NASA Technical Memorandum 87019

Manrating Orbital Transfer Vehicle Propulsion

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Prepared for the
Twenty-first Joint Propulsion Conference
cosponsored by the AIAA, SAE, and ASME
Monterey, California, July 8-10, 1985

NASA

MANRATING ORBITAL TRANSFER VEHICLE PROPULSION

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E-2570

Abstract

Studies of the United States Space Transportation System show that in the mid-to-late 1990s expanded capabilities for Orbital Transfer Vehicles (OTV) will be needed to meet increased payload requirements for transporting materials and men to geosynchronous orbit. The requirement to provide manrating offers challenges and opportunities to the propulsion system designers. To provide a perspective on manrating, this paper reviews the propulsion approaches utilized in previous manned space vehicles of the United States. The principals of reliability analysis are applied to the Orbit Transfer Vehicle. Propulsion system options are characterized in terms of the test requirements to demonstrate reliability goals and are compared to earlier vehicle approaches.

Introduction

From the earliest days of the United States Space Program, the issues concerning mán in space have challenged the vehicle designers. This paper presents discussions, observations, and analysis of propulsion system characteristics for manrating an advanced Orbit Transfer Vehicle.

For the 1990s and beyond it is envisioned that an integrated Space Transportation System consisting of the Space Shuttle, a Space Station, an Orbit Maneuvering Vehicle, and an Orbit Transfer Vehicle will exist to deploy, service, and retrieve payloads in high or geosynchronous orbit (GEO). The system would operate as shown in Fig. 1. In this scenario, the Space Shuttle would deliver and return payloads to the station located in low earth orbit. Potential payloads would include spacecraft to be placed in higher orbits, Orbit Transfer Vehicles, and propellants to transport them, as well as supplies for the space station and free flying platforms for low earth orbit. It is envisioned that in addition to its scientific and industrial roles, the space station will become the operations and service center for Orbit Transfer Vehicles. Payloads from the Shuttle would be mated to the OTV, propellants loaded and prelaunch checkouts conducted. Upon return the OTV would rendezvous with the Space Station, payloads would be retrieved, and maintenance performed to ready the OTV for the next mission. The Orbit Maneuvering Vehicle would serve as the utility spacecraft for low earth orbit. It transfers payloads and supplies between the Shuttle and Space Station as well as places, retrieves, and services free-flying satellites in low earth orbits. The Orbit Transfer Vehicle would operate primarily between low earth orbit and geosynchronous orbit as a reusable spacecraft and as an expendable vehicle for planetary missions.

It is envisioned that the advanced OTV will be a reusable vehicle, based and maintained primarily at the space station. The majority of its missions will be to deliver satellites to geosynchronous orbit. The vehicle will also be manrated for servicing missions at geosynchronous orbit. Furthermore, it will be a versatile vehicle which can be used for planetary transfers and delivery of large, acceleration limited space structures to geosynchronous orbit. The vehicle will incorporate some form of aeroassist on return to the low earth orbit as shown in Fig. 2. This maneuver uses the drag induced by the earth's atmosphere to reduce the OTV velocity and thereby reduces the propellants required for the retroburn.

The characteristics of the advanced OTV are the subject of ongoing NASA studies,[1-5] as well as earlier Space Station studies.[6-13] The role of the Orbit Transfer Vehicle in placing, retrieving, and servicing payloads in high earth orbits represents a significant departure from current design and operational philosophy for upper stages and is driven by the need to achieve significant reductions in payload placement costs and provide manned operations beyond low earth orbit. The requirement to provide manrating of the OTV offers a number of opportunities and challenges to the propulsion system designers.

United States Space Program Manrating Experience

Each new spacecraft and vehicle system in the space program has brought with it a unique set of conditions in terms of the fiscal, political, legal, regulatory, military, and technical environments. As such, what manrating is, and how and when it is achieved have differed considerably. Manrating, in the most general sense, can only be specified within a given environment. It is only the perception that all practical effort has been expended to eliminate life-threatening events and provide for safe return to earth of the space traveler. Many of the techniques utilized by designers to eliminate risk and increase system confidence have been built upon the foundations of previous manned space projects. Although each was unique in its environment, a reliance on redundancy, comprehensive quality assurance, and testing have been the cornerstones.

Project Mercury

Project Mercury began with a series of suborbital flights launched by the Redstone ballistic missile. These were followed by orbital flights lofted by the Atlas ballistic missile. Because of the urgency of the program, no major modifications were possible prior to committing to manned flight. However, an intensive inspection effort was instituted to select each missile component to ensure that each was as close to the nominal design point as possible. As an added precaution, a simple solid propellant escape rocket was added to the capsule. Monopropellant hydrogen peroxide was used for attitude control and solid propellant motors for deorbit. Both systems incorporated redundant units.

Project Gemini

Project Gemini, which followed Mercury, relied upon the Titan II ballistic missile as the booster. Early in the project, it was felt that the Titan II could be used without substantial change. However, during flight tests a serious problem was encountered. The rocket could develop large oscillating acceleration loads (POGO) which would endanger the astronauts life. Significant modifications to the Titan II were required to eliminate this hazardous situation. The escape rocket of the Mercury Project was replaced by ejection seats. Simple pressure fed hypergolic propellants were used for the attitude control and maneuver thrusters. Redundancy was once again used in the attitude control and maneuver thrusters, as well as the solid propellant deorbit rockets. In addition, the maneuver thrusters acted to "backup" the deorbit rockets. They were capable of placing the capsule into a fail safe orbit which would reenter the atmosphere even if the deorbit rockets failed to function.

