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ROCKET ENGINE SELECTION CRITERIA

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ABSTRACT

This paper considers many of the factors and criteria which have to be considered and evaluated when selecting a specific rocket engine for a given vehicle application. The lists of criteria can be helpful as check-lists in design and systems engineering of a rocket propulsion device. About ten different applications are examined to illustrate the relative importance of some of these selection criteria. There will be groupings of four major types of criteria; namely, performance, operational, economic and so-called judgment criteria. In many cases the last three categories are equally or more important than the performance criteria in selecting one of several rocket engines for a specific application. The actual selection usually is a compromise to make the rocket engine responsive to several important criteria.

INTRODUCTION

There are many different types of rocket engines; each is particularly suitable for certain classes of applications. For each specific application there are a number of key rocket propulsion parameters, or characteristics, which are usually emphasized in the selection process. Table 1 lists ten different types of typical vehicle applications, together with a few of the more common key propulsion characteristics. It is easy to see that the rocket engine types used in each of these applications are very different from each other in physical size, appearance, performance, and are designed specifically for each of these jobs. The characteristics that are "of value" in one type of vehicle are not necessarily germane or "of value" in another.

In order to illustrate the nature of various selection criteria, two different applications have been chosen for more detailed discussion. They are:

1. Liquid propellant upper stage maneuvering rocket engine for long-duration space flight.
2. Solid propellant aircraft launched rocket for military air-to-air or air-to-ground weapons.

Since this discussion covers more than one class of application, it is quite general. It will be limited to chemical propulsion (solid and liquid propellant rockets); hence, it does not include more advanced propulsion schemes, because these are not yet operational.

The equivalent vacuum vehicle velocity increment of a given application (as listed in Table 1) is the hypothetical velocity the vehicle would attain in a gravitationless vacuum by the application of the total impulse of its rocket propulsion device; it is an indicator of the difficulty of the mission as well as an indicator of the relative importance of obtaining high rocket engine performance. Of the ten applications listed, the upper-stage space maneuver rocket has the highest performance requirement; the upper-stage ICBM and the upper-stage AICBM are second highest.

The other columns in Table 1 are descriptors which are peculiar to the various applications. The last column lists some of the important selection criteria peculiar to each application; these and other criteria will be discussed in more detail.

PERFORMANCE CRITERIA

Table 2 gives a list of typical selection criteria which have been used for evaluating rocket engine performance and a correlation for each of the listed criteria with ten different applications. The table is divided into several parts, each having to do with engine performance, storage, vehicle factors, reliability and other criteria. All the criteria listed are important and have "value" in at least one application. Several of the more interesting or unusual criteria will now be arbitrarily singled out and discussed in more detail for the two arbitrarily chosen applications. Many of the items listed in this and subsequent tables are not discussed here; they could easily become the subject of some further stimulating

discussion; however, this article would then become very long. The levels of importance and the criteria listed in Table 2 and subsequent tables are based largely on the author's experience and may not coincide with the experience of others in similar applications.

The performance indicated by a high equivalent vehicle velocity increment (see Table 1) means the following in terms of rocket engine parameters:

1. Select propellant combination with the highest possible theoretical specific impulse to attain the ultimate in performance (see Table 1). This means that cryogenic propellants such as oxygen-hydrogen (I_s = 391 sec*) or fluorine-hydrogen (I_s = 410 sec) should be used for the upper-stage space engine. Cryogenic propellants give better performance than other types of propellants, as shown in Fig. 1. Since the equivalent vehicle velocity increment for an air-launched missile is relatively low, a well-known composite solid propellant (I_s = 262 sec) is adequate; although the performance is lower, this propellant has other very desirable characteristics. In military applications, a low volume or high density is usually important. As seen from Table 1, the solid propellant has a good value of density specific impulse.

2. Select designs which give good combustion efficiency and a high nozzle efficiency and thus come as close as possible to the theoretical specific impulse values. This applies to all of the rocket applications, for it is desirable to avoid unnecessary energy losses.

3. Minimize the rocket propulsion weights, both the hardware and residual propellant weights. This applies again to all rockets; however, this and the previous item are particularly important in applications where the equivalent vehicle velocity increment is high; usually extra development effort is spent to reduce weight and increase combustion efficiency even if it is only a small improvement.

*The specific impulse values are quoted at 1000 psi chamber pressure and expansion to sea level atmosphere pressure.

4. At very high altitude and in a vacuum, it is possible to expand the gases further and to effectively use a large nozzle exit area to give an additional small increase in exhaust velocity or effective specific impulse. Thus, spacecraft engines (both the maneuver engines and the attitude control engines) should operate with as large an exit nozzle as is practical without causing undue weight penalties.

The residual propellant is the portion of the liquid propellant (usually 1/2 to 4 percent) which is not used but remains in the vehicle or in parts of the engine (residual liquid propellant trapped in tanks, plumbing or cooling jacket). In the case of solid propellant grains there are residual "slivers" of solid propellant that are not used effectively. In high-performance applications, such as liquid propellant space maneuver engines, there is a considerable premium on reducing this residual propellant to a minimum in order to assure good mass ratio and maximum flight performance. This is illustrated by Fig. 2 for a typical upper stage, where a small variation in residual propellant causes a large variation in payload. Here sophisticated design features are appropriate, such as special tank expulsion devices, automatic mixture ratio controls (to assure simultaneous emptying of both the liquid fuel and the liquid oxidizer tank), minimum volume plumbing, or clever injectors which can operate satisfactorily with a mixture of propellant and pressurizing gas. In applications where performance is not so significant, such as in a solid-propellant air-launched missile or a barrage rocket, the sliver loss may well be tolerated and can be offset by a simpler grain design with attendant improvements in cost and reliability.

A space maneuver engine can be exposed to gravity-free vacuum for long periods of time. This implies that the exposed materials must be carefully chosen to prevent evaporation of paints or protective or thermal coatings and to prevent freezing of bearing surfaces and lubricants (on thrust vector control devices or valves). Also, propellant vent lines may have to be heated to prevent freezing of residual propellant in the line due to evaporation. A solid frozen plug in a vent line will prevent the venting function from occurring. The lack of gravity may bring about flight

conditions where the tank outlet of partially emptied propellant tanks may not be covered by liquid propellant, but instead by pressurizing gas. When a liquid propellant rocket engine is started it must be fed with liquid propellant, for the engine will not operate safely when fed with a gas or a mixture of liquid and pressurizing gas. A positive-propellant expulsion device (e.g. a flexible bladder or a bellows-separating liquid propellant from pressurizing gas) must therefore be used inside the propellant tanks in all engines which have start-under-zero-gravity conditions, such as from a coasting flight in space. Clever design features in the expulsion devices, which permit a low residual propellant fraction, multiple starts and simple mechanism, will be very desirable.

Many performance parameters are sensitive to various external influences, and their variation is usually an important selection criteria. The rocket propulsion system manufacturer must guarantee a certain minimum performance or the maximum deviations from nominal performance (e.g., nominal thrust, specific impulse, start interval time to reach full thrust, etc.) and, therefore, has to establish (by analysis and test) the variation of this performance with various environmental parameters.

