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PROPOSED RELIABILITY COST-MODEL

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Systems/Products Office

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16. ABSTRACT

The research investigations which were involved in this study include: cost analysis/allocation, reliability and product assurance, forecasting methodology, systems analysis, and model-building. This is a classic example of an interdisciplinary problem, since the model-building requirements include the need for understanding and communication between technical disciplines on one hand, and the financial/accounting skill categories on the other.

The systems approach is utilized within this context to establish a clearer and more objective relationship between Reliability Assurance and the subcategories (or subelements) that provide, or reenforce, the reliability assurance for a system. Subcategories are further subdivided as illustrated by a tree diagram. The reliability assurance elements can be seen to be potential alternative strategies, or approaches, depending on the specific goals/objectives of the trade studies. The scope was limited to the establishment of a proposed reliability cost-model format.

The model format/approach is dependent upon the use of a series of subsystem-oriented CER's, and sometimes possible CTR's, in devising a suitable cost-effective policy.

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PROPOSED RELIABILITY COST-MODEL

SECTION I. INTRODUCTION

As a prior condition to the logical development of any cost relationships, it was found necessary in the case of reliability to strive for a clearer understanding of the means needed to establish and/or enhance reliability for a system or subsystem. All of these things, collectively, will provide Reliability Assurance. Many of these items may not be directly involved in a reliability program, although their contributions (or lack of it) will clearly affect reliability; e.g., Quality Control.

A. Subsets of Reliability Assurance

As noted above, the need was recognized for a better understanding of the various subelements of Reliability Assurance. A Reliability Assurance tree diagram, Figure 1, has been constructed to provide better visibility of five categories of Reliability Assurance. An attempt has been made to provide an exhaustive set of factors under each category, each of which contributes in some degree to the assurance of reliability. Some of these elements lend themselves more readily to quantification than others in any attempt to establish specific contributions to the overall system reliability, and/or to a specific subsystem. Within this context, the terms "Hard" or "Soft" have been used to estimate the degree of difficulty in establishing a direct link with reliability cost values. For example, the introduction of "High Reliability" parts into a design which formerly had utilized commercial grade parts will generally provide a predictable increase in reliability (hard). On the other hand, the introduction of increased spending in the area of manned flight awareness could hardly be expected to provide a discrete increase in the reliability estimate, and for this reason is termed soft. In order to provide further visibility concerning the potential contributions of the subcategories shown in Figure 1, a systems analysis matrix was used (see Appendix C), to indicate applicability of the various subcategories versus hardware subsystems. Also, a systems analysis matrix was used in Appendix D to play the same subcategories of Reliability Assurance against the various hardware subsystems (hard or soft measurable effects on Reliability Assurance). In both of these items we can

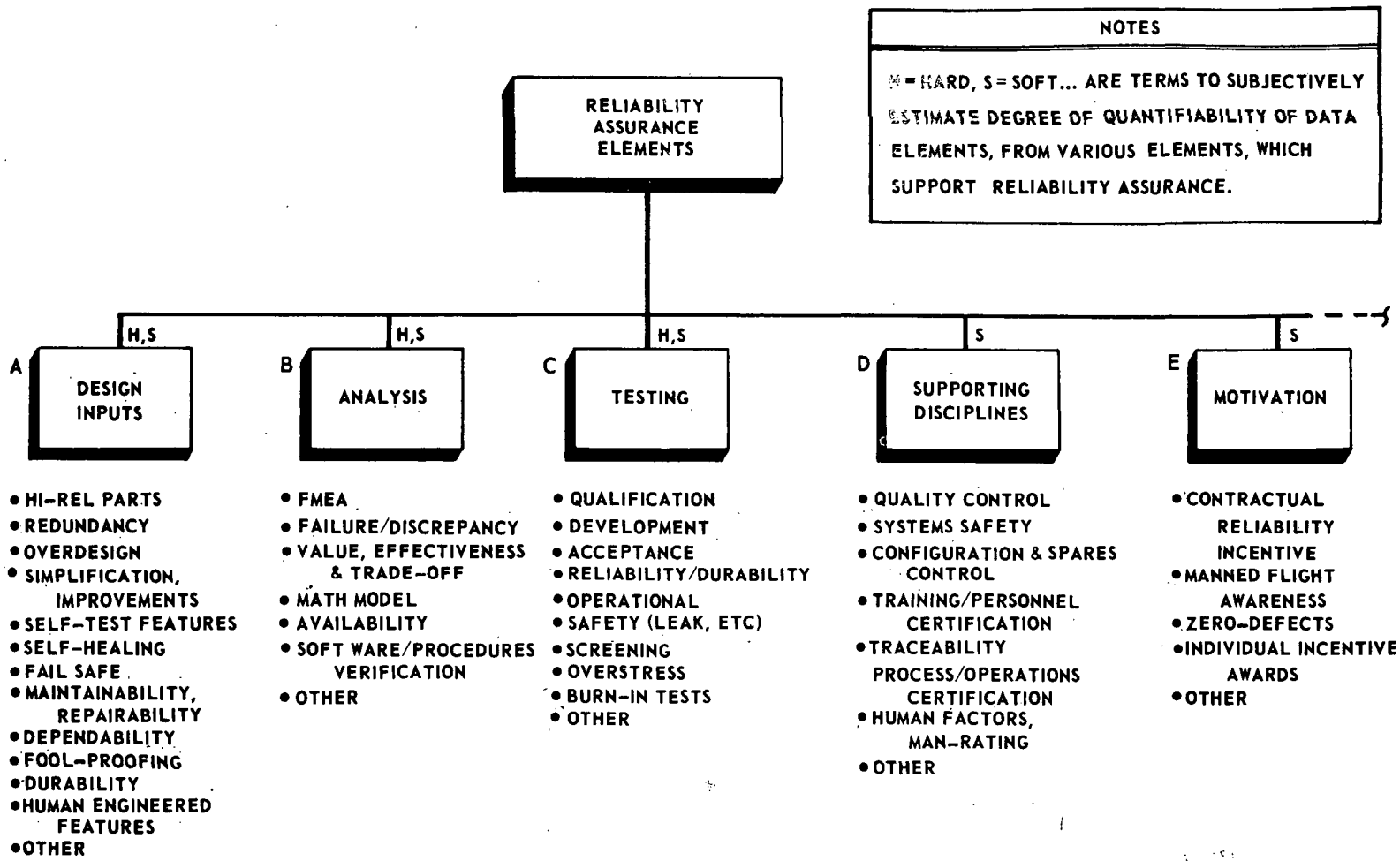

Figure 1. Reliability Assurance tree diagram.

observe that a desire to increase or decrease reliability is not a simple matter of spending more or less funds, and/or allocation of lesser or greater portions of the available resources. The establishment of reliability estimates is both complex and heterogenous. Approaches that are effective for electronic/electrical components and subsystems may either not be suitable for mechanical systems, or just simply not available as an alternative. Consequently, approaches for reliability improvement have been categorized in the trade by the type of hardware subsystem.

B. Cost-Estimating Definitions of Reliability

For similar reasons the development of cost-estimating relationships (CER) may be observed to be structured by hardware subsystem reliability versus cost (see Figure 2).

In order to complete this milieu for reliability cost sensitivity, another parametric aspect should be considered. This parameter might be termed design configuration type (DCT). A graphical illustration of this type of variability may be seen in Figure 2. One of the curves illustrates the cost sensitivity of an EOS type spacecraft to reliability, and the other curve indicates the reliability versus cost factors for a COMSAT-type spacecraft. Different ground rules, assumptions, and/or variations in technical/mission requirements could account for such differences in variability and cost sensitivity between these two sample design configurations. Further research and data expansion will be necessary in order to include this source of variability with the other factor in structuring a final master function which could be used to explain an overall reliability cost-model. A more detailed account of the interrelationships of the cost estimating activities will be given below as a part of the proposed model description.

Based on the information displayed in Figure 1, as well as Appendices B and C, the primary system elements for which CER's can be established for reliability assurance will be the hardware subsystems. Typical subsystems may be: Electrical, Mechanical, Attitude/Guidance Control, Structural, etc. If an adequate data base is obtained from aerospace firms such as Boeing, Lockheed, McDonnell-Douglas, etc., then the next lower level of CER's could be developed to depict the cost variation of reliability for the functional categories shown in Figure 1. The previously discussed aspects of "applicability" and "quantifiability" must be considered in this review. At this time it does not appear feasible to include the "Motivation" category as suitable for CER development. For this reason, subsequent illustrative examples will not include motivation as a viable CER candidate.