Project Apollo

Project Apollo ushered in a new era in manned space flight. For the first time, the tal vehicle system was designed with manned missions as the focus. No longer did adaptations of ballistic missiles suffice. As expressed in "What Made Apollo a Success,"[14] "The primary consideration governing the design of the Apollo system was that, if it could be made so, no single failure should cause loss of any crew member, prevent the successful continuation of the mission, or, in the event of a second failure in the same, prevent a successful abort of the mission." In applying this philosophy to the propulsion system elements, each mission phase was analyzed so that, when feasible, a credible backup means of safe return was available. Backup propulsion was available up through the lunar landing. At this point, an extremely simple engine was utilized for the ascent stage. It was pressure fed with hypergolic propellants to ensure ignition. Quad redundant valves were incorporated since they represented the most probable failure point. The thrust chamber was ablatively cooled. It was designed as though it were a structural element and had significant safety margins.

This type of engine was also used on the service module since it had no backup for the lunar escape burn. Prior to this, the lunar descent engine acted as the backup.

It was during the Apollo Program that the concept of "limit testing" was invoked to provide the means to control test costs while meeting the requirements for manned flight. Hardware was subjected to testing significantly in excess of the mission requirements - pushing to the limit. The mission requirements of the third stage of the Saturn V called for an engine burn application of 500 sec, but each engine possessed a minimum usable life of 3750 sec. Limit testing provided the means to demonstrate reliability and confidence without a prohibitively large test sample hardware cost.

This combination of component redundancy, backup redundancy, limit testing, and a comprehensive quality assurance program provided the Apollo manrating.

Shuttle

The Shuttle Program brought further change and refinement to the manned space program. The concept of a reusable spacecraft was introduced. This meant much longer operating times, more cycles, refurbishment/servicing - new challenges to a space program which had been built on expendable hardware. The Shuttle was also distinctive in that the first flight carried men. Earlier programs had flown several test flights prior to "manrating." The techniques developed in these earlier programs provided the needed confidence for the Shuttle.

Component and backup system redundancy is used extensively within the Shuttle. For example, there are five main computers configured into redundant sets and three Auxiliary Power Units. The two solid rocket motors and three Shuttle main engines provide capability for safe return to Earth in the event of failures. The deorbit capability is derived from the dual engines of the Orbit Maneuver System. These pressure fed engines are fueled by hypergolic propellants from redundant tank sets. The feed lines are crosslinked so that sufficient propellants are available to either engine to deorbit in the event of a failure. In addition, these redundant engines are "backed up" by auxiliary propulsion thrusters which are certified for extended duration burns. They are crosslinked to the main propellant supplies in addition to the auxiliary propulsion supply.

OTV Manrating

As we advance into the 1990s, the environment within which we define "manrating" is continuing to change. Having demonstrated the technical feasibility of space exploration we now seek to exploit the benefits of space. In this environment cost effectiveness has become a predominant concern. This requires incorporation of new technologies and reduced margins to improve performance and life. The design challenge is to maintain safety for the manned missions while delivering cost effectiveness.

The historical data base suggests that at least two main engines will be needed for a manned Orbit Transfer Vehicle. However, this heuristic approach of specifying redundancy doesn't resolve the questions of acceptable risk and best use of resources to minimize risk. For this, reliability analysis of the vehicle and propulsion approaches is needed.

Reliability Analysis

The optimum use of resources dictates that maximum system reliability be provided for minimum development and life cycle costs. However, the designer can only speculate as to what will be the system reliability goal and then seek to provide the minimum cost approach. Factors influencing the selection of the minimum cost approach include risk assessment, subsystem allocations, mission profile, tests costs, redundancy, and nonindependent failure probabilities.

Risk Assessment

Analysis of competitive OTV concepts requires that an overall system reliability goal be established which can then be passed down to compare subsystem options. While any goal could be established for reliability, a more credible approach[15] is to derive an overall system reliability based on comparative mortality risks. The objective is to provide a similar risk for the astronaut as encountered in other career fields. As shown in Fig. 3, an astronaut with a 10 mission career would need a OTV mission reliability of 0.999 be equivalent to an airline pilot risk over a 30-yr career. A deficiency in this method is that a comparable career must be chosen, as well as determining the mortality associated with that career. The data shown in Fig. 3 is for mortality data of 1969. Progress in safety and environmental health programs have reduced these by nearly 50 percent.[16] If these trends continue, by the mid 1990s the OTV mission reliability will need to be ∿0.9995 to be comparable to mid 1990s commercial pilots. This compares to 0.999 for comparable mortality with 1969 data.