For example, the starting interval time and chamber pressure rise rate of cryogenic liquid propellant engines depend on slight variations in the vapor pressure and, therefore, the temperature of the propellant reaching the thrust chamber. Therefore, a careful control of the heat absorbed by the cryogenic temperature of the first propellant reaching the thrust chamber can be critical. The ambient pressure (or altitude) can influence the setting of a pressure regulator which in turn determines the tank pressure and, thus, indirectly the thrust level. Excessive water absorption of a nitric acid oxidizer liquid has been shown to cause an abnormally high pressure rise at ignition. Contamination of propellant or flow passages with dirt and foreign particles has been responsible for clogging of filters, malfunctions of valves and injector misimpingement, which in some cases can cause a performance loss or a chamber burnout. Water droplets and moisture in a cryogenic propellant pipe will quickly be changed to ice crystals, which also cause clogging.

The thrust level of a solid-propellant air-launched guided missile can vary up to ± 25 percent, depending on the ambient temperature of the grain, and a propellant with a low temperature sensitivity is therefore very desirable. Small impurities or processing variations in the manufacture of solid propellant can cause significant changes in burning rate and, therefore, thrust.

Temperature cycling during storage is a most significant selection criteria for an air-launched missile. Viscoelastic materials, such as solid propellant, certain types of igniters, seals, gaskets and insulation, can experience severe thermal stresses as the ambient storage temperature changes in typical day-to-night cyclic variations. This causes progressive damage within the material to the point where it can no longer fulfill its intended design function. In some applications, environmental storage temperature variation can be severe, for example in solid-propellant missiles which are stored external to aircraft; here a typical aircraft flight will encounter hot sea level air (+170°F in the sun), cold altitude air (-65°F or lower) and in some cases temporary severe aerodynamic heating (over 300°F). The stresses in such a solid-propellant grain can cause cracks in the grain, which progress with every thermal cycle. These cracks can lead to subsequent violent rocket failures.

Heat transfer from hot flames by radiation and convection to exposed parts of the vehicle is a problem in many applications; it can be minimized by clever engine design, good installation design, and thermal protection of exposed parts. In a space engine there is a further expansion of the gases outside the nozzle which can cause an excessive convection-type heat transfer to vehicle surface unless the nozzle protrudes beyond the vehicle skin (see Fig. 3). Thus, space maneuver rockets usually have their nozzles outside the vehicle itself.

The rocket engine exhaust flame gives off (or absorbs) radiations in the visible part of the spectru, the ultraviolet and infrared regions and in many cases also in the radio frequency spectrums. These effects are complex and involve the species in the exhaust, the interaction with the atmosphere, the altitude, and the shock pattern in the jet. In some applications, these effects are desirable and should be enhanced by clever design; for example,

high-intensity visible emissions will assist in optical tracking of vehicles on experimental launch ranges and certain additions to the propellant (such as a small amount of sodium) will augment this emission. On the other hand, strong flame emissions are undesirable in ballistic missile application, because they allow an early detection, tracking and, thus, an early warning of impending attack; certain propellant formulations and additives and also clever nozzle and thrust chamber design can minimize these emissions.

The hot exhaust gases contain electrically active species (ions and electrons), and these generate or interfere with radio frequency signals. For example, flames can absorb or attenuate telemetry signals so that telemetry reception from a spacecraft is disturbed during a period of the operation of the maneuver rocket engine. On the other hand, the flame can create spurious or distorted radio or radar returns; the exhaust of an air-launched guided missile can interfere with the target tracking function or the radio guidance signal transmission. In some cases, radio frequency signals are created by the exhaust flame, and this would permit passive tracking of the vehicle. Clever rocket design or changing the composition of propellants can influence and alter these radio frequency effects.

Thrust vector control is essential for space maneuver engines, ICBM propulsion, anti-ballistic missile, or space launch vehicles. There are a variety of different concepts (gimbal suspension of thrust chamber, side-injection of secondary fluids, jetevators, jet vanes, etc.), and each have their particular merit for specific applications. The angle of motion, the moment of inertia, the performance losses to the engine, the angular acceleration, and rate of the moving parts, the actuating forces or torques, the actuating power, the response characteristics, the required accuracy, duration, and the dynamic interaction with the vehicle are important selection criteria in choosing one thrust vector control concept over another.

Other important criteria to an upper-stage space maneuver rocket are flexibility for alternate mission (e.g., In case of certain spacecraft failure the engine may be used in an emergency mode for a thrust duty cycle different from that originally planned for a normal mission--and the engine design should thus permit operation in such an emergency mode.), the ability to

withstand very severe vibration during the operation of the booster stage prior to its own operation, or the precision and tolerances of the thrust buildup (to prevent (a) unsafe engine conditions and (b) excessive vibration excitation of the vehicle structure), as well as the thrust decay. (Here a precise and predetermined cut-off impulse magnitude and vector direction is desired in order to achieve a predetermined terminal velocity.) Important also are the engines' ability to restart in a zero gravity environment perhaps six to ten times and the assurance that combustion will at all times be stable and free of combustion vibrations (which cause excessive heat transfer, damaging vibrations and can cause rapid failure of an engine). In some missions, an upper-stage engine has to have a variable thrust or throttling feature, usually a variation of 10 to 1, but sometimes as much as 100 to 1. The assurance of a high reliability is important in all applications, but it gains additional importance in a space mission because of the high cost per flight and, in some cases, because a man's life is at stake; features such as traceability of the prior history (material, fabrication, inspection test and other records) for each major component, the need to requalify the engine (or key parts) in case of changes in material, fabrication, process or supplier, safety devices that will prevent complete opening of propellant valves until ignition is satisfactorily established, reliability of related vehicle subsystems and flight instruments, proper design to minimize the hazards from the propellant chemicals, the careful review of prior flight and test experience--all these are very significant in this application.

For the air-launched missile application, the following are important criteria (in addition to those already mentioned): Surveillance during storage is important to determine if any rocket units have deteriorated or suffered damage which will make it dangerous to operate, longest possible life (e.g., ten years of storage in hot and/or cold weather), ability to take considerable acceleration, both sideways as well as longitudinally (this may require piston expulsion devices in liquid propellant versions). Precise start-up and shut-down tolerance is salient here but for different reasons than the ones mentioned for the upper-stage application (see Fig. 4). In an air-launched missile, you may want a slow or delayed start to permit

the missile (which is ejected from its launch aircraft) to be a safe distance away from the aircraft and an unsymmetrical shutdown (with an inadvertent sideforce) may throw the missile off course; also, too rapid a start-up may cause undesirable forces on gyro equipment. Instant readiness, without time delay due to fueling or checkouts, is a necessity in most military missiles. A smoke-free exhaust is also desirable, because it makes detection by the enemy more difficult.