Figure 2. Electrical subsystem — CER.

C. Variations in Cost Collection Modes

During the course of this study it has been recognized that instead of there being only a single approach to relating cost to reliability in CER's, there may be two or more modes which are feasible. Several of these possible strategies will be discussed below to provide a better understanding of the complexities involved.

1. Subsystem unit cost versus reliability estimate values. This type CER relates the subsystem total cost to variations in subsystem reliability estimates;

2. Reliability peculiar costs for a subsystem versus variations in the reliability estimate;

3. Total system unit cost versus reliability estimate values for the total system; and

4. Total program costs per unit versus variations in the reliability estimate. This type of cost value includes not only the direct reliability-related costs, and hardware costs; but also management, burden, and other administrative-type costs.

Each of the above modes explains the cost variability of reliability in a slightly different way. Depending on the objectives of a particular model, one, all, or additional CER's may be desirable.

SECTION II. OBJECTIVES/STATEMENT OF PROBLEM

A. Objectives

Questions have frequently been raised concerning the marginal cost of reliability. Stated differently, a question might logically be: "How much will it cost to increase the reliability estimate of system X from, say, 95 percent to 97 percent, or even 99 percent?". As discussed above, it can be readily seen that such complex objectives are very difficult to implement. There may be several alternative approaches to reliability improvement, as well as several candidate subsystems which may have the capability to accept part, or all, of the allocated increase in reliability performance. The same consideration would also have to be given to an allocated decrease in a reliability estimate since the allocation would have to be distributed among suitable subsystem candidates, in order to optimize cost-effectiveness within the system as a

whole. Any change in reliability requirements may be introduced either from the bottom up, or from the top down, depending on how a change in requirements is specified. Consideration must be given to the subsystem that offers the best opportunity for improvement or trade-offs. In certain electrical, or electronic subsystems, the mere substitution of components could effect a significant change in subsystem or system reliability, with their associated cost elements.

Another starting point in a Reliability System Analysis could be a condition requiring a reduction in cost. This might involve use of the unique capabilities of the Space Shuttle/Tug for the maintenance and refurbishment of spacecraft systems. With the assumption of such capabilities, requirements for high reliabilities and excessively long life cycles could be relaxed, with an accompanying reduction in reliability and program costs.

Briefly stated, the objectives of a Reliability Cost-Model might be one, or all, of the following:

1. Provide a means to forecast effects on the reliability of the overall system, based on changes in one or more of the reliability-cost relationships of the several subsystems.

2. Provide a means to allocate programmed increases or decreases in the cost-reliability function (whole system) downward to the several relevant subsystems.

3. Provide a system methodology to permit evaluation of the cost effectiveness of alternative system configurations and/or program operating plans (trade studies, etc.).

B. Statement of Problem

In full consideration of previously stated background information, there exists a need both in the aerospace industry and in other industries, for a methodology which will permit decision-making for reliability/cost considerations to be made based on quantitative relationships. Such a methodology tool has been termed a "Proposed Reliability Cost-Model", because the development of an operational cost model to explain reliability is unquestionably outside of the scope of the meager resource allocated to this effort.

Based on these considerations a more specific statement of the problem for this study effort would be to generate, or structure, the framework for a

Reliability Cost-Model. This smaller and optimistically more-manageable goal for a single investigator still represents a formidable obstacle, since, in spite of the fact that the need has been recognized for some time, proposed solutions or methodology are virtually non-existant.

C. Approach

Based on discussions of the objectives and the statement of the problem, structuring of a Reliability Cost-Model framework will, of necessity, be tempered by those considerations. At this point we are more interested in establishing methodology that can be shown to service the practical needs of cost modeling and/or iterations of alternative trade-offs of system parameters. Feasibility of any proposed model should be demonstrated first, before any subsequent effort is made to construct automated computerized versions of the model algorithm. This approach to model development might be termed a "stepping-stone" approach, with the distinct rationale being that low-cost approaches for space programs should also be cost-effective. Hand solutions of sample problem applications should be made first to demonstrate feasibility. If the demonstrated methodology shows promise, then more sophisticated solution-methods involving computer programs could be a next logical step.

The initial step approach for this study will be based on a non-automated cost-model framework. The general approach will consist of the mathematical integration of a set of subsystem cost-estimating relationships (CER's) to form a single master function which can be used to explain the overall cost variability (of reliability) for the overall system. In other words, the cost variability for reliability of the several subsystems will be embedded mathematically into a single cost figure-of-merit/reliability master function. Further descriptive details of the model-building method will be given in Section IV.

SECTION III. ASSUMPTIONS, GROUND RULES, AND CONSTRAINTS

A. Assumptions

Assumptions are based on previous descriptive information concerning the logic, rationale, and goals for the proposed model framework. They will include consideration of all these prior aspects and are listed as follows:

1. Cost-Estimating Relationships (CERs) can be formulated based both on historical data obtainable primarily from one or more of the larger aerospace contractors, or from certain internal government sources.

2. Certain Cost Trade Relationships (CTRs) may also be needed to establish sufficiency for utilization of the cost models.

3. To prevent possible misinterpretation of sample information it will be assumed that hardware relative cost values are based on first unit costs, with no learning, progress, or improvement aspects implied.

4. Information implied or shown as CERs or CTRs should be utilized primarily as planning or forecasting tools, and not in detail cost estimating.

5. Inflation and/or changes in productivity should normally not be considered as sources of variability in the sample cost information.

B. Ground Rules and Constraints

1. Cost values, CERs, CTRs, and/or other mathematical functions displayed in this document are for informational uses only, and should not be used for any other purpose. (This is not a working model.)

2. The cost elements utilized in the sample model are either relative cost values, or cost figure-of-merit type values which result from a mathematical embedding process to integrate the cost sensitivities (for reliability) of the selected set of subsystems.

3. No attempt has been made to isolate, or even to separate, the "reliability unique or peculiar" costs from other system cost elements, so far as this initial reliability cost-model format is concerned. (The next lower level of cost elements would presumably involve such information.)

4. The prototype model described in Section IV is limited to the subsystem level, based primarily on the lack of sufficient quality and quantity of data for the lower levels displayed in Figure 1.

SECTION IV. DESCRIPTION OF A PROPOSED MODEL FORMAT

A. Background

The approaches utilized in this model building exercise have employed support from a sizeable group of engineering, management, statistics, mathematics, and econometric disciplines. The unique aspect perhaps being that the as-built model configuration does not rely, to any great extent, on any one of these discipline areas as a prime theoretical source. The general approach is based primarily upon a systems engineering methodology, since the principal aspect being exercised in the proposed model (Reliability) has been termed a systems specialty factor. Systems specialty factors in general specify or define the degree of engineering confidence or assurance, that a particular system will perform when compared or referenced to its established requirements (mission, cost, technical, etc.).

Quite often, in the past, questions have been posed in management meetings which might take form in the following alternative ways:

1. If a reduction in program funding should occur, with a corresponding reduction in reliability assurance allocation, how shall this reduction in resources be dispersed among the several subsystems to minimize impact?

2. Given a reduction in resource allocation to a specific subsystem, how shall this reduced support be subdivided among the various affected subdisciplines; e.g., design inputs, analysis, testing, etc.?

3. If there is an urgent need to upgrade or increase overall program reliability, to satisfy a national or international requirement (e.g., increase reliability of unmanned space launches to reduce possible embarrassing launch failure of NATO satellite using U.S. launch vehicle such as DELTA), how can reliability of system be increased most economically, and how shall proposed increase be allocated among several subsystem candidates?

This group of questions is not intended to be exhaustive, and should only be considered as typical. The intent here is to illustrate the fact that such questions are natural in decision-making environments involving top management.

If such questions are not unexpected, can a quantitative basis be established for decision-making? It is fully realized that historically most decisions of this type have had to be made with little or no precision, or even methodology. Hopefully, the following information may provide a first step toward the fulfillment of these needs.

B. Model Requirements

Requirements for the proposed model framework have already been at least partially introduced by the set of questions outlined in the previous section. What should be recognized, however, is that the stated requirements must be considered preliminary until some experience is gained with the approaches outlined, and the availability of necessary data has been assured.

