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Executive Summary

Space Tug Systems Study (Storable)

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Presented to;
George C. Marshall
Space Flight Center

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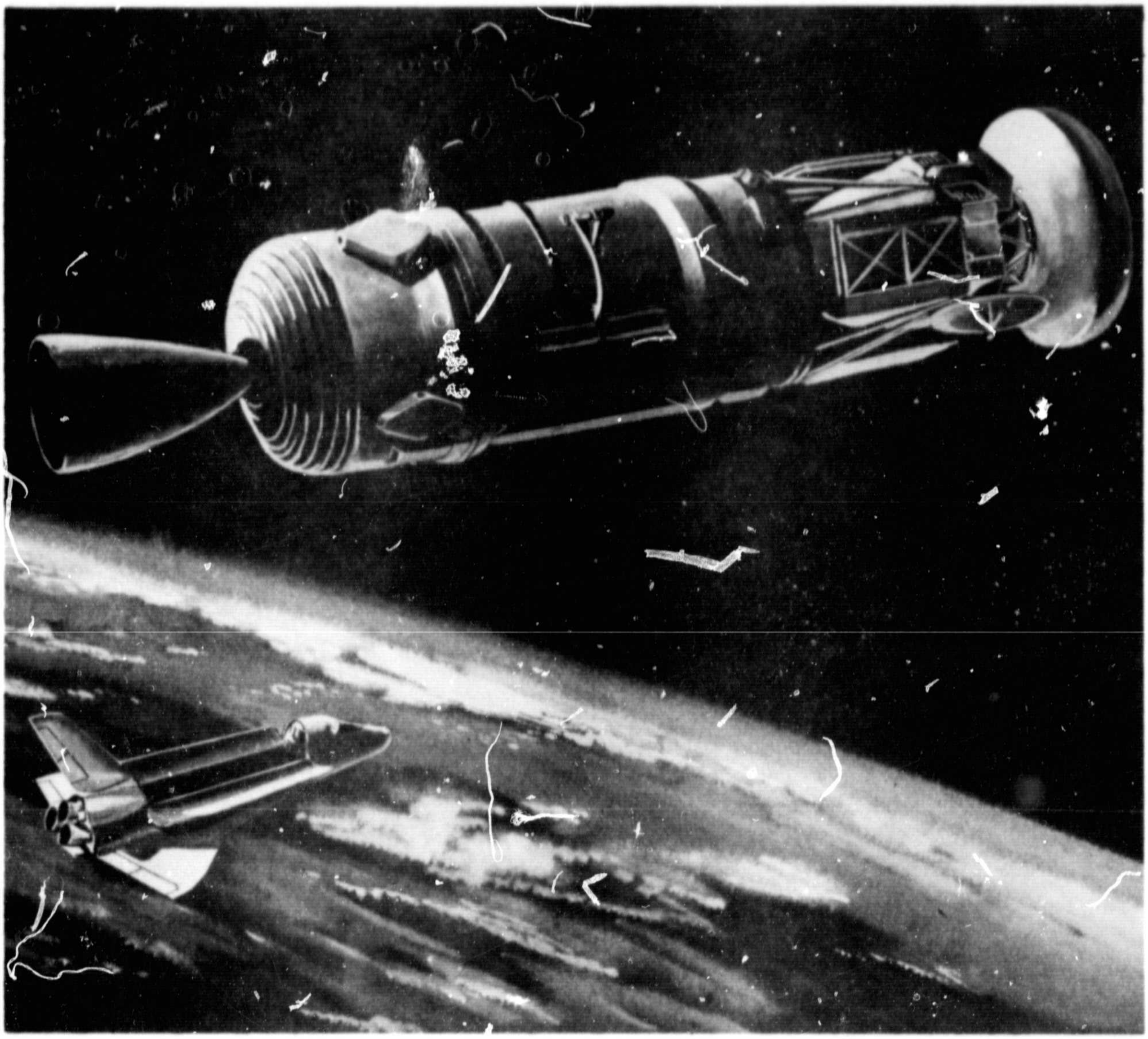

Martin Marietta Version of Space Tug (Storable) with Spacecraft

MCR-73-314
Contract NAS8-29675

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EXECUTIVE SUMMARY

SPACE TUG SYSTEMS STUDY (STORABLE)

Presented to:

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FOREWORD

This final report is submitted in accordance with the requirements of Data Requirement MA-04 of the Data Procurement Document of contract NAS8-29675, as clarified by NASA letters No. PD-TUG-C-73-207 dated October 26, 1973, and PD-TUG-C-74-6, dated January 17, 1974, signed by Robert J. Davies, Study Manager.

This final report is submitted in three volumes:

Volume 1 - Overview Presentation

Volume 2 - Compendium

Volume 3 - Executive Summary

ABSTRACT

Program plans are established for a storable propellant space Tug used to perform high energy orbit transfers from the Space Transportation System (STS) Orbiter. The mission model for the STS in the 1980's is analyzed. Performance and mission requirements are determined. Various flight operations modes are evaluated and selected. Subsystems are selected and synthesized into various Tug configurations. Program options for these configurations are defined, analyzed and selected. Selected program options are further defined and optimized, including program requirements, Tug vehicle definition, mission accomplishment, ground and flight operations, programmatics and costs.

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I. INTRODUCTION

The Space Transportation System (STS) requires an upper stage to complement its basic low earth orbit capability. This upper stage or Tug will be used to deliver spacecraft to planetary, geostationary, and other earth orbits beyond the capability of the Shuttle Orbiter. The Tug will also be used for spacecraft servicing, inspection, and retrieval to obtain the maximum cost benefit from the STS. The Tug will be a high-performance reusable machine with a high level of reliability, safety, and autonomy.

National budget constraints make commitment of DDT&E expenditures for Tug difficult during the years of peak STS development activity. Evaluation of various Tug options is therefore necessary for selection of the most cost-effective development plan without sacrificing potential economic benefits during the STS operational phase.

Tug program planning generally has assumed a cryogenic propellant stage to maximize the performance capability of the Tug. This study evaluated Tug program alternatives using storable propellant stages.

The objective of the study was to determine how a storable propellant Tug program can perform the basic requirements of the STS and the mission plan of the 80s in the most cost-effective manner.

The key issues and problems considered during the study are:

1) Does a storable Tug have sufficient performance to meet mission model delivery and retrieval requirements?

2) What flight operation modes are best for storable Tugs to meet the mission model delivery and retrieval requirements?

3) How can the inherent advantages of storable propellants (safety, high density, simplified operations, long on-orbit life) be used to optimize the Tug program plan?

4) What subsystem innovations and Tug configurations can be used to minimize mass fraction and maximize performance?

5) Can a storable Tug achieve a high level of safety and reliability without incurring unnecessary performance and cost penalties?

6) What program plan optimizes DDT&E, production, and operations costs and peak-year funding?

7) What program plan minimizes program risk while maximizing mission model capture with the fewest number of Shuttle/Tug flights?

II. METHOD OF APPROACH AND PRINCIPAL ASSUMPTIONS

A. STUDY APPROACH

To select the Tug program options that best satisfy the key issues, mission requirements were assessed, component and subsystem candidates evaluated, and Tug configurations synthesized; three Tug program options were selected for detailed definition and evaluation. The study consisted of the following tasks:

1) Mission Analysis (Task 1) - Task 1 defined mission requirements, supported the selection of Tug systems meeting these requirements, and provided resulting mission accomplishment data. An assessment of requirements was presented on April 13, 1973 (Ref 1).

2) Subsystem Analysis (Task 2) - This task defined subsystem functional requirements, collected data on candidate components and subsystems, evaluated alternatives, and selected subsystem candidates to be used in the synthesis of Tug configurations. A review was presented on May 30, 1973 (Ref 2).

