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Status of Advanced Orbital Transfer Propulsion

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STATUS OF ADVANCED ORBITAL TRANSFER PROPULSION

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ABSTRACT

A new Orbital Transfer Vehicle (OTV) propulsion system will be required to meet the needs of space missions beyond the mid-1990's. As envisioned, the advanced OTV will be used in conjunction with the Space Shuttle, Space Station and Orbit Maneuvering Vehicle. The OTV will transfer men, large space structures and conventional payloads between low earth and higher energy orbits. Space probes carried by the OTV will continue the exploration of the solar system. When lunar bases are established, the OTV will be their transportation link to earth.

The first step in the development of an advanced OTV propulsion system is to define the system requirements. This paper describes critical engine design considerations based upon the need for low cost payload delivery, space basing, reusability, aeroassist maneuvering, low g transfers of large space structures and man rating. The importance of each of these to propulsion design is addressed based upon extensive vehicle system and propulsion analyses by the aerospace community. Specific propulsion requirements discussed are:

High performance H_2/O_2 engine

Multiple engine configurations totalling no more than 15 000 lbf thrust

15 to 20 hr life

Space maintainable modular design

Health monitoring capability

Safety and mission success with backup auxiliary propulsion

NASA is funding the development of OTV engine technology at Aerojet, Pratt & Whitney, and Rocketdyne. Each company has selected a different approach to meeting the propulsion system requirements. Selected results are presented.

INTRODUCTION

This paper presents discussions, observations, and analyses of advanced propulsion concepts for Orbital Transfer Vehicles, factors influencing their design, and, reviews ongoing NASA sponsored efforts directed toward demonstration of technology to support development of an advanced engine in the early 1990's.

For the 1990's 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 Orbital 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, Orbital 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 Orbital 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 Orbital Transfer Vehicle would operate primarily between low earth orbit and geosynchronous orbit as a reusable spacecraft and as an expendable vehicle for planetary missions.

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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 delivery of satellites to geosynchronous orbit. The vehicle will also be man rated for servicing missions at GEO. Furthermore, it will be a versatile vehicle which can be used for planetary transfers and delivery of large, acceleration limited space structures to GEO.

The characteristics of the advanced OTV have been the subject of numerous NASA and industry studies. The role of the Orbital Transfer Vehicle in placing, retrieving, and servicing payloads in high earth orbit 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 operation beyond low earth orbit.

The projected propulsion system requirements for an OTV in the late 1990's will, of course, be influenced by the assumed missions and their frequency, the Shuttle capabilities in terms of payload weight and volume, and the basing mode of the OTV. The space based, manned, aeroassist, and Low G Transfer missions are the technology driver missions for the OTV propulsion concepts. Their impact will be felt as requirements for enhanced reliability, reusability, life and on-orbit maintenance, as well as improved performance and versatility.

ORBITAL TRANSFER VEHICLES

Many factors have contributed to shaping the current requirements and needs for Orbital Transfer Vehicles. Chief among these have been missions in the mission model and technological advancements with associated operational changes.

Mission Models

Orbital Transfer Vehicle Mission models were introduced in the late 1970's. They served to better characterize frequency and types of OTV missions so that economic analysis of competing approaches could be performed. Various models have been assembled by government and by the aerospace community. As illustrated in Fig. 2, the models have been subject to nearly continuous revision. The principal changes have been in reduction of the number of missions. Operational experience and budgeting realities have shown that the Space Shuttle cannot support the launch frequency envisioned in early OTV mission models. Additional revisions have arisen from the identification of new missions and the deletion of cancelled, delayed, redefined, and reassigned missions.

Some of the notable additions have been the missions for manned satellite servicing at Geosynchronous Orbit and those for transfer of large space structures with low acceleration limits.

Technological & Operational Changes

Early designs (Ref. 1) of the Orbital Transfer Vehicle were all propulsive. The main engines provided all the necessary thrust to transfer and circularize at higher orbits, as well as return and circularize in low earth orbit. The current Orbital Transfer Vehicles incorporate some form of aeroassist on the return to low earth orbit as shown in Fig. 3. This maneuver uses the drag induced by the earth's atmosphere to reduce the OTV velocity and thereby reduce the propellants required for the circularization burn.

Another change in OTV operation has been the general acceptance of multiple perigee burn transfers as shown in Fig. 4. An OTV designed for multiple perigee burns can deliver greater payload than an OTV designed for a single transfer burn, primarily as a result of reductions in engine weight for the lower required thrust for multiple burns. This approach had been originally limited to the low g transfer of large space structures. However, it is now felt that even manned missions can be multiple perigee burn. Recent studies (Ref.2) have shown that the radiation dosage at Geosynchronous orbit is likely to set the shielding requirements for manned OTV missions. Multiple passes through the Van Allen belts will be readily accommodated by GEO shield requirements.

The introduction of the Space Station has caused a major restructuring of OTV operations. Early studies (Ref. 3) of reusable Orbital Transfer Vehicles assumed the OTV would be flown to LEO with its payload and returned for maintenance on earth. However, studies are now focusing on the benefits and issues of basing and maintaining the OTV in space.

Another concept recently introduced into the OTV scenario is the mobile geo service station (Ref. 4). As shown in Fig. 5, the MGSS is permanently deployed at geosynchronous orbit. It allows the OTV mission planners to better manifest the OTV and store propellants and supplies at the MGSS to service satellites. The mass requirements of manned missions can be reduced from approximately 14 000 to 8000 lb round trip which significantly reduces the gross lift off weight and the required thrust for a manned mission.

ORBITAL TRANSFER VEHICLE PROPULSION

In 1981, NASA initiated an Advanced OTV Propulsion Technology Program. The objective of this program was to establish by the early 1990's, the technology base for a high performance, multiple restart, variable thrust, orbital transfer propulsion system which could be man rated, space or ground based, and compatible with aeroassisted maneuver concepts. The uncertainties of the missions in the OTV mission models and the continual evolution in OTV operation, technology, and supporting infrastructure necessitated a broad statement of the program requirements and goals.

The requirements as listed in Table 1 included limitation to cryogenic hydrogen-oxygen propellants and a total vacuum thrust level of 10 000 to 25 000 lb. These parameters were selected to be compatible with a manned sortie to geosynchronous orbit.

In addition to the specific required characteristics, the program established several goals reflecting characteristics desirable for an advanced engine. These goals are listed in Table 2. In total, they represented a set of highly ambitious characteristics, and were established as technical challenges to generate options and tradeoffs, since all goals may not be achievable singularly or concurrently. The rationale which led to the specific numerical requirements and goals are discussed in Ref. 5. Studies to define propulsion concepts based upon these requirements and goals were completed in 1983 by Aerojet General-Aerojet TechSystems Company, United Technologies Corporation - Pratt & Whitney Aircraft Group, and Rockwell International-Rocketdyne Division. The three engine concepts identified in these studies were baseline systems for defining technology needs for an advanced engine. The identified technologies could generally be applied to engines in the 2500 to 25 000 lb thrust range.

The concepts defined in these studies are summarized below. Additional description of the concepts and technologies is available in Ref. 5.

Aerojet Techsystems Company

A dual propellant expander cycle engine sized for a nominal thrust of 3000 lb was baselined. The engine is throttleble over a 30:1 range with tank head idle mode producing 100 lb of thrust and a 15:1 continuously throttleable pumped mode from 200 to 3000 lb of thrust. The engine's specific impulse, in excess of 480 s at a mixture ratio of 6.0, would be obtained through utilization of a chamber pressure of 2000 psia and a nozzle area ratio of 1200:1. When applied to an advanced OTV, a multiple engine installation would be utilized to achieve the desired total thrust level.

The flow schematic of the Aerojet concept is shown in Fig. 6. The key feature of the dual propellant expander cycle is that both hydrogen and oxygen are used to drive their respective turbopumps. This approach enables a much higher chamber pressure to be obtained than with the conventional hydrogen expander for this engine thrust size. It also eliminates interpropellant seals in the oxidizer turbopump and could eliminate inert gas on the OTV to purge interpropellant seals.

The critical technology issue identified for this engine concept is the hazard of explosion or combustion of oxygen turbine materials exposed to the warm gaseous oxygen in the dual propellant cycle.

Pratt & Whitney

A hydrogen expander cycle sized for a nominal thrust level of 15 000 lb with oxidizer preheating and hydrogen regeneration was selected. The concept is throttleable over a 30:1 range with 3 discrete operating modes; tank head idle (1 percent thrust), pumped idle (5 percent thrust) and full thrust. The concept has a chamber pressure of 1500 psia and a nozzle area ratio of 640:1 resulting in a specific impulse in excess of 480 s at a mixture ratio of 6.0.

