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Space Division
North American Rockwell

SATURN SUSTAINING ENGINEERING REPORT

SD72-SA-0032

SPACE TUG POINT DESIGN STUDY FINAL REPORT
VOLUME I
SUMMARY

FEBRUARY 11, 1972

Prepared for

George C. Marshall Space Flight Center

Approved by

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Chief Program Engineer

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FOREWORD

The final report on the Tug Point Design Study was prepared by the North American Rockwell Corporation through its Space Division for the National Aeronautics and Space Administration's George C. Marshall Space Flight Center in accordance with SA 2190 and Contract No. NAS7-200.

The study effort described herein was conducted under the direction of NASA MSFC Study Leader, Mr. C. Gregg. The report was prepared by NR-SD, Seal Beach, California under the direction of Mr. T.M. Littman, Study Manager. The study results were developed during the period from 4 November 1971 through 11 February 1972 and the final report was submitted in February of 1972.

Valuable guidance and assistance was provided throughout the study by the following NASA/MSFC personnel:

C. Gregg - Study Leader
S. Denton - Structures
A. Willis - Avionics
J. Sanders - Propulsion
R. Nixon - Thermal Protection
A. Young - Flight Performance
R. L. Klan - Cost

The complete set of volumes comprising the report includes:

I Summary

II Operations, Performance, and Requirements

III Design Definition

Part 1 - Propulsion and Mechanical Subsystems, Avionic Subsystems, Thermal Control, and Electrical Power Subsystem

Part 2 - Insulation Subsystems, Meteoroid Protection, Structures, Mass Properties, Ground Support Equipment, Reliability, and Safety

IV Program Requirements

V Cost Analysis

This volume summarizes the information contained in the other four volumes.

ABSTRACT

The primary objective of the Tug Point Design Study was to verify through detail design and analysis the performance capability of a baseline design to deliver and retrieve payloads between 100 nautical miles/28.5 degrees inclination and geosynchronous. The Tug as groundruled for the study, is ground-based, reusable for 20 mission cycles, and is shuttled to and from low earth orbit by an Earth Orbital Shuttle (EOS) with a 65,000 pound payload capability. A 1976 state-of-the-art also was groundruled for the investigations.

The results of the effort show that the baseline concept can be designed to meet the target performance goals. Round trip payload capability to geo-synchronous orbit is 3720 pounds; 720 pound margin over the established goal.

The design analysis performed to ascertain the Tug propellant mass fraction encompassed definition of the vehicle primary structure, thermal control, meteoroid protection, propulsion and mechanical subsystems, and avionics including power generation and distribution.

Graphite-epoxy composite material was determined to be feasible for Tug use and resulted in considerable weight savings. The concept of employing the primary load-carrying outer shell as a multi-function element integrating the meteoroid shield and insulation purge bag requirements is also feasible and enhances design simplicity. In addition, the use of a dual-mode pressure schedule during boost to orbit when applied loads are highest resulted in minimum tank weight. This, combined with an integrated gaseous O_2/H_2 auxiliary propulsion for stability and control, main tanks prepressurization, and fuel cell usage yield a minimum weight and operationally simple system.

Reliability and Safety analyses verified that no single failure of a component would result in a critical or unsafe condition. This was accomplished employing redundancy as required, notably in propulsion subsystems valving and attitude control components.

Program requirements were developed to verify the feasibility, producibility and operational capability of the point design. The results indicate that an "on-condition" maintenance approach similar to that used by commercial airlines and military operations would effectively serve Tug requirements.

Technology development study effort was concentrated on identifying the technologies needed for the baseline design. The more critical technologies requiring development include high performance engines, high performance insulation, large composite structures, and avionics.

A preliminary program development schedule was structured summarizing the integrated activities necessary to support the Tug through design development, production, and ground and flight testing.

The cost analysis performed covered the five major cost categories of DDT&E, first unit production, SR&T, average flight maintenance and refurbishment, and flight test vehicle refurbishment.

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1.0 INTRODUCTION

The Space Tug is a high performance propulsion stage designed to operate as an orbital maneuvering stage launched by the two-stage Space Shuttle. Because of the nature of the Tug mission, performance capability is very sensitive to Tug mass fraction. This study was conducted to answer the questions "What Tug mass fractions are really achievable by 1980?", and "What level of technology effort is required in order to build a Tug having the high performance defined in NASA/MSFC's Study Plan (Reference 1)?". Both questions are discussed below.