In addition to the performance criteria listed in Table 2, there are others which are used in evaluating other specific applications. For example, the time to target is very important in unguided air-to-air or ground-to-air missiles, and the man-machine relationships are of particular concern in manned vehicles. Other examples are the growth potential designed into an engine (e.g., higher thrust, more specific impulse, more thrust vector deflection, longer duration), the extent and complexity of interfaces with other vehicle subsystems, the vibration excitation imparted to the vehicle through the engine mount, the margin of safety used in the design, the demonstrated reliability of the engine in prior static and flight tests, the heating, noise, and vibration imparted to adjacent vehicle components (such as electric equipment).

OPERATIONAL CRITERIA

Table 3 gives a list of typical criteria used to evaluate operational characteristics of rockets for the same two applications. Again, several are arbitrarily selected and discussed in more detail here.

For the upper-stage maneuver engine there is emphasis on being able to service, inspect and replace key components once the engine is installed in the vehicle; good accessibility is therefore important. The need for good documentation, traceability and records is salient. One of the most important criteria in case of engine failure, without causing damage (fire, explosion) to the vehicle. Even though this may throw the vehicle off course and cause an abort of the mission, a safe shutdown may in many cases permit a return or salvaging of the vehicle.

In the case of air-launched missiles the shutdown must not endanger the launching aircraft.

Decontamination is the process of chemically de-activating hazardous residual liquid propellant after the operation of an engine, such as after a test. This usually is a post-operational procedure for removing or neutralizing the residual propellant in the rocket engine and for thoroughly cleaning, flushing and drying the propellant passages. This is necessary to (1) permit personnel to safely handle the engine without exposure to toxic, skin-burning, flammable, health-hazardous propellant material (for example, after a static test), (2) to remove undesirable elements from the propellant passages (e.g., a slight amount of residual moisture can cause severe corrosion or chemical reactions with nitrogen tetroxide; with a cryogenic propellant the pressure of CO_2 or moisture would create frozen particles which plug up filters or injectors), or (3) to condition the surface of the passage prior to, or after, the introduction of a strong oxidizer (such as liquid fluorine) to avoid a chemical reaction with the wall materials. This decontamination procedure involves flowing one or more fluids (e.g., alcohol, hot inert gas, etc.) through the passage. A complex passage geometry (many intrical valves, bent piping, trapped spaces, instrument taps, etc.) will require opening the feed line at several places and a more tedious or lengthy procedure in order to assure proper decontamination.

In military applications where very large numbers of relatively simple missiles are used (e.g., field barrage rocket, air-launched forward firing anti-tank rocket, and usually also simple air-launched guided missiles), the supply and logistics have to be very simple and understandable to an average soldier. For example, it is important that outdoor storage is permissible over a wide range of environmental conditions (rain, snow, sun, sleet, saltspray, alternatively hot and cold temperatures), that there be essentially no field service or field maintenance (therefore only very simple checks, such as igniter circuit continuity or no checkout at all). A particular case of "simple" checkout would be to see if the nozzle weather seal (that keeps the solid propellant from absorbing moisture) is not damaged

or pierced, that there are no dents or chips in the metal case or fins; no tools are required for this. If this type of rocket is dropped or dented in handling, then it is usually heated like ammunition; it is returned to the manufacturer or thrown away, rather than fixed without proper know-how or tooling.

This type of logistics is very different from space vehicle rocket engines where relatively few are built, but each one is checked and inspected repeatedly, tested in various ways at various times, under meticulous surveillance from the time of engineering drawing release to the completion of the mission. Here expensive checkout equipment is "valuable" in assuring proper operation during the space mission and detecting not only failures (does not work at all) but components whose performance falls outside relatively narrow pre-set specification limits.

Operating limitations under extreme environment and combined effects are important in most applications. The rocket engine for a particular application has to withstand certain specified environmental "stresses" or "exposures," such as hot and cold ambient temperatures during storage or during operation, a pre-determined variation in applied electrical voltage, predetermined variations in propellant feed pressure or composition, ability to withstand designated altitudes, accelerations, radiation environment (from the sun or from nuclear effects), salt spray, humidity, vibrations, drop tests, fungus exposure (to test for tropical climate), etc. These usually represent the best estimates of the likely worst, or most extreme, environmental conditions to which the engine is exposed during typical flights. While it is usually possible to estimate and design for the effects of any one of these environmental exposures, the prediction of combined effects is often quite difficult. For example, what happens to engine operation in an aircraft rocket system when the airplane is flying upside-down (tanks are then difficult to empty), with periodic random accelerations due to gusts, and contaminated, dirty fuel? Or what happens when an upper-stage rocket engine experiences severe aerodynamic heating (which increases the propellant temperature), encounters severe vibrations during the operation of the booster rocket engine, coupled with trapped air

in the propellant line? The probability of encountering some of these effects concurrently are subject to analysis and considerable judgment.

ECONOMIC CRITERIA

Some of the economic criteria are listed in Table 4 as they pertain to the two selected applications. In the upper-stage maneuver engine, cost is not anywhere near as important as it is in the air-launched missile rocket unit. In the former, the engine cost is only a small portion of the total program cost, and additional expenses (e.g., extra testing) to obtain additional reliability or performance improvement are warranted. In the latter, the propulsion cost can be a substantial portion of the total missile cost, and mass production in large quantities accentuates any cost reduction.

While it is quite obvious that engine costs (R&D, production and operating costs) are important evaluation factors, it is usually not so obvious that considerable additional engine costs are incurred in the vehicle integration, the procurement of appropriate ground support equipment, the furnishing of propellants and pressurizing fluids (which are often furnished and funded separately) or the cost of field support and crew training. In some applications the actual cost incurred by the engine manufacturer is small in relation to the total costs allocated for propulsion; in these cases a design feature which will increase engine delivery costs may still be very effective, if this same design feature allows a substantial reduction in operating costs.

Also, costs (and incidentally also reliability) seem to be very sensitive to engine performance (such as specific impulse), particularly when the performance is very close to the theoretical maximum, as is usually the cast in an upper-stage space vehicle application. This can be seen in Fig. 5; the attaining of the last few percent of specific impulse is very expensive in both R&D and production (difficult tolerances) and often cause reliability problems due to combustion difficulties, heat transfer, and tight specifications. As with many other performance criteria there are important trade-offs; in this case it is engine performance and reliability versus cost and weight.

JUDGMENT CRITERIA

Even though management and judgment criteria happen to be listed as the last section, they are often some of the most significant items for evaluation and selection. Table 5 is a typical, but probably not complete list of such criteria; they are used for evaluating one engine in relation to other competing engines for the same application, as well as in arriving at the key points in a negotiation between the propulsion company and its customer.

Prior and current contractor performance is a most important criterion. It used to be that a clever proposal with some feasible novel concepts and some promises on attaining good performance, reasonable costs and schedules was sufficient for winning a competition. Today the customers systematically investigate the current and prior performance of a rocket engine supplier, check with other customers, other government agencies, and the resident government representatives of the supplier's plant. The Department of Defense, for example, has instituted a Contractor's Performance Evaluation System, which has accumulated detailed records of prior jobs, their technical, cost and schedule performance, the reasons and rationales for failing to meet specifications, deliveries or the causes of overruns. A number of cases now exist where a company has failed to win a competition (even though their engine proposal was generally more than satisfactory), because of troubles on current contractual obligations. More so than ever before, the first prerequisite for being selected is a good performance record on current and prior jobs.