1. The model should provide a tool for planners and top management for consideration of the interplay between reliability requirements and resource allocation.

2. The model should permit approximate subsystem reliability versus cost estimates or forecasts.

3. The model should be sufficiently simple in format such that information necessary to iterate the model can be displayed either in the form of a table of parametric cost versus reliability values, or characteristic curves displaying the same information.

4. The model should embody a systems engineering methodology which will integrate the cost versus reliability sensitivities of the set of subsystems which are designated as representative of the overall system. This information shall also be either displayed in tabular form, or by a master functional characteristic curve. The master function will be comprised of reliability estimates versus cost figure-of-merit values representative of the whole system.

5. The model will be constructed such that the range of useful applications may be specified by the user for each technical system to which this approach is applied. A typical range could be, for example, between reliability estimates of 90 percent to 97 percent.

C. Model Format Description

As previously noted, the intent is not to attempt to provide a detail working model but rather a set of descriptors which indicate the approach. The reader, therefore, should focus his attention on the methodology and not on the specific numbers and/or estimating relationships, which are included primarily as illustrations. The layman or practitioner wishing to utilize a model of this type should establish his own CERs based on his own unique set of technical reliability and cost experiences. The examples shown in Figure 2 illustrate two CERs based on relative, rather than actual, cost values. The curves of Figure 2 represent basically two types of spacecraft design configurations that could represent a wide range of cost-to-reliability sensitivity. Both of these curves represent data reported by aerospace researchers, and indicate possible cost-estimating relationships for a typical electrical subsystem. As might be expected, the relative cost values increase slowly at first, for small increases in reliability. After a certain point has been met, the relative cost values start to increase at a more rapid rate for each additional increase in reliability requirements. This same diminishing return type of response function is also typical for many other physical and/or socio-economic activities; e.g., learning curves, material quantity discount cost functions, organization and/or discipline progress functions, etc.

The approach suggested here is based on the utilization of a set of subsystem CERs with each cost-sensitive system; e.g., electrical subsystem, mechanical subsystems, etc. The selection of a suitable set is up to the decision-maker or analyst as long as the overall model constraints and requirements are met, and the following list of special constraints:

1. Each of the subsystem CERs used to comprise the system set must be either monotonically increasing, or decreasing, but in the same direction.

2. For the benefit of clarity, all functional plots comprising the established system set (ESS), will be plotted on the same type of coordinates; e.g., Cartesian, log-log, semi-log, etc.

3. All diophantine cuts will be linear, and for each model will be either parallel to the ordinate, or the abscissa axis.

4. If subsystem functions are such that cuts might intersect the function more than once, the intersection points for the higher reliability values will be posted.

5. Initially, cuts will be made at regular intervals; e.g., 10 percent, 20 percent, 30 percent, etc., but more frequent cuts may be needed for those portions of the CER curves that indicate very rapid rate of change.

6. To simplify arithmetic computations all values from cutting plane samples will be converted to natural logarithms, and then entered in tabular form into a matrix.

Finally, having observed the above constraints, the log values from the matrix table may be plotted to form a characteristic Reliability Assurance master function as indicated in Figure 3. This function was generated in the same manner as described above. In essence, the framework for a Reliability-Cost Model has been established, thus making it possible to propose various reliability/relative-cost trades.

Mathematically speaking, the model bears resemblance to models described elsewhere — such as the multiplicative model described by Benjamin [1], or the log-normal by Chow [2], or the similitude models by Gukhman [4], et al. There is a common thread through all of the examples cited: the commonality being that a series of parameters (or factors) can be used to explain an overall system effect or cumulative resultant, provided the parametric values are multiplied together, or added geometrically by summing the logarithms of the numbers rather than the discrete numerical values themselves. The application of these concepts may be extended to include variates which are either discrete or continuous, dependent or independent. The multiplicative format tends to embed each of the participating variates, one with the other. The embedding process tends to minimize unknown or indeterminate interaction or internal influence effects between the various subelements of the ESS. So, if we let Q = cost figure-of-merit for the ESS, Y_n = relative cost of various factors and,

$$Q = Y_1 \cdot Y_2 \cdots Y_n \cdots\cdots , \tag{1}$$

by taking the natural logarithm of both sides of the equation, the following expression results:

$$\log_e Q = \sum_1^n \log_e Y_n \cdots\cdots \tag{2}$$

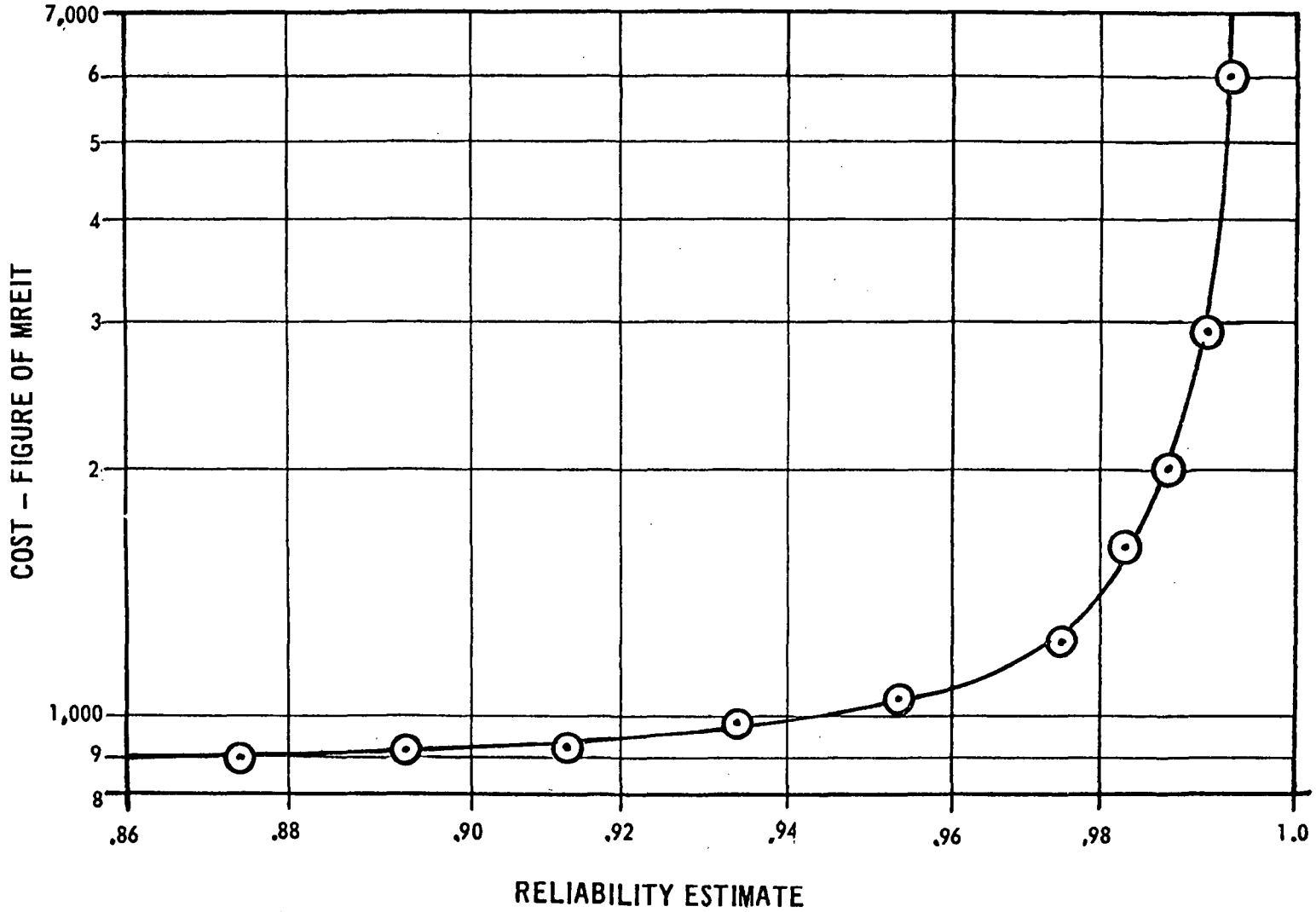

Figure 3. Reliability versus cost figure of merit, master function.

or

$$l_n Q = l_n Y_1 + l_n Y_2 + \dots l_n Y_n \dots \quad (3)$$

If, for example, the individual values of Y represent functions of subsystems (CERs) as we have above, and if we take the geometric sum of these subsystem functions, then the resulting curve should assume a geometrical shape which approximates the shape of the individual elements. For the conditions existing in the reliability CERs, the subsystem functions are approximately exponential. Therefore, it is not surprising that the master function (see Figure 3) also assumes an approximate exponential shape. As such, this master function is a characteristic function representing the expected reliability/cost performance for the whole system. There appears to be no definite limit on the number of subelements which are included in the ESS. If the master function values are normally distributed ($\log_e Q$) as indicated by Chow, then Q would be logarithmico-normally distributed, based on argument of Central Limit Theorem. Also, a closely related concept is involved in the understanding of the network — the model is also related to the Law of Large Numbers [7]. Agreement with a certain reliability estimate, or failure rate could be made arbitrarily close to some predetermined value by making "n" sufficiently large.