1.1 BACKGROUND

Several pre-Phase A Tug/OOS (Orbit-to-Orbit Shuttle) studies have been conducted for NASA and USAF agencies with a wide variation in the mass fractions quoted. NR performed a reusable Space Tug study for NASA-MSC in 1970-71 (Reference 2) and both NR and MDAC evaluated OOS feasibility for SAMSO/Aerospace Corporation in 1971 (References 3, 4). Additionally, two European teams conducted Tug system studies for the European Space Agency (ELDO) during 1970-71 (References 5, 6). Investigations have also been accomplished by MSFC and Aerospace Corporation. These studies considered a wide variety of design concepts and autonomy limits, ground and space-based operational requirements, degree of reusability, unmanned and manned payload implications, single and multi-stages, and different technology bases.

Projected NASA and DOD missions for the 1980's and beyond demand a Tug designed for a high degree of reusability and operational flexibility to assure significant improvement in space flight economy. Furthermore, Tug design must be compatible with Shuttle orbiter cargo bay size, weight limitations, and environment. For a ground-based system, consideration also must be given to Shuttle transport of a mated Tug/Payload.

1.2 OBJECTIVES

This point design study had one primary aim which was to be verified by design detail and analysis; namely, that a reusable, ground-based Space Tug with an IOC target by about the end of 1979 (1976 state-of-the-art) can carry a 3000-pound round trip payload between orbits at 100 nautical miles/ 28.5 degrees inclination and geosynchronous. The key constraint was use of a Space Shuttle having a 65000 pound orbital delivery capability. A minimum usable propellant mass fraction of 0.895 also was desired. Additional study objectives were to (1) define the necessary supporting research and technology (SR&T) activities and their associated funding, and (2) determine Tug development, first production, and maintenance/repair costs.

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1.3 STUDY SCOPE

The detail design of an integrated system was performed for a baseline concept. The concept was derived from MSFC's Study Plan and NR-selected materials, fabrication techniques, and subsystems resulting from currently available data and new trade studies.

Concurrent with the baseline study, options were evaluated having the potential for improving Tug mass fraction and mission performance. Emphasis was placed on the areas of alternate materials and subsystems, flight mode and operational variations, and use of advanced technology.

The study logic of Figure 1.3-1 depicts the major functional activities and outputs of these activities. The analyses performed to satisfy study objectives can be subdivided into three inter-related major efforts which started at study outset and ran concurrently to completion. Initiation of these efforts at the same time was made possible by the large amount of technical data available from the data bank. System requirements and criteria definition and program support gave the design definition effort the input data necessary for realistic structural, mechanical, thermal, and avionics subsystems design taking into account reliability and safety requirements. The three major tasks formed an iterative loop to the extent that the study schedule permitted. As the design of each component and subsystem evolved, the results were fed to the supporting activities which served to increase the depth of analysis and visibility of the overall system characteristics with each succeeding step. This approach also adapted itself to the timely establishment of performance sensitivities and development of potentially attractive subsystem concepts.