The propellant flow schematic for this expander cycle engine is shown in Fig. 7. A unique element of this concept compared to the other contractor approaches is the hydrogen cooled gears in the turbopump assembly which synchronize the oxygen and hydrogen pumps and drive the low speed inducers.

The gears have been identified as a critical technology item for the engine concept. Although other rocket engines such as the RL10 family have successfully utilized gears, the long life goal and much higher speeds of this concept require significant technical advancement.

Rocketdyne

A hydrogen expander cycle with oxidizer preheating and hydrogen regeneration was selected as the advanced propulsion concept. The concept was sized for 15 000 lb thrust throttleable over a 30:1 range in three discrete operating modes; tank head idle (1 percent thrust), pumped idle (5 percent thrust) and full thrust operation. At a mixture ratio of 6.0, the concept has a specific impulse in excess of 480 s with a chamber pressure of 2000 psia and an extendable nozzle of 1300:1 area ratio.

The propellant flow schematic for this expander cycle is shown in Fig. 8. Key features identified as technology advancements are chamber heat extraction and life enhancements from longitudinal fins on the hot gas side and fins in the coolant channels.

TECHNOLOGY PROGRAMS

Based upon the engine concepts and identified technology needs, a comprehensive effort was begun in 1983 to demonstrate technology readiness of each concept for a Design, Development, Test and Engineering (DDT&E) program in the early 1990's. Highlights of selected efforts are summarized below for generic research applicable to all concepts, and concept specific activities.

Aerojet Techsystems

Materials for high pressure oxygen turbomachinery. The use of warm gaseous oxygen to drive the oxygen turbopump raised concerns of ignition hazard of the materials in the turbine. Frictional rubbing or particle impact could produce disastrous results. A review of the literature indicated these potential problems might be overcome by careful selection of materials based upon their Burn Factor (Ref. 6)

$$\text{Burn Factor} = \frac{\text{heat of oxidation}}{\text{thermal diffusivity}}$$

A series of tests have been completed at NASA-JSC facilities in White Sands, New Mexico. Both frictional rubbing and particle impact methods have been conducted to provide confirmation of the ranking and selection of materials by Burn Factor. A description of the apparatus and test procedures are available in Ref. 7. It has been found that materials with high Burn Factors such as 316 Stainless Steel and Hastelloy X were easily ignited. Those of low Burn Factor such as Nickel 200 and Zirconium Copper were extremely difficult to ignite or would not ignite. Oxygen pressures up to 3000 psia have been evaluated. Typical results are shown in Fig. 9.

Advanced cooling long life chambers. Obtaining high performance with long life has required the identification of advanced cooling concepts for the thrust chamber. One approach is to increase the density of cooling channels. Figure 10 shows a test specimen incorporating 0.010 in wide channels at nearly triple the normal density. Increased number of coolant passages also result in smaller lands. This complicates the process of completing chamber closeouts and raises concern over possible debonding of the closeout. Several candidate closeout materials have been investigated. Shown in Fig. 11 are photomicrographs of specimens of electroformed nickel alloy over electroformed copper before and after heat cycling. Bond integrity was maintained.

Pratt & Whitney

High speed long life gears. The synchronizing gear train forms an integral element of the turbomachinery and control concept for the Pratt & Whitney engine. The gear life and speeds are two to four times that demonstrated for the engines of the RL10 family. Literature reviews have shown that very little design data is available for hydrogen cooled gears and none for the design speed and load range of the advanced engine. Evaluation of RL10 gears has shown that deep wear patterns are generated at the base of the gear teeth as shown in Fig. 12. Pitting and scoring are evident toward the tips. In order to meet the life goals for the advanced engine improved designs, materials, coatings, and lubricants are being evaluated.

Long life chamber materials. The copper alloy, Narloy Z, used in the Space Shuttle Main Engine thrust chamber has shown a tendency to undergo surface roughening in operation. This leads to undesirable heat transfer conditions and premature failure through wall cracking. Since the OTV engine may require space based inspection and maintenance, methods to avoid these material related failures is desirable.

One potential method to produce copper alloys with better Low Cycle Fatigue performance is rapid solidification rate powder metallurgy. Using this process, materials are produced with supersaturated concentrations of desirable agents for enhanced ductility, strength, and microstructure phase stability. The fine grain structure is evident in Fig. 13 compared to wrought material. Copper alloy systems with Chromium, Zirconium, Halfnium, Silver, and with dispersed metal borides and silicides have been investigated. Several pounds of alloys have been produced by atomization, then consolidated, processed, and tested for alloy characteristics. Most copper alloys exhibit improved mechanical properties and thermal stability.

Rocketdyne

Thrust chamber heat load maximization. The expander cycle derives its turbopump drive energy from heat extracted from the chamber and nozzle. Maximizing the energy extracted provides for highest chamber pressures and smallest engine envelop for a given expansion ratio. One method to increase energy extraction is to provide ribs on the hot gas side of the chamber to increase the available surface area and enhance the heat transfer coefficient over the smooth wall condition. Evaluation of this concept with hot air test has been completed. As shown in Fig. 14, enhancements of nearly 50 percent in energy extraction were obtained compared to the standard smooth wall.

Two stage partial admission turbine. O_2-H_2 expander cycle engines of the OTV thrust class require very high speed fuel turbomachinery operating at relatively small amounts of turbine flow to deliver high pump discharge pressures. In order to avoid excessive speeds and extremely short turbine blades, a two stage partial admission turbine has been selected. The affect of various second-stage nozzle positions and arc of admission changes are being evaluated. The projected effect of increasing second stage nozzle angulation by 40° from the baseline angulation is shown in Fig. 15.

Generic

High area ratio nozzle performance. Calculation of engine specific impulse by the engine contractors has resulted in significant differences as shown in Fig. 16. The source of the differences lie in different approaches to boundary layer losses and energy extraction in very high area ratio nozzles. Experimental data to anchor the models has been available only to 400:1 area ratio. Efforts are now underway to extend the data base to 1000:1 for uncooled and cooled nozzles and to establish standard analytical procedures for the high area ratio nozzle.

ENGINE CONCEPT EVOLUTION

Since 1981, when the OTV engine concepts and technologies were identified, additional studies (Ref. 8-12) of Orbital Transfer Vehicles have been conducted. These studies have served to confirm the merits of the engine concepts and to provide updates to propulsion requirements and needs. The future directions for the engine concepts have been influenced by the continued evaluation of propellants, engine number and thrust, space based maintenance, aeroassist concepts, and economics of advanced engines.

Propellants

Continued changes to the OTV mission model, space infrastructure, and projected transportation costs requires that propellant selection for the Orbital Transfer Vehicle be periodically reassessed. A number of propellant combinations including cryogenics, space storable and earth storables have been evaluated. As shown in Fig. 17, cost is the predominant propellant discriminator representing upwards of 80 percent of the total OTV Life Cycle Cost. For the current mission model of approximately 12 flights per year, hydrogen-oxygen is a clear winner because of its high specific impulse and the availability of scavengable propellants from the Space Shuttle.

Engine Number and Thrust

Total OTV thrust requirements have been steadily decreasing as the sizing missions have decreased in payload weight, and innovations such as aeroassist and multiple perigee burn transfers have gained acceptance. At the same time, engine redundancy has emerged as the most cost effective means to provide high reliability for both manned and unmanned missions.

As shown in Fig. 18, studies (Ref. 13) now conclude that optimum propulsion for unmanned OTV is provided by two engines each with 2500 to 7500 lb of thrust depending upon the number of perigee burns.

The number of engines for manned missions is not resolved at this time. Studies (Ref. 14) have shown that previous manned spacecraft have utilized two engines with a "backup" propulsion capability. This approach or addition of a third engine is being considered.

Space Based Maintenance

As shown in Fig. 19, the optimum design life for the OTV engines is between 15 and 20 missions when engine replacement costs and the development costs of long life engines are considered. However, the mean time between repair of the engines is likely to be approximately one-half the design life based on a normal distribution of failures. Several approaches have been identified for engine repair ranging from complete engine replacement to replacement of subcomponents of the engine. As shown in Fig. 20, replacement of engine modules results in the lowest cost maintenance approach when production, transportation, replacement time and facilities are considered. These modules consist of groups of engine components such as the hydrogen turbomachinery, valves and lines, or the thrust chamber and injector, or the nozzle, or the control and diagnostic units.