The mechanics of the subject model framework does not resemble any of these to any significant degree, since what is strived for in the model at hand is an artificial population of reliability/economic indicators. A related approach was used by the author in structuring a model for learning [3]. This model does bear a strong methodological similarity, as well as a theoretical commonality based on the aspect of complexity, which is the nemesis of both reliability and learnability.

SECTION V. DISCUSSION

In the previous section the suggested model approach was described in sufficient detail to permit a potential user to assemble his own model. The level of detail, however, was not sufficient to permit a "cook-book" style mimicry of the methodology. This was no oversight, since such procedures are not in keeping with the intent of this document.

In the past, many questions have been raised concerning the relationship of reliability with other systems engineering specialty factors such as

safety and quality. These disciplines both have many subelements which either overlap, or have at least the common bond of purpose. In other words, many of the things that are done in the name of quality, such as inspection, and/or traceability also tend to provide a more reliable product. Similarily, in the safety area, hazard analysis, or the requirement for fail-safe design features, also tends to provide a product which is not only safer, but more reliable. Indeed, there are many instances where it is almost impossible to separately classify a product improvement as being specifically for either quality, safety, or reliability, since, usually, an improvement involves all of them. Recently, the term Product Assurance has been used to include the effects of Safety Assurance, Reliability Assurance, and Quality Assurance. A functional tree diagram (see Figure 4), has been included to indicate the relationships of these three important specialty factors, as well as illustrate the model-building approach for Reliability Assurance. Although not specifically indicated in the diagram, a further expansion of the functional CER could be made at the level indicated by such subcategories as test, design inputs, analysis, etc. Depending on the availability of data, and, of course, on the need, this same approach could be continued to even the next lower level of detail. For example, under the Test category we could track the influence of material testing on the cost of reliability, or the relationship of systems check-out to the cost of reliability improvements. If the same approach is maintained throughout, it will be possible to assemble a compatible set of influence factors, each of which will explain some factor, or subfactor, or sub-subfactor of the cost sensitivities in Reliability Assurance. Eventually, a computerized version of the model can be assembled with no extreme difficulty. This would apply not only to the particular problem at hand (Reliability Assurance), but also for the higher level Product Assurance model. Premature attempts to computerize these models before they are definitized and operational, can only lead to a waste of resources.

Recently, much attention has been given to a reliability-related term called Man Rating. A particular reference was made to this aspect during a meeting of a House Committee on Science and Astronautics, June 15-17, 1971 [5]. In this meeting the following statement was made relative to man-rating costs, quote: "For example, the cost of a Titan II, modified for Gemini, including the addition of redundant flight control systems and man rating, increased from $5 million for a standard vehicle to an average of $23 million". A public relations handout [6] entitled "Man-rating the Gemini Launch Vehicle" characterized man-rating as "... an awesome task, requiring the support and contributions of personnel in many specialties". The company attributed involvement of personnel in practically all aspects of operations, logistics, quality, manufacturing, test, and design as being involved in man rating. The firm also listed a design configuration change in addition to redundancy, namely the Malfunction Detection System (MDS).

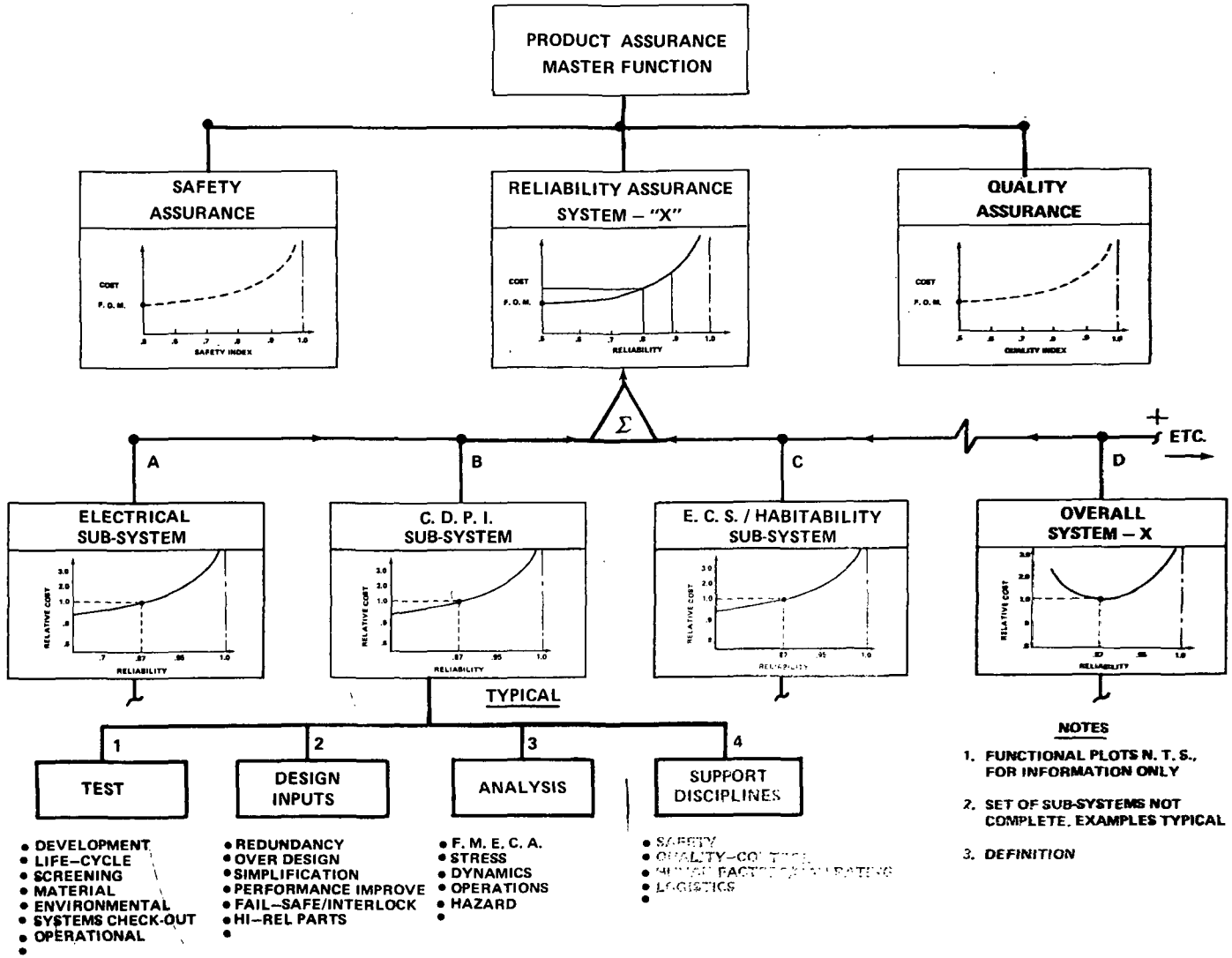

Figure 4. Cost-Model relationships.

One of the key aspects stressed in the discussion of the MDS is the feature that, based on the information provided by the special Malfunction Display Panel, made it possible for crew members to become in reality a part of the "loop". They could use such information in deciding whether to abort all, or part, of the mission in the interest of personal safety, or to prevent possible damage to the equipment. Its contribution to the increase in cost no doubt was sizeable, but the recognized increase in overall Product Assurance could justify the addition of such a system to the design configuration. As may be observed by reference to the points made above and also to other sources, man rating is a rather loose term which is defined in several ways, and can mean many different things to different people. (See Glossary for comparison). Without resorting to a detailed cost-effectiveness analysis, it is perhaps permissible to comment that sometimes quite sizeable increases in the cost of Reliability and/or Product Assurance might eventually become quite reasonable when compared with the potential failure of a major space venture.