Subsystem Allocation

After establishing OTV system reliability, allocation of acceptable levels of reliability to the subsystem is next. Several methods can be utilized. One approach would be to analyze each system and subsystem within the vehicle and optimize each reliability with respect to total development and life cycle cost. Those systems and subsystems which have low development and high life cycle costs would receive greater reliability requirements. Those with high development and low life cycle costs receiving lower reliability requirements. This would require more detailed description of the vehicle elements and has not been pursued for this paper. A simple approach based on historical data projections and analogy to existing systems has been utilized.[15] In the case illustrated in Fig. 4 the main propulsion system contributes 25 percent of the total unreliability and must be ∿0.9999 to meet the selected manrating reliability point for the mid 1990s of 0.9995.

Mission Profile

Having assigned the propulsion system a mission reliability of 0.9999, it is necessary to analyze the OTV mission so that the single burn reliability can be determined. It is this reliability which is to be demonstrated by testing.

Successful completion of a manned OTV mission to geosynchronous orbit will require at least four main propulsion burns - Geo transfer, Geo circularization, earth transfer, and Earth circularization. Multiple perigee burns may be used when additional payload capability is needed. Midcourse correction burns may also be needed. When these multiple burn scenarios are applied to the previously assigned propulsion reliability, R_p, the single burn reliability, R_{SB}, requirement must be increased with each additional mission burn, N.

$$R_{SB} = 1 - [1_N - R_p]$$

For a four burn mission, the single burn propulsion reliability would be 0.999975 and 0.9999875 for an eight burn mission. This becomes an important factor when the test costs to achieve high reliability are considered as shown in Fig. 5. Achieving 0.999975 for a single engine would require ∿27 000 tests and 0.999875 would require 55 000 tests. With full up-engine test costs of up to 10 000 dollars/tests, this would be one-half billion dollars for reliability demonstration tests. It should be pointed out that testing for reliability is initiated only after a considerable degree of system maturity has been obtained and further modifications are unlikely.

Redundancy

Clearly the test requirements for a single engine of 0.999975 or greater reliability are extreme. Redundancy can be utilized to significantly reduce the test requirements to achieve the desired reliability. As illustrated in Table 1 for 0.9999 propulsion reliability, increasing the number of engines can reduce the test requirements significantly. This applies so long as the remaining engine(s) can successfully complete the mission.

The redundancy approach can be extended beyond identical elements to include different engine types or entire propulsion systems as long as the mission requirements can be met by the individual redundant elements. Thus, the reaction control propulsion was redundant to the deorbit propulsion in Project Gemini.

Both enabled the astronaut to deorbit. It should be noted that specifying redundancy requirements such as fail-operational or fail-safe are insufficient without a reliability requirement. Overall reliability, R_S, of redundant systems is high or low depending on the component reliability (R_C) and the number of redundant elements.

$$R_S = 1 - (1 - R_C)^n$$

Nonindependent Failures

When redundant components are utilized in a system, the issue of nonindependent failures must be addressed. These are the failures which result in total loss of system ability to perform the required activities. For the OTV this would be loss of propulsion capability during the mission. These failures might be a result of a catastrophic explosive engine failure which terminates the function of adjacent engines. They could also be more subtle design, manufacturing, or maintenance flaws which result in the loss of propulsion capability from all engines or propulsion systems during the course of the mission. Examples of this type of failure include the failure of two Shuttle Auxiliary Power Units on the STS 9 flight[17] and the three engine failures on L-1011 from faulty seal replacement.[18]

The nonindependent failure probability, c, is incorporated into the calculation of propulsion system reliability, R_p, as[19]

$$R_p = \sum_{j=}^{k} \frac{n!}{(n-j)!j!} (Re)^{n-j} (1 - Re)^j (1 - C)^j$$

where Re is the single engine, single burn reliability, C is the probability that an engine failure is not independent and will result in propulsion system failures, and a cluster of n engines can operate with up to k engine failures.

As illustrated in Fig. 6, for a mission with a total of eight main engine burns, the effect of nonindependent failures is to significantly increase the required single burn-single engine reliability from that without nonindependent failures. For example, to achieve the 0.9999 propulsion mission reliability with two engines and 3 percent nonindependent failures requires 0.9998 single burn reliability, 0.99988 with 5 percent nonindependent failures but only 0.99 with nonindependent failures. As shown in Table 2 this can significantly increase the number of engine reliability tests. The sensitivity to nonindependent failures increases as high mission propulsion reliability is sought.

The absolute level of nonindependent failures is configuration specific and can be determined only through test and operation. Several rocket engines have had no operational failures and thus have had 0 percent nonindependent failures - thus far. Test stand results for engines of similar complexity to the envisioned OTV engines have yielded correlations of 5 to 7 percent. In view of this, assuming 5 percent nonindependent failures should result in a conservative design reliability. Every effort, of course, would be exerted to eliminate all flaws and maintenance problems such that a 0 percent failure probability would be obtained.

Manrating Propulsion Approaches

As previously discussed, redundancy is a primary method of reducing testing associated with reliability certification. The design, fabrication, inspection, quality control, and operational costs for the propulsion system are not likely to vary greatly over the range of reliability requirements. Thus, testing costs and schedule may be significant discriminators in defining the propulsion system.