The relative status of the state-of-the-art of competing engines can help decide which is likely to be more reliable or available. With the steady growth of our technology and the active government support in advancing the state-of-the-art through research and development contracts, new concepts and approaches are continually being evolved for improving rocket engines and their key components. The normal process for a new idea (e.g., a new ingredient for a solid propellant) takes place in the following typical and sequential steps: (1) basic and applied research that will discover and characterize the ingredient, subsequently to mix the ingredient with

other materials into small samples of propellants and timely rocket motors which are tested in various ways; (2) if this effort is successful, then an exploratory development program will follow, where somewhat larger rocket motors are built and tested in many more different ways, where processing variations are explored and the characteristics of the propellant are more fully determined; (3) if this effort is successful, then this is followed by an Advanced Development Program, wherein a full-scale motor may be developed and tested under simulated flight rating conditions; (4) only when the feasibility of this new ingredient is thoroughly proven and understood should an Advanced Development Program for a specific rocket motor for a given application be undertaken; this should include a series of simulated preliminary flight rating tests, actual flight tests, and thereafter an elaborate series of qualification tests to determine readiness for production. The selection of a specific rocket engine for a specific application must therefore be based on a demonstrated and experimentally proven state-of-the-art that will give a good assurance that the engine design will cope with all the likely technical problems brought about by incorporating new advanced technical features and that there is little chance for unexpected technical difficulties to arise which will cause a delay and additional costs.

The engine developer therefore has the difficult problem of finding the happy solution to two conflicting requirements: (1) on one side he wants to promote rocket propulsion devices which include novel concepts, new propellant and better performance, but (2) on the other hand he must go through the expensive process of properly demonstrating the feasibility and practicality of these improvements to the state-of-the-art before his engine can be acceptable for an application. The determination as to which features and concepts are critical and therefore require a great deal of relevant research and development effort, are indeed subject to personal judgment.

SELECTION PROCESS

Many different skills are needed to evaluate and select a rocket engine; therefore, the organization which selects a rocket propulsion device for its vehicle must have an evaluation "team." The team must include:

engineers experienced in various aspects of rocket engine technology (such as thrust chamber expert, reliability experts, propellant chemists, etc.), engineers skilled in installation problems and system engineering, one or more purchasing agents, some field service personnel, manufacturing and facility people, experts in contract administration, planning, quality control, cost analysis, and in some cases even legal and patents; in special application the team is reinforced, with specialists such as physicists skilled in flame radiation emission, or facility engineers with a background in specialized test equipment. Team membership, size, formality of team efforts, documentation of criteria and ratings and general operating procedure will vary with the organization and engine application under evaluation. This can be a team within the company (e.g., rocket engine development organization or vehicle installations company or system integration company) or a combination of several organizations. Usually a rating procedure is established giving extra emphasis to those engine characteristics which have "value" to the user or which are particularly important.

Review of recommended selection is often made by a second team, which usually has a somewhat different set of rating criteria and a different point of view (e.g., a team of government representatives evaluating the recommendation of a prime contractor's prior evaluation).

Evaluations and selections of rocket engines for any one particular type of application are really made several times and each time for at least one of four reasons:

1. Selection by a vehicle prime contractor or customer of a new rocket engine to be designed or developed specifically for a new vehicle (new missile, aircraft, space launcher, spacecraft, etc.).
2. Selection by a prime contractor or vehicle customer of modified existing rocket engine for a given vehicle application.
3. Selection of the basic design features of a new experimental engine; here the ultimate application is usually not well defined.

4. Selecting the critical technical areas for phenomological research and component development for future new rocket engines.

The last two selections are largely made by rocket engine developing organizations or a government R&D agency usually with assistance of vehicle experts.

CONCLUSION

In picking one of several rocket engines for any one application, there is a need to compromise, for none of the available or conceivable rocket engines has only desirable features. By reducing requirement in one criterion (e.g., engine specific impulse or engine sophistication) it is possible to improve the rating in other criteria (e.g., complexity, cost, combustion stability or reliability).

There is a need for having a carefully prepared list of selection criteria for each application. This article should be useful as an initial checklist. Many of the selection criteria in the tables will only be important for certain classes of applications.

It is not always possible to predict all the important selection criteria, particularly for a new application where the environment or combined stresses are not too well established. For example, a moon landing rocket engine's transient performance characteristics immediately before landing are in part guesses, particularly since surface interaction effects are not known.

Frequently, many of the operational, economic and judgment criteria are equally or more important in arriving at an engine choice than the performance criteria.

Very often more than one rocket engine can satisfy a particular requirement. For example, both liquid-propellant and solid-propellant rockets can be used in certain jobs. In these cases, the selection has to be based on minor differences, prior experience, and the background and opinions of those that make the selection. Even though the checklists shown above have to be tailored to a specific application and are not complete, they can be useful as checklists.

By carefully anticipating the critical selection factors in an upcoming competition for a new rocket propulsion application, it is possible to design the engine and tailor the program in such a manner that it will do a very much better job of satisfying the performance, economic, operational and other selection requirements and thus win the competition by having a most suitable and feasible proposed product.

TABLE 1. PROPULSION CHARACTERISTICS OF SEVERAL TYPICAL ROCKET APPLICATIONS

Typical Application	Equivalent Vacuum Vehicle Velocity Increment (ft/sec)	Typical Thrust Level (lb)	Manner of Thrust Application	Typical Propellant	Range of Delivered Specific Impulse (sec)	Range of Operating Duration	Significant Other Special Features
Launch Vehicle Booster	4,000 to 10,000	100,000 to several million	Constant thrust single operation	a) Composite solid-perchlorate b) Liquid O_2 - kerosene c) Nitrogen tetroxide-amine fuel	250 to 265 (sea level)	1 to 8 minutes	Ability to test cluster with vehicle; thrust vector control
Upper Stage for Launch Vehicle and Space Maneuvers	8,000 to 20,000	5,000 to 200,000	Several starts 3 to 1 throttling	a) Oxygen-hydrogen b) N_2O_4-amine type fuel	300 to 450 (altitude)	1 to 10 minutes	Very high nozzle area ratio; thrust vector control; space and vacuum environment
Attitude Control of Spacecraft	100 to 3,000	0.001 to 20,000	Many (thousands) pulses for varying duration	a) cold gas b) monopropellant hydrazine c) subliming d) N_2O_4-N_2H_4	70 (N_2) to 290 sec (N_2O_4-MMH) (altitude)	Cumulative duration of 100 to 10,000 sec	Very short pulses (0.020 sec); high reliability; space & vacuum environment; no maintenance in orbit
Air-Launched Guided Missile	1,000 to 6,000	2,000 to 20,000	Constant or stepped thrust (boost-sustain)	Composite solid propellant (NH_4CO_4) or pre-packaged storable liquid (N_2H_4-amine)	235 to 250 (sea level)	2 to 25 seconds	Variable environmental temperatures; severe vibration of aircraft; high average density-impulse; long storage life
Aircraft Super Performance Power Plant	1,000	1,500 to 10,000	10 to 1 throttling of thrust; multiple restart	H_2O_2-JP4	220 to 255	2 to 8 minutes	Simple engine replacement & servicing, long time between overhauls, operation during aircraft maneuvers