SECTION VI. CONCLUSIONS AND RECOMMENDATIONS

A. Conclusions

1. The use of CERs as a tool in estimating iterative trade-offs of various system specialty factor values versus system costs is a necessary approach.

2. The necessary CERs can be established, provided sufficient data is made available to build these functions.

3. Assuming the above conclusions can be fulfilled, it should be possible to subsequently build system-oriented Reliability Cost-Models.

4. Such models should permit management executives, analysts, et al, to forecast the change in reliability estimates by variations in the volume of resources allocated to reliability. Another way of saying this would be: Model users should be able to predict the marginal effect on the reliability of a system from either increases or decreases in the allocated resources.

5. Although many strategies are available to the decision-maker seeking to iterate the reliability of a system (see Figure 1), those approaches which lend themselves to discrete measurement should be given priority over the soft or indirect methods.

6. Previous methodologies for making work breakdown structures (WBS) do not readily lend themselves to generation of the needed data to support the subject model. A WBS standard procedure is urgently needed.

7. Irrespective of existing problems, the subject proposed model format does satisfy the intent of the objectives as outlined in Section II.

8. The relationships which are depicted graphically in Figure 4 indicate the flexibility and universality of the model concepts described herein and also in a previously published dissertation on applied learning theory [3].

9. The expansion of the model concepts to include the higher level systems specialty factor of Product Assurance appears to be a logical next stop. Prediction models for other systems specialty factors appear to be completely feasible.

10. At present there are no known technical reasons to prevent an operational Reliability Cost-Model from being assembled.

11. Problems in systems engineering have occurred in the past and will presumably continue because of a tendancy to view systems specialty factors in a non-hierarchial and/or synecdochical manner. System elements which are subordinate to other elements are frequently treated as equal, or superior, to such items. Quite frequently also, an approach is taken whereby the natural overlap between Safety, Reliability, and Quality Assurance is not recognized as such (See Figure 5).

12. The modeling concepts outlined herein and in Reference 3 provide a response to the subject modeling problem, but, more importantly, also show the way to a family of models having a broad and generalized scope of application. Practical applications of these models should be both simplistic and cost-effective, because hand solutions can generally be used efficiently. Computerization is possible, but not essential, for most situations.

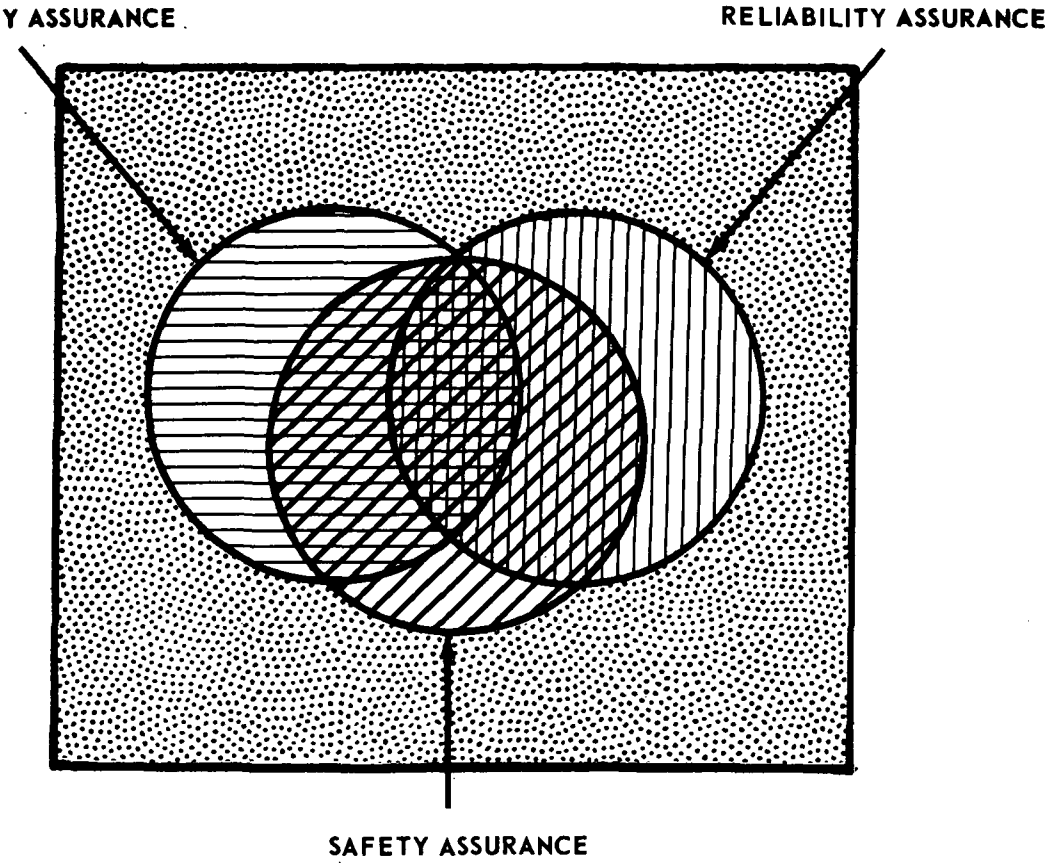

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Figure 5. Product Assurance Venn diagram.

B. Recommendations

1. A follow-on effort should be initiated to assemble a demonstrational Reliability Cost-Model based on the information and guidelines presented in this document.

2. Another follow-on project is suggested to define the model-elements for a Product Assurance Cost-Model as suggested in previous sections.

3. Further study should be initiated to define the necessary and sufficient criteria for the Completely Generalized Model, as outlined briefly above. The applicability of this proposed model would be extendable to virtually all areas of parameter/factor analysis.

4. Also, an activity should be initiated to formulate an algorithm/procedure for WBS, since relevant cost-experience data cannot be recorded without a logical cost structure.

5. Consideration should be given to the proposition of a pilot project involving hardware, which would permit iterations of reliability cost-parameters under closely controlled conditions.

6. A companion effort should be generated to collect the necessary cost data to build CERs for the demonstrational model.

APPENDIX A

GLOSSARY OF KEY TERMS

1. CER — This acronym represents the words Cost Estimating Relationship(s). CERs are usually displayed as functional curves (see Figure 2), although a tabular format may be utilized. In either case, cost is referenced to some system performance/design parameters, or system specialty factors, such as weight, power, volume, thrust, impulse, reliability, durability, maintainability, etc. Such functions are used in making estimates, forecasts, predictions and the like, but are not usually considered precision measures of either. CERs are not recent inovations, since cost estimating relations based primarily on weight have existed for many years. Volume and power were also used to a somewhat lesser extent.

2. Complexity Function (CF) — This term refers to approximate relations, emperically relating complexity to some other parameter, such as cost or reliability. In general, such functions depict reliability decreasing, and cost increasing as the complexity of a system or design increases.

3. Cost Figure-of-Merit (CFOM) — This term represents a multiplicative parametric value which is created by adding the logarithms of the various cuts taken from each of the selected CERs in the Established System Set (ESS). Since each group of cuts for the ESS is made at a specific reliability value, it is therefore possible to plot CFOM against reliability and thus create an overall or master cost function for the system. An illustrative example of such a function is shown in Figure 3.

4. CTR — This acronym represents the words Cost Trade Relationship(s). CTRs are usually displayed as functional curves, although the information may also be presented in a tabular format. As implied, the CTR is used generally as a tool in making trade studies. Such factors as power requirements, R and D cost, weight, volume, etc., are used to generate CTRs such that technical requirements and/or mission objectives can be optimized, or at least logically specified in systems planning exercises. A typical approach would be to relate weight, volume, or power for a subsystem versus the performance of the subsystem or system in order to select a cost-effective combination of design criteria. CTRs are frequently used to provide inputs to the CERs.

5. Design Complexity (DC) — This form of complexity has to do with features or parameters of an engineering design which contribute to its complexity. Examples of such features which tend to increase the measure of design complexity are such aspects as total number of parts, number of fasteners, or number of subassemblies. Others might be the number of different steps or processes required to fabricate, assemble, and inspect.