This change in engine maintenance philosophy from engine to module replacement is a significant challenge. Engine designers must provide clever packaging, light weight, easy maintenance interfaces and adequate health monitoring to identify failed or degraded engine modules.

Aeroassist Concepts

As discussed earlier, utilization of aeroassist reduces the OTV propellant requirements as compared to an all propulsive OTV. For equal propellant load, aeroassist can significantly increase the payload capacity. This particularly is true for round trip payload missions, such as the manned missions. As shown in Fig. 21, the payload delivery to GEO with aeroassist is nearly double that of the all propulsive OTV. Increases of this magnitude are, of course, dependent on lightweight aeroassist devices. The number of aeroassist concepts being studied by industry and government continues to grow. As shown in Fig. 22, they range from low lift to drag concepts (<0.75) such as the inflatable ballute and aerodynamic brake through moderate (0.75 to 1.5) lift to drag biconic shapes, to high lift to drag (>1.5) vehicles. The operational considerations and limitations of these concepts differ significantly, creating a challenging environment for the propulsion designer.

Care is being taken to ensure compatibility with whichever aeroassist concept is selected for the OTV. This has meant issues such as throttleability, and nozzle extension-retraction have remained open.

Advanced Engine Economics

The propulsion system characteristics of the advanced OTV have evolved to the point where using existing rocket engines, such as the RL10A-3-3A, represent serious cost and operational barriers. Various derivatives in the RL10 family, as well as the three advanced engine concepts, have been evaluated based on cost, timing, and benefits. As shown in Fig. 23, advanced engines have the lowest life cycle cost even when benefits are discounted. In addition, advanced engines provide for overall greater capability and flexibility than do the RL10 derivatives.

The concept of preplanned product improvement is also gaining acceptance as a means of spreading the development costs over a greater number of years. The advanced engine would be designed for the ultimate goals of high performance, variable thrust, man rating, long life, and space based maintenance. However, the initial engines would have limited demonstrated capability focused on high engine performance which is most beneficial to early payload delivery missions. Later, as needed, space based maintenance, health monitoring and diagnostics, and extended life could be demonstrated.

FUTURE DIRECTIONS

The ultimate development of an advanced OTV engine is intimately related to the development of an advanced OTV. As shown in Fig. 24, current planning envisions a space based OTV in the mid-to-late 1990's. This is supported by an Aeroassist Flight Experiment in the late 1980's to select an aeroassist approach and an engine development program in the early 1990's.

Prior to the initiation of engine development, an integrated components program is planned for the engine concepts as shown in Fig. 25. Technology results will be incorporated into engine simulators for component evaluation. This approach has an additional benefit of permitting system level uncertainties and problems to be uncovered prior to development commitment. This program will be based upon a revised set of requirements and goals which reflect the current advanced OTV definitions. Shown in Table 3 are likely 1986 engine design parameters.

CONCLUDING REMARKS

Analyses of mission models for Orbital Transfer Vehicles continue to support the need for and economic justification of developing a new vehicle with enhanced capabilities. The analyses suggest that the vehicle be reusable, space basable, and utilize aeroassist technology. The propulsion needs for the vehicle differ significantly from any existing rocket engine. In particular, the engine is most likely to use hydrogen-oxygen propellants with a thrust in the range of 2500 to 7500 lb, depending on the number of perigee burns. The engine will have a life of 15 to 20 hr between overhauls and will be modularized with health monitoring diagnostics to facilitate space based maintenance.

NASA has a program to establish advanced engine technology for a future Orbit Transfer Vehicle propulsion system. The program's objective is to provide the technology to enable a low risk and minimum cost design, development, test and engineering (DDT&E) program for an advanced OTV engine to proceed in the early 1990's. Currently, three engine concepts and associated technologies have been evolved providing a range of options to satisfy future missions.

A comprehensive technology program is underway and a new program is being initiated in 1986 to incorporate the results of the technology efforts into engine system simulators.

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TABLE 1 Required Advanced OTV Propulsion System Characteristics

Characteristic	Requirement
Propellants - fuel	Hydrogen
oxidizer	Oxygen
*Vacuum thrust (design point range)	10 000 to 25 000 lbf
Engine mixture ratio, O/F (design point)	6.0
Engine mixture ratio range, O/F	5.0 to 7.0
Propellant inlet temperature - Hydrogen	37.8° R
oxygen	162.7° R
Thrust vector control	±6.0° (square pattern)
Start cycle	Chilldown with propulsive dumping of propellants, engine start with pump inlets at propellent tank vapor pressure.

*Vacuum thrust range may be obtained from either a single engine or multiple engine configurations having total thrust within the specified range.

TABLE 2 Advanced OTV Propulsion System Goals

Characteristic	Goal
Vacuum specific inpulse, lbf-sec/lbm	520
Vacuum thrust throttle ratio	30:1
Net positive suction head, ft-lbf/lbm	
Hydrogen	0
Oxygen	0
Weight, lbm	360
Length (stowed), in.	40
Reliability	1.0
Service life	
Between overhauls, cycles/hours	500/20
Service free, cycles/hours	100/4

TABLE 3 Design Goals and Requirements for Advanced OTV Propulsion Research Engine Program

Parameter	Goal/design requirement
Basing	Space & Ground Based
Man-rating	Yes
Design criteria	Fail operational, fail safe
Propellants - fuel	Hydrogen
- oxidizer	Oxygen
Vacuum thrust (design point)	6000 - 15 000 lbf total
Number of engines	2 minimum
Engine mixture ratio, O/F (design point)	6.0
Engine mixture ratio range, O/F	5 to 7
Propellant inlet temperature -	TBD
hydrogen	
oxygen	
Gimbal	±20° minimum
Start cycle	Chilldown with all-propulsive dumping of propellants. Engine starts with pump inlets at propellant tank vapor pressure.
Vacuum thrust throttling	Tank head and pumped idle, minimum
Vacuum specific impulse*	480 s minimum
Net positive suction head (NPSH) -*	TBD
hydrogen	
oxygen	
Weight*	360 lbm total weight all engines
Length*	40 in
Reliability (90 percent confidence level)*	TBD
Service life*	20 hr or 200 starts

*Goal.

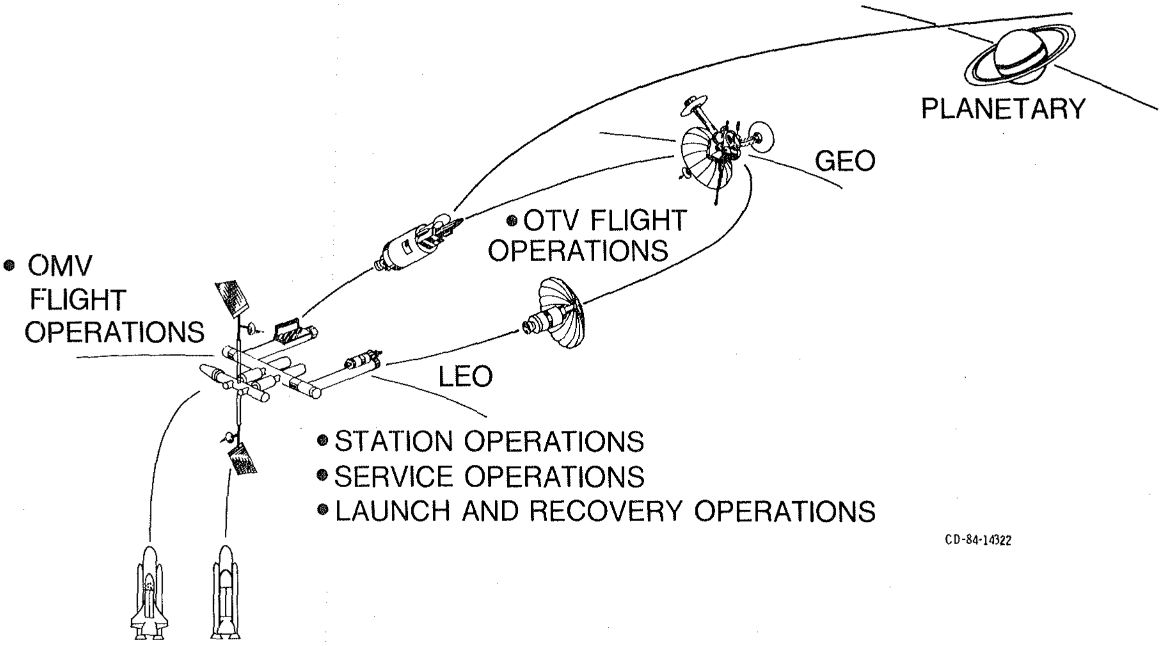


Figure 1. - Integrated space transportation systems. 1990's scenario.

