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Final Report | *March 15, 1961 to October 15, 1962*

A SURVEY AND EVALUATION OF HIGH ENERGY LIQUID CHEMICAL PROPULSION SYSTEMS

PART I: PROPELLANT SELECTION CRITERIA FOR SPACE MISSIONS

Prepared for:

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION
WASHINGTON, D.C.

CONTRACT NO. NASr-38

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ABSTRACT

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This report presents the results of a study to develop a procedure for evaluating liquid propellants in order (a) to select the most appropriate propellant (from among those under development) for each of several applications on each of the various missions in the NASA program, or (b) to select new propellants (from among those being proposed) for initiation or continuation of research and development.

The analysis begins with a consideration of requirements--either for the specific application or for the various classes of applications. The known characteristics of the propellant or propellants to be evaluated are then put into a convenient form for evaluation. The next step is to determine whether or not there are requirements that simply cannot be met by the propellant. If the propellant passes this test, an optimum vehicle configuration using the propellant (and meeting all requirements) is estimated. (The configuration should be optimized with respect to the total resource consumption for all aspects of the mission, including R&D, production, logistics, and operation.) The total resource consumption for this configuration is then compared with that for similar configurations using other propellants (and meeting all requirements equally well). If all factors have been properly taken into account, this comparison of resource consumption will complete the evaluation.

Such an evaluation may be performed several times, in increasing detail and with correspondingly increasing accuracy, as an R&D program proceeds, and the accuracy of the data as well as the cost of the next step in the program increase. The procedure is superior to those in common use in that it minimizes both the amount of analytical work and the number of points at which subjective value judgments are made.

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I INTRODUCTION

In the last two decades many sources of energy for missile propulsion have been investigated or proposed. These have been classified into chemical, nuclear, and electrical types. Chemical sources have commonly been subdivided into solid and liquid propellants.

While it is expected that prototype nuclear propulsion systems will be available in the near future--practical systems for major applications are predicted within the decade--rocket power currently is derived solely from chemical propellants. Some of the more significant variables which influence choices between the two types of chemical propulsion systems for specific applications are: simple, reliable, and relatively low-cost mechanical components, plus convenient, dependable storage and handling characteristics for solid propellants; high specific impulse, low propellant cost, low hardware to propellant weight ratio, and versatility in thrust control for liquid propellants. The ranges of the various characteristics of solid propellants generally overlap those of liquid propellants, and compensating differences in characteristics tend to narrow the performance differences between the two propellant types; however, as mission requirements for higher total velocity changes are encountered, high specific impulse becomes a controlling characteristic. For this reason the NASA space program for 1960-70 is emphasizing the development of liquid chemical systems for rocket propulsion. Beyond this period, developments in nuclear and other new systems will doubtlessly affect the competitive position of liquid chemical propulsion systems.

The current interest in liquid propellants has created an urgent need for a reliable, accurate, and convenient method of evaluating the relative merit of liquid propellant combinations. Such evaluations must be carried out many times during the development of a propellant combination, from preliminary studies to actual use in a specific mission. Three variants of the basic evaluation problems which occur at successive stages are:

(1) Identification of potential applications for new propellant combinations, by comparison of the new combination with the best existing one for each application.

(2) Assessing what effect improvements in the characteristics of a propellant combination or of engines using it, or improvements in the accuracy of the information available on such characteristics, would have on the competitive position of the propellant combination.

(3) Selecting the best available propellant combination for a given application in a specific mission.

The same basic method may be used for these variants; however, the amount of detail and the accuracy of the details will differ.

NASA requires an evaluation program which ensures the development of appropriate liquid propellants and their assignment to applications in a manner that minimizes the total resource consumption of the whole NASA space program. Hence, the evaluation procedure must give a complete picture of the applications for which various propellants are technically suited and the resources consumed in developing and applying each propellant for each application. This must be done assuming the use of the propellant in various combinations of applications, since the over-all level of usage of a propellant will influence the desirability of using it in any given application.

It would be extremely convenient if liquid propellant combinations could be rated by a measurable characteristic or simple combination of characteristics. The theoretical specific impulse, I_{sp}--the thrust, in pounds force, theoretically obtainable from the propellant burning at the rate of one pound mass per second--has been widely used as an index of propellant performance. However, such a practice ignores the effect of the hardware ratio--the ratio of the propulsion system weight, including residuals, at burnout to its weight, including full propellant load, at ignition. To a rough approximation, this effect can be taken into account by using the volume specific impulse, $I_{sp}d$--the thrust, in pounds force, obtainable from the propellant burning at the rate of one cubic foot per second--and somewhat more accurately by using a modification of this, $I_{sp}d^n$, where n is an exponent whose value varies between zero and unity depending upon the application. However, such an index cannot be an infallible guide, even when applied to a single application for a specific mission, since it ignores many factors that have a significant bearing on performance. Furthermore, performance is not the only important consideration in evaluating a propellant, and its relative importance varies with the application. Inasmuch as no index based solely on measurable characteristics of the propellants will be appropriate as an indicator of merit for the gamut of applications, missions, and schedule of usage which may develop within the NASA space program, it is necessary (1) to find some rating basis which takes into account all factors related to the propellant components, the propulsion system, and the planned space missions which could influence the technical and economic feasibility and efficiency of the NASA space program, and (2) to integrate the data so that a comparison of competing systems can be made with a minimum of effort and with all of the assumptions on which the comparisons were drawn clearly evident.

Further consideration of this problem has led to the conclusion that in the ultimate analysis the most desirable propellant combination for a given application is that which satisfies all specified requirements when used in the application and which also results in the lowest total consumption of resources for the complete NASA space program. Therefore, the Comparative Total Resource Consumption (CTRC) is proposed as the basis for comparison of competing propellant systems.

For this criterion to have meaning, all factors which can influence CTRC differentially as a function of the choice of propellant must be either explicitly specified or accepted as being of no concern to the user.

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II EVALUATION PROCEDURE

A. Method of Approach

Evaluation of the comparative merit of any system involves:

1. Compilation of available pertinent information on the functions to be accomplished and on the capabilities and characteristics of proposed alternative solutions.

2. Reduction of this information to a form that permits comparison of capability vs. requirement and the elimination of deficient solutions.

3. Selection of a criterion of merit.

4. Calculation of value of criterion for each proposed solution.

5. Rating solutions in order of values of criterion.

If the input information is complete and accurate, this process is straightforward. However, if fixed values of either requirements or capabilities are not fully available (this is usually the case), the results are less clear cut. For inexact or doubtful inputs, best estimates of a range of values must be used; the evaluation then gives not a simple rating according to a selected criterion, but a range of values for each proposed solution. These ranges of values may still permit the desired degree of comparison to be accomplished. If this is not true, the evaluation problem no longer is simply to compare the merit of alternative systems but entails comparing the validity of input information or generating more exact data.

The evaluation process must:

1. Provide a criterion of merit for comparison.

2. Identify pertinent input information so that errors of omission do not occur and time is not wasted on irrelevancies.

3. Establish procedures for condensing information to a minimum of comparative factors.

4. Organize the data to reveal the assumptions on which the evaluation is based and the relationship of input data to the various evaluative factors.

5. Minimize the effort to arrive at the desired conclusions.

The basic outline of the propellant evaluation procedure that has been evolved to accomplish these objectives is given in Chart I. This chart shows the procedure recommended for carrying out the over-all evaluation of liquid propellants to meet the requirements of the NASA space program. The chart describes a multiply iterative process in which a minimum-cost propulsion system using each propellant is designed for each application in which the propellant could be used, and then that combination of systems is found which results in the minimum total program resource consumption for all applications.

B. Description of Procedure

The complete analytical procedure for an individual propellant is shown in Chart II* and the various steps are described in the following paragraphs of this section. (Modifications to adapt it to particular types of problems are discussed in Section II C.)

1. Assembly of Input Information

a. NASA Requirements and Specifications

This category consists of the available information on the need for propulsion systems by the NASA space program and the specifications, restrictions, and requirements pertaining to them. The types of information which are pertinent to the evaluation are tabulated under the heading "NASA Requirements and Specifications" in Chart IIc and are described and discussed in detail in Section III of this report. Since there is a different set of requirements and specifications for each of the several different uses of propulsion systems, the information is organized according to application except for items which are applicable

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* For convenience, Chart II is presented in three parts, a, b, and c.

to all or to a wide variety of uses. When selecting the best available propellant combination for a given application, only those items of data related to that application will be of interest.

b. Propellant Characteristics, Performance, and Cost Data

This category consists of the propellant characteristics, performance, and cost data. The pertinent items required are listed under this heading in Chart IIa.

2. Comparison of Requirements and Capabilities, and Identification of Deficiencies

To the extent that requirements for propulsion systems have been fixed, an immediate comparison is made between the requirements and the capabilities of the prospective propellants. Propellant combinations which cannot fulfill the requirements can then be eliminated with a minimum of wasted effort.

In most instances the form of the basic input information on the capabilities of the propellant combination will not be such that a direct comparison can be made with stated requirements. More frequently a number of pieces of input data must be used to derive a comparative parameter by computation or judgment. The general nature of the comparative parameters and the input data from which they are derived are shown in the chart. The specific nature of the parameter can be determined only after the form and dimensions of the requirement have been established. These parameters are 1) storage life, 2) corrosion and compatibility, 3) pollution, contamination, and personnel safety, 4) thrust application and control, and 5) availability. They are discussed in detail in Section IV of this report.

To the extent that requirements are established as a function of application of the propulsion system, the comparison of capability with requirement must follow this pattern. Where the propellant capability is found not to meet the requirement, the propellant combination is rejected as a candidate for the application covered by the requirement.

Where the requirement can be met only by incurring some penalty in weight or in resource consumption, the propellant is not rejected; the effect of the penalty will be assessed in later stages of the evaluation.

3. Tabulation of Potential Applications of Proposed Propellant Combinations

For a propellant combination not totally eliminated in step 2, a tabulation is made of the applications from which it has not been eliminated. The converse of this tabulation--propellants which are not eliminated for a specific application--will be generated if the evaluation problem is a search for propellant combinations for an application rather than evaluation of the use potential of a propellant combination.

4. Selection or Construction of Representative Examples of Each Potential Application

For each type of application for which the propellant is potentially a candidate there will normally be a plurality of missions differing in payload, ΔV (velocity change), and thrust level requirements. To reduce the evaluative effort required, a minimum number of typical missions should be selected (or representative missions constructed) whose characteristics bracket the range of characteristics of these potential missions. (Obviously, this step would be omitted when evaluating various propellants for an application in a specific mission.)

5. Determination of Component Weights of Optimum Propulsion System

For each application of the propellant in each typical or representative mission identified in step 4, the design weight of the optimum propulsion system must be calculated. Accomplishing this will require that the attainable specific impulse of the propellant be obtained.

Where the propellant is proposed for a major application of a mission requiring a multistage vehicle an iterative optimization procedure involving the results derived in succeeding steps of the evaluation may be required to obtain the optimum design of the component systems. An example of this procedure is contained in the Appendix. The calculations involved in this step will be made in much more detail when choosing propellants for a specific mission than when searching for possible uses for a new propellant.

6. Total Hardware Weight and Propellant Usage

From the design data compiled in step 5, the size, weight, number, and kind of units for the total program using the proposed propellant are calculated, and the total proposed usage of propellant is calculated.

7. Estimation of Costs

From the weights obtained in step 6, the input mission schedules from Requirements Chart and the input cost data from Propellant Characteristics, Performance and Costs Chart, the total program hardware costs are calculated. For applications other than earth launch vehicles the program costs must include an item for delivery to the point in space at which the propulsion system is to be used.

Propellant costs for the total program are calculated from weights, schedules, and input data as with hardware. Again, for applications other than earth launch vehicles the mission costs include an item for delivery to the point of use.

Total development costs are compiled from the input data on component development costs, the schedule and reliability specifications, and hardware and propellant design weight data. This is the only place in the evaluation procedure where the effect of performance reliability is introduced. It is obvious that for valid comparisons among propellants, costs must be calculated on the assumption that a minimum specified reliability of operation must be demonstrated before development is considered complete.

Operating costs are a summation of the input data under launch operations.

8. Summation of Program CTRC

The goal of the primary evaluation process is to determine the total resource consumption involved in the space program when the candidate propellant system is employed. This total is obtained by summing the costs determined in step 7.

9. Identification of Sensitive Parameters

In the usual evaluation problem, many parts of the input information cannot be fixed quantitatively. An estimate of the most probable value or the average of an expected range of unfixed inputs will be used in the initial calculation of CTRC. If the CTRC value obtained in the primary evaluation is not judged to be excessively unfavorable, CTRC values are computed using, in turn, extreme values of one uncertain input with most probable or average values of all other uncertain inputs. From the values of CTRC so obtained, the parameters to which CTRC is appreciably sensitive are identified.

10. Assessment of Propellant Merit

CTRC values are then calculated for a matrix of sensitive parameters varied over reasonably probable ranges. The merit of the propellant combination is assessed by a comparison of the CTRC values so obtained with those similarly obtained for competing combinations. If the CTRC values do not support a firm conclusion, the parameters which contribute to the uncertainty are identified, and the problem of propellant evaluation must then be deferred until the uncertainty of the sensitive input parameters can be reduced.

C. Adaptation to Particular Types of Problems

The procedure outlined in the preceding section is designed to identify information pertinent to the evaluation of a propellant combination and to provide an order of procedure to consolidate the information into comprehensible form for comparison of the relative merit of competing combinations. As presented, the scheme of evaluation is designed to cover the analysis of a propellant combination proposed for any or all applications on any or all missions of the NASA space flight program. Not all propellant evaluation problems will be of this type. Another type of problem is the selection, from among available combinations, of the most advantageous one for a specific application on a specific kind of mission. Still another is a partial comparison where the desire is to assess the effect on CTRC of an altered characteristic (either actual or the effect of improved information) of a propellant relative to the unaltered material, or to assess the relative advantage achieved by some technological advance in materials, design, or knowledge of space environment.

The advantage of the procedure as outlined is that suitable variations make it applicable to all of the cases mentioned. It is clear that to select the existing combination that is best suited to a particular application on a specified kind of mission, only the input data pertinent to the one mission of interest must be processed. (There is a potential pitfall in this approach for major propulsion systems on types of missions where numerous launches are planned. The selection of a propellant for one application may improve its competitive position for all other applications for which it qualifies. If a propellant has several potential applications and is the logical choice from among the available systems for most of these applications, it may also be the logical choice for an application in which it does not rate highest when that particular usage is considered separately. Thus, strictly speaking, it is not safe to evaluate propellant combinations only for a specific mission or application. For first approximations it is a justifiable short cut, however.)

