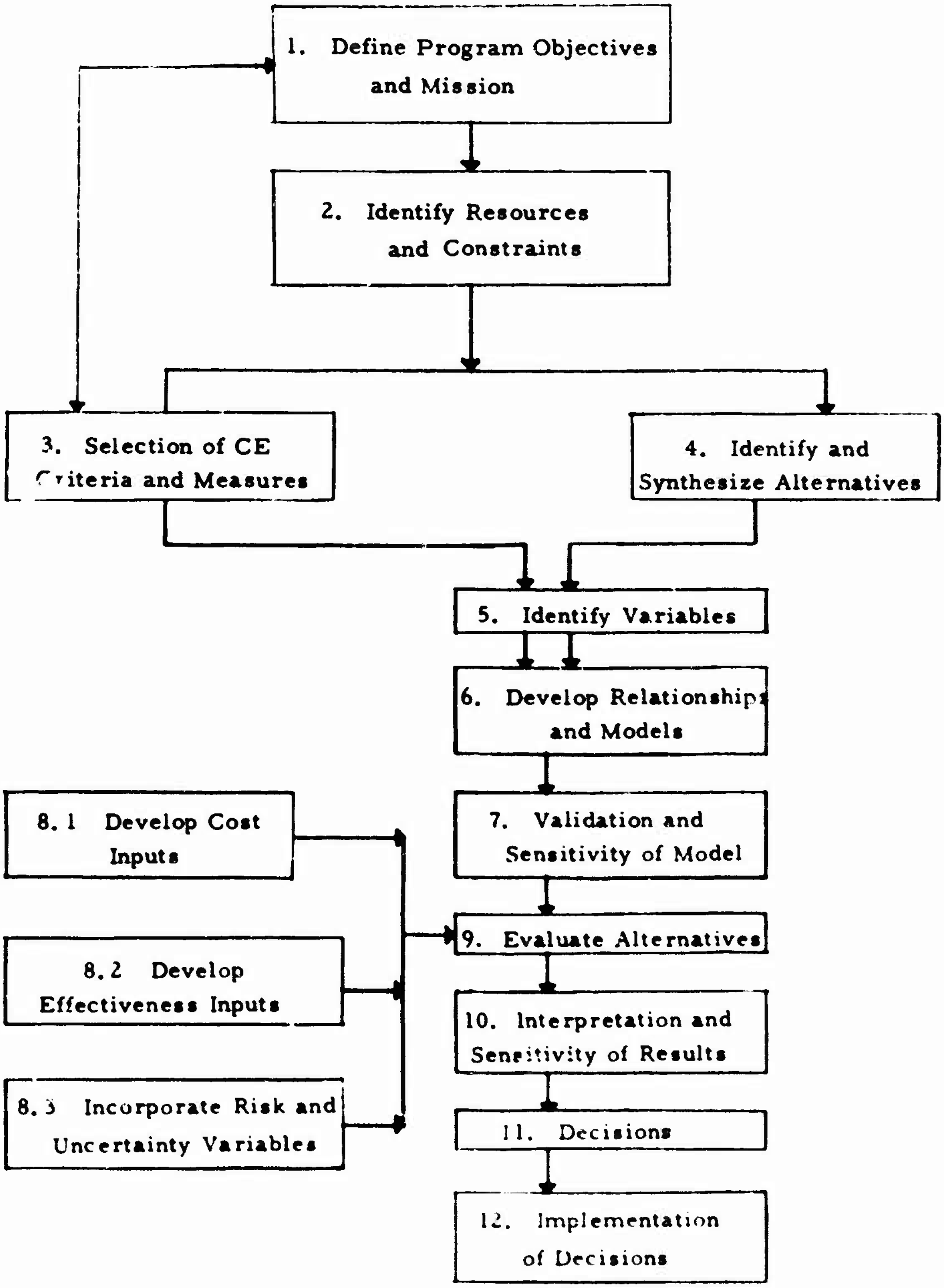

FIGURE 1. TASK RELATIONSHIPS IN A TYPICAL COST-EFFECTIVENESS STUDY

provide greatest effectiveness in accomplishing the required task per amount of resource expenditure requires an even more detailed knowledge of the available resources, together with the relationship of resources to alternative means of meeting the stated task.

3. Selection of Cost-Effectiveness Criteria and Measures The optimization process is essentially one of achieving a combination of resource use and attained effectiveness that is best by some criterion. In order to render the optimization process feasible, a criterion must be developed that is expressed in precise, quantifiable terms. These criteria are developed in recognition of the stated program objectives and those limitations inherent in the available resources.

The quantitative terms or measures generally associated with the effectiveness criteria are usually expressed in terms of cost, which generally represents expenditures not only of dollars but also of time, manpower, and other resources.

4. Identify and Synthesize Alternatives The ability to optimize a system depends on the availability of alternate means of meeting the requirements. Alternatives include the means, approaches, or techniques which can be employed to meet the program objectives and missions within the constraints of the resources. As can be seen from Figure 1 the optimization approach is generally based on a fundamental sequence of:

a. Identification of alternatives
b. Evaluation of alternatives
c. Selection of that alternative or combination of alternatives which provides the most cost-effective system.

The task of identifying alternatives consists basically of examining the objectives and missions together with the basic system concept proposed and listing all possible alternative means of meeting the objectives. The alternatives thus listed should then be screened against the available resources and stated bounds to insure that they are in fact feasible.

Synthesis of alternatives consists of those steps needed to definitize the alternate design configurations, operational plans, etc associated with listed alternatives to that degree of detail needed to permit their subsequent evaluation.

5. Identify Variables A variable is defined here as a parameter or quantity the use of which, when varied, will result in variations in resources or the effectiveness with which the program objectives are accomplished. This step in the optimization process consists of identifying those variables which will influence the evaluation of each alternative listed from the preceeding task.

6. Develop Relationships and Models The next step in the basic optimization process is to relate the variables used with each other and with the resources which are affected. These relationships must be expressed in such a manner that the variables and resources can be expressed in terms of the established cost-effectiveness criteria and measures. Development of relationships is carried to the point where all resources and variables can eventually be related to either a single common denominator, (usually dollars), or to a cost denominator (dollars) and an effectiveness measure. The relationships so developed are then expressed in model form, which is essentially a mathematical, logical, or physical representation of the interdependencies between the variables, resources, and measures of effectiveness.

7. Validation and Sensitivity of Model It must be recognized that the models developed above will not be exact replicas of the "real world." Accordingly, they should not be used blindly. Portions of every model are usually common to previously used models or can be related to quantitative knowledge of trends available from past experience. The model is validated by checks in as many familiar regions as possible. The model is also checked for sensitivity of its output to changes in its basic structure. These sensitivity checks are made in all areas where simplifications have been made from the "real world" case or where anomalies have resulted from the validation checks.

8. Develop Inputs This step requires no description other than to indicate that it must include documentation of all input data, its associated

range of uncertainty, and other validating information. Inputs are required in areas of cost of vehicles, bases, etc., effectiveness values such as kill probabilities, readiness, probabilities, etc., and estimates of risk probabilities.

9. Evaluate Alternatives This step consists of application of the developed models and input data to each alternative. This task may be accomplished in several increments, starting with evaluation of alternatives on an individual basis and ending with a series of iterations or simulation of the complete system based on the individual analysis results. This task may also be accomplished as a single step by application of a complete system model or simulation technique.

10. Interpretation and Sensitivity of Results During and after the accomplishment of the cost-effectiveness analysis, the results of the study must be interpreted in terms useful for the decision process. Of particular importance is the sensitivity of the results (i. e., in terms of cost-effectiveness measures) to variations in the input data. Thus, if the cost-effectiveness measure varies greatly with some design parameters, the decision process must consider carefully the uncertainty and the price paid by failure to achieve a design goal.

Interpretation is particularly difficult due to the usual communication problems among people of differing backgrounds and interests. This difficulty is amplified by the nature of qualifying statements which must be made concerning cost-effectiveness results due to risk and uncertainty and related result sensitivity.

11. Decisions It should be stated again that the executive, not the analyst or the CE study, makes the decision. The study helps eliminate uncertainty just as performance data helps the engineer select a component for a system. Other factors must enter into the decision process.

12. Implementation of Decisions It is not enough for the executive to announce his decision. The total study program has failed if proper steps for implementing the decision are not devised and enacted.

B. FACTORS

There can be no other point of departure in a systems cost effectiveness study than an understanding of the physical characteristics of the air frame (physical system), the equipment within the air frame, the ground-support equipment, the interrelation among individuals and the various subsystems, and the effect of enemy action and technology. This is best indicated schematically by Figure 2. Development of the understanding to an adequate level of detail will in turn permit the analyst to reduce these characteristics into the factors which relate to cost effectiveness. The basic factors which enter into a cost-effectiveness optimization analysis may be categorized as:

Effectiveness factors;
Cost factors; and
Risk and Uncertainty factors.

The term factors, as referred to in this discussion, is defined as those quantitative terms which enter into the models and/or equations by which cost-effectiveness is quantified and optimized. The typical factors within these categories are listed in Table I. They are further defined in succeeding sections of this report.

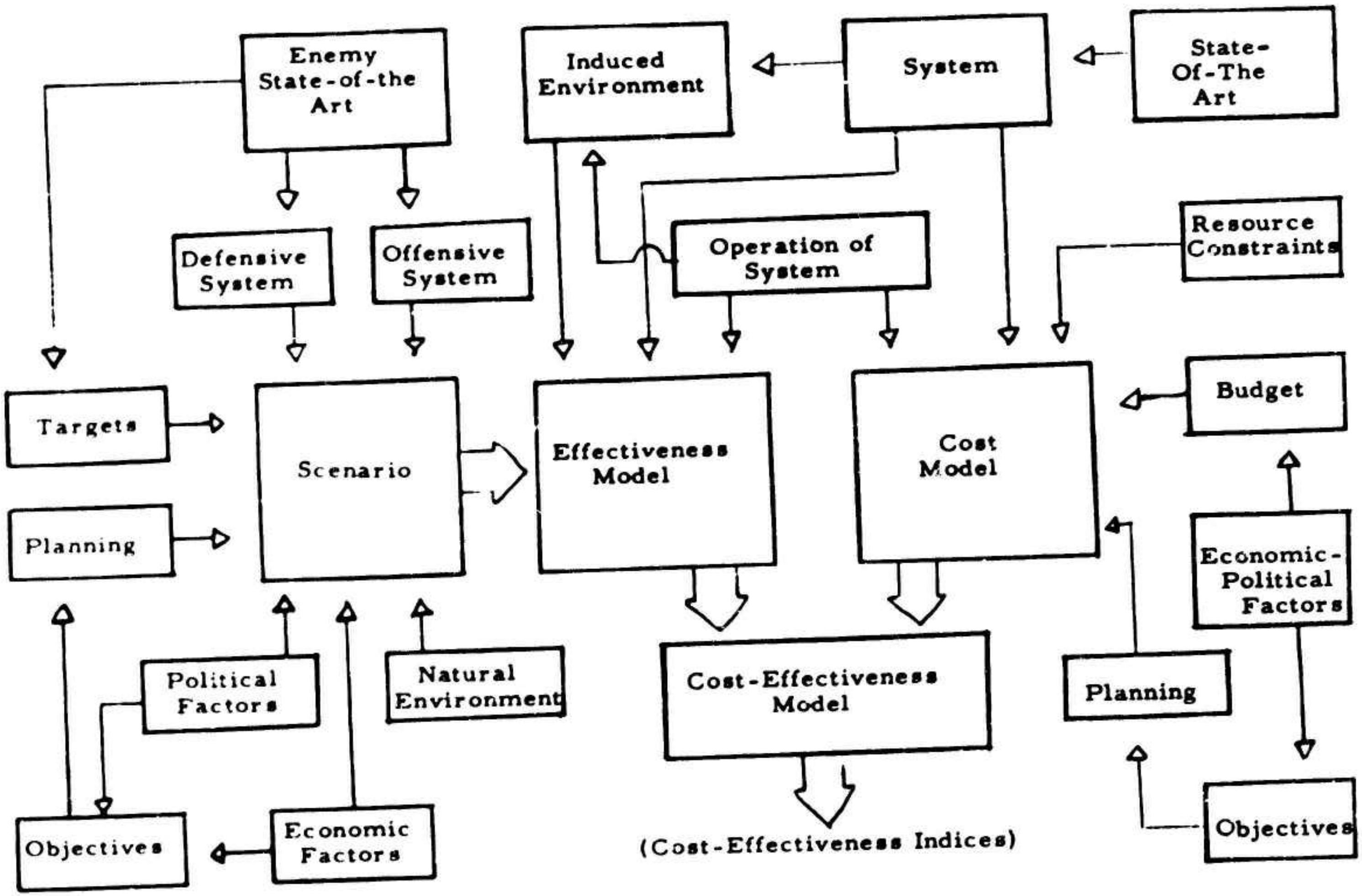

FIGURE 2

THE COST-EFFECTIVENESS STUDY PROCESS

TABLE I

TYPICAL FACTORS INCLUDED IN A COST-EFFECTIVENESS ANALYSIS

EFFECTIVENESS				COST		RISK AND UNCERTAINTY	
Availability	Survivability	Reliability	Mission Capability	Dollars	Other Resources	Cost of Reducing	Cost of Bearing
. Alert Reliability . Support Capability	. to blast . to electro-magnetic pulse . to environ-ment	. Launch Reliability . Mission Reliability	. Penetrability . Lethality . Time-over Targets per Orbit . ΔV in Orbit . etc.	. Direct Operating Cost . Indirect Operating Cost . Burden	. Amount of Critical Commodities . Time . Volume . Manpower and Skills . etc.		

SECTION III

INPUTS AND RELATIONSHIPS[1/]
(TASKS 1-5)

This section discusses the first five tasks in Figure 1 as they apply to second and third level analysis.

In the introduction, it was indicated that there are three basic identifiable levels of cost-effectiveness analyses. They are:

1. Selection of mission
2. Given mission--selection of competing systems
3. Given system--selection of optimal resource use.

Also stated in the introduction, the first level analysis is a Department of Defense level function and is not within the scope of this report. It is, however, necessary to recognize that these levels of analysis must be coordinated. Figure 3 depicts the relationship of the analyses levels and the types of information required for integration.

A. DEFINE PROGRAM OBJECTIVES, MISSION AND CONSTRAINTS (TASKS 1 and 2)

The output of the mission selection analyses conducted at DOD level is a statement of what the program is to accomplish. Historically, this input covers the end-item functions which are to be accomplished (target destruction, reconnaissance, space exploration, etc.) and the conditions and geographic locations within which these functions are to take place. The optimization processes that take place during the lower level cost-effectiveness studies consist mainly of synthesizing alternate means of meeting stated objectives, evaluating them, and selecting the combination of such alternatives which secures the most favorable cost and effectiveness relationship.

1/ References 1, 2, and 3 provide additional information on this subject.

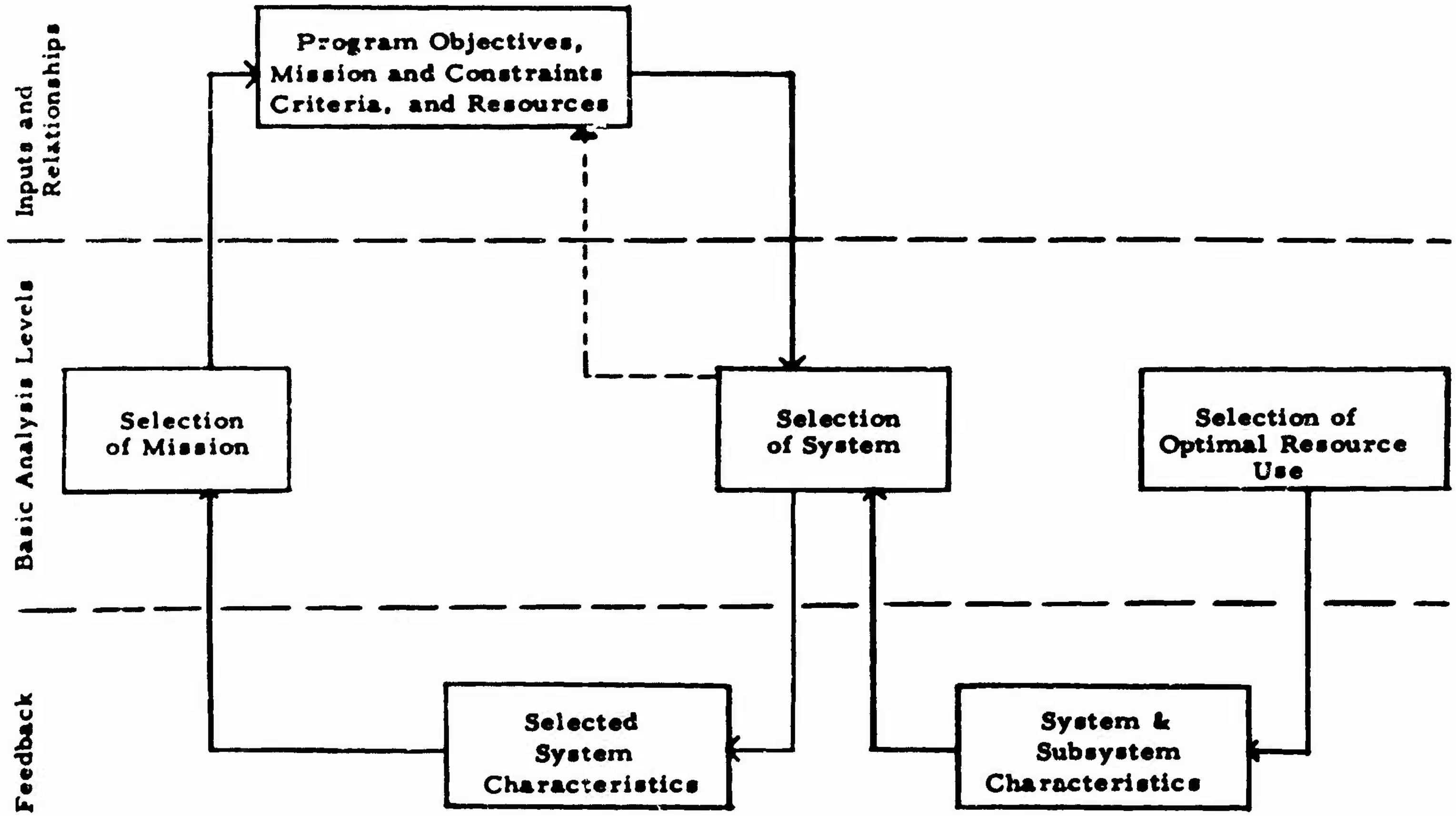

FIGURE 3

RELATIONSHIP OF COST-EFFECTIVENESS ANALYSIS LEVELS

It follows that if the statement of program objectives severely limits the alternatives which can be considered, the ability to achieve optimum cost-effectiveness during the lower level analyses is correspondingly reduced. Thus, the statement of program objectives and mission derived from the first level analyses should define what is to be done rather than how the task is to be accomplished. It is recognized, however, that additional constraint and relationship data must be provided in order that system and resource-use selection correspond to the basis on which the mission was initially justified.

In order for a mission to have been selected, it must have been previously justified on the basis of a grossly estimated set of effectiveness and cost figures. Operational data and system life must also have entered into the justification. Alternatively, a mission may be selected contingent upon an ability to accomplish it within a given cost or above a minimum level of effectiveness. The point here is, once a mission has been selected and justified by the DOD-level analyses, gross economic value and gross effectiveness measures must have been evaluated and judged acceptable. No doubt there also exist limits on maximum cost, minimum effectiveness, or combinations thereof beyond which the selected mission is no longer justified.

Accordingly, during the mission selection phase it is possible to develop, from this inherent or implicit justifying data, the information on constraints and relationships which is required to conduct lower level optimizations. Typical types of such data are:

(1) maximum total cost beyond which the mission is not justified;

(2) minimum effectiveness level below which the mission is not justified, together with the measures used to assess effectiveness level;

(3) calendar time phasing associated with the above values (this variation generally results from the availability of competing or complementing missions);

(4) limitations on or values associated with resources to be expended in accomplishment of the mission;

(5) maximum acceptable level of risk of failure to complete program objectives, or a dollar value associated with varying degrees of risk.

Data of this type would provide the necessary constraints in a manner or form that assures minimum exclusion of possible alternatives. It should be noted that all of the data types listed need not be furnished for a selected mission since the list includes alternative means of stating the same basic constraint.

B. CRITERIA SELECTION (TASK 3)

A cost-effectiveness optimization process is essentially one of achieving a combination of resources and attained effectiveness that is best by some criterion. In defining an optimizing criterion, the system analyst is faced with a problem similar to that of stating in precise, quantifiable terms the rules or criteria for choosing the "best" painting or "best" automobile. These examples do have some quantifiable (though not necessarily pertinent) characteristics, such as the size of the painting, rating of the artist, or the dimensions (roominess) of the automobile; however, artistic judgment and user experience, respectively, are also factors in the final choice. In the same sense, the choice of the best weapon system is greatly influenced by the use of good engineering, economic, and operational judgment.

It is most important, however, that the optimizing criterion which includes as many significant factors as possible, be defined for the following reasons:

(1) The inputs provided to the analyst through use of the criterion can reduce the size of the problem to a point where a judicious choice can be made.

(2) Defining a criterion forces the analyst to examine all possible alternatives in an objective manner so that the criterion can be adapted to mathematical representation and analysis.

(3) It is easier to incorporate the ideas and experience of others if a formal basis for optimization is established.

4. The (partial) basis for final choice is in precise, quantifiable terms and can, therefore, be reviewed and revised, and can provide inputs to a learning process for future optimization problems.

When a criterion for optimization is being formulated, the system and the boundaries must be explicitly defined. This definition will influence the choice of parameters in the optimization model. The purchaser of a new automobile, for example, may or may not consider the service policies of the manufacturer and dealer. If he does, the system is both the automobile and service policies; if he does not, the system is only the automobile. In attempting to optimize a weapon system such as a bomber, the analyst has to consider whether the system is to be defined as a single bomber, a squadron of bombers, or the complete bomber fleet. It is possible that optimizing with respect to a single bomber (a sub-optimization) may not yield the optimum "squadron" system, which may not, in turn, give a force-wide optimum. (See reference 2).

As part of the system-definition process, the analyst also determines the fixed and variable factors pertinent to the system. This task requires a preliminary analysis, since consideration of all possible alternatives will usually lead to problems of unmanageable size. Some factors may be considered fixed if results of previous analyses, perhaps sub-optimizations, indicate the values that have attained the best results in the past. The maintenance trouble-shooting routine, for example, might normally be considered as a variable factor, but past research in this area may be used to select a particular routine applicable to the system under study, or perhaps to restrict the range to several alternatives.

Once the mission profile is defined, consideration can be given to the physical and economic limitations that will have to be imposed. These limitations are based on requirements and availabilities, and may involve such factors as minimum system output, minimum reliability, minimum maintainability, maximum development time, maximum weight and volume, and type and number of support and operational personnel. Through such consideration an envelope of design, development, operational and support alternatives can be established in such a way that each over-all configuration within the envelope will meet physical and economic limitations as well as minimum performance goals.

Now the analyst must select a decision criterion by specifying the types of effectiveness and cost parameters to be investigated and by assigning numerical values where required. For this purpose the effectiveness measures defined should be as precise as possible. They must also provide an understandable and calculable measure of the system's capability for successful accomplishment of mission objectives. As suggested above, they should also include as many significant factors as possible. The choice of objectives and criteria is perhaps the most difficult task in system effectiveness optimization. It is expected, however, that current effort in the optimizing of system effectiveness will develop theory and accumulate experience to help overcome some of the difficulties of this task.

It is impossible to establish rigid ground rules or procedures for formulating a criterion for optimizing Cost-Effectiveness of a weapon system. The answers to the following two basic questions, however, will provide a great deal of insight for such formulation:

1. Why is the system being developed?
2. What physical and economic limitations exist?

The answer to the first question essentially defines the mission profile of the system. Where possible, the definition should be translated into quantitative parameters--a difficult task in many cases. A performance measure such as kill-probability for a SAC bomber may be assignable, but the bomber may also have a mission to act as a deterrent--a measure that is difficult, if not impossible, to quantify. It is for this type of multimission case that judgment will become especially important. Even if quantitative requirements can be placed on all mission types, weighting factors would have to be introduced to quantify the relative importance of each mission. However, when it is possible to quantify the factors involved, one might evaluate the effectiveness of a multiple mission system from:

$$E = \sum_i f_i I_i E_i$$

where the subscript i indicates mission type, and other factors are:

f_i - fractional application to mission i

I_i - a measure of the relative importance of mission i

E_i - effectiveness of the system in accomplishing the objectives of mission i

Factors that have relatively little impact on over-all effectiveness or cost can be considered to be fixed or, possibly, can be ignored. There is, of course, a risk involved if factors chosen to be fixed or unimportant would have had a significant effect if they had been allowed to vary. Factors that fall in this "gray area" may have constraints imposed upon them in such a manner that the more detailed analysis to be performed in the optimization process will indicate final disposition. For example, if a questionable factor might have a monotonic influence on effectiveness, consideration of only extreme values might be all that is necessary to determine the significance of this influence.

It is important that factors selection, variability, and the final choice of system definition be clearly indicated so that the scope of the optimization process will be known and areas for possible modification of the formal mathematical solution will be made explicit.

In many areas cost-effectiveness criteria or measures are commonly accepted. These are often stated in terms of dollars per unit of task performed. These measures are analogous to sales prices for units of measureable materials used in the civilian market, such as dollars per gallon, dollars per pound, etc. These measures are easily understood and lend themselves to the spirit of the drive to produce or purchase the most for the least. Table II lists some examples of cost effectiveness criteria and the field of endeavor in which they are used.

TABLE II

EXAMPLES OF COST-EFFECTIVENESS CRITERIA
IN VARIOUS AREAS OF ENDEAVOR

Area of Endeavor	Example of a Cost Effectiveness Criterion *
Non-Military:	
Building	Dollars per square foot
Air passenger	Dollars per passenger mile
Freight	Dollars per ton mile
Computer	Dollars per bit
Communications	Dollars per message unit
Electricity	Dollars per kilowatt hour
Gas	Dollars per cubic foot
Public highways	Dollars per mile
Farming	Dollars per acre
Military:	
Launch vehicles	Dollars per pound payload in orbit
Satellites	Dollars per hour of successful operation in orbit
Missiles	Dollars per kill
Interceptors	Dollars per intercept

* Cost per successful effort is different for military than for non-military since success is usually probabilistic in nature in the military situations.

C. IDENTIFY AND SYNTHESIZE ALTERNATIVES (TASK 4)

The ability to optimize a system depends on the availability of alternate means of meeting the requirements. Alternatives include the means, approaches, or techniques which can be employed to meet the stated requirements within the constraints of the resources. Obviously, if no alternatives present themselves or if they are ruled out by the statement of requirements and resources, there is no problem in selection. It also follows that when alternatives do present themselves, decision between them is required. If the system is to be optimized with respect to cost effectiveness, then the optimization process must extend to each decision made on the alternatives presented.

Table III shows an example of the types of alternatives considered in optimization studies.

It is possible to arrive at the optimum system of a given type by designing a great number of alternative systems, estimating cost and effectiveness for each, and simply selecting the best one. However, the large number of man-hours required render such an approach impractical. As a result, it is necessary to consider only a very few basic configurations or candidate systems within a given system type. A completely adequate cost effectiveness optimization of the system can often be accomplished with as little as one basic configuration. However, due to the small number of basic configurations thus explored, it is necessary that each basic configuration be optimized within itself. This is accomplished by synthesizing and evaluating variations or alternatives at several levels within the basic configuration. These alternatives may take the form of either physical or performance characteristics.