TABLE 1 (Cont'd)

Typical Application	Equivalent Vacuum Vehicle Velocity Increment (ft/sec)	Typical Thrust Level (lb)	Manner of Thrust Application	Typical Propellant	Range of Delivered Specific Impulse(sec)	Range of Operating Duration	Significant Other Special Features
Assist for Aircraft Take-Off	500	250 to 5,000	Constant thrust	Nitrate or per-chlorate-type solid propellant	200 to 245 (sea level)	5 to 15 seconds	Low cost and simplicity; long storage life
Booster for ICBM	4,000 to 10,000	100,000 to 500,000	Constant propellant flow; single operation	Composite solid propellant	240 to 250 (sea level)	½ to 2 minutes	Long storage in ready-to-operate condition; thrust vector control
Upper Stage for ICBM	8,000 to 15,000	15,000 to 100,000	Constant propellant flow; single operation with precise thrust termination	Composite solid propellant	260 to 300 (altitude)	½ to 2 minutes	Special thrust termination devices; long storage in ready-to-operate condition; TVC
Upper Stage for Anti-Ballistic Missile	6,000 to 14,000	40,000 to 150,000	One or two periods of operation; constant thrust	Composite solid or storable liquid propellant	260 to 310 (altitude)	1 minute	High side and axial accelerations; operate in zero "g"
Unguided Infantry Support Anti-Tank Rocket Weapon	500 to 2,000	1,000 to 25,000	Short-duration thrust	Smokeless solid propellant (usually double-base type)	200 to 240 (sea level)	0.1 to 0.5 sec	Simple, reliable, low-cost unit; wide environmental limits; smokeless exhausts; tube-launched

TABLE 2. PERFORMANCE CRITERIA

	Space Launch Vehicle Booster	Upper-Stage Maneuver Engine for Space Vehicle	Attitude Control System	Air-Launched Guided Missile	Aircraft Super-Performance Power Plant	Assisted Take-Off Unit for Aircraft	ICBM Booster	ICBM Upper Stage	Anti-Ballistic Missile Upper Stage	Anti-Tank Unguided Infantry Weapon
Attain the ultimate in specific impulse	2	1	2	2	2	3	2	1	2	3
Attain efficient combustion and nozzle expansion	1	1	1	1	1	1	1	1	1	1
Close tolerance on thrust magnitude	2	2	2	2	3	3	2	1	2	3
Precise shutdown impulse and timing	1	1	1	1	3	3	1	1	1	3
Precise thrust buildup tolerance and timing	1	1	1	1	2	3	1	1	1	1
Minimize engine weight	2	1	2	2	2	2	2	1	1	2
Highest possible nozzle area ratio	3	1	1	2	2	4	3	2	2	4
Minimize residual propellant	1	1	1	1	1	2	1	1	1	2
Minimize engine volume	2	3	2	2	2	4	2	2	2	2
Ability to restart	4	2	1	3	1	5	4	4	3	5
Widest possible storage and operating temperatures	3	3	2	1	2	1	4	4	3	1
Minimize sensitivity of performance to variations in propellant purity, density and environment	2	2	2	2	2	3	2	1	2	2
Good performance in short-duration pulses	5	5	1	5	5	5	5	5	3	5
Ability to withstand flight environment (vibration, temperature, noise, UV, fog, etc.) prior to rocket operation	5	1	1	1	1	5	5	1	1	5

1 Very significant
2 Usually important
3 Sometimes important
4 Rarely or never important
5 Never [illegible]

TABLE 2 (Cont'd)

ENGINE PERFORMANCE (Cont'd)	Space Launch Vehicle Booster	Upper-Stage Maneuver Engine for Space Vehicle	Attitude Control System	Air-Launched Guided Missile	Aircraft Super-Performance Power Plant	Assisted Take-Off Unit for Aircraft	ICBM Booster	ICBM Upper Stage	Anti-Ballistic Missile Upper Stage	Anti-Tank Unguided Infantry Weapon
Combustion stability	1	1	2	1	1	1	1	1	1	1
Tolerance on the selection of proper thrust level magnitude for mission	3	3	3	3	3	4	3	3	3	3
Ability to vary thrust level in flight (throttle)	4	2	4	3	3	5	5	4	3	5
STORABILITY										
Long storage life of hardware (without propellant)	3	3	3	2	2	2	2	2	2	2
Long storage life of fueled hardware	4	4	3	1	2	1	1	1	1	1
Maximum possible temperature variation in storage	4	4	4	1	3	1	4	4	4	1
Ability to take many temperature cycles	4	4	4	1	4	1	4	4	4	1
Ability to withstand prolonged vacuum or altitude exposure	4	1	1	2	2	4	4	1	1	4
Ability to perform checkout after final installation and prior to operation	2	2	2	3	2	4	2	2	2	4
Ability to perform checkout of engine or critical components during storage	4	4	4	2	4	2	3	3	3	2
Deterioration of propellant and/or performance (usually solid propellant and corrosive liquid propellants)	3	4	2	2	4	2	2	2	2	2

1 Very significant
2 Usually important
3 Sometimes important
4 Rarely or never important
5 Does not apply

TABLE 2 (Cont'd)

VEHICLE RELATED FACTORS	Space Launch Vehicle Booster	Upper-Stage Maneuver Engine for Space Vehicle	Attitude Control System	Air-Launched Guided Missile	Aircraft Super-Performance Power Plant	Assisted Take-Off Unit for Aircraft	ICBM Booster	ICBM Upper Stage	Anti-Ballistic Missile Upper Stage	Anti-Tank Unguided Infantry Weapon
Adaptable to cluster operation	2	2	2	4	4	2	3	3	4	5
Flexibility for alternate missions (e.g., different thrust programs, vectoring or durations)	4	1	1	3	1	4	4	3	4	4
Heat transfer from flame to vehicle parts	1	1	1	3	2	2	1	1	1	3
Ability to operate in zero "g"	5	1	1	3	4	5	5	3	1	5
Flame emissions and absorptions (radar and telemetering interference)	2	2	3	1	4	4	1	1	1	4
Ability to take side acceleration	3	3	3	1	2	4	3	3	1	4
Ability to take severe longitudinal acceleration	3	3	4	2	3	4	2	2	1	1
RELIABILITY										
Identification and traceability of prior fabrication and test history of each key component of propulsion system	1	1	1	2	2	4	2	2	2	4
Degree of built-in redundancy	2	1	1	4	3	4	3	3	2	4
In-flight failure sensing and safe shutdown devices	3	3	2	4	1	3	4	4	4	4
Ability to check-out engine or critical components prior to use	2	2	2	4	2	4	2	2	2	4

1 Very significant
2 Usually important
3 Sometimes important
4 Rarely or never important
5 Does not apply

TABLE 2 (Cont'd)