To assess the effect of a changed characteristic or an information or technological advance, the CTRC values for the original conditions are, of course, required as a reference standard. It is then necessary to calculate only the difference in CTRC which the changed condition produces, which usually will be much less work than the original CTRC calculation.

Since the difference in CTRC required to effect a change in the order of rating of the existing systems is known, a further short cut may become evident by an analysis of the maximum possible effect on CTRC of the changed condition. As an example, if the changed condition is a reduction by half in the price of a propellant and the propellant cost item in the base CTRC calculation is only 10 percent of the total, it will be immediately obvious that the rating order of the competing systems can change only among those which differ initially by less than 5 percent.

It is obvious that in many instances much of the input data will not exist at the time when the results of the evaluation are desired, or will exist only in the form of estimates of variable or unknown accuracy. This necessitates making preliminary evaluations on uncertain evidence which may be dependable only in revealing gross differences. If and as research and development on the propellant is continued, available information will become more accurate and complete, and periodic calculations and re-evaluations will possess the increasing accuracy required in decisions to commit larger sums of money to the program. In each re-evaluation, a check is first made to determine whether or not the propellant meets fixed requirements. If it passes this test, a check is made to determine whether it is superior to the best otherwise propellant in all respects or not. Only if the issue is then still in doubt, is it necessary to carry out the more laborious calculations of optimum configurations.

D. Comparison with Other Approaches

Much propellant evaluation work has been done by many organizations using many methods. The methods that have been and are being used generally differ from the method outlined in this report in the choice of a basic evaluation criterion, of the factors to be considered, and/or of the manner in which they are taken into account.

As has already been indicated, many evaluations are based solely upon performance or some factor indicative of performance. This is undoubtedly a quite valid criterion for some applications, in which the cost of delivery of the propulsion system to the point of use is large compared with the cost of the propulsion system itself. On the other hand, as is coming to be accepted, for earth launch boosters the cost of a propulsion system of a given capability is more important than its weight, and many evaluators recognize that for large systems this is also true for second and perhaps even third stages. It is also increasingly recognized that other factors such as reliability and safety may be very important. However, when these additional factors are considered, they are generally taken into account by arbitrarily choosing a weight coefficient for each factor, rating a propellant with respect to each factor (usually on an arbitrary one-to-ten scale for those factors that are essentially qualitative rather than quantitative in nature), and obtaining a merit rating as a sum of products of weight coefficients and rating values. All too frequently these arbitrary choices are made by the evaluator in the middle of the evaluation procedure, and neither the nature of the subjective judgments nor their effect on the results is made clear to the prospective user of the results.

It is this subjectivity, together with a failure to take into account all of the important factors, which leads to the wide variation in merit ratings assigned to the same propellant by different evaluators and thus to serious doubts as to the validity of such merit ratings. In the procedure outlined in this report each factor is taken into account either by specifying a value for it as an absolute requirement at the start of the evaluation or by seeking the value that will minimize CTRC. This places the responsibility for making any arbitrary decisions where it belongs--that is, on the persons who specify requirements and use the results, rather than on the persons who make the evaluation.

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III NASA REQUIREMENTS FOR PROPULSION SYSTEMS

The proposed evaluation process judges the merit of propellant systems on their applicability to a postulated program of space activity rather than on the individual propellant's performance characteristics. Thus a prerequisite is knowledge of the nature and scope of NASA goals in space activity involving the use of liquid propellants. A most desirable simplification would be the assumption that these goals exist as a fixed and knowable reality. It must be accepted, however, that such is not, and cannot be, the case. It is recognized that what is planned today for ten years hence is subject to cancellation, revision, reduction, postponement, or expansion as the result of a multitude of unpredictable factors--available budget, technological progress, accident, political expediency, changing scientific values. Furthermore, the NASA liquid propellant programs constitute only one of several approaches to propulsion problems, and progress on any of the others will affect decisions on the liquid propellant programs. The rate of progress in solid propellant, nuclear, and ion propulsion systems can have a strong influence on the evaluation of liquid propellants for NASA space programs.

Despite these complicating factors which make it impossible to anticipate reliably the time, scope, and character of NASA space activity, it is considered appropriate and desirable to predicate the evaluation on the assumption of a known set of requirements and specifications for liquid propellant propulsion systems. At any point in time there are some plans being implemented, some decisions in force, some factors unplanned or undecided, which can be treated parametrically. A postulated program of propellant requirements determined by using such information should provide a basis for evaluating the merit of propellants which is far superior to any basis which ignores this available information.

This section presents a scheme of organization of the available data according to the five major applications of propellant systems: earth launch vehicles, planetary launch vehicles, lunar launch vehicles, space maneuver, and auxiliary power. This scheme was chosen since each requirement may impact entirely differently on the evaluation of the worth of a propellant depending on the proposed application. This naturally leads to considerable repetition of headings in the listing of requirements for different applications. There are, of course, considerations which apply independently of use; these considerations have also been listed for each application, which leads to some further repetition.

This section also describes in detail the information on NASA plans, decisions, and specifications required for the evaluation of proposed propellants. The inclusion of an item in this listing does not imply that NASA has or will have a requirement, limitation, or specification as listed, but it does imply that if such a requirement limitation or specification does exist, it will be a pertinent consideration in the evaluation.

The actual quantitative values for the items making up this set of input information, such as schedule and volume of usage, performance tolerances, prohibitions and specified limitations, etc., will be subject to continual modification and must be updated frequently to remain useful.

A. Earth Launch Vehicles[2,4,11]

The quantity of propellants used in earth launch vehicles is several times greater than for all other applications combined, and therefore the problem of selecting the best propellant system for this use is of major consequence. However, the importance of this problem is not necessarily in direct proportion to the quantity usage compared with other applications. This is because, under existing circumstances, the cost of propellant delivered at the use site is a much smaller fraction of the total cost for the earth launch vehicle than for other applications such as planetary launch or space maneuver.

This relatively small percentage cost of propellant for earth launch vehicles occurs as a result of very large hardware research, development, and production costs amortized over a relatively small number of launches, and the relatively minor delivery costs for the propellant for this use compared with delivery costs for space usages. For these latter applications the detrimental consequences from the choice of a propellant system that is not the best available may be greater than for a similar error for an earth launch vehicle in spite of the latter's larger usage of propellant. Thus, in spite of the quantity of propellant involved, a less precise determination of the relative worth of competing systems may give tolerably small value errors for earth launch systems. Also, the high development cost for large earth launch systems gives propellant systems which are in an advanced development stage a cost advantage that may be difficult to offset by any performance advantage that can reasonably be postulated for an untried chemical propellant system. The magnitude of this advantage may be altered by the advent of recoverable boosters, expansion of the proposed number of launches, improved materials technology, and advancing development of new systems for other than earth launch use. Hence, although at the present time a relatively cursory study may suffice to establish the superiority of systems already in an advanced development stage as choices for earth launch propellant systems, probable developments in the space field will undoubtedly require a more precise evaluating procedure in the near future.

Earth launch vehicles may be single or multiple stage systems. NASA requirements may be pertinent to the total launch system or have different impacts on the various stages. Therefore, these requirements are treated in three sections: over-all requirements, requirements applied to boosters, and requirements applied to upper stages.

1. Over-all Requirements[1,2,7,8,15]

The scope and schedule of proposed launch activity, the consequences of aborted missions, and the impact of specifying performance reliability are discussed.

a. Matrix of ΔV's, Payloads, Number of Launches, and Launch Schedule

These items represent the plans and goals of NASA space activity in terms useful in formulating an estimate of NASA usage of earth launch propellant systems. Since all space activity starts with earth launch it is obvious that this must be an inclusive coverage of NASA planned space activity.

This information is also the foundation on which all of the succeeding evaluation process is based. It is essential that this compilation of data and estimates be as accurate and reliable as available information permits since the results of any evaluation made on this base can be no more reliable than the base and will, in any event, be pointless if the program to which they pertain differs greatly from the one actually executed.

In compiling this information it will be necessary to make estimates and decisions which are, in part, dependent upon the outcome of the evaluation. It must be accepted, therefore, that some iteration of the evaluation procedure is a necessary part of the procedure.

(1) Payload and ΔV's

There are numberless variations in the destinations, trajectories, and other details of individual earth launch missions. Every mission will require, however, the acceleration of some specified payload to some velocity. It is adequate for propellant evaluation to extract from the details of the mission the size of the payload and the acceleration to be imparted to it. This can be conveniently expressed in terms of the required ideal velocity consisting of the sum of the terminal velocity and losses due to gravity, drag, and trajectory expressed as equivalents of velocity. Earth launch missions divide into two major classes, escape missions and earth orbit missions. Escape missions require a minimum ideal velocity of about 37,000 ft/sec. Earth orbit missions require a minimum velocity which depends upon the desired orbit elevation; a common elevation used for purposes of example (it is frequently noted as being optimum for various proposed space maneuvers) is 300 miles for which an ideal velocity of about 27,000 ft/sec is required. These minimum values will be increased by gravity and drag losses to about 43,000 ft/sec for escape missions and 33,000 ft/sec for 300-mile-altitude orbit missions. The ideal velocities actually required for specific missions will exceed these values by a relatively small amount depending on the launch trajectory. For single stages the size of launch vehicle required to achieve these velocities for a specified payload is fixed by the hardware ratio of the stage and the specific impulse of the propellant used.

Payload for launch vehicles includes everything launched by the vehicle. This includes any propellant required for velocity changes subsequent to that imparted by the launch vehicle. Hence, the choices of propellants for the upper stages will have a significant effect on the required payload of the earth launch vehicle to achieve any specified space goal. Thus the evaluation of the earth launch propulsion systems must follow decisions on post-launch propellants or be modified as assumed decisions change.

(2) Number of Launches and Launch Schedule

The number of launches categorized by required ideal ΔV, payload, and launch date must be estimated to determine the quantity usage and procurement schedule for propellants. This quantity-time schedule can be critical in the evaluation of possible propellant systems to the extent of ruling them out on an availability basis or changing the competitive cost relationship.

It must be recognized that in most instances estimates of launch numbers and dates are more accurately characterized as target goals with variable gains and penalties for improving on or missing the goal. Therefore, although it would be a convenient simplification in the evaluation process to fix on some base line schedule of propellant usage, a rigorous evaluation will undoubtedly require that this factor be treated as a variable. Thus the desired compilation is a time schedule of launches categorized by ideal ΔV and payload with all invariant points identified and any ranges from acceptable to unacceptable scheduling supported by as definitive a statement as possible of the bonuses and penalties accruing to the launch program from variations within these ranges.

b. Abort Safety

In any launch system there will always be some unavoidable, finite probability of malfunction leading to mission abort. The nature of the abort may vary, from prelaunch discovery of a defective part or system requiring unloading of the vehicle, to catastrophic failure during launch with destruction of the vehicle and adjacent ground facilities. Operating policy will be formulated to reduce the frequency of aborted missions and to minimize the damage resulting from them.

Operating policy will include consideration of the safety of on-board personnel, ground support personnel, ground support facility, local population, and local property (equipment, structures, vegetation, domestic animals, and wild life). A much more conservative policy can be anticipated when the launch mission includes on-board personnel.

In any event, policy decisions will be made in the interests of safety, public relations, and political expediency which can strongly influence the evaluation of a propellant system. Meeting the specifications of established policy may affect the availability date and relative cost of competing systems, or a system may be eliminated entirely on the basis of incompatibility with established policy.

The basic data for the evaluation of propellant systems must, then, include a compilation of existing restrictions on operational procedure at the launch sites. This is not to imply that existing doctrine is inviolate, inflexible, and all-encompassing but that any evaluation must either take account of all restrictions within which the system must operate or hedge the resulting conclusions with the proviso that these restrictions be removed.

Furthermore, the nature of existing policy may serve as a guide in predicting necessary, probable, or desirable policy changes as applied to proposed new propellant system developments.

Restrictions imposed on earth launch vehicle propellant systems in the interest of safety in the event of aborted missions apply, of course, to all propellant systems contained in the complete vehicle and are not limited to the launch vehicle propellants. This consideration may be of consequence when, as previously noted, the competitive position of a launch vehicle propellant system is altered by the choice of propellant for upper stages or space maneuver applications. Typical of the type of operational restriction to be looked for are: limits on quantity of a toxic or otherwise hazardous material that may be stored in one container or one area, minimum distance between storage containers, limits on maximum amount of material allowed to escape to the atmosphere, and limits on toxicity and corrosivity of propellant components or combustion products to man, vegetation, fish, bird, and animal life. In a subsequent section consideration is given to appropriate methods of expressing these restrictions for convenience in comparing propellants. At this stage only a compilation of operational restrictions as they appear in published policy or are observed in practice is required. This compilation must not be limited to explicitly stated restrictions but must include implied limitations imposed indirectly by such decisions as choice of launch site, etc.

c. Minimum Allowable Probability of Achieving Specified Major Objectives

Development of a propulsion system to the point where a high probability of successful performance can be assured has been a time-consuming, expensive operation for all propulsion systems developed to date and can be expected to continue to be a major problem for new systems at least for the short-term future. At the same time the total cost of large scale launches, the safety of on-board personnel, and political considerations demand a system of known high reliability. Thus, it is entirely likely that for specific missions or classes of missions specifications on minimum reliability of performance may be established.

The possible extreme effect that such specifications can have on the cost and date of availability of a propulsion system makes it essential that estimates be compiled, by specific launch or class of launch, of the probable required performance reliability expressed as the minimum acceptable probability of successful performance.

2. Boosters[2,5,13]

The booster is the largest element of the launch vehicle and uses several times as much propellant as all other elements combined. The choice of optimum propellant therefore is critical. Fortunately, however, the large size simplifies the problem by drastically narrowing the possible choices.

Very heavy costs are encountered in developing a large booster to a state of demonstrated high reliability. This means that propellant systems already in advanced development have a competitive advantage which an undeveloped system can overcome only by a very substantial performance advantage. Also, the very large quantity of propellant required for even a moderate launch vehicle will limit the choice of propellant to those products for which large volume production facilities and materials are quickly available. It is not probable that many combinations of materials will be found to meet these requirements.