Each military system has a number of physical characteristics that affect cost, performance and effectiveness. A list of physical characteristics to cover all systems will not be attempted. A few of those common to most systems include weight, volume, shape, energy levels, mechanical and electrical packaging, and environmental capabilities. The physical characteristics of a system affect the cost elements incurred in

TABLE III

TYPICAL ALTERNATIVES POSSIBLE IN COST-EFFECTIVENESS OPTIMIZATION

Basic Concept

- Manned Versus Unmanned
- Liquid Versus Solid Rockets

System and Subsystem Type

- Battery power versus generation
- Materials Choice

System and subsystem configuration

- Redundancy
- Maintenance
- Hi-Reliability versus MIL Std Parts

Operational modes

development, procurement and support. There is obviously a broad range of cost sensitivity as cost elements are compared for different design alternatives of a given system requirement as well as for different technology alternatives within a given design alternative.

When one considers the area of performance characteristics of military systems, it is difficult to prepare a comprehensive listing, and few performance characteristics are common. Typical performance characteristics for a few military systems include: accuracy, speed, thrust, memory capability, computational capability, signal to noise ratio, range, power output, discrimination, etc. Relationships between cost elements and performance characteristics are fertile areas for optimization. A particular cost element will vary as the performance characteristic varies over the range of values possible for the design alternative. For a given requirement level of a performance characteristic, cost element variation as a function of the different design alternatives and technology alternatives within a design alternative, are of prime importance. The constraints on performance characteristics are generally set by scientific, engineering, and manufacturing knowledge and capabilities.

In listing the alternatives, primary importance should be given to those which have a significant impact on cost or the resources established in the statement of requirements. It is a value engineering maxim to dig where experience and engineering judgment indicate there is likely to be gold. A preliminary analysis of an initial system design can indicate the major impact areas.

The number of alternatives to be considered in the optimization process can, in many cases, be reduced by screening these alternatives against the available resources established in the statement of requirements. In the area of cost, physical characteristic constraint relations established outside the cost area will often bound and limit the feasibility or scope of alternatives.

As an example of such screening, let us look at a case wherein an isotope power source is being considered as an alternative to a power system design more compatible with current state-of-the-art. If the required date for system operational capability is relatively early in time, the isotope power source may be automatically ruled out by lack of availability by the required date.

An example of an alternate type of screening problem could occur when comparing the same isotope energy source against an operational date stated as a variable. Assuming that system effectiveness or value decreases as the operational date is delayed, it may be possible to eliminate the isotope energy source from further detailed consideration on the basis that the cost or effectiveness gains associated therewith do not compare favorably with the value or effectiveness lost due to the corresponding slide in operational date.

In preparing a list of alternatives, one should associate them with the level at which decisions upon the alternatives are to be made. At system level, decisions should be made on alternatives which impact on the basic system configuration or operational mode. Decisions which do not directly or substantially affect basic configuration and operational mode should be made at lower levels using trade-off factors developed for the entire system. If such lower level decisions are attempted as a part of the over-all system optimization process, the scope of the system level problem may become unmanageable. It is recognized, however, that the basic system may change significantly as a result of optimizations at system level. Further, the trade-offs and optimizations made at subcontractors level with a single sub-assembly or black box may have far-reaching effect on system effectiveness. Thus, any system for handling cost effectiveness must permit optimization to feed both up and down through the various system levels and/or tiers of customer/contractor/subcontractors. The process of feeding up and down through the system must be recognized as an iterative one, wherein it may be necessary to reiterate some of the lower level sub-optimizations to insure that the basic system changes have not altered previously established conclusions.

D. IDENTIFY VARIABLES (TASK 5)

For each alternative on which a decision must be reached, one can proceed to list the significant variables which should be considered in the optimization analysis. Table IV shows examples of variables which can influence the choice of alternatives. In a cost-effectiveness optimization, it is evident that although many variables exist and could influence final selection of an alternative approach, the variables which are significant can be limited to those which have an impact on cost, resources available, or the effectiveness with which the system performs its function. Variables which do not influence these quantities significantly should not be included in the optimization process.

Variables can also be screened to a certain extent. In general, some variables can be arbitrarily treated as fixed quantities as a result of elements in the statement of requirements, limitations on resources, or other previously established decisions on the program. In other cases, a legitimate variable can be treated as a fixed quantity initially. Then, after initial optimizations have been completed, the effect of altering the variable can be expressed in terms of impact on the final answer. In many cases, judicious fixation of variables in this manner can save a large amount of manpower expenditure if the decision to fix the variable is based upon probable insensitivities of the answer to the magnitude of variation expected.

The range of each variable to be considered should, for economy of analysis effort, be limited. Constraints on physical characteristics often limit the range of performance characteristics or other variables which can be considered. Preliminary sensitivity analysis, rough-cut analysis, or an extreme (maximum and minimum) value analysis are also useful in indicating probable limits of variables. Variables thus limited should be reexamined after completion of the optimization study. If a definite optimum point is reached within the limits of each variable, it is generally safe to assume that the limits established were reasonable.

TABLE IV

TYPICAL VARIABLES INFLUENCING COST-EFFECTIVENESS EVALUATION OF ALTERNATIVES

Cost

Weight

Payload Carried

Mission Length

State-of-Art

Time Required

Reliability

Safety

Maintenance

Availability

Vulnerability

Survivability

SECTION IV

COST-EFFECTIVENESS
MODELS, CONCEPTS, VALIDATION AND SENSITIVITY
(TASKS 6 & 7)

A. MATHEMATICAL FORMULATION OF EFFECTIVENESS AND COSTS

A basic problem which confronts any military planner is that of providing assurance that he is "buying the most for the military dollar." In general terms, the military service procures a system (or improvement thereon) with effectiveness or potential effectiveness E (or effectiveness improvement ΔE). The system is paid for in resources which are usually related to dollar costs C (or ΔC in case of the improvement). The military planner wants to be sure that units with the highest E are obtained for the C units expended.

1. Effectiveness as a Function of Various Parameters The effectiveness (E) of any system is, in part, a function of parameters (X_i) which are controllable. Some of these parameters may be constrained by the state-of-the-art (X_{L_i}) at a particular point in time. Unfortunately, E is also, in part, a function of factors not under the control of designer, purchaser, or user. These include characteristics of weapons in the enemy arsenal, or of targets for the subject weapon system. Thus, E will be degraded with time (t) if the enemy capability improves. (This degradation function may be discontinous. For example, E may be constant and high until some point in time when the enemy has developed and deployed a counter weapon. At this point E may suddenly drop to or near zero.) E is also a function of time when one is either procuring a new system or improving an existing system. Thus, the effectiveness for a new system is ordinarily zero until the development is completed and the deployment of the operational system is initiated.[2/] Change of effectiveness

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[2/] Under concurrency, some limited capability may exist in the so-called IOC (Initial Operational Capability) phase, when "Development," in a formal sense, may be far from complete.

of an existing system does not occur until modification is initiated. We may write

$$E = E(X_i, t), \quad O \leq X_i \leq X_{L_i} \qquad (1)$$

where all design parameters have been defined so that they are positive and limited at some upper bound.

Figure 4, which displays a sample effectiveness function plotted against time, is intended to illustrate some of the factors which contribute to effectiveness. Projections of effectiveness must be updated frequently so that sufficient lead time is allowed for procuring new or modifying existing systems to replace those whose effectiveness is either declining or inadequate.

Figure 5 shows effectiveness as a function of two controllable (i.e., independent variable) parameters. For illustrative purposes, mean time to failure and the reciprocal of mean down time per failure (which can be called the repair rate) were used as variables. Limits of the state-of-the-art are shown as functional limits rather than as strictly constant limits.

The controllable variables which are important depend upon the type of system and the stage in planning, development, or employment being considered. For example, in planning an atmospheric bombing system, force size, speed, range, payload, altitude, availability, reaction time, turn-around capability, invulnerability, penetrability, accuracy, etc. would all be of interest.

During the development and procurement stages, availability may be of paramount importance, and may generate a high level of interest in both failure rates and repair rates. Other factors such as speed, range, payload, etc. could reenter the picture if either the planning estimate for the state-of-the-art or the prediction of cost were found to be in error at a later time. For a defensive radar system, these variables could become the number of radars, search range, lock-on range, target capacity per unit, angular accuracy, range accuracy, availability, false alarm rates, etc..

The appropriate unit of measurement for effectiveness, in general,

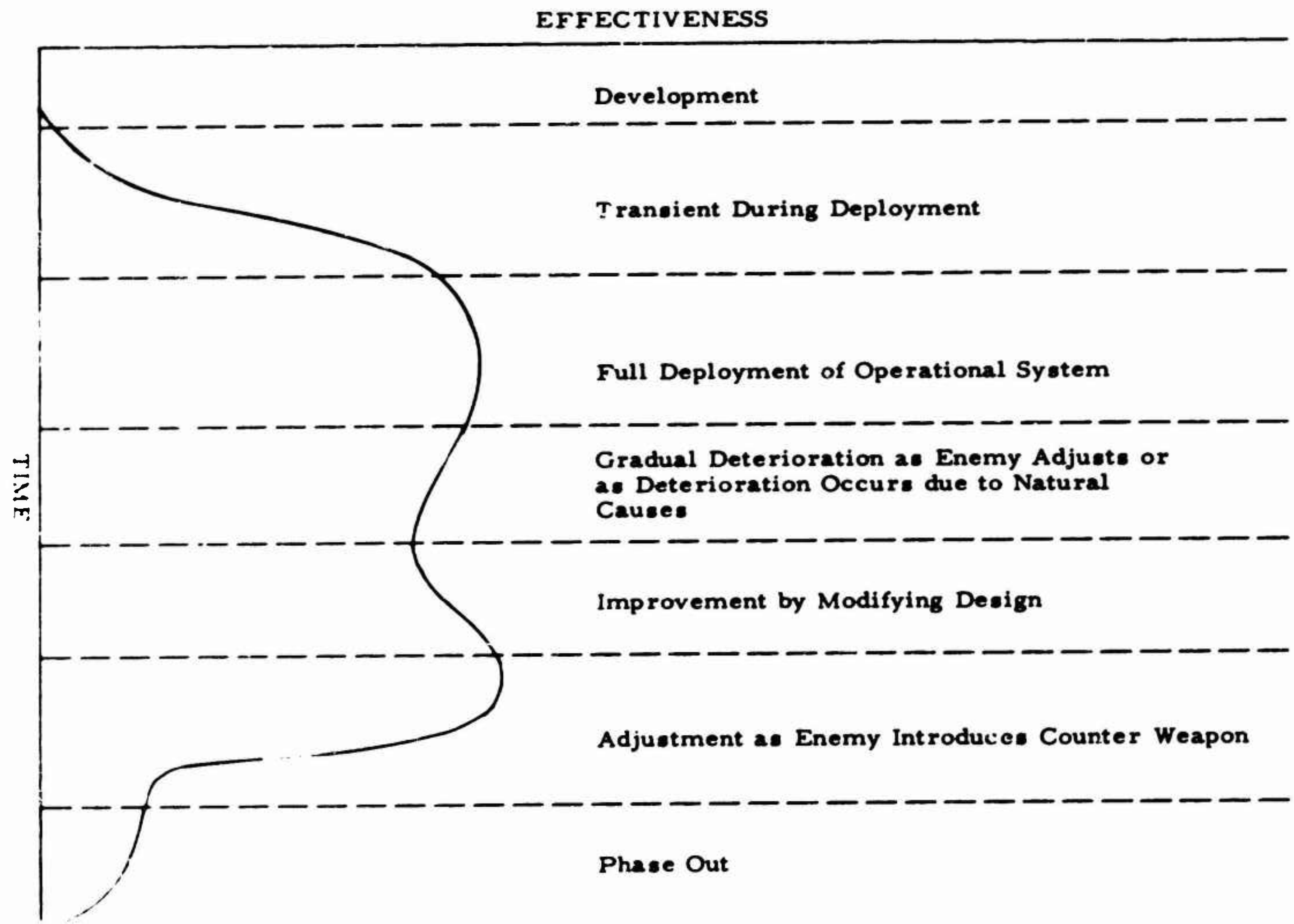

FIGURE 4. EFFECTIVENESS AS A FUNCTION OF TIME

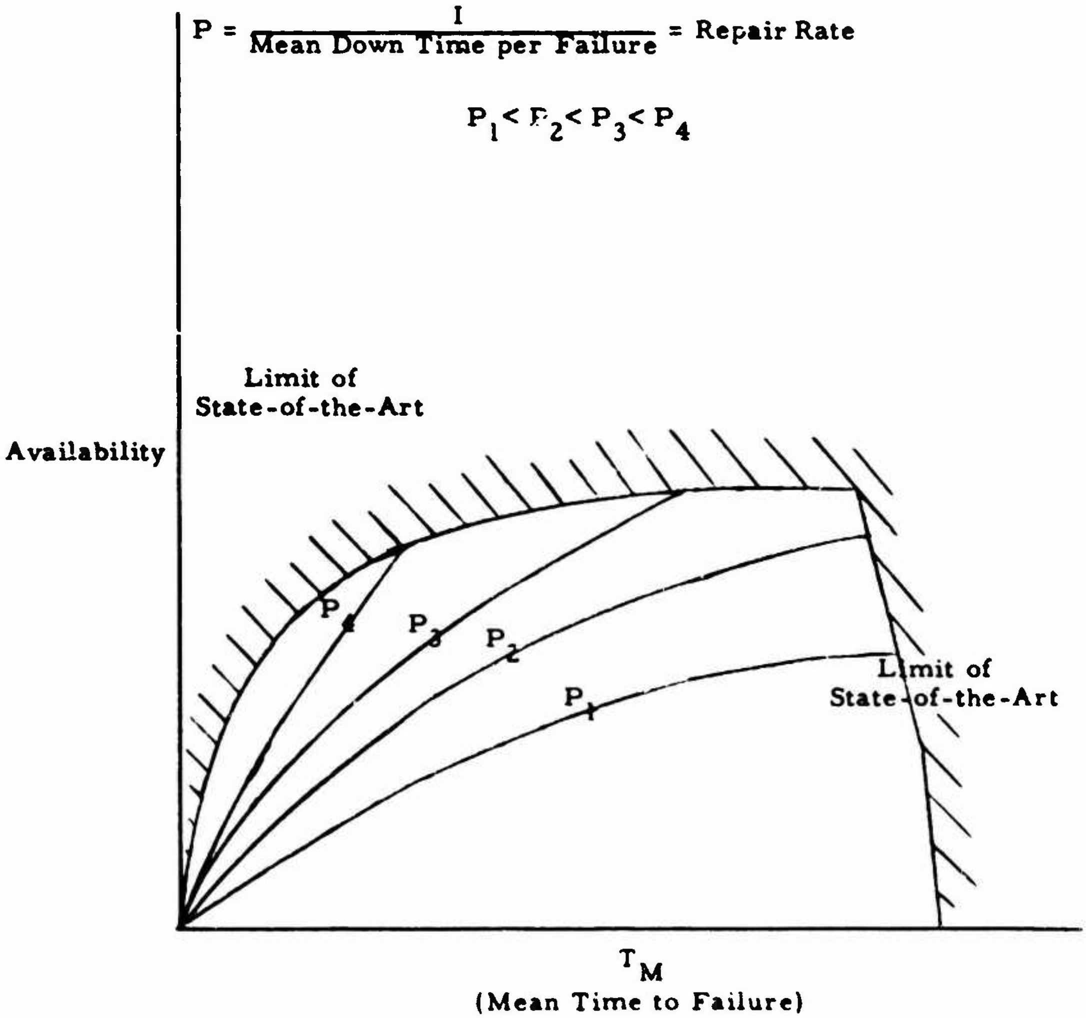

FIGURE 5

AVAILABILITY AS A FUNCTION OF TWO CONTROLLABLE PARAMETERS: REPAIR RATE AND MEAN TIME TO FAILURE depends upon what mission the system is expected to perform. Thus, a bombing or missile system's effectiveness could be related to the number of enemy targets of a given kind which could be destroyed by an assumed force in a prescribed time under prescribed conditions. A defensive radar system could be rated according to the number of targets an assumed net could handle under given conditions. However, it is possible to formulate effectiveness, E, so that all systems may be related to a common measure. One alternative is the expected fraction of the total number of required individual missions within a class which would be completed successfully.

2. Cost as a Function of Various Parameters The cost (C) for obtaining a system with effectiveness (E) is also a function of the parameters X_i. Like E, C also depends on time, but in a different manner. C is influenced by the speed with which one may want to obtain a system with a given level of effectiveness. Urgency may lead to parallel developments on critical items involving risk or uncertainty, and certainly will lead to overtime and waste due to errors.

Estimates of time to completion (for a given level of project effort) can be obtained from PERT networks. Combination of this with PERT-Cost analyses or the use of other techniques (e. g., Critical Path Scheduling) can lead to plots of cost versus time. A conceptual trade-off is shown in Figure 6, with effectiveness, E, as a third parameter.

The curves of Figure 6 are asymptotic to lines parallel to both the cost and time axes. However, past experience has shown that adding more dollars, when near minimum development time, may actually cause time delays. Extension of project "deadlines," as a revision of an original well-planned program not only can, but usually does, lead to increased cost.

From the foregoing, it should be evident that the cost of obtaining a new system or improving an existing one is a function of controllable system parameters (X_i) and development time (t_d). Thus,

$$C = C(X_i, t_d). \qquad (2)$$

Useful life and, therefore, "long-term effectiveness" of the system

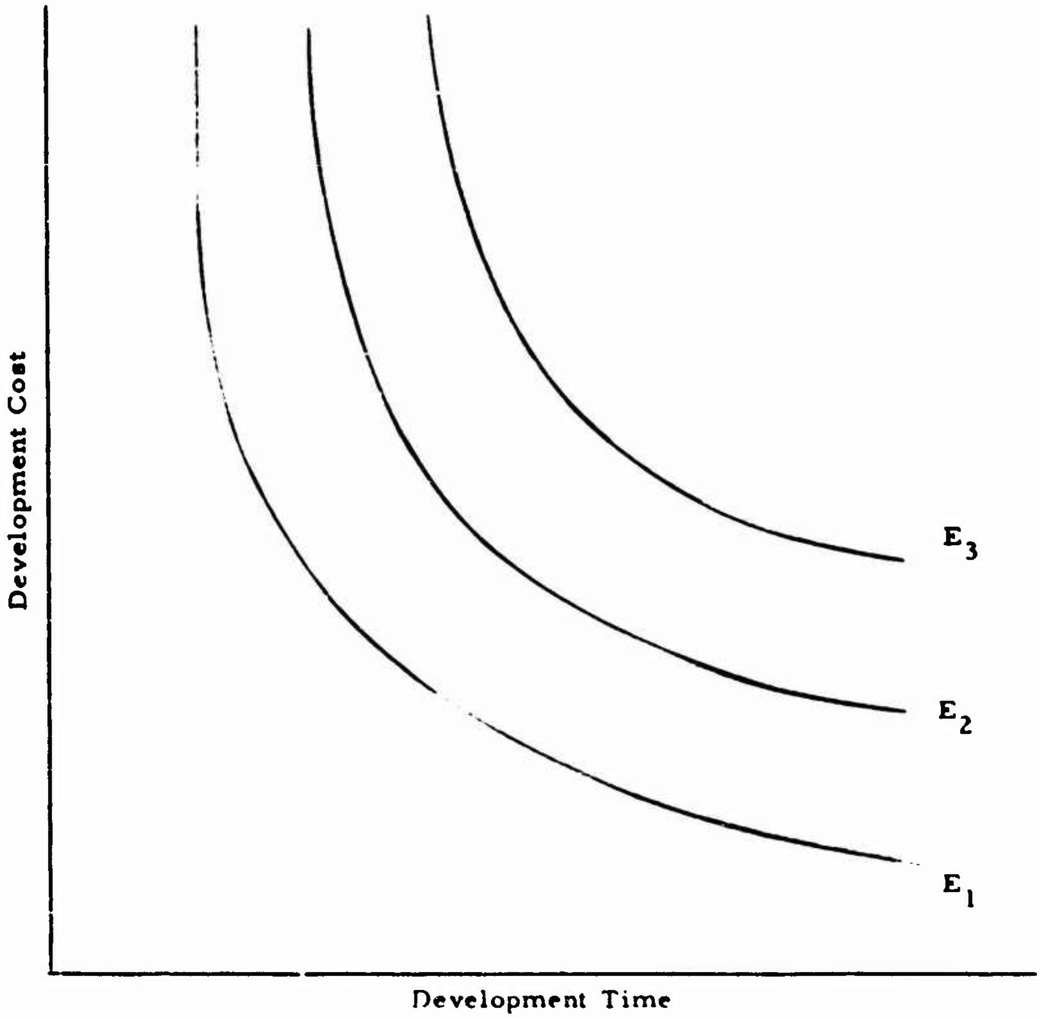

FIGURE 6

DEVELOPMENT COST VERSUS DEVELOPMENT TIME

$(E_1 < E_2 < E_3)$

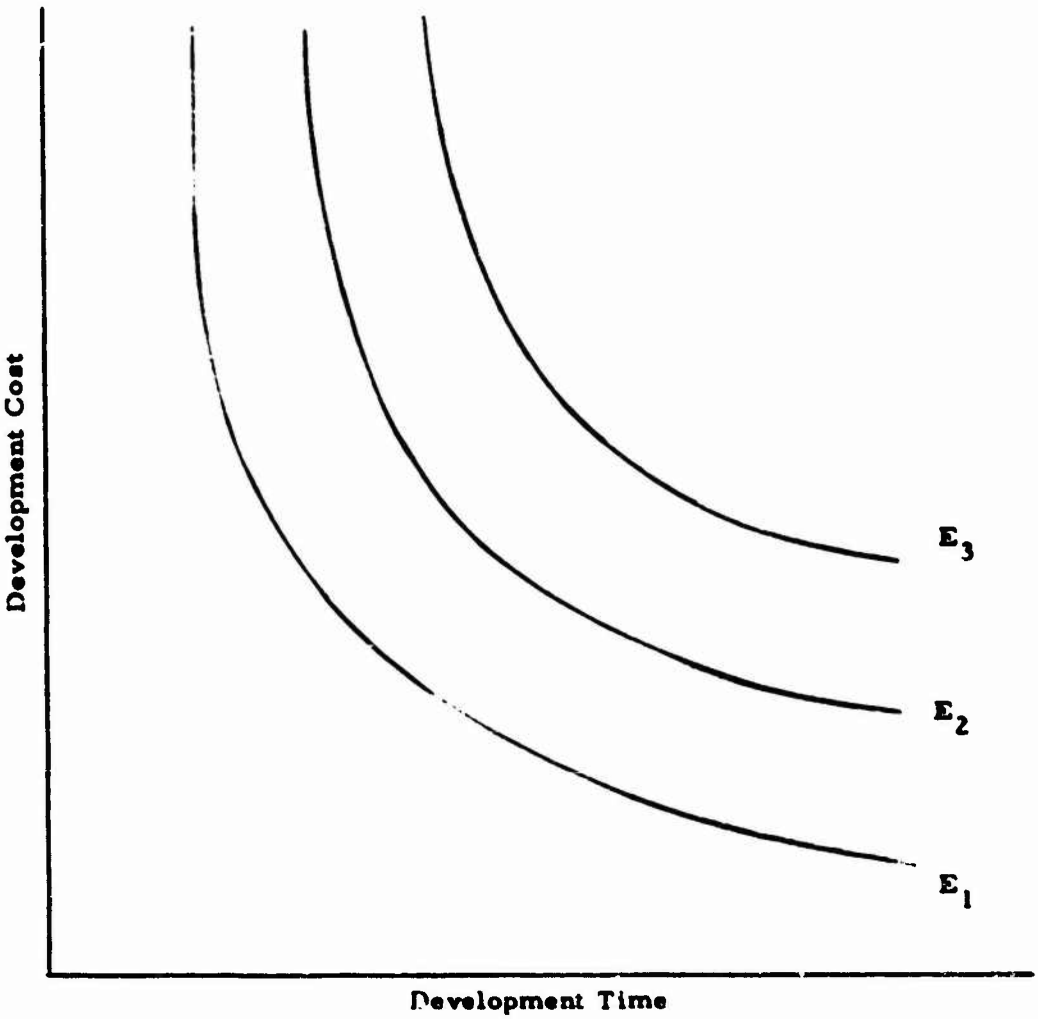

FIGURE 6

DEVELOPMENT COST VERSUS DEVELOPMENT TIME

$(E_1 < E_2 < E_3)$

only be accurately calculated after the fact and often has low accuracy if estimated at any point in the life of the system. During development and procurement, both modification costs and the effect of modifications on such things as system effectiveness and operational and support costs cannot be accurately assessed. If they could, such modifications would probably have been included in the initial design. Furthermore, at any point in the system lifetime, only those costs still to be incurred are of interest; those already made are unrecoverable.

The foregoing discussion of effectiveness, cost, and time was included here to provide a meaningful background for the consideration of the cost-effectiveness models which follow. Detailed consideration of these factors (i. e., effectiveness, cost, and time) and models for their determination are given in other portions of this report. It is sufficient to note here that, where C is total cost and C_i is the i^{th} cost element, C is given by

$$C = \sum_i C_i . \qquad (5)$$

Often effectiveness will be measured in terms of a probability of success. If E is effectiveness, and P_i is the i^{th} conditional probability element, E is given by

$$E = \prod_i P_i \qquad (6)$$

$$= P_{avail.} \cdot P_{launch/avail.} \cdot P_{flight/launch} \cdot P_{penetrate/flight} \cdots \text{etc.}$$

B. STATEMENT OF THE OPTIMIZATION PROBLEM

The problem is to define and evaluate cost-effectiveness models which can be used to choose an "optimum" configuration for:

(1) a new system, or

(2) modifications to an existing system.

Three measures which depend upon system parameter choices are used here to determine when a best configuration has been achieved. These are:

(1) cost (C);

(2) effectiveness level (E);

(3) long-term effectiveness (I_E) which involves: (E); time of activation -- related to development time (t_d); and time of obsolescence (t_o).

It is fairly certain that the optimization or decision process will occur under various constraints. These may include:

(1) Total cost (C) is either given or constrained by an upper bound;

(2) effectiveness (E) is specified or constrained by a lower bound;

(3) time of activation (t_d) and cost (C) are specified or constrained by an upper bound;

(4) time of activation (t_d) and effectiveness (E) are specified or constrained by upper and lower bounds respectively;

(5) some system performance parameters (example: missile range) may be specified or bounded.

All of the dependent factors are functions of controllable parameters (X_i) (ignoring the problems of risk and uncertainty). Thus,

$$C = C(X_i, t_d) \tag{7}$$
$$E = E(X_i)$$
$$t_o = t_o(X_i)$$
$$I_E = (t_o - t_d) E$$
$$0 \leq X_i \leq X_{L_i}$$

where t_d has been selected as a controllable variable. For the present discussion, we will assume the E is constant during the useful system life, and zero elsewhere.

Although the above equations have been written so that symbols are obviously those for development-procurement, what follows is just as applicable for system modification.

It is a natural human trait to seek conciseness in considering measures of value (e.g., Cost-Effectiveness). Thus, we are seeking cost-effectiveness models which provide measures in terms of cost units/mission or cost units/unit of time/mission. Examples include dollar/kill of 100 psi point target, dollar/year/ICBM detected, etc.

C. SOME POSSIBLE MODELS

In the following, only three basic cost-effectiveness models are considered. This should not be interpreted as indicative that other models are of no value. Indeed, the reader is encouraged to broaden his study by looking elsewhere. However, the three models discussed here should be sufficient to exemplify the factors of importance.

The models considered here are what may be referred to as the "profit," the "cost-effectiveness (level) ratio," and the "cost-effectiveness (long term) ratio" models. Variations on these, usually in terms of constraints, are also discussed but are not considered as constituting a separate basic model type.