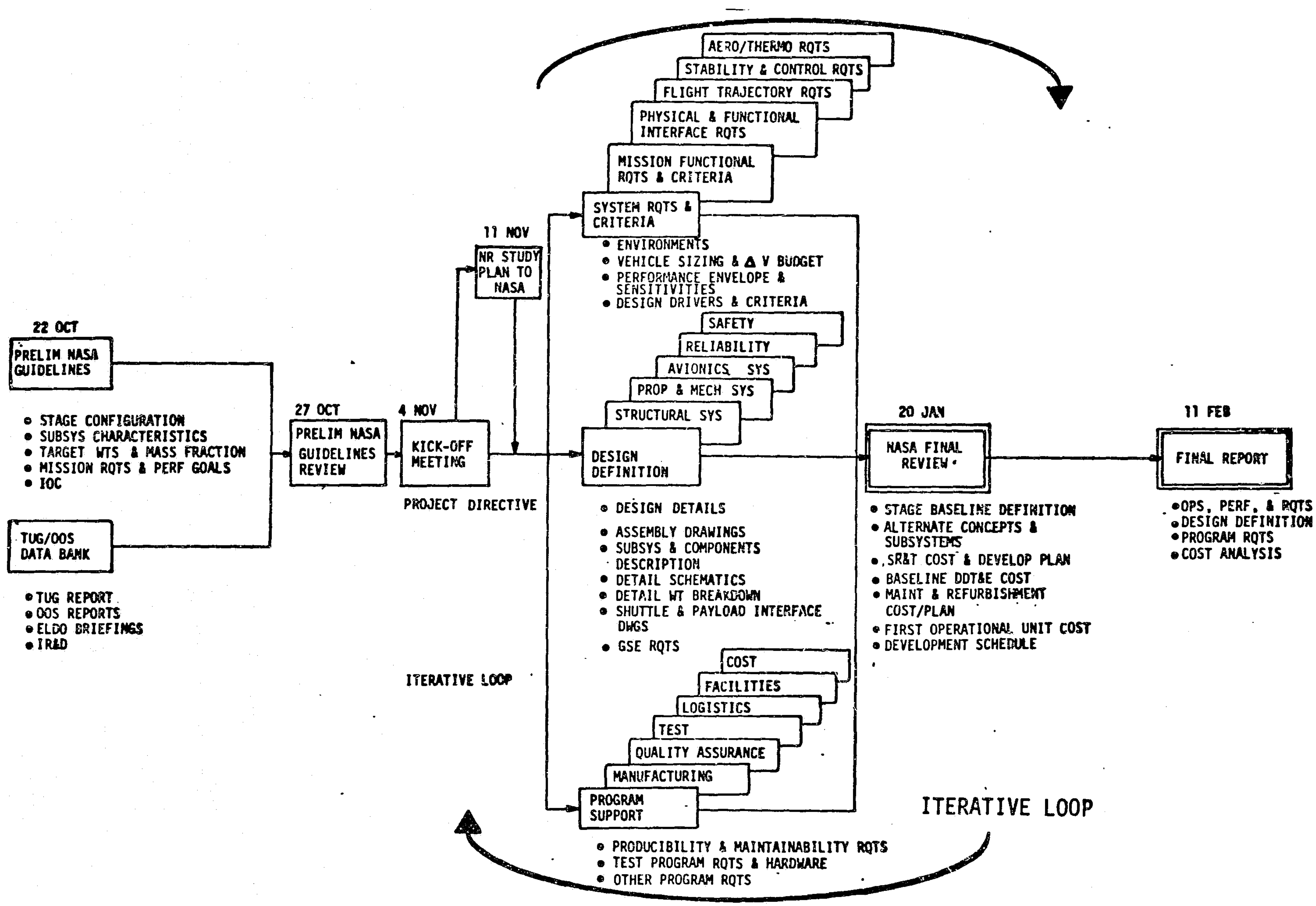

Figure 1.3-1 Top Level Study Logic

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1. Tug Point Design Study Plan, October 25, 1971, P.D. Office, Program Development, MSFC

2. RST Study, MSC - Pre-Phase A Study for an Analysis of a Reusable Space Tug, NAS9-10925; Report SD 71-291-1 through -6, 22 March 1971

3. NR OOS Study, SAMSO - Orbit-to-Orbit Shuttle (Chemical) Feasibility Study (OOS) Contract F04701-71-C-0171, 4 October 1971, SD 71-730-1 through -7; AF No. SAMSO-TR-71-238, Vol. I-VII

4. MDAC OOS Study SAMSO - Orbit-to-Orbit Shuttle (Chemical) Feasibility Study, Contract F04701-71-C-0173, SAMSO-TR-71-221

5. European Space Tug System (Pre-Phase A) - MBB Group: BAC, SNIAS, ELLIOTT, SELENIA, ETCA

6. European Space Tug System (Pre-Phase A) HSD Group: SLL, BELL, CAG, OSGMBH, ERNO, FIAT, FVW, SDD, SAEM, MSPA

2.0 STUDY GUIDELINES

This section highlights those elements of the NASA Study Plan (Reference 1) which were most influential in directing the NR effort toward the achievement of the aforementioned objectives.