As space programs continue and expand, however, there are several factors which will tend to narrow the built-in advantage of already developed booster launch propulsion systems. Amortizing development costs over larger numbers of launches, improved technology from experience of past development programs, clustered or segmented engine designs, and development costs borne by upper and space stage systems will all tend to reduce the development costs assessed against proposed new systems for earth launch boosters.

Thus, as time passes there will be a requirement to assess the worth, relative to then existing systems, of undeveloped booster propellant systems with a potential performance improvement margin which today would be considered narrow enough to reject the system.

a. Thrust to Vehicle Weight Ratio

For vertical launches, thrust to vehicle take-off weight ratio must be greater than unity. Unless techniques are developed for other than vertical take-off, then, it can be assumed that all proposed propellant systems must be evaluated on the basis of performance in vehicles which meet this requirement. In most designs for optimization of thrust to weight ratio of booster, the optimum ratio has been found to lie between 1.05 and 1.25 with a rather flat curve in the neighborhood of the optimum. The optimum design must strike the best balance among losses to gravity, losses to atmospheric resistance, and weight penalties for increasing thrust.

b. Burnout Altitude

Booster propulsion systems vary in performance with altitude as a result of the changes in the ambient atmosphere. Designs which are efficient at sea level are not as efficient under vacuum conditions as designs specifically engineered for vacuum operation. It is, therefore, desirable that all upper stages of an earth launch vehicle be designed for vacuum operations. When this is done the performance of these stages will be penalized unless the booster has a burnout altitude above the sensible atmosphere. Also, studies have indicated that either single or two-stage vehicles will be most efficient in achieving 300-mile-altitude earth orbit and escape velocities. Therefore, it is a reasonable assumption that for optimum performance not more than one stage should be designed for non-vacuum performance. This will, then, lead to a requirement that the booster propellant systems be evaluated on the basis of performance in vehicles with the booster burnout altitude above the sensible atmosphere.

c. Tolerances on Thrust Buildup and Cutoff, Total Impulse, and Propellant Utilization

In any launch mission the achievement of a successful lift-off depends upon smooth ignition, rapid thrust buildup, stable burning, and smooth and rapid cutoff. For multi-engine operation the thrust buildup and cutoff must also be uniform to avoid unbalanced thrust moments. Furthermore, for every launch mission there is some minimum total impulse below which the launch will fail, and there also may be a maximum limit.

For any given propellant combination, achievement of satisfactory ignition and thrust buildup and stable burning depends upon proper design of injection systems and start sequences. Achievement of the required total impulse and thrust balance depends upon provision of an adequate supply of each propellant component and of adequate instrumentation and controls for adjusting the propellant mixture ratio and total flow rate (and in some instances for in-flight cutoff). Since improvements in the accuracy of propellant flow control can reduce the weight of residual propellant at the cost of an increase in control weight and complexity, it is possible to optimize the design for minimum burnout weight and thus for maximum performance.

Several characteristics of propellants can influence the difficulty of these design problems. Hypergolicity, flame stability, density, and sensitivity of specific impulse to the fuel/oxidizer mixture ratio are examples.

In evaluating propellant systems, therefore, consideration must be given to the requirements for control of ignition, thrust buildup, cutoff, and total impulse, to the advantages and requirements for high percentage utilization of on-board propellant, and to the relation between the design requirements and the state of the art technology for the propulsion system.

d. Normal Operation Safety

Restrictions imposed on normal booster operations in the interest of safety may be different in kind or degree from those imposed by the possibility of an aborted launch because of the expected more frequent occurrence of successful launches. Restrictions on the concentration of propellant and combustion products within the vehicle, in the launch site working areas, and in the surrounding atmosphere, as well as the allowable surface contamination by corrosive materials or solids, may be much more stringent.

To evaluate a propellant system for earth launch boosters it will be necessary, then, to know what operating restrictions are in force or should reasonably be expected to apply for the protection of

(a) on-board personnel
(b) ground support personnel
(c) ground support facility
(d) local population
(e) local property (equipment, structures, vegetation, domestic animals, and wild life)

These restrictions would normally be in the form of upper limits imposed on peak and time-integrated values of

(a) acoustical noise level
(b) vibration intensity
(c) concentration of propellant or its combustion products in the atmosphere
(d) earth surface contamination by solids deposition

all as a function of distance from the launch pad.

In addition, it is possible that restrictions may apply to contamination of the launch vehicle surfaces by corrosive products.

3. Upper Stages

Launches requiring high terminal velocities are normally made with multistage vehicles as a matter of technical necessity in most instances and for economic and operational advantages in others.

NASA-imposed requirements for the propellants used in these upper stages may differ in some respects from the requirements for booster applications:

a. All Vacuum Operation

For an efficient design of a multistage launch vehicle the booster should as a general rule have a burnout altitude above the sensible atmosphere. Propellants for upper stages will, therefore, operate only under vacuum conditions and should therefore be evaluated on the basis of performance in vacuum.

b. Altitude Start and Restart Capability

Upper stage propulsion systems must be ignited at high altitude under vacuum conditions. Since failure to achieve ignition on schedule can result in an aborted mission the reliability of the ignition operation is critical and thus places a premium on a propellant system in which reliable ignition performance can be expected. (Hypergolic mixtures would, in this respect, offer the possibility of a desirable advantage over those mixtures which are not.) Also the trajectory plans may call for a coast period requiring cutoff and reignition, further accentuating the need for reliable ignition performance. NASA specifications for ignition reliability in upper stages can be expected, therefore, to be more stringent than for booster propellant systems.

c. Tolerances On Start and Cutoff Accuracy

Attaining the desired trajectory and orbit characteristics of a launch mission with a multistage vehicle may require precise control of upper stage start and cutoff operations and lead to specified close tolerances on the accuracy required in any proposed propellant system for upper stage use.

d. Tolerances On Propellant Utilization and Total Impulse

Control of the terminal velocity and other trajectory characteristics depends on accurate control of the total impulse imparted to the payload which, in efficient designs with minimum excess propellant, is keyed to close control of propellant utilization. In multistage vehicles it is commonly planned to use upper stages to compensate for errors in the programmed total impulse of lower stages. Thus for these higher stages the degree of accuracy specified for control of total impulse may be much more precise than for the booster stage. In evaluating upper stage propellant systems these specifications on required accuracy of total impulse must thus be considered.

e. Normal Operation Safety

Since upper stage propellant systems function only at high altitudes, normal operation (as contrasted with abort) safety considerations cover a narrower range of problems than for the booster systems. Consideration must be given, however, to the safety of on-board personnel at all times and to servicing personnel during the loading and launching operations. This may lead to the specification of operating restrictions which will influence the evaluation of different propellant systems.

An additional consideration will be the allowable limit of contamination or corrosion of exposed parts of the launch vehicle.

B. Planetary Launch Vehicles[1,7,12,13,16]

Evaluation of propellant systems for planetary launch vehicles requires consideration of the same factors as for earth launch vehicles. The relative importance of these factors is vastly different, however, because factors which are critical in one case can be practically ignored in the other.

NASA requirements and operational restrictions for planetary launch vehicles will be treated in the same format here as in the preceding sections on earth launch vehicles.

1. Over-all Requirements

a. Matrix of ΔV's, Payloads, Number of Launches, Launch Schedule and Launch Location

These items represent NASA's planned schedule of needs for propellant systems for planetary launches. They are very similar to the items considered under earth launch vehicles except that the launch location is of critical importance here. The differences to be encountered among planets with respect to atmosphere, gravity, temperature, and distance can give these factors controlling consequence in the comparison of potential propellant systems.

As a practical matter, however, the available information on the problems of planetary launch is so meager that only a very few launch missions can be planned usefully before the experience of the earliest missions is available and assimilated. The compiled schedule of planned planetary launches must therefore include a far less extensive set of missions or must be based on much more nebulous estimates than for earth launches.

b. Storability[9,16,19,20,21]

Propellants for planetary launch vehicles must have a useful storage life that exceeds the total of earth launch preparation time, inflight time, planned planetary residence time, and planetary launch preparation time. There is also the possibility of delay time in earth orbit or at other points en route.

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2. Boosters

The specific requirements for booster propellants systems, additional to the over-all requirements, follow the same pattern as for earth launch boosters.

a. Thrust to Vehicle Planetary Weight Ratio Greater Than Unity

The optimum thrust to weight ratio will depend upon the values for planetary atmospheric drag and gravity. Since these values will differ substantially from those for earth launches, the optimum ratio may also differ.

The effect of thrust to weight ratio on selection of propellants comes from the limitation placed on the maximum launchable payload with the largest propulsion system of demonstrated specified reliability available on the desired schedule. If this maximum payload does not exceed the minimum necessary payload the propulsion system is obviously not appropriate.

b. Burnout Altitude Above Sensible Atmosphere

The desirability of using a single stage to achieve an altitude above the planetary sensible atmosphere applies as with earth boosters.

c. Tolerances On Propellant Utilization and Total Impulse

The restrictions that these tolerances place on choice of propellant systems are the same as for earth launch vehicle systems. The cost penalty for low propellant utilization, however, whether stemming from the need for high safety factors, sensitivity of impulse to mixture ratio, or other causes, may result in the need for the specification of closer tolerances than for earth launch systems.

d. Compatibility of Propellant and Exhaust Products With the Atmosphere

The composition of some planet atmospheres and the wide range of chemicals that might be considered for propellant systems presents the possibility of an undesirable combination of atmospheric constituents, propellants, and exhaust products creating corrosive, toxic, explosive, or fire hazards.

e. Normal Operation Safety

In the absence of a planet-based support facility, normal operation safety considerations would parallel those considered under abort safety.

With the establishment of a planet-based support facility consideration would be given to hazards imposed on the facility and personnel by the propellant system. The problem of corrosion would be of greater consequence than toxicity since personnel, as stated earlier, would probably require protection from the ambient atmosphere.

The restrictions on limits or nature of contamination of the planet atmosphere and vehicle or planet surface would not likely differ from those considered under abort safety.

3. Upper Stages

If the booster takes the vehicle out of the planetary atmosphere, the operating environment for the planetary launch vehicle upper stages will be comparable to that for earth launch vehicle upper stages and the same operating limitations for propellant systems will apply.

C. Lunar Launch Vehicles[1,12,16,22,23]

The moon, as the nearest space body of substantial size, is of unique importance to space programs. Its nearness makes it the natural target for the first manned space trips to acquire space flight knowledge and experience and its low gravity may be exploited by using the moon as a base for expeditions to more distant bodies. For these reasons the requirements established for propellants for lunar launch vehicles are of special importance in the evaluation of proposed propellant systems.

NASA requirements and operational restrictions for lunar launch vehicles would not be expected to include considerations radically different from those for earth and planetary launch vehicles and should be treated in comparable manner.

1. Over-all Requirements

a. Matrix of ΔV's, Payloads, Number of Launches, and Launch Schedule

These items, as for earth and planetary launch vehicles, represent the compiled estimate of quantity and schedule of usage of propellants for lunar launch vehicles. The factor which is likely to have an over-riding influence on these items is the extent to which the moon is found advantageous as a base for more distant space flights. This is likely to require that this matrix be considered through a wide range of values in initial propellant evaluations.

b. All-Vacuum Operation

Since the moon is free of any sensible atmosphere, propellants for use on it should be evaluated on the basis of performance in vehicles designed for all-vacuum operation.

c. Vacuum Start Capability

The absence of atmosphere will require vacuum start capability for all propellant systems considered for lunar launch vehicles.

d. Storability[9,16,19,20,21]

A trip onto and return from the moon will require a minimum time of about one week. The possibility of desirable, necessary, or unplanned delays may lead to the specification of substantially longer storage life which must be considered in propellant system evaluations.

e. Earth Launch Abort Safety

The possibility of an earth launch abort of a vehicle carrying a lunar launch system will impose the same requirements as for planetary launch systems with respect to safety and pollution considerations.

f. Lunar Launch Abort Safety

Requirements established because of the possibility of an aborted lunar launch mission will parallel those for aborted planetary launches.

g. Minimum Allowable Probability of Achieving Major Objectives

As with planetary launches the major objective of the lunar launch vehicle propellant systems is to get the vehicle payload safely to orbital or escape velocity. The proximity of the moon to the earth makes the problem of personnel rescue in the event of unsuccessful vehicle performance less formidable than in the case of planetary launches, and may lead to a different relative emphasis being placed on performance, reliability and efficiency.

2. Boosters

a. Thrust to Vehicle Lunar Weight Ratio Greater Than Unity

As with planetary launch vehicle boosters, the effect of thrust to weight ratio on selection of propellants comes from the limitation placed on the maximum launchable payload with the largest propulsion systems of demonstrated specified reliability available on the desired schedule.

b. Tolerances on Propellant Utilization and Total Impulse

The same considerations apply here as for earth and planetary launch propellants.

c. Normal Operation Safety

The considerations with respect to safety under normal operation will parallel those for planetary launch vehicles, although the limits placed on vehicle and lunar surface contamination may not be numerically the same.

3. Upper Stages

Because of the low gravity and absence of atmosphere, present concepts for lunar launch vehicles require only a single (or booster) stage to reach orbiting or escape velocity. In the event that new concepts employed multiple stages the propellant requirements for the upper stages would parallel those for earth launch upper stages.

D. Space Maneuver[1,12,16,22,23]

Space maneuver in this context is taken to mean any maneuver, other than a launch operation, involving an appreciable change in vehicle velocity by means of on-board propulsion devices. Typical maneuvers will be involved in transfers between interplanetary trajectories and earth, lunar, or planet orbits, and deceleration for entry to earth or planetary atmospheres or for lunar landing.

1. Matrix of Total ΔV's, Number of ΔV Increments, Increment Schedules, Payloads, Number of Launches, and Launch Schedule

This matrix represents the planned or estimated schedule of needs for propellant systems to effect the space maneuvers included in planned space missions.

2. All-Vacuum Operation

By definition it is obvious that the systems included in this category will be designed for all-vacuum operation.

3. Space Start and Restart Capability

All maneuvers included in this category will be initiated in space and some, but not all, will require cutoff in space. These latter will in some instances require restart in space.

4. Tolerances on Start and Cutoff Accuracy

Control of such factors as orbit height, flight schedule, reentry velocity, and landing point may be effected with space maneuver propulsion systems. The attainable accuracy of start and cutoff with respect to timing and thrust change may be of critical consequence in such cases and result in the imposition of specified tolerances for acceptable performance.