1. Profit Model The profit model is simply the application of the commercial concept of return on investment. This may be stated in terms of absolute return:

$$P = E - C$$

$$= \text{Value Received} - \text{Cost Expended} \qquad (8)$$

or:

$$= \text{Value expected} - \text{Cost expected.}$$

or rate of return

$$r = \frac{E - C}{C}. \qquad (9)$$

The usefulness of these models is contingent on solution of the rather difficult problem of finding a common unit of measure for E and C. This has been done in the past by such arbitrary means as indexing each on a common scale (e.g., 0 to 100) or by relating E to value of targets killed, value of property defended or protected, etc.. However, such arbitrary actions -- whatever the logic upon which they are based -- often lead to gross misunderstandings and frustrations on the part of those involved in the decision-making process. As an illustration, consider the case of an air-to-air missile designed to be used against bombers which are attacking important targets. Let cost, as a function of in-flight reliability, R, be given by

$$C = 10000 + \frac{1000}{1 - R} \tag{10}$$

and let effectiveness, in terms of single shot kill probability, be given by

$$E = .80R\,. \tag{11}$$

Now let the value of effectiveness (V_E) be given by

$$V_E = KE \tag{12}$$

where K is an arbitrary constant. Some may wish to determine K from the value of the bomber (there is a possible wide variety of bomber values), or values of the target which the bomber might attack (an even wider variety), or both. Mathematical manipulations lead to the conclusion that the optimum reliability is given by

$$R = 1 - \sqrt{\frac{1250}{K}} \qquad \text{for } K \geq 1250\,. \tag{13}$$

Extremely high values for K can lead to an R precariously near 1. When this is substituted back into the cost formula, a rather costly missile may result. Admittedly, the foregoing example suffers from oversimplification. It is a suboptimization in an extremely complex problem. However, it is indicative of the importance of the problem of selecting a value scaling factor (or function) for the "profit" model.

The second "profit" model (i.e., rate of return) suffers from an additional difficulty occurring with ratio functions. Under some circumstances, the optimum may occur at the origin and one finds that "the best system version is no system at all." As an example of this, consider the cost and effectiveness functions:

$$C = AX \tag{14}$$

where X is some system parameter related to effectiveness by

$$E = B(1 - e^{-DX}) \tag{15}$$

and A and B are constants of proportionality.

Substitution of (14) and (15) into (9) leads to an optimum with $X = 0$. On the other hand, switching the C and E functions leads to $X = \infty$ for the optimum. Thus, in the first case, the maximum rate of return occurs when we spend no resources or only a minute amount. In the second, we should spend all the resources at our disposal. However, let us return to reality. The first system (optimum at $X = 0$) may still be an extremely good system at non-optimum points when compared with other systems available for the same mission. Further, it must be remembered that we may be considering a useful mission which we must be prepared to perform. Thus, the negative conclusion may be either incorrectly or incompletely stated.

No extensive discussion of solutions to this dilemma will be presented here. However, if one is enamored with rate of return as a concise way of presenting the value of a system, then one should remember that, in general, side conditions (constraints) are usually involved in this evaluation process. Thus, for example, we may be interested only in systems for which effectiveness is above a certain level and we have an upper limit on resources available. We may then maximize r with equality constraints for varying levels of either E_C or C_C until the other constraint is encountered. Thus, stated mathematically,

$$\text{Maximize} \left[r = \frac{E(X_i) - C(X_i)}{C(X_i)} \right] \tag{16}$$

with constraints

$$E(X_i) \geq E_C \tag{17}$$

$$C(X_i) \leq C_C \tag{18}$$

The results, in terms of r, may then be plotted versus C and/or E and decisions made on some rational basis. It should be noted that this is equivalent to the following:

$$\text{Maximize } [E(X_i)] \text{ with constraint } C(X_i) - C_C = 0 \qquad (19)$$

or

$$\text{Minimize } [C(X_i)] \text{ with constraints } E(X_i) - E_C = 0 \qquad (20)$$

at each of several constraint values (E_C or C_C as appropriate) and then examining the results in terms of r.

If some single function for the value of E can be found to represent the rational process followed in the final decision, then an optimum may be obtained in a direct manner. However, many factors involved in decision-making are either not reducible to a mathematical expression, or can only be represented in an imprecise way. The model can still provide a useful tool in reducing the scope of the area which must ultimately be investigated in a more rational way.

The other dilemma (optimum at $X \to \infty$) will not be discussed further here since it is analogous to the first problem.

Consideration of I_E (i.e., long range or integrated effectiveness) in either version of the profit model is different from consideration of E, itself, by virtue of lifetime support costs in large part. The element of time is introduced along with significant costs of support. Since the implications of time are more readily seen in terms of the cost-effectiveness (long range) ratio model, discussions of this measurement concept will be given later.

2. Cost-Effectiveness (Level) Ratio Model As indicated by the name, this model is given by

$$C_{EL} = \frac{C}{E} \qquad (21)$$

The model has the advantages of providing measure values in natural terms. Thus, in terms analogous to transportation (cents per ton-mile or cents per passenger-mile), weapon cost-effectiveness values may be given in terms of dollars per kill, dollars per intercept, or other measures of dollars per mission. However, we are again faced with the dilemma associated with ratio functions. This problem has already been considered in relation to the rate of return version of the Profit Model. As in that case, a useful approach is that of employing Lagrange multipliers (see references 4 and 5) to find extrema. Such a problem might be stated as

$$\text{Maximize } E + \lambda_C(C - C_C) + \lambda_t(t_d - t_C), \tag{22}$$

where λ_C and λ_t are the Lagrangian multipliers for the cost and time constraints respectively, or

$$\text{Minimize } C + \lambda_E(E - E_C) + \lambda_t(t_d - t_C). \tag{23}$$

The cost-effectiveness value of the system may then be presented in terms of C_{EL} (as computed from Equation (21)) and plotted versus C_C or E_C as appropriate. For simplicity of presentation, constraints have been indicated in (22) and (23) through the use of undetermined Lagrange multipliers without regard to any mathematical questions which may arise. A time-of-activation constraint has also been shown to indicate how this factor may be introduced into this type of model for cost-effectiveness considerations. Other constraints may be encountered, such as those imposed on system design parameters by either state-of-the-art or other causes.

3. Long Range Cost-Effectiveness Ratio Model The functional relationship for this model is given by:

$$C_{ELR} = \frac{C}{I_E}. \tag{24}$$

Considering the assumed relationships given in Section IV-B, Statement of the Optimization Problem, the equation may be transposed to:

$$C_{ELR} = \frac{C}{(t_0 - t_d) E}. \tag{25}$$

This form displays the sometimes desired measures of value in terms of dollar/year/mission. This combines the relevant factors of cost, longevity and effectiveness potential into a single measure.

D. OPTIMIZATION TECHNIQUES

The use of the technique of undetermined (Lagrangian) multipliers as a tool of optimization was mentioned above. This technique is useful when well defined analytical relationships exist among the variables, and when the constraints are expressly stated as fixed, single valued requirements. Alternative techniques are preferable when the relations among the variables are empirical, disjointed, or discrete and whenever the constraints are stated as a range of acceptable values. For example, when a finite number of discrete alternatives exist, optimization would ordinarily be accomplished by the straight-forward procedure of direct comparison of the calculated cost and predicted effectiveness of each alternative.

When the data is empirical, as opposed to analytical, graphical techniques will usually prove to be more useful and are particularly useful when the constraints are given as a bounding range of acceptable values.

In addition to the above techniques, there are a number of others discussed in the literature. Among the more common are:

- marginal analysis
- dynamic programming
- simple maximization
- Pontryagin's maximum principle
- linear programming
- calculus of variations
- method of steepest ascent
- "mini-max principle" of the theory of games.

In a report of this length it would be impossible to present an intelligible illustration of each of these techniques. The task group has therefore arbitrarily chosen to limit its examples to illustrations of those methods which are simple to grasp, easy to exploit, and have a fairly wide application to reality, namely: exhaustion of feasible alternatives; graphical techniques; simple maximization; and dynamic programming.

This limitation should not be construed as an unqualified endorsement of these techniques to the exclusion of the others.

Further discussion of optimisation including principles, criteria and techniques is contained in Section II of Volume III of the final report of Task Group IV.

E. MODEL VALIDITY AND SENSITIVITY.

1. Assumptions All assumptions required for the model should be explicitly stated and, if possible, supported by factual evidence. If no such evidence exists, it is advisable to state the reason for the assumption (like mathematical simplicity) in order to indicate the degree to which the assumptions will require further justification, and to pinpoint the areas in which errors might be introduced.

2. Adequacy A model must be adequate in the sense that all major variables to which the solution is sensitive are quantitatively considered, where possible. Many of these variables will have been preselected. Through manipulation of the model, some of the variables may be excluded or restricted, and others may be introduced. Non-quantifiable variables must be accounted for by modification of the solution rather than by direct incorporation into the model. In this sense they become quantifiable.

3. Representativeness Although no model can completely duplicate the "real world," it is required that the model reasonably represent the true situation. For complex problems, this may be possible only for subparts of the problem, which must be pieced together through appropriate modeling techniques. As an example, analytic representation may be possible for various phases of a complex maintenance activity. The outputs from these analyses may then be used as inputs to a simulation procedure for modeling the complete maintenance process.

4. Probabilistic Aspects--Risk and Uncertainty The various types of unknowns involved in the problem cannot be ignored, nor can they be "assumed" out; they must be faced squarely. There may be technological

uncertainties involved with some of the system alternatives, operational uncertainities involved with planning and carrying out the mission, uncertainties about enemy strategy and action, and statistical uncertainties governed by the laws of chance (referred to as risk). Risk analysis may be applied in cases involving statistical uncertainties, functions-of-random-variables theory or such procedures as Monte Carlo techniques. The non-quantifiable area of uncertainties is a matter of expert judgment. The probability of guessing correctly for every uncertainty is quite small. The general approach is to examine all major contingencies and compute resultant cost-effectiveness parameters. The optimization criterion, then, must be adaptable for use in the evaluation of the set of cost-effectiveness results. The developments of decision theory and game theory conceptually become most applicable in the selection of a decision model in these cases, since different alternatives may be best for different contingencies.

5. Validity The final test of the model is whether or not it yields the best system. Unfortunately, this determination can be made only after systems are developed and in use, if it can be made at all. However, certain questions will disclose weaknesses that can be corrected:

(a) Consistency - are results consistent when major parameters are varied, especially to extremes?

(b) Sensitivity - do input-variable changes result in output changes that are consistent with expectations?

(c) Plausibility - are results plausible for special cases where prior information exists?

(d) Criticality - do minor changes in assumptions result in major changes in the results?

(e) Workability - does the model require inputs or computational capabilities that are not available within the bounds of current technology?

(f) Suitability - is the model consistent with the objectives; i.e., will it answer the right questions?

F. CONCLUSIONS

From the foregoing discussion of basic model types, it should be apparent that no single one of the basic types will be the best for application to all systems and optimization problems. The selection of basic model types should be based on consideration of:

- definition of mission
- form of criteria and measures
- nature of constraints
- type and extent of information furnished from or deriveable from results of preceeding higher level studies.

Application of the profit models will potentially yield more information from the optimization analysis and provide a better insight into the economics of the system as they relate to competing systems and missions. However, use of the profit models requires a great deal more input data and relationships. The problem of scaling effectiveness and/or costs to equivalent units will generally be controversial and, in some cases, will be impossible.

A less difficult method for presenting a combined measure of value for a system is the cost-effectiveness ratio model. The second version (i.e., long-range effectiveness) provides the best vehicle for combining all factors involved during the procurement process, since it provides an indication of the effects of the important factors: cost, time to activation, longevity, and effectiveness potential.

For the purpose of studying operational and support procedures after system activation--when procurement costs have already been paid--the cost-effectiveness (level) ratio model is probably most appropriate with cost being given in terms of \$/year for operation and support.

If system modifications are being considered--after activation-- the cost-effectiveness (long range) ratio model again takes precedence with $(t_0 - t_d)$ indicating time remaining after completion of modification. Costs

(C) are the total costs, including development, investment or indirect costs relevant to modification, and subsequent direct operational and support costs. Usually, modifications should be evaluated in terms of incremental costs, changes in effectiveness potential. etc.

In any application of ratio models, the real life situation (involving budget factors and the "facts of life" related to requirements for effective systems plus problems associated with defining ratio functions so that useful and meaningful extrema may be derived) dictates that the optimization process be performed on a basis of maximizing effectiveness (of constant cost) or minimizing costs (of constant effectiveness) with appropriate constraints imposed. Occasionally, it may be desirable to minimize development time or maximise system life with appropriate constraints.

The formulation of models is not the principal problem associated with system evaluation. Models are somewhat arbitrary methods for deriving a measure of system value. The choice of models must ultimately be based upon consideration of the meaning associated with the measure of cost-effectiveness resulting from a particular form of model. Caution must always be exercised in interpreting model results.

The principal problem associated with system evaluation is that of developing methods for obtaining meaningful estimates of values for the factors of cost, effectiveness potential, and time. Associated with this is the problem of obtaining valid and compatible input data for use in the various models.

In the preceding, costs have, in general, been used in the context of economic units such as dollars. It often becomes necessary to consider limited resources such as skilled manpower or critical material. Due to the characteristics of these limitations, it is sometimes difficult to relate such expenditures to the dollar units in which other cost factors are ordinarily expressed. This difficulty may be surmounted either by considering the problem as a suboptimization--if this can be done in a meaningful way--or by introducing an appropriate constraint (for the limited resource) into the over-all optimization problem.

SECTION V

DEVELOPMENT OF COST INPUTS TO COST-EFFECTIVENESS MODELS (TASK 8.1)

A. OBJECTIVES

In the preceding chapter, the reader has seen several possible cost-effectiveness models. In each model it was essential to develop the costs of each element of major subsystems and weapon systems in order to arrive at cost-effectiveness values. The objective of this section is to outline factors of a method for better estimating costs. The method outlined will enable one to insure that all factors vital to cost-effectiveness trade-offs are included in the analysis.

We refer to cost estimates that are done as part of the procedures for Air Force selection of optimum weapon systems at the Specific Operational Requirement (SOR) and pre-Request-for-Proposal (pre-RFP) stages of weapon system procurement. The cost estimates considered here are also the type of parametric cost estimates which industry needs to help select the most cost-effective designs for representing their weapon systems approaches to the Department of Defense (DOD). We are not speaking of the inherently proprietary proposal cost data submitted at the final stages of weapon system procurement. This point must be emphasized: The costs dealt with herein are to be used for Air Force decision-making as to preferred systems and are not the costs in the contractors' proposals to build vehicles and to make internal company decisions.

Although some method of arriving at costs is mandatory, the particular approach presented here is not to be construed as "official" or "the only acceptable" approach. There should be sufficient flexibility to adjust to varying situations. It is more important to have a consistent definition of cost categories and estimating procedures (not overlooking important cost factors) than to try to insist on one best method. In the past, otherwise excellent weapon system studies have overlooked important cost categories such as R & D, trainin ts, etc., thus making the subsequent weapon system comparisons ur r suspect, to say the least. Adequate weapon selection among alternatives requires that contractor teams be able to develop cost breakouts in proposals and studies which include all of the factors and elements mentioned herein and that the breakout should be understandable to the procuring agency.

It is no doubt true that when developing cost data on a specific weapon system, a more inclusive presentation can be made than is defined in a general way in this section.

B. THEORY AND PRACTICE

Before discussing methodology for estimating costs, it might be well to discuss the philosophy on which the task group based its approach. Many take the approach that costs are a great unknown factor, and that it is impossible to make acceptable and useful cost predictions of future weapon systems.

We refuse to accept this philosophy. The business of estimating costs is not like coping with an unknown phenomenon in the area of physics or in the sciences. For example, there are fundamental gaps in man's understanding of particles in the atomic nucleus and hence man's methods of predicting and controlling the nuclear forces are often rudimentary and approximate. But this stumbling block is a real one, namely, lack of fundamental knowledge. This is certainly not the case with costs for existing commercial systems, as witness the detailed cost-knowledge of automobiles and television sets available in the appropriate industries, nor is it necessarily the case with the military systems.

A particular aggregation of existing hardware has a finite number of pieces. The only reason it may be difficult to ascertain the costs of a system in being, like a B-52 or an Atlas missile, is that pertinent data have probably not been kept in a form suitable for conventional cost estimating purposes. Of course, the costs of future systems presents uncertainty, especially if they depend upon new technological methods.

The major sources of uncertainty[3/] in cost analysis of future system and force structure proposals may be classified in various ways. Here, we somewhat arbitrarily select two major headings: requirements uncertainty and cost-estimating uncertainty. Requirements uncertainty refers to variations in cost estimates stemming from changes in the configuration of the system or force being costed. Cost-estimating uncertainty refers to variations in cost estimates of a system or force where the configuration of the system or force is essentially constant. These latter variations arise for numerous reasons -- e.g., differences in individual cost analysts, errors in basic data used in cost analysis, errors in cost-estimating relationships used in making cost estimates, and so on.

Requirements uncertainty is considered first, because all the empirical studies suggest rather conclusively that requirements uncertainty is the major source of uncertainty in cost analysis of military system and total force structure proposals. Let us attempt to get a better fix on what is meant by "requirements uncertainty." Suppose that early in the development program a total system cost estimate is developed for a certain system, using the best information and data available at that time. Then suppose that some years later when the system is being initiated into the active inventory, a new system cost estimate is made, using all the information and data available at that time. Typically we find that the original estimate is less than the second one and the difference may be quite large. What is the reason for this? Two factors immediately come to mind: (1) The price level may have increased during the time interval; (2) The quantity (size or force) of the system may be larger in the second estimate.

These two factors do in fact typically play a significant role. However, even after adjusting for them -- i.e., putting the two estimates on a comparable basis with respect to price level and quantity--the inequality still remains in many instances. Studies of this phenomenon in the past indicate that the ratio (adjusted) may be 1.5, 2, 3 or sometimes even higher. These

3/ From G. H. Fisher, A Discussion of Uncertainty in Cost Analysis, The RAND Corporation, RM-3071-PR, April 1962.

studies also indicate that the primary reason for this is that the configuration of the system has changed, and that these configuration changes tend to be cost-increasing in their effect. In other words, the subject being costed initially is often markedly different from that costed later. Here system configuration change means change in hardware characteristics and/or change in system operational concept (soft vs hard, fixed vs mobile, concentrated vs dispersed, low alert vs high alert, low activity vs high activity rate, etc.).

Numerous reasons may be given for changes in system configuration. The following are a few examples:

1. With respect to the system's hardware, the original design may fail to produce the desired performance characteristics, and as a result, the hardware configuration has to be changed. Or, sometimes performance characteristics themselves may be changed (upward) with a resultant change in hardware specifications and hence cost. Another possibility is that an attempt may be made to get the system sooner than was originally intended by substituting resources for time.

2. A change in system specifications may be induced purely by errors of omission in establishing requirements initially for some part of the system. For example, in the early phase of the ICBM program this happened with respect to the ground support equipment (GSE). Correction of the error led to rather marked changes in system GSE requirements, and hence to an increase in GSE cost.

3. A change like that mentioned in Example 2 above may have an indirect effect on other parts of the system. It is possible that personnel requirements may be changed. Also, an item like personnel requirements often is very sensitive to changes in system operational concept (e.g., degree of system dispersal, alert capability, etc.).

4. The strategic situation may change. This may lead to a respecification of hardware performance characteristics. Or, even if the hardware is not affected, the method of deploying and employing the system may have to be changed. For example, to reduce vulnerability of the system to surprise attack, a higher degree of dispersal, hardness, or alert capability

may be required to meet the new strategic situation. The impact of such changes on system installations and personnel requirements, to cite two examples, is obvious. A re-evaluation of the strategic situation may produce changes in system force size (number of units to be procured for the operational force), or in some cases a change in the number of years the system is planned to be kept in the operating inventory. Both of these situations may be regarded as a form of requirements uncertainty, resulting in a substantial impact on total system cost.

The above are only illustrative examples of a few of the many reasons the configuration of a system may change. But the key point is that requirements uncertainty can lead to wide variations in total system cost, even in the complete absence of cost-estimating uncertainty (if this were possible). There is such a thing as cost-estimating uncertainty, of course, but as mentioned previously, it tends to be small relative to requirements uncertainty.

Too often cost elements have been lumped and presented in a cumulative form before the analyst begins his work. It is then not possible to answer questions about the significance of training costs alone, or of R & D costs alone, etc. For purposes of advanced planning, cost elements must be kept in an easily identifiable form as explained below. Data in the pre-cumulated form, perhaps on punched cards or tape, can be analyzed from different viewpoints to answer varying questions and to compare the same cost subheadings across weapon systems. The resulting cost-data bank will then be a fruitful source of present and future data for cost-effectiveness decision-making. The Air Force has not fully required keeping of past program cost data in a form appropriate to decision-making heretofore. This failure jeopardizes the ability to make good future procurement decisions.

There must also be uniformity in the major data categories which are recorded, as well as in the definitions of those categories. Cost estimating techniques must then be established to help estimate the costs under each of the major sub-headings which are defined.

In generating pre-procurement parametric cost data, items such as the following must be given specific consideration:

1. Identify cost categories covering all sources of major system cost. The cost of a booster vehicle, for example, goes far beyond the direct procurement and launch costs of the booster. There are costs of training programs, logistic support, manufacturing facilities, tooling, GSE, etc. For maximum Air Force management and decision visibility, a thorough cost breakout is needed and costs must be tabulated under numerous standard sub-headings.

2. Costs in various units are needed since several resource constraints exist and confront the Air Force. For example, the "cost" of a new weapon system is constrained in terms of the availability of man-years of critical scientific, engineering, and technician effort needed to develop and operate the system. Also, the number of man-years of various military support and command skill levels needed to operate the system must be considered to be a constraint. The numbers of tons, gallons, or other units of critical materials (e.g., amounts of fissionable material or cubic yards of concrete for bases, or tons of light metals, etc.) needed to develop and operate the weapon system must be presented. Suppose that in 1970 a new ballistic missile system is to be procured. It would be helpful then to have the historical data on the amount of engineering man-hours, manufacturing hours, critical materials, etc., which were necessary to develop the Atlas, the Titan, the Minuteman, and other missile families.

Even the influence of the proposed weapon system procurement on other industries may be helpful. In the early fifties, the Air Force was considering development of Atlas and Titan I. The need for expansion of liquid oxygen production if these systems were to be developed, tested, and operated was a "cost" whose projection was vital to full cost-effectiveness understanding of the importance of these systems.

3. Costs in each of the cost units defined in paragraph 2 must be calculated per year as well as in total. The reason for this is that a given weapon system in total cost units (of critical manpower skills, critical

materials units, or in dollars) may satisfy the total resource level available, but the annual expenditures may exceed a smooth budget pattern during certain years. This becomes a serious problem to the funding and man-loading of other weapon-system development programs which are proceeding simultaneously. Critical manpower peaks and valleys are to be avoided.

4. Cost sensitivity and cost variance considerations should be included in the presented cost data. (See Section VII on risk and uncertainty.) A cost estimate standing alone on the page of a report does not inform the reader as to its firmness relative to other cost data presented on other pages of a study. Thus some indication of the precision of the estimate should be given with the cost data, and the sensitivity of final results to the cost uncertainties should be portrayed. Thus, in some way the more tenuous cost estimates must be highlighted so that: (a) the proper confidence in the ultimate cost-effectiveness number can be conveyed to the reader; and (b) remedial effort and perhaps recommended testing can be undertaken by the Air Force to further identify and refine the data. The latter will lead to better cost information on the technological area in question and thus future cost-effectiveness studies will be more valid.

C. A GENERAL COST METHODOLOGY

1. Identify the various critical cost commodity categories:

l_{ij} = man-years of effort of type i needed in year j to develop, make operational, and operate the proposed weapon system or major weapon subsystem.

m_{ij} = tons, pounds, yards, or other units of critical material of type i needed in year j to develop, make operational, and operate the proposed weapon system or major weapon subsystem.

Examples of types i are: fissionable materials, fuels (of given type), concrete, machine tools, heavy metals (of given type), light metals (of given type), etc. Dollar costs may be obtained by arithmetically operating with the l_{ij} and m_{ij}.

$$\text{(Dollars in year j)} = (\$)_j = \sum_i \left[l_{ij} \times (\$/\text{unit } l_{ij}) \right] + \sum_i \left[m_{ij} \times (\$/\text{unit } m_{ij}) \right] \qquad (26)$$

2. In order to estimate the amounts of l_{ij} and m_{ij} and hence the dollars needed annually over the life-time of a weapon system it is useful to develop a cost-breakout chart of the type shown in Figures 7, 8 and 9. Note that the estimation of facility sizes, for example, the size of the manufacturing facility, etc., is dependent on the total force level of the weapon-system procurement. The learning curve effects are also dependent on this force level. For these reasons, the estimating of the l_{ij} costs, the m_{ij} costs, and the total yearly dollar costs should be done parametrically for various planned force-level procurements of the weapon system.

The effect of force size on some constraining "costs" and the insensitivity of other cost elements to force size can be seen in Figures 10 and 11. Figure 10 shows that the number of engineers needed to develop, test, and operate a weapon system is relatively insensitive to force size. On the other hand, the dollars per year for all items of manpower and materials (IOC and DOC) may depend very heavily on the force size procured, as shown in Figure 11. Note that R & D costs are the same for the two planned force levels in Figure 11.

