NASA's Space Tug and Hydrogen Oxygen Auxiliary Propulsion

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A functional description of NASA's projected versatile, nominally space-based, reusable manned/unmanned Space Tug is presented. Potential missions include Earth-orbital transfers, maneuvering, satellite servicing, and lunar and planetary missions. Estimated velocity-change and thrust requirements for the Tug's primary H_2/O_2 propulsion system are given. Primary emphasis of the paper is on the Tug's auxiliary propulsion system (APS), for which prevaporized O_2/H_2 propellants and a supercritical feed system are suggested. Schematics of four typical candidate systems are presented. Technology needs for APS development are summarized; they are of an engineering rather than a fundamental nature. The Tug's propulsion module may be compatible with both the U.S. Air Force and the European Launcher Development Organization requirements for orbit-to-orbit shuttle applications.

Introduction

THE Space Tug is envisioned to be a reusable, space- or ground-based transport vehicle capable of performing a variety of manned and unmanned space operations in support of Earth-orbital, lunar and planetary missions (Table 1). Work on a contracted 9-month study[1] was begun in June 1970. Emphasis of this "Pre-Phase A" study for NASA is on mission requirements, operational modes, hardware interfaces, system requirements and technology implications, plus feasibility of a single Tug to support adequately missions of interest, rather than on specific designs. Follow-on "Phase A" studies, which will emphasize preliminary design aspects of the Tug system and provide insight into subsystems such as the auxiliary propulsion system (APS), are being considered.

The Air Force is studying[2] potential requirements for a similar system, a chemical Orbit-to-Orbit Shuttle (OOS) for unmanned applications. The European Launcher Development Organization (ELDO) also is conducting studies of a Space Tug/OOS-type system. Their initial 6-month contractual propulsion and system studies were initiated in July 1970.[3] All three groups, NASA, Air Force, and ELDO, envision a system with O_2/H_2 primary propulsion which is compatible with and transportable in an Earth-to-Orbit Shuttle (EOS), often called the "Space Shuttle." Very preliminary studies and considerations suggest that a single development program, at least for the propulsion module and possibly other modules, to satisfy NASA, Air Force, and ELDO missions may be possible.

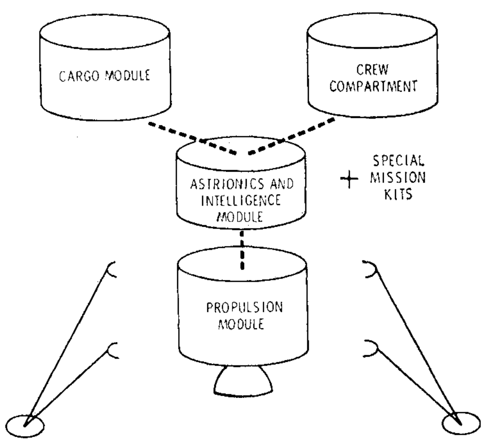

Fig. 1 Space Tug concept.

The Space Tug concept (Fig. 1) is based on modules (propulsion, astrionics, cargo, etc.) which may be augmented by special mission kits such as a lunar landing kit, a manipulator kit, or a satellite repair and maintenance kit. It is a service vehicle for the Space Station/Space Base, Nuclear Shuttle, Lunar Orbit Space Station, and Lunar Surface Base. The order of priority of performance capabilities is earth-orbital, lunar, and planetary operations. Table 1 shows wide spreads of mission velocity change (ΔV) and payload requirements for the typical potential missions. A very flexible design which also is practical from cost and operations viewpoints is needed. High-energy missions may be accomplished by use of drop tanks or by staging two Tugs, one or both of which are recovered.

Estimates of the desired characteristics for the O_2/H_2 main engine(s) are shown in Table 2. Lunar landings may require multiple engines for increased thrust. From a performance standpoint, the propulsion requirements are within the state of the art, except possibly for a desired specific impulse (I_{sp}) greater than 460 sec. On the other hand, the requirements for reuse, in-space maintenance, and long life tend to exceed the existing technology. Since the emphasis in this paper is on auxiliary propulsion, further discussion of the prime propulsion system is not included.

Auxiliary Propulsion System (APS)

The APS must provide the impulses for 1) attitude control by limit cycling, 2) rendezvous and docking by a series of small translational velocity increments, and 3) other translation maneuvers, which could be required for propellant settling, drag makeup, and orbital station keeping. Effects of altitude and solar orientation on total impulse requirements are shown in Fig. 2.[4] The drag makeup corresponding to the minimum drag orientation is also shown. In low Earth orbit there is a tradeoff between the total impulse required for solar orientation and the amounts of propellant boiled off because solar orientation is not maintained. In lunar orbit the drag problem is eliminated, and the orientation requirements are primarily the result of gravity gradients.