2.1 KEY ASSUMPTIONS AND GUIDELINES

The items listed below provided the key design and operational drivers for the Tug:

1. 1976 Materials and Concepts Technology
2. Unmanned Design, Fail-Safe Operation
3. Reusable - Lifetime of 20 Missions
4. Ground-Based - Refurbishment After Each Mission
5. 6-Day on Orbit Stay Time Unattached to Shuttle
6. Flight Between 100 n mi Circular, 28.5 degrees inclination and geosynchronous orbit
7. Payload Deliver/Retrieve Mixes in Pounds

Baseline	3K/3K	
Alternates	0/4.16K 8.06K/0	Sizes Outer Shell Structure

8. Abort From Orbit Only and Propellant Dump/Inerting From Cargo Bay
9. Integrated Main Propulsion Subsystem and Auxiliary Propulsion Subsystem

Low vehicle weight was a key design criterion due to the aforementioned performance objectives. Therefore, strong emphasis was given to the use of advanced materials and concepts deemed part of the 1976 technology base, but achievable without incurring severe cost penalties or high development risks. Fail-safe (FS) operations also provide for lower weight due to redundancy limitations (compared to the more demanding FO/FS requirements as employed in the OOS studies). However, FS does necessitate the highest practical component reliability to achieve an acceptable (over 0.9) mission success probability. Fail-safe is defined here as no failure modes which would cause an unsafe situation for the Shuttle or its crew, or destruction of the Tug payload. In the event of mission abort (limited to abort from orbit) while the Tug is still in the cargo bay, propellant dumping, tank inerting, and subsystems safing are required. These capabilities also are specified for normal re-entry and landing conditions to minimize hazards.

Unmanned design necessitates a high degree of subsystem/operational autonomy with ground support provided as emergency backup or when it yields weight and design simplicity advantages.

Reusability for 20 mission cycles (which may cover a period in excess of 3 years) can only be achieved in a practical cost-effective sense if airline-type servicing techniques are developed for Tug (as is planned for Shuttle). Strong attention must be given to assure a design compatible with this approach (accessibility, ease of inspection, and checkout).

The six-day orbital stay time affects cryogenic tankage protection and the total space exposure (for 20 missions) specifies meteoroid shielding requirements.

The baseline (3000 pound round trip) payload capability represents the most demanding from a performance (mass fraction) viewpoint. However, normal Shuttle ascent and descent carrying the Tug and the alternate payloads were employed to size the Tug outer shell structure, based on the flight load factors provided by MSFC for the study.

One additional assumption agreed to between MSFC and NR, use of an integrated LOX/LH_2 propellant system for both main and auxiliary propulsion, provides design simplicity as well as weight and performance advantages.

2.2 TUG BASELINE CONCEPT

The NASA baseline configuration (Figure 2.2-1) which served as the starting point for this study is a single stage orbital propulsion system. It is limited to a maximum overall diameter of 15 feet and a maximum length of 35 feet, including Shuttle/Tug and Payload/Tug docking mechanisms. This vehicle is intended to separate from the Shuttle in orbit at 100 n mi/ 28.5 degrees inclination with a 3000-pound payload (15 ft x 25 ft) attached, ascend to geosynchronous orbit, deploy the up payload, retrieve a 3000-pound payload within 6000 n mi of the deployed payload, return to the near-vicinity of the Shuttle, redock, and return to earth. Payload center-of-gravity was defined as being at the geometric center of the 15 x 25 feet payload envelope.

The Tug has a non-integral tankage arrangement and is sized for a total propellant capacity of 56,394 pounds including 350 pounds of reserve plus allocations for reaction control/auxiliary propulsion (APS), fuel cell, residuals, and losses. The LH_2 tank has hemispherical bulkheads and a cylindrical section, whereas the LOX tank consists of two ellipsoidal bulkheads.