D. COST ESTIMATING RELATIONSHIPS (CER)[4/]

A functional expression which states that the cost of something may be estimated on the basis of a certain variable or set of variables is called a Cost Estimating Relationship (CER). These expressions may be simple or complex in terms of functional form and/or the number of variables taken

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4/ Section D is taken largely from HQ AFSC Cost Estimating Relationship Program Plan, 31 July 1962

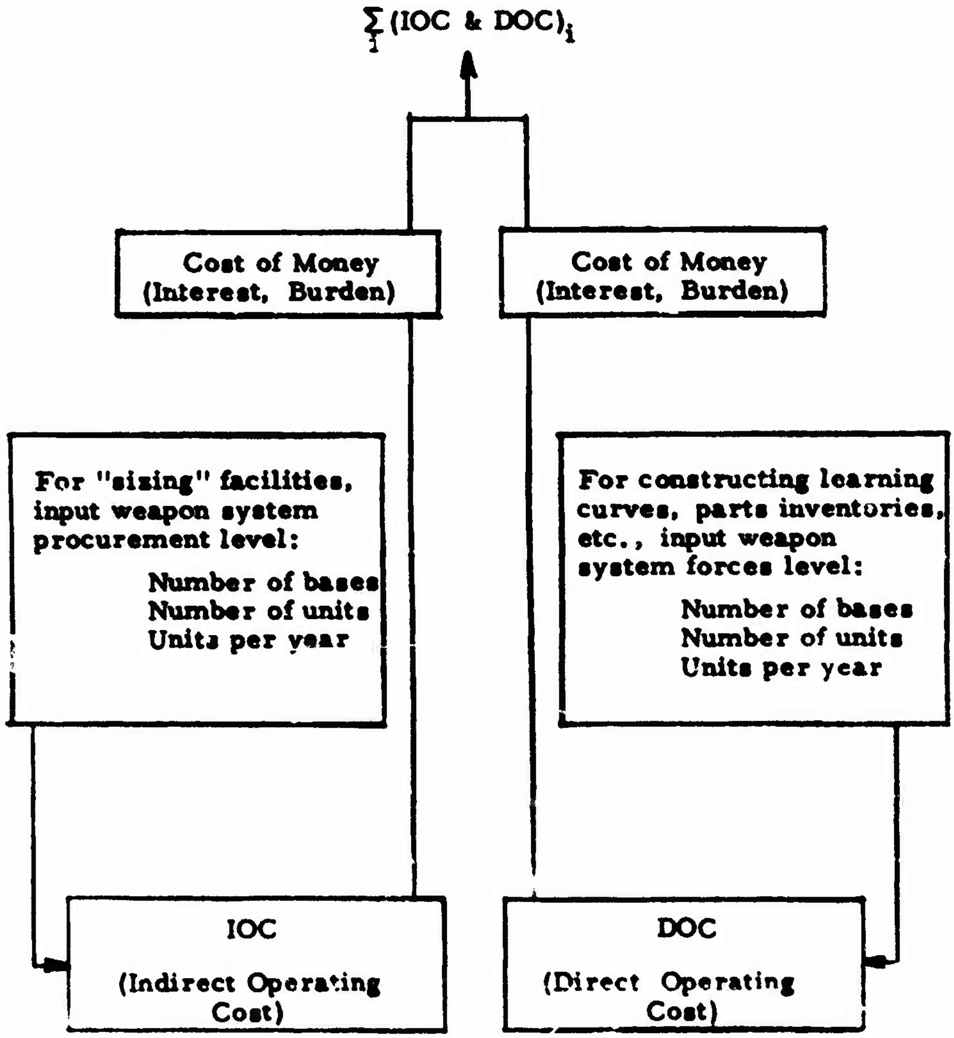
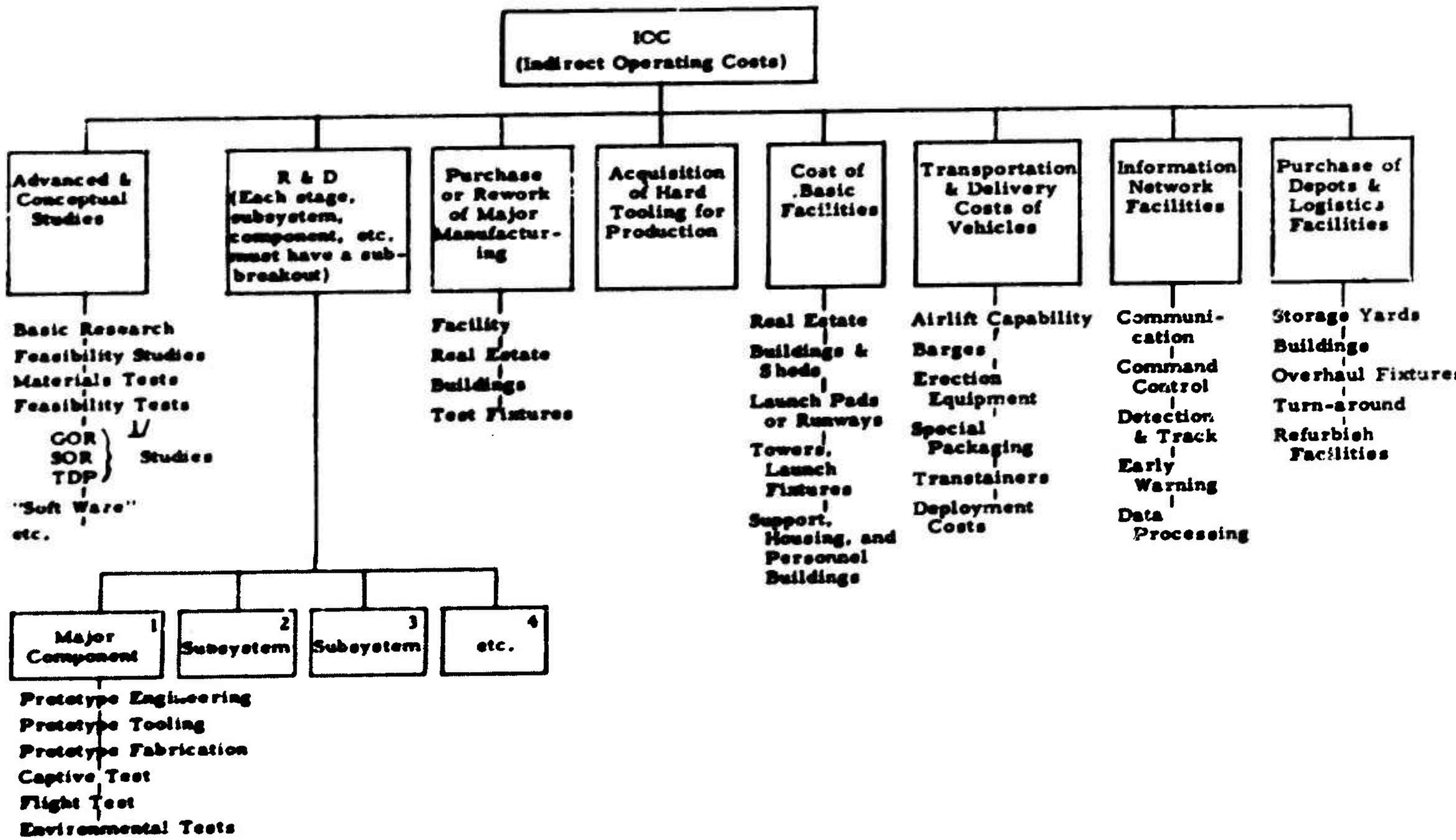


FIGURE 7

COST BREAKOUT CHART FOR ESTIMATING CRITICAL RESOURCE UNITS REQUIRED TO DESIGN, DEVELOP, AND OPERATE A WEAPON SYSTEM



1/ GOR = General Operating Requirement
SOR = Specific Operating Requirement
TDP = Technical Development Plan

FIGURE 8

ASPECTS OF INDIRECT OPERATING COSTS

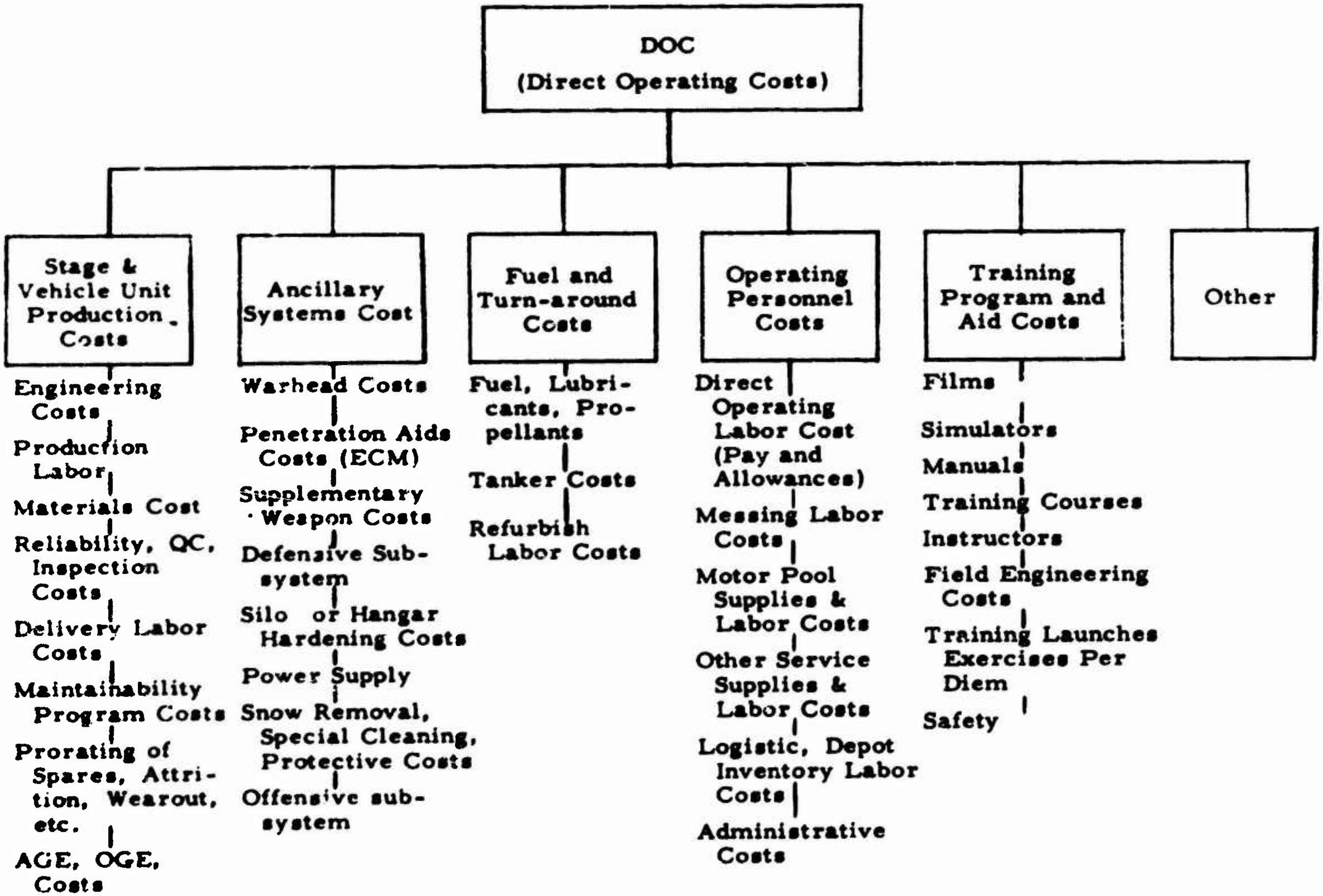


FIGURE 9. ASPECTS OF DIRECT OPERATING COSTS

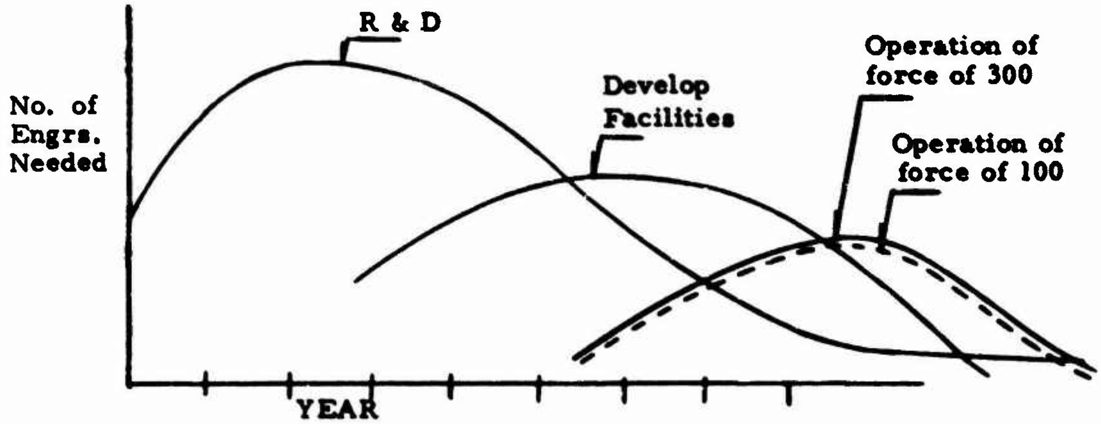
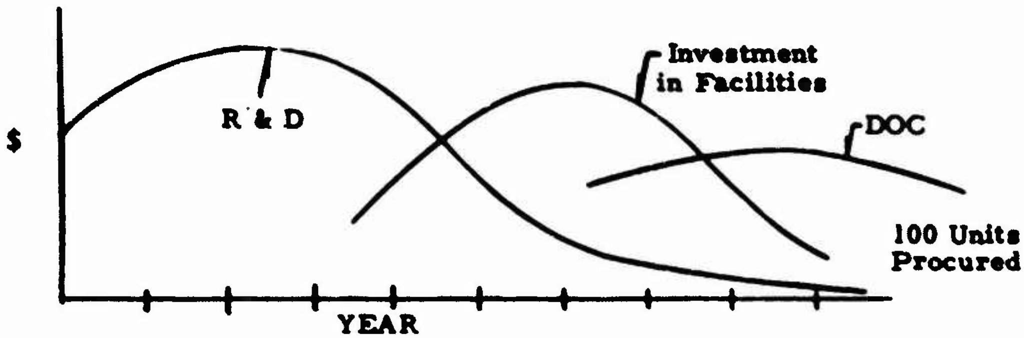


FIGURE 10
NUMBER OF ENGINEERS NEEDED TO DEVELOP AND OPERATE A WEAPON SYSTEM



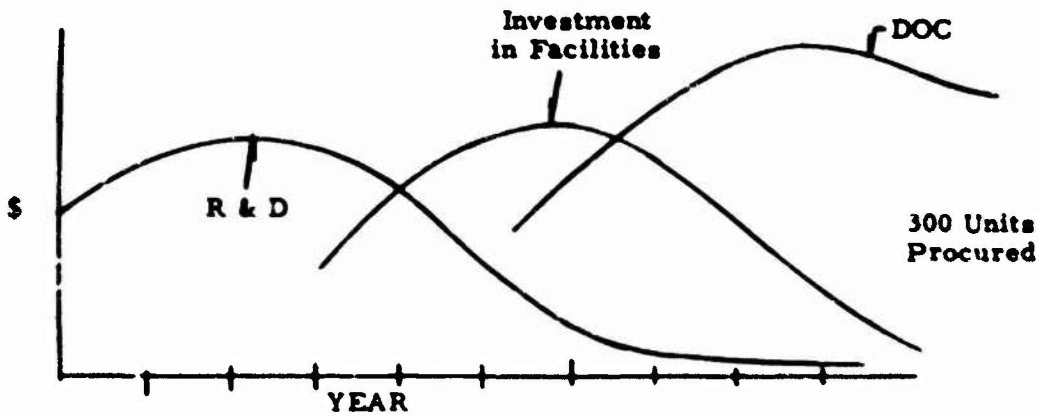


FIGURE 11

DOLLARS NEEDED TO DEVELOP AND OPERATE WEAPON SYSTEM AT TWO FORCE LEVELS into account. Many Cost Estimating Relationships (CER's) such as that shown in Figure 12 exist in the literature. Excerpts from Headquarters AFSC Cost Estimating Relationship Program Plan dated 31 July 1962 are included in this Section D. These CER's are helpful in generating cost estimates for the many cost categories of Figures 7, 8 and 9.

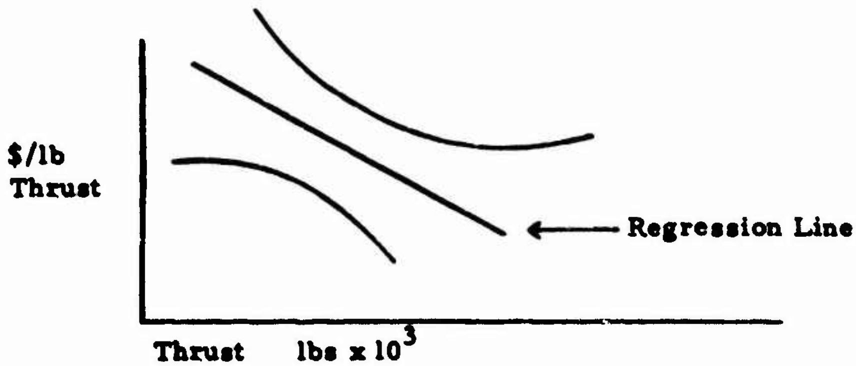


FIGURE 12

TYPICAL COST ESTIMATING RELATIONSHIP (CER)
BASED ON PAST PROGRAM DATA

The process of estimating is, by definition, approximate. The variability of an estimate will be relatively small if the item being costed is essentially the same in the future as it was in the past. For example, for the cost of flying a B-47 from New York to Los Angeles, the number in the crew, the pay per person, and the B-47 fuel costs per hour are established and can be expected to stay essentially the same, assuming a constant dollar. The variability will also be small if the item being costed varies in relation to some predictable parameter. For example, the cost of a landing strip varies with the number of cubic yards of concrete, even if a projected landing strip is much longer and thicker than any existing strip.

The costing problem becomes much more complex in the case of a weapon system or supporting system that is greatly different from any system on which actual cost data are available. Since historical costs are the only basis for projecting future costs, some historical relationship must be found. If the analyst had time to break the future system down into its most detailed elements, we would find that many of the detailed elements were similar to elements in earlier systems and could be related; e.g., cost of micro-circuit elements.

It is often possible to estimate costs by some broader aggregation than micro-circuits at the component or even the subsystem level, based on some parameter of performance or specification which has a reasonable correlation with cost. For discussion purposes, the correlation between that parameter and cost is referred to as the Cost Estimating Relationship (CER) for that element of cost. A CER can also be identified for non-hardware cost elements, such as fuel and lubricant costs as a function of flying hours or depot maintenance might be given as a per cent of acquisition cost. Obviously, the broader the cost element for which a CER can be established, the less time is required to compute the total cost estimate.

The Cost Analyst should not wait until he needs a CER to collect historical data, determine the most appropriate correlation, and document the CER. This is a time-consuming effort and, at least for the more obvious elements of cost, a CER should be anticipated and established between specific cost-estimating assignments. Each assignment will undoubtedly reveal a requirement for still other CER's that are not available, but the time required can be minimized by proper planning and preparation of the CER.

CER's should be prepared for different levels of aggregation (in equipment cost, for example, not only at the subsystem level but also at the component level) where possible and appropriate so that the cost analyst has some flexibility in their use. Depending on, first, the degree of detail to which a system can be described for the cost analyst and, second, the time available to prepare the estimate, the cost analyst can then use the broader CER (involving less computation time; possibly less accurate) or the finer CER (involving more computation time; possibly more accurate).

E. DEVELOPING CER's

A Cost Estimating Relationship is simply a functional expression which states that the cost of something may be estimated on the basis of a certain variable or set of variables (see Figure 12). These expressions may be simple or complex in terms of functional form and/or the number of variables taken into account. The simplest possible case is where the cost of something may be estimated almost entirely as a function of a single variable. Examples are: "Cost per flying hour," "Cost per pound structure," "Cost per bit of memory," etc. At other times more complicated multivariate functions of various mathematical types may be used in CER's. Also, it should be pointed out that a cost estimating relationship need not necessarily be "continuous." It may be discontinuous, or a "step function."

In any event, a cost estimating relationship expresses cost as a function of a variable or variables. The fundamental steps in developing cost estimating relationships are as follows:

1. Determine what these variables are. This is easier said than done. There is no known method to readily identify what the key variables are. The graphical fitting appraoch, together with discussions with appropriate engineering and manufacturing personnel, seems to be the only method of determining the significant variables. Success in identifying the variables is largely dependent upon the ingenuity of the analyst and the amount of effort and time spent in exploring the various combinations of all identifiable parameters. The simplest variables such as: cost related to quantity, cost related to weight, cost related to size, ratios, etc., probably should be tried first. Use of percentage relationships are also helpful. For example, on rocket engine pumps past data may show that the costs are: labor - 45 per cent, material - 33 per cent, overhead - 22 per cent.

2. Determine an appropriate functional form. The representation of how cost will vary in relationship to some variable is a cost pattern, or cost behavior. A cost pattern may be shown graphically or possibly expressed algebraically. Plotting a graphic picture of the data is a way to find a suitable functional form and to assess and determine the variability of costs.

3. Estimate the numerical value of the parameters in the functional form. In using a visual method of averaging a curve through the data plot points, there would be little probability of two persons drawing the same curve. It would be desirable to have a method where the same curve would be consistently obtained from the same data. This can be accomplished by the method of least squares or other commonly used curve-fitting procedures.

4. Where possible, give some indication as to the confidence associated with the estimating relationships. In a statistical sense, this may be accomplished by furnishing standard errors of estimate, confidence intervals, and the like. Where this is not possible, less formal (perhaps non-quantitative) statements may be used.

5. If the relationships hold only for certain ranges of the "cost-generating" variables, these ranges should be stated. Stating the problem in five straightforward steps like 1-5 above, may convey the impression that the task of developing usable cost estimating relationships is a relatively simple process. This is definitely not the case, especially in the field of advanced weapon-system cost analysis. A fundamental problem is the paucity of meaningful quantitative data. And even when data are available, the number of observations (the "sample size") is likely to be small.

F. AFSC FORMAT FOR RECORDING CER's

Careful, concise documentation is essential in establishing a reliable cost estimating relationship. Ideally, it should be possible for any analyst to retrace from beginning to end the specific steps originally taken in deriving each cost-estimating relationship. More important, however, is that the documentation would enable another analyst to decide intelligently whether a given CER can be used reliably in costing a particular system to solve a particular problem. Even though the analyst has little confidence in the CER, he should document it in the manner prescribed so that there is a specific record and a basis for further research. He will thereby save time for himself and others in researching the same sources again. Further, it will identify a problem area. Figure 13 is a possible format (as used by

(Security Classification)

COST-ESTIMATING RELATIONSHIP PROGRAM

(Code)

(Date)

Subject: ______________________
(System & Subsystem for which CER is Developed)

CER Formula (and graph is appropriate) Derived:

Definitions Used:

Assumptions:

Data Sources Used in Developing CER:

Specific Item	No. of Items	Cost	Year	Source of Data	Nonfinancial parameters
					Identify
					(Examples of nonfinancial parameters: weight, size, thrust, range, materials, rate, RPM, output, power, time, etc.)

Developed by: ______________________

(Organization)

Statistical Techniques and Methods Used:
(Including Cost Adjustments)

Degree of Confidence and/or Limitations:

Other Comments:

FIGURE 13. AFSC FORMAT FOR RECORDING CER's

AFSC) upon which to start documentation. It is not to be confined to one page, as the CER itself will dictate the amount of detail required.

Codes may follow the areas of systems, subsystem and components as follows:

1st Digit		2nd Digit	
Aircraft	- 1	Research	- 1
Missile	- 2	Development	- 2
Electronics	- 3	Investment	- 3
Space	- 4	Operating	- 4

3rd & 4th Digits

Airframe	- 01	Data Processing	- 08
Propulsion	- 02	Communications	- 09
Guidance & Control	- 03	Equipment	- 10
Missile Launcher	- 04	Manpower	- 11
Facilities.	- 05	Equip & Install Replace	- 12
Re-entry	- 06	Training	- 13
Data Acquisition	- 07	System Maintenance	- 14

A CER for development of a Communication Space Satellite would be coded 4-2-09. This will then permit a minimum of four major classifications upon which to file all CER's, even though the level of the CER might be at the very lowest component category.

G. THE FUTURE DEVELOPMENT OF COSTING

Many companies have already developed computerized cost models which utilize breakdowns of the type shown in Figures 7, 8 and 9, using hundreds of cost relationships (CER's) of the type shown in Figure 12. The National Aeronautics and Space Administration (Future Projects Office, MSFC, Huntsville, Alabama) has developed an IBM 7094 Launch Vehicle Cost Model which can generate annual costs in the various categories; R & D, Facilities, Direct Costs, etc., for launch vehicles.

Another aspect of the cost estimation problem is sensitivity to inputs. Too often there is a refusal to estimate costs because the data inputs are not precise or accurate. An estimate of the variability of (1) over-all costs per year, and (2) total program costs can be made by using the cost variance concept, a PERT-type procedure, in which each cost element estimate is inserted in three forms: least possible, expected, and maximum possible cost (see BIBLIOGRAPHY, "Cost Variance: A Proposed New Cost Prediction Method").

SECTION VI

EFFECTIVENESS FACTORS FOR COST-EFFECTIVENESS MODELS (TASK 8.2)

A. INTRODUCTION

In Section IV the reader was presented several possible cost-effectiveness models. In each model, it was essential to develop effectiveness measures and cost factors in order to arrive at cost-effectiveness values. Section V presented cost estimating procedures. The objective of this section is to outline the ingredients for a better evaluation of effectiveness. The factor so identified will enable one to insure that all essential factors are included in effectiveness measures. The Task Group II Report presents more detailed methodology appropriate for the measurement of these effectiveness elements.

B. EFFECTIVENESS FACTORS

Effectiveness is a far-ranging and comprehensive concept when applied to military weapon systems. For example, an individual ballistic missile system can be considered "effective" only if it can satisfy a rather long list of requirements. Typically, the list will include: (1) be in a launch-ready condition when the order is given to fire; (2) decode and accept the launch signal; (3) go through a pre-launch verification sequence; (4) launch and fly a planned trajectory; (5) stage one or more times; (6) cut off the engine when proper velocity and direction are attained; (7) separate the payload, arm, and fuse; (8) arrive within a specified distance of ground zero; and (9) detonate the warhead at the correct altitude with (10) a specified minimum yield.

Because of this proliferation of requirements, we have chosen to consolidate the elements of effectiveness somewhat. We will discuss them here more nearly in the context of Secretary McNamara's description of "dependability" (applied to both missiles and aircraft) which he defined as the product of Availability, Survivability, Reliability, and Penetrability.[5/] To this list we will add Lethality, and we will treat Launch Reliability and Mission Reliability separately.

The effectiveness elements for an aircraft are, for the main part, essentially the same as those of a missile--that is, the system has to be ready, survive any enemy attack, reach the target area, penetrate enemy defenses and deliver a lethal blow. An additional requirement unique to aircraft systems is the safe return to a friendly base.[6/] For ground equipment, like radars,[7/] or L-systems (Command and Control), the effectiveness elements are similar, provided one substitutes performance measures for penetration and lethality.

We will attempt to show here how each of these effectiveness elements is influenced by one or more operational factors. Then we will give some examples of how certain individual or collective elements can be quantified through the application of mathematical models, and, where possible, show some applications to actual systems.

C. AVAILABILITY

The first effectiveness element to be discussed here is Availability, which has also been referred to in the past (not always accurately) as Operational Availability, Operational Readiness, Alert Readiness, Ready Rate, and Real In-Commission Rate. It can be defined as the probability that the system will be in a good or usuable condition at some randomly chosen time in the future.

5/ Statement of Secretary of Defense Robert S. McNamara before the House Armed Services Committee on the Fiscal Year '65-'69 Defense Program and the 1965 Defense Budget, January 27, 1964. The Task Group II Report, Vol. III, adds propellant depletion probability, command and control probability, guidance accuracy, and targeting policy to this list.

6/ See Example A, Vol. III, of the Task Group II Report.

7/ See Example C, Vol. III, of the Task Group II Report.

A system may be unready to launch because of scheduled or unscheduled maintenance activities, periodic inspection, crew training, or other activities. Even if not in one of these unready states, the system may fail to countdown successfully because of an existing, but previously undiscovered defect. In the latter case, the deficiency may have been inadvertently ascribed alternatively to Availability (we thought it was ready, but it really wasn't), or to Launch Reliability (the lights were green, but the countdown was NO-GO). In those instances where a function is neither checked periodically nor monitored continuously, we will interpret a defect or failure of the function as a contribution to unreliability of launch or flight.

Mathematically, long-run or steady-state availability can be expressed as

$$A = \frac{MTBI}{MTBI + MTTR} \qquad (27)$$

where MTBI is the mean-operating-time-between-interruptions, for any cause, and MTTR is the mean duration of those interruptions. Thus, MTBI has the connotation (though not always the precise meaning) of mean-time-between failures. MTTR has the sense of a mean-time-to-repair, which we will generalize to support capability. Improvements in either alert reliability or support capability (i.e., higher MTBI or lower MTTR) result in improved (increased) availability.

The quantification of availability through this simple formula is seldom found to be directly useful in real-world cases. MTBI can only be interpreted as an inherent quality in the special case of continuous (and complete and accurate) monitoring. MTTR can be independent only where there is immediate administrative response, and continuous availability of maintenance resources. Generally, both are functions of several interrelated parameters.

Typical of actual operations are periodic (and in some ways imperfect) inspection or checkout, administrative (or "policy") delay in maintenance response, waiting for maintenance resources ("queuing") and an imperfect quantitative knowledge concerning the system parameters which determine operational availability. Several examples in the Technical Supplement

(Volume III of the final report of Task Group IV) explore the subject of inspection policy, support policy, and testing policy as they may affect availability (and system effectiveness) through their effect on MTBI and MTTR.

1. Mean-Time-Between-Interruptions (MTBI) The mean-time-between-interruptions of the alert status of a weapon system is a measure of how long the system can be expected to remain in a status of real (as opposed to "green light") readiness before that status is terminated by scheduled maintenance (checkout, Technical Order compliance, etc.), unscheduled maintenance (repair of a mission-critical failure discovered through continuous monitoring, or periodic testing) or the occurrence of an initially hidden mission-critical failure. (This last notion gives rise to the distinction between "real" and "green light" readiness.) The MTBI is affected by the reliability state-of-the-art, the level of system complexity, the maintenance-operations plan (continuous monitoring or periodic inspection, with repair or replacement as necessary or periodic mandatory replacement without inspection), the operational (physical) environment, the predictive capability of testing procedures, and time, as it involves reliability growth.