3) Configuration Concepts (Task 3) - Candidate Tug configurations were synthesized and screened against certain criteria. "Tug families" were selected for each of seven capability options, referred to as "buckets." Operations, supporting equipment, interfaces, and programmatics were also defined. Results were presented on July 19, 1973 (Ref 3).

4) Supporting Programmatics and Costing Analysis (Task 4) - This task provided schedule and cost data to support the evaluation of Tug subsystems and configurations throughout the study--including test, manufacturing, refurbishment, facility and logistic plans, project schedules, and detailed costing analysis.

5) Program Definition (Task 5) - Three program options were selected from the seven capability options of Task 3 for detailed definition in Task 5--including subsystem definition, Tug inboard profiles, mass properties, performance evaluation, mission accomplishment, and programmatics and cost. Sensitivity and trade studies were conducted. Results were presented at the "September Data Dump" (Ref 4). Additional analyses were conducted after the September Data Dump to incorporate results of sensitivity and trade studies into the baseline option definitions.

B. PRINCIPAL ASSUMPTIONS

Principal guidelines used for the study were provided in the Data Package (Ref 5) and the Payload Accommodations document (Ref 6). Additional ground rules and assumptions evolved throughout the study. Principal assumptions directed by the government and/or derived by the contractor are:

1) The Orbiter park orbit will be 160 n mi in all cases. The Tug will return for Orbiter rendezvous to a 170-n-mi circular orbit.

2) The Tug will be returned to earth in the Orbiter and be re-used, with minimum maintenance/ground turnaround time.

3) The Tug will use earth storables as main-engine propellants.

4) The reliability goal for the Tug shall be 0.97.

5) The Tug will provide a 0.995 probability of no mission failures due to meteoroid penetration.

6) The total gross weight of the Tug, cradle and spacecraft will not exceed 65,000 lb. The Tug will not exceed 35 ft in length.

7) No single Tug failure will result in a hazard that jeopardizes the flight or ground crews. No single Tug failure will result in unprogrammed motion of the Tug while in the vicinity of the Orbiter.

8) The Tug will withstand normal landing loads with propellant tanks full. The Tug will maintain structural integrity under crash loads with propellant tanks empty.

9) The Tug will be designed for vertical or horizontal loading/unloading of the Tug into or out of the Orbiter, with or without Tug payload, and propellant tanks empty or full.

10) For programmatic considerations, the number of Orbiter flights will be limited to three in 1980 and 21 in 1981. For programs with an IOC of 1981 or later, a reasonable two-year build-up will be determined. Tug reliability losses are assumed to be one per hundred flights.

III. BASIC DATA AND SIGNIFICANT RESULTS

A. MISSION REQUIREMENTS (Task 1)

The Standardized Mission Model was reviewed to determine delta velocity requirements, mission durations, subsystem operating times and limits, autonomy levels, and redundancy levels required for each mission. Tug performance parameters were established to match the delta velocity/spacecraft weight requirements. For a single-stage storable-propellant Tug, specific impulse of greater than 330 sec and vehicle mass fraction of 0.945 are required. A Tug with these parameters can meet spacecraft delivery requirements of the Standardized Mission Model but is limited in its ability to accomplish spacecraft retrieval requirements. Various flight operation modes were evaluated to augment the Tug performance capability to accomplish the spacecraft retrieval requirements.

The following flight operation modes were evaluated:

1) Single-stage Tug with expendable kick stages;

2) Two-stage Tugs using simple staging techniques;

3) Two-stage Tugs using "trapeze" staging techniques with Tug-to-Tug rendezvous;

4) Stage-and-a-half Tug with expendable drop tanks;

5) Kick-stage deorbit of spacecraft;

6) Use of spacecraft station-keeping propulsion to deorbit spacecraft;

7) Delayed retrieval for spacecraft recovery.

Results of the flight operation modes evaluation are:

1) Two-stage Tug concepts offer greater retrieval capability than single-stage, at the expense of more complex flight operations.

2) The delta velocity required for nodal regression correction offsets most of the performance gains of trapeze staging.

3) Stage-and-a-half concepts offer greater delivery capability than single-stage, at the expense of more complex flight operations and higher recurring costs.

4) Kick-stage deoribt and spacecraft propulsion-system deorbit are not competitive with delayed retrieval for spacecraft recovery.

5) Delayed retrieval allows a single-stage Tug to be competitive with a two-stage Tug for spacecraft retrieval and permits the single-stage storable-propellant Tug to meet all mission model requirements.

The principal of delayed retrieval is to convert the residual propellants available after spacecraft delivery into reducing the energy of the orbit of another spacecraft that is to be retrieved. Residual propellants are generally available because the Tug delivery capability is significantly greater than the largest spacecraft in the mission model. After spacecraft delivery, the Tug rendezvous with the spacecraft to be retrieved in a fashion similar to a round-trip mission. The Tug then burns the excess propellant from the delivery mission and deorbits the spacecraft to a lesser-energy orbit. It then releases the spacecraft and returns to the Orbiter.

The spacecraft, now in a lesser-energy orbit, is then recovered at some later date in exactly the same fashion as for a normal retrieve-only mission.

No additional operations are required. Software is the same. Ephemeris information requirements for the new lower-energy orbit retrieval mission and a geostationary retrieval mission are the same. The net impact of the entire delayed retrieval operation is to increase the effective spacecraft retrieval capability from 1800 lb to more than 6000 lb, at the expense of only one additional rendezvous and docking operation.

The most significant result of this task and of this study is the determination that delayed retrieval permits single-stage storable-propellant Tugs to perform all the spacecraft retrieval requirements of the mission model without having to resort to additional Tug flights, operationally difficult flight modes, kick stages, or spacecraft propulsion systems.

With delayed retrieval, stage-and-a-half and two-stage Tugs can be eliminated as possible storable-propellant Tug candidates.

Other results from Task 1 are:

1) Position and attitude updates are required to meet Orbiter rendezvous accuracy requirements. However, the update requirement does greatly relax guidance hardware accuracy requirements because multiple updates can compensate for a less accurate guidance system.

2) Cost guidelines for performance improvements were identified. One second of specific impulse improvement has the same effect as a reduction of 50 lb of dry weight. Engine specific impulse improvements can be achieved at a DDT&E expenditure rate of approximately \$2.5M/sec; therefore, dry weight savings that can be achieved for less than \$50K/lb are as cost effective as engine improvement.

B. SUBSYSTEM ANALYSIS (Task 2)

The primary Tug subsystems consist of structures, thermal control, avionics, and propulsion. Many concepts and components were considered for each of these subsystems. Candidates were systematically screened in Task 2 and survivors retained for further evaluation in Task 3. Subsystem selection, optimization, and detailed definition continued throughout Tasks 3 and 5.

1. Structures

Four basic vehicle concepts were derived from various approaches considered to capture the mission model:

1) A single-stage vehicle sized to carry 57,000 lb of propellant and limited to no more than 35 ft in length.

2) A single-stage vehicle sized to carry 57,000 lb of propellant, but limited in length to 17.5 ft so that, by off-loading propellant, two-stage operation could be achieved.

3) A two-stage combination of vehicles, each sized for 28,500 lb of propellant and with their total length limited to no more than 35 ft.

4) A stage-and-a-half vehicle with drop tanks sized to carry 50% to 80% of the 50,000 lb of propellant.

Within these vehicle concepts, various structural candidates were evaluated to define the main propellant tanks, skirt structure, and engine thrust structure.

For the tank evaluation, dome shapes, structural arrangement, and materials were considered. Hemispherical and various elliptical dome shapes were evaluated. Structural arrangements considered were isolated tandem, isolated side-by-side, common-dome tandem, and common-wall tanks. Materials considered were 2219-T87 aluminum and Ti-6A-14V titanium alloy.

Both closed shell and open truss were considered for skirt structure. These consisted of aluminum honeycomb (graphite epoxy face sheets over aluminum core), aluminum skin-stringer, aluminum integral-rib-stiffened, and graphite-epoxy composite tubular-truss construction.