As seen in Figs. 7 and 8, the introduction of the nonindependent failure affects the benefits of adding redundancy to the propulsion system. With 0 percent nonindependent failures, increased redundancy reduces the number of tests required to achieve a reliability level, as shown earlier in Table 2. However, at higher levels of nonindependent failure probability, the increased redundancy actually increases the number of required tests. The crossover point for equal tests for additional engines is a function of overall reliability and number of mission burns and it decreases as these increase. An alternative to adding main engines is to provide a redundant backup propulsion capability, APS. This system would be of an alternative design to eliminate common design, manufacturing and maintenance defects. It would be located in a different area of the vehicle to reduce the probability of explosive nonindependent failures.

The use of a backup system is introduced into the reliability analysis by first separating the propulsion system into the main and backup systems with their individual reliabilities. Then the main propulsion system is separated into single engine-single burn reliabilities for each engines. The nonindependent failure equation is used in both steps. The probability of nonindependent failures of the backup and main propulsion is used in the first step and the probability of main engine nonindependent failure in the second step.

As shown in Fig. 9, the introduction of a backup propulsion system has the effect of desensitizing the test requirements to main engine and backup propulsion failures as compared to no backup propulsion. This reduces the number of tests. As shown in Fig. 10, a wide range of propulsion system reliability requirements can be accommodated with very little change in number of tests. Also note in these figures that two engines without APS backup is mathematically equivalent to a single engine with APS backup.

Based on these results, it would appear that a two main engine configuration is the appropriate choice for the anticipated nonindependent failure probabilities of ~5 percent. This remains valid down to 1 percent, where a three engine OTV would have lower test costs. Two engine vehicles also should have a life cycle cost advantage over greater engine numbers due to reduced system cost, maintenance and transportation charges.

Utilization of a backup propulsion system would further reduce main engine tests and would parallel the deorbit capability in the Space Shuttle. It provides the lowest test requirements down to ~0.1 percent nonindependent failures. Furthermore, the Space Shuttle utilizes two engines backed up by auxiliary propulsion when returning from low earth orbit. This is analogous to the OTV return from geosynchronous orbit and selection of a similar approach for OTV propulsion would be supported by historical precedent.

Incorporation of backup propulsion, however, will likely depend on its development and life cycle costs relative to performing additional main engine tests to demonstrate the required reliability. Costs for a suitable backup propulsion system are projected to be on the order of 50 million dollars. Additional main engine tests would cost no more than 50 percent of this amount. Offsetting this development cost penalty is the possibility that a true backup propulsion capability could reduce insurance rates for the missions. Current rates are up to 20 percent of the payload value.[20] Sources within the insurance industry speculate that rates could be reduced by up to one-half for an OTV with the additional redundancy of auxiliary propulsion backup to the main engines. This would result in savings of upwards of 20 million dollars per flight for a 100 million dollar payload and 100 million dollar OTV and propellant cost. These savings could be applied toward development costs and the cost of carrying extra propellants to offset the lower performance of the backup propulsion.

Concluding Remarks

In the course of this paper we have reviewed that propulsion system approaches utilized for previous United States manrated vehicles. The systems have been very successful, inasmuch as there have been no fatalities or serious injuries resulting from flight failures. Careful design, quality control, extensive testing and utilizing redundancy, and backup systems have been integral parts in the success record.

The Orbital Transfer Vehicle designers will build upon this foundation. Reliability analysis will be one of their principal tools to resolve what manrating is when exploitation of space benefits rather than exploration is the objective.

Factors such as risk assessment, subsystem reliability, mission profile, redundancy and, nonindependent failure probabilities will be resolved.

In this paper, issues associated with these factors have been explored. It appears that, in order to provide an astronaut with a career mortality roughly equivalent to a commercial pilot, at least a two main engine configuration will be required. Nonindependent failures of redundant engines may represent a serious problem requiring many additional tests to assure that the reliability goal has been met. However, backup propulsion capability provided by an independent auxiliary propulsion system reduces the number of tests and desensitizes the test requirements to changes in reliability goals and nonindependent failure probability. Reductions in insurance rates for an Orbital Transfer Vehicle with the additional redundancy of backup auxiliary propulsion could easily offset the increased development and operational costs. Furthermore, selection of a two-main engine system with backup auxiliary propulsion would be supported by historical precedent. The Space Shuttle utilizes two engines backed up by auxiliary propulsion to return from low earth orbit which is analagous to the OTV returning from geosynchronous orbit.

References

1. Orbital Transfer Vehicles: Concept Definition and Analysis Study, First Interim Briefing, NASA contract NAS8-36017, Marietta Aerospace, Oct. 1984.

2. Orbital Transfer Vehicle: Concept Definition and Analysis Study, First Interim Briefing, NASA contract NAS8-36017, Boeing Aerospace Co., Oct. 1984.

3. Schoenman, L., "Orbit Transfer Rocket Engine Technology Program," Aerojet Liquid Rocket Co., Sacramento, CA, 1983. (NASA CR-168157)

4. Brown, J.R., "Orbit Transfer Rocket Engine Technology Program," Pratt & Whitney Aircraft, West Palm Beach, FL, Apr. 1984. (NASA CR-168156)

5. Martinez, A., "Orbit Transfer Rocket Engine Technology Program, Vol. 1, Study Results," Rockwell International Corp., Canoga Park, CA, RI/RD-83-131-2-VOL-1, Mar. 1984. (NASA CR-168158)

6. "Space Station Needs, Attributes and Architectural Options Study," TRW Space Technology Labs, Los Angeles, CA, Apr. 1983 (NASA CR-172947 and NASA CR-172952)

7. "A Study of Space Station Needs, Attributes and Architectural Options" General Dynamics Corp., St. Louis, MO, Apr. 1983. (NASA CR-173997)

8. "Space Station Needs, Attributes and Architectural Options," MDC-H0180A, McDonnell Douglas Astronautics Co., Apr. 1983.