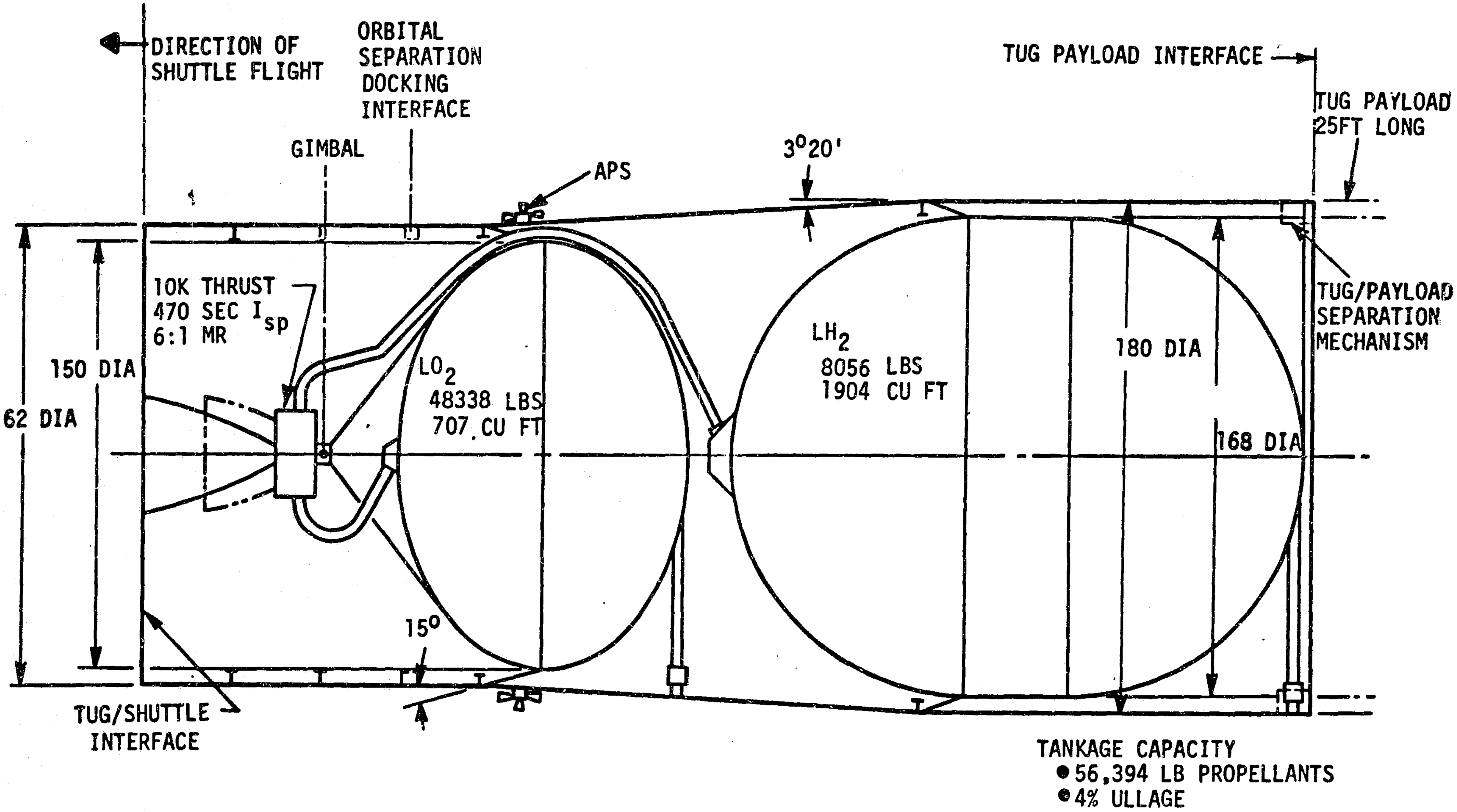

Figure 2.2-1 NASA Tug Baseline Concept & Sizing

The docking systems are designed such that the active portion is left with the Tug in the Tug/payload interface and with the Shuttle in the Tug/Shuttle interface.

Other pertinent features are indicated on the profile. It should be noted that the Tug is attached at its aft end to the forward part of the orbiter cargo bay and thus is transported between Earth and orbit in an inverted attitude.

2.3 TUG WEIGHT TARGETS

Table 2.3-1 lists the "bogey" weights provided by MSFC as design goals to assure meeting mass fraction requirements with the constraints of a 65000 pound Shuttle capability and a 3000 pound Tug payload. No specific allocation was made for Tug-supportive hardware and fluids which remain in the EOS cargo bay. Instead, these were assumed to be contained within structure and other subsystems.