The rendezvous and docking impulse requirement is basically a function of the gross weight; ~1 lb-sec/lb of initial weight is required per rendezvous in earth or lunar orbit. With

Presented as Paper 70-719 at the AIAA 6th Propulsion Joint Specialist Conference, San Diego, Calif., June 15–19, 1970; submitted July 28, 1970; revision received November 25, 1970.

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Table 1 Typical potential Space Tug missions

Operation	ΔV, 1000 fps	Payload, 1000 lb	Propellant,[a] 1000 lb
a) Earth-orbital missions			
Space Station module orbital transfer	0.5–3.5	180–250	5– 40
Space Station module maneuver for assembly	0.5–1.0	180–250	6– 18
Experiments module orbital transfer	1.5–3.5	20–30	2– 7
Experiments module orbital maneuvering	0.5–3.0	20–30	1– 7
Nuclear power plant orbital transfer	1.5–3.5	40–80	5– 12
Interspace-Station personnel transfer (<30°)	1– 14	7–12	5– 27
Low Earth orbit to synchronous orbit	26– 30	7–12	90–360
Low Earth orbit to synchronous satellite deployment	26– 30	10–12	50–120
Satellite deployment, maintenance, and repair:			
Low Earth orbit	2– 10	7–25	1– 20
Synchronous orbit	2– 5	7–25	1– 7
Summary, Earth orbital missions	0.5– 30	7–250	<10–360
b) Lunar and planetary missions			
Space Station module lunar orbit injection (one-way Tug)	3	70–120	17– 30
Lunar surface base landing (lunar orbit to surface)[b]	7	50–100	40– 75
Personnel delivery and return			
Earth to lunar orbit direct[b]	6[c]	20–25	10– 15
Earth to lunar surface direct[b]	19[c]	20–25	110–140
Lunar orbit to lunar surface to lunar orbit shuttle			
No plane change	13	7–50	30– 60
90° plane change	19	7–25	70–110
Unmanned planetary spacecraft			
Injection	12–25	2–15	20– 30
Midcourse	0.2–0.5	80–200+	1– 7
Braking	5–10	80–200+	35–220
Summary, lunar and planetary missions	0.2–25	2–200+	<10–220

[a] Approximate requirement, LOH/LH$_2$, I_{sp} = 450 sec, integrated type stage; mass fraction variable with weight of propellant required.
[b] Saturn V to lunar injection.
[c] Does not include ΔV contribution to lunar injection.

large payloads (compared to the Tug) the center of gravity (c.g.) of the Tug plus payload could be located in the payload envelope. In this case, it becomes a problem to provide transverse translation without inducing a pitch or yaw moment. The ability to translate in three orthogonal planes minimizes the impulse requirements for rendezvous and docking.[4] An additional translation impulse might be required to settle propellant prior to starting the main engine. This requirement is dependent on the main engine start sequence and could be performed by the main engine in idle mode. Propellant settling time can be minimized by using a dual-thrust-level settling mode.[5]

Propellant System

Candidate propellants include 1) monopropellants, such as hydrazine, 2) storable bipropellants, such as N_2O_4-monomethyl hydrazine, and 3) cryogenic bipropellants, such as O_2/H_2. (F_2/H_2, although desirable from a performance and bulk density point of view, poses significant problems because of corrosive exhaust products and operational problems associated with other system interfaces.) The mono- and storable-bipropellant systems represent conventional state-of-the-art systems. Only the cryogenic O_2/H_2 system will be discussed herein; other systems will be considered in Air Force and NASA studies.[1,2]

Use of O_2/H_2 for the APS offers the advantages of integration with the main propellant supplies to allow maximum operational flexibility. It is conceivable that in the case of a main propulsion system failure, all of the propellant could be used by the APS, thus providing an emergency backup system. The clean propellants and exhaust products are highly desirable. In space and on the lunar surface, residuals of O_2 and H_2 undoubtedly have wider general utility than residuals of other propellant combinations.

Propellant prevaporization and ignition

Only gas-gas injection is being considered in NASA's technology efforts for O_2/H_2 APS thrusters because of the near

Table 2 Desired characteristics for main propulsion system

Performance	
Thrust	10K–30K lb
I_{sp}	460$^+$ sec
Throttling	Continuous 10 to 1
Step thrust (idle mode)	To 300 lb
Operational	
Restarts per mission	4 to 20
Total starts (lifetime)	Up to 1000
Burntime	Up to 100,000 sec/life
Chilldown	Not desirable
Minimum time between starts	Seconds to minutes
Gimbal angle	Up to 7°
Pressurization	Gaseous propellants
Maintenance	
Single mission duration	Up to 30 days active; Up to 180 days quiescent
Repair and refurbishment	In space
Operational life	3$^+$ yr