2. Support Capability (Mean-Time-To-Repair) Support Capability is the other side of the availability coin; some refer to it broadly as "logistics," implying the traditional military supply-support activities.[8] We will interpret it here as MTTR, the time required to restore a weapon system to a truly ready condition, whether from preventive maintenance (formerly "scheduled" maintenance), corrective maintenance (formerly "unscheduled" maintenance), or other non-ready states. As such, it is evident that MTTR is affected by anything which adds time to the process. Some more important examples are: (1) the quantity of maintenance ground equipment (waiting caused by shortages); (2) spares level and location; (3) depot repair capability; (4) transportation; (5) maintenance manpower skills and numbers;

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[8] Others use the term "maintainability," which we interpret here more restrictively as the quality of repairability as exemplified through "human engineering."

and (6) maintenance management policies. In the Technical Supplement mentioned above, there is an example of how Maintenance Ground Equip - ment (MGE) and manpower provisioning can directly affect the Mean Time to Repair.

D. SURVIVABILITY

Survivability is the probability that a system will either (1) be launched and removed from the threatened environment before it can be attacked (as with warning), or (2) "ride out" some anticipated initial attack. In the first instance (applicable primarily to manned aircraft), the basic parameters are the amount of reliable warning time, and the reaction time from "commit" through reaching a "safe" environment. In the latter case, which is commonly assumed for hard-site ballistic missiles, many things can become important: blast hardness (i.e., resistance to overpressure); electronic hardness; dispersal mobility; deception; active defense; and above all, the weight or severity of the expected attack. If a weapon system is intended to provide a credible deterrent threat for a substantial time (say days or even weeks) after initiation of hostilities, it must not only survive possible missile attacks, but perhaps also manned-bomber attacks. In addition, such extensive periods of operation must be supported in the likely absence of "normal" (i.e., peacetime) services like commercial power, telephones, and even highway travel.

E. RELIABILITY

1. Launch Reliability Launch Reliability is the probability that an "available" system (i.e., in-commission and having no hidden defects detectable by monitoring or periodic checkout) can be launched on command. In general, it can be thought of as being made up of Command Reliability (receive, interpret, and act within a specified time period upon the launch signal), Countdown Reliability (accomplish the specified pre-launch procedures within the allotted time), and Initiation Reliability (perform the irreversible or "one-shot" sequence of launch events such as firing squibs, door ordnance, igniters, etc.). All three of these subelements depend also in some fashion on the quality of maintenance activities accomplished

during the period of strategic alert. In other words, they are affected by the same things as MTBI, though not necessarily in the identical manner. For example, the pre-launch procedures are often similar and sometimes identical to periodic exercises performed for verification of alert status.

2. Mission Reliability Mission Reliability (Flight Reliability for ballistic missiles) is the probability that the system will execute the proper flight sequence. We mean to include performance capability (a function of the design) as an integral part of this mission reliability. For example, the failure of a missile to reach the target due to insufficient fuel capacity is attributable to design inadequacy rather than "failure" in a more conventional sense.

For ballistic missiles, Mission Reliability ordinarily includes, in addition to propulsion and control and other factors, proper engine cut-off, staging, and guidance. For manned aircraft, both hardware performance and human performance (correct navigation to target, aiming, and weapon delivery) are involved. For an ALQ-27 Jammer System, it would include detection of enemy radiation, selection of response mode, and subsequent radiation of the proper jamming signals. Once again, the hardware reliability is related to the quality of maintenance in the ground environment for both aircraft and missiles.

F. PENETRABILITY

Penetrability is theprobability that a weapon system will survive a defense environment and arrive at the target intact. For manned aircraft, this probability is a function of such things as the penetration mode (for example, low level flight to avoid detection), speed, maneuvers, electronic countermeasures, decoys, etc. For ballistic missiles, for example, penetrability may be expected to be 100% against a no-defense environment, while anti-ICBM environments make penetration aids and terminal maneuvers important. This is an area where time is also certain to be a factor; chronological improvements can be expected in the quality of both offensive and defensive tactics, so particular levels of either must be associated with a particular point in time.

G. LETHALITY

Lethality is the probability that weapon effects will destroy the target. For a point target, this is a function of the accuracy of delivery, usually expressed as a Circular Error Probable (CEP), and the lethal radius (L R), which is in turn a function of warhead yield, burst altitude, and target hardness. For area targets, lethality can be related to these same parameters through simple nomograms, which can give (in addition to simple probability estimates) the expected fraction of an area target that will be destroyed. (This type of information is also available for multiple warheads, or multiple weapon launches.) The latter quantity can be considered a figure of merit attributable to such elements as yield, aim point, CEP and height of burst.

H. OTHER CONSIDERATIONS

Certain other qualities of a weapon system may be important relative to total effectiveness, even if their impact is more difficult to quantify. For example, the ability to retarget a ballistic missile quickly and simply may allow a reduction in the extent of overlapping coverage for high-priority targets, and thus permit either an improvement in the long-term coverage of secondary targets, or alternatively a reduction in the required size (and cost) of the total force structure. The inherent flexibilities of manned systems are likewise significant, even if hard to quantify.

For many weapon systems safety is a paramount consideration. Unless safety features are carefully considered during the development process, there may be a significant probability that a system is activated by error (operator, maintenance, spurious signals, failure of a critical circuit or function, etc.) Military and strategic consequences of such errors are enormous, and their prevention is frequently an overriding factor in the choice of its design and configuration.

For some systems security is a vital factor. What is the probability that a saboteur could take over a system and render it incapable of use, or worse, use it against us? Although it may be difficult to quantify both safety and security, there can be no question that system design and operation criteria must reflect a thorough assessment of these real probabilities.

SECTION VII

RISK AND UNCERTAINTY IN COST-EFFECTIVENESS (TASK 8.3)

Buyers and designers of weapon systems face two types of future events which can affect their plans. One is risk; the other is uncertainty. Both are involved in the expectations of the future stream of events. Although it may be conventional to class the results of all future events which can lead to degradation of mission accomplishment as risk and uncertainty, we shall demonstrate that a useful and realistic distinction can be made between the two concepts from the effectiveness as well as from the cost point of view.[9]

A. RISK

Risk refers to the variability of outcome which is quantitative and measureable. It is not necessary that we be able to predict the outcome of a particular event; e.g., that a specific black box will fail within a specific period of time. On the contrary, it is only necessary that the probability of outcome; i.e., rate of failure, be established from a large number of observations.

Probability of outcome can be established in one of two ways. The a priori probability of outcome can be established when the characteristics are known beforehand; the empirical probability can be established when there are enough sample observations repeatedly made. In both cases, we are able to predict the statistical probability of outcome with a degree of certainty which we classify as risk. The key here is that the likelihood (risk) of an adverse event (leading to lower effectiveness) may be insured against and that we can, therefore, associate a cost with risk.

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[9] Frank Knight is generally considered the originator of this approach. His classic treatment Risk, Uncertainty, and Profit, published originally in 1921 by Houghton Mifflin Co., is now in its 8th impression. See Reference 6 for further insight on Bayesian approaches to the problem.

For example, the cost of the support of a weapon system (logistics, maintenance, etc.) reflects in large part costs arising from limitations of an engineering nature in contrast to costs arising from events external to the system. Based upon probabilities of failure, repair policies, turn-around times, etc., an expected support cost may be determined. If we estimate that a component will have an unacceptably high probability of failure during the mission, redundancy may be utilized, or more effort may go into reliability development of that component. The cost of risk in this latter case is the added cost of redundancy and/or development.[10]

In the case of risk, it is not difficult to handle the impact on decision making and use of resources. Since we are concerned with the mean or modal outcome, or range and dispersion of outcomes, any possible losses or degradation of performance can be incorporated into the design of the system and added to the cost relative to the added level of protection.

Risk relates to the phenomenon which creates variability, but which can be overcome (or insured against) by adding to costs. It does not preclude objective decision making since it can be reduced to a matter of cost. It is uncertainty which gives rise to the need for an entirely different framework for decision making and resource use.

B. UNCERTAINTY

The distinction between risk and uncertainty is that the latter cannot be established empirically or quantitatively but instead is the result of a subjective reasoning process. Uncertainty always exists when the parameters of the probability distribution (for example, the expected availability of the system, its variance or skewness, etc.) cannot be determined. Uncertainty is an abstract phenomenon, entirely subjective and peculiar to each individual evaluator. It is this aspect of subjectivity that gets us into difficulty in

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[10] What may be risk in one case; e.g., to the military service in terms of the outcome for several systems, may be uncertainty in another. For that matter, risk and uncertainty are not always "black and white."

cost-effectiveness analysis. (There are few things more difficult, more necessary and yet so ill-defined as the process of establishing specific performance requirements, given the mission definition.

Note the contrast with risk. When we refer to the failure rate of a component or system, we may estimate the risk of failure either through past experience or by comparing to similar components and systems. From this we may be able to estimate what the probability distribution looks like. Such a prediction of failure characteristics would then be based on quantitative experience rather than opinion.

Under uncertainty, subjective probabilities may be assigned through the opinions and judgment of the evaluator, but there is no method by which actual numerical values may be computed. Uncertainty in this form is not readily insurable; unlike risk it cannot be reduced directly to a cost. The concept of uncertainty can be viewed very broadly to include all circumstances in which decisions must be made without objective probabilistic knowledge of key events in the future.[11/] (By key event we mean those which, if we had known about them before they occurred, would have influenced our decisions on resource use.)

C. USE OF RISK AND UNCERTAINTY

Under risk, factors generally are found to be technical or engineering in nature, granted that some fall in a gray area of either recently being of an uncertain nature or are put into a risk-taking form by assumption. The chemistry and physics of component parts, their design, quality control, and assembly processes all lead to empirical probability estimates of performance. These parts in turn--either in terms of performance characteristics or such measures as system availability--may be described by the parameter estimates of the resulting distribution. Here risk becomes part of the cost-effectiveness picture and a design factor; expected system values

11/ All "assumptions" fall within the definition of uncertainty, although some may be subject to calculations of risk.

with a narrow range or variance, or expected system values in distributions that are skewed to the right (that is, there is a smaller chance of lower values occurring) are considerations in effectiveness as well as cost. Alternative configurations and redundancies can result in more desirable distributions of system availability at some finite cost. It is in this sense that risk is a necessary ingredient in the cost-effectiveness picture.

Now let us view uncertainty over and above risk. We divide uncertainty into two areas: (1) those non-engineering areas outside the system (the mission and policy areas) and (2) those involved in the system design, operation and maintenance. The following examples are classified accordingly:

1. Non-Engineering -- Extrinsic

a. Mission level - peace versus war, limited versus central war, political back-up, enemy response, alternative force-structure requirements.

b. Performance characteristics - relative to the mission, what accuracy, range, speed, vulnerability will we seek? Are there other criteria? What priority do they have?

c. Political and economic environment - national and international.

d. Physical environment - operational versus controlled.

e. Maintenance policy - number of echelons, repair-discard level. premium transportation, technician capability.

2. Intrinsic

a. Technical and technological breakthrough - e.g., the micro area.

b. Reliability - physics of failure.

c. Design versus maintenance talent - technician interface with design, module size, repair-discard, degree of automatic checkout.

d. Cost functions - reliability, maintainability, research and development, lifetime support costs.

To a large extent uncertainty is a problem of imperfect knowledge, with varying degrees of unknowns. This is the reason that one must set aside a separate cost for uncertainty, even though it cannot be done with the same assurance as in cases of risk. Imperfect foresight, unless it is recognized beforehand, can result in costly solutions for problems that either do not exist or are initially overstated.12/ Perhaps even more important, solutions which turn out to be inadequate due to lack of consideration of uncertainty, can result in the waste of resources that could have been available for more productive purposes. This is particularly the case on the force-structure level of analysis although it holds also for lower level problems such as the engineering alternatives encountered within a single system.

On a system level, the degree to which a Request for Proposal provides force-structure detail to the respondents can affect in large part what is proposed, since cost-effectiveness analyses by the contractor are likely to be sub-optimal on a force level. Again, lack of knowledge (uncertainty) restricts optimization. As a case in point, perfect response to an RFP can also fail to take into account the need for alternative capabilities over time and therefore not provide a sufficient solution in the total force context. This is typical of the case of highly specialized and less costly systems versus higher cost systems with broader capabilities, which over a period of time can prove to be more effective.

Although the above pertains mostly to the buyer side of the picture, these are considerations for designers as well.13/ The designer must take

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12/ Imperfect foresight always exists. The problem is to account for uncertainty in a manner that provides for a level of effectiveness over a period of time with costs appropriately weighed against the likelihood of events.

13/ While not discussed, we also recognize the buyer's major uncertainty as to the capability of the successful bidder to produce the proposed system within time and dollar limits.

into account the added costs of uncertainty due to policies of the Air Force in addition to his own intrinsic engineering uncertainties noted in part above.

What does this all add up to in terms of the purchase or design of a system? So overwhelming are the cost considerations of uncertainty, that a separate area in an RFP or proposal might well be set aside for it. Each of the uncertainties involved would be delineated for a system; a cost or set of alternative costs (related if at all possible to each uncertainty element) would be generated. These costs may then be evaluated in the final cost-effectiveness stage. As the system evolves in the several gyrations and iterations during R & D, decisions to accept or reject the uncertainty cost may also be made. The normal result of this procedure would be the conventional cost-effectiveness analysis, with separate categories for the cost of risk and the cost of uncertainties as constraints which limit the choices available to key decision makers.

D. EXAMPLES OF RISK AND UNCERTAINTY CONSIDERATIONS

We now delineate elements contributing to estimates of cost and effectiveness, and attempt to demonstrate how changes in these elements (or more careful consideration of the resulting effect of them) may be costed out in accord with previously discussed concepts of risk and uncertainty. We will show that the analysis of risk and uncertainty is concerned with determining a standard or base point of reference, and then asking what would happen "if"... --that is, leaving it open to the "decision-makers" as to the level of risk and the amount of uncertainty they can permit, given the likely costs.

1. Cost of Risk

For a specified level of over-all system availability, the optimized (for cost versus reliability and maintainability) cost of the components determines uniquely the optimum configuration of the system, as well as the maintainability and reliability of the over-all system and each of its component parts.[14/] This generalized statement may be viewed within the context of four system characteristics which determine system effectiveness under the following conditions:

a. The mission time period is defined and, after a mission completion, facilities are available for maintenance;

b. Units of the system are either failed or non-failed in terms of the design objective;

c. A system condition depends on the present and future performance and not on the past;

d. Units of the system are mutually independent.

Then, the four system characteristics are:

(1) System Operational Availability - a function of previous operational reliability, maintenance diagnosis, repair capability, logistics, etc.

(2) System Readiness - a function of diagnosis during alert, operational policy, system flexibility and backup.

(3) System In-Flight Reliability (or Availability) - a function of reliability and in-flight repair capability.

(4) System Design Adequacy - a function of design specifications, mission requirements, performance capabilities, external environment.

The fourth characteristic, the most difficult and one about which the least is known, ties in closely with several points raised previously under uncertainty. The remaining characteristics--quantitative in nature--are discussed under effectiveness and may be classified under risk.

Examples of risk variables encountered in treating aspects of (1) to (3) above are listed in Table V. The variables of Table V (column 2) make up the cost basis for risk (since the variables and their effect are quantifiable)

14/ For proof, see Goldman, A. S., Economics of the Trade-off Among Reliability, Maintainability and Supply, RM 62-TMP-42, TEMPO/GE, Santa Barbara, 1962.

TABLE V. RISK VARIABLES

Major Subject Area	Variable (Event)	Particular Areas to Investigate to Determine Change in System Cost	Effect on System Characteristics
Periodic Inspection or Checkout	Rate that system fails Time period to correct failure Time period for checkout Time interval to next checkout Checkout time after repair Frequency of operational exercise and checkout within RT time periods	System "GO" when bad System NO-GO when OK Change in resource costs and in end unit costs	Average problems System "OK" Increase in failures Detection of undiscovered failures
Waiting Line--Maintenance Resource Use (Man and Equipment)	Frequency of demand by subsystem and system for resource Service time Randomness of demand cost of resources Average time not calling for service Number of repair channel teams Number of shifts and length of work day Frequency of inspection "Cue" length for service	No. & length of malfunctions/month Time to correct Change in resource costs and in end unit costs	No. of days capability lost as variables altered No. of units waiting for service
Maintenance Intervals	Rate of failure while on alert Prob. that operation will trigger failure Exercise time Time to correct failure Time since system last verified	Change in resource costs and in end unit costs	Alert capability compatible with support Confidence statement on level of capability
System Replacement Rate	Mean Time between end unit replacement Time period of end unit operation	Change in resource costs and in number of end units	Degradation in capability over time at alternative replacement rates
Frequency of testing inactive systems	Time to repair Inspection stress effect on failures Time system down due to inspection	Can check too often change equipment & manpower needs How much to test?	

and may be used for evaluating the result of changes on cost and effectiveness (availability in this case since the variables refer to reliability and maintainability). The added (or reduced) costs resulting from changes in variables of column 2 result in an effect on the characteristics falling under column 4--in terms of expected values and/or the effect on the variances. It is this added cost (from an existing or reference standard point) to attain the level of confidence in mission success that we classify under the cost of risk.

2. Cost of Uncertainty

The areas of uncertainty depending in large part on judgment are as follows:

a. Mission Requirements - These are the 'reason for being' of the system and are usually in terms of performance criteria, represented by a time series of demands. Weapons are capable of multiple objectives--primary, secondary, etc. For each objective, more than one criterion may apply. 15/

From a cost-effectiveness standpoint, it is essential that Requests for Proposal provide not only specific criteria but also alternative performance levels ranked according to priority. With relatively minor increases in cost, it is sometimes possible to design a more flexible weapon to fit better into the weapons mix (rather than be forced into multiple uses in a later stage of its life). In fact, the multiple capability of a weapon could well be the deciding factor in final selection process based on cost-effectiveness analysis. 16/ Ideally, mission analysis should include the game

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15/ A mission requirement refers to performance capability through time. The performance capability might include as factors: accuracy, range, speed, and altitude (in general, engineering specifications). These factors are directly responsible for effectiveness elements of the weapon--for example, vulnerability or penetrability .

16/ The area of mission analysis is jealously guarded by military services. A contradiction seems to exist here in that during program definition, knowledge of the mission by the contractor can only aid in system selection. Although there are some striking exceptions, the evidence points to too little contractor thought on the mission level. Such knowledge on the part of the contractor does not limit the military in their prerogative of final decision and choice.

aspect of the opponent's moves; this could be done by the military in partnership with industry to include "what-if" moves by the enemy which may render a system obsolete or alter priorities in the force mix.

b. Environment -This refers to the physical, atmospheric, and climatalogical environment in which the system would operate and is more related to technological capability than strategic. The military must provide its best understanding of the unique aspect of environmental conditions and the proposal effort should separately cost out a detailed plan of the environmental work to be undertaken. Closely related here is the likelihood of technological breakthroughs and the possible benefits that may result.

c. Maintenance Policy - What support echelons are to be included? At what echelon should repair occur? What degree of repair? What limits are placed on transportation? Inspection policy? The ground rules in this area must be spelled out in the RFP since a system "optimised" for one support concept may not necessarily be optimal for another.

d. Cost Area -This refers to the elements of cost, and submodels going into the total cost function.

The variability of cost estimates is one thing that is not likely to be overcome in the near future, but it would help if buyers and sellers were in agreement on basic method and technique. Also, costs may be reduced by omission (legally OK) thereby permitting "slick" cost proposals to be the objective. To limit this within reason, a detailed breakdown of cost areas and the basis of the costing technique is to be recommended covering

development production expected modification operation support	time oriented with cost elements

Depending on the weapon and stage of development, certain of the above phases are of no concern to the Air Force. As a general rule, only those costs are of importance which affect the purchase, operation and support and alter the cost-effectiveness choice.

E. SUMMARY

Each of the cost areas may be classified into the two areas of risk and uncertainty:

1. Risk: Specific questions asked on a "what if" basis to evaluate possible cost increases in areas where increased effectiveness can be obtained.

2. Uncertainty: Specific cost evaluations made where human judgment is paramount, and cost alternatives are significant.

Requests for Proposal should distinguish between the two in a manner that forces a response that has added realism for cost-effectiveness evaluation among alternatives.

SECTION VIII[17]

EVALUATION OF ALTERNATIVES AND OPTIMIZATION (TASK 9)

The purpose of this section is to describe methods used to evaluate alternatives, rank them, and determine the optimum point for the system under evaluation. It is recognized that the approach described is only one of many which could be used, and further, that it may not be applicable in all cases. The optimization approach described involves adding cost-effectiveness improvement items to a basic, feasible system. Alternative improvements are then incorporated in an order such that optimal use of the affected resources is obtained. Functional steps involved in this portion of the cost-effectiveness study are:

(1) Evaluation of individual improvement alternatives.

(2) Ranking of individual alternatives in order of preference or priority.

(3) Determination of optimum or cut-off point.

(4) Derivation of outputs for decision support.

A. EVALUATION OF INDIVIDUAL IMPROVEMENT ALTERNATIVES

Prior to this point in the over-all optimization process, alternatives have been synthesized and variables and resources defined as stated in Section III, and the basic model selected, as indicated in Section IV. This evaluation model, in conjunction with its related criteria, forms the final basis for decision as to optimum point and also, will direct the basic priority by which alternatives are ranked. In evaluating individual alternatives, variables and resources involved should be expressed in relationship to each other, or as parametric relationships in such a manner that they match the established model framework. Cost-effectiveness optimization inherently involves only two major parameters; that of cost and that of effectiveness. Accordingly, the models in the individual evaluations should relate all variables and resources to the terms of these two parameters, or of cost

[17] The discussion given here is illustrated by example in Appendix II.

or value if a profit form model is used. Further, the format in which these relationships are expressed should be such that it is compatible with all of the alternatives to be evaluated and ranked for the total system.

At the more detailed levels of evaluation, two general situations can confront the evaluator. The simplest situation occurs when the majority of requirements have already been fixed by prior optimizations and/or decisions. As an example, let us consider an electrical power system for which the power output level and mission length have been previously established. The only alternatives then involve basic system design approach, improvement approaches, etc. In this case, individual alternatives are evaluated independently. Estimated weights, costs, reliability levels, and other variable items are assessed as to their impact on the variables and resources appearing in the evaluation model structure. The other situation that may confront the evaluator is one in which performance requirements are not fixed but are to be optimized with the rest of the system. In the case of the power system, this may involve the amount of power required, mission lengths, and number of units to be procured, in addition to the alternatives noted in the simplest situation. In this situation, parametric expression of variables is required. As might be expected, many situations will exist in which the size of the matrix or the size of the family of parametric curves could become prohibitive. In these cases, it is generally best to treat one or more of the variables as a fixed quantity, initially, and successively reiterate the quantity as the system becomes more completely defined.

B. RANKING OF ALTERNATIVES

The basic principle involved in the ranking of improvement alternatives is to incorporate these alternatives in the order which provides the greatest amount of cost-effectiveness improvement per unit of critical resource expenditure. Referring to some of the basic models described in Section IV, this principle would apply as follows:

1. In a situation where effectiveness is to be maximized at constant over-all cost, alternatives would be ranked in that order which gives the

greatest amount of improvement in effectiveness per unit of critical resource expenditure.

2. Against criteria requiring minimization of cost at constant effectiveness, alternatives would be ranked in the order which provides greatest over-all cost savings per unit of critical resource expenditure.

3. For a profit model criteria, alternatives would be ranked in the order providing the greatest incremental profit per unit of critical resource expenditure.

The term "critical resource" refers to that program resource which is in most short supply or most limiting with respect to satisfaction of the optimization criteria. In the initial phases of the analysis, a rough, approximate resource analysis should be accomplished to determine which of the resources will be the most critical. As an alternative, an assumption can be made as to which of the resources is critical. The criticality of the resource is verified after initial determination of the optimum point. If the preliminary estimate of resource criticality is in error, the ranking of alternatives must be rerun in accordance with whatever resource has in fact, proven to be most critical.

In applying this technique to the design of a hardware system, a number of constraints affecting the ranking of alternatives will become apparent. These constraints are the result of technical or hardware interfaces and are of two basic types:

Type I - An alternative cannot be incorporated until after some other alternative has been incorporated.

Type II -An alternative cannot be incorporated if some other alternative has been previously incorporated.

An additional factor influencing the ranking is caused by non-linearities in effectiveness and resource elements. These non-linearities are such that the magnitude of effectiveness, cost, or profit improvement associated with a given alternative will depend upon the point in the ranking at which the alternative is installed in the system.

These non-linearities, in conjunction with the above constraints, lead to the following observations:

a. Ranking is an iterative process wherein installation of the best alternative forces re-evaluation of all remaining alternatives prior to installation of the next best alternatives, and so on.

b. Occasionally, at low levels of reliability, a reversal in ranking factor will occur which cannot be eliminated.

c. Some alternatives will not expend any of the critical resource and thus will have a ranking factor of $\pm \infty$. Those involving net loss, ($-\infty$), may change to $+\infty$ at some point in the ranking process.

d. An alternative subject to Type I constraint above may be ranked earlier if combined with its constraining alternative.

e. An alternative subject to Type II constraint above may eventually be of such value that it is installed at the expense of deleting its constraining alternative.

C. DETERMINATION OF OPTIMUM POINT

The purpose of this step is to establish the over-all maximum, minimum, or cut-off point against the established optimization criteria. The use of the term "optimum" must be clarified by saying that a mathematical or theoretically rigorous definition of the term as applied here is not intended. As should be obvious, the real world as well as the analysis and optimization technique used will impose constraints and limitations on the ability to, in fact, arrive at an optimum point or even to know with certainty that a point thought to be optimum is in fact correct. Further, in the technique shown here, the so-called optimum point is determined by an iterative or feed-back process, in which an initial apparent or pseudo-optimum is first determined and the process is reiterated a number of times to arrive at a closer approximation of the true optimum point.

The optimization technique described here will take somewhat different forms depending upon the circumstance. Accordingly, this technique will be discussed in the light of the several cases which can occur. The first case which we will discuss involves maximization of effectiveness.

The results of the ranking process are shown in curve form, Figure 14. In this case, expenditure of the critical resource does not reduce effectiveness and the optimum point is a cut-off which occurs at the limit of the available resource. Figure 15 shows a different situation involving the same conditions as the one above, except that effectiveness reaches a maximum and proceeds to decrease. If the limit of the critical resource is beyond the maximum point then the maximum becomes the optimum.

The second basic case which can occur involves a situation where expenditure of the critical resource diminishes effectiveness. If the decrease in effectiveness is linear with respect to the resource expenditure, then the impact of the resource expenditure can be accounted for in the initial ranking. The approach used to determine the optimum point will then take the same form as in the cases described above. However, if the relationship of effectiveness to critical resource expenditure is non-linear, then its impact cannot conveniently be handled during the ranking process. In this case, its impact is ignored during the ranking and a curve is plotted based on gross effectiveness improvement per unit of critical resource expenditure. A second curve defining the relationship of effectiveness to critical resource expenditure is shown in Figure 16. The optimum point is determined by superimposing these two curves as shown in Figure 17. The optimum point occurs at the point of tangency of the two curves.

The same general forms and logic used in the cases illustrated above applies to use of the profit model or to cases where effectiveness is maintained as a constant and cost is being minimized.