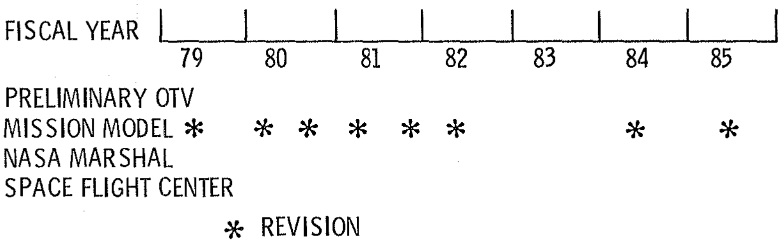


Figure 2. - Revisions to NASA MSFC preliminary OTV mission model.

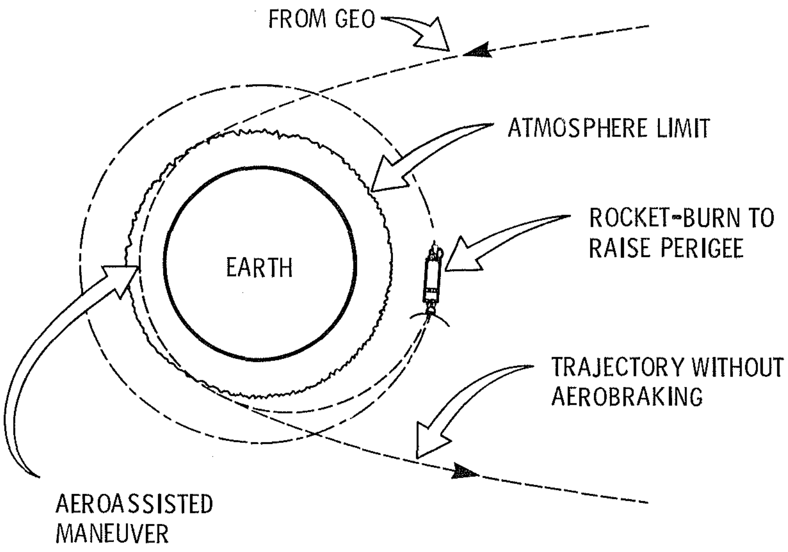
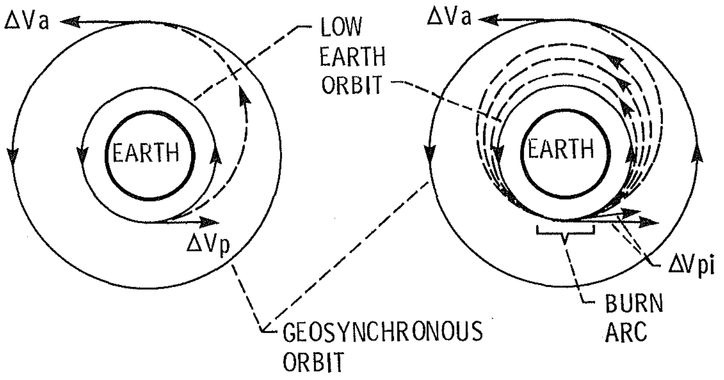


Figure 3. - Aeroassisted vehicle maneuver.



(a) Hohmann transfer.

(b) Multi-burn at perigee.

Figure 4. - Orbital transfer burn options.

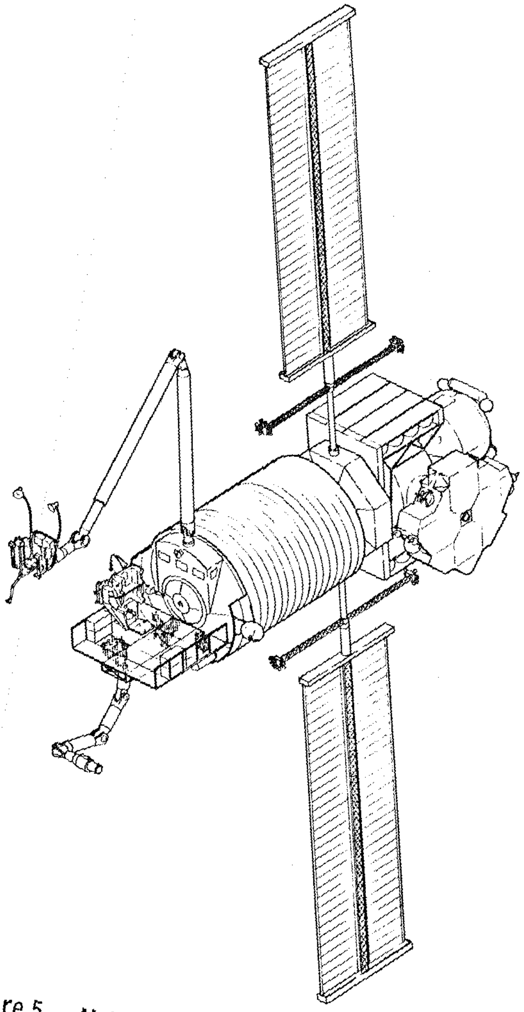
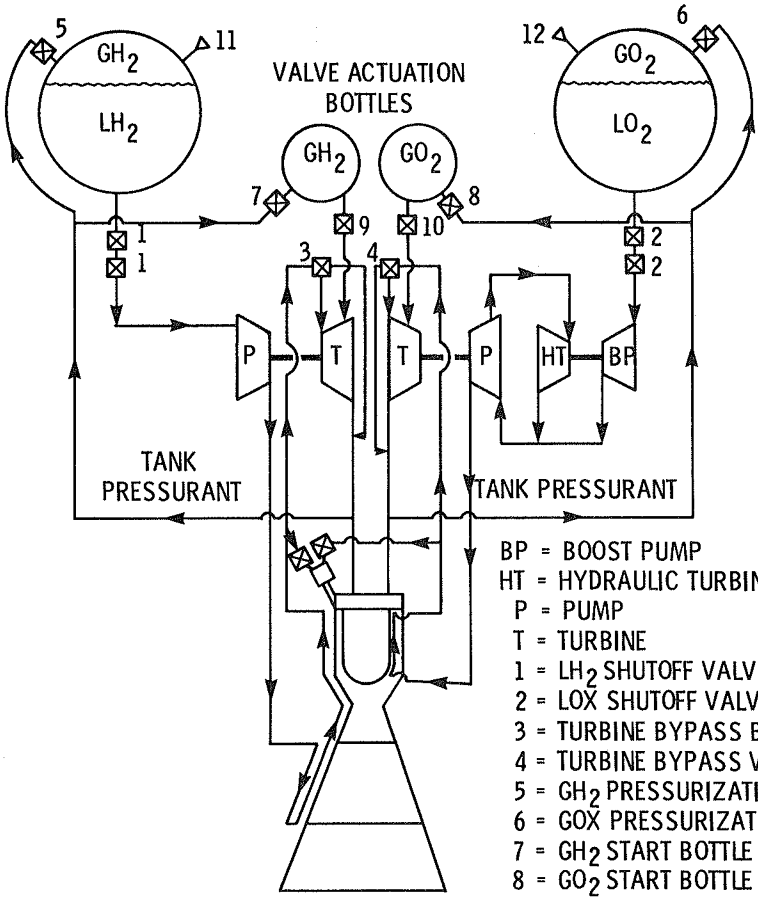


Figure 5. - Mobile GEO service station (MGSS).



BP = BOOST PUMP
HT = HYDRAULIC TURBINE
P = PUMP
T = TURBINE
1 = LH_2 SHUTOFF VALVES
2 = LOX SHUTOFF VALVES
3 = TURBINE BYPASS BALVE GH_2
4 = TURBINE BYPASS VALVE GO_2
5 = GH_2 PRESSURIZATION FLOW VALVE
6 = GOX PRESSURIZATION FLOW VALVE
7 = GH_2 START BOTTLE CHECK VALVE
8 = GO_2 START BOTTLE CHECK VALVE
9 = GH_2 TURBINE START VALVE
10 = GO_2 TURBINE START VALVE
11 = LH_2 TANK VENT VALVE
12 = LO_2 TANK VENT VALVE
IGN = IGNITION SYSTEM

Figure 6. - Flow schematic; Aerojet advanced OTV propulsion concept.