RELIABILITY (Cont'd)	Space Launch Vehicle Booster	Upper-Stage Maneuver Engine for Space Vehicle	Attitude Control System	Air-Launched Guided Missile	Aircraft Super-Performance Power Plant	Assisted Take-Off Unit for Aircraft	ICBM Booster	ICBM Upper Stage	Anti-Ballistic Missile Upper Stage	Anti-Tank Unguided Infantry Weapon
Time between overhauls (re-usable engine only)	5	5	5	5	1	5	5	5	5	5
Need for requalifying any changes in engine fabrication process or material	1	1	1	1	1	1	1	1	1	1
Traceability of prior flight experience	1	1	1	3	2	4	2	2	2	4
Reliability of related auxiliary systems (e.g., electric, hydraulic, telemeter)	1	1	1	2	2	3	2	2	2	3
Reliability of flight instruments	1	1	1	5	1	5	3	3	3	5
OTHER PERFORMANCE CRITERIA										
Minimize noise emission	2	3	4	4	3	3	3	4	4	3
Minimize vibration excitation from engine to vehicle	2	2	2	2	2	2	2	2	2	2
Ability to instrument, monitor or measure performance during operation	2	2	2	4	2	4	3	3	3	4
Avoid smoke in exhaust	4	4	2	1	2	2	4	4	4	1
Thrust vector control (TVC)	1	1	3	4	4	5	1	1	1	5
Growth potential (more thrust, specific impulse)	3	3	3	3	3	4	3	3	3	3
Man-machine relationship (primarily for manned vehicles)	3	3	2	5	2	4	5	5	5	3

1 Very significant
2 Usually important
3 Sometimes important
4 Rarely or never important
5 Does not apply

TABLE 2 (Cont'd)

OTHER PERFORMANCE CRITERIA (Cont'd)	Space Launch Vehicle Booster	Upper-Stage Maneuver Engine for Space Vehicle	Attitude Control System	Air-Launched Guided Missile	Aircraft Super-Performance Power Plant	Assisted Take-Off Unit for Aircraft	ICBM Booster	ICBM Upper Stage	Anti-Ballistic Missile Upper Stage	Anti-Tank Unguided Infantry Weapon
Complexity of interface and ease of installation into vehicle	1	1	1	1	1	1	1	1	1	1

1 Very significant
2 Usually important
3 Sometimes important
4 Rarely or never important
5 Does not apply

TABLE 3. OPERATIONAL CRITERIA

SAFETY	Space Launch Vehicle Booster	Upper-Stage Maneuver Engine for Space Vehicle	Attitude Control System	Air-Launched Guided Missile	Aircraft Super-Performance Power Plant	Assisted Take-Off Unit for Aircraft	ICBM Booster	ICBM Upper Stage	Anti-Ballistic Missile Upper Stage	Anti-Tank Unguided Infantry Weapon
Minimize hazards (toxicity, fire, detonation, corrosion)	1	1	1	1	1	1	1	1	1	1
Need for malfunction detection and safe shutdown devices	3	3	3	4	3	5	4	4	4	5
Ability of rocket engine to abort or shut down safely in case of malfunction	1	1	1	1	1	1	1	1	1	1
Simple decontamination procedures	2	2	2	4	1	5	3	3	3	5
Ignition safety monitor (assure ignition before main stage combustion)	1	2	4	5	1	5	3	4	4	5
Emergency cut off for range safety	2	2	5	3	3	5	2	3	3	5
SUPPLY AND LOGISTICS										
Ease of storage surveillance	3	3	3	2	2	2	2	2	2	2
Ease of engine replacement	2	2	2	2	1	2	3	3	3	4
Ease of filling (or detanking) liquid propellants in field	2	2	2	4	1	5	3	3	4	5
Ease of servicing or replacing of key components on installed unit	1	1	1	4	1	4	3	3	3	5
Minimize requirements for special tooling for field inspection, repair and replacement of engine	2	2	2	2	2	1	2	2	2	1

1 Very significant
2 Usually important
3 Sometimes important
4 Rarely or never important
5 Does not apply

TABLE 3 (Cont'd)

SUPPLY & LOGISTICS (Cont'd)	Space Launch Vehicle Booster	Upper-Stage Maneuver Engine for Space Vehicle	Attitude Control System	Air-Launched Guided Missile	Aircraft Super-Performance Power Plant	Assisted Take-Off Unit for Aircraft	ICBM Booster	ICBM Upper Stage	Anti-Ballistic Missile Upper Stage	Anti-Tank Unguided Infantry Weapon
Mobility of checkout and handling equipment	3	3	3	2	2	2	2	2	2	3
Quality of traceability records	1	1	1	2	2	4	1	1	1	4
Need for detailed handbooks and service instructions	1	1	1	2	1	2	1	1	1	2
Need for extensive training of operating crew	2	2	2	4	2	4	2	2	3	4
OPERATIONS										
Ability to operate under extreme environments and combined stress	1	1	1	1	1	1	1	1	1	1
Minimize time, effort required for checkout, replacement, overhaul	3	3	2	2	2	3	3	3	3	3
Minimize number of interconnects, instruments, engine controls	2	2	2	2	2	1	2	2	2	1
Instant readiness for launch/operation	4	4	4	1	2	2	1	1	1	1
Maximum number of operations without overhaul	4	4	1	5	1	5	5	5	5	5
Overhaul capability	3	3	3	4	1	3	3	3	3	4
High skill level for servicing and repair crew	2	2	2	4	2	4	2	2	3	4

1 Very significant
2 Usually important
3 Sometimes important
4 Rarely or never important

TABLE 4

ECONOMIC CRITERIA

Criteria	Upper-Stage Space Maneuver Engine	Propulsion for Air-Launched Guided Missile
Cost of Engine Development	Usually expensive to get maximum performance and reliability. A	Should be nominal. A
Cost of Vehicle Integration	A	A
Cost of Production	Usually a small part of total cost.	Very significant; should be low.
Cost of Support Equipment (check-out, propellant supply, pressurant supply)	Usually complex and expensive.	Should be minimal.
Spare Parts	For all critical components.	As few as possible; preferably none.
Operating Costs (check-out, servicing, crews, base)	Expensive.	Should be small.
Basing Concept	Extensive check-out servicing, maintenance spares at launch site--overhaul at propulsion manufacturer's plant.	A couple of trained men at each base for inspection; all repair, replacement and overhaul at propulsion manufacturer's plant.
Test Location	At propulsion and stage manufacturer's plants; also at government test facility.	Mostly at propulsion manufacturer's plant, some at government facility.
Availability of Engine, Tooling, Special Test Equipment, Training Aids, Overhaul Facilities, Shipping Containers.	A	A
Location of Manufacturer's Plants, Test Facilities, Overhaul Depots	Where thereis the best capability.	For military weapons it is desirable to have at least two of each type in different parts of country.

A Important when selecting from several competing engines.