9. "Space Station Needs, Attributes and Architectural Options Study," Martin Marietta Aerospace, Denver, CO, SOC-SE-03-01; Vol. 1: Executive Summary (NASA CR-172691); Vol. 2: Mission Definition (NASA CR-172692); Vol. 2 Appendix C (NASA CR-172693); Vol. 3: Mission Requirements (NASA CR-172700); Vol. 4: Mission Implementation Concepts (NASA CR-172701); Vol. 5: Cost Benefits and Programmatic Analyses (NASA CR-170358), Apr. 1983.

10. "Space Station Needs, Attributes, and Architectural Options Study," Rockwell International Corp., Downey, CA, SSD-83-0032-1, Vol. 1: Missions and Requirements (NASA CR-172696); SSD-83-0032-2 Vol. 2: Program Options, Architecture and Technology (NASA CR-172697); SSD-83-0032-3 Vol. 3 Cost and Benefits (NASA CR-172698); SSD-83-0037, Final Executive Report (NASA CR-172695), Apr. 1983.

11. "Space Station Needs, Attributes, and Architectural Options, Vol. 1, Executive Summary," Lockheed Missiles and Space Co., Sunnyvale, CA, LMSC-D889718-VOL-1, Apr. 1983. (NASA CR-172792)

12. "Space Station Needs, Attributes, and Architectural Options, Vol. 1, Executive Summary," Grumman Aerospace Corp., Bethpage, NY, SA-SSP-RP007, Apr. 1983. (NASA CR-173710)

13. "Space Station Needs, Attributes, and Architectural Options," Boeing Aerospace Co., Seattle, WA, D180-27477-6, Apr. 1983. (NASA CR-173335)

14. What Made Apollo a Success? NASA SP-287, 1971.

15. "Orbital Transfer Vehicle Concept Definition Study, Vol. 1, Executive Summary," Boeing Aerospace Co., Seattle, WA, D180-26090-1 thru D180-26090-6, M80. (NASA CR-161783 through CR-161788)

16. Accident Factors: 1982 Edition, National Safety Council, 1982.

17. "APU Fires May Affect Shuttle Launch," Aviation Week Space Technology, Vol. 119, No. 25, Dec. 19, 1983, pp. 26-27.

18. "L-1011 Recovers From Triple-Engine Failure," Aviation Week & Space Technology, Vol. 118, No. 19, May 9, 1983, p. 30.

19. Kapis, K.C., and Lamberson, L.R., Reliability in Engineering Design, Wiley, New York, 1977.

20. Aviation Week & Space Technology, Vol. 122, No. 2, Jan. 14, 1985, p. 13.

TABLE 1. - EFFECT OF ENGINE REDUNDANCY ON RELIABILITY TEST REQUIREMENTS

[0.9999 propulsion system reliability; 50 percent confidence.]

Number of engines	Tests	Testing cost, dollars	Individual reliability
1	~7000	70 000 000	0.999
2	~70	700 000	.99
3	~7	70 000	.90
4	1	10 000	.684

TABLE 2. - EFFECT OF FAILURE CORRELATION ON TEST REQUIREMENTS

[Two engine configuration; four burn mission.]

Correlation, percent	Propulsion system reliability	
	Tests	
	0.997	0.999
0	~150	~270
1	~275	~650
5	~1000	~2700
10	~1900	~6800