6. Design Configuration Type (DCT) — A Design Configuration Type is a term used to designate a category or generic class of system configurations for which both the technical and cost parameters could be expected to be typical. When estimating costs of large systems, example DCTs would be solid propellant boosters, nuclear-powered submarines, army tanks, or jet airliners. Such examples represent rather distinct examples of large system types, each of which is made up of a unique set of subsystems and hardware components.

7. Established System Set (ESS) — This term refers to a group or set of cost sensitive subsystem CERs which has been selected as representative of the overall system (Design Configuration Type, DCT). Each cost model will have a characteristic ESS, depending not only on the unique set of subsystems involved, but also on the type of design configuration involved; e.g., electronic, mechanical, power supply, etc.

   A typical ESS might be a group of CERs for the following: electrical power, mechanical guidance and control, and environmental control subsystems.

8. Factor — This term can be considered a synonym of parameter as far as this research is concerned.

9. Figure of Merit (FOM) — This term can be considered a numerical performance rating which is a measure of the relative performance of a system or design. Term is usually dimensionless or is considered so in its applications to decision theory.

10. Learning Curve (LC) — A learning curve is a graphical plot on either Cartesian or on double logarithmic paper, which represents the rate of learning progress by humans, usually in performance of some task or group of tasks. In the engineering discipline this plot is usually made with time as the ordinate parameter, and number of units complete or simply number of units as the abscissa. In general, these curves will aproximate an exponential-shaped function, if the progress is normal. This function should be separated from progress and improvement functions by the fact that only human learning progress is to be included in a learning curve; not tooling, design, or other gains in performance, which may be a part of progress or improvement functions.

11. Log-Linear — This term is often used to describe learning curves which are plotted on double-logarithmic paper. In general, such curves will appear as straight lines. This greatly simplifies computation of the slope, and will, of course, make these curves easier to plot.

12. Man Rating — Man Rating is defined as the philosophy and plan for marshalling the disciplines necessary to achieve a satisfactory probability of crew survival. It can be seen that achieving a satisfactory level of crew survival requires that careful consideration be given to such launch vehicle items as:

    1. Component and/or system redundancy, which can improve the reliability of the launch vehicle.

    2. Analysis of launch vehicle modes, followed by design of a reliable Malfunction Detection System.

    3. Functional utilization of the crew as part of the Malfunction Detection System.

    4. Tradeoffs in checkout philosophy, with emphasis on minimizing the probability of launching a bad vehicle.

    5. Test, countdown, and launch procedures that will maximize launching a good vehicle.

    6. Tradeoffs of system complexity versus reliability.

Man Rating requires the very best in engineering, manufacturing, test and quality control, as well as in the supporting procurement, logistics, planning, configuration control, and general management functions. Enforcement of rigid disciplines every step of the way from program inception to liftoff is mandatory.

Man Rating is a many-sided process of improving the reliability of the basic vehicle, by modifying existing systems, by using redundant components, adding special systems for crew safety purposes, special handling of critical components, meticulous selection of qualified people, and by developing procedures in the entire design-production-manufacturing-test-launch cycle that establishes, as a goal, flawless performance from the launch vehicle.

13. Maturation — This term refers to the sub-set of improvement or progress factors which relate to the segment of progress by individuals or other organisms that results from a time-related maturing or growing-up process. Maturation is not considered a normal part of learning progress.

14. Model — A Model is an approximation of reality which is frequently used to forecast or predict performance approximations of real world situations. Models may be physical or analytical within this context. Analytical models are sometimes referred to as math models, or as algorithms, which consist of a necessary and sufficient set of terms, values, and formuli needed to compute or predict an output value based on a known input or set of input values and recognized constraints or limitations.

15. Monotonic Function — This term is used to designate a mathematical function, either theoretical or empirical, which has single maximum and minimum points. If the function is an increasing function, it would be referred to as a monotonic increasing function and conversely a monotonic decreasing function. Learning curves are normally monotonic-decreasing-functions over time.

16. Parameter — For purposes of this study, the terms factor, design feature, or parameter may be used interchangeably. A Parameter is a term which is used to measure or gauge some feature or physical characteristic of a system or design. This measure is usually defined in some unit which is officially accepted, such as weight in grams or volume in cubic feet, etc.

17. Product Assurance (PA) — Product Assurance is a system specialty factor which combines several of the subfactors such as Reliability Assurance, Quality Assurance, and Safety Assurance. PA includes all activities which directly or indirectly support or increase the likelihood that a product or system will perform its intended function in accordance with established criteria, standards, specifications, or other requirements.

18. Quality Assurance (QA) — This systems specialty factor includes all those activities which may quantify the degree or increase the likelihood that a system or product will be produced and delivered such that adherence to the established criteria, standards, specifications, or other requirements will be optimum.

    Typical examples of Quality Assurance activities include inspection, qualification and durability tests, subsystem and system functional checkout, acceptance testing and statistical sampling plans.

19. Reinforcement — This term frequently appears in psychological journals and is used to infer that anything which tends to help a person to recall from memory or to accelerate the learning process, is considered a reinforcement. Sometimes reinforcements may be considered as positive or negative depending on the purpose or objective. One form of reinforcement would be to repeat a rule to a group of army recruits to assure a transfer to memory. A memorized poem may be repeated over several times by a student to reinforce the memorization of this passage.

20. Reliability Assurance (RA) — This systems specialty factor includes all those activities which quantify or increase the likehood that a product or system will perform it's intended function(s) when called on to do so. This performance must be within the established criteria, specification, or other requirement limits, either at a discrete point in time; e.g., rocket engine ignition, or for specified time intervals as posted in the requirements.

21. Safety Assurance (SA) — This systems specialty factor includes all those activities which may quantify the degree or increase the likelihood that a person, system, or product will perform the intended function(s) in such a manner that no unplanned activity or condition will cause damage, destroy, or otherwise incur harm to equipment, facilities, or persons.

22. System — A System is a planned, integrated assembly or grouping as hardware, software, and/or human elements which function as a unit to produce some specific or unique desired effect or result. A subsystem is subordinate to a system, but must meet the same definition criteria.

23. Systems Engineering (SE) — The discipline in which engineering principles are used to plan, group, design, integrate, coordinate, specify, analyze or otherwise bring together all of the elements or component parts of a system such that each element operates in unison with all other elements of the system to produce a predictable and desired effect or output when operating in a specified environment.

24. System Specialty Parameters (SSP) — Expressions of system performance variables or characteristics concerned with the overall technical effectiveness of an integrated system. System specialty parameters are used in system modeling, system trade studies, technical performance measurements, and assessments. Typical examples of specialty parameters are reliability, availability, maintainability, safety, survivability, etc.

25. Time Series — This well-known statistical analysis technique employs an artificial parameter (called Time Series) which is created from selected subfactors additively or by a multiplicative process. This macrovariable, when plotted over time, produces a trend line which is one basis for forecast or predictions of future performance.

26. Weighting Coefficients — These values are usually expressed in fractional parts and are used to transfer the desired emphasis to alternative performance ratings or estimates of value. The sum of such weights must always equal 1; if whole numbers are preferred the sum must equal 10. If there is no particular emphasis desired by the decision maker, then each alternative will receive an implied weight of one.

APPENDIX B

RELIABILITY COST-MODEL SYSTEMS ANALYSIS (APPLICABILITY)