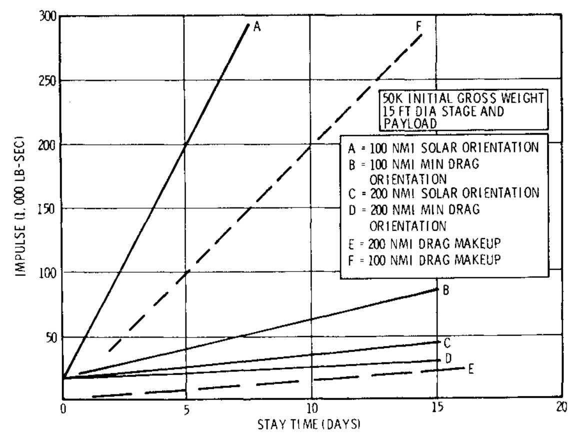

Fig. 2 APS impulse requirements for low Earth-orbit missions.

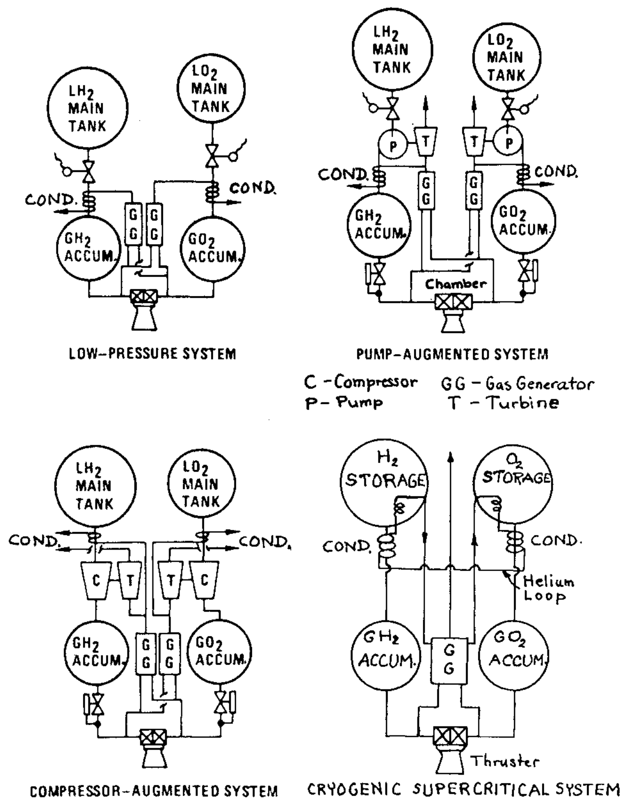

Fig. 3 Candidate O_2/H_2 auxiliary propulsion systems.

impossibility of distributing single-phase liquid propellants in small lines to the thrusters. Thus, propellant vaporization is required. (Gaseous storage of the propellants is out of the question due to the effect of low-density storage on tank volume and weights, Table 3.) This type of conditioning requires gas generators, heat exchangers, accumulators, etc. A key question is whether or not the conditioning losses are severe enough to offset the high I_{sp} of O_2/H_2. Also, as the size of the APS is reduced, as it is for the Tug application compared to the EOS application, does the hardware weight further offset the high I_{sp}? The answers to these questions are not obvious for a vehicle the size of the Tug; in-depth investigation will be required.

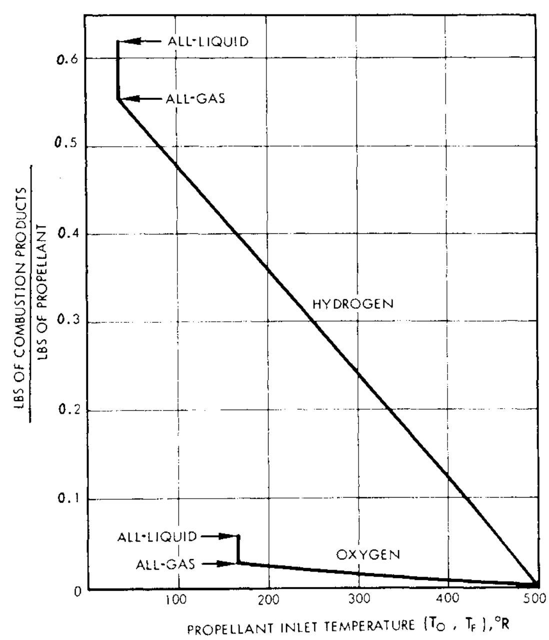

Fig. 4 Propellant preheating requirements for propellant outlet temperature of 500°R and a preheater mixture ratio (O_2/H_2) of 1.

Table 3 Comparison of storage volumes[a]

Storage condition	v_{O_2}, ft³/lb	v_{H_2}, ft³/lb	v_m, ft³/lb
Liquid at normal boiling point	0.014 + ullage	0.226 + ullage	0.056
Gas at 500 psia and 300°R	0.201	3.22	0.805
Gas at 40 psia and 300°R	2.51	40.3	10.07

[a] ρ = density; ρ_m = mixture density at oxidizer fuel ratio of 4.