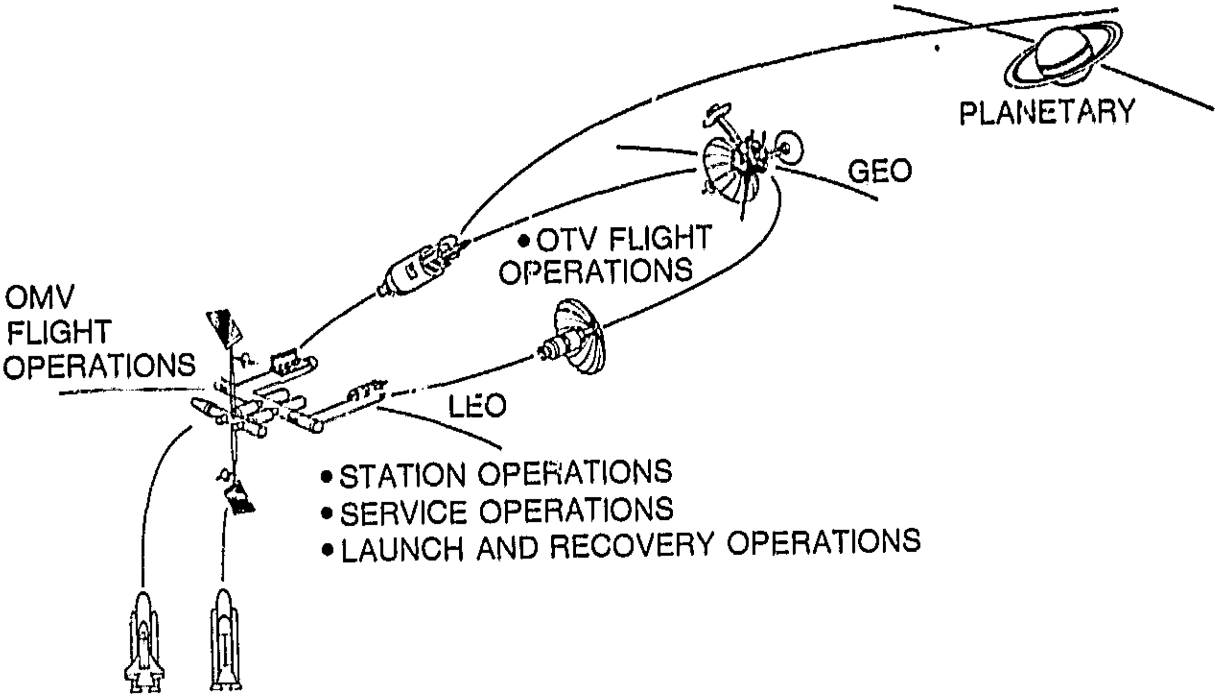

Figure 1. - Integrated space transportation systems, 1990's scenario.

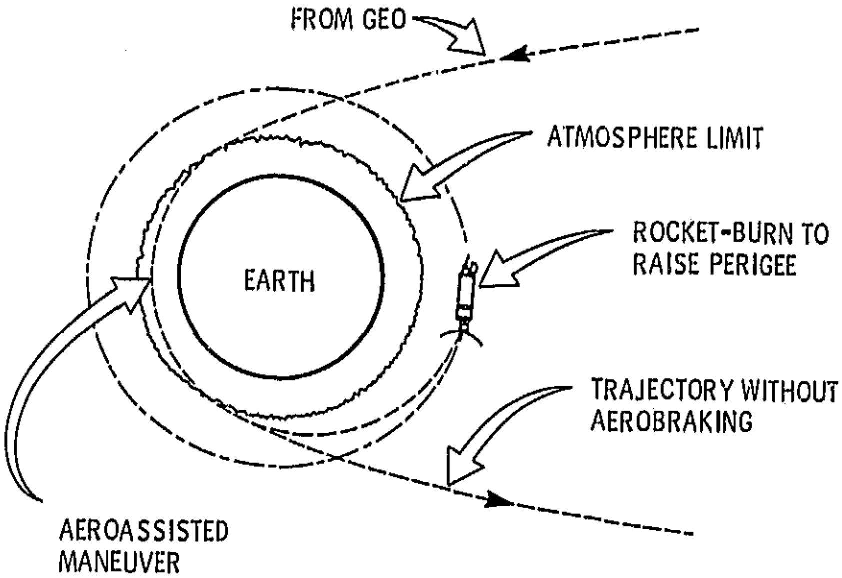

Figure 2. - Aeroassisted vehicle maneuver.