TABLE 5

MANAGEMENT AND JUDGMENT CRITERIA

1. INTANGIBLES AND JUDGMENT CRITERIA

Relative advance in the state-of-the-art

Existence of experience background and its applicability to a specific application

Interference of the work on the selected engine with other urgent work in same factory or same organization

Applicability of same engine to other vehicles (versatility)

Relative importance of engine program to other programs (priority)

Availability of funds

Type of contract offered and guarantees or warranties furnished by contractors

2. MANAGEMENT

Reputation of engine manufacturer and his current and prior performance, including cost and schedule on similar jobs

Credibility of attaining promised performance, cost and schedule

Management ability (including means for obtaining visibility, progress measurement, setting plans and implementing changes)

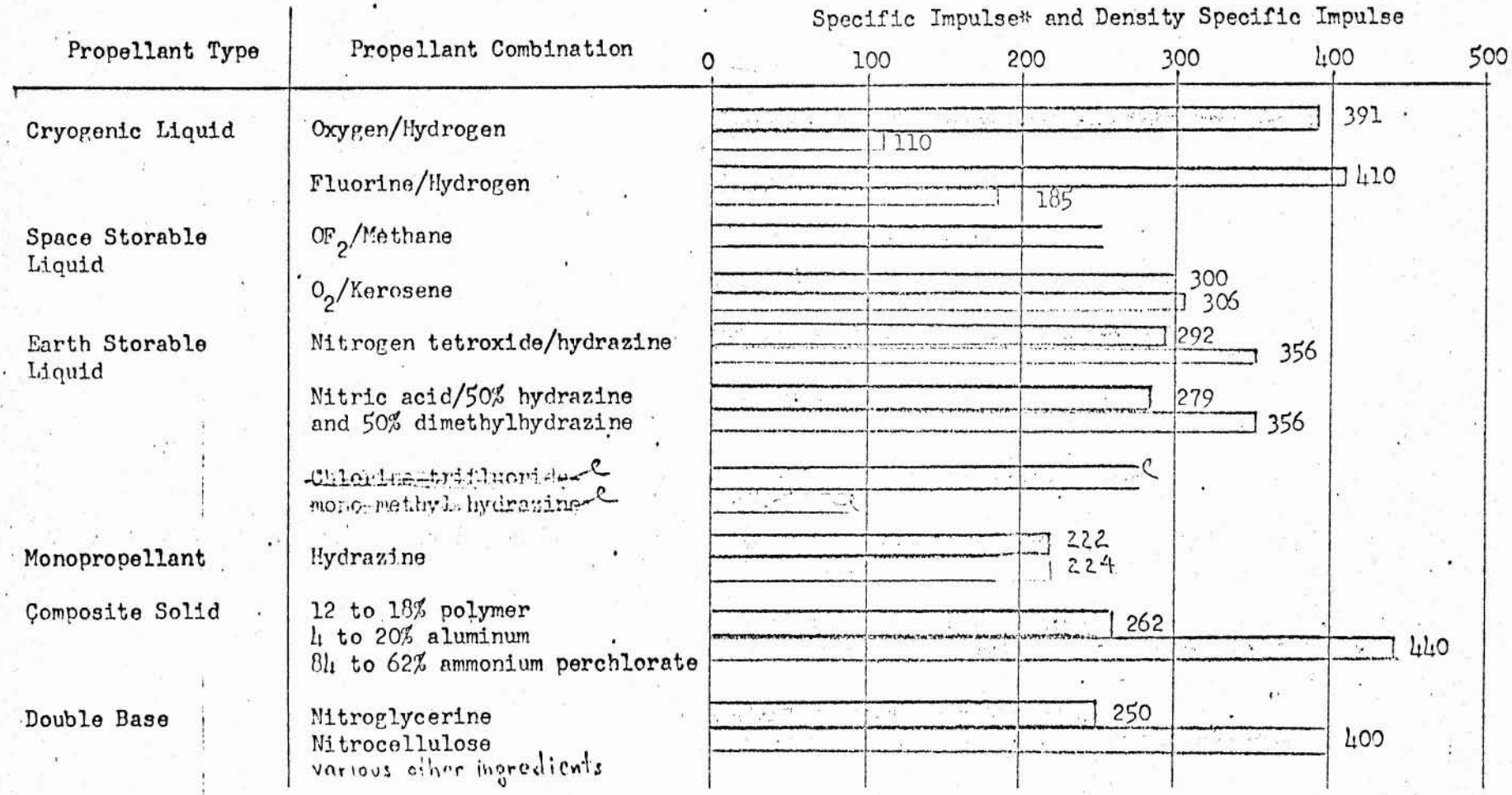
Reputation, competence and background of key personnel

Evaluation of subcontractors of key components or critical parts (also percentage of work which is subcontracted)

Effectiveness and detail of computerized internal management information systems (e.g., parts or material inventories, shop planning and control, program and subdivision of work budgets, schedules and actual costs, automatic test data recording and reduction, report retrieval, etc.)

Effectiveness and speed of processing and implementing contract and program changes

FIGURE 1. PERFORMANCE OF DIFFERENT PROPELLANT TYPES



*Theoretical value with shifting equilibrium at 1000 psi chamber pressure with expansion to sea level.