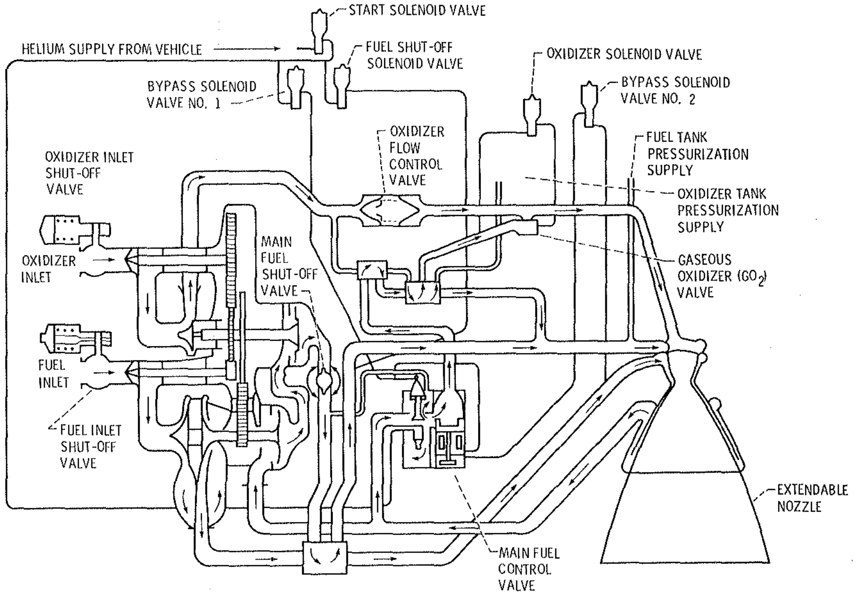


Figure 7. - Flow schematic; Pratt and Whitney advanced OTV propulsion concept.

ENGINE CONTROLS

(1) IFV - INLET FUEL VALVE
(2) IOV - INLET OXIDIZER VALVE
(3) MFV - MAIN FUEL VALVE
(4) MOV - MAIN OXIDIZER VALVE
(5) TBV - TURBINE BYPASS VALVE
(6) OTBV - OXIDIZER TURBINE BYPASS VALVE
(7) GOV - GASEOUS OXIDIZER VALVE
(8) DFV - DUMP FUEL VALVE
(A) FULL FLOW HYDRAULIC TURBINE FOR LOW PRESSURE LOX PUMP

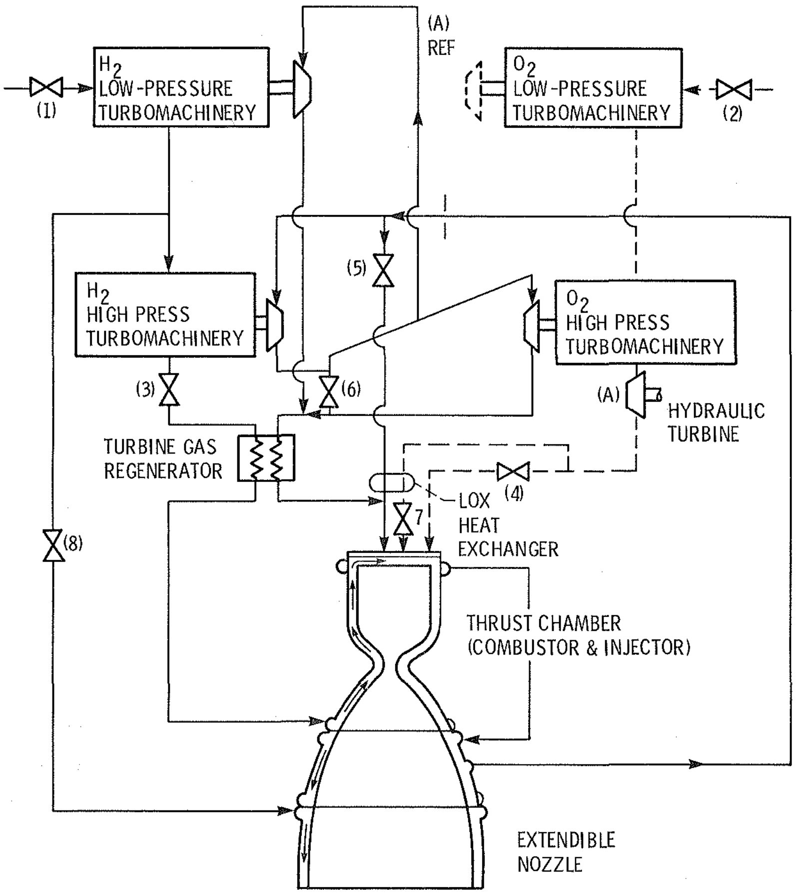


Figure 8. - Flow schematic; Rocketdyne advance OTV propulsion concept.

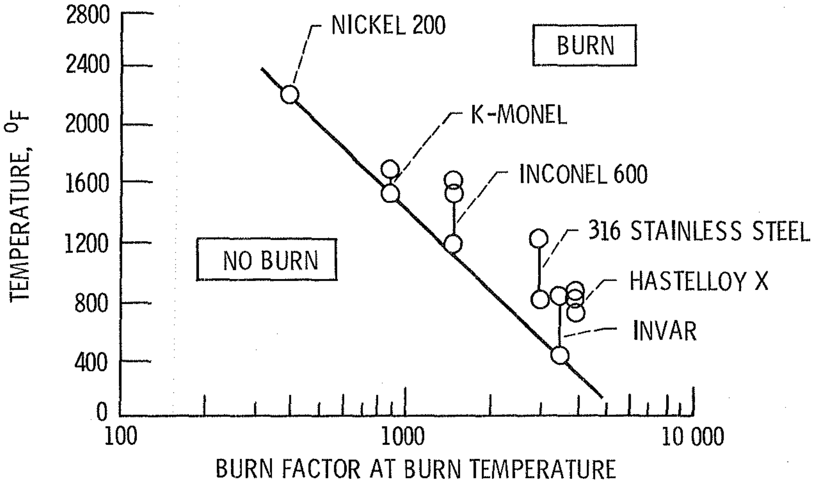


Figure 9. - Sample temperature vs burn factor at time of sample ignition.

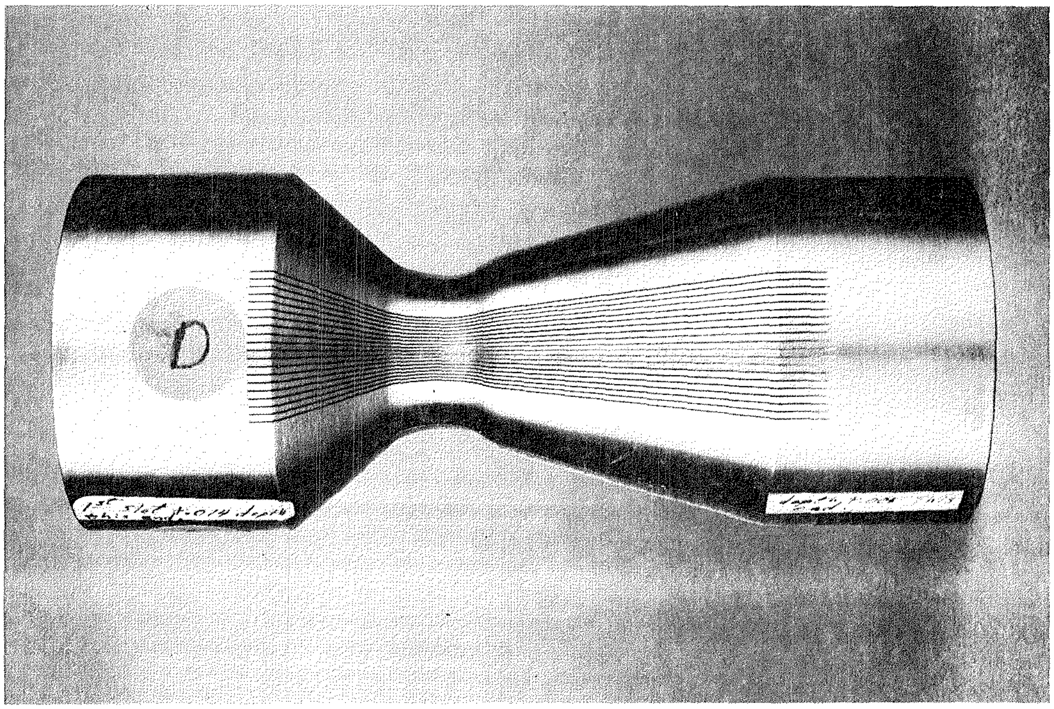
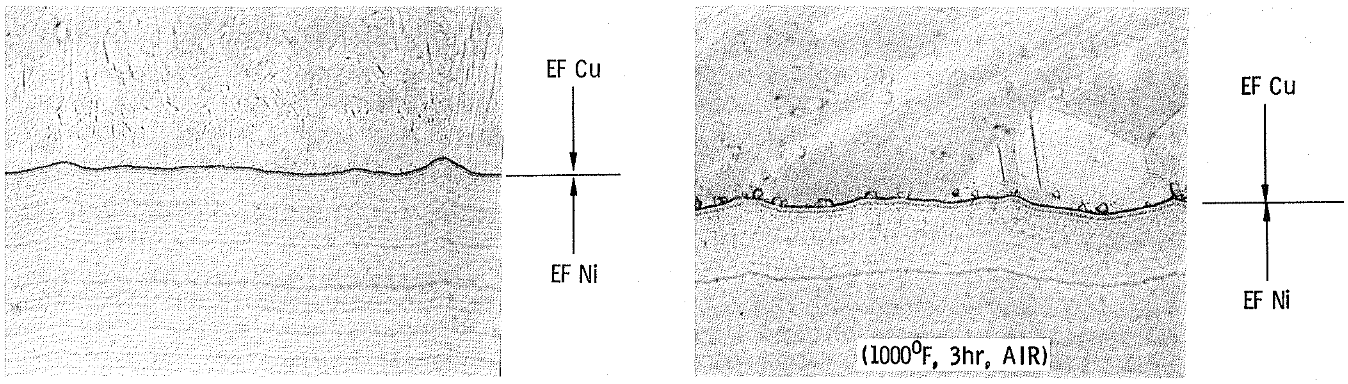