	No.	SYSTEM ELEMENTS / PARAMETERS	ELEC/POWER	STRUCTURAL	PROPULSION	G & C, NAVIGATION	ENVIRON & LIFE SYS	COMM/DATA M.	ONBOARD TEST/CO	EXPERIMENT/INSTR	HABITABILITY	ELECT GSE	MECHAN GSE
A	1	DESIGN INPUTS											
	2	HI-REL PARTS	Y	N	N	Y	N	Y	Y	Y	N	Y	N
	3	REDUNDANCY	Y	N	N-	Y	N	N-	N	Y	N	Y	Y
	4	OVERDESIGN	Y	Y	Y	Y	Y	Y	N	Y	Y	Y	Y
	5	SIMPLIFICATION/IMPROVE.	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y
	6	SELF - TEST FEATURE	Y	N	Y	Y	Y	Y	Y	Y	N	Y	Y
	7	SELF - HEALING	N	Y	N-	N	Y	N	N	N	N	N-	N-
	8	FAIL-SAFE	Y	N-	Y	Y	Y	N	N	N	Y	Y	Y
	9	MAINTAINABILITY	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y
	10	REPAIRABILITY	Y	Y	N-	N	Y	Y	Y	N-	Y	Y	Y
	11	DEPENDABILITY	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y
	12	FOOL - PROOFING	Y	N	Y	Y	Y	Y	Y	Y	N	Y	Y
	13	DURABILITY	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y
	14	HUMAN - ENGINEERED	Y	N	N	Y	Y	Y	Y	Y	Y	Y	Y
B	1	ANALYSIS											
	2	FMEA	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y
	3	FAILURE/DISCREP.	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y
	4	VALUE	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y
	5	EFFECTIVENESS	Y	Y	Y	Y	Y	Y	Y	Y	N	Y	Y
	6	TRADE-OFFS	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y
	7	MATH MODEL	Y	Y	Y	Y	Y	Y	N	Y	N	N	N
	8	AVAILABILITY	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y
	9	SOFTWARE/PROCEDURE VERIFICATION	Y	N	Y	Y	Y	Y	Y	Y	Y	Y	Y
	10	TECHNICAL PERFORM./ SPECIFICATION COMPARISON	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y
C	1	TESTING											
	2	QUALIFICATION	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y
	3	DEVELOPMENT	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y
	4	ACCEPTANCE	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y
	5	RELIABILITY/PURABILITY	Y	N	Y	Y	Y	Y	Y	Y	N	Y	Y
	6	OPERATIONAL	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y
	7	SAFETY	Y	Y	Y	Y	Y	N	N	Y	N	Y	Y
	8	SCREENING	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y
	9	OVERSTRESS	Y	Y	Y	Y	Y	N	N	Y	N	Y	Y
	10	BURN-IN-TESTS	Y	N	Y	Y	Y	Y	Y	Y	N	Y	Y
D	1	SUPPORTING DISCIPLINE											
	2	QUALITY CONTROL	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y
	3	SYSTEMS SAFETY	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y
	4	CONFIG./SPARES - CONTROL	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y
	5	TRAIN./PERSONNEL CERT.	Y	Y	Y	Y	Y	Y	Y	Y	N	Y	Y
	6	TRACEABILITY	Y	Y	Y	Y	Y	Y	Y	Y	N	Y	Y
	7	PROCESS/OPERAT. CERT.	Y	Y	Y	Y	Y	Y	Y	Y	N	Y	Y
	8	HUMAN FACTORS/MAN RATING	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y
E	1	MOTIVATION											
	2	CONTRACTUAL RELIABILITY INCENT.	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y
	3	MANNED-FLIGHT AWARENESS	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y
	4	ZERO-DEFECTS	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y
	5	INDIVIDUAL INCENTIVE	N-	N-	N-	N-	N-	N-	N-	N-	N-	N-	N-

Notes: Y = Applicable or Relevant
N = Not Applicable
N- = Marginal or Partial

	No.	SYSTEM ELEMENTS / PARAMETERS	ELEC/POWER	STRUCTURAL	PROPULSION	G & C, NAVIGATION	ENVIRON & LIFE SYS	COMM/DATA M.	ONBOARD TEST/CO	EXPERIMENT/INSTR	HABITABILITY	ELECT GSE	MECHAN GSE	
A	1	DESIGN INPUTS												
	2	HI-REL PARTS	H	H	H	H	H	H	H	H	S	H	H	
	3	REDUNDANCY	H	S	S	H	H	H	H	H	S	H	H	
	4	OVERDESIGN	H	H	H	H	H	H	H	H	S	H	H	
	5	SIMPLIFICATION/IMPROVEMENT	H	H	H	H	H	H	H	H	S	H	H	
	6	SELF-TEST FEATURES	H	S	S	H	H	H	H	H	S	H	H	
	7	SELF-HEALING	H	S	S	H	H	H	H	H	S	H	H	
	8	FAIL-SAFE	H	S	S	H	H	H	H	H	S	H	H	
	9	MAINTAINABILITY	H	H	H	H	H	H	H	H	H	H	H	
	10	REPAIRABILITY	H	H	H	H	H	H	H	H	H	H	H	
	11	DEPENDABILITY	H	H	H	H	H	H	H	H	H	H	H	
	12	FOOL-PROOFING	H	S	S	H	H	H	H	H	S	H	H	
	13	DURABILITY	H	H	H	H	H	H	H	H	H	H	H	
	14	HUMAN-ENGINEERING	H	S	S	H	H	H	H	H	H	H	H	
B	1	ANALYSIS												
	2	FMEA	H	H	H	H	H	H	H	H	S	H	H	
	3	FAILURE/DISCREPANCY	H	H	H	H	H	H	H	H	H	H	H	
	4	VALUE	S	S	S	S	S	S	S	S	S	S	S	*
	5	EFFECTIVENESS	H	H	H	H	H	H	H	H	H	H	H	
	6	TRADE-OFFS	S	S	S	S	S	S	S	S	S	S	S	*
	7	MATH MODEL	H	H	H	H	H	H	H	H	H	H	H	
	8	AVAILABILITY	H	H	H	H	H	H	H	H	H	H	H	
	9	SOFTWARE/PROCEDURE VERIFICATION	H	H	H	H	H	H	H	H	H	H	H	
	10	TECHNICAL PERFORMANCE/ SPECIFICATION COMPARISON	H	H	H	H	H	H	H	H	H	H	H	
C	1	TESTING												
	2	QUALIFICATION	H	H	H	H	H	H	H	H	H	H	H	
	3	DEVELOPMENT	H	H	H	H	H	H	H	H	H	H	H	
	4	ACCEPTANCE	H	H	H	H	H	H	H	H	H	H	H	
	5	RELIABILITY/DURABILITY	H	H	H	H	H	H	H	H	H	H	H	
	6	OPERATIONAL	H	H	H	H	H	H	H	H	H	H	H	
	7	SAFETY	H	H	H	H	H	H	H	H	S	H	H	
	8	SCREENING	H	H	H	H	H	H	H	H	S	H	H	
	9	OVERSTRESS	H	H	H	H	H	H	H	H	S	H	H	
	10	BURN-IN TESTS	H	H	H	H	H	H	H	H	S	H	H	
D	1	SUPPORTING DISCIPLINES												
	2	QUALITY CONTROL	H	H	H	H	H	H	H	H	S	H	H	
	3	SYSTEM SAFETY	H	H	H	H	H	H	H	H	S	H	H	
	4	CONFIG./SPARES CONTROL	H	H	H	H	H	H	H	H	H	H	H	
	5	TRAIN./PERSONNEL CERT.	H	H	H	H	H	H	H	H	S	H	H	
	6	TRACEABILITY	H	H	H	H	H	H	H	H	S	H	H	
	7	PROCESS/OPERATIONS CERT.	H	H	H	H	H	H	H	H	S	H	H	
	8	HUMAN FACTORS/MAN-RATING	H	H	H	H	H	H	H	H	H	H	H	
E	1	MOTIVATION												
	2	CONTRACTUAL/RELIABILITY INCENTIVE	S	S	S	S	S	S	S	S	S	S	S	
	3	AWARENESS (e.g., MAN-FL.)	S	S	S	S	S	S	S	S	S	S	S	
	4	ZERO-DEFECTS	S	S	S	S	S	S	S	S	S	S	S	
	5	INDIVIDUAL INCENTIVE AWARDS	S	S	S	S	S	S	S	S	S	S	S	

Notes: H = Hard
S = Soft with respect to measurable affect on reliability estimates
* = Assumption made: reliability value is held constant

REFERENCES

1. Benjamin, Jack R. and Cornell, Allin C.: Probability, Statistics, and Decision for Civil Engineers. McGraw-Hill Book Co. New York, 1970.

2. Chow, Ven Te: The Log-Probability Law and It's Engineering Applications. Proceedings American Society of Civil Engineers, vol 80, New York, November 1954.

3. Delionback, Leon M.: A Design-Oriented Prediction Model for Learning Rates of Individual Mechanical Assembly Tasks. Doctoral Dissertation, Oklahoma State University, Stillwater, Oklahoma, May 1972.

4. Gukhman, A. A.: Introduction to the Theory of Similarity. Academic Press, New York, 1965.

5. Low, George M., Dr.: Mariner 8 Failure, discussed before House Sub-Committee. NASA Activities Bulletin. vol 2, no. 7, Washington, D. C., July 15, 1972.

6. Man-Rating the Gemini Launch Vehicle. Martin-Marietta, ER-12521-15, Kennedy Space Center, Florida.

7. Meyer, Paul L.: Introductory Probability and Statistical Applications. Addison-Wesley, Reading, Massachusetts, 1965, p. 43.