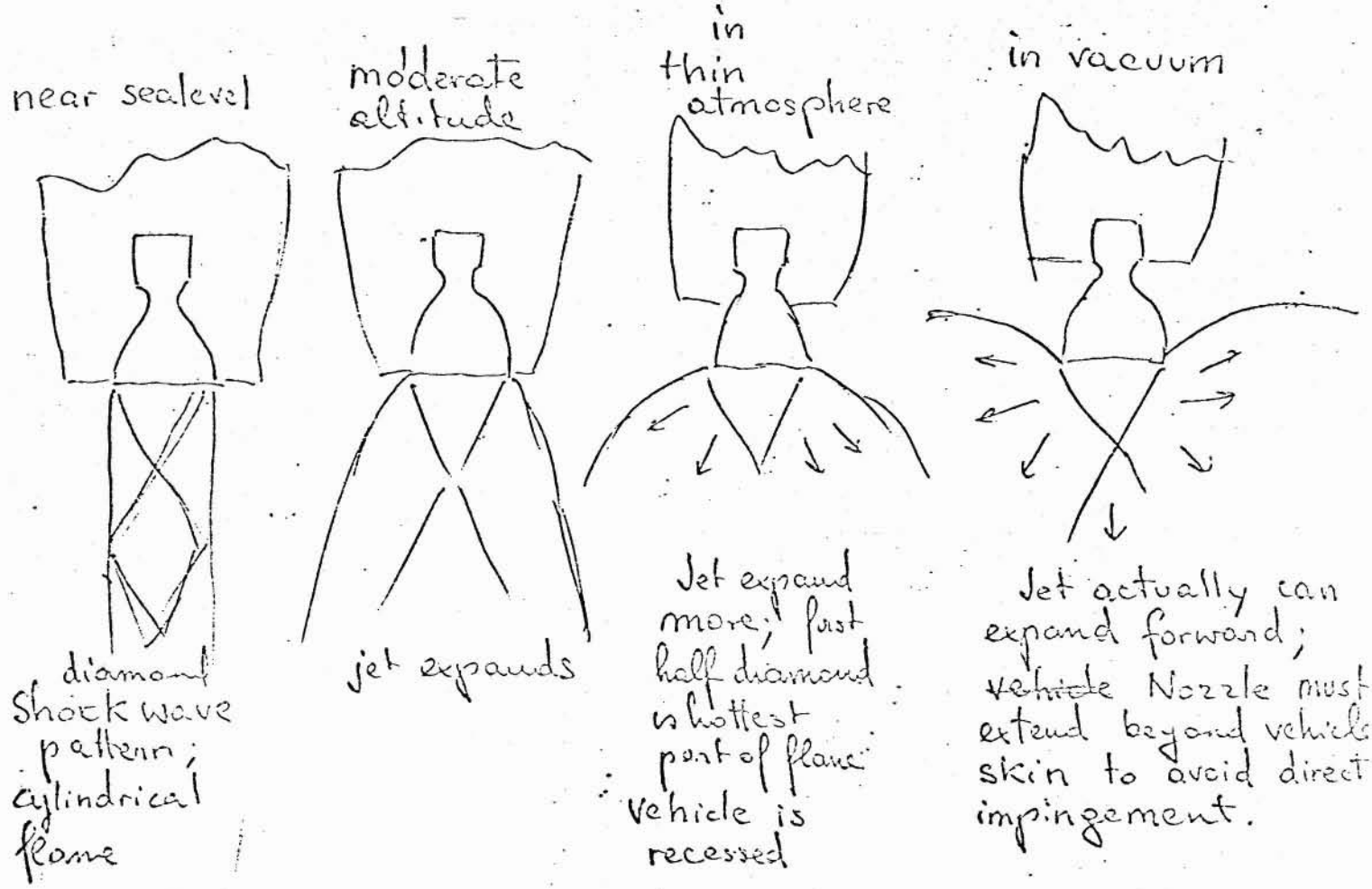


Figure 3 Flame expansion pattern

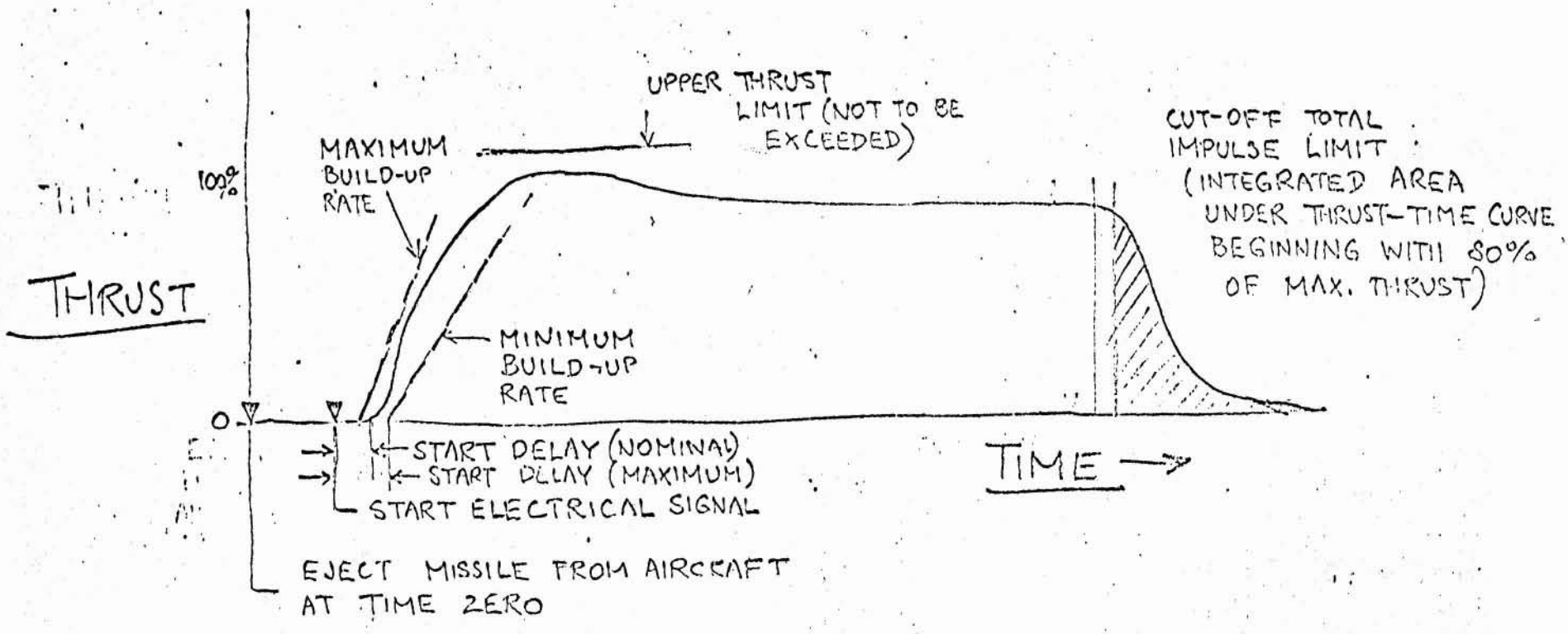


FIGURE 4. LIMITATIONS ON THE THRUST-TIME CURVE FOR A TYPICAL AIRLAUNCHED ROCKET UNIT.

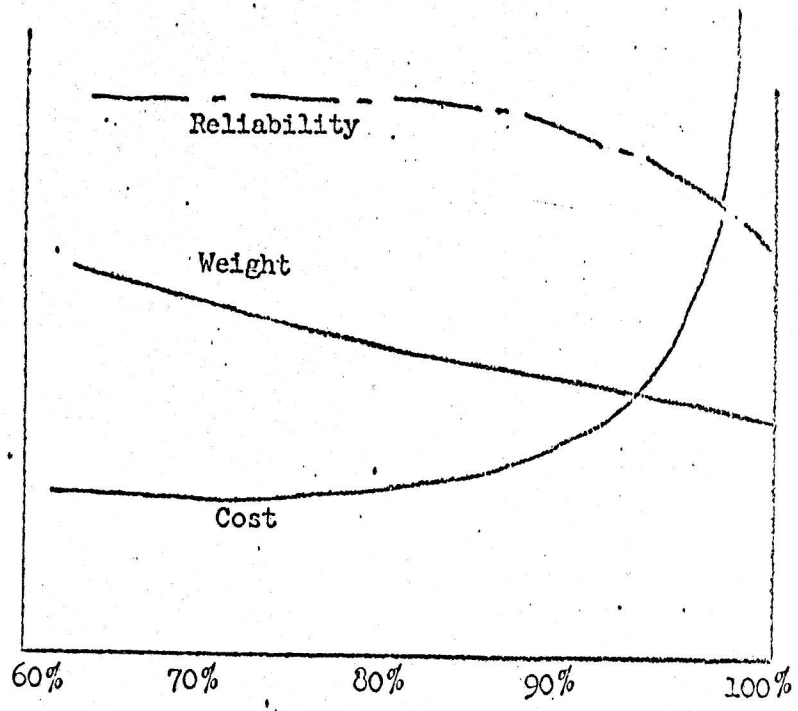


Fig. 5 - Reliability, Weight and Cost Factors as a Percent of the Theoretical Maximum Engine Performance (e.g., Specific Impulse)