Because the O_2/H_2 combination requires an ignition system, the need to produce minimum impulse bits becomes a design problem. Potential ignition systems include a) propellant additives (usually added to the O_2) which render the propellants hypergolic, e.g., ozone difluoride (O_3F_2); b) catalytic systems, wherein a small percentage of the propellant flow, fuel-rich to keep the temperature down, is passed through a catalyst bed, such as Shell 405; c) plasma ignition (requiring development), which borrows from the technology developed for thermal arc-jet engine and uses an arc-generated plasma of secondary flow propellant for ignition of the main flow; and d) spark ignition, wherein a small portion of the propellant is injected in the vicinity of the spark device to ignite and pilot the remaining propellant. The propulsion industry tends to favor either the catalytic- or spark-type systems. Such factors as the instability of the additives, poor performance predictability, and contamination of the oxygen for use in other systems, such as fuel cells and life support systems, have virtually eliminated additives from serious consideration.

Propellant feed systems

Four candidate feed systems are shown schematically in Fig. 3, and their pertinent features are summarized in Table 4. All employ accumulators to insure ready availability of propellant during the transient periods. The low-pressure system would have the largest accumulator, and the supercritical system would have the smallest. All but the

Table 4 Features and limitations of candidate propellant feed systems

Low-pressure	Large line size, large accumulator Very-low-pressure-drop components May require phase-separation device in propellant tank System pressure limited by main engine tankage structure limits
Compressor	Requires vapor-liquid separator Inlet temperature control very critical Hydrogen compressor outlet flow requires conditioning to match oxygen compressor temperature rise Oxygen compressor temperature rise limit System pressure limited to compressor pressure ratio of 25:1
Pump	Requires liquid feed, or two-phase pump inducer development System pressure constrained by specific head-flow characteristics of pump design (low flows in this application may limit head rise to 1000 psi)
Supercritical	No phase separation required Normal heat leak through insulation reduces system energy requirements System pressure limited only by practical considerations (increased thermal energy needed to maintain constant pressure) Possible use to pressurize main tanks

supercritical system require liquid-vapor separation devices to insure reliable operation.

The supercritical APS concept provides a basic high-pressure, high-density storage system which pressurizes the propellant without requiring either turbomachinery or a propellant phase separation device. The propellants are stored at pressures higher than critical and higher than required by the thrusters. As they are withdrawn from storage, heat is added to maintain tank pressure, and additional energy is added to each propellant before delivery to the thrusters. Supercritical storage of H_2 and O_2 is well-developed and is an Apollo flight-proven feed-system concept. A closed helium loop is used for tank pressurization and fluid heating with a gas generator which burns small amounts of the primary propellants as the heat source. The helium loop which transfers heat from the gas generator to the propellants precludes freezing of the gas generator combustion products, which contain water at roughly 50% by weight. (The helium loop heat transfer scheme is equally applicable and desirable for the other APS feed system types to avoid heat exchanger freeze-up.)

In the low-chamber-pressure system, liquid propellants are drawn from the main tanks and vaporized prior to entering their accumulators. The gaseous propellants in the accumulators are then routed to the various thrusters as well as the gas generators which provide the heat source for propellant vaporization. This system, while the simplest of the cryogenic concepts, suffers from low I_{sp} due to the limited thruster expansion ratio at low chamber pressure (P_c). Operation at higher P_c may be realized by using either a pump or compressor to raise the pressure in the respective accumulators. In the compressor system, saturated vapor from the propellant tanks is supplied to the compressor where its pressure is raised prior to entering the accumulator. For the pump-augmented system, liquid propellant is drawn from the tanks, pumped to a higher pressure, then vaporized after it leaves the pump and before entering the accumulator. Both the turbocompressor and the turbopump systems use the gas generator efflux to drive the turbines before exhausting overboard.

All four systems require conditioners to control propellant temperature. Figure 4 illustrates, as an example, the nature of the conditioning energy requirements wherein the combustion of O_2/H_2 at a mixture ratio of 1:1 is used to heat O_2 and H_2 from an initial inlet temperature to a 500°R outlet state. Significant energy is required to heat H_2 (because of its high specific heat); therefore, both the quantity of H_2 and the temperature rise should be minimized. The propellant preheating penalty as a function of outlet temperatures and thruster mixture ratios is presented in Fig. 5.[6] In some cases part of this penalty might be eliminated by using the exhaust gases from the gas generator for thrust instead of dumping them overboard. However, the APS feed system output temperature and pressure are directly dependent upon the thruster requirements for performance variability and physical size. Additionally it is noted that higher-pressure, warm-gas, APS feed systems could provide pressurization gases for the main engine tanks and thus eliminate the need for a separate pressurization subsystem. Moreover, the stored propellants are heated during the course of system operation, so that the supercritical feed system conditioning penalty decreases during the mission. The other feed system types require a fixed propellant state in the storage tankage to insure proper operation and their conditioning penalties are constant. To a first approximation, with common conditioner outlet temperatures, the initial conditioning penalties for all four systems are comparable, but only the supercritical system operates with a constantly decreasing conditioning loss.