BIBLIOGRAPHY

Advanced Spacecraft Subsystem Cost Analysis Study. Final Report Stabilization and Control System, Honeywell Aerospace Division, December, 1969.

Allen, R. G. D.: Mathematical Analysis for Economists. St. Martin's Press. New York, First Edition, 1938.

Arnold, Barry C.: Some Characterizations of the Exponential Distribution by Geometric Compounding. SIAM Journal on Applied Mathematics. Ames, Iowa, September 21, 1971.

Baker, B. E.: Operational Considerations and Systems Reliability. NATO, Agard Lecture Series no. 47, Reliability of Avonics Systems. Rome and London, 1971.

Bartholomew, C. S.: Reliability and Program Decision Making. Proceedings of Annual Symposium on Reliability. Washington, D. C., 1967.

Benware, L. T.: Cost Versus Reliability Tradeoff. Proceedings of Annual Symposium on Reliability. Washington, D. C., 1967.

Blanchard, Benjamin S., Jr. and Lowrey, Edward E.: Maintainability. McGraw-Hill Book Company, New York, 1969.

Borchers, C. R. and Churchill, R. E.: System Design Tradeoffs and Economic Planning. IBM Corporation. Owego, New York.

Brigham, Peter B.: Realistic Reliability for the Cost Conscious Program. Proceedings of the National Symposium on Reliability. Boston, Ma., 1968.

Bussolini, J. J.: Methods of Specifying and Controlling Design Reliability. NATO, Agard Lecture Series no. 47, Reliability of Avionics Systems. Rome and London, 1971.

Carey, Frank R.: System Reliability Cost Trade-Offs Methodology. 10th Annual West Coast Reliability Symposium. Los Angeles, Ca, February, 1969.

Carter, A. D. S.: Mechanical Reliability. John Wiley and Sons, New York, 1972.

Chestnut, Harold: Systems Engineering Methods. John Wiley and Sons, Inc., New York, 1967.

Chisholm, Roger K. and Whitaker, Gilbert R., Jr.: Forecasting Methods. Richard D. Irwin, Incorporated, Homewood, Il., 1971.

Codier, Ernest O.: Reliability Growth in Real Life. Proceedings of the National Symposium on Reliability. Boston, Ma., 1968.

Colandeive, B. T.: Program Costs versus Reliability. Proceedings of the National Symposium on Reliability. 1964.

Cost-Benefit Analysis. American Elsevier Publishing Company, Inc., NATO Scientific Affairs Committee, New York, 1971.

English, J. Morley: Cost Effectiveness. John Wiley and Sons, Inc., New York, 1968.

Fisher, Gene H.: Cost Considerations in Systems Analysis. The Rand Corporation and American Elsevier Publishing Co., New York, 1971.

Goldman, A. S. and Slattery, T. B.: Maintainability: A Major Element of System Effectiveness. John Wiley and Sons, Inc., New York, 1964.

Grouchko, Daniel: Operations Research and Reliability. Gordon and Breach, Science Publishers, New York, 1971.

Guide for Reviewers of Studies Containing Cost-Effectiveness Analysis. Research Analysis Corporation, McLean, Va., July 1965.

Hecht, Herbert: Economic Formulation of Reliability Objectives. 11th Annual West Coast Reliability Symposium. Beverly Hills, Ca.. May 1970.

Heiss, Klaus P.: Our R & D Economics and the Space Shuttle. Astronautics and Aeronautics. Philadelphia, Pa., October 1971.

Hevesh, Avery H.: Cost of Reliability Improvement. Proceedings of the National Symposium on Reliability. Chicago, 1969.

BIBLIOGRAPHY (Continued)

Hinley, J. T. and Shelley, B. F.: Reliability Optimization in the Conceptual Phase. Proceedings of Annual Symposium on Reliability. Washington, D. C., 1967.

Hunter, Maxwell W., II; Miller, Wayne F. and Gray, Robert M.: The Space Shuttle Will Cut Payload Costs. Astronautics and Aeronautics, vol 10, no. 6. Philadelphia, Pa., June 1972.

Hymans, Saul H.: Probability Theory. Prentice-Hall, Inc., Englewood Cliffs, N. J., 1967.

Ireson, W. Grant: Cost Data-Collection and Use. Symposium on Reliability Proceedings. San Francisco, Ca., 1966.

Jacks, Herbert G.: The Reliability of Long Life Repairable Equipment. 10th Annual West Coast Reliability Symposium. The Reliability Division. Los Angeles, Ca., February 1969.

Kettelle, J. D., Jr.: Least Cost Allocation of Reliability Investment. Journal of Operations Research Society, vol 10, no. 2. March-April, 1962.

Kivenson, Gilbert: Durability and Reliability in Engineering Design. Hayden Book Company, Inc., New York, 1971.

Landers, Richard R.: Reliability and Product Assurance. Prentice-Hall, Incorporated. Englewood Cliffs, N.J., 1963.

Leve, Howard L., Dr., and Platte, Maurice M.: Effects of Reliability Variations on System Cost. Symposium on Reliability Proceedings. San Francisco, Ca., 1966.

Lifson, Melvin W.: Decision and Risk Analysis. Cahners Books, Boston, Ma., 1972.

Misra, Krishna B.: Reliability Optimization of a Series-Parallel System. IEEE Transactions on Reliability, vol R-21, no. 4. New York, November, 1972.

Neuner, G. E. and Miller, R. N.: Effectiveness Evaluation Using Dynamic Programming. Proceedings of the National Symposium on Reliability. Boston, Ma., 1968.

Nowlan, F. S.: The Relationship Between Reliability and the Periodicity of Scheduled Maintainance. 5th Annual West Coast Reliability Symposium. Los Angeles, Ca., February, 1964.

Pett, Martin T.: The Effect of Value Engineering on System Reliability. 10th Annual West Coast Reliability Symposium. Missile Systems Division. Los Angeles, Ca., February, 1969.

Pieruschka, Erich: Principles of Reliability. Prentice-Hall, Inc., Englewood Cliffs, N. J., 1963.

Rau, John G.: Optimization and Probability in Systems Engineering. Van Nostrand Reinhold Company, New York, 1970.

Reliability Assurance Provisions for Government Agencies. NASA, MSFC S & E-QUAL 5320. Redstone Arsenal, October, 1972.

Rivett, Patrick: Principles of Model Building. John Wiley and Sons, London, 1972.

Salating, Nicholas and Feistman, Myron: Cost Effectiveness via Weighted Factor Analysis. Proceedings of the National Symposium on Reliability. Chicago, 1969.

Sasaki, M.: Slide Methods for Redundant Mission Availability. Proceedings of the National Symposium on Reliability. Chicago, 1969.

Scarlett, Neil J.: Reliability Tradeoffs During Concept Formulation. Proceedings of the National Symposium on Reliability. Boston, Ma., 1968.

Seiler, Karl, III: Introduction to Systems Cost-Effectiveness. Wiley-Interscience, New York, 1969.

Starr, Martin Kenneth: Product Design and Decision Theory. Prentice-Hall, Inc., Englewood Cliffs, N. J., 1963.

BIBLIOGRAPHY (Concluded)

Tall, M. M.: Relationships Between Program Test and User Support Costs. NATO, Agard Lecture Series no. 47, Reliability of Avionics Systems. Rome and London, 1971.

Taylor, Ervin F.: Reliability: What Happens If ... ? Proceedings of the National Symposium on Reliability. Chicago, 1969.

Weiden, van der H.: Status on Reliability in the Netherlands. Proceedings of the National Symposium on Reliability. Boston, Ma., 1968.

Wylie, Jack E.: The Optimization of Systems Reliability. Symposium on Reliability Proceedings. San Francisco, Ca., 1966.

Younger, George O.: A Method for Reliability-Cost Trade-Off Analysis. Proceedings of Annual Symposium on Reliability. Washington, D.C., 1967.

APPROVAL

PROPOSED RELIABILITY COST-MODEL

By Dr. Leon M. Delionback

The information in this report has been reviewed for security classification. Review of any information concerning Department of Defense or Atomic Energy Commission programs has been made by the MSFC Security Classification Officer. This report, in its entirety, has been determined to be unclassified.

This document has also been reviewed and approved for technical accuracy.

LUDIE G. RICHARD
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