Figure 10. - Hydrogen cooled throat segment incorporating .010in. channels and .011in. lands.



(a) As received specimen, 400x

(b) Heat cycled specimen, 400x

Figure 11. - Photomicrograph of electroformed copper to electroformed nickel bond.

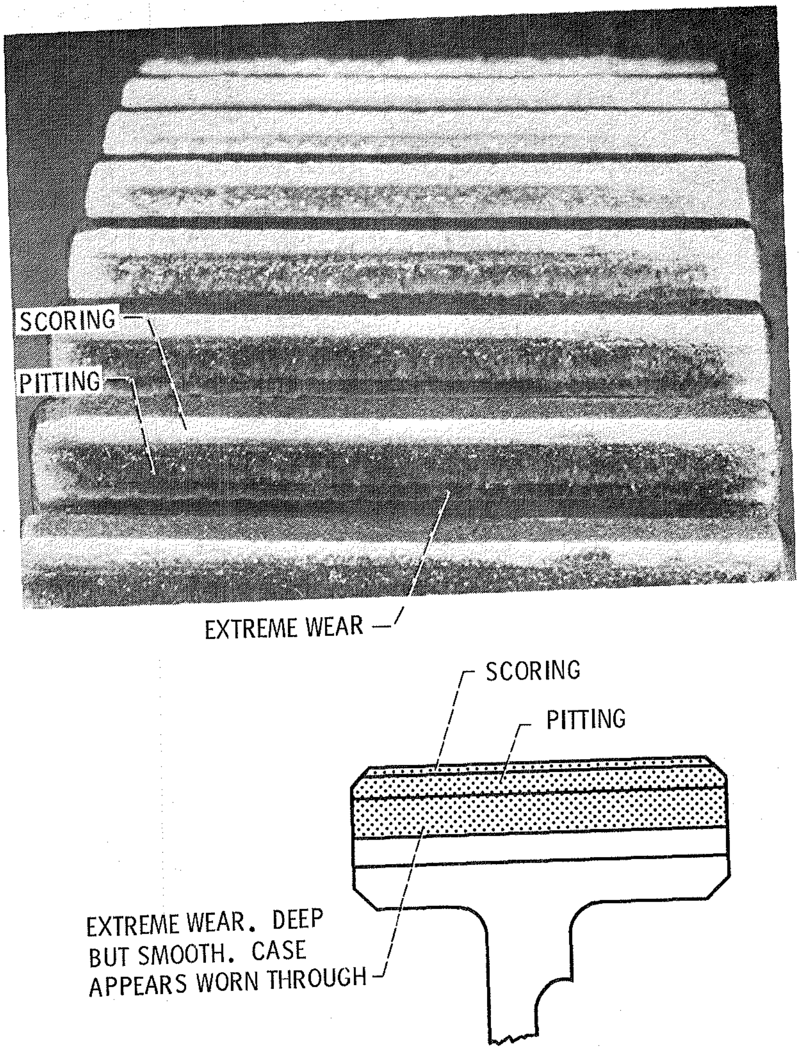


Figure 12. - RL10 gear teeth wear patterns.

(a) Wrought alloy (600X)

(b) RSR alloy (600X)

Figure 13. - RSR copper alloy microstructure comparison.

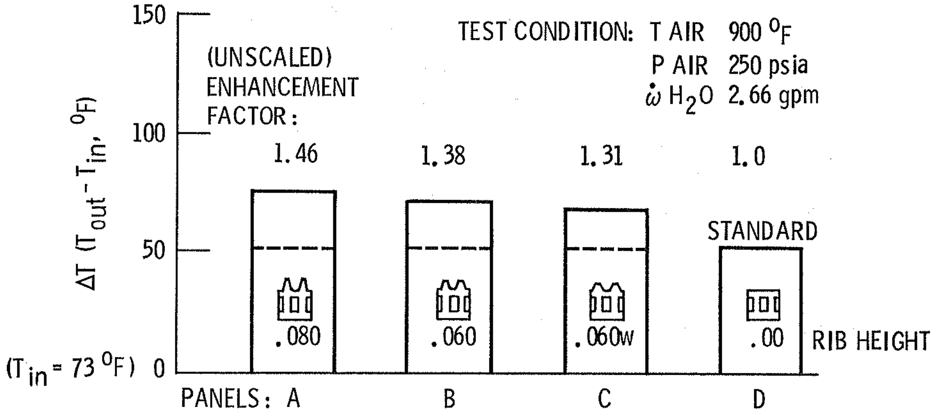


Figure 14. - Comparison of enhanced energy extration chamber ribs to standard smooth wall.

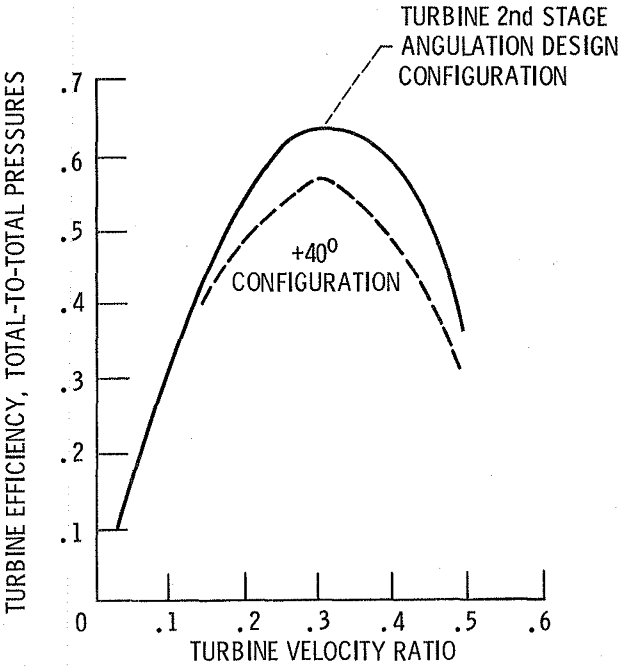


Figure 15. - Predicted turbine efficiency as a function of turbine velocity ratio for design and increased second stage turbine angulation.

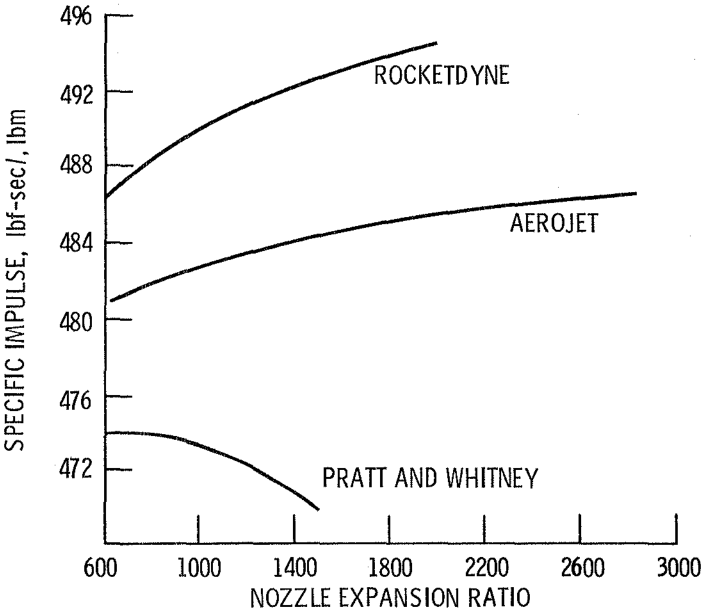


Figure 16. - Specific impulse vs expansion ratio for 5000 lbf thrust engine.