As was noted above, the initial determination of optimum point is made on the assumption that one particular resource is critical. In some cases, the necessity of selecting a critical resource is eliminated or the number of resources from which the critical item must be selected is reduced if it is possible to relate one resource in terms of another. In the optimization techniques used here, this is generally feasible only in cases where most of the relationships are linear or nearly so. In the usual case there will still be two or more resources involved in the determination of

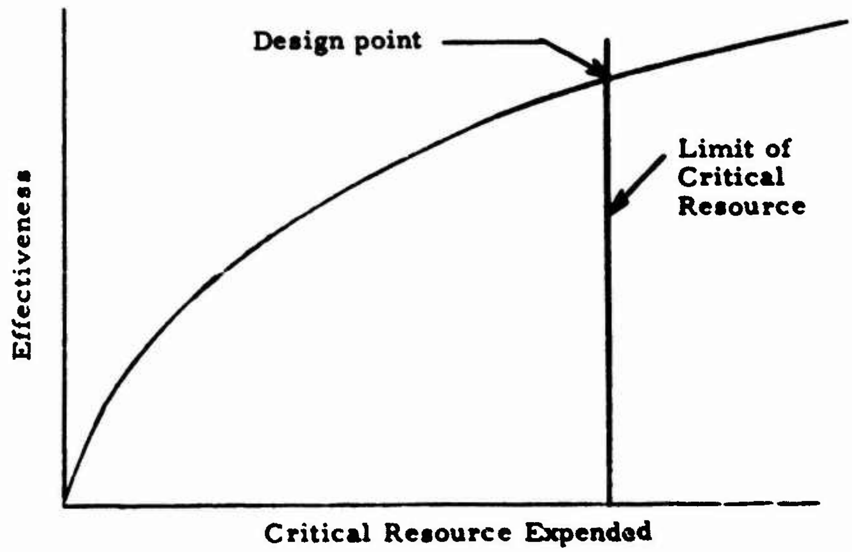

FIGURE 14

MAXIMIZATION OF EFFECTIVENESS - OPTIMUM POINT
AT THE LIMIT OF THE CRITICAL RESOURCE

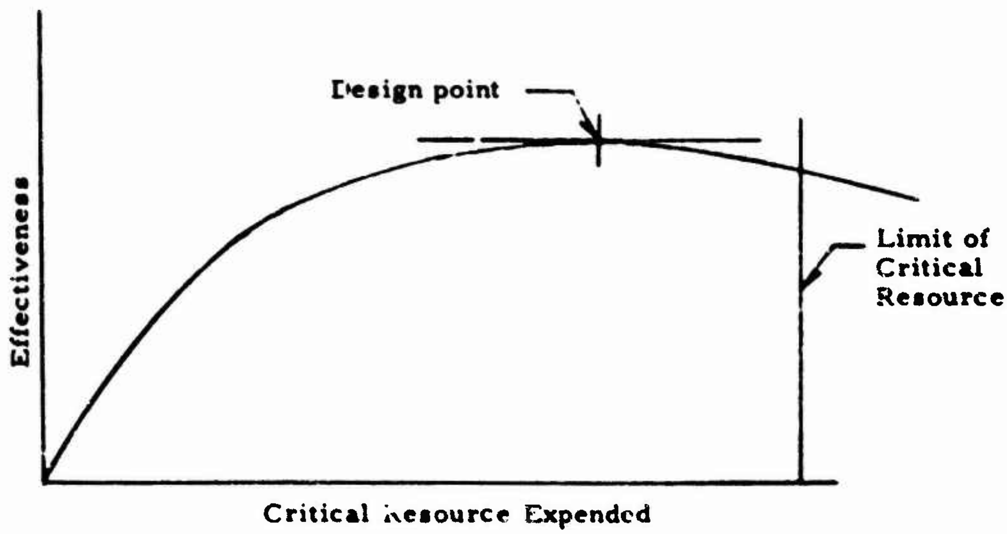

FIGURE 15

MAXIMIZATION OF EFFECTIVENESS - LIMIT OF THE CRITICAL
RESOURCE BEYOND THE OPTIMUM POINT

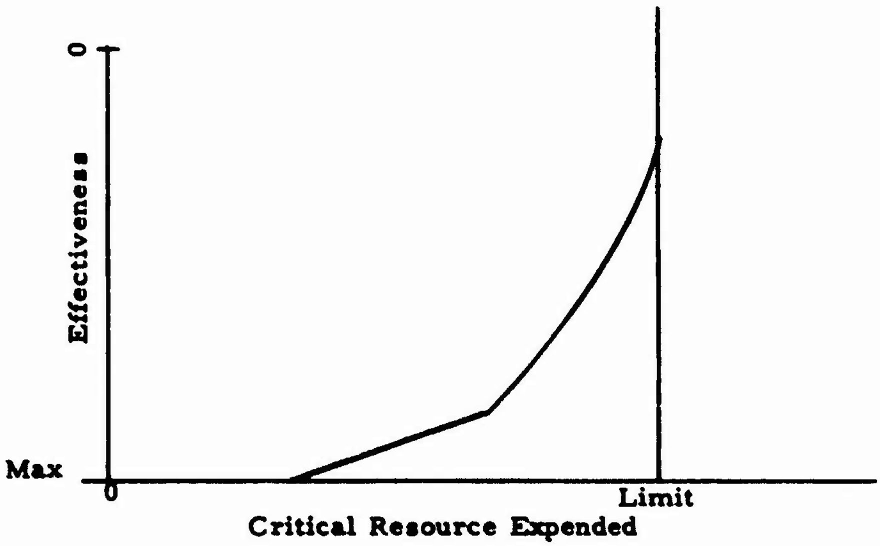

FIGURE 16

RELATIONSHIP OF EFFECTIVENESS TO CRITICAL RESOURCE EXPENDITURE

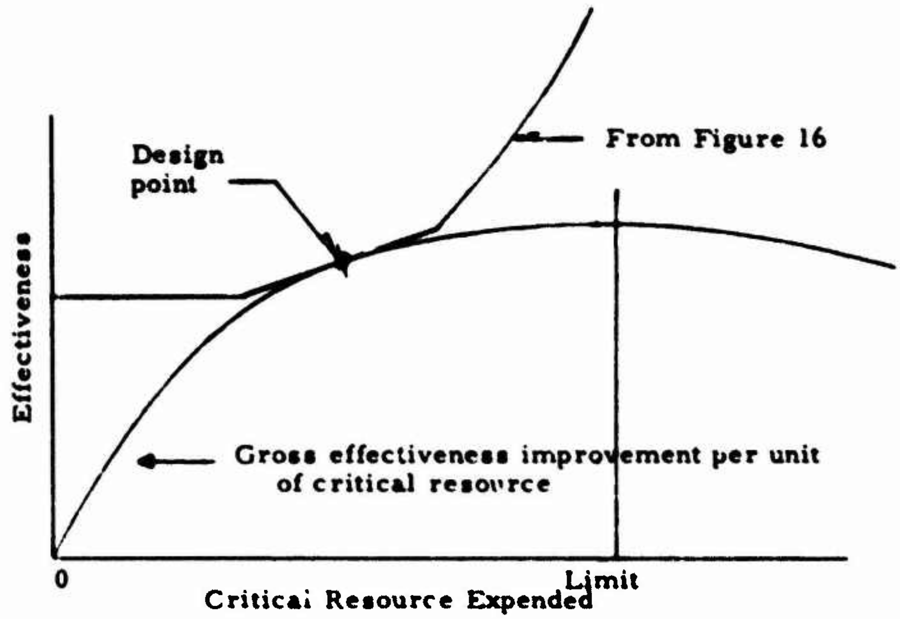

FIGURE 17

LOCATING OPTIMUM POINT WHEN RELATIONSHIP OF EFFECTIVENESS TO CRITICAL RESOURCE EXPENDITURE IS NON-LINEAR the optimum point. In such a case, when the optimum point has been determined, the remaining or non-critical resources must then be surveyed to determine whether or not their availability has been completely expended. If the availability of a resource previously thought to be non-critical has been exceeded, then the alternatives must be re-ranked in order to conserve this resource rather than the one previously thought to be critical, and the optimum point redetermined.

In general, at this stage of analysis, one or more of the non-critical resources will be in plentiful supply at the point where the critical resource has been exhausted, or is limiting. Generally, in these cases, further improvement can still be obtained by use of alternatives which tend to deplete the plentiful resources in exchange for increasing the supply of the one which is critical. Synthesis and evaluation of alternatives of this nature are best accomplished after the first step ranking and initial optimization point is determined.

D. MODEL OUTPUTS FOR DECISION SUPPORT

Unless the outputs or final results of the cost optimization study is in or can be placed in a form suitable for support of program decisions, then the application of such optimization principles becomes only an academic exercise. The type of decision support outputs which can be generally derived from the optimization technique shown here can be categorized as follows:

(1) Definition of design and mission associated with the optimum point.

(2) Criteria for evaluation and decision on future improvement alternatives.

(3) Parametric data for use in studies of other systems.

The basic optimization techniques described here involve incorporation of alternative approaches up to the optimum or cut-off point. Inherently, this approach, once the optimum or cut-off point has been defined is such that a definition of the configuration, mission and other scenario associated with the optimum point is readily determined by reading out the definition of those alternatives which were incorporated prior to reaching the optimum point. As the program progresses through Definition Phase and through its operational life, the description of alternatives involved in the optimization process will become increasingly definitive and, accordingly, the definition of the system corresponding to the optimum point will become increasingly definitive. In addition to system definition outputs associated with the optimum points, a number of other requirements type parameters may be calculated. Examples of such parameters are reliability level, maintainability level, required number of operational units, etc. In short, it should be possible to either take directly from the plots from which the optimum point was derived or to calculate, based on the resulting system definition, quantitative values for all of the principal elements of effectiveness and cost.

It must be recognized that in the time period following completion of an optimization analysis, further system improvement alternatives will be considered for incorporation. The scope and complexity of an over-all system optimization analysis are generally such that it is undesirable to rerun the entire study each time such an improvement alternative is to be considered. As a result then, it is generally desirable to derive evaluation models and criteria from the optimum point and the resource relationships accompanying this point, in such form that future improvement alternatives can be evaluated somewhat independently of the over-all system analysis. There is admittedly an implicit danger in following such an approach in that, when a large enough number of such alternatives have been incorporated into the system, the original optimization analysis from which the individual evaluation criteria was derived becomes invalid, thus admitting the possiblity of erroneous decisions. Determination of the circumstances and/or frequency under which the total optimization must be reiterated is a matter of individual judgment. General guidelines for formulation of evaluation criteria for future improvements are:

a. It is desirable to issue such criteria in a form such that an individual designer can use it.

b. The form must be such that a single criteria or cut-off is used. Thus, supporting data and relationships must be provided so that all variables and resources which are involved in future evaluations can be related in terms of common denomination, namely, the denomination associated with the selected criteria.

The third type of decision support output which can be gained from an optimization analysis is basically the type of parametric data used as inputs to future studies conducted at a more gross level on similar systems.

SECTION IX

INTERPRETATION OF RESULTS, SENSITIVITY, AND LIMITATIONS (TASKS 10, 11)

The cost-effectiveness indices derived from a given set of input data used in studies and models of the type described in this report should be considered as measures of "goodness" or "badness" of a particular system or system configuration. The validity of the indices, then, depends on the validity of the model and the input data. But even though a particular submodel may represent reality only on a gross basis, or a particular piece of input data may be only a gross estimate of reality, the resulting index may still deserve confident consideration as a measure of goodness. The key is the sensitivity of the result to such gross representations. In sensitive areas associated with risk or uncertainty, "warning flags" must be attached and some idea of upper and lower bounds for the measure should be given. These are called sensitivity checks.

Sensitivity checks are needed since the output of a cost-effectiveness optimization study is used to support program decision. Sensitivity checks are intended to determine the effect of uncertainty in the output data on the decisions involved. Three fundamental types of sensitivity checks will generally be applicable to the results of most cost-effectiveness studies. They are:

(1) Sensitivity to basic system or mission requirements,

(2) Sensitivity to uncertainties in estimated or extrapolated data,

(3) Validity of simplifying assumptions or arbitrarily fixed variables.

The basic steps involved in a sensitivity analysis are:

(1) An estimate or guess should be made as to the possible numerical range of uncertainty involved. Per the definition of uncertainty outlined in the previous sections, it should be recognized that such estimates or guesses will generally be unsupported by any data or background information. They are usually a matter of judgment.

(2) Using both the maximum and minimum values of the range, the optimization analysis or necessary portions thereof, should be rerun. The results of the nominal and extreme values can then be compared as required to determine whether decisions which would have been derived from the nominal analysis would be altered if the extreme values were believed.

(3) If it becomes apparent that the possible range of uncertainty does have significant effect on output decisions, steps should be taken to reduce the range of uncertainty, through either improvements in input data or testing for more or better data, improved analysis techniques or preparation of estimates at a lower level. In general, experience with this type of analysis has shown that only a small percentage of study inputs involving a range of uncertainty will be such that this range of uncertainty will influence output decisions.

As an alternative, there are some situations where the basic design of the system can be altered in such a manner that the system is no longer sensitive to the estimated range of uncertainties. If it is not possible to remove the effects of the uncertainty range on the decisions involved, this effect should be shown in visible or parametric form along with analysis results.

If they are to be of value, the results of cost-effectiveness studies must be given in terms which are meaningful to those who make decisions and understand the implications and results of these analyses. Thus, the analysts should appreciate the problems of communication with a broad spectrum of people including design engineers, company managers, military managers, military planners and, sometimes, congressmen and the general public.

In interpreting the results of these studies, it must be remembered that the state-of-the-art, resource constraints, political and military thinking and philosophy, enemy posture, etc., are in a constant state of flux. Thus, these results should not become associated with hard, fast, unchanging rules. A current finding that a reliability of 0.9 is best for a particular component should not become permanent dogma. The results should never be the basis for hindering research. Rather, they should provide better guidelines to design exploratory experiments so that the results of the tests will yield the more fruitful and a greater quantity of information for further analyses.

The limitations of cost-effectiveness studies have already been suggested in the foregoing paragraphs. The reader should bear in mind that, whatever shortcomings or dangers may be associated with analytical studies such as these, decisions based on intuition, experience which has not been thoroughly analysed, or a sample of personal opinions ("gut" feelings) are certainly less defensible and more subject to omission of important factors. One would not build a bridge by intuitive design, over-looking sound structural engineering practice. Yet, many unknowns exist in regard to material mechanics and random loading behavior of structures.

Although, in a sense, statements on limitations of cost-effectiveness analyses may be regarded as platitudes, we present some of them here as reminders.

1. Cost-effectiveness indices cannot be meaningful unless derived from a model which represents the "real world" fairly closely. Reality should not be buried under mountains of details nor does great detail, by itself, create reality in a model.

2. It must be remembered that cost-effectiveness analysis is an iterative process. Early results should not be permitted to create such a lasting impression (favorable or unfavorable) as to lead one to ignore the results of later refinements. This can lead to disillusionment on the part of all concerned and, thence, lead to abandonment of a valuable tool.

3. Cost-effectiveness analysis can never replace good engineering and management practices. It should be regarded as a supplementary tool to provide meaningful information. Final decisions must still be based upon sound judgment. This must be particularly emphasized since too many political, psychological (e.g., an individual's drive to solve a particular problem), prestige value, and other factors cannot be considered in a satisfactory manner at this time in such analyses.

4. When results are sensitive to factors associated with high degrees of risk or uncertainty, "warning signs" must be posted. The results must then be used judiciously in making decisions.

In much of what has been said in the foregoing, there is an obvious attempt to build up the importance of cost-effectiveness consciousness. Considerable emphasis has been placed on developing models for obtaining cost-effectiveness indices and optimization thereof. However, it must be remembered that these do not provide a final answer. They do provide guidelines, but judgment must still play a large part.

Perhaps this is best expressed by Dr. Alain Enthoven's statement:[18] "Do judgment and experience have no place in this approach to choice of weapon systems and strategy and design of the defense programs? Quite the contrary. The statement that the issue is judgment versus computers is a red herring. Ultimately all policies are made and all weapon systems are chosen on the basis of judgments. There is no other way and there never will be. The question is whether those judgments have to be made in the fog of inadequate and inaccurate data, unclear and indefinite issues, and a welter of conflicting personal opinions, or whether they can be made on the basis of adequate, reliable information, relevant experience, and clearly drawn issues. The point is to render unto computers the things that are computers' and to judgment the things that are judgment's. In the end, there is no question that analysis is but an aid to judgment and that, as in the case of God and Caesar, judgment is supreme."

Thus, although there are limitations in this modeling process to obtain cost-effectiveness indices, it must be remembered that this approach allows us to:

1. Organise and set into proper perspective the many alternatives of the problem,

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18/ From a lecture, "Decision Theory and Systems Analysis," delivered during the Distinguished Lecture Series, sponsored by the Board of Trade Science Bureau, Washington, D.C., December 5, 1963.

2. Establish many "if-then" statements pertaining to the alternatives of the problem,
3. Evaluate properly data uncertainties,
4. Examine many cases quickly which would require years of simulated combat to test,
5. Explore systematically those cases which <u>cannot</u> be tested (you cannot go to war to test system effectiveness).

SECTION X

CONCLUSIONS AND RECOMMENDATIONS

A. DISCUSSION ON ACCOMPLISHMENTS AND IMPLEMENTATION

The work of Task Group IV of the Weapon System Effectiveness Industry Advisory Committee has provided a framework for cost-effectiveness studies and a common basis for using the results of these studies in evaluating systems. No single "cookbook" model or set of rules is provided since such does not seem possible or desirable at this point in time. Instead, appropriate formulae and check lists of factors which must be considered for relevancy are provided.

During the course of this study, existing deficiencies and problem areas have become apparent. Many of these have been examined by this and other task groups of WSEIAC. One of the principal problems is associated with the fact that, although the concept is not new, the "Cost-Effectiveness Art (or science)" is really in its infancy. There is presently only little appreciation for what is involved in such studies and only slightly more appreciation for the usefulness of the results of such studies. There is a general fear that an attempt is being made to find a model to "solve all problems for all time," and that we are "looking for black cats in a dark basement." Since these are quotes from qualified people deeply involved in various aspects of development or evaluation of weapon and space systems, it seems fair to say that there is an apparent need for indoctrination and clarification of intent. Recognition of the problems associated with estimating performance and cost for system elements at early stages of development should not lead to avoiding the issue of system evaluation at that time. Instead, this recognition should point up the need for such evaluations in view of the risks and uncertainties involved. Admittedly these early evaluations may leave much to be desired in terms of preciseness of the results; but, at least, they permit recognition of this impreciseness on a quantitative basis. Further, they should provide a better basis for decision in concentrating efforts to erase key uncertainties before irrevocably committing large sums of money.

There are already many data available from past and present systems which permit application of available techniques in determining reliability, maintainability, penetrability, survivability, lethality, performance and costs. This report reviews the technique and the types of data required. There is still much to be done in improving and validating existing submodels and in identifying and quantifying additional factors which should be considered in cost-effectiveness analyses. There is also necessity for inducing additional effort in formulating and disseminating meaningful measures of cost-effectiveness for a broader spectrum of systems.

The approach and models given in this report should be recognized as being useful to both the military and industry and provide a "check list" and a framework for performing cost-effectiveness studies. They should be used. At the very least, the elements listed must be considered for relevancy. No single model is given for considering all systems, simply because one cannot "model the universe." However, the elements, models, submodels, and "warning signals" (e.g., risks and uncertainties) given here constitute the basis for what must be done, considering costs, effectiveness, and constraints, to derive figures of merit for use in the decision process.

The benefits of application of cost-effectiveness studies are readily apparent. The use of quantitative measures of cost-effectiveness and decisionary emphasis on them automatically induces an economic consciousness. It adds another dimension to system design, which was previously dominated solely by technical considerations. With additional application of these tools and subsequent decision making based on cost-effectiveness measures, that point will be reached where it should be possible to specify a quantitative system effectiveness which can be enforced and to establish cost-effectiveness goals. Certainly this will encourage contractors to produce better systems for less money.

The cost-effectiveness approach must not be introduced as "revolutionary," or disillusionment is inevitable. Although this approach should take its place as rapidly as possible, the place must be appropriate and the process of introduction must be "evolutionary." Time is necessary to improve the approach, the models, the data collection process, "optimization" technique, and to develop a better appreciation for the usefulness of this management tool. It must be remembered that good judgment by intelligent and qualified people is necessary in both the cost-effectiveness studies and in the final decision process.

B. CONCLUSIONS

1. Cost-effectiveness as an art, science, or discipline is still in its infancy.

2. No single "cookbook" method for performing cost-effectiveness studies is possible or desirable at this time.

3. Task Group IV has shown that a general framework for performing cost-effectiveness studies on a more common basis, leading to standardization of methods and evaluation of results, is possible and very desirable.

4. Standardization and availability of data to perform effective cost-effectiveness studies is seriously lacking.

5. Many persons have little knowledge of or appreciation for either the usefulness or the intent of cost-effectiveness studies.

6. More study and education of the methodology and techniques for performing cost-effectiveness studies is needed.

C. RECOMMENDATIONS

The Air Force should:

1. Continue its efforts to indoctrinate their personnel in the principles and techniques of cost-effectiveness and instill in them a cost-effectiveness consciousness on an organizational and individual basis and insist that their prime contractors do the same. Relevant training programs (e.g., for maintainability and system program office personnel) should contain appropriate "doses" of cost-effectiveness information.

2. Provide guidelines to be used in specifying and evaluating cost-effectiveness studies in requests for proposals, contracts, and other programming documents.

3. Apply the cost-effectiveness evaluation approach on a cradle-to-grave basis with the details included being appropriate to the level of information available.

4. Identify those elements in cost-effectiveness analysis on which further research must be done to increase the utility of this approach to system evaluation and to improve the tools for performing cost-effectiveness analyses. This should include development of better submodels, methods for building up comprehensive models, approaches to "optimization," and standardizing cost analyses.

5. Continue to support a program to assure that a data collection, analysis, storage, and retrieval system is appropriate for supporting cost-effectiveness analyses. The data system should contain as many functional relationships as possible, as well as raw data, so that raw data do not have to be analyzed repeatedly in a similar way for similar studies.

6. Provide a better method for specifying the over-all system environment (e.g., enemy systems and practices) to permit establishing realistic models for the "scenario" in which both military and contractors have confidence. The aim of the method should be to reduce the possibility of eliminating superior systems through misinterpretation of relevant environments or by inconsistent evaluations.

7. Exercise considerable care to assure that the cost-effectiveness approach does not get a "revolutionary hold" on the decision-making processes but rather that it is introduced as "evolutionary."

The above recommendations will necessarily have to be transformed into policy documents (regulations, program management instructions, manuals and the like) and into specific projects and Air Force management objectives. In addition, some agency must be designated to implement and/or monitor each recommendation. Whether this should be done through normal administrative procedures or through a special office must be decided.

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APPENDIX I

COMPILATION OF ABSTRACTS FROM EXAMPLES OF VOLUME III OF TASK GROUP IV FINAL REPORT

EXAMPLE A - AIRCRAFT SYSTEM OPTIMIZATION

A system cost-effectiveness model is developed for an Air Force training base at which daily bomber training flights are made. In the event of enemy attack, the base bomber force is assigned to targets. The objective of the example is to illustrate the optimization of the bomber effectiveness by trading off reliability, maintainability, performance and cost factors. The system effectiveness model is developed along the mathematical lines presented by Task Group II in Volume II of their final report. Optimization is accomplished by computing and comparing the costs of eight possible measurement and support policies in terms of two alternative figures of merit:

(1) For each target, there will be a 0.95 probability that at least one of the attacking aircraft will successfully accomplish the bombing run.

(2) There will be an average success probability of 0.95 for all assigned targets.

A significant aspect of this example is its illustration of the need for re-evaluating the criterion for optimization in terms of the realized output of the evaluation effort.

EXAMPLE B - RELIABILITY ALLOCATION

A method for allocating system reliability requirements among subsystems (or lower level units) is presented. The method considers serial and redundant interconnections among the subsystems. The relationship between system reliability requirements and system effectiveness requirements is considered.

EXAMPLE C - BALLISTIC MISSILE PAYLOAD ALLOCATION

Each element of a ballistic missile's payload--warhead, guidance and penetration aids--will increase in effectiveness with an increase of weight allocated to the element. For a missile that is to be employed against a defended "point" target, this example presents a method for determining the optimum division of the missile's payload between the three competing (for weight) elements, when their individual weight-effectiveness relationships are known. For the case of a single missile per target, using a most basic application of the stepwise optimization philosophy of dynamic programming, the problem is formulated as a two-stage weight allocation process. The first stage determines the optimum trade-off between warhead (lethal radius) and guidance (CEP); the second stage determines the optimum division between penetration aids and an optimum mix of warhead and guidance. The simple arithmetical method that results is demonstrated by an example. The same optimization process is useful for the cases of sequential and simultaneous multiple missile employment per target. Although this design optimization problem can be solved, functionally, for the modes of missile employment considered, its applicability to a real allocation problem is confounded by the design, intelligence and employment estimates required in the analysis. Use of this method could show, however, the influence of the estimated uncertainties on the optimal payload division and could thereby serve as a useful point of departure for design compromises.

EXAMPLE D - OPTIMIZING A PRELAUNCH CHECKOUT

This example presents a procedure for determining the optimum test content of an ICBM prelaunch checkout that is subject to a time constraint. Cost considerations are not introduced as a constraint, but instead are employed after the test content has been optimized for each possible test duration constraint in order to select between designs. An example is given and references are cited that contain an explanation of the estimation of the parameters associated with the design technique.

EXAMPLE E - MISSILE AVAILABILITY

The availability of a system subjected to a sequence of calendar spaced checkouts is considered. Formulae for calculating the optimum frequency of checkout are given for the situation which considers checkout time as down time. Imperfect repair, imperfect checkout, and resource limitations are treated. A technique for the estimation of two parameters of the availability model is also given.

EXAMPLE F - A VULNERABILITY MODEL FOR WEAPON SITES WITH INTERDEPENDENT ELEMENTS

This example describes a simple "counting" model, employing probability grid transparent overlays, which aid in the determination of the trade-offs, measured in survival probability, between site dispersal and hardening for a weapon complex composed of several interdependent elements, separated by distances of less than two lethal radii. The survival-probability expressions are obtained through the use of Markov chains. An example of vulnerability estimation is given.

APPENDIX II

EXAMPLE OF COST-EFFECTIVENESS
ANALYSIS FOR THE
DEFINITION PHASE

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APPENDIX II

EXAMPLE OF COST-EFFECTIVENESS ANALYSIS FOR THE DEFINITION PHASE

1.0 INTRODUCTION

It is the purpose of this example to illustrate the application of the principles of cost-effectiveness analysis. The example selected illustrates the type of simplified analysis that occurs early in the Definition Phase of a program when there is a relative dearth of data. The simplifications employed are compatible with the accuracy of available data.

The steps in this example correspond roughly to the first nine steps outlined in Section II of this report, although in certain instances the division is not explicit.

It is not the purpose of this example to illustrate the techniques used in estimating reliability, cost, and weight, but rather to show how such estimates are used in the optimization process.

2.0 LEVEL OF APPLICATION

This example deals with the third, or lower, level of cost-effectiveness analysis: that of optimization of a system. The two higher levels: selection of mission, and selection of system are assumed to have been completed. The outputs of these higher level analyses have defined the mission and the basic system.

3.0 PROGRAM OBJECTIVES AND MISSION

The system to be considered in this example is an orbiting space station. The purpose of this space station is to serve as a manned laboratory for performing experiments.

The program objectives require the completion of fifteen separate experiment tasks or functions. Each task and the equipment required for the conduct thereof is assumed to have been defined. The tasks are independent. Success criteria have been established defining the number of successful operating man-hours required to complete each task. The successful operation of the experimental equipment for the full duration of an individual mission is not required. If the equipment fails prior to completion of the planned mission, only the uncompleted portions of the task need to be run on a subsequent flight.

The planned duration of each mission has been fixed at thirty days. The total weight of the experimental equipment to be carried is 7670 pounds. The total time required for completion of all experiments is 2160 man-hours.

4.0 IDENTIFY RESOURCES AND CONSTRAINTS

4.1 A Priori Resources and Constraints It is assumed that prior optimizations have selected the booster and re-entry vehicle to be used in the program. Selection of the re-entry vehicle automatically establishes the number of crewmen involved. Resupply or ferry operations have been established as being uneconomical. The basic station configuration, dimensions, and weights are given.

Within the above framework, together with the preceding statement of program objectives, resources can be identified and constraints established.

4.2 Customer Resources and Constraints The usual resources which the customer has to devote to satisfaction of his needs are cost and calendar time.

4.2.1 Cost: Cost is a customer resource which is always involved in a program. Bounds on cost should be established from the higher level optimizations as those cost amounts beyond which the selected mission or system is no longer competitive with alternative missions or systems.

4.2.2 Calendar Time: In this example the experiment results are assumed to be required by a specified date in order to support development schedules for other programs. Thus calendar time is stated as a constraint or bound.