TABLE 2.3-1. TUG BOGEY WEIGHTS

	WEIGHT (LB)
STRUCTURE	2,552
THERMAL CONTROL	476
AVIONICS	1,011
PROPULSION	1,057
DRY WEIGHT	5,096
10% CONTINGENCY	510
NON-USABLE FLUIDS	842*
BURNOUT WEIGHT	6,448
USABLE MAIN ENGINE PROPELLANT	55,148
USABLE APS PROPELLANT	404
MISC FLUIDS & LOSSES	--
TUG FLIGHT WT AT TUG/EOS SEPARATION	62,000
EOS PAYLOAD - CHARGEABLE INTERFACE PROV	--
TUG GROSS WT AT EOS LIFTOFF	62,000
GROSS EOS PAYLOAD AT LIFTOFF	65,000
MASS FRACTION, λ	0.895

*INCL. 350 LB PROP RESERVE

Structure includes all dry structure (docking mechanisms, meteoroid shield, outer shell, supports, thrust structure) and tankage subsystems. Thermal control includes cryogenic insulation, avionics cooling/heating hardware, and purge systems. Avionics contains GN&C, communications, data management, power generation and distribution, rendezvous and docking, and Tug electrical interfaces for ground and Shuttle and provisions for on-board checkout. Propulsion includes dry main engine, propellant feed, pressurization, fill/drain and vent/purge umbilicals, propellant dump, tank baffles/screens, APS thrusters/feed system/tanks, main engine actuators, and ullage venting control.

Non-usable fluids include propellant reserves, pressurant, thermal control fluids, and residuals. The main engine propellant bogey weight contains all propellant burned by the main engine during a nominal mission. APS propellant includes all burned attitude control and small delta-V translational maneuver requirements during a nominal mission. The miscellaneous fluids category contains all other unburned fluids (fuel cell, reactants, and vent/childown/start-stop losses). These have been numerically lumped together with non-usable fluids in the bogey weight table.

3.0 BASELINE DESIGN/PROGRAM

The Space Tug, as the upper stage of the Space Transportation System, must accommodate many elements which are normally not considered by an upper stage design. Many of these requirements stem from the vehicle reusability and mission profile. Employing the baseline Tug concept, flight mode and study guidelines described earlier (including use of a 65,000 pound Shuttle delivery capability) NR has demonstrated that a system can be designed to meet the target performance goals. The depth of design analysis, supported by programmatic considerations such as producibility confirms that use of advanced materials and concepts affords a sufficient payload margin to permit consideration of greater redundancy for improved reliability. It would also allow reduction in SR&T and development requirements thereby lowering program costs and risk. Furthermore, preliminary investigations have indicated a number of potentially attractive flight mode and design alternatives warranting further consideration.

The guidelines target goal of a late 1979 IOC (allowing just over four years for Phase D) appears to require an accelerated manufacturing and test program which could raise development costs substantially. A "normal" one-shift work program covering a period of five years yielded a one-year IOC delay. However, first flight test occurs in mid-1980 and could carry a useful payload.

An output of this study was definition of technology requirements to achieve the predicated 1976 technology base. The estimated cost of Tug-unique activities is almost $9M, excluding currently funded efforts (advanced LOX/LH_2 main engine, auxiliary propulsion system, laser radar, etc.) as well as pertinent research not directed toward specific applications in materials, multilayer insulation, avionics, etc.

3.1 BASELINE CONFIGURATION

The baseline configuration as shown in Figures 3.1-1 and 3.1-2 is comprised of a shell structure which supports the propellant tanks, the engine system, avionics equipment, and thermal control. The structure has been designed with a multi-purpose function to minimize weight. For example, the outer shell provides the primary load path, and also functions as a purge bag and meteoroid shield. Purge bag/meteoroid shields are also provided at the forward end of the forward skirt and at the aft end integrated with the thrust structure. Eight panels of avionics equipment are located forward of this barrier in the forward skirt providing ready access from the forward end of the Tug. Four avionics panels, are also provided in the aft skirt. The equipment mounted on the latter location includes the fuel cell, and associated coolant pump and controls. The coolant is manifolded to four radiator panels located on the aft skirt outer skin 90 degrees apart. As in the forward end of