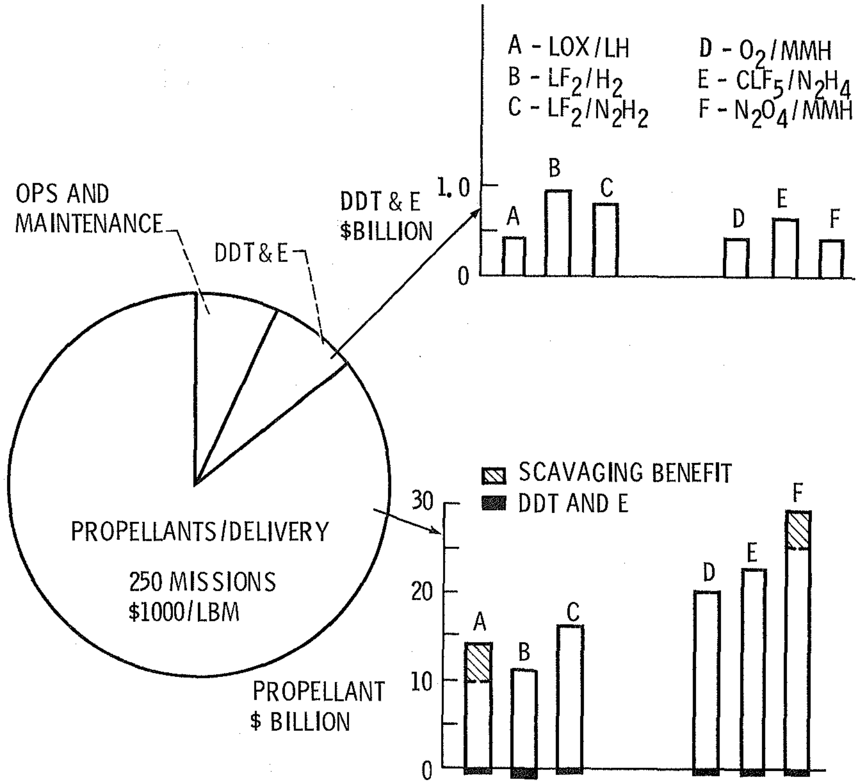


Figure 17. - OTV propellant economic analysis.

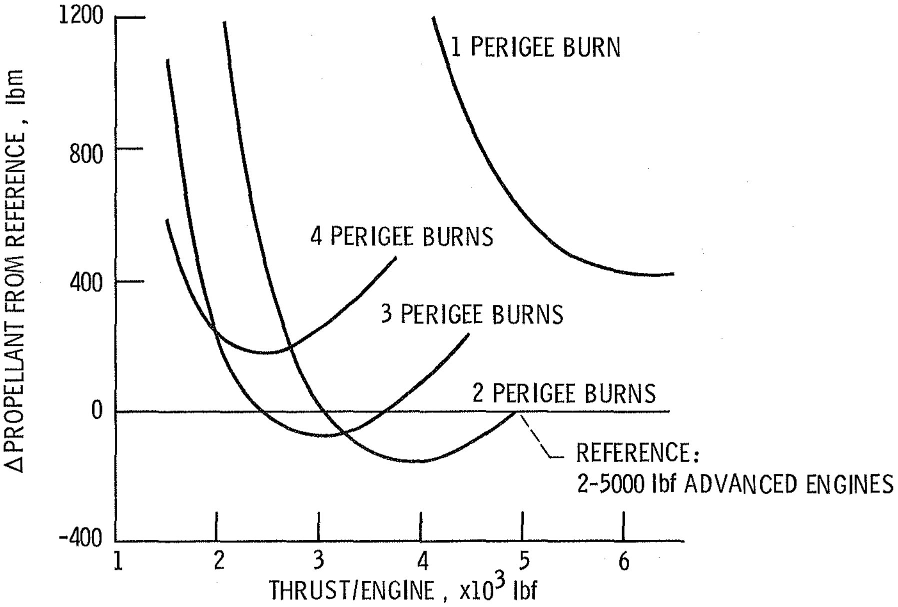


Figure 18. - Propellant sensitivity to thrust and number of perigee burns for 16 000 lbm GEO delivery mission with two engine stage. (Ref. 13).

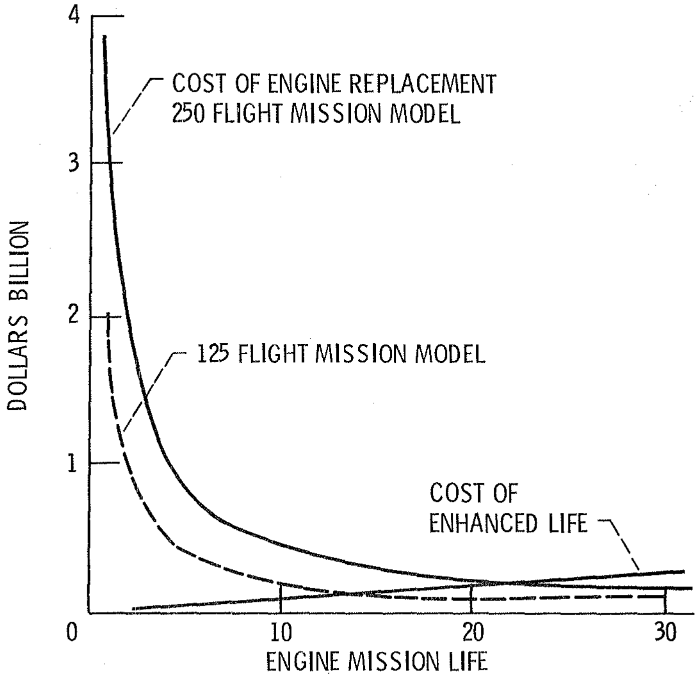


Figure 19. - Advanced engine replacement costs and cost of demonstrating enhanced life as a function of engine mission life.

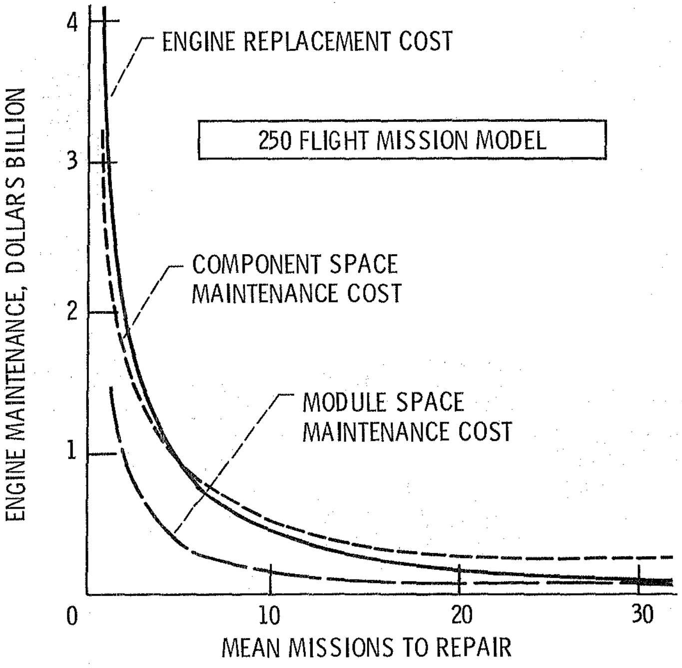


Figure 20. - Costs of advance engine maintenance options as a function of mean missions between engine repairs.