5. Tolerances on Propellant Utilization and Total Impulse

The success and safety of the mission will depend on having adequate power on board to execute the planned space maneuvers. The necessary velocity changes will be subject to some planning error and the performance of any propulsion system will have a finite variability. These two factors will create the need for carrying excess power for space maneuvers as a safety factor. The more reliable and predictable the performance of the propulsion system is, however, the smaller this safety factor can be to give the same degree of reliability. Specific tolerances may, therefore, be specified for propellant utilization and total impulse.

6. Storability [9,16,19,20,21]

The required reliable storage life of space maneuver propellants may vary from days to years depending on the mission. This variability in the ranges of application may lead to the establishment of arbitrary specifications of storage life for acceptable systems based on extreme requirements rather than each mission's requirement. Whether or not this occurs, consideration must be given to the necessary or specified storage lifetime.

7. Earth Launch Abort Safety

Requirements imposed as the result of the possibility of earth launch abort must be considered in the same light as for propulsion systems in earth launch vehicle upper stages.

8. Planetary or Lunar Launch Abort Safety

The possibility of an aborted lunar or planetary launch will impose requirements on the space-maneuver propulsion system propellants comparable to those for the lunar and planetary launch booster systems.

9. Normal Operation

a. Safety of On-board Personnel

The space maneuver propulsion system will be in closer proximity to the manned section of the payload for a longer period of time than any of the launch stages. Special consideration may therefore be necessary with respect to containment of the propellants and to their physiological effects in the event of seepage or other accidental escape. Specifications imposed in consideration of safety of on-board personnel would be similar to those for upper stage earth or space launch vehicle propulsion systems.

b. Limits on Vehicular Surface Corrosion or Contamination

The vehicle payload will have exposed surfaces, windows, instruments, antennas, control mechanisms, etc., which may be vulnerable to damage from corrosive or contaminating materials. Space maneuver propulsion system exhaust products may present greater hazards to these components than launch stage systems. Consideration must then be given to the limits which may be set on permissible vehicle surface component corrosion or contamination.

E. Auxiliary Power[16,22,23]

In addition to the vehicle acceleration requirements there are some relatively small scale power requirements in the accomplishment of space missions which may be satisfied by liquid propellant systems. These are stage separation, ullage rockets to position liquid propulsion propellants, and steering and attitude control.

1. General

a. Matrix of Number of Launches, Launch Schedule, Units per Launch, Impulse Increments, and Increment Schedule

This matrix of estimated usage requirements and schedule is needed more to define the number of units, size of units, and delivery schedule than the quantity of propellant as was the case with the usage matrixes for launch vehicle propulsion systems. The amount of propellant used for these auxiliary uses will be so small that cost and production problems will be of lesser consequence than performance characteristics.

b. Space Start

Use of the auxiliary systems will be almost exclusively under vacuum conditions.

c. Abort and Normal Operation Safety

Considerations with respect to safety will parallel those for space maneuver propulsion systems.

d. Reliability

Although of relatively minor size and cost, failure of the auxiliary power systems could result in complete mission failure. Emphasis will undoubtedly be placed on dependable performance with a very high reliability specified.

2. Stage Separation

a. Small Thrust

These units used to jettison burned-out launch stages need provide only a small thrust without a high degree of accuracy.

b. Single Use

Individual units will be used only once.

c. Storability

The useful storage life for the stage separation propulsion system must at least match that of the propulsion system of the stage being jettisoned.

3. Ullage Rockets

In a zero gravity environment the positioning of liquid propellants in storage tanks for successful starting of the main propulsion systems may be accomplished by a slight acceleration imparted to the vehicle with auxiliary rockets. If these rockets are themselves powered by liquid propellants they would need to be stored in tanks providing positive discharge from pressurized bladders or other devices.

a. Small Thrust

Settling the propulsion propellant would require only a small thrust to exceed the effects of small perturbations acting on the vehicle and the surface tension effect of the propellant.

b. Restart Capability

In instances where more than one propulsion stage was involved or a stage was being restarted, the ullage rocket would require restart capability.

c. Storability

The useful storage life must be at least equal to that of the last stage in which the propulsion propellants required positioning.

4. Steering and Attitude Control

Control of the vehicle is accomplished by a group of small engines which may be powered by liquid propellants.

a. Tolerances on Start, Stop, and Thrust

The key specification on the performance of control and steering engine performance will be the tolerances permitted on accuracy of start, stop, and delivered thrust.

b. Restart

The control engines may be in continuous or intermittent operation and will therefore be subject in some instance to specifications on restart capability.

c. Storability

The useful storage life of the control system propellants must be at least equal to that of the last propulsion system on the vehicle.

F. Minimum Comparative Total Resource Consumption for Over-All Space Program

This evaluation scheme will be predicated on the assumption that if all specifications with respect to performance, reliability, and safety are satisfied by more than one propellant system the merit of competing systems will then be rated on the basis of total consumption of resources for the complete space flight program.

IV PROPELLANT EVALUATION PARAMETERS

A. Introduction

To establish how well a proposed propellant combination satisfies a specified set of requirements, the technical (design and performance) and economic (cost and availability) characteristics of an appropriate propulsion system may be expressed in terms of certain parameters. These include: thrust application and control characteristics; on-board storability characteristics; toxicity, corrosivity, and contaminativity characteristics; availability; specific impulse; propulsion system hardware/total weight ratio; and comparative total resource consumption per unit propulsion system weight. The thrust, storability, toxicity, and availability characteristics of a propellant combination may prevent it from satisfying the requirements of certain applications. Where this does not occur--that is, where a propulsion system using the propellant combination can be designed to satisfy all requirements--the parameters will depend in so complex a fashion upon each other and upon the requirements to be met that they can be fully determined only by a complete design optimization study. However, in the course of development of a new propellant combination, or in the course of development of vehicles for a new mission, it is necessary and possible to derive successively closer approximations to the final values of the evaluation parameters.

The first approximation will generally be a set of theoretical values for some of the parameters, derived from basic information on the physical and chemical properties of fuel, oxidant, and exhaust products (melting point, vapor pressure, heats of fusion and vaporization, specific heats, density, viscosity, surface tension, stability, heat of formation, combustion properties, explosive mixture limits, toxicity, and compatibility with storage and handling equipment materials), and basic information on the availability of raw materials and on feasible production processes for the fuel and oxidant. When results from early test engine work are available, the theoretical values obtained as a first approximation can be modified and supplemented to arrive at a second and more complete approximation. Further approximations are derived as test engines more nearly approach flight configurations.

B. Thrust Application and Control [2,4,11,14,23]

The most elementary design study and experimental test program for development of a propulsion system must be concerned with the problems of engine ignition and starting and stopping procedures. Attention will also be given to restarting, throttling ranges, and propellant utilization. Attainable performance in these characteristics can strongly limit applications of the system. Performance will be determined by the design concepts employed, but these will be influenced by the characteristics of the propellant. Information concerning these operating functions will therefore be pertinent in evaluating proposed propellant systems and will be available early in the development program.

1. Rate and Variability of Thrust Buildup

The nature of the specific mission, the function of the propulsion system, and the design of the vehicle and its control system require thrust buildup characteristics which may tax the capability of the propulsion system particularly with respect to the rate of thrust buildup and the predictability or variability of this rate.

The rate of buildup may limit the applicability to some functions or missions, and the variability may affect the vehicle reliability in following the prescribed trajectory or impose burdensome safety factor requirements on the vehicle design with respect to control functions and total impulse.

Implicit in this consideration is the problem of ignition. Troublesome ignition, total failure, erratic or delayed ignition may cause extreme thrust buildup variability and can result in catastrophic failure. The effect of ignition difficulty on predictable performance or reliability may eliminate the propellant for specific uses from the standpoint of safety and performance or from economic and schedule considerations.

Data on the thrust buildup performance should be sought:

a. At sea level and earth gravity conditions if the propellant is proposed for use in earth launch boosters.

b. In vacuum and less than earth gravity conditions if the propellant is proposed for use in upper stage earth and other planet launch vehicles and lunar launch vehicles.

c. In vacuum and zero gravity conditions if the propellant is proposed for use in orbiting and space travel vehicles.

2. Rate and Variability of Thrust Cutoff

In some applications the rate and variability of thrust cutoff may be as critically important as thrust buildup. Available data on thrust cutoff should be compiled for the pressure and gravity conditions that the proposed propellant applications indicate, as outlined for thrust buildup, so that the limiting effects of this characteristic of the propellant combination can be assessed.

3. Restart Procedure

For applications requiring the propulsion systems to function more than once, consideration must be given to the problem of restarting in the environment where restart is required. The characteristics of the propellant, and the complexity of the engine design, which may in part be dictated by propellant characteristics, will influence the extent of the restart problem, the weight penalty involved in it, and the reliability of restart performance. Information on the complexity of the restart procedure and on the reliability achieved in the environments where restart is required will thus serve as a useful propellant evaluation parameter.

4. Throttling Range

Trajectory requirements may also demand a variable output below full thrust of the propulsion system. The characteristics of the propellant can limit the throttling range achievable, as well as the weight penalty associated with it. This information should be compiled as early as possible in the evaluation of the propellant to aid in setting limits on potential applications.

5. Propellant Utilization

Efficiency of propellant utilization is the most important of the various factors that limit the predictability of the total impulse obtainable from the propellant loaded into a propulsion system. Deviations from the planned fuel-oxidant ratio will change the specific impulse obtained from the propellant during burning, and also (assuming that burning continues to exhaustion of one of the propellant components) will add to the fraction of unusable (residual) propellant in the system and thus decrease the achievable stage mass ratio. The accuracy to which the mixture ratio can be controlled for a given propellant, and the sensitivity of the specific impulse and stage mass ratio to variations in the mixture ratio, will determine how large a safety factor must be provided in specifying the propellant load. Furthermore, in instances where burning is allowed to continue to exhaustion of one propellant component, these considerations may determine whether or not specified mission tolerances on total delivered impulse can be met.

C. On-board Storage [9,10,15,16,19,20,21]

Propellants for use in earth launch vehicles must be storable for relatively short periods, under the environmental conditions existing in the vehicle prior to and during launch. Propellants for any other application must be storable for much longer periods under the environmental conditions existing in space. In either case, the problem is to provide a system which will contain the propellant components in usable condition for the required time with minimum penalty from weight, product loss, and propellant deterioration. In addition to the time stability of the propellant components, requirements for thermal insulation and for shielding against radiation and meteorites must be considered.

The required system will obviously be highly sensitive to the physical and chemical characteristics of the propellant components.

1. Insulation Requirements

All liquid propellants require some provision for temperature control in space storage. At the point of use the components must be above the freezing or solidifying temperature, and at all times the upper temperature limit must be held to the point where the vapor pressure does not exceed the strength of the container, or cause excessive boiloff and loss of the component if the container is vented. The techniques for controlling propellant temperature include controlled orientation of the vehicle, configuration and location of tankage, thermal insulation, mechanical refrigeration, heating units, controlled boiloff of propellant, temperature adjustment before loading, and increasing tankage strength. For many possible propulsion systems, determining the combination of techniques which will result in optimum performance for a given mission is a complex problem, solvable only by detailed vehicle design studies. There are, however, propellant characteristics which can be used as a guide to qualitative estimates of the penalties involved in providing the required temperature control.

Low propellant volume, whether achieved by high density or high specific impulse, is an obvious advantage.

A freezing or solidifying point below the lowest temperature encountered in the operating environment, and a vapor pressure that does not exceed the permissible maximum at the highest operating environment temperature, would essentially eliminate the problem. The more closely these conditions are approached the lower will be the penalty imposed by temperature control. High specific heat and heat of vaporization also are favorable characteristics.

In addition to the problem of temperature control for individual propellants, there are serious design problems that arise from extremes in temperature difference between the fuel and oxidizer.

The ingenuity of the designer is taxed to conceive a structurally sound design which will tolerate extreme temperature differences between the two components or extreme changes in temperature of either without adding excessive weight over the requirements for structural support, containment, and shielding. This temperature problem is present even for the short term storage in earth launch vehicles and can be of great consequence in this application because of the size of elements involved.

2. Shielding Requirements

In addition to being protected from thermal effects, propellants to be stored or used in space must be protected from radiation and from meteorites.

Studies have indicated that propellant components seriously considered for use heretofore are not likely to be adversely affected by any radiation expected to be encountered. For newly proposed components it should be determined whether or not this conclusion is applicable.

The unlikely possibility of transparent tankage combined with photosensitive components could conceivably create a problem, but developments to date indicate no strong probability of photosensitivity becoming troublesome insofar as vehicular storage is concerned.

The greatest known peril to be countered by shielding is meteorites. The extent of this problem and the most effective ways to combat it are still unresolved. The propellant characteristics which bear on the problem are apparent, however.

No matter what type of shielding or means of avoiding tank puncture or damage is developed, the smaller the volume of tankage required the smaller the weight penalty to provide protection, or the lower the probability of puncture for a given weight of shielding. Thus, high density and high specific impulse are desirable attributes from this consideration also.

In the event of meteorite collision with the propellant tankage the resulting damage will, in part, be determined by the characteristics of the propellant components. With some mission concepts, limited damage might not entirely jeopardize success. In these cases there is an advantage in having propellant components with characteristics which tend to minimize the damage resulting from collision with meteorites.

The impact of a meteorite can deform or puncture the tank wall and cause spalling of the interior surface. Leakage and loss of propellant would be the primary damage from a puncture unless the propellant component's characteristics compounded the problem. Spalling and deformation could expose unpassivated surfaces in the case of tankage where such treatment had been employed to contain corrosive material; this would result in corrosion, perforation of the tank wall, and loss of component. In the case of chemically active material such as fluorine, burning of the wall and catastrophic failure might occur. In any event, corrosive material would tend to enlarge the original puncture and to damage exposed parts of the vehicle exterior to the tanks. With a monopropellant or leakage from both fuel and oxidizer tanks, fire or explosion would be additional hazards.

A shock-sensitive material would present a further hazard of explosion from simple impact with or without puncture.

Loss of material through small punctures could be slower for products of higher viscosity.

It cannot be argued, however, that details of the effects of a puncture are considerations of major consequence. For storage of appreciable quantities for substantial periods it is almost certain that effective shielding from meteorite impact must be provided at least for the smaller meteorites. The degree of protection provided would be gauged so that the probability of encountering a meteorite large enough to penetrate the tankage would be small enough to tolerate, even on the basis that such an encounter would result in mission failure. Thus the only propellant characteristic of major consequence to meteorite shielding is low total volume.