The candidates chosen for engine thrust structure consisted of both open-truss and closed-cone. The open-truss structures evaluated were made of titanium, aluminum, and graphite epoxy. The closed-cone configurations consisted of titanium skin-stringer construction and a composite graphite-epoxy honeycomb.

Each of these structural candidates was first screened against a list of essential requirements. Surviving candidates were then compared on a relative basis for cost, reliability, complexity, safety, producibility, and ease of handling. Structural candidates surviving for further study in Task 3 are in Table 1.

Table 1 Structural Concepts Selected for Further Study

Tug Configuration	Structural Concepts
Single-stage, 57,000 lb of propellant, mixture ratio 2:1	Isolated tanks, Titan III Stage II tank arrangement Isolated Tanks, fuel tank forward, elliptical domes Isolated tanks, equal-volume tanks (MR 1.65:1) Common-dome tanks, hemispherical domes
Two-stage, 28,500 lb of propellant per stage	Common elliptical domes
Stage-and-a-half, various propellant splits & tank arrangements	20/80 propellant split, core plus 2 drop tanks, common elliptical domes

Significant conclusions from structural subsystems analyses are:

1) Side-by-side tanks were rejected because of poor mass fraction compared to stacked tanks.

2) For optimum mission capture, optimum Tug length is 28 ft or less.

3) Isolated tanks are preferred over common-dome tanks for reuse, inspection, and safety, despite performance and length disadvantages.

4) Thin-gage titanium is preferred over thin-gage aluminum for tank construction because of greater fracture toughness and durability.

5) The oxidizer tank should be aft for cg control.

2. Thermal Control

The thermal-control subsystem is required to maintain Tug subsystems within allowable temperature limits for ground, launch, orbit, postorbit, and landing conditions. The orbital time requirement varied from 36 hours to 7 days--up to 30 days as a goal.

Thermal-control methods considered for the Tug configurations included:

1) Passive control through the use of multilayer insulation (MLI);

2) Passive control through the use of optical solar reflectors (OSR);

3) Passive control through the use of paint patterns and special surface finishes;

4) Active control through the use of fluid loops, heat pipes, and radiators (Active control would use the waste heat from the fuel cell for those configurations using it as a power source.);

5) Various combinations of these.

Selection of the thermal-control subsystem depended on selection of the Tug configuration and other subsystems. Both active and passive thermal-control subsystems were retained for consideration in Task 3. Passive thermal control (MLI, coatings, and heat pipes) was selected for detailed definition in Task 5 on the basis of minimum cost, complexity, and weight. An aluminum forward compartment was used for thermal balance of avionics components.

3. Avionics

The avionics subsystem consists of guidance, navigation, and control; data management; communications; and electrical power.

Guidance Navigation and Control (GN&C) - Two generations of subsystems were considered for GN&C: existing designs with 1979 availability, and lightweight designs that will be available by 1983. Components evaluated were gimbaled and strapped-down inertial measurement units (IMUs), star trackers, horizon sensors, video cameras, rendezvous and docking radars (both RF and laser), and actuators. Primary consideration was given to cost, reliability, and weight.

IMUs for both the 1979 and 1983 systems were driven to skewed redundant strap-down units by safety and reliability requirements. Based on weight and cost, the Hamilton Standard redundant strapdown IMUs, and the Autonetics Micron IMUs were selected for the 1979 and 1983 generations, respectively.

Star-tracker selection criteria were long mean time between failures and a reasonable light weight. This led to the selection of the Ball Brothers CT 401 unit, which is fully developed, low in cost, and has relatively good accuracy.

The horizon sensor was chosen on the criterion of a position update device, rather than the usual attitude update device. From a position update viewpoint, there is only one system that meets the requirements--the Quantic ETC 321B, Model IV. The horizon sensor is alternative equipment required only for Autonomy Level I.

Power, weight, and short-range resolution were the factors used in selecting the scanning laser radar (SLR) over more conventional RF ranging systems for rendezvous and docking. The SLR is built by ITT and weighs about 60 lb.

Although a TV camera may not be required when docking to an attitude-stationary spacecraft, it will be required as an adjunct when docking to a rotating coning target spacecraft. For the video system, the existing Apollo 15/16 TV camera system, at 13 lb, was selected. The video system would be used for both autonomous docking (target pattern recognition) and man-in-the-loop docking.

Integrated tandem hydraulic actuators, similar to those used on modern high-performance aircraft, were selected for main-engine pitch and yaw control. Roll control, as well as all attitude control in the coast phase, is provided by attitude control thrusters. The selection was based on evaluation of rotational and translational dynamics associated with limit cycling, docking, and propellant efficiency.

Data Management - Three approaches to data management systems design were examined. Principal differences were in the approach to providing interface services. The central hub approach (typical 1958 to 1965) uses a wire pair per function between a central box (or sets of boxes) and each user, with resulting heavy cabling weight, interface complexity, and high costs. The intermediate bus approach (mid 1960s-early 1970s) uses time division multiplexing over a large portion of cabling length to save cable weight, but the costs associated with interface complexity persist. The flexible signal interface (FSI) (Tug for 1980 and beyond) places standardized dedicated hybrid circuits in the "serviced black boxes" to further use the advantages of time division multiplexing. This approach reduces systems integration costs by eliminating unique interface designs and design coordination while offering many opportunities for performing needed functions. It also reduces weight by eliminating the need for separately packaged remote multiplexed interface units at or near the "serviced black boxes." The FSI was selected for detailed definition because it provided maximum capability and flexibility for minimum weight and cost, and minimized interfaces with the Orbiter, spacecraft, and ground equipment.

Communications - A mixed system of K_u-band (relay satellite link) and S-band (ground and orbiter links) was compared with an all-S-band system. Existing or planned relay satellites were found incompatible with the requirement for continuous Tug communications to and from the ground at altitudes above 3000 mi. A 35-lb satellite "add-on" communications package using standard Tug components was recommended to provide the relay satellite with the needed relay function. Existing communications hardware technology was determined adequate to perform all required functions. The modular all-S-band approach was recommended because it gave the highest operational flexibility with redundancy backup at the least cost and weight.

Electrical Power - Electrical power sources considered were battery, solar array, fuel cells, and nuclear systems.

The nuclear systems were discarded due to extremely high cost, weight, volume, and safety problems.

Batteries were selected for short missions where no power is provided to the spacecraft. The selection would be driven to solar arrays if the spacecraft were to require power.

Solar arrays and fuel cells remained the subject of trade-offs for longer missions. After careful evaluation, it was concluded that the solar array system offered the least weight, least overall program cost, and simplest Orbiter interfaces, while providing the most flexible modularized system with greatest growth potential for longer missions.

4. Propulsion

Main Propulsion - Fuel candidates considered for the Tug were UDMH, N_2H_4, A-50, and MMH. With N_2O_4 oxidizer, MMH was selected after considering such items as performance, cost, heat sensitivity, freezing point, and commonality with the Orbiter OMS and RCS systems.

Main-engine candidates considered for the Tug are listed in Table 2.

Table 2 Main-Engine Candidates Considered

Engine	I_{sp} (sec)	Description
Class I*	338.0	New, 1500°F chamber wall, gas generator
Class I	339.5	New, 3000°F chamber wall, gas generator cycle
Class II	340.8	New, 1500°F chamber wall, staged combustion cycle
Class II*	344.0	New, 3000°F chamber wall, staged combustion cycle
Bell 8096	304.2	Min mod HDA/UDMH + SO additive
Bell 3096A	317.0	New injector HDA/UDMH + SO additive
Bell 8096B	327.6	New injector N_2O_4/MMH + SO additive
Bell 8096B-1	327.2	New injector N_2O_4/A50 + SO additive
Bell 8096B-2*	332.1	8096B with new chamber and 12,000-lb thrust
OME 125 P_c	325.0	OME with boost pumps, MR = 1.65
OME 150 P_c*	327.0	OME with boost pumps, MR = 1.9
OME 240 P_c*	331.0	OME with boost pumps, MR = 1.9

*Preferred and used for further evaluations.