4.2.3 Crew Skills: This is a potential resource if it is established that use of in-flight maintenance is a feasible or desirable improvement alternative. The maintenance skill of the customer-furnished flight crew limits the selection of maintenance alternatives. There are two basic bounds here:

(1) the level of skill available in the personnel inventory without additional training costs, and

(2) the level of skill beyond which it is not feasible to go because of calendar limits on available training time.

4.3 Mission and System-Imposed Resources and Constraints

Examination of the program requirements indicates that mission and system-imposed upper and lower bounds exist for:

(1) weight of experimental equipment put into orbit, W_e

(2) power required to operate station

(3) volume required to accommodate crew and experiments

(4) crew time to accomplish the required functions, T_e.

Since power and volume can be expressed in terms of equivalent weight, the list of primary resources can be reduced to:

(1) weight

(2) crew time.

Bounds on the weight resource are established by the payload capability of the preselected booster.

The extent of the crew time resource is determined by deducting requirements for such items as eating, sleeping, and recreation from the twenty-four hours available each day.

5.0 SELECTION OF COST-EFFECTIVENESS CRITERIA

In this example it is necessary to distinguish between single mission effectiveness and total program effectiveness. System effectiveness for a single mission may be defined to be a function of station payload capability and the probability that any given successfully launched booster will fly the proper trajectory; inject the station into orbit; and that the station, its re-entry vehicle, and its experimental payload will survive for a specified period of time in the proper orbit. Total program effectiveness, on the other hand, should be stated in terms of satisfying the program objectives.

For the system covered in this example, the program requirements as previously stated are clear. "The objective of the program is to complete 2160 man-hours of task time, which requires the successful orbiting and functioning of 7670 pounds of payload equipment."

No probability is expressly attached to these objectives. Accordingly, we shall regard these requirements as fixed and let the number of launches and the effectiveness of each mission vary to achieve these requirements. In view of this decision we shall define the cost-effectiveness criterion to be:

> Minimize the total expected program cost by varying system effectiveness, subject to the constraint that sufficient flights must be accomplished to place 7670 pounds of successfully operating experimental payload in orbit and to perform 2160 man-hours of experiment time.

It should be carefully noted that this implies that the optimum value of system effectiveness is that value which minimizes the expected cost of the program. There is a calculable risk attached to attaining the program objectives at the expected cost, a fact which we shall consider in a later section.

6.0 IDENTIFY VARIABLES

Variables of an analysis are those parameters or quantities the use of which, when varied, will result in variations in resources or the effectiveness with which the program objectives are accomplished. In the present example we shall make use of the following parameters:

A_1^i = Nonrecurring cost of the i^{th} improvement alternative

A_2^i = Recurring cost of the i^{th} improvement alternative on each flight attempt

C_o = Nonrecurring base cost of the program

c_f = Recurring cost of a flight attempt excluding the recurring costs of station improvements

C_t = Total program cost

ΔC_t^i = The change in total program cost resulting from adding the i^{th} alternative to the primitive system

E = Single-mission system effectiveness

f_j = Expected number of flights required for the j^{th} experiment

k = Fraction of station failures that occur in orbit

L_m = Mission duration in days

λ_s = Station failure rate in orbit

M_i = Average man-hours per day expended on in-flight maintenance of the i^{th} improvement alternative

N_a = Expected number of flight attempts required to complete program

N_s = Number of successful flights required to complete program

P_b = Probability that launch vehicle will be successful

P_r^b = Probability that re-entry vehicle will survive boost phase

P_s^b = Probability that station will survive the boost phase

P_e = Experiment reliability

P_m = Mission reliability of rocket launcher, station, and re-entry vehicle

P_r^s = Probability that re-entry vehicle will survive in orbit

P_s^s = Probability that station will be available in orbit for a specified length of time

Q = (General definition) probability of failure

r_i = Reliability of a subsystem after incorporation of the i^{th} improvement alternative

r_i^o = Reliability of the i^{th} subsystem prior to incorporation of an improvement alternative

R_j = Reliability of the j^{th} experiment

R_s = Total station reliability for a time duration L_m

R_{s_o} = Reliability of "stripped" station

R_s^s = Reliability of station in orbit for a time period L_m

T_a = Time available for experiment work per successful flight (man-hours)

T_c = Time available for experiment or maintenance work per day (man-hours) based on "stripped" station

T_e = Equivalent total man-hours required to complete all experiments

T_N = Total man-hours required to complete all experiments

t_1 = Planned start time of the j^{th} experiment measured from start of station orbit

t_2 = Planned stop time of j^{th} experiment measured from start of station orbit

$\bar{t}_f$ = Expected time to station failure in time L_m

W_e = Total equivalent weight of all experiment or payload hardware in program

W_{h_i} = Weight of the i^{th} improvement alternative

W_j = Weight of the j^{th} experiment

W_p = Experiment payload per flight

W_{p_o} = Payload capability of stripped station

Z_i = Ranking index (dollars change in program costs divided by weight increase of station).

In view of the definition of a variable given above, virtually all of these parameters may be regarded as variables. In the present example we shall treat the parameters W_{h_i}, r_i, and M_i as variables. The remainder of the parameters will be treated as constraints except insofar as they are altered by one of the three above.

7.0 DEVELOP RELATIONSHIPS AND MODELS

7.1 Method of Approach The analysis commences with a "stripped" orbiting station. This primitive system consists of the least amount of hardware required to accomplish the objectives of the program. It is the least costly system to build; it weighs the least; and it provides the maximum amount of available experiment payload weight since the difference between the rocket booster payload capability and the station and crew weights represents the maximum available experimental payload that may be loaded aboard the station. Unfortunately, this primitive system is also the least reliable. Thus, from the point of view of the cost of accomplishing the fixed program objectives, it is apt to prove to be less satisfactory than a more costly laboratory having less payload capability. The reason for this is that a low station reliability implies a larger number of required flights to attain the fixed program objectives. On the other hand, station reliability improvement can only be attained by adding station equipment redundancy which implies an increase in station weight and a resultant decrease in the weight that is available for the experiment payload. Thus an increase in reliability can result in either a decrease in required number of flights or an increase in the required number of flights depending upon whether the increase in reliability decreases the expected number of flight failures faster than the attendant increase in station weight increases the need for a larger number of flights because of reduced experiment payload capability. The equations which we shall shortly proceed to develop will relate the economics of improving the reliability of the station to the cost of performing additional flights. Station reliability will be a parameter which will be permitted to vary as we seek a minimum cost program that will meet the fixed program objectives.

As was indicated earlier, we shall seek to minimize the expected cost of the program. We shall calculate this expected cost on the basis of the expected number of flight attempts required to achieve 2160 man-hours of experiment time or 7670 pounds of experiments in orbit, whichever represents the worst constraint, thus the total cost of the program will be expressed as:

$$C_t = \text{(expected number of flight attempts) x (recurring cost of a flight) + (nonrecurring program cost)}$$

This function will approach a minimum value and then increase as the reliability of the station is increased. The minimum value corresponds to the "optimum" choice of station configuration. It should be carefully noted that this minimum is not an absolute minimum; it is only best in the sense that it reflects the best choice among a given finite set of alternatives proposed by a given design group. Lower cost may in fact be achievable by other designs.

7.2 Mission Success Probability As noted earlier, system effectiveness may be defined as:

$$E = f[P_m, P_e, W_p] \tag{1}$$

where

P_m = mission success probability of rocket launcher, station, and re-entry vehicle

P_e = experiment reliability

W_p = station payload capability.

We shall not write a specific expression for E, but instead will treat the components P_m, P_e, and W_p separately. Accordingly, we define:

$$P_e = \prod_{j=1}^{K} R_j . \tag{2}$$

R_j = reliability of the j^{th} experiment of a flight of K experiments

and,

$$P_m = P_b P_s^b P_s^s P_r^b P_r^s \tag{3}$$

where

P_b = probability that launch vehicle will be successful

P_s^b = probability that station will survive the boost phase

P_s^s = probability that station will be available in orbit for a specified length of time

P_r^b = probability that re-entry vehicle will survive boost phase

P_r^s = probability that re-entry vehicle will survive in orbit

Although P_m may be regarded as a constant from flight to flight, P_e cannot be. Therefore we shall account for P_e in terms of an equivalent number of required successful station flights.

7.3 <u>Expected Number of Flights</u> Let it be assumed that N_s successful flights are required and that the probability of achieving a successful flight is a constant p. The expected number of flight attempts N_a required to achieve N_s successes is given by:

$$N_a = N_s \left\{1 \cdot p + 2(1-p)p + 3(1-p)^2 p + \cdots\cdots\right\}$$
$$= N_s \sum_{k=1}^{\infty} kp(1-p)^{k-1} = \frac{N_s}{p}. \qquad (4)$$

We must now relate p and N_s to experiment weight, launch booster payload capability, and system effectiveness.

Consider N_s. The program is not complete until all experiments have been conducted. This requires a number of totally successful flights N_s determined by either man-hours available for conduct of experiments per flight (T_a) or by experiment payload (W_p) per flight. Thus the number of flights is given by either:

$$N_s^T = \frac{T_e}{T_a} \qquad (5a)$$

or by

$$N_s^W = \frac{W_e}{W_p} \qquad (5b)$$

whichever is greater, where

T_e = total equivalent man-hours of experiment time required

T_a = total man-hours of experiment time available per flight

W_e = total equivalent weight of experiments in the total program

W_p = total experiment payload weig : that can be carried per flight.

The time available per flight (T_a) in man-hours is given by:

$$T_a = (T_c - \sum_{i=1}^{K} M_i) L_m \qquad (6)$$

where

T_c = time available per day for either experimentation or for additional station maintenance activities based on stripped station

M_i = average man-hours per day expended on the i^{th} improvement alternative to the stripped station

L_m = mission duration in days.

We may determine T_e from the following considerations. Let the reliability of the j^{th} experiment be R_j. We shall assume that each experiment is scheduled for two flight attempts at most. The second flight is required only if it fails its first flight. Further, the man-hours expended on an experiment that fails are not wasted. Only that portion of the experiment not completed needs to be conducted on the subsequent flight. In view of these assumptions the expected number of flights f_j required for the j^{th} experiment is:

$$f_j = 1 \cdot R_j + 2(1 - R_j) \qquad (7)$$

$$= 2 - R_j.$$

Hence if the time required to complete all experiments is τ_N we may write equation (5a) in terms of equations (6) and (7) as:

$$N_s^T = \frac{T_N}{\left(T_c - \sum_{i=1}^{K} M_i\right) L_m} \left(\frac{1}{N} \sum_{j=1}^{N} (2 - R_j)\right). \tag{8}$$

For equation (5b) we have that

$$W_p = W_{p_o} - \sum_{i=1}^{K} W_{h_i} \tag{9}$$

where

W_{p_o} = experiment payload capability of the stripped station

W_{h_i} = weight of the i^{th} improvement alternative to the stripped station.

If the j^{th} experiment weighs W_j pounds, we must be prepared to carry a total equivalent payload W_e of

$$W_e = \sum_{j=1}^{N} (2 - R_j) W_j. \tag{10}$$

Thus equation (5b) becomes

$$N_s^W = \frac{\sum_{j=1}^{N} (2 - R_j) W_j}{W_{p_o} - \sum_{i=1}^{K} W_{h_i}}. \tag{11}$$

Strictly speaking, the R_j should be averages obtained by

$$R_j = \int_{t_1}^{t_2} \lambda_s e^{-\lambda_s t} R_j(t - t_1)\, dt \tag{12}$$

where

λ_s = station failure rate in orbit (assumes exponential failure distribution for station)

$R_j(t)$ = reliability of the j^{th} experiment

t_1 = planned start time of j^{th} experiment measured from start of station orbit

t_2 = planned stop time of j^{th} experiment measured from start of station orbit.

However, for our present purposes it is sufficiently accurate to ignore this refinement of the analysis and simply regard the R_j as constants independent of the station failure rate in orbit (λ_s).

Since we have accounted for experiment reliability in W_e and T_e we may identify p of equation (4) with P_m of equation (1). Thus we have that

$$N_a = \frac{N_s^T}{P_m} \quad \text{or} \quad \frac{N_s^W}{P_m} \tag{13}$$

whichever is the greater.

Our development is not complete until we have examined P_m. We require an expression for the factor P_s^s of P_m which accounts for the fact that a station which fails in orbit will, in general, have performed some useful service. It is assumed that its usefulness will be linearly proportional to the time nonfailed, thus P_s^s is given by

$$P_s^s = \frac{\overline{t}_f}{L_m} \tag{14}$$

where

$\overline{t}_f$ = expected time to station failure in time L_m

L_m = scheduled mission duration.

If it is assumed that the station fails exponentially in orbit at a rate λ_s, then,

$$\overline{t}_f = \int_0^{L_m} e^{-\lambda_s t}\, dt = \frac{1 - e^{-\lambda_s L_m}}{\lambda_s} \tag{15}$$

where $e^{-\lambda_s t}$ is the total station reliability for a time "t". Thus,

$$P_s^s = \frac{1 - e^{-\lambda_s L_m}}{\lambda_s L_m}. \tag{16}$$

If the station reliability is reasonably high,

$$P_s^s = \frac{1 - e^{-\lambda_s L_m}}{\lambda_s L_m} \approx \frac{1 - \left(1 - \frac{\lambda_s L_m}{1!} + \frac{(\lambda_s L_m)^2}{2!} - \cdots\cdots\right)}{\lambda_s L_m} \tag{17a}$$

$$\cong 1 - \frac{\lambda_s L_m}{2} \tag{17b}$$

which to the same order of approximation is

$$1 - \frac{\lambda_s L_m}{2} = (1 - \lambda_s L_m) + \frac{1 - (1 - \lambda_s L_m)}{2}$$

$$\cong R_s^s + \frac{Q_s^s}{2} \tag{17c}$$

R_s^s = reliability of station for a time period L_m in orbit

Q_s^s = $1 - R_s^s$ for same time period.

Thus we may write P_m to a first order approximation as

$$P_m \cong P_b P_s^b P_r^b P_r^s \left(R_s^s + \frac{Q_s^s}{2}\right). \tag{18}$$

If we define mission unreliability Q_m as

$$Q_m \triangleq 1 - P_b P_s^b P_r^b P_r^s R_s^s \tag{19}$$

then P_m may be expressed as

$$P_m \cong 1 - (Q_m - P_b P_r^b P_r^s P_s^b \frac{k Q_s)}{2} \qquad (20)$$

where

$$k Q_s \triangleq Q_s^s \qquad (21)$$

k = fraction of station failures that occur in orbit

Q_s = total station unreliability = $1 - R_s$

R_s = total station reliability for a time duration L_m.

We shall assume that the station reliability R_s may be expressed in terms of the stripped station reliability R_{s_o} by the series relationship

$$R_s = R_{s_o} \prod_{i=1}^{K} \frac{r_i}{r_i^o} \qquad (22)$$

where

r_i = the reliability of the i^{th} improvement alternative

r_i^o = the reliability of the i^{th} "subsystem" before incorporation of the i^{th} improvement alternative.

Note that this equation requires that when two successive station improvements are made to one subsystem, the second improvement must either cancel the first or else be defined in terms of a new r_i^o.

7.4 Development of Cost Equation We are now in a position to write down the total cost C_t of the program.

$$C_t = N_a \left(C_f + \sum_{i=1}^{K} A_2^i\right) + \sum_{i=1}^{K} A_1^i + C_o \qquad (23)$$

where

C_f = the recurring cost of a flight attempt excluding the recurring costs of station improvement

A_2^i = the recurring cost of the i^{th} station improvement on each flight attempt

A_1^i = the nonrecurring cost of the i^{th} station improvement

C_o = the nonrecurring base cost of the program

and

$$N_a = \frac{N_s^T}{P_m} \quad \text{or} \quad \frac{N_s^W}{P_m}$$

whichever is greater, and

$$N_s^T = \frac{T_N \frac{1}{N} \sum_{j=1}^{N} (2 - R_j)}{\left(T_c - \sum_{i=1}^{K} M_i\right) L_m} \tag{24a}$$

$$N_s^W = \frac{\sum_{j=1}^{N} (2 - R_j)\, W_j}{W_{p_o} - \sum_{i=1}^{K} W_{h_i}} \tag{24b}$$

$$P_m \cong 1 - (Q_m - P_b P_r^b P_r^s P_s^b \frac{k Q_s)}{2} \tag{25}$$

$$R_s = 1 - Q_s = R_{s_o} \prod_{i=1}^{K} \frac{r_i}{r_i^o} . \tag{26}$$

Equations (23) through (26) are all that are required to perform the required analysis.

8.0 IDENTIFY ALTERNATIVES AND DEVELOP MODEL INPUTS

As noted earlier, the first step used here is to establish a basic stripped down, or primitive, design which meets functional requirements with absolute minimum expenditure of resources. This design is minimum weight, minimum cost, and is stripped of all redundance, in-flight spares, or other improvements.

Since the system meets functional requirements, improvement alternatives are generally confined to items which improve station reliability. Types of alternatives considered are shown in Table I.

For each station subsystem, various levels and types of redundancy and in-flight maintenance (Table I) are considered. Between six and twelve such alternatives should be established for each subsystem. Usually this will be accomplished by the individual design groups responsible for the subsystems involved.

The definition of each alternative should include:

(1) schematic showing functional relationships

(2) description of any required cross-connecting or monitor/transfer devices, and

(3) failure mode and effect analysis.

For maintenance items, the definition includes additionally:

(1) description of required maintenance actions

(2) listing of required tools and fault isolation equipment

(3) notation of any repackaging required to permit maintenance, and

(4) description of any crew-member training needed to perform maintenance.

Table II is an example of alternatives considered for the electric power subsystem of the station which is diagrammed in Figure 1. The basic, or primitive, subsystem contains two fuel cell modules, both of which must continue to function throughout the mission in order to achieve mission success. The reliability of this subsystem is 64 per cent (r_i^o of Table II).

The i.d. column of this table lists, by code number, the alternatives which are being considered for this subsystem. These alternatives are described as follows:

TABLE I

IMPROVEMENT ALTERNATIVES

A. BASIC FAILURE RATE REDUCTION

B. REDUNDANCY

   1. LEVEL

      (a) Component
      (b) Subsystem

   2. TYPE

      (a) Dual Item With Manual Monitor and Transfer
      (b) Dual Item With Automatic Monitor and Transfer
      (c) Duality of Several Items With and Without Intermediate Crossovers.

   3. OPERATING MODE

      (a) Standby
      (b) Continuous Operating

C. IN-FLIGHT MAINTENANCE

   1. TYPE

      (a) Adjustment
      (b) Remove and Replace
      (c) Repair

   2. CONFIGURATION; MAINTENANCE TO:

      (a) Single Thread Systems
      (b) Redundant Systems, As Listed Above

         (1) Using On-Board Spares
         (2) Cannibalizing Parallel Systems

D. COMBINATIONS OF THE ABOVE

TABLE II

ELECTRICAL POWER SYSTEM

i.d.	r_i^o	r_i	A_1^i (in 10^6 dollars)	A_2^i (in 10^6 dollars)	W_{h_i} (pounds)	M_i (man-hours)	Z_i ($\$10^6$/pounds)
a-1	.641	.9452	.06	.1971	165	-	+ .0308
a-2	.99402	.99992	.03	.1573	165	-	- .0077
a-3	.641	.6421	.01	.04	10	-	- .0321
a-4	.6410	.643	.02	.0685	20	-	- .0273
a-5	.6410	.6592	.05	.0802	10	-	- .0311
a-6	.641	.6497	.045	.042	20	-	- .0100
a-7	.641	.6422	.025	.025	16	-	- .0130
a-8	.641	.6462	.03	.0511	16	.0011	- .3232
a-9	.641	.652	.015	.0211	5.1	.0015	+ .0028

c_f = 60 x 10^6 dollars

$N_s \cong$ 4

T_c = 18 man-hours/day

R_{s_o} = .0372

r_a^o = .641

L_m = 30 days

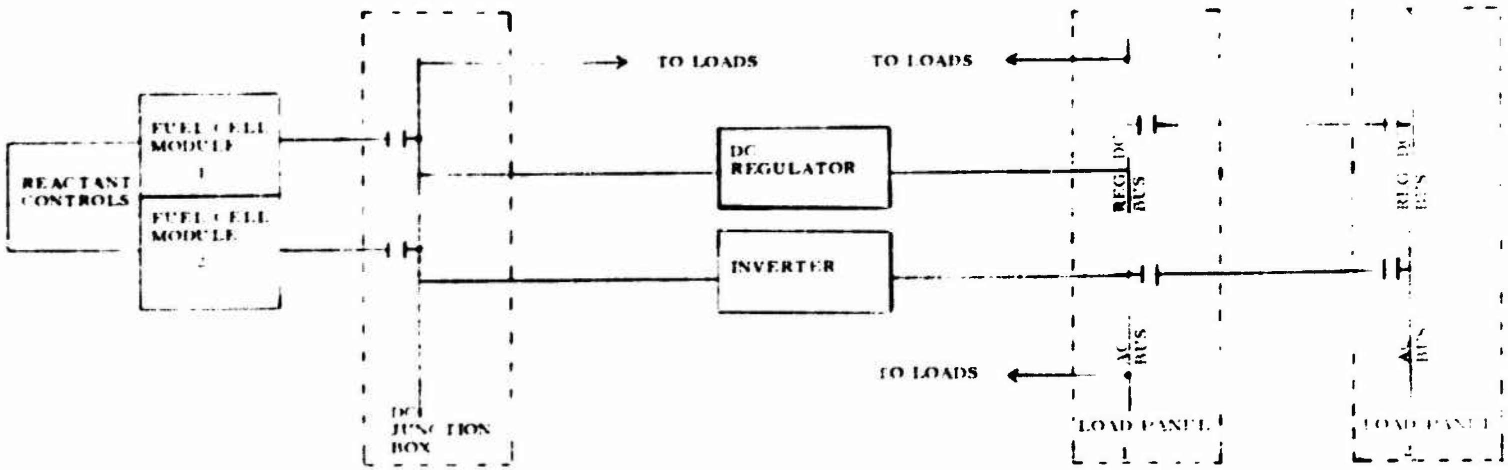

FIGURE 1

ELECTRIC POWER SUBSYSTEM DIAGRAM

a-1 Provide one redundant fuel cell module making a total of three, with only two required to satisfy the power load.

a-2 Add second redundant fuel cell module making a total of four, with only two required to satisfy the power load.

a-3 Add redundant D.C. regulator to power distribution subsystem.

a-4 Add redundant inverter in power distribution subsystems.

a-5 Add a redundant fuel cell reactant control package.

a-6 Provide one redundant set of functional components in electrical load panels.

a-7 Add one redundant set of functional components in junction boxes.

a-8 Provide tools and spare parts for in-orbit maintenance of power distribution subsystem.

a-9 Provide tools and spare parts for maintenance of reactant controls.

The r_i^o column indicates the reliability level of the stripped-down subsystem. The r_i column indicates the subsystem level which would result from incorporation of the alternative, except in the case of alternative a-2. In this latter case the r_i^o column contains the combined reliability of the fuel cells and the r_i column shows the increase in subsystem reliability due to fuel cells alone.

Columns A_1 and A_2 indicate the cost of the hardware involved in the improvement. For redundant items, the cost includes the design and development cost of the redundant item and its associated monitor/transfer and/or cross connection devices, plus the recurring cost of the additional procured items. The cost of maintenance items includes the cost of any repackaging of equipment necessary to permit maintenance, together with the cost of the spare parts, tools, fault-isolation equipment and any training required to enable the crewmen to successfully perform the specified maintenance. A_1 is the nonrecurring portion and A_2 is the recurring portion of this cost.

The W_h column indicates the amount of weight expended in order to incorporate the improvement. In the case of redundant elements, the weight figures include the additional hardware, plus any monitor/transfer or other interconnecting elements required to make the redundant element function. For maintenance items, the weight figures include the spare parts, tools, and fault-isolation equipment needed to accomplish the maintenance.

Column M indicates the estimated average maintenance man-hours per day expended on proposed maintenance items. This value is calculated as the estimated maintenance man-hours for each occurrence of failure multiplied by the probability that said failure will occur.

The Z column shows the ranking index for each alternative which is the cost reduction calculated from equation (23), divided by the weight expended to incorporate the alternative. The reason for this index will be discussed in the next section.

As noted in the introduction, it is not the purpose of this example to illustrate the development of model inputs, but rather to illustrate the use of inputs in arriving at an optimum cost-effectiveness solution. The reader is referred to the examples of Task Group II and the open literature for guidance in the estimation of parameters. We shall simply assume here that the reliability, weight and cost of each alternative and of the primitive system and the experiments have been assessed. The net result for each case is shown in Tables III, IV and V. The information in these tables constitutes the data base for exercising equations (23) through (26).

9.0 EVALUATION OF ALTERNATIVES

9.1 Determination of N_s As noted earlier N_s is given by either (24a) or (24b) whichever is greater. In the first instance we have, using the data of Tables II, IV, V and VI

$$N_s^T = \frac{2289.6}{(18 - \Sigma M_i)\,30} \qquad (27)$$

The alternative expression, N_s^W is from Tables III and VI and equation (4):

$$N_s^W = \frac{8360}{3500 - \Sigma W_{h_i}} \qquad (28)$$

TABLE III

CHARACTERISTICS OF THE PRIMITIVE SYSTEM

C_o	=	\$250 x 10^6 = program nonrecurring base cost
c_f	=	\$60 x 10^6 per flight attempt
W_{P_o}	=	3500 pounds (launch vehicle limited)
T_c	=	18 man-hours/day
L_m	=	30 days
P_b	=	0.85
P_s^b	=	.992
$R_{s_o}^s$	=	0.0372
P_r^s	=	0.9936
$P_r^b P_r^s$	=	0.975
T_e	=	2160 man-hours
k	=	0.92 (assumed constant for all system improvements)

TABLE IV

CHARACTERISTICS OF THE EXPERIMENTS

Experiment Number	Weight (pounds)	Reliability
1	1400	.85
2	1200	.87
3	200	.96
4	500	.94
5	650	.94
6	350	.97
7	350	.93
8	300	.95
9	900	.90
10	550	.90
11	250	.96
12	600	.95
13	150	.98
14	70	.97
15	200	.99

TABLE V

CHARACTERISTICS OF THE ALTERNATIVES

Designator	Reliability of Stripped Subsystem r_i^o	Reliability of Improved Subsystem r_i	Weight of Improvement (W_{h_i}) in pounds	Maintenance Time Required M_i in man-hours	Recurring Cost A_2^i in 10^6 dollars	Nonrecurring Cost A_1^i in 10^6 dollars
bb-3	.6514	.9813	8.6	.0053	.0034	.003
bc-1	.70979	.943	14	0	.0186	.008
d-1	.5175	.98y2	90	0	.2981	.16
e-3	.4262	.9917	195	.032	.179	.09
bc-2	.943	.9968	12.7	.0102	.0122	.006
bd-4	.9251	.9331	2	0	.003	.001
a-9	.641	.652	5.1	.0015	.0211	.015
f-4	.7568	.81093	24	.00198	.0251	.011
a-1	.641	.9452	165	0	.1971	.06
f-2	.81093	.9688	100	0	.2447	.01
be-1	.85185	.99504	100	0	.1229	.05
a-50	.641	.64806	4.9	0015	.0802	.05
a-6	.641	.6497	20	0	.042	.045
bb-6	.6514	.66171	32	0	.0146	.006
ba-3	.9197	.9935	170	0	.1149	.045
a-8	.641	.6462	16	0	.0511	.03
bd-1	.9251	.928	12	0	.0068	.003
ba-60	.9197	.92336	15.7	.00068	.0342	.015
a-7	.641	.6422	16	0	.025	.025
bb-7	.6514	.65288	25.1	.0097	.0019	.001
c-1	.99	.995	150	0	.0005	.0003
bf-3	.97704	.9978	525	0	.1597	.06
ba-40	.9935	.9994	140	0	.0979	.04
c-2	.995	.999	500	0	.0015	.0009
a-2	.99402	.99992	165	0	.1573	.03
be-20	.85185	.85433	1400	0	.695	.4
a-4	.641	.6421	20	0	.0685	.02

TABLE VI

EQUIVALENT EQUIPMENT WEIGHT

EXPERIMENT NUMBER	INSTALLED WEIGHT W_j	RELIABILITY R_j	EXPECTED FLIGHT $(2 - R_j)$	EQUIVALENT WEIGHT
1	1400	.85	1.15	1610
2	1200	.87	1.13	1360
3	200	.96	1.00	208
4	500	.94	1.06	530
5	650	.94	1.06	690
6	350	.97	1.03	360
7	350	.93	1.07	375
8	300	.95	1.05	315
9	900	.90	1.10	990
10	550	.90	1.10	605
11	250	.96	1.04	260
12	600	.95	1.05	630
13	150	.98	1.02	153
14	70	.97	1.03	72
15	200	.99	1.01	202

ΣW_j = 7670 pounds $\qquad$ W_e = TOTAL EQUIVALENT WEIGHT = 8360 pounds

9.2 Ranking the Improvements Table V lists 27 alternatives that must be considered in evaluating equation (23). If we approach this task in a brute force manner we would first evaluate C_t for the primitive system and then again for each of the 27 alternatives, one at a time. The next step would be to incorporate into the station that alternative which yielded the greatest reduction in C_t for the least expenditure of W_h. We would now have 26 alternatives to evaluate again using the new improved station reliability. It is clear that this process requires that 379 separate calculations be made --- not an inconsiderable amount of labor. If our computation process is to be efficient it is desirable to find a short cut. Therefore we shall, in fact, proceed as follows.