Thrusters

Thruster operation at a thermodynamic state higher than the storage condition requires the addition of energy. However, a system operating at the lowest P_c would not necessarily be different from that at the highest P_c, as a regulator could be interposed between the accumulator and the thrusters to reduce the feed pressure. Increased accumulator pressure reduces the required volume for a fixed quantity of propellant, and if the accumulator blowdown pressure range is large, a greater amount of the stored gas can be withdrawn.

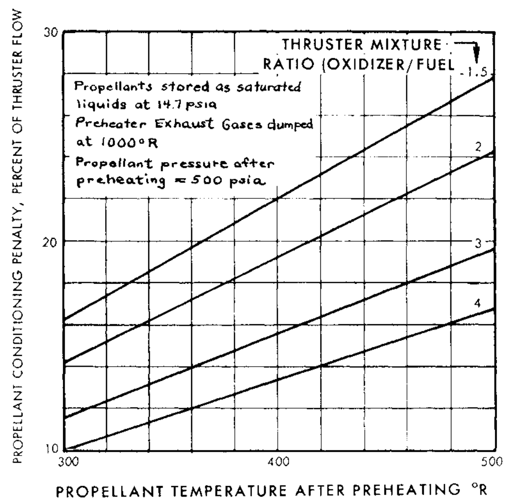

Fig. 5 Total-mission penalties for propellant preheating by O_2/H_2 gas generators.

The number of APS thrusters depends on several factors. Because of the difference in c.g. location and system inertias from mission to mission, it appears desirable to provide pitch, yaw, and roll with coupled pairs of thrusters rather than single thrusters. Sufficient moment arms can be provided by locating thrusters at opposite ends of the Tug for both pitch and yaw. The roll couples can be located diametrically opposite each other. Additional pairs of thrusters, facing fore and aft, must be provided for longitudinal translation. Transverse translation can be obtained by selective firings of the pitch or yaw thrusters. Such a system is shown conceptually in Fig. 6. With large payloads, the c.g. location may be somewhere in the payload envelope. This would require simultaneous use of the pitch or yaw thrusters with the translational thrusters while performing a transverse translational maneuver to eliminate moments induced by the translational thrusters. The payload bay constraints of the EOS together with possible variable geometry of the Space Tug might require that the thruster modules be deployed on booms. This would also alleviate possible plume impingement and/or payload contamination problems. It might be desirable to add additional translational thrusters to provide adequate axial accelerations rather than increasing the thrust level. This could permit one common thrust level for all thrusters, resulting in a smaller spares inventory and would simplify the in-space maintenance operation.

For a given expansion area ratio, the physical size of an O_2/H_2 thruster is defined for all practical purposes by the ratio of thrust to chamber pressure (F/P_c). Figure 7 shows nozzle exit diameter, chamber length, and engine length

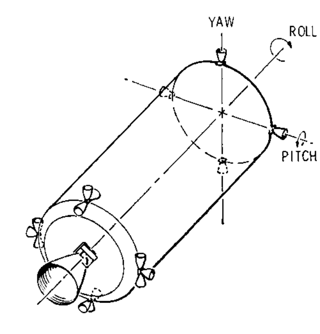

Fig. 6 Locations of thrusters.

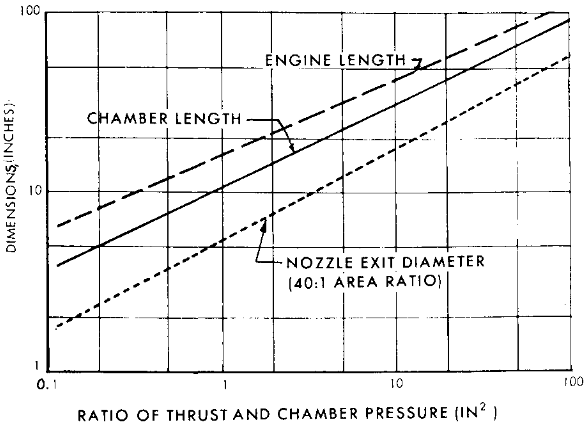

Fig. 7 Thruster dimensions vs F/P_c.