After further assessment it was concluded that:

1) For low-cost, nongrowth options, the Bell 8096B-2 and OME 150 engines are equally effective.

2) For high-performance options, the Class I 338 engine is preferred over all other options. The Class II 344 engine offers slightly more performance, but at a significantly higher cost and with greater performance risk. The Class I 338 is nonrisk, state-of-the-art, and relatively inexpensive ($58M DDT&E).

3) Engine phase development is not cost effective.

The pressurization system candidates included helium stored at both ambient and cryogenic temperatures, autogeneous, dedicated gas generator, combinations of the previous, helium blowdown and main-tank injection. Because of the low pressurization requirements based on engine-mounted boost pumps, all but the simplest and most reliable ambient stored-helium system using composite materials for the helium sphere were eliminated.

For propellant acquisition, both screen surface-tension devices and propellant settling thrust from the auxiliary-control propulsion system were considered. Based on trade-study results, the surface tension device shows a performance advantage. These data, combined with the unlimited life characteristics with little or no maintenance, lead to the selection of a surface-tension device consisting of a refillable screen trap in the bottom of each propellant tank.

For propellant utilization (PU) and gaging, trade studies were conducted to evaluate the advantage of an active PU system. The resulting system consists of point level sensors and an integrator that drive an engine-mounted flow control valve. In addition to showing a performance advantage, the PU system can compensate for propulsion-system component performance deviations, which allow relaxation of component tolerances, thus improving reliability and reducing cost. For these reasons, a PU system was selected.

Auxiliary-Control Propulsion System (ACPS) - Preliminary ACPS requirements led to consideration of both bipropellant and monopropellant systems. For the bipropellant system, the fuel selected was MMH, due to thruster availability and commonality with the main propulsion system, OMS, and RCS. Monopropellants considered were hydrazine and hydrogen peroxide. Hydrazine was selected over hydrogen peroxide for its higher delivered specific impulse and improved storability. A detailed evaluation of total impulse required was performed for the delivery-only mission and the delivery/retrieval mission (round trip). The analysis considered Tug/Orbiter separation, spacecraft, spin-up, inbound midcourse correction, attitude hold, and performance reserves. Results of the trade study indicated a hydrazine system over the bipropellant due to performance (weight) and cost.

The nozzle arrangement selected has 16 thrusters, each with a thrust level of 25 lb, with four nozzles per quadrant, similar to that used on the Apollo service module. This arrangement provides control in all six degrees of freedom for complete Tug control during Orbiter separation, spacecraft release, and Orbiter retrieval of the Tug. With 16 thrusters, there is a one-engine-out capability, which is required to meet fail-operational/fail-safe criteria.

Other systems considered were a bipropellant ACPS integrated with the main system and a bipropellant vernier system with a smaller monopropellant system for attitude control. Both of these systems added cost and complexity with no performance gain and were therefore rejected.

There are several techniques for management and acquisition of propellants for the ACPS. Nonmetallic bladder and diaphram tanks are generally used for hydrazine systems. Ethylene propylene rubber compounds are normally used with hydrazine to obtain better cycle life than Teflon; however, these rubber compounds have not been compatible with N_2O_4. Surface-tension devices were selected because they offer all the advantages of light weight, reuse, minimum maintenance, and potential for unlimited life.

C. CONFIGURATION CONCEPTS (Task 3)

Subsystem candidates selected in Task 2, together with the various flight operation modes identified in Task 1, were synthesized into Tug candidates. Some 48 initial Tug candidates were identified and screened against the required performance and mission constraints defined in Task 1. Some 33 Tug candidates survived the initial screening. These were sorted into seven capability options or "buckets" which specified programmatic and performance constraints, as shown in Table 3.

Table 3 Space Tug Concept Selection Capability Options

Capability Options, Initial/Final	Development Approach	Minimum Geosynchronous Payload, Performance, lb		IOCs
		Deployment	Retrieval	
1. Interim (w/o Rendezvous & Dock)	Direct	3500	NA	Dec 79
2. Interim (with Rendezvous & Dock)	Direct	3500	2200	Dec 79
3. Interim (w/o Rendezvous & Dock)/ Interim (with Rendezvous & Dock)	Phased	3500 3500	NA 2200	Dec 79/ Dec 83
4. Full Capability	Direct	--	3500	Dec 83*
5. Interim (w/o Rendezvous & Dock)/ Full Capability	Phased	3500 --	NA 3500	Dec 79/ Dec 83
6. Interim (with Rendezvous & Dock)/ Full Capability	Phased	3500 --	2200 3500	Dec 79/ Dec 83
7. Interim (with Rendezvous & Dock)	Direct	3500	2200	Dec 83

*Sensitivity of moving IOC up to two years earlier shall be provided.

For assessment and comparison, at least one single-stage, one two-stage, and one stage-and-a-half Tug candidate were placed in each of the seven capability options. Mission capture and programmatic assessment were conducted on all Tug candidates in each of the seven capability options, and a preferred Tug candidate was recommended for each capability option. Total transportation costs were used as a discriminator with Shuttle flight costs computed at $10.5 million per launch. A summary of the results of preferred Tug candidate and programmatics is in Table 4.

Table 4
Task 3 Results, Selected Tug Candidates and Programmatics by Capability Option

Capability Option	1	2	3	4	5	6	7
Preferred Tug	Single Stage	Single Stage	Single Stage	Single Stage	Single Stage	Single Stage	Single Stage
Perf Del/ Ret (Geo., lb)	6300/ NA	6300/ 1230	7800/ 2300	7800/ 2300	7800/ 2300	7800/ 2300	7800/ 2300
DDT&E ($,M)*	244	274	337	300	337	343	300
Total Tug Cost ($, M)	510	663	726	689	726	732	689
Total Transportation Cost ($, M)	3309	6124	5449	4179	5564	5725	4179

*Includes $18 to $26 million DDT&E for kick-stage development with retrieval capability.

The significant conclusions from Task 3 are:

1) Single-stage Tugs are preferred over stage-and-a-half and two-stage Tugs.

2) A limited number of kick stages are required for all configuration Tugs for high-energy planetary missions. Kick stages are not required for spacecraft deorbit if delayed retrieval is used. Kick stages are therefore not a discriminator.

3) Rendezvous and docking capability is relatively inexpensive to develop (approximately $30 million), but expensive to routinely implement (approximately $7-$10 million per spacecraft).

4) Eighty-five percent of the transportation costs are Shuttle costs. Multiple spacecraft deployment from a single Tug is the most effective way to reduce transportation costs for small users.

5) Length is as critical as delivery weight capability for optimizing multiple spacecraft deployment, determining total number of flights and, therefore, in determining total transportation costs.

6) Capability Options 2 and 6 are not realistic (spacecraft retrieval in 1979). Capability Options 3 and 5 are the same and Capability Options 4 and 7 are the same because delayed retrieval removes retrieval performance constraints.

Following a period of assessment by the customer, three Tug options were selected for further definition in Task 5.

D. SELECTED OPTION DEFINITIONS (Task 5)

1. Option Requirements

General requirements for the option definitions are summarized in Table 5. Options 1, 2, and 3 are single-stage verisions; Option 3A is a stage-and-a-half version with the same requirements as Option 3. Option 1 has an early IOC, no retrieval capability, low DDT&E, no growth capability, and is limited to a 36-hour delivery mission. Option 2 has a late IOC, is direct-developed, and has maximum delivery and retrieval capabilities. Options 3 and 3A are phase-developed options with initial delivery-only capability in 1979, and retrieval and increased performance capability incorporated in 1983.