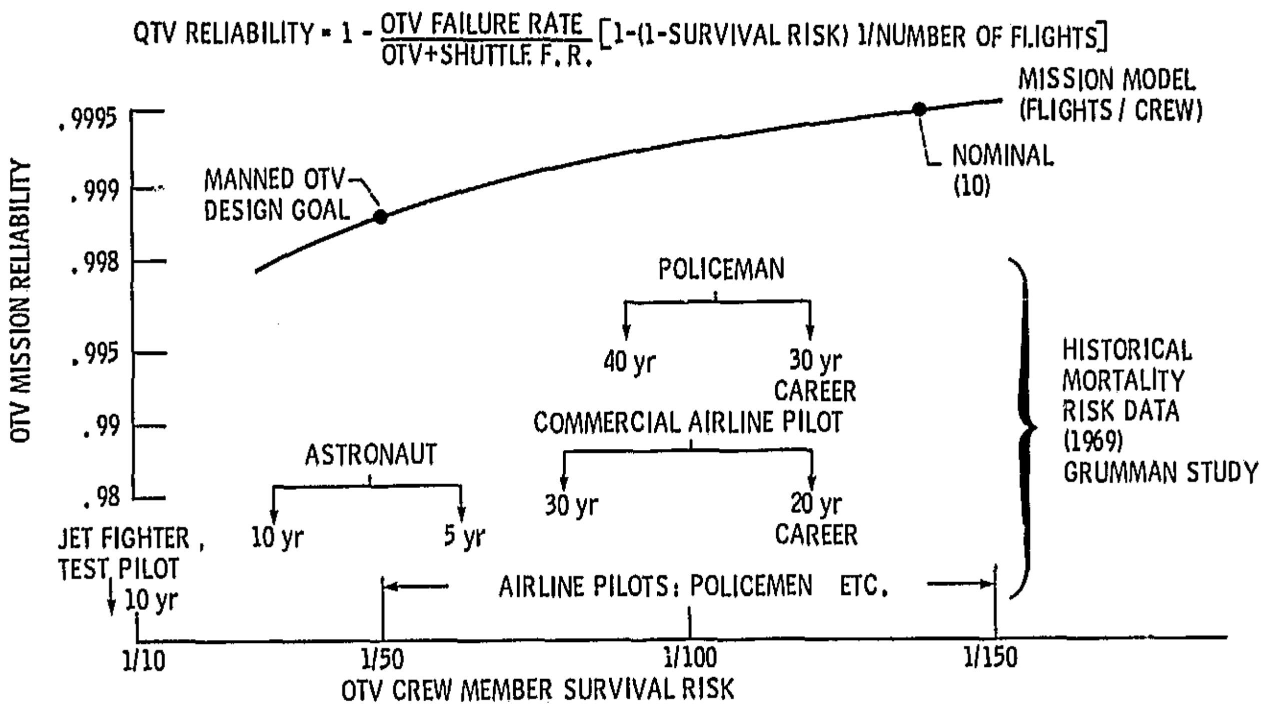

Figure 3. - Manned OTV mission reliability requirements for mortality risks of comparable professions. (ref 15).

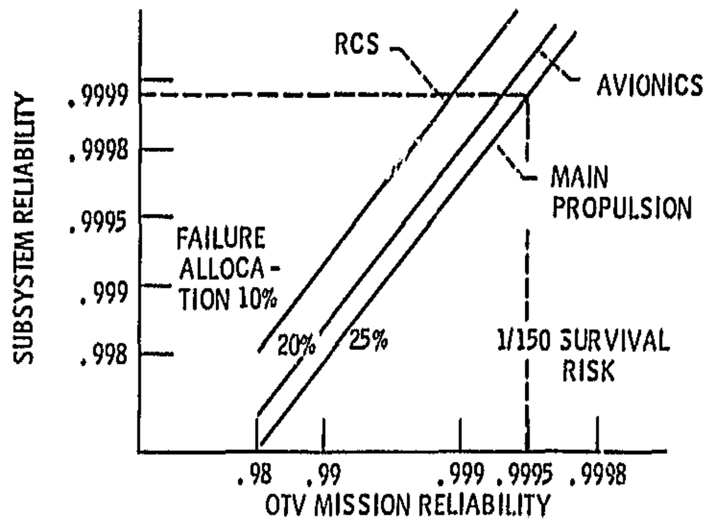

Figure 4. - Manned OTV subsystem reliabilities (ref 15).

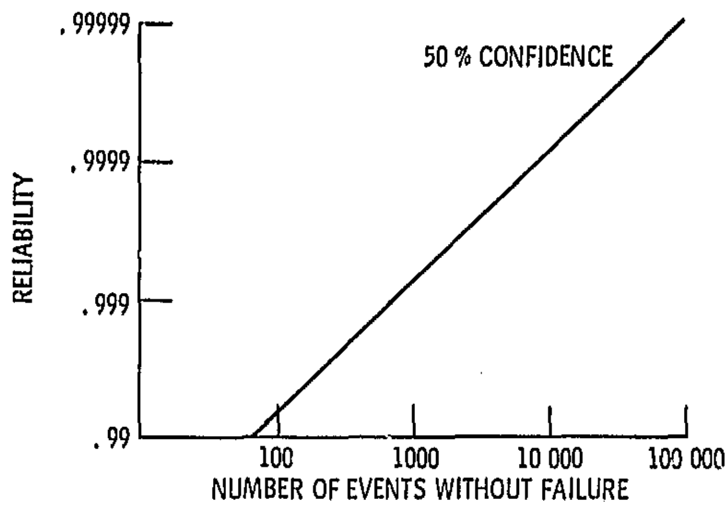

Figure 5. - Demonstrated reliability for tests performed.

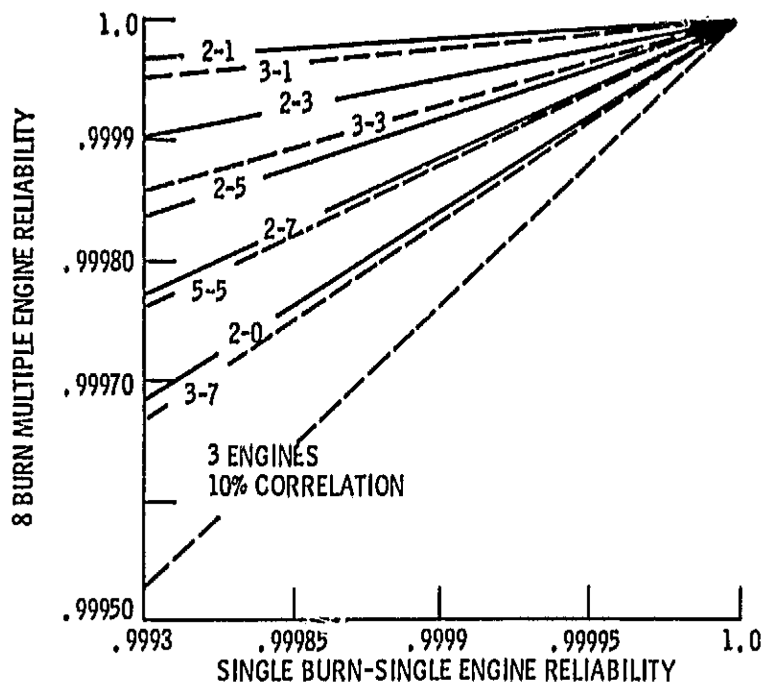

Figure 6. - Effect of correlation factor on propulsion system reliability for 8 burn mission.