(including valves) vs F/P_c. (Thruster weight also can be correlated with F/P_c; the slope is slightly greater than the slopes for dimensions.) For a 150-lb-thrust size, for example (on the high side for the Tug), design pressures of 10 psia and 300 psia would call for engine lengths of 50 in. and 12 in., respectively, with nozzle exit diameters of 21 in. and 4 in., respectively. From a performance standpoint several effects point to operation at a high P_c. The optimum mixture ratio for kinetic performance is closer to 4:1 and a higher performance level is achievable by higher pressure. (At $P_c < 100$ psia, the optimum kinetic performance closely approaches the frozen equilibrium mixture ratio of 2.5:1.) Opposing effects are the increased heat-transfer levels at the higher P_c's and the greater energy required to deliver the propellants at increased pressure levels.

Thruster performance as influenced by inlet pressure and temperature variations ultimately dictates the APS feed system conditioning control requirements. Numerical examples for a low and a high pressure thruster system are presented in Figs. 8 and 9, illustrating the effects of inlet temperatures and pressure variations on total flow rate and mixture ratio. The mixture ratio is not affected as long as the fuel and oxidizer pressures are equal. A variation in inlet temperature produces an inverse shift in mixture ratio. Pressure mismatches in fuel and oxidizer conditions are more significant influences on thruster performance than are differences in temperatures. However, the effect of temperature becomes extreme if the oxygen approaches its saturation temperature. The implications are that it is desirable to have tight control on the propellant pressures at the thruster valve inlets while the more important aspect of temperature control is to keep the oxygen sufficiently above its saturation temperature.

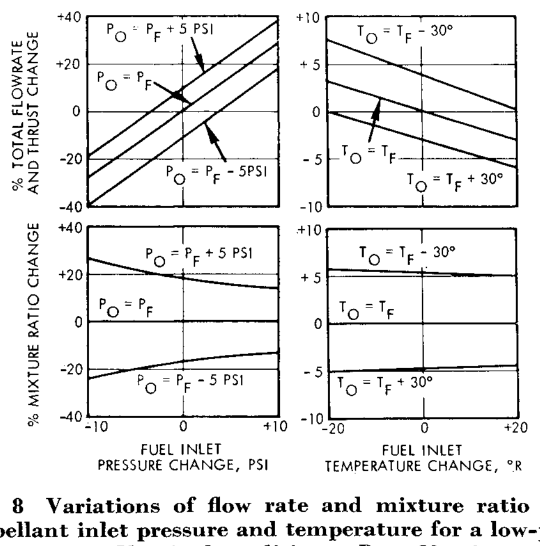

Fig. 8 Variations of flow rate and mixture ratio with propellant inlet pressure and temperature for a low-pressure system. Nominal conditions: $P_c = 20$ psia; propellant inlet: 300°R and 35 psia; mixture ratio = 2.5.

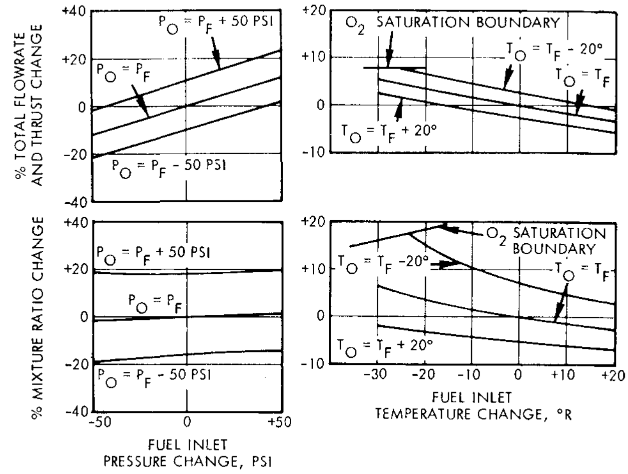

Fig. 9 Variations of flow rate and mixture ratio with propellant inlet pressure and temperature for high-pressure system. Nominal conditions: $P_c = 300$ psia; propellant inlet: 300°R and 450° psia; mixture ratio = 4.

Technology Requirements

The supercritical feed system concept appears as a very strong candidate primarily because no fundamental technology limitation exists. The main disadvantage is that the APS propellant volume is limited by the size of the APS propellant storage tanks. The low pressure and turbomachinery systems have direct access to the main propellant tanks. In a system like the Space Tug which normally has a number of main engine burns per mission, this disadvantage can be partially overcome. During a main propulsion burn the APS propellant storage tanks can be fully or at least partially refilled by tapping part of the main engine liquid propellant flow. The feasibility of this approach has been established (by Pratt and Whitney for TRW)[6] with tapoff of up to 15% of the main engine propellant flow from an RL-10-A-3-3 engine. The turbomachinery cycles are also attractive, but the fundamental propellant phase separation problem must be resolved by developing reliable and acceleration-insensitive phase-separation devices (preferably passive devices). With the availability of a reliable phase-separation device, the pump system could be the preferred approach. Each of the APS concepts requires "zero-leakage" valves to preclude propellant loss.