The weight penalty resulting from provision of meteorite and radiation protection including thermal radiation will be a minimum if they can be provided by the same shielding structures.

3. Time-stability

The required minimum useful life for propellants varies from the order of a week for lunar flights to a year for interplanetary flights. Obviously, long term stability widens the realm of possible applications for a propellant. Especially for long term storage there are a great many ways that a propellant can undergo change with detriment to its performance. This is particularly true if the fuel or oxidizer is a mixture of materials rather than a single compound or element. Examples are: thermal decomposition, polymerization, or gelling; reaction with the tank wall, pressurizing gases, bladders, sealing materials, or its own components; separation by settling, layering, or differential boiloff.

Thus, before accepting a propellant for consideration in applications requiring storage for appreciable time, reliable evidence must be available to demonstrate its time-stability under the proposed storage conditions.

D. Toxicity, Corrosivity, and Surface Contamination [4,11,15]

The release, either planned or accidental, of propellant components or their combustion products will in general constitute a potential hazard to personnel and equipment aboard a space vehicle, to ground support personnel and facilities, and to the surrounding environment, due to toxic, fouling, and/or corrosive properties of the released material. The degree of the hazard is determined by the chemical and biological activity of the materials released, the total amount, distribution, and rate of release, and the proximity of vulnerable life and non-living material.

1. Toxicity

The working term for the degree of toxicity to life of a chemical compound whose biological effects are considered essentially non-cumulative is the maximum allowable concentration (MAC) for some specified time of exposure. For industrial situations this specified time is commonly some number of minutes, an eight-hour day, or a forty-hour week. If the possibility of cumulative effects exists, the allowable exposure may be expressed as a maximum integrated value for the product of concentration and exposure time for some specified time period. This period may be a workday, week, month, year, or lifetime depending upon the time cycle involved in the ultimate physiological fate and effect of the chemical.

Values of maximum allowable peak and time-integrated concentrations of propellant components, exhaust products, and products of reaction of each component with the atmosphere, must be established for the atmospheres to which on-board and ground support personnel and the local population are exposed. The likelihood that these limits may be exceeded will depend upon the quantities of propellants involved, the rate and distribution of release of the propellants or their combustion products, the precautionary and protective measures taken (use of protective clothing, hermetic sealing of enclosures, surrounding of launch sites with water sprays, etc.), and the prevailing meteorological conditions. For a given launch site and a given choice of precautionary and protective measures, it may be possible to establish a maximum allowable value for the weight of any propellant component or reaction product that might be expelled from a vehicle assembly divided by the MAC for that material for short-period exposure. If this maximum is not exceeded by any of the actual quotients for the quantities of the various components and possible reaction products associated with the use of a given propellant combination in a given size propulsion system, that propellant combination may be considered safe for use in that size system. There will in general be different values of the maximum for abort conditions than for normal operation, and the value for normal operation will depend upon the application. If the effects of two or more of the components or products are similar enough to be additive, a single quotient must be calculated for the combination, for comparison with the maximum allowable quotient. This will also be true for materials whose effect in combination is greater than the sum of their individual effects.

a. Catastrophic Abort

The possibility of a catastrophic abort of a mission during launch from the earth, another planet, or the moon complicates the pollution problem in that the proportions and composition of the products released and the distribution and rate of release will depend upon the circumstances under which the abort occurs. These uncertainties will undoubtedly force the establishment of limits on the basis of the most perilous possible combination of circumstances. That is, the pattern of distribution, rate of release, and nature of products disseminated to the atmosphere will be postulated as those that would create the most toxic concentrations at points where vulnerable life is anticipated; all propellants on board (not merely those used in the launch propulsion system) must be included in determining the nature of the products disseminated. On the other hand it would be expected that the frequency of catastrophic aborts occurring under circumstances that create the most hazardous conditions would be low, and that in such unlikely events, the imposition of such emergency precautionary actions as personnel evacuation could be tolerated. Thus, whether or not the possibility of catastrophic abort will result in a controlling limit on allowable pollution as compared with normal operation will depend upon decisions made on other than strictly technical grounds. In any event, it cannot be concluded without study that the circumstance of catastrophic abort will be more hazardous than normal operation.

b. Normal Operation

For normal operation the materials released will be limited to the exhaust products from the operating propulsion system, and the amount, rate, and distribution of release can be predicted quite accurately. It may be expected that the limits on allowable release per operation will be set so as not to exceed the amount that can be safely tolerated without recourse to any emergency precautions. For earth launch vehicles, if the exhaust products from a given propellant combination are judged to have a cumulative effect a limit may be set on the total usage of that propellant at the launch site or on the long term rate of usage, in addition to the limit on the amount per launch. Launch operations from other celestial bodies and interplanetary space operations presumably will not affect the local population, but restrictions may be imposed on the amount or nature of materials released in order to preserve the natural environment.

2. Corrosivity and Surface Contamination

In addition to the effects of propellant components and combustion products on life, there may be undesirable effects on exposed materials and structures. These effects may consist of chemical reaction effects, fouling by deposition of solids, or both. There will be differences in the nature and extent of these effects for catastrophic aborts and normal operations, corresponding to the previously described differences in toxic effects. However, in a catastrophic abort the primary damage to vehicles and immediately adjacent structures will be fire and explosion damage.

a. Maximum Allowable Reactivity of Propellant Combustion Products

The exhaust products of a normally operating propulsion system will come in contact with the exposed parts of the vehicle and payload, and for launch operations with the launch site structure and equipment and local offsite property such as buildings, motor vehicles, fences, etc. Depending upon the materials of construction of the exposed parts and their position relative to the exhaust nozzles or launch pad, there will be a variable vulnerability to attack and damage by chemical reaction with the exhaust products that will require setting limits on allowable reactivity of the exhaust products, use of resistant materials for exposed parts, banning or removal from the area of vulnerable items, or combinations of these precautions. The evaluation of the propellant must include consideration of all such existing or necessary limiting precautionary measures.

b. Maximum Allowable Deposition of Solid Reaction Products

If the exhaust products consist wholly or partly of solid material they may create difficulties by deposition, with or without the added hazard of corrosion, which will lead to restrictions on the use of the propellant or to a need for precautionary or corrective measures. Solids in the combustion products can have unacceptably deleterious effects on vehicle and payload parts such as windows, exposed instruments, antennas and control mechanisms; on launch site machinery, power transmission line insulation, and communications equipment; and on off-site power lines, antennas, motor vehicles, and vegetation. The limits that must be imposed on the deposition of solids for the protection of these items may become a limiting factor in the selection or evaluation of a propellant.

E. Availability[1,4,11,12,16]

The availability of the propellant components and propulsion system hardware in terms of quantity and time will be important considerations in the evaluation of the propellant combination. Availability will often become a critical factor for earth launch propellants and propulsion systems because of the amounts of propellants and the physical size of the systems involved; propellant tonnages will be large even in terms of the heavy chemical industry, and engine and tankage sizes will present serious problems to metal forming and machining facilities. The development, testing, and production of the hardware (engines, tankage, pumps, turbines) for such large propulsion systems is a process requiring several years for completion. The same is true for the facilities to transport and assemble the vehicle hardware and to produce, transport, transfer, and store the propellant.

Since the comparative merit of a proposed propellant system is strongly dependent upon the scope of potential applications and this in turn upon the availability schedule, it is of critical importance that the best possible estimate of development schedule be used in its evaluation. A corollary to this is that the state of development of alternative systems must also be assessed accurately; thus, too optimistic expectations for systems currently under advanced development can lead to an unwarranted restriction in the presumed scope of application of a new system, and can result in as serious ultimate detriment to the space program as too optimistic expectations for new systems.

Determination of the scope of potential applications for a system is, of course, as dependent upon accurate estimates of quantity and schedule requirements as upon accurate estimates of availability. As a starting point the theoretical scope of usage of a propellant system for a given class of application can be taken as NASA's total requirements for systems for that class of application, excluding only those requirements for which firm commitments have already been made for other propellant systems. These requirements may be grouped on some appropriate basis such as thrust level, and typical representatives of each group chosen for consideration of propulsion system hardware development problems. Based on the estimated numbers and sizes of units in each group, together with estimates of delivered specific impulse and vehicle hardware ratio, an estimate can be computed of the quantity of propellant required for operational systems as a function of calendar year. To this amount must be added the estimated quantity required for development and testing to obtain the total potential usage of propellant.

F. Specific Impulse

As a single criterion of relative propellant performance specific impulse is, justifiably, the most widely used index of merit. Theoretical specific impulse depends upon the molecular weights of the combustion products, the specific heats and heats of formation of the components and combustion products, the mixture ratio of fuel and oxidizer, and the combustion chamber pressure, ambient pressure, and expansion ratio. Computer programs have been written to calculate theoretical specific impulse from inputs which can be obtained at the time a product is proposed as a component of a propellant. Thus, in addition to being a powerful indicator of propellant merit, theoretical specific impulse has the valuable advantage of being available with little effort and at an early date. In fact, no material would be seriously proposed for use in a propellant system without at least a good estimate of its specific impulse.

Useful as it may be, specific impulse is not, unfortunately, an infallible indicator of propellant merit; it is a measure only of the potentially available power in the propellant. It does not reflect the weight and cost of the system of hardware that must be provided, which vary widely for different propellants independent of specific impulse. In an attempt to include the effect of these factors specific impulse is sometimes expressed on a volume (lb thrust per ft^3/sec) rather than a weight (lb thrust per lb/sec) basis. This is because, as has been indicated earlier, much of the vehicle weight (and the cost associated with it), specifically tankage, meteorite and thermal shielding, plumbing, and pumps, varies more directly with propellant volume than weight. This is not wholly successful, however. In fact, no fully reliable rating means is available short of a detailed optimized design study, in which the specific impulse and hardware weight are treated as separate variables (but not independent ones, since they both depend upon propellant densities, mixture ratios, etc.). This unfortunately is a time-consuming, expensive process. If competing propellant systems cannot be eliminated on other grounds there is, however, no alternative.

For a design study to be made it will be essential to have data on specific impulse as a function of mixture ratio of fuel and oxidizer, combustion-chamber pressure, ambient pressure, and expansion ratio, since obtaining optimum performance from a specified propellant for any specific mission will be dependent on selection of the optimum combination of values for these variables.

G. Hardware Weight[2,4,5,11,13,14]

With a continuing stream of new or modified concepts for propulsion systems and vehicle configuration, construction and control, there is a seemingly endless number of factors that must be weighed in the design of a vehicle if optimum performance for a given mission is to be approached. Many of these factors will be either directly or indirectly sensitive to propellant characteristics as well as to the payload and ΔV fixed by the mission. Thus evaluating a propellant leads ultimately to the need for a complete optimized vehicle design study. Ideally, the vehicle design study would be oriented toward the least-total-cost solution for the set of missions contemplated. In practice the problem is so complex that it is impossible to develop a design fully optimized for least cost in a straightforward manner. Much sub-optimization of components and operating conditions is necessary. And it is rarely obvious in this sub-optimization whether designing for least weight or least cost for specified performance will result in the best component for the least total program cost.

Engines are designed initially for minimum weight to thrust ratio and tankage for minimum weight to volume ratio. The effect of varying operating characteristics, chamber pressure, expansion ratio, mixture ratio, etc., on total hardware weight is then investigated and the conditions for minimum complete propulsion systems weight determined as a function of total impulse and thrust level. From this point, the relative weight and cost of alternative materials, configurations, and operational concepts can be evaluated and an optimum design determined as a function of payload weight and ideal ΔV.

For applications involving substantial velocity changes, as in earth launch vehicles that are to accelerate payloads to orbit or escape velocity, the advantage of multiple staging must be investigated. If multiple staging is indicated the proportioning of stages must be optimized for minimum mission cost which requires a complete analysis of cost and weight of each stage as a function of thrust level and stage size.

It is obvious that the design of an optimum vehicle for a specified mission is a formidable task not to be undertaken if avoidable. For that reason the investigation of hardware weight and cost factors is not proposed in the evaluation or selection of a propellant until all other requirements and characteristics have been explored and there is assurance that aside from hardware weight and cost considerations the proposed propellant is an appropriate candidate.

Although a propellant can never be selected for a mission without a complete design study, useful estimates can sometimes be made of the probable relative weight of hardware for a proposed propellant by using as references fully designed systems employing similar propellants. Such estimates may show that the propellant is either markedly inferior or markedly superior to others without the expense in cost and time of a complete design study. It is true that estimates of expected hardware weight for propulsion systems must be approached with extreme caution. Really good designs come only from adroit exploitation of the unique favorable characteristics of the propellant and equally adroit circumvention of its unfavorable characteristics; failure to recognize all of these favorable and unfavorable characteristics at an early stage can lead to disaster. Nevertheless there are some characteristics of propellants whose impact on hardware weight can, on the basis of experience to date, be predicted qualitatively with reasonable reliability.

Low propellant volume, whether achieved by high density or high specific impulse, leads to low hardware weight. Its effects are realized in smaller tanks, plumbing and pumps or pressurization systems, reduced insulation and meteorite shielding and reduced size of support structure and control system. Plumbing, pressurization or pump system weights can be estimated reliably from knowledge of propellant density, viscosity, vapor pressure, and chemical reactivity characteristics. Insulation requirements can be estimated from the vapor pressure, volume, and specific and latent heats. Hypergolicity eliminates the need for ignition systems and may reduce the complexity of shutdown and restart procedures. The manner in which specific impulse varies with mixture ratio, combustion pressure, combustion temperature, and expansion ratio will affect the choice of these engine operating conditions; the choice of these conditions will in turn influence the weight of the engine, feed system, and tankage.

Thus, assuming a general knowledge of an appropriate design concept, hardware weight estimates can be made, by utilizing available information about propellant characteristics. These estimates, although admittedly less accurate than those derived from a detailed design study, are available at a much earlier date in the development of the propellant and are potentially more reliable than estimates generated without reference to the known propellant characteristics.

For applications involving large ΔV's the desirability of multiple stage vehicles may have to be explored. Such exploration will involve cost-optimized proportioning of stages.

This optimum proportioning process will require a knowledge of the ratio of hardware weight to total stage weight for parametric values of thrust, thrust to propulsion system weight, and (where applicable) space storage time as a function of mixture ratio, expansion ratio, and combustion chamber pressure and temperature.