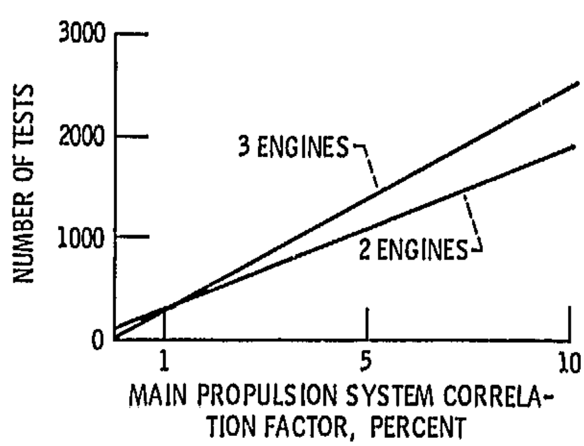

Figure 7. - Engine tests for .9997 reliability of 4 burn mission.

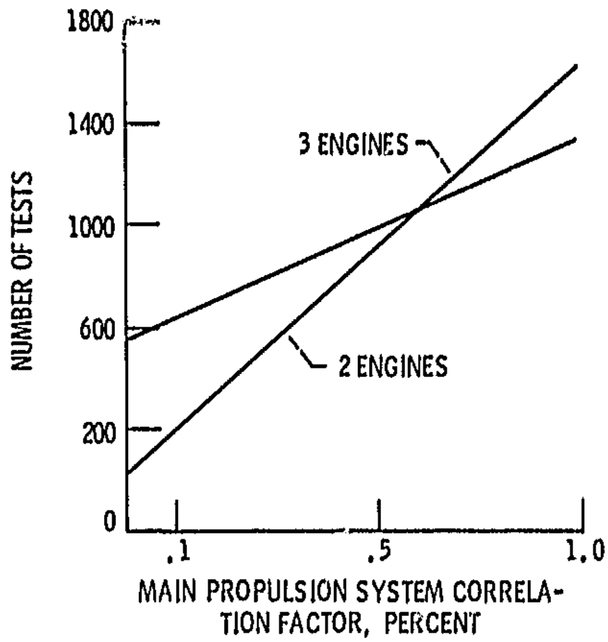

Figure 8. - Engine tests for .9999 reliability of 8 burn mission.

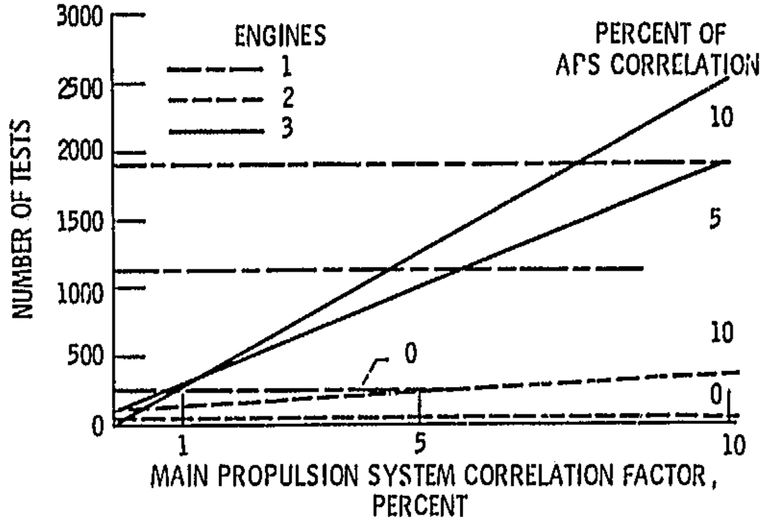

Figure 9. - Effect of backup propulsion on engine tests for .9997 reliability of 4 burn mission.

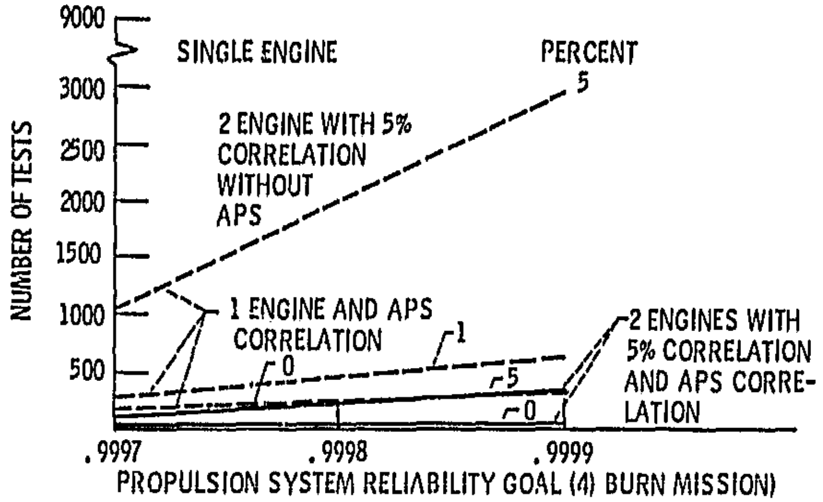

Figure 10. - Effect of backup propulsion APS on reliability test requirements.