Table 5 Summary of Requirements

	Option 1	Option 2	Option 3	Option 3A
IOC	1979	1983	1979/1983	1979/1983
Spacecraft Requirement				
Delivery	3500 lb	3500 lb	3500 lb	3500 lb
Retrieval	--	3500 lb	2200 lb	2200 lb
Vehicle	Single-stage	Single-stage	Single-stage	Stage-and-a-half
Additional Requirements	Delivery-only	Direct-developed	Phase-developed	Phase-developed
	Low DDT&E dollars	Delivery & retrieval in 1983	Delivery-only 1979-1983	Delivery-only 1979-1983
	No growth		Retrieval & increased performance in 1983	Retrieval & increased performance in 1983
	36-hr max duration			

2. Option Descriptions

Figure 1 is the general inboard profile for the single-stage Tugs used in Options 1, 2, and 3. Figure 2 is the inboard profile for the stage-and-a-half Tug used in Option 3A. Table 6 summarizes and compares physical characteristics, performance capabilities, and major subsystems.

The configuration for Option 1 is identified as an Interim Tug that uses a low-thrust OME engine and current state-of-the-art inertial measurement unit (IMU). Because the mission is limited to 36 hours and the spacecraft do not require electrical power from the Tug, batteries are used.

Option 2 employs a Direct-Developed Tug that uses a separation module for spacecraft delivery and a docking module for spacecraft retrieval. Dry weights and performance capability for both configurations are shown in Table 6. The Direct-Developed Tug uses a new Class I engine and lightweight IMU. A laser radar is used in the retrieval version for rendezvous and docking. Solar arrays are used for electrical power.

Option 3 is a phase-developed program with a Phased Tug-Initial and a Phased Tug-Final. The Phased Tug-Initial is similar to the Interim Tug used in Option 1, differing in tank size (optimized for retrieval rather than delivery), main engine, and electrical power. The Phased Tug-Final is identical to the Direct-Developed Tug used in Option 2 and is used for both delivery and retrieval, with the appropriate separation or docking module.