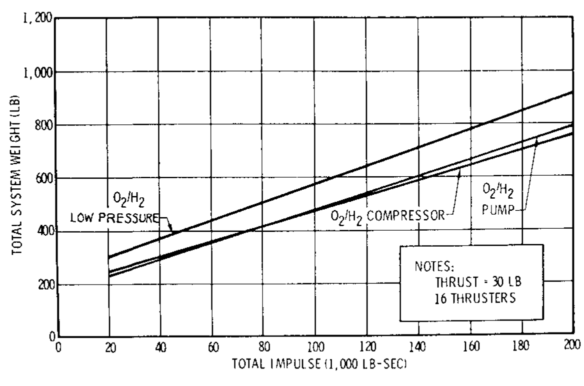

Fig. 10 Weight comparison of auxiliary propulsion systems.

Table 5 Estimated Space Tug APS characteristics

Propellants	O_2/H_2
Lifetime (burn time) of thruster	100,000 sec
Total impulse/mission	$\leq$500,000 lb-sec
Minimum impulse/thruster	1 lb-sec
	Possible range
Thrust level of thruster (fixed) F	30–200 lb
Number of thrusters	16–24
Chamber pressure P_c	10–200 psia
Mixture ratio (oxidizer/fuel)	2–5.5

Although NASA has been developing conditioner and thruster technology for several years with Rocketdyne[7] and TRW,[8] additional investigations will be necessary; e.g., the compressor and pump cycles require study of the routes of hardware implementation to fulfill the requirements for long life, multiple starts, and high head rise at low flow. Other critical technology needs are two-phase pump inducer development; definition of temperature limitations of metallic materials applicable to thrusters and heat exchangers in terms of creep and high cycle fatigue; definition of reliable, long-life ignition devices for thrusters and gas generators; low-leakage, high-response propellant valves having both long life and ease of maintenance; and transducers which can detect incipient degradation of mechanically loaded devices (e.g., pressure vessels) and thermo-mechanically loaded devices (e.g., heat exchangers) which will be required for onboard checkout and status monitoring. In summary, the additional efforts needed for the various components systems tend to be of an engineering rather than a fundamental nature.

Preliminary Studies by Industry

Typical results of a preliminary comparison by industry of the low-pressure-fed, pump-fed, and compressor-fed systems are shown in Fig. 10.[9] The system weights shown include all inert hardware, pressurants, and APS propellants. The pump and compressor-augmented APS's offer the lighter systems. The slight weight advantages of the compressor system compared to the pump system do not appear significant enough to warrant the recommendation of this system. Turbopump technology, per se, for O_2/H_2 has been around for a considerable time. Turbocompressors on the other hand, have not been developed for cold-gas applications of O_2 and H_2. Consequently, the validity of the turbocompressor weight estimates used in this study may be suspect due to lack of a "real hardware" baseline system. A large disparity in turbocompressor weight estimates was noted in the data from the several engine manufacturers (Rocketdyne, TRW, and Aerojet). In all probability, the turbocompressor weights could be heavier than used in this comparison and would vitiate their apparent advantage.

The low-pressure system does not show up favorably in the example comparison, because the large size and hence weight, of the low-pressure accumulators negated the advantage of eliminating turbomachinery. Further analysis in this area may result in schemes which would reduce the accumulator volume and thereby make the low-pressure system more competitive. Certainly, the lack of turbomachinery is appealing (as it is for the supercritical system discussed earlier but not included in this example study).

Studies similar to the illustrative example[9] have been conducted by other contractors[10–13] as part of their IR&D and preproposal efforts for NASA's Space Tug Study.[1] In addition, Aerospace Corporation has been conducting Space Tug/OOS APS studies under their joint Air Force/NASA study efforts.[2] The various engine manufacturers provided data and analysis in support of all these studies which have, of course, included APS propellants other than O_2/H_2. Storable bipropellant and monopropellant systems are well developed, and a ground-based approach to a Tug tends to favor a storable-propellant APS, whereas the space-based approach favors an O_2/H_2 APS.[2] However, either type could be used in the Tug or the OOS.

A composite summary of the estimated Space Tug APS O_2/H_2 characteristics is shown in Table 5. Since many of the parameters are dependent on Space Tug configuration, mission and payload, a range of values is given rather than discrete numbers.

Current O_2/H_2 APS Technology Efforts

There is presently no direct technology effort on the main propulsion system or the APS for a Tug, but the EOS Program has extensive O_2/H_2 main propulsion and O_2/H_2 APS technology efforts underway. (The NERVA nuclear flight system definition studies[14–16] favor an O_2/H_2 APS for the Nuclear Shuttle, but the NERVA program is not currently supporting any APS technology.)