First, we shall calculate the change in C_t (denoted by ΔC_t) for each of the 27 alternatives applied one at a time to the primitive system. Second, we shall rank each ΔC_t in accordance with its efficient use of the weight reserve. That is, we shall use a ranking index Z_i defined as[1/],

$$Z_i = \frac{\Delta C_t^{\,i}}{W_{h_i}} = \frac{\text{dollars}}{\text{pounds}} \qquad (29)$$

$\Delta C_t^{\,i}$ = the change in total program cost resulting from adding the i^{th} alternative to the primitive system

W_{h_i} = the weight of the i^{th} alternative.

The logic of this approach is contingent upon the fact noted earlier; that weight is a resource which has value. Thus, in installing improvement alternatives, it is necessary to install these alternatives in an order which will permit the maximum possible amount of cost reduction per unit of expenditure of this resource.

We shall then incorporate sufficient alternatives in the order of this ranking until the station reliability has substantially increased. Then

---

1/ Note that Z_i is positive if a cost decrease occurs when the alternative is incorporated, and negative if the cost increases.

we shall rerank the remaining alternatives using the augmented reliability of the station as the new basis for comparison of the effect of incorporating alternatives one at a time. There is a danger in this short cut approach which is illustrated in Figure 2. This figure illustrates the manner in which Z_i changes as R_s^s changes. Note that alternative a-8 is worse than useless when $R_s^s \leq .125$, but for larger values it may prove to be valuable. The saving element here is that all the Z_i tend to increase as R_s^s increases so that, in practice, several alternatives can be incorporated before the basic station reliability is increased by a sufficient amount to radically alter the ranking. For the present example there are sufficient alternatives to bring the station reliability to levels in excess of 90 per cent. Accordingly, the alternatives which remain after the station reliability has reached 50 per cent will be re-evaluated based upon a revised "initial" station reliability of 70 per cent, a value which was midway between the 50 per cent and 90 per cent levels. The remaining alternatives which proved favorable will be retained based on the values of the second ranking.

It must be remembered that once an alternative is incorporated, some of the other alternatives may be rendered technically infeasible or the amount of reliability improvement gained by them may be radically altered due to the functional relationships between the various alternatives. Therefore, during the ranking process, the functional interfaces and interferences between alternatives must be kept in mind. Alternatives must be redefined and re-evaluated as required by prior incorporation of interfacing components. For example, alternatives a-5 and a-9 as described in paragraph 8.0 above, are so related that when a-5 is incorporated a-9 is no longer profitable. Thus, a-5 is redefined to include cancellation of a-9 and is identified as a-50 in Table V.

9.3 Model Exercise We shall illustrate the use of the equations developed herein in detail for one alternative. Consider the first alternative (bb-3) of Table V. From equation (29),

$$Z_1 = \frac{\Delta C_t^1}{W_{h_1}} = \frac{\text{Cost of program using stripped station - Cost of program using station with first alternative incorporated}}{\text{weight of first alternative}} \quad (30a)$$

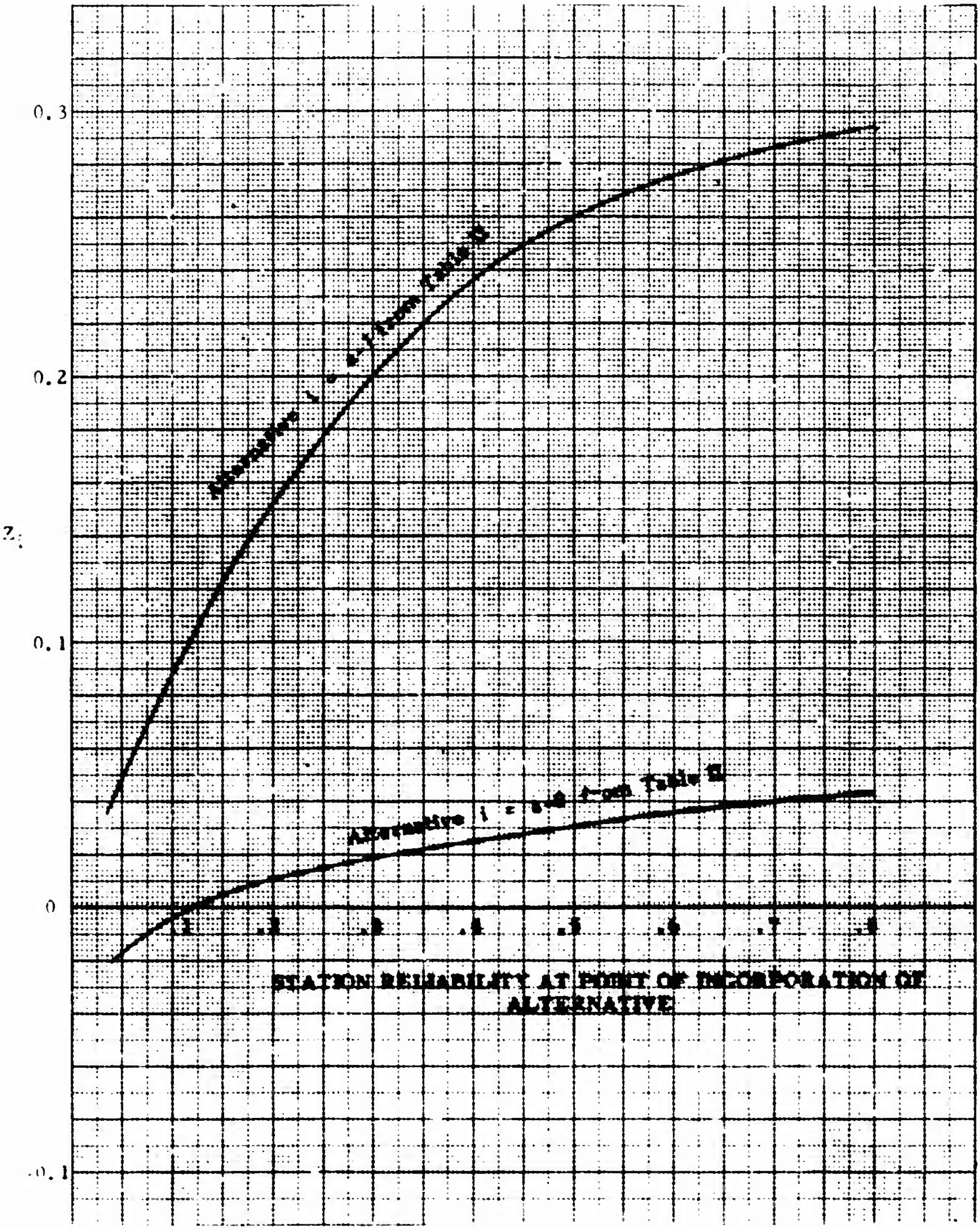

FIGURE 2

VARIATION OF RANKING INDEX
AS A FUNCTION OF STATION RELIABILITY

$$Z_1 = \frac{\Delta C_t^1}{W_{h_1}} = \frac{N_{s_o} \; c_f}{W_{h_1}\left(1 - Q_{m_o} + P_b P_r^b P_r^s P_s^b \frac{k Q_{s_o}}{2}\right)} \tag{30b}$$

$$- \frac{N_{s_1} \; (A_2^1 + c_f)}{W_{h_1}\left(1 - Q_{m_1} + P_b P_r^b P_r^s P_s^b \frac{k Q_{s_1}}{2}\right)} - \frac{A_1^1}{W_{h_1}}$$

From equation (27) and Tables III and VI,

N_{s_o} equal the greater of

$$\frac{T_e}{T_c L_m} = \frac{2289.6}{18 \times 30} = 4.24 \tag{31a}$$

$$\frac{W_e}{W_{p_o}} = \frac{8360}{3500} = 2.39 \tag{31b}$$

Hence,

$$N_{s_o} = 4.24 \tag{31c}$$

and from equation (28),

N_{s_1} equal the greater of

$$\frac{T_e}{(T_a - M_1) L_m} = \frac{2289.6}{(18 - .0053) \; 30} \cong 4.24 \tag{32a}$$

$$\frac{W_e}{W_{p_o} - W_{h_i}} = \frac{8360}{3500 - 8.6} = 2.395 \; . \tag{32b}$$

Hence,

$$N_{s_1} = 4.24 \tag{32c}$$

For purposes of preliminary ranking we may set

$$N_{s_o} = N_{s_i} \cong 4 \tag{32d}$$

and to further simplify the calculations, it is convenient to make the additional coarse approximation

$$P_b P_r^b P_r^s P_s^b = 1 \tag{33}$$

Now, from equation (26) and equation (1),

$$R_{s_i} = \frac{R_{s_o}}{r_i^o} r_i \tag{34a}$$

$$= \frac{.0307}{.6514} .9813 = .0463. \tag{34b}$$

Hence,

$$Z_1 = \frac{4 \times 60 \times 10^6}{8.6\left(.0307 + \frac{.92 \times .9628}{2}\right)} - \frac{4 \times 60.0054 \times 10^6}{8.6\left(.0463 + \frac{.92 \times .9439}{2}\right)} \tag{35}$$

$$- \frac{.003 \times 10^6}{8.6}$$

$$= .8367 \times 10^6 \ \frac{\text{dollars change in program costs}}{\text{weight increase in station}} .$$

This calculation is repeated until all the alternatives have been evaluated. Then the alternatives are arranged in descending order of Z_i.

Next we assume that we have incorporated sufficient of these ranked alternatives to raise the station reliability to about .50. It is now necessary to rerank the remaining alternatives, since as was noted in Figure 1, we may now have serious errors in our ranking. Accordingly, the alternatives which remain after the station reliability has reached .5 are re-evaluated based upon a revised "initial" station reliability of .7, a value approximately midway between .5 and the total potential reliability of .95 that is achievable using all the alternatives. The results of this second, and final, ranking are shown in Table VII.

The total ranking list for the station produced by the addition of the first and second ranking iterations will show discontinuities in Z_i at the

TABLE VII

ADJUSTED RANKING OF THE ALTERNATIVES

Alternative (i)	R_m	R_s	Z_i
0	.0307	.0372	
bb-3	.0463	.056	.8367
bc-1	.06155	.07445	.4790
d-1	.1172	.142316	.2363
e-3	.2725	.331146	.2735
bc-2	.2882	.350038	.3554
bd-4	.2907	.353065	.3715
a-9	.2957	.359124	.2609
f-4	.317	.384811	.2543
a-1	.467	.567431	.2339
f-2	.558	.677897	.1906
be-1	.652	.791846	.1808
a-50	.659	.800568	.1847
a-6	.6682	.811434	.0701
bb-6	.679	.824276	.0583
ba-3	.733	.890419	.0532
a-8	.739	.897643	.0458
bd-1	.741	.900457	.0298
ba-60	.7445	.904040	.0194
a-7	.746	.905733	.0054
bb-7	.748	.907791	.0043
c-1	.7515	.912375	.0042
bf-3	.767	.931761	.0035
ba-40	.772	.937295	.0016
c-2	.775	.941063	.0010
a-2	.780	.946648	-.0003
be-20	.782	.949404	-.--25
a-4	.783	.951034	-.0069

point where the second ranking was started. This discontinuity is reduced by reranking of alternatives in the area of discontinuity. All discontinuities cannot be eliminated in the area where station reliability is lower than 50 per cent due to the extreme nonlinearities of the reliability and cost functions in this regime. (In the present instance the reranking was extended back from a-1, the approximate 50 per cent reliability point, to e-3).

We are now in a position to calculate the total program cost as a function of the successive incorporation of alternatives. Table VIII illustrates this calculation using equation (23). Figure 3 illustrates the results of Table VIII in graphic form plotted against ΣW_{h_i}. Minimum total program cost clearly occurs at the point that all alternatives up to and including c-1 have been incorporated. At this point,

$$\begin{aligned} W_p &= 2321 \text{ pounds} & \Sigma M_i &= .0599 \text{ man-hours} \\ \Sigma W_{h_i} &= 1179 \text{ pounds} & R_s &= .9124 \\ & & R_m &= .7515 \\ & & C_t - C_o &= 310.4 \times 10^6 \text{ dollars} \\ & & C_t &= 560.4 \times 10^6 \text{ dollars.} \end{aligned} \tag{36}$$

Note that the number of successful flights is still time constrained at this point. The payload constraint would not take effect until the next alternative is incorporated. Note that this implies that flights somewhat longer than thirty days are desirable. This, of course, would require a change in the original requirements.

9.4 Errors of Approximation The results which have been obtained above were based on a variety of simplifying approximations, the most serious of which was the replacement of R_s^s by equation (17c). The effect of this approximation is indicated by the dotted line in Figure 2. Note that agreement is good for $R_s \geq 0.75$, but below this figure there is a rapid divergence between the exact and approximate equations. Fortunately, this has no effect on our final result since $R_s > .9$ at the optimum. However, it

TABLE VIII

WORKSHEET ILLUSTRATING COST COMPUTATION

Alternative	R_m	R_s	Q_s	$.378 Q_s$	ΣA_2	$C_f + \Sigma A_2$	ΣA_1	ΣM	$N_e^T = \frac{2209.6}{(18 - \Sigma M) 30}$	ΣW_h	$W_{R_b} - \Sigma W_h$	$N_e^W = \frac{8360}{W_{R_b} - \Sigma W_h}$	$X = .378 Q_s + R_m$	$\begin{Bmatrix} N_e^T \\ N_e^W \end{Bmatrix} \frac{(C_f + \Sigma A_2)}{X} + \Sigma A_1$
0	.0307	.0372	.9620	.3639	0	60	0	0	4.24	0	3500	2.39	.3946	644.7
bb-1	.0461	.056	.9665	.3570	.0054	60.0054	.003	.0053	4.24	8.6	3491.4	2.394	.4033	630.9
bc-1	.06155	.07645	.9256	.3499	.0260	60.026	.011	.0053	4.24	22.6	3477.4	2.404	.41145	618.6
d-1	.1172	.142116	.8577	.3242	.1221	60.1221	.171	.0053	4.24	112.6	3387.4	2.460	.4414	579.6
e-1	.2725	.311146	.6669	.2520	.5011	60.5011	.241	.0515	4.25	[illegible]	3192.4	2.619	.5253	489.8
bc-2	.2802	.346030	.6500	.2457	.5133	60.5133	.267	.0475	4.25	[illegible]	3179.7	2.629	.5339	482.0
bd-4	.2907	.353065	.6469	.2445	.5163	60.5163	.268	.0475	4.25	322.3	3177.7	2.631	.5352	480.8
e-9	.2957	.350124	.6409	.2423	.5374	60.5374	.283	.0490	4.25	327.4	3172.6	2.635	.5380	478.5
f-4	.317	.366811	.6152	.2325	.5625	60.5625	.294	.0510	4.25	351.4	3148.6	2.655	.5495	468.7
e-1	.467	.567433	.4326	.1635	.7596	60.7596	.354	.0510	4.25	516.4	2983.6	2.802	.6305	409.9
f-2	.558	.677097	.3221	.1218	1.0043	61.0043	.364	.0510	4.25	616.4	2883.6	2.899	.6798	381.8
bc-1	.652	.791846	.2082	.0787	1.1272	61.1272	.414	.0510	4.25	716.4	2783.6	3.003	.7307	355.0
e-50	.659	.800460	.1994	.0754	1.2074	61.2074	.464	.0495	4.25	721.3	2778.7	3.009	.7344	354.7
e-6	.6682	.811436	.1886	.0713	1.2494	61.2494	.509	.0495	4.25	741.3	2758.7	3.030	.7395	352.5
bb-6	.679	.824276	.1757	.0664	1.2600	61.2600	.515	.0495	4.25	773.2	2726.7	3.066	.7454	349.8
bc-3	.711	.890419	.1095	.0414	1.3709	61.3709	.560	.0495	4.25	943.3	2556.7	3.270	.7744	337.4
e-8	.719	.897641	.1024	.0387	1.43	61.43	.592	.0495	4.25	959.3	2540.7	3.290	.7777	336.3
bd-1	.741	.900417	.0995	.0376	1.4360	61.4360	.593	.0495	4.25	971.3	2528.7	3.306	.7786	335.9
ba-60	.7445	.904040	.0960	.0363	1.4710	61.4710	.600	.0502	4.25	987.0	2513.0	3.327	.7808	335.2
e-7	.746	.905711	.0941	.0356	1.4960	61.4960	.633	.0502	4.25	1003.0	2497.0	3.340	.7816	335.0
bb-7	.748	.907791	.0922	.0348	1.4979	61.4979	.636	.0549	4.25	1029.1	2470.9	3.383	.7828	334.5
c-1	.7515	.912175	.0876	.0331	1.4904	61.4904	.6343	.0599	4.25	1179.1	2320.9	3.602	.7846	333.8
bd-1	.767	.931761	.0682	.0258	1.6581	61.6581	.6943	.0599	4.25	1704.1	1795.9	4.655	.7928	362.7
ba-80	.772	.937295	.0627	.0237	1.7560	61.7560	.7343	.0599	4.25	1844.1	1655.9	5.048	.7957	392.5
c-2	.775	.941063	.0589	.0223	1.7575	61.7575	.7352	.0599	4.25	2344.1	1155.9	7.232	.7973	560.9
a-2	.780	.946648	.0534	.0202	1.9160	61.9160	.7652	.0599	4.25	2509.1	990.9	8.437	.8002	653.6
be-20	.782	.949094	.0506	.0191	2.6098	62.6098	1.1652	.0599	4.25	3909.1	not feasible			
e-4	.781	.951036	.0490	.0185	2.6703	62.6703	1.1052	.0599	4.24	3929.1	not feasible			

NOTE: Up to and including C - 1 flights N_e are determined by T.
After C - 1, N_e is determined by ΣW_h.

$$C_t = \Sigma A_1 + \frac{\begin{Bmatrix} N_e^T \\ N_e^W \end{Bmatrix} (C_f + \Sigma A_2)}{R_m + \frac{.92 Q_s}{Z} P_b P_r^b P_r^e P_e^b}$$

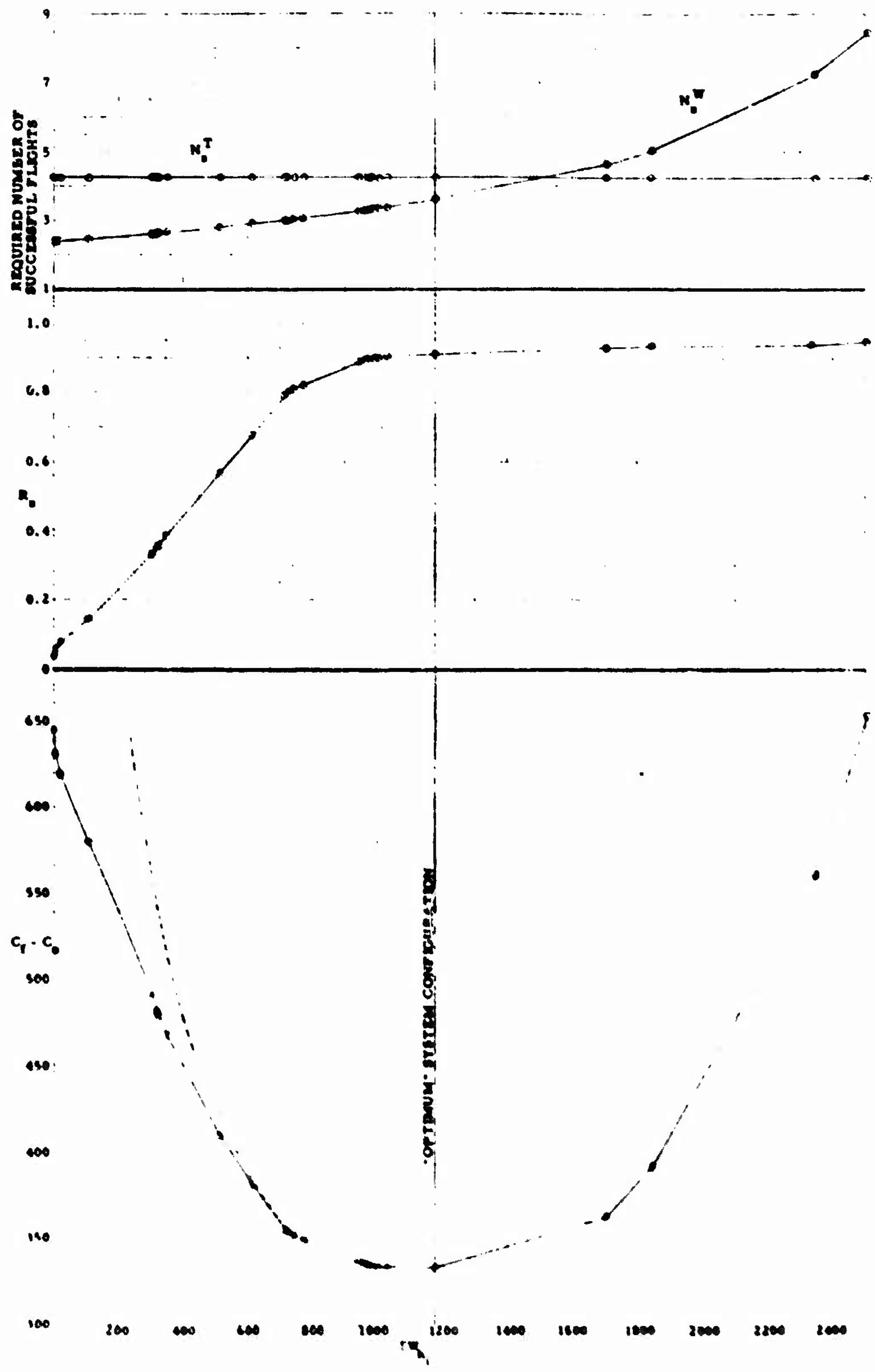

FIGURE 3. RESULTS OF TABLE VIII SHOWN GRAPHICALLY

must be borne in mind at all times that the use of approximations requirec that the analyst review his results carefully.

10.0 INCORPORATION OF RISK AND UNCERTAINTY

Our discussion would not be complete if we ignored the questions of risk and uncertainty. We will dwell on this aspect of the analysis only in sufficient detail to illustrate its importance.

In the present example the uncertainty aspects will evidence themselves in estimating cost, weight, and reliability. In view of this, it is unwise to interpret the scale of Figure 3 as an absolute index of cost. On the other hand, there is considerably more certainty in the relative ranking of the alternatives since errors made in judging cost, weight, and reliability from one alternative to another will tend to vary in much the same direction. Thus we may be relatively sure that the optimum point of the program cost curve of Figure 3 represents the best choice of alternatives.

The question of risk is synonymous with the question of calculable odds. That is, the probability of completing a given mission successfully with the optimum system of Figure 3 is

$$R_m P_e^{1/4} = .7515 \times .782$$
$$= .588$$

where

R_m = probability that station will be successfully orbited and will remain nonfailed for the time duration L_m

P_e = probability that all fifteen experiments will remain nonfailed

$P_e^{1/4}$ = average experiment probability per flight

Based on this figure the expected number of flights is

$$N_a = 5.64 \cong 6.$$

The entire program can be completed in four totally successful flight (N_s = 4). The probability that this will occur is

$$P\,[N \equiv 4] = R_m^4\; P_e$$

$$= (.7515)^4\; 0.373 = 0.119.$$

The probability that it will take exactly five flights to terminate the program is approximated by

$$P\,[N \equiv 5] \cong \left\{\binom{4}{1} R_m^3\; P_e^{3/4} (1 - R_m P_e^{1/4})\right\} R_m\; P_e^{1/4}$$

$$+ \binom{4}{1} R_m^3\; P_e^{3/4} (1 - R_m P_e^{1/4})^2$$

$$= 0.334$$

The first term of this equation corresponds to the probability that exactly one flight and/or experiment failure occurs in the first four flight attempts, and that the fifth flight is an unqualified success. The second term accounts for the possibility that two successive flights do not fully succeed. Under a ground rule established earlier, no experiment is scheduled to be carried on more than two successive flight attempts; hence, two successive flight failures (or partial successes) eliminates any further consideration of these particular experiments.

We shall bypass the question of six flights temporarily and consider the full impact of this ground rule. We may interpret this as implying that there is a maximum number of flight attempts. Specifically, if there is a succession of seven failures (or partial successes), the program will terminate on the eighth flight attempt irrespective of the results achieved in the program. The probability that this will occur is

$$P\,[N \equiv 8] = (1 - R_m P_e^{1/4})^7 = 0.002$$

Similarly, the only way in which the program can terminate in exactly seven flight attempts is to have a succession of six failures (or partial successes) preceeded or followed by a fully successful flight. Hence,

$$P[N \equiv 7] = 2(1 \quad P_e^{1/4})^6 R_m P_e^{1/4} = 0.006.$$

Then the probability that the program will terminate in exactly six flight attempts is given by:

$$P[N \equiv 6] = 1 - P[N \equiv 4] - P[N \equiv 5] - P[N \equiv 7] - P[N \equiv 8]$$

$$= 0.539$$

Under this ground rule, then, the probability that the program will terminate on the N^{th} flight is given by:

N	P_N
1	0
2	0
3	0
4	0.119
5	0.453
6	0.992
7	0.998
8	1.000

Clearly, this ground rule makes it easy to say one should buy six stations and take an option on two spares. On the other hand, this ground rule has a very inflexible ring to it. If the experiments are worth doing at all, a string of total flight failures is unlikely to cause abandonment of the scheduled experiments. It is more likely to lead to rescheduling and a total slippage of program schedule with the inevitable rise in total program cost. Obviously a management review of the ground rules would be necessary before over-all program cost could be predicted with certainty.

11.0 SUMMARY AND CONCLUSION

A method by means of which it is possible to seek a minimum cost program has been illustrated in some detail. This method is particularly useful when there are fixed program objectives and system effectiveness is not constrained.

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13 ABSTRACT This report discusses the philosophy of cost-effectiveness and techniques for trade-off and optimization studies. It lists and discusses twelve tasks necessary to perform a cost-effectiveness analysis. A methodology is outlined for identifying and standardizing cost and effectiveness factors. Descriptive analytical models for cost-effectiveness are provided, including discussion of their sensitivity and validity. One section defines and discusses risk and uncertainty and their effect on the decision making process. Included is an extensive bibliography on cost-effectiveness. Examples of some of the techniques are covered in detail in a "Technical Supplement," which is Volume III of this final report of Task Group IV. Abstracts of these examples will be found in Appendix I of this report. Appendix II of this report illustrates a technique for cost-effectiveness optimization in the Definition Phase when there is a relative dearth of data, program objectives are fixed, and system effectiveness is unconstrained.

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