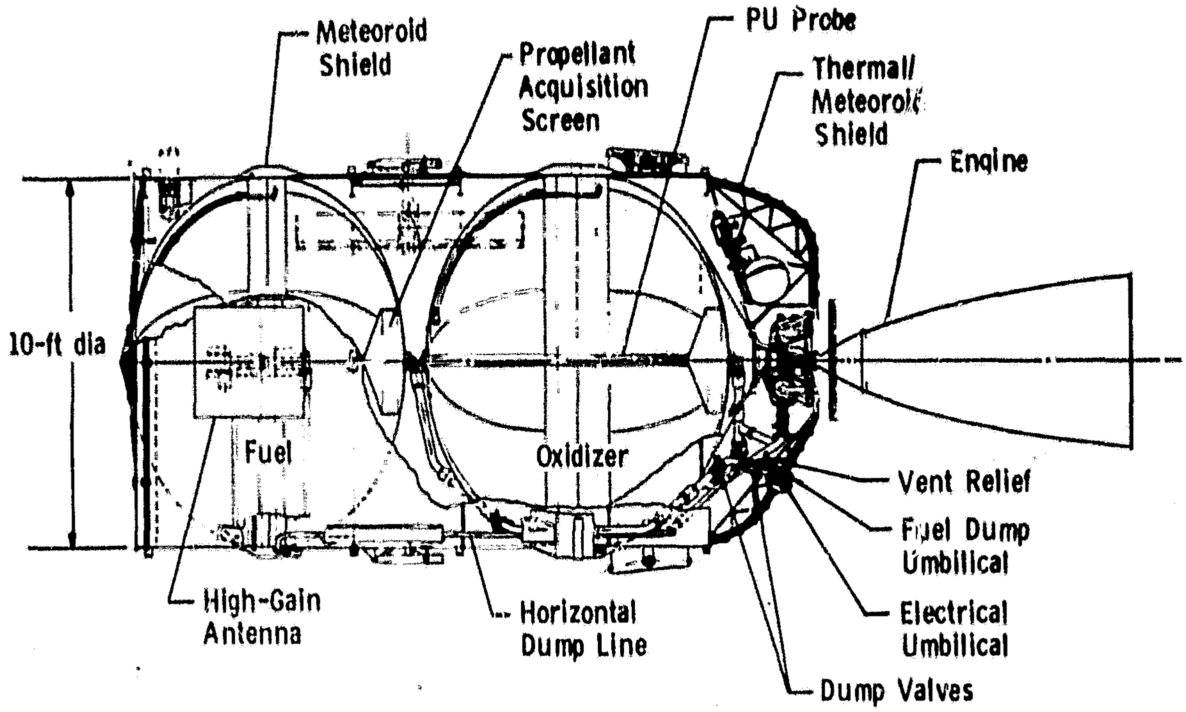


Figure 1 Single-Stage Tug Inboard Profile

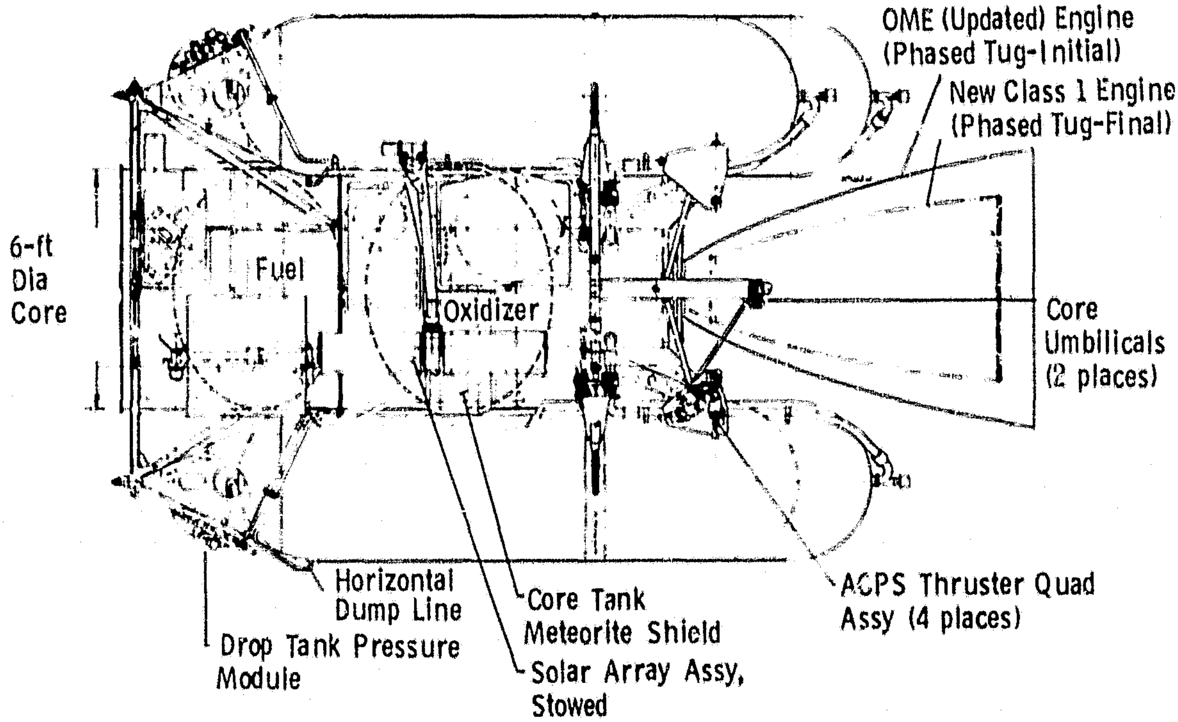


Figure 2 Stage-and-a Half Tug Inboard Profile

Table 6 Summary of Option Definitions

	Option 1	Option 2		Option 3			Option 3A		
Development	Direct	Direct		Phased			Phased		
Stages	Single	Single		Single			Stage-and-a-Half		
Configuration	Interim	Delivery	Retrieval	Initial Delivery	Final Delivery	Final Retrieval	Initial Delivery	Final Delivery	Final Retrieval
IOC (Dec)	1979	1983		1979	1983		1979	1983	
Dry weight	2,886 lb	2,750 lb	2,982 lb	2,934 lb	Same as Option 2 Delivery	Same as Option 2 Retrieval	4,004 lb	3,820 lb	4,043 lb
Length	27 ft 2 in.	26 ft 11 in.		27 ft 9 in.			22 ft 11 in.	22 ft 1 in.	
Propellant Weight	56,700 lb	59,800 lb		59,800 lb			59,800 lb		
Spacecraft Capability* Delivery	3,800 lb	6,000 lb	4,900 lb	4,400 lb			4,900 lb	6,500 lb	5,300 lb
Retrieval	——	——	1,800 lb	——			——	——	1,900 lb
Propulsion	Low-P_c OME	Class I		High-P_c OME			Same as Option 3		
Avionics	FSI, Current IMU	FSI, Light Weight IMU, Laser Radar for Retrieval		Same as Option 1					
Power	Battery	Solar Array		Solar Array			Solar Array		
Structure	Isolated Titanium Tanks; Titanium, Aluminum, & Composite Body Structure						Same as Options 1, 2, & 3 plus Aluminum Drop Tanks		
Thermal	Passive Paint; MLI each end; Base Heatshield								

*Spacecraft capability to geostationary orbit

Option 3A is similar to Option 3 except that a stage-and-a-half Tug configuration with external drop tanks is used.

All options require auxiliary stages (kick stages) for some high-energy planetary missions. These are identified as Kick Stage 10, Kick Stage 1.5, and Kick Stage 10/1.5. Kick Stage 10/1.5 is a dual kick stage, consisting of Kick Stages 10 and 1.5 in tandem. Figures 3 and 4 are inboard profiles of Kick Stages 10 and 1.5, respectively. Kick Stage 10 uses approximately 10,000 lb of propellant; Kick Stage 1.5 uses approximately 1500 lb.

3. Mission Accomplishment

All selected options are capable of capturing 100% of their respective mission models. Results are presented in Table 7. Option 1 does not retrieve any spacecraft. Option 2 has fewer spacecraft missions because it does not become operational until 1983. Use of multiple spacecraft delivery reduces the number of flights required to accomplish the delivery requirements; Tug overall length is a significant factor.

Table 7
Summary of Mission Accomplishment (100% Capture)

	Option 1	2	3	3A
Spacecraft Delivered				
NASA	201	136	201	201
DOD	159	122	186	186
Total	360	258	387	387
Spacecraft Retrieved				
NASA	---	90	87	87
DOD	---	89	84	84
Total	---	179	171	171
Total Spacecraft	360	437	558	558
Delivery Flights				
NASA	124	75	115	107
DOD	114	39	80	79
Total	238	114	195	186
Retrieval Flights				
NASA	---	90	87	87
DOD	---	89	84	84
Total	---	179	171	171
Total Flights	238	293	366	357

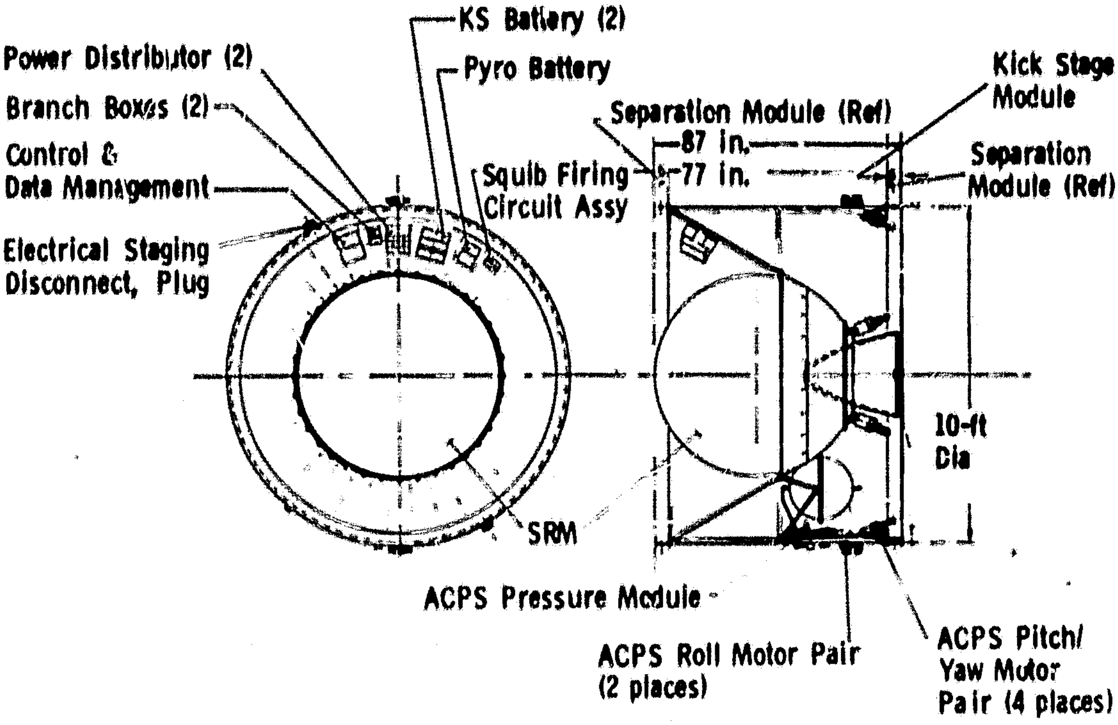


Figure 3 Kick Stage 10 Inboard Profile

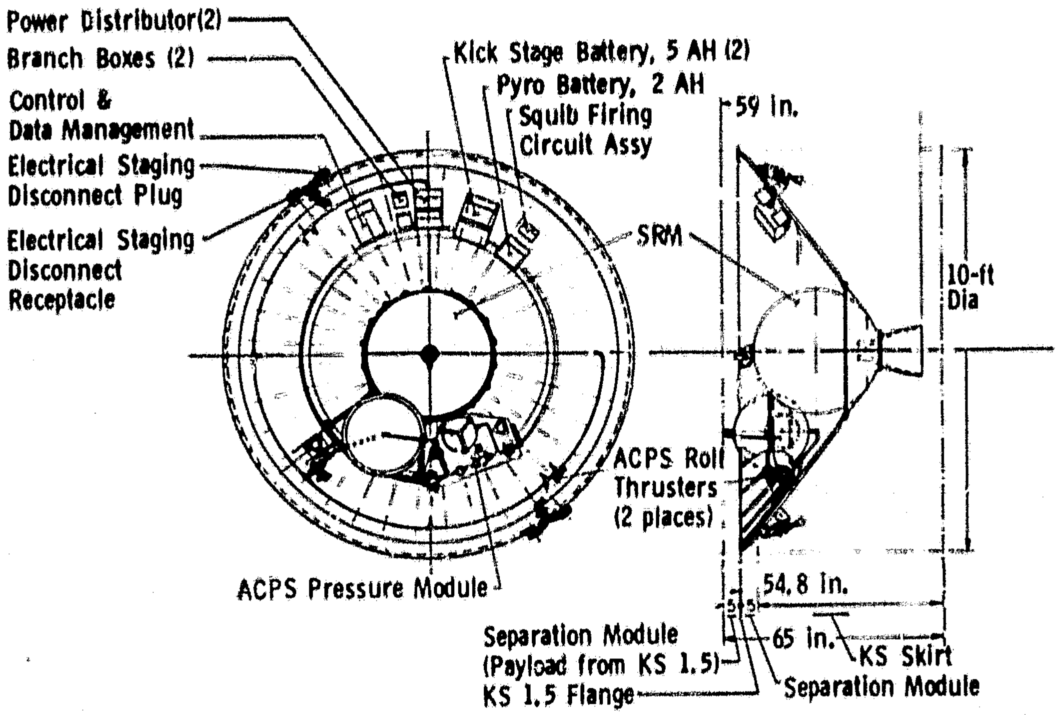


Figure 4 Kick Stage 1.5 Inboard Profile

The retrieval capability of the Tugs used in Options 2 and 3 is limited to 1800 lb, which is less than the 2200 lb required. This problem has been solved by the use of "delayed retrieval." Because these Tugs can deliver 4900 lb, which is in excess of the 3500 lb required, the residual energy can be used to deorbit a spacecraft for later retrieval. The Tug delivers spacecraft to geostationary orbit, rendezvous and docks with a spacecraft to be retrieved, performs a partial deorbit burn dependent on the residual energy from the delivery mission, and releases the spacecraft into an intermediate orbit for later "delayed retrieval flight."