The total O_2/H_2 EOS APS technology efforts and the APS-related EOS primary propulsion technology efforts are too varied and extensive to be covered here in any detail; however, each of the critical technology needs discussed previously is included in existing or planned EOS technology efforts, ranging up to tests of breadboard APS's and studies of engine onboard checkout and component life prediction that will include transducers and degradation detection devices. These efforts are considered adequate at this time to support the potential propulsion requirements of the Space Tug. At an appropriate later time a coordinated effort is planned to satisfy the unique requirements of the Space Tug, which are considered to be less technologically difficult than those of the EOS. The EOS is currently planned to have an initial operational capability (IOC) in late 1977, with the basic Space Tug IOC one or two years later. This early Tug will be unmanned and employed primarily for Earth-orbital operations. NASA mission kits, crew module and system requirements for lunar and planetary missions can be introduced later as mission requirements are established.

Summary Comments

The auxiliary propulsion (APS) for the Space Tug must be able to meet the requirements of a variety of projected missions and payloads. These operational variables have directed the APS design toward high-specific-impulse propellants with a wide range of total impulse capability. Further, it appears that the APS should have multiple thrusters at different locations to cope with variations in c.g. and system inertia which occur with the wide range of the Tug payloads. Requirements and over-all operational considerations tend to drive the selection to cryogenic O_2/H_2 propellant systems. A high-pressure, high-density supercritical fuel feed system is suggested. With the development and availability of a reliable phase-separation device or technique, the pump-fed system could prove to be optimum. The critical technology needs are being satisfied adequately at present by the existing and planned APS and primary propulsion system technology efforts for the Space Shuttle. Identified technology requirements tend to be of an engineering (i.e., application) nature rather than a fundamental nature.

Both the NASA and the industry activities to date have been "quick look" studies; no definitive conclusions can be drawn at this time. After completion of the currently planned Space Tug/OOS studies, more detailed subsystem studies, including the APS, will be required and are planned. The Space Tug propulsion module appears compatible with the Air Force and ELDO applications. The Space Tug could well be an interagency as well as an international development effort to the benefit of all concerned.

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MARCH 1971 J. SPACECRAFT VOL. 8, NO. 3

Exploratory Tests on a Downstream-Cathode MPD Thruster

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Substantial improvement in the thrust performance of a low-power MPD arc thruster has been achieved in the specific impulse range of 600 to 2100 sec. The thruster tested utilizes a cathode positioned in the exhaust beam, downstream of the anode, as opposed to the conventional position upstream of the anode. Xenon is the propellant used, and testing is conducted in a background pressure of 1.6 × 10^{-5} torr. Operation achieved in the above specific impulse range is at thrust levels from 6 to 16 mN, power levels of 180 to 720 w, and thrust efficiencies of 13 to 24%.

Nomenclature

g = gravitational constant
I_{sp} = specific impulse
$\dot{m}$ = propellant mass flow rate
P_D = power supplied to discharge
T = thrust
η_T = thrust efficiency

Introduction

A SIMPLE, low-power magnetoplasmadynamic (MPD) arc thruster is attractive for such auxiliary propulsion applications as satellite station keeping and attitude control.[1] An electrical discharge is maintained in an axial magnetic field between a cylindrical anode and a cathode centered on the anode axis. The cathode of a conventional MPD arc thruster is located upstream of the anode-discharge region (Fig. 1). Such a thruster performs best (T/P_D vs I_{sp}) when operating on xenon propellant.[2]

Theory places a 40% to 70% limit on thrust efficiency η_T for specific impulses in the range of 700 to 2000 sec (when xenon propellant is used).[3] Severe loss to the thruster backplate appears to be a possible source of additional energy loss in many existing thrusters. This backplate loss may explain, in large part, why it is impossible to achieve η_T's even one-half of those predicted by the theory.

Data are presented for a new thruster (Figs. 2 and 3) in which four major modifications have been made: 1) the cathode is in the exhaust, downstream of the anode, electromagnets and propellant injection points; 2) an orifice plate is added to the tip of the hollow cathode; 3) magnetic pole pieces are added to the thruster anode chamber region; and 4) the magnetic field is produced by edgewound electromagnets.

Placing the thruster cathode downstream of the anode eliminates an impressed electrostatic field which tends to

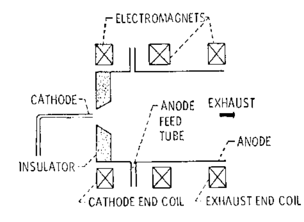

Fig. 1 Schematic of the low-power MPD arc thruster (conventional arrangement) investigated by Johansen et al. (Ref. 2).

Presented as Paper 70-1084 at the AIAA 8th Electric Propulsion Conference, Stanford, Calif., August 31–September 2, 1970; submitted September 29, 1970; revision received December 4, 1970.

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