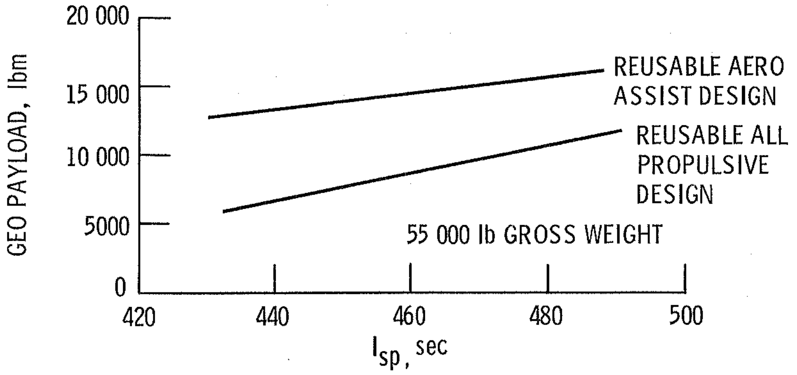
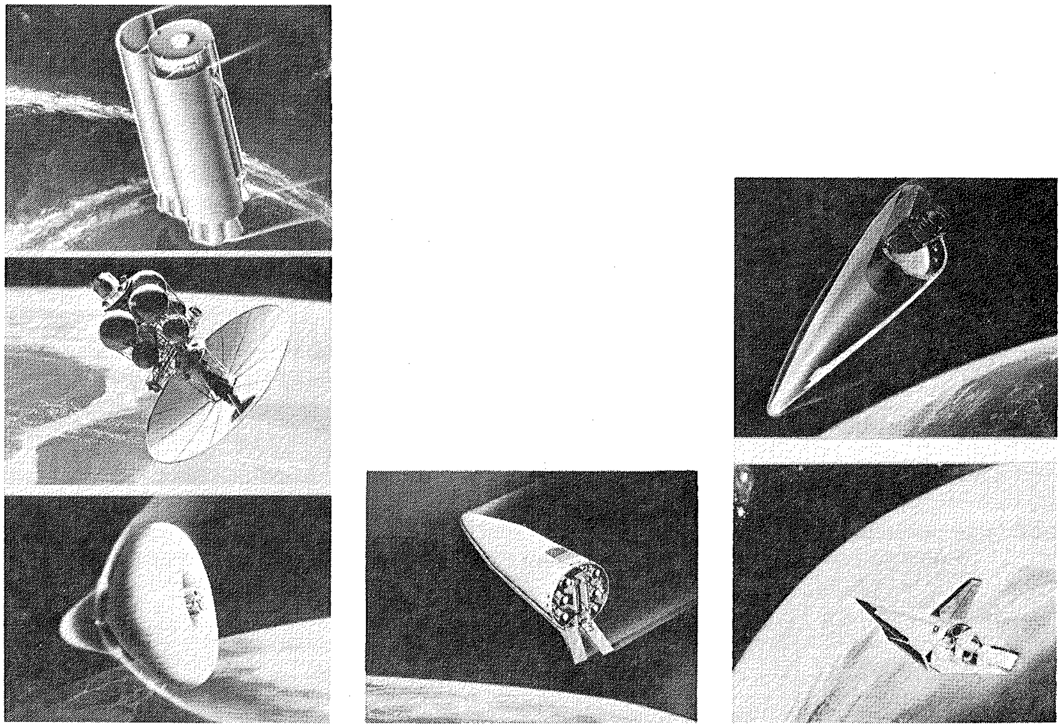


Figure 21. - OTV payload capability for GEO delivery.

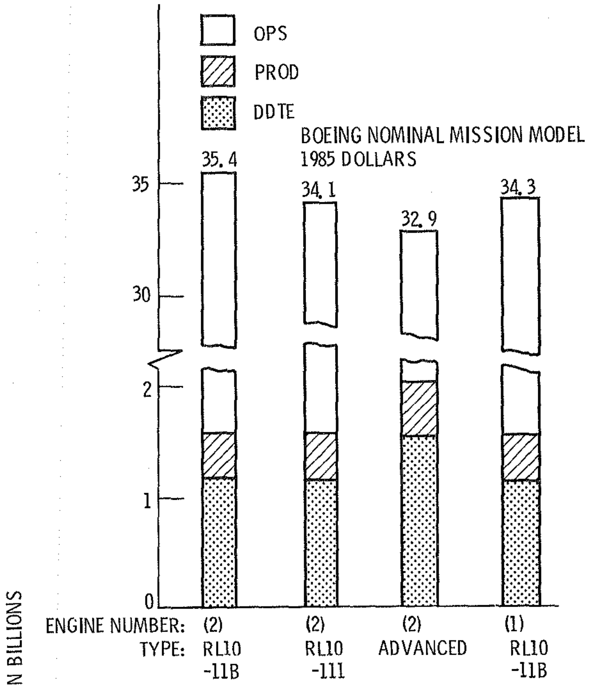


(a) Low lift/drag. (<.75)

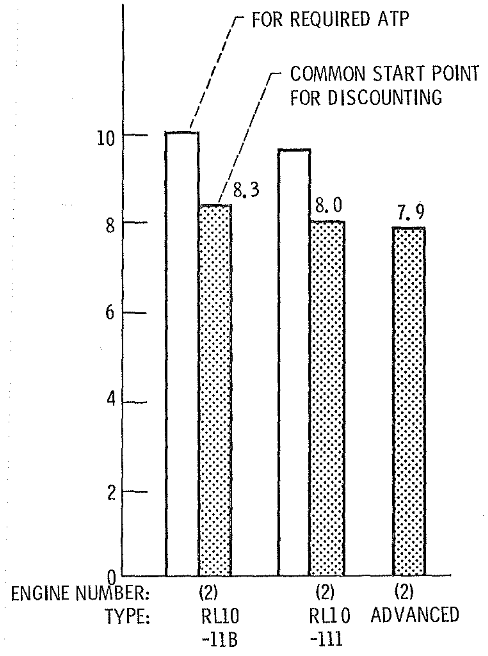
(b) Medium lift/drag. (.75 to 1.5)

(c) High lift/drag. (>1.5)

Figure 22. - Aeroassist vehicle concepts.



(a) UNDISCOUNTED



(b) Discounted 10%

Figure 23. - Main engine influence on OTV program life cycle cost.

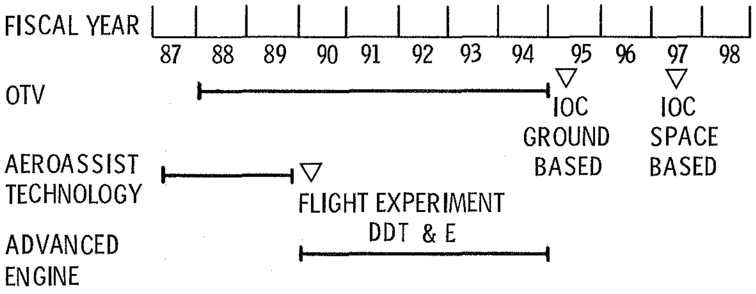


Figure 24. - Aeroassist orbital transfer vehicle development.

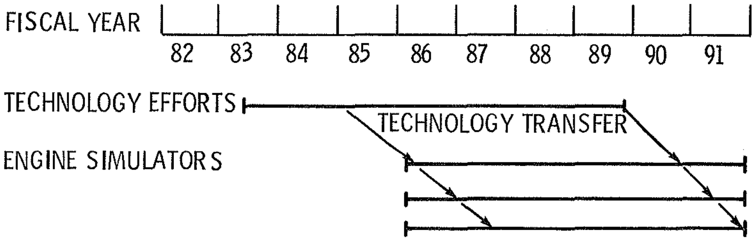


Figure 25. - Advanced OTV propulsion technology and engine simulators schedules.

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16. Abstract

A new Orbital Transfer Vehicle (OTV) propulsion system will be required to meet the needs of space missions beyond the mid-1990's. As envisioned, the advanced OTV will be used in conjunction with the Space Shuttle, Space Station and Orbit Maneuvering Vehicle. The OTV will transfer men, large space structures and conventional payloads between low earth and higher energy orbits. Space probes carried by the OTV will continue the exploration of the solar system. When lunar bases are established, the OTV will be their transportation link to earth. The first step in the development of an advanced OTV propulsion system is to define the system requirements. This paper describes critical engine design considerations based upon the need for low cost payload delivery, space basing, reusability, aeroassist maneuvering, low g transfers of large space structures and man rating. The importance of each of these to propulsion design is addressed based upon extensive vehicle system and propulsion analyses by the aerospace community. Specific propulsion requirements discussed are:

High performance H_2/O_2 engine
Multiple engine configurations totalling no more than 15 000 lbf thrust
15 to 20 hr life
Space maintainable modular design
Health monitoring capability
Safety and mission success with backup auxiliary propulsion

NASA is funding the development of OTV engine technology at Aerojet, Pratt & Whitney, and Rocketdyne. Each company has selected a different approach to meeting the propulsion system requirements. Selected results are presented.

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