Use of delayed retrieval provides a major breakthrough in solving the performance limitations of the Storable Tug. Any spacecraft delivered can be retrieved without needing additional Tug flights.

4. Ground Operations

The Storable Tug design permits easy ground operations; interfaces with the Orbiter are simple (two dry propellant lines and two eight-pin connectors). Storable propellants do not require purging, venting or topping after loading. The Tug design will permit the Tug to land loaded or empty, and permits propellant dump in the vertical or horizontal position when on the ground.

A trade study was conducted to determine the best location for loading propellants. It was concluded that propellants should be loaded on the launch pad, but out of the Orbiter. This eliminates off-site loading facilities and the need to transport the Tug with propellants loaded. Loading propellants in the Orbiter would complicate Orbiter interfaces and impose potential contamination of the Orbiter cargo bay.

Another trade study indicated that considerable cost savings could be achieved by using a Centralized Tug Maintenance and Checkout Facility (CTMCF) instead of individual facilities at ETR and WTR. The CTMCF concept is more efficient and reduces crew size, facilities, and GSE requirements. GSE requirements can be further reduced by acceptance testing in the CTMCF.

5. Flight Operations

The Storable Tug exhibits effective performance in that only a few kick stages are required during the entire operational phase; staging operations and resultant complex flight modes are reduced by using the single-stage concept. Capability for communications with relay satellites eliminates ground network constraints and provides for ease of operation in meeting the monitor/override requirement for critical on-board functions. Autonomy Level II is maintained with maximum flexibility for monitor and override/workaround capability in unplanned situations, due to the flexible signal interface (FSI) design. Further, the FSI minimizes and simplifies the interfaces with the Orbiter and spacecraft while retaining this extensive monitor/control capability.

The physical interfaces with the Orbiter are limited to two dry propellant lines and two eight-pin electrical connections. Propellants can be dumped sequentially or simultaneously in flight. In a powered abort mode, the oxidizer only could be dumped and meet the 32,000-lb cargo-bay weight landing goal. Orbiter cg constraints are met under all conditions from propellant tanks full to empty, and with any spacecraft.

6. Programmatic Factors

For programmatic considerations, the number of flights is limited in the initial years and one Tug reliability loss is added for each 100 flights. Table 8 presents the resulting number of flights and fleet sizes. The Tug provides maximum reusability, which permits a small fleet to accomplish many flights.

Table 8 Programmatic Factors (Revised)

	Option 1	2	3	3A
Launch Operations (Years)	11	7	10	10
Number of Flights*				
NASA	119	139	185	180
DOD	108	115	151	151
Total	227	254	336	331
Expendables				
Tugs (Main Stage)	10	6	8	8
Kick Stage 10	3	5	5	5
Kick Stage 1.5	4	--	--	--
Kick Stage 10/1.5	4	--	4	4
Drop Tanks	--	--	--	279
Fleet Size				
Tugs (Main Stage)	15	12	15	15
*Includes reliability losses & limited flights in first two years	3	3	4	4

Other programmatic factors resulting from trade-study recommendations and used in the cost estimates are:

1) DDT&E span times are optimized for minimum peak-year funding (Options 2 and 3).

2) DDT&E is preceded by extensive SRT and Phase B effort (not included in total Tug costs).

3) No full-scale Life Test Article or Thermal Effects Test Models are required.

4) A Central Tug Maintenance and Checkout Facility (CTMCF) is used.

5) Propellants are loaded on pad, but out of the Orbiter.

6) Existing facilities are used (modified).

7) Acceptance testing is performed in the CTMCF.

8) The engine is not phased (Options 3 and 3A).

7. Cost Summary

Table 9 summarizes the Tug and STS costs. Revisions subsequent to the September Data Dump are incorporated. DDT&E costs for the kick stages are not included because these costs may be shared with other programs. Shuttle costs are based on $10.5 million per flight.

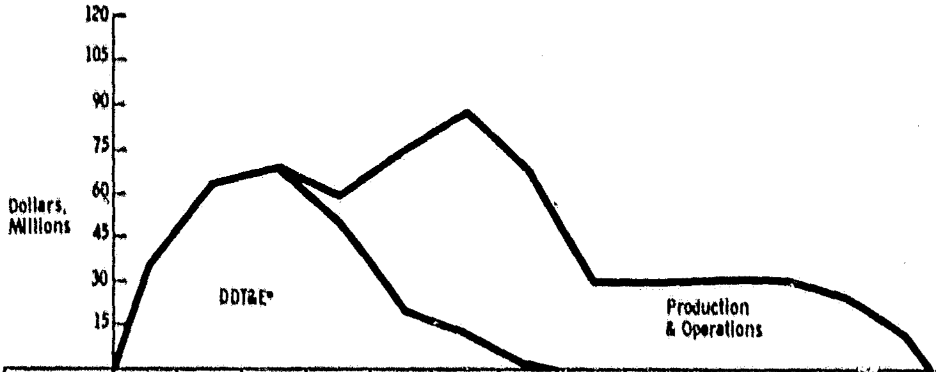
Table 9 Cost Summary (Revised)

All Costs in Millions	Option 1	2	3	3A
Tug Costs				
SRT	($12.2)	($19.8)	($19.8)	($20.0)
DDT&E	$ 183	$ 254	$ 263	$ 286
Production	158	153	190	361
Operations	224	208	256	261
Total	$ 565	$ 615	$ 709	$ 908
Number of flights	227	254	336	331
Average Operations Cost per flight	$0.99	$0.82	$0.76	$0.79
Shuttle Costs	$2384	$2667	$3528	$3476
Transportation Costs	$2949	$3282	$4237	$4384

( ) Not included in total costs.

Transportation costs are driven by Shuttle costs. Transportation costs for Option 3A are higher than for Option 3 despite Option 3A's fewer total flights. This is due to the significantly higher Tug recurring costs of Option 3A resulting from expenditure of the drop tanks.

Figure 5 shows typical yearly funding requirements. In this case (Option 2), DDT&E is started in November 1978, and ETR and WTR are operational in December 1983.



FY	79	80	81	82	83	84	85	86	87	88	89	90	91	Total
DDT&E	37.4	62.6	69.7	50.3	20.9	13.0	0.7							254.6
Production				9.0	54.1	54.5	34.7	0.5						152.8
Operations						21.1	31.0	28.5	28.7	30.6	30.8	24.6	12.3	207.6
Total/Year	37.4	62.6	69.7	59.3	75.0	88.6	66.4	29.0	28.7	30.6	30.8	24.6	12.3	615.0

*Kick stage DDT&E cost not established, SRT & Phase B Not Included

Figure 5 Funding Requirements Option 2 (Revised)

8. Sensitivity Studies

IOC sensitivity studies indicate that stretching out development time can reduce annual peak funding requirements, although this slightly increases total DDT&E costs. Peak funding should be a key factor in choosing the optimum program for the Tug.

Sensitivity studies also show that use of the DOD programmatic approach reduces risk, but delays production. With the relatively small fleet size, this results in an uneven distribution of annual funding requirements. Therefore, it is recommended that commit-to-production not be constrained by flight-test evaluation.

Engine sensitivity studies indicate that the engine should not be phased in Option 3.