H. Comparative Total Resource Consumption[2,5,14,17,18]

In rating proposed propellant systems not eliminated on the basis of mission requirements or the limiting characteristics of propellants, the order of merit will depend on complete-program comparative total resource consumption. What the total required resources of materials, facilities, time, and man power will be for a specified program with a particular propellant is extremely difficult to estimate accurately. This is particularly true for earth launch propulsion systems--not that it is easy for other applications, but only that the required order of accuracy for meaningful merit rating is greater. For nearly all other than earth launch uses, the cost of delivering the system to the use site is so great (it includes the cost of the earth launch system) that relative performance as reflected in total weight of propellant and hardware overshadows all but extreme differences in cost; hence, cost estimates of lesser accuracy and detail are adequate for merit ordering of candidate systems provided that reasonably accurate weight estimates are available.

Several very extensive studies have been made of total program costs for earth launch systems, and computer programs for estimating costs have been written. Unfortunately, several of the crucial inputs to these programs have wide ranges of uncertainty which seriously degrade the value of the output estimates. Chief among these are the composite costs to develop a system to a known degree of reliability and the total usage of the system over which these development costs can be legitimately amortized. For propulsion systems other than earth launch vehicles little information on costs has been uncovered in this study. Further work will be necessary to obtain such information as exists and to determine the degree to which earth launch system costs are applicable to other than earth launch system.

Costs to be used as a propellant evaluation parameter can be compiled under three major groupings: 1) propellant cost, 2) vehicle hardware costs, and 3) launch operation costs. For other than earth launch vehicle applications, there is a fourth cost input parameter--the best state of the art cost, per pound, to transport the propulsion system from the earth launch point to the point in space at which it is to be used.

1. Propellant Costs

The costs of the propellant materials are an obvious starting point in determining the cost of a particular propellant system. Since the unit cost of materials may vary over several orders of magnitude this cost may have a sizable effect on the over-all cost of the launch program and thus be significant in the merit rating of the propellant. The unit cost of materials may vary with the rate and time schedule of usage; hence costs must be determined as a function of rate of production and the schedule for total planned production. The costs of producing propellants may be grouped conveniently under three headings:

(1) Cost of raw materials and facilities.

(2) Cost of production and facilities.

(3) Cost of transportation and facilities.

The combination of these costs will determine the unit price delivered at the earth launch site.

a. Raw Materials and Facilities

The sources and total supply of raw materials and the facilities for their production must be considered to determine what limitations on total usage of the propellant may be imposed, or what cost penalties either to unit cost or capital investment may be incurred as a function of quantity of propellant to be produced.

b. Propellant Production and Facilities

If the propellant components are not normal materials of commerce, or if a large increase over normal usage is anticipated, the availability and capital cost of expanded or new production facilities must be considered. For a high rate of usage and a demand of uncertain duration, the need for new production facilities may present burdensome difficulties with respect to capital investment and time of availability which can degrade the merit of a propellant relative to a material for which the need for new production facilities is less extreme.

c. Transportation and Facilities

The handling, transporting, and storing of propellant components may represent a substantial part of the total cost of the propellant as delivered to the launch vehicle. Although the cost of the propellant at the earth launch site may not constitute a large fraction of the total mission cost, it can involve a large sum in actual dollars, and, other considerations being equal, a propellant which can be handled cheaply has an advantage over those which cannot.

The major factors which will determine the logistics cost are listed here. The data for qualitative rating of propellants should be available as soon as the propellant is available in research quantities. Refinement of the evaluation to a quantitative basis will depend on determination of quantity usage and production site.

(1) Tankage and Piping Material Required.

Ordinary steel is the most economical material for tank and pipe construction. If a more expensive metal such as stainless steel, nickel, or monel or a rubber plastic or glass-lined construction must be used to contain and transfer the propellant, the cost will be increased.

(2) Insulation Required.

Some propellant components can readily be held at ambient earth temperatures without loss or deterioration. On the other hand, cyrogenic materials may require expensive temperature-control facilities. The economics of insulation cost versus loss of product, and venting versus reclaiming the boiloff, must be determined for low boiling components. Appropriate techniques for handling the components should be available when the propellant is proposed for use.

(3) Ventilation Required.

If there is substantial boiloff with or without temperature-control provisions or if the vaporized material is toxic or corrosive, special facilities may be required for ventilation or to control escape of the material. The extent of such required facilities should be determined.

(4) Spill and Disposal Facilities Required.

Facilities must be provided to cope with the problems resulting from spilled or contaminated components and to control damage from fire, explosion, and toxic vapors. Substantial spatial isolation of storage tanks may be necessary with consequent expense for space, piping, and pumping. The cost of the earth launch site can thus be affected by the propellant. These expenses are also incurred at the manufacturing site. Unless manufacture is accomplished at the launch site, however, the costs would normally be reflected in the pricing of the propellant rather than in the launch site capital cost.

In any event, the comparative effect of this factor for competing propellants can be estimated as a function of proposed volume of usage whenever the basic physical and chemical data are available and the proposed manufacturing and logistics procedure fixed upon.

(5) Launch Site Personnel Protection Required.

In addition to the protection afforded by the launch site layout and installed facilities, personnel may require additional protective measures.

The problem of providing adequate protection increases with increasing toxicity of the propellant components and their reaction products and may become particularly burdensome if the toxic effects are cumulative or incompletely known.

Protective measures may include protective clothing, shields and masks; barricaded, enclosed, pressurized or remote operating positions; special training, limited exposure time, and special selection of personnel.

(6) Transportation Safety Procedures Required.

If the propellant components are not manufactured at the earth launch site the problem of safe transportation from the manufacturing site must be considered.

A hazardous product may be produced simply and safely in a plant where all personnel can be properly trained, equipped, and supervised. Transporting the material through populated areas, however, may present difficulties which are expensive to contend with or which may prohibit the transport entirely. Until it has been ascertained that public safety and regulatory agencies will permit transport of the proposed propellant component in the necessary quantity by some practical means and route, the comparative evaluation of the propellant may have to be based on the assumption of manufacturing the component at the launch site which may have an adverse effect on the competitive merit of the system.

(7) Transportation Distances.

If the economical site for manufacture of the propellant component is distant from the earth launch site the comparative price of the component must, of course, include the shipping cost. Consideration must be given, in addition, however, to the problem of scheduling delivery at the required rate, the adequacy of common carrier facilities or the need for special transport equipment, product loss in transit and storage, and insulation requirements, to ensure that all the expenses involved have been included in the shipping costs.

2. Vehicle Hardware Costs

For nonterrestrial launches as well as launches from the earth the cost of hardware will be at least as great as the propellant cost. Since both the weight of the hardware and its unit cost may be sensitive to the choice of propellants for each propulsion system, the costs of hardware become an important parameter in the rating of propellants.

It is desirable because of the effect on costs of different characteristics of various propellants, and convenient because of contractual custom, to assemble and consider hardware costs under the general headings of 1) engines, 2) tankage, 3) structures (air frame) and 4) integration and transportation.

a. Engines

The engine of a propulsion system consists of the combustion chamber, nozzle, expansion cone, injection and ignition systems, cooling system, and the plumbing and mechanical parts for the transfer and control of propellant from storage to the combustion chamber. Engines must be designed for their specific application and propellant. Engine performance characteristics may include specifications on thrust level, ignition time, cut-off time, thrust buildup rate, throttling range, restart capability, etc.

The design of engines for large scale propulsion purposes is an immensely complex process involving the optimization of many design and operating parameters and is further complicated in that the optimum design is not independent of other elements of the total vehicle. The primary criterion of performance merit is the ratio of thrust to total weight. The criterion for cost is total cost per unit as a function of maximum thrust level attainable by the engine.

For purposes of propellant evaluation, engine costs should be compiled under three major headings: 1) research and development, 2) production and 3) testing.

(1) Research and Development.

Designing and developing an engine to a highly reliable state is a costly process and for the nominal production anticipated for space flight programs represents a large fraction of the total engine cost. Since the state of development of engines, the cost of development, and the production base over which the costs can be amortized all may vary for the specific propellants under comparison, it is essential that the research and development costs be considered as a separate item.

(2) Production Facilities and Operation.

The complexity of the production operation, the extent to which new facilities and techniques are required, the necessary investment and the schedule of production, as well as the cost on a unit and per pound basis may all vary for production of engines for different propellants and must therefore be investigated as important considerations in evaluating propellants.

(3) Test Facilities and Operation.

The cost of engine development and production test facilities and their operation will depend upon the propellant, because of site location requirements, handling problems, and the cost of the propellants used in the tests. For large engines these cost differences may be appreciable.

b. Tankage

On-board storage tanks for the propellant used in launch propulsion systems form a large part of the total weight and a smaller but appreciable part of the cost of the propulsion system. Propellant characteristics affect the size, strength, configuration, pressurization system, vortex control, and materials of construction of the tankage and therefore influence its cost. The parameter to be considered is cost per unit of volume as a function of volume.

The costs of tankage are best compiled for propellant evaluation purposes under the headings of (1) research and development and (2) production facilities and operation.

(1) Research and Development.

For large units very substantial efforts are justified to develop an optimum design for the tankage of a launch vehicle. The costs of this development and the base over which it can be amortized will vary appreciably among propellants to be evaluated because of differing stages of development at the time of evaluation and differing problems with respect to size, materials, configuration, etc. These costs, therefore, should be segregated for consideration in the evaluation.

(2) Production Facilities and Operation.

For very large units the techniques of production and the capacity of existing production facilities may be exceeded or the location of existing facilities may be inappropriate. To the extent that new facilities and tooling for novel techniques and materials must be provided, the cost of production facilities may vary substantially among propellants; so also may the cost of operation of the facilities. Thus for large units these costs may be of consequence in the evaluation procedure.

c. Structures

For each stage and for the several stages of multistage vehicles, the engines, tankage and payloads must be assembled into a structurally stable unit and the necessary shielding provided for payloads and propellant to control temperature, exposure to radiation and damage by meteorites. Depending upon construction and configuration design a variable amount of the shielding may be integral with the tankage construction. In fact the complete design, development, and production of the structure of a stage (or a complete vehicle) may be carried out as a unified program with the tankage design. Practice to date has been along this line in contractual arrangements for major propulsion stages. However, the sensitivity of the weight and cost of the structural parts of the vehicle to characteristics of the propellant is different from that of the tankage, so that to the extent possible it is helpful in propellant evaluation to have the costs separately available, organized under headings of 1) research and development and 2) production as for tankage costs.

d. Integration and Transportation

For major propulsion systems the engine is contracted for and built separately from the tankage and structural elements. Furthermore in multistage vehicles each stage and the payload may have been produced independently. The combining of the several parts into a complete, tested vehicle constitutes a sizable part in the total effort of producing the vehicle. For large units the costs involved may be appreciably sensitive to the choice of propellants, primarily because of the influence of the propellant on the size and weight of components, the capital cost of transport and test facilities, the choice of assembly site, and the production base over which capital costs can be amortized.

Costs should be available for:

(1) Component (engine, tanks, etc.) stage and complete vehicle transportation facilities and operation.

(2) Stage and complete vehicle assembly and checkout facilities and operation, and

(3) Complete vehicle test facilities and operation.

3. Launch Operation Costs

The site for the launching of space vehicles from the earth is an expensive complex of launch pads; transport; storage facilities; control, tracking and communication systems; service, checking and maintenance facilities; emergency safety and damage control systems; and other accessory support activities. The site must be sufficiently remote to protect the public from nuisance, property damage and personal injury resulting from normal launch operations, aborted launches and ground-level accident. For large launch vehicles, the acquisition, construction and equipping of a launch site is sufficiently expensive and time-consuming that multiple sites are not likely to be practical. Once the site has been selected, which would appear now to have been done, all subsequent selections of propellants must be compatible with the chosen launch site. If compatibility can be achieved only by addition to or modification of the site, the costs involved must be considered in evaluating the propellant.

The major propellant-dependent costs associated with the launch operation are:

(a) Necessary increase in launch site size.

(b) Propellant storage and loading facilities and operations.

(c) Launch structures, equipment and operation.

(d) Abort damage control facilities and operation.

V CONCLUSIONS AND RECOMMENDATIONS FOR IMPLEMENTATION

The key steps in the procedure outlined and described in this report are: 1) the assembly of pertinent information on NASA requirements and on propellant characteristics; 2) comparison of requirements with characteristics to identify technically feasible applications for the propellants; 3) estimation of system designs using the propellants in feasible applications; 4) estimation of the total resource consumption that would result from the use of these propellants in these applications; and 5) the evaluation of each propellant on the basis of its usefulness in minimizing the total resource consumption of the NASA space program.

This procedure will be carried out many times as decisions are required in the course of an R&D program, with increasing detail and accuracy as the completeness and accuracy of the input data and the cost of the next phase of the program increase. (It should be pointed out, however, that application of the procedure over a period of time will reveal general relationships that will make it possible to answer many specific questions about propellant merit without going through the complete evaluation routine.) The procedure is superior to those in common use in that the amount of analytical work and the number of points at which subjective value judgments are made are kept to a minimum.

In this phase of the research the pertinent input information has been identified in detail and the form in which it should be expressed to facilitate the evaluation has been indicated.

The following have not been done:

1. Compilation of the quantitative data needed to express the requirements of the NASA program in numerical form

2. Compilation of the data needed to describe quantitatively the pertinent characteristics of currently available propellants

3. Analysis of current design, development, production, operation, and costing concepts to ascertain the mathematical relationships by which estimated values of evaluative parameters (particularly propellant and hardware weight and cost) may be calculated from the information on requirements and propellant characteristics.

The evaluative procedure cannot be applied to specific examples until these things have been done.

The large amount of routine information storage and retrieval, sorting and calculation work involved in carrying out an evaluation can most readily be accomplished with the aid of a digital computer. It is possible that computer programs developed by various agencies in the furtherance of other purposes may be adaptable to this work. Computer routines are available to calculate earth launch program costs and individual component costs from well-defined input information. Design programs to calculate weights of individual components, stages, and complete vehicles are available, as well as routines for the calculation of specific impulse from basic chemical and thermodynamic data. Adaptation of these routines to the requirements of the propellant evaluation procedure particularly with respect to the weight and cost factors should permit CTRC values to be generated rapidly and with relative ease.