Other sensitivity studies indicate that:

1) Autonomy levels do not have a significant effect on Tug weight and performance, except Autonomy Level I.

2) Safety and reliability criteria are equal drivers.

3) The storable Tug can readily accomplish a 30-day servicing mission with little additional cost.

4) DOD communications, spacecraft command and checkout, and spacecraft spin/despin do not have a significant effect on Tug performance.

5) Leak-before-burst design criteria drive design life.

6) Rendezvous and docking have a significant effect on performance, cost, and program risk.

7) Providing electrical power to the spacecraft would drive Option 1 to solar arrays.

E. SAFETY

Safety was established as a selection consideration at the onset of the study. "Must" safety criteria were created for all candidate subsystem selections. Where multiple candidate subsystems met the "must" criteria, relative safety criteria were then used in the subsystem selection process.

Particular attention was directed toward meeting the Orbiter manned rating requirements. Fail-operate/fail-safe criteria were used for the subsystem affecting operations in and around the Orbiter. The level of subsystem redundancy required to meet these criteria were also generally required to meet the required mission reliabilities (0.97 for the geostationary mission), leading to the conclusion that safety and reliability were equal system and subsystem design drivers. The selected Tug options all contained redundant IMUs, data buses, general processors and memories, ACS nozzles (pure couple system), and communications systems.

Safety considerations were also highly influential in the following Tug selections:

1) Both horizontal and vertical dump provisions;

2) Both propellant dump provisions and capability to land fully loaded;

3) Isolated propellant tanks;

4) Double isolation of all commodities;

5) "Fail-leak" rather than "fail-burst" pressure vessels;

6) On-pad but out-of-Orbiter propellant loading operations.

A safety analysis was conducted in Task 5. Energy sources, single-point failures, and potential design and operations hazards were identified and systematically analyzed to determine criticality. Techniques to eliminate, control/monitor, or control by procedures were identified. Residual hazards and risk assessment were identified and documented. Titan II weapon system history was used to help establish appropriate propellant-system management techniques. It was concluded that all Storable Tug concepts presented are safety manageable and offer significant advantages for safe system operations.

SUPPORTING RESEARCH AND TECHNOLOGY (SRT)

The Tug concepts identified in this study are feasible and largely based on near-state-of-the-art technology. Table 10 summarizes an SRT program to ensure a high degree of confidence in all aspects of the Tug necessary for its success in the Shuttle program. Figure 6 shows the funding distribution for the SRT program, based on Option 2. The majority of the early funding is to establish the feasibility of spacecraft rendezvous and docking.

Table 10 SRT Requirements/Recommendations

	Dollars In Thousands	Span In Months
Structures		
Analysis	1,003	18
Material Characterization	409	18
Manufacturing Techniques	731	22
Inspection Techniques	413	18
Avionics		
Rendezvous and Docking	5,956	36
Guidance and Navigation	1,989	24
Communication and Data Management	807	18
Electrical Power	1,122	18
Propulsion		
Main Propulsion	4,635	18
Attitude-Control Propulsion System	599	15
Thermal	656	18
Manufacturing	214	18
Flight Operations	1,268	18
Total	$19,802	

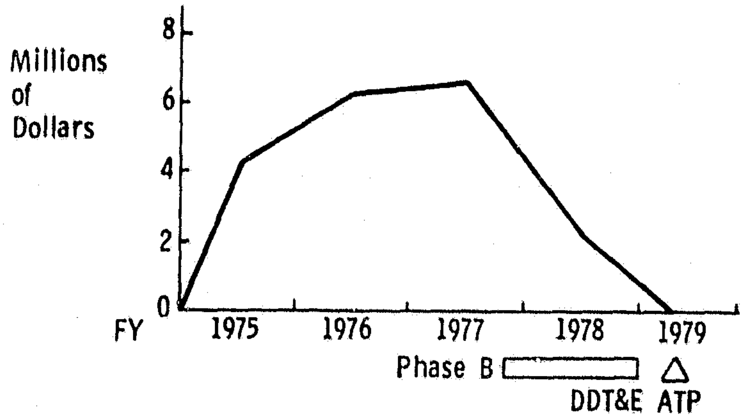


Figure 6 SRT Funding Requirements (Option 2)

IV. CONCLUSIONS

Tug programs that can perform the basic requirements of the STS and the mission plan of the 80s in a cost-effective manner have been defined in depth. Specific conclusions to the key issues and problems addressed in this study are:

1) The Storable Tug can achieve 100% capture of the Standardized Mission Model. In addition, the Storable Tug can readily perform a 30-day servicing mission.

2) A few (approximately 10) Tugs and kick stages must be expended to capture the very high-energy planetary missions. A "delayed retrieval" flight operation mode provides the capability to retrieve any spacecraft delivered. Multiple spacecraft delivery minimizes the number of Shuttle flights; therefore, Tug length is as important as delivery capability.

3) Storable Tugs offer efficient use of payload-bay volume, simple interfaces with Orbiter and ground systems, safe operating modes, and simple design, leading to low DDT&E costs. Storable propellants provide maximum safety due to their stability and precise reaction predictability; tank venting is not required after loading.

4) The Tug should consist of a single main stage with propellant tanks in tandem and isolated for safety. Components and subsystems have been selected to provide maximum capability with a Tug mass fraction of 0.95.

5) A high level of safety and reliability can be achieved without incurring unnecessary performance and cost penalties. Safety and reliability are equal drivers.

6) The reusability of the Storable Tug provides minimum production and operating costs. Extending DDT&E time reduces peak funding, but increases total cost.

7) Use of near-state-of-the-art concepts with extensive SRT and Phase B programs provides maximum performance at minimum risk.

V. RECOMMENDATIONS

A. SUGGESTED ADDITIONAL STUDIES

During the Space Tug Systems Study, it was decided that DOD would provide an Interim Tug, referred to as the Orbit-to-Orbit Shuttle (OOS), while NASA would pursue the long-range High-Technology Space Tug (HTST).

NASA should make maximum use of the Space Tug System Study results, modified to include the interim OOS in the Space Transportation System (STS) planning. Results of these studies should be maintained, combined, and modified to provide a cost-effective plan to integrate the HTST into the STS in the 1985 period. Emphasis should be placed on continuation of mission modeling, identification of performance and programmatic requirements, detailed advanced design studies in certain areas, investigation of the entire spectrum of upper stages, continuation of mission and ground operations studies, and resolution of safety issues.

The technical and managerial impact of the transition from OOS to the HTST should be studied in depth. The need to retain the OOS in the stable after HTST IOC should be determined. Benefits of the HTST should be confirmed, including economic studies of spacecraft retrieval. Technical and programmatic requirements for the HTST should be developed, resulting in an overall performance specification and program plan.

B. SIMULATION/HARDWARE RECOMMENDATIONS FOR CONCEPT VERIFICATION

Certain SRT tasks presented in Section III are critical to the HTST or Orbiter interfaces. It is recommended that the following tasks be started in FY 1975:

1) Hardware and software for man-in-the-loop and autonomous rendezvous and docking should be developed and tested in the laboratory. Workable techniques must be established early to support HTST development.

2) Hardware and techniques for transferring data and commands during deployment/retrieval of the Tug should be developed and tested to minimize the impact on Orbiter design.

3) The system benefits and inherent cost savings of the flexible signal interface (FSI) system should be demonstrated.

4) The feasibility and safety of simultaneous propellant dump should be demonstrated to establish design criteria and verify no impact on Orbiter systems.

5) Analytical tools to represent behavior of elastic bodies during docking when one body is spinning should be developed to provide adequate recovery time and support rendezvous and docking simulations.

6) The feasibility of using lightweight fibrous composites should be determined.

7) The ability of thin-gage titanium (6Aℓ-4V) to satisfy Tug mission life-cycle requirements should be determined to verify welding techniques, determine life-cycle characteristics, and minimize production risks.

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