APPENDIX

PROPELLANTS FOR MULTISTAGE LAUNCH VEHICLES

It is important to recognize that since the final evaluation of a propellant is to be based on CTRC values, comparisons should be made between configurations of equivalent performance; hence, the effect produced on the total resource consumption for the entire mission by a change in the propellant used for a particular propulsion system is to be determined. Thus the CTRC estimate must include not only the CTRC for research, development, and production of the propulsion system, but also the CTRC required to deliver it to the point of use. For an earth launch booster, this is the CTRC required to deliver it to Cape Canaveral and fire it. For a propulsion system to accomplish space maneuvers on a return trip from Mars to Earth, the CTRC to be considered includes the CTRC of the Mars launch vehicle, the space maneuver system for the Earth-Mars trip, and the Earth launch vehicle. When propellants are being evaluated for a particular stage of a multistage launch vehicle, the CTRC to be considered is the total CTRC of the launch vehicle, with stage sizes optimized with respect to CTRC. This optimization may be accomplished by a method such as the one developed by C.H. Builder.[3] The optimization, as well as the calculation of vehicle CTRC, requires values of the derivative of stage CTRC with respect to stage weight. The stage CTRC values must include the CTRC required to deliver the stage to the point of launch (to Cape Canaveral for an Earth launch vehicle, or to the surface of Mars for a Mars launch vehicle).

As illustrations of the operation of the evaluation procedure, rough comparisons have been made of the relative merits of LO_2 /RP-1, LO_2 /LH_2 , and LF_2 /LH_2 for use in earth launch boosters, and of LO_2 /LH_2 and LF_2 /LH_2 for use in upper stages of earth launch vehicles and in space maneuver propulsion systems. Detailed analyses of mission requirements, physical and chemical characteristics of propellants, and resource consumption factors were not made by SRI for these comparisons. Instead, values of evaluation parameters for the various propellants were derived from information presented in reports issued by Boeing Airplane Company and North American Aviation, Inc., on advanced propulsion systems studies they performed under Air Force contract.[4,11] A considerable amount of disagreement was found between information presented by one contractor and that presented by the other, and neither contractor presented complete information. However, it was possible to infer from the information presented that the requirements postulated by those organizations for Air Force missions can be met by boosters using any of the three propellants, or by upper launch vehicle stages and space maneuver systems using either of the latter two; also it was possible to obtain rough estimates of the appropriate evaluation parameters for each propellant. (CTRC values were obtained from total program cost estimates by a normalization process.) Since the data presented by the two organizations did not agree, the estimates of evaluation parameters were based on values intermediate between those reported.

These estimated values are presented in Table I. The specific impulse values are assumed to be effective values for appropriate chamber pressures and expansion ratios--the earth booster values for operation through an altitude range corresponding to a typical flight path, and the vacuum stage values for operation in space. The hardware weight/stage weight ratios are assumed to be independent of type and size of stage, an assumption that can be made only for rather rough calculations. The CTRC for each propellant appears to be a nearly linear function of stage weight. The base line and the size of the CTRC unit were arbitrarily chosen so that the function for LO_2/RP-1 would be a line through the origin with a slope of unity; the slopes of the CTRC lines represent ratios of the weight-sensitive costs for each propellant combination to those for the reference combination, and the intercepts are measures of the amounts by which the weight-insensitive costs exceed those of the reference. The base line can be set in this arbitrary fashion if, and only if, comparisons are to be made among configurations with equal numbers of stages. The CTRC values were derived on the assumption that one hundred propulsion systems of any one type under consideration would be built over a period of ten years.

Table I

TENTATIVE EVALUATION PARAMETERS FOR
LO_2/RP-1, LO_2/LH_2, LF_2/LH_2

	A	B	C
	LO_2/RP-1	LO_2/LH_2	LF_2/LH_2
Earth booster I_{sp}	278	370	387
Vacuum stage I_{sp}	315	425	440
$\frac{\text{Hardware weight}}{\text{Stage weight}}$	0.0510	0.0640	0.0570
$\frac{d\text{ (stage CTRC)*}}{d\text{ (stage lb)}}$	1.0	1.5	1.7
Lim (Stage CTRC)* Stage wt → 0	0	$2.8 \cdot 10^5$	$4.2 \cdot 10^5$

* CTRC based on assumption that a total of 100 propulsion systems of the type under consideration will be built, over a period of 10 years.

It may be seen from the table that no propellant is superior to any other in all respects. Hence, it is necessary to calculate total CTRC values for optimum configurations to complete the evaluation.

With the data presented in Table I, optimum stage weights were calculated for two-stage earth launch vehicles, employing various combinations among the three propellants, that would give a payload of 100,000 lb an ideal velocity gain of 35,000 ft/sec. Optimum stage weights were also calculated for three-stage vehicles that would give the same payload an ideal velocity gain of 45,000 ft/sec. (The ideal velocity gain is the velocity gain that would be produced if there were no atmospheric drag or gravitational effects; an ideal velocity gain of 35,000 ft/sec corresponds roughly to a launch into a 300-nm (nautical mile) earth orbit, and one of 45,000 ft/sec to a launch into an earth-moon trajectory.) CTRC values were then computed from each stage weight and were summed to obtain total CTRC values for each vehicle configuration. The results of these calculations are shown in Tables II and III. These results clearly indicate that LO_2/RP-1 is not the best choice of propellant for upper stages of a launch vehicle. They also suggest that LF_2/LH_2 may be superior to LO_2/LH_2 for the final stage of a launch vehicle.

Again using the data presented in Table I, the weights of LO_2/LH_2 and LF_2/LH_2 space maneuver propulsion systems capable of giving a 50,000 lb payload a velocity change of 10,000 ft/sec were calculated. These propulsion systems and their payloads together represented payloads of 112,000 lb and 108,000 lb, respectively, to the vehicles that would be required to launch them. Stage weights of selected two-stage vehicles that could give them 35,000 ft/sec ideal velocities and three-stage vehicles that could give them 45,000 ft/sec ideal velocities were then computed by multiplying weights given in Tables II and III by the appropriate ratios of payload weights. CTRC values were then computed for each space maneuver system and launch vehicle stage, and summed to obtain totals for each configuration. The results of these calculations are shown in Table IV. It may be seen that a slight difference in total mission CTRC appears for a space maneuver system launched into an earth moon trajectory (the LF_2/LH_2 system being superior), but not for one launched into a 300-nm earth orbit.

These calculations are presented primarily as an example of the optimization procedure required in the evaluation of propellants for multistage vehicles. As has been indicated, the input data for the calculations was derived from propellant evaluation studies by other organizations. The evaluation procedure followed by these organizations differed from the one outlined in this report in several important respects and the effects of these differences cannot be assessed because of the limited information presented in the available reports. Tables II, III, and IV therefore should not be construed as results from the application of the complete evaluation procedure outlined in this report.

Table II

CTRC FOR TWO-STAGE LAUNCH VEHICLES USING VARIOUS PROPELLANT COMBINATIONS
(Payload 100,000 lb, Ideal Velocity Gain 35,000 ft/sec)

Stage Propellant		First Stage		Second Stage		Total	
1st	2nd	$wt \cdot 10^{-5}$	$CTRC \cdot 10^{-5}$	$wt \cdot 10^{-5}$	$CTRC \cdot 10^{-5}$	$wt \cdot 10^{-5}$	$CTRC \cdot 10^{-5}$
A	A	65	65	9.5	10	75	75
A	B	26	26	8.0	15	34	41
A	C	19	19	8.5	19	28	38
B	B	18	29	5.5	11	23	40
B	C	13	22	5.0	13	18	35
C	C	13	26	5.0	13	18	39

Table III

CTRC FOR THREE-STAGE LAUNCH VEHICLES USING VARIOUS PROPELLANT COMBINATIONS
(Payload 100,000 lb, Ideal Velocity Gain 45,000 ft/sec)

Stage Propellant			First Stage		Second Stage		Third Stage		Total	
1st	2nd	3rd	wt·10^{-5}	CTRC·10^{-5}	wt·10^{-5}	CTRC·10^{-5}	wt·10^{-5}	CTRC·10^{-5}	wt·10^{-5}	CTRC·10^{-5}
A	A	A	145	145	41	41	6.1	6	192	192
A	A	B	48	48	36	36	8.0	15	92	99
A	A	C	40	40	29	29	8.0	18	77	87
A	B	B	31	31	23	37	4.2	9	58	77
A	B	C	26	26	19	31	4.3	11	49	68
A	C	C	24	24	18	35	3.8	11	46	70
B	B	B	27	43	18	30	4.0	9	49	82
B	B	C	21	34	18	30	4.2	11	43	75
B	C	C	21	34	16	31	3.5	10	41	75
C	C	C	19	37	16	31	3.5	10	38	78

Table IV

CTRC FOR SPACE MANEUVER PROPULSION SYSTEMS
USING VARIOUS PROPELLANT COMBINATIONS AND LAUNCHED FROM EARTH BY
TWO-STAGE AND THREE-STAGE LAUNCH VEHICLES

(Payload 50,000 lb; Ideal Velocity Gain 10,000 ft/sec; Launch Vehicle Ideal Velocity 35,000 ft/sec for Two-Stage Launch, 45,000 ft/sec for Three-Stage Launch)

Space Maneuver System			Launch Vehicle									Total System
			First Stage			Second Stage			Third Stage			
Prop.	$wt \cdot 10^{-5}$	$CTRC \cdot 10^{-5}$	Prop.	$wt \cdot 10^{-5}$	$CTRC \cdot 10^{-5}$	Prop.	$wt \cdot 10^{-5}$	$CTRC \cdot 10^{-5}$	Prop.	$wt \cdot 10^{-5}$	$CTRC \cdot 10^{-5}$	$CTRC \cdot 10^{-5}$
B	0.62	3.7	A	29	29	B	9	16	-	-	-	49
C	0.58	5.2	A	28	28	B	9	16	-	-	-	49
B	0.62	3.7	A	35	35	B	26	42	B	4.7	10	91
C	0.58	5.2	A	34	34	B	25	41	B	4.5	10	90

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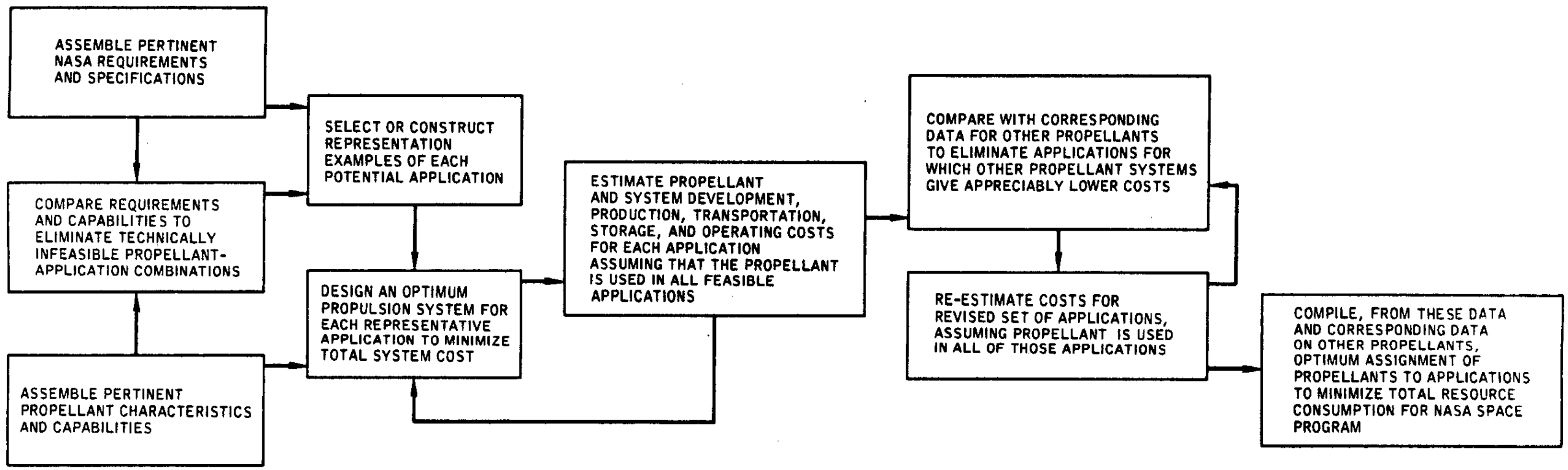
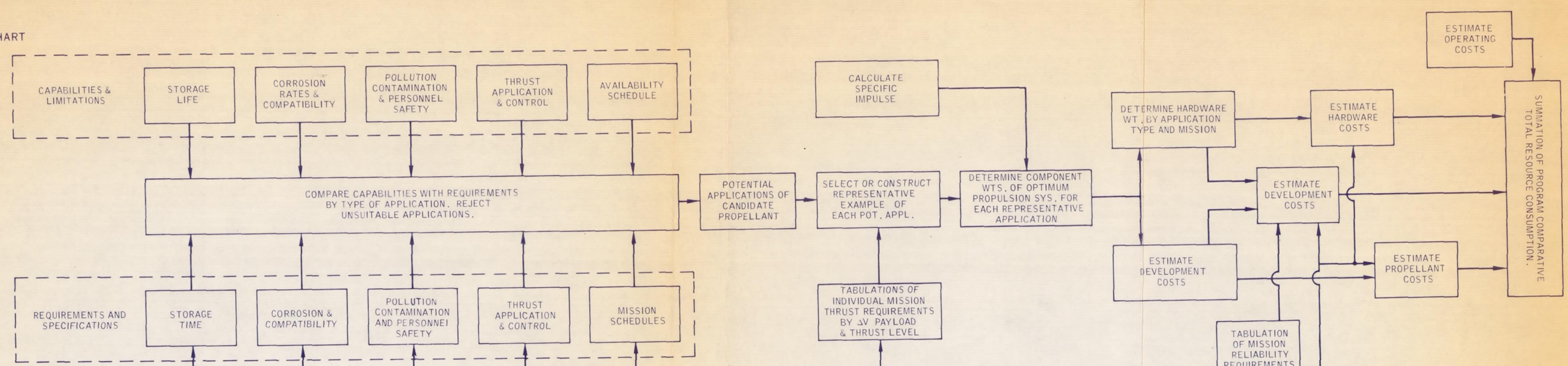


CHART I BASIC OUTLINE OF EVALUATION PROCEDURE

IIB OPERATION FLOW CHART



IIC NASA REQUIREMENTS AND SPECIFICATIONS

A. ALL LAUNCH REQUIREMENTS
1. EARTH LAUNCH SITE ABORT SAFETY
   a. AREA & CONCENTRATION LIMIT ON AIR POLLUTION
   b. AREA & CONCENTRATION LIMIT ON SURFACE CONTAMINATION

B. ALL NON-TERRESTRIAL LAUNCHES
1. PLANETARY OR LUNAR LAUNCH ABORT RESTRICTIONS FOR SAFETY OF:
   a. ON BOARD PERSONNEL
   b. PLANET OR LUNAR SUPPORT PERSONNEL
   c. PLANET OR LUNAR SUPPORT FACILITY
2. RESTRICTIONS ON PLANET OR LUNAR GASEOUS POLLUTION
3. RESTRICTIONS ON PLANET OR LUNAR SURFACE CONTAMINATION

C. EARTH LAUNCH VEHICLE
1. OVER-ALL REQUIREMENTS
   a. SPECIFIED RELIABILITY
2. BOOSTERS
   a. LAUNCH SCHEDULE
   b. ΔV^S & PAYLOADS
   c. TOTAL IMPULSE TOLERANCES
   d. NORMAL OPERATION RESTRICTIONS FOR SAFETY OF:
      (1) ON BOARD PERSONNEL
      (2) GROUND SUPPORT PERS.
      (3) GROUND SUPPORT FACILITY
      (4) LOCAL POPULATION
      (5) LOCAL PROPERTY
   e. NORMAL OPERATION AREA OR CONCENTRATION LIMIT ON:
      (1) AIR POLLUTION
      (2) VEHICLE CONTAMINATION
      (3) EARTH SURFACE CONTAMINATION
3. UPPER STAGES
   a. LAUNCH SCHEDULE
   b. ΔV^S & PAYLOADS
   c. VACUUM OPERATION
   d. ALTITUDE START & RESTART
   e. START & CUT OFF ACCURACY
   f. TOTAL IMPULSE TOLERANCES
   g. RESTRICTIONS FOR SAFETY OF ONBOARD PERSONNEL
   h. LIMITS ON VEHICLE SURFACE CORROSION OR CONTAMINATION

D. PLANETARY LAUNCH VEHICLES
1. OVER-ALL REQUIREMENTS
   a. ON-VEHICLE STORAGE LIFE
   b. SPECIFIED RELIABILITY
2. BOOSTERS
   a. LAUNCH SCHEDULE
   b. ΔV^S & PAYLOADS
   c. TOTAL IMPULSE TOLERANCES
   d. COMPATIBILITY WITH PLANET ATMOSPHERE
   e. NORMAL OPERATION RESTRICTIONS FOR SAFETY OF:

(1) ON BOARD PERSONNEL
(2) PLANET SUPPORT PERSONNEL
(3) PLANET SUPPORT FACILITY

f. NORMAL OPERATION AREA OR CONCENTRATION LIMITS ON:
(1) ATMOSPHERE POLLUTION
(2) VEHICLE CONTAMINATION
(3) PLANET SURFACE CONTAMINATION

3. UPPER STAGES
a. LAUNCH SCHEDULE
b. ΔV^S & PAYLOAD
c. VACUUM OPERATION
d. ALTITUDE START & RESTART
e. START & CUT OFF ACCURACY
f. TOTAL IMPULSE TOLERANCES
g. NORMAL OPERATION RESTRICTIONS FOR:
(1) SAFETY OF ON BOARD PERSONNEL
(2) VEHICLE CORROSION
(3) VEHICLE SURFACE CONTAMINATION

E. LUNAR LAUNCH VEHICLES
1. OVER-ALL REQUIREMENTS
a. ALL VACUUM OPERATION
b. VACUUM START CAPABILITY
c. ON-VEHICLE STORAGE LIFE
d. SPECIFIED RELIABILITY
2. BOOSTERS
a. LAUNCH SCHEDULE
b. ΔV^S & PAYLOAD
c. TOTAL IMPULSE TOLERANCE
d. NORMAL OPERATION RESTRICTIONS FOR SAFETY OF:
(1) ON BOARD PERSONNEL
(2) LUNAR SUPPORT PERSONNEL
(3) LUNAR SUPPORT FACILITY
e. NORMAL OPERATION AREA OR CONCENTRATION LIMITS ON:
(1) VEHICLE SURFACE CONTAMINATION
(2) LUNAR SURFACE CONTAMINATION
3. UPPER STAGE
a. LAUNCH SCHEDULE
b. ΔV^R & PAYLOAD
c. RESTART CAPABILITY
d. START & CUT OFF ACCURACY
e. TOTAL IMPULSE TOLERANCES
f. NORMAL OPERATION RESTRICTIONS FOR:
(1) SAFETY OF ON BOARD PERSONNEL
(2) VEHICLE CORROSION
(3) VEHICLE SURFACE CONTAMINATION

F. SPACE MANEUVER
1. ALL VACUUM OPERATION
2. SPACE START & RESTART CAPABILITY
3. START AND CUT OFF ACCURACY
4. SPECIFIED RELIABILITY
5. LAUNCH SCHEDULE PAYLOADS,
6. ΔV^R, INCREMENT SCHEDULE
7. TOTAL IMPULSE TOLERANCES
8. ON-VEHICLE STORAGE LIFE
9. NORMAL OPERATION RESTRICTIONS:
a. FOR SAFETY OF ON BOARD PERSONNEL
b. ON VEHICLE SURFACE CONTAMINATION OR CORROSION

G. AUXILIARY POWER
1. GENERAL
a. SPECIFIED RELIABILITY
b. NORMAL OPERATION RESTRICTIONS FOR:
(1) SAFETY OF ON BOARD PERSONNEL
(2) ON-VEHICLE SURFACE CONTAMINATION OR CORROSION
2. STAGE SEPARATION
a. LAUNCH SCHEDULE
b. NUMBER OF UNITS, TOTAL IMPULSE
c. SPACE START
d. ON-VEHICLE STORAGE LIFE
3. ULLAGE ROCKETS
a. LAUNCH SCHEDULE
b. NUMBER OF UNITS, TOTAL IMPULSE
c. SPACE START & RESTART CAPABILITY
d. ON-VEHICLE STORAGE LIFE
4. STEERING AND ATTITUDE CONTROL
a. LAUNCH SCHEDULE
b. NUMBER OF UNITS, TOTAL IMPULSE
c. SPACE START & RESTART CAPABILITY
d. START & CUT OFF ACCURACY
e. TOTAL IMPULSE TOLERANCES
f. ON-VEHICLE STORAGE LIFE

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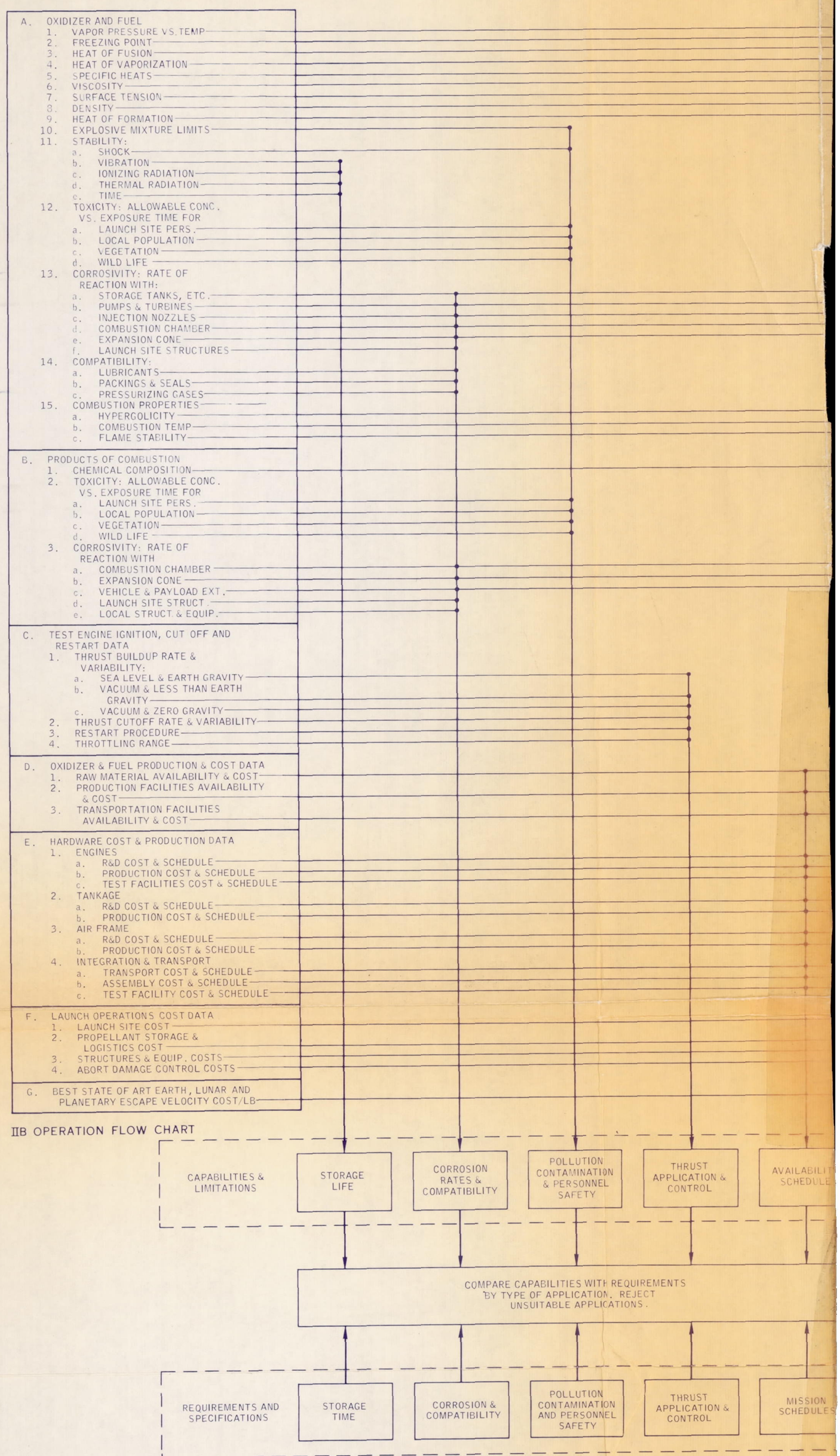
CHART II CONCLUDED

IIA PHYSICAL-CHEMICAL COST INPUT DATA



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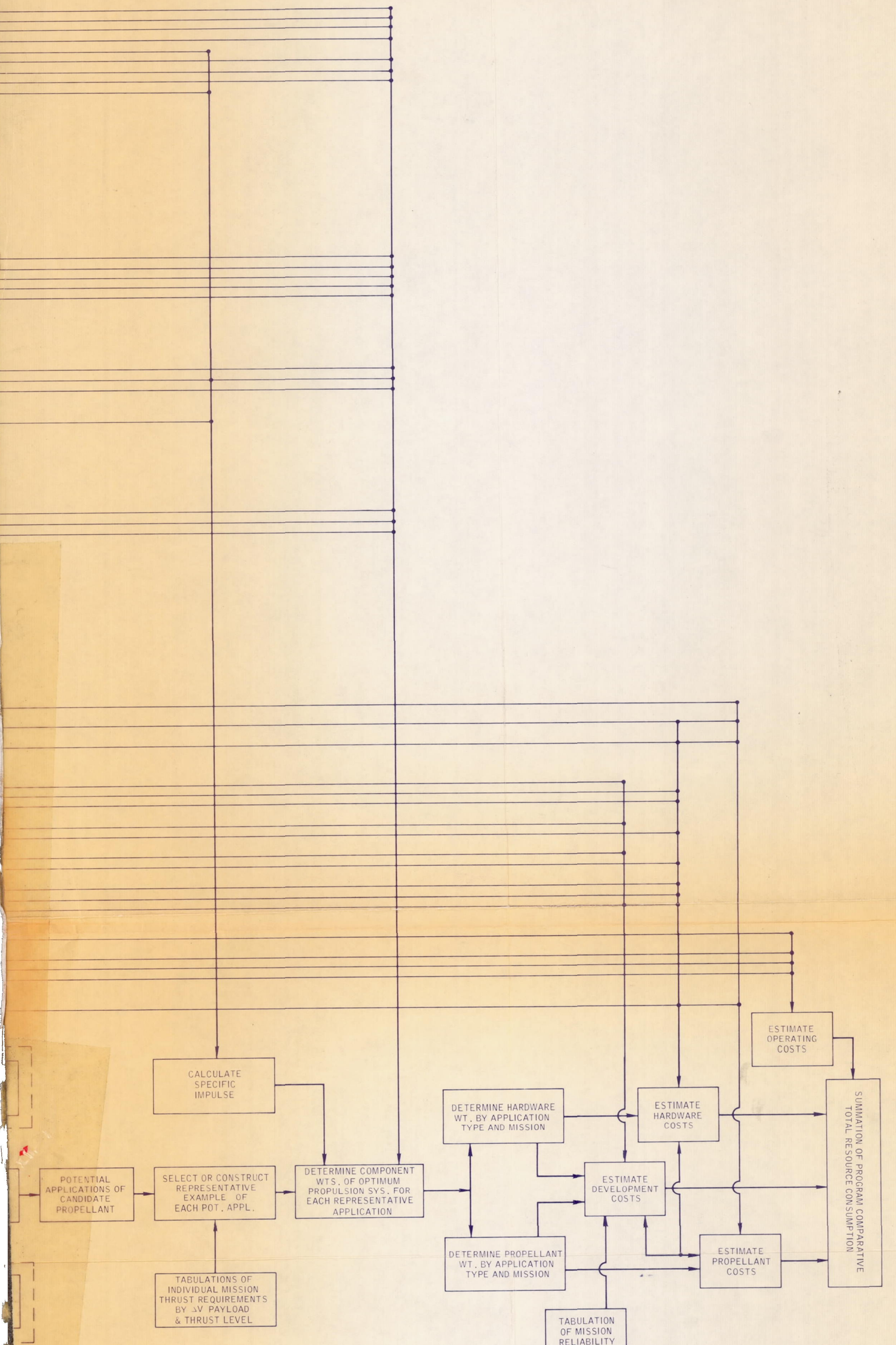

CEDURE FOR INDIVIDUAL PROPELLANT

RC-3652-19

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