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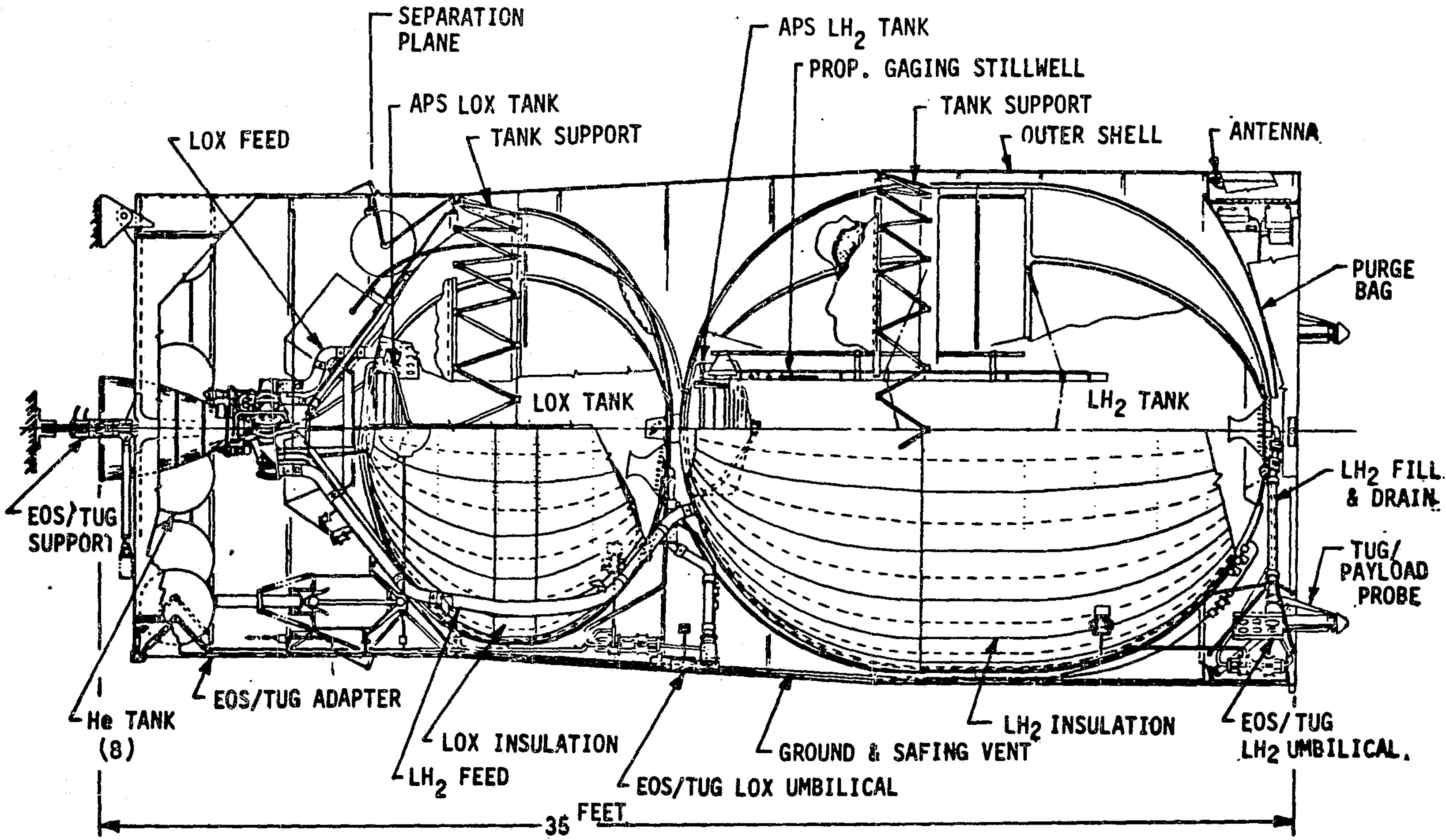


Figure 3.1-1 Tug Point Design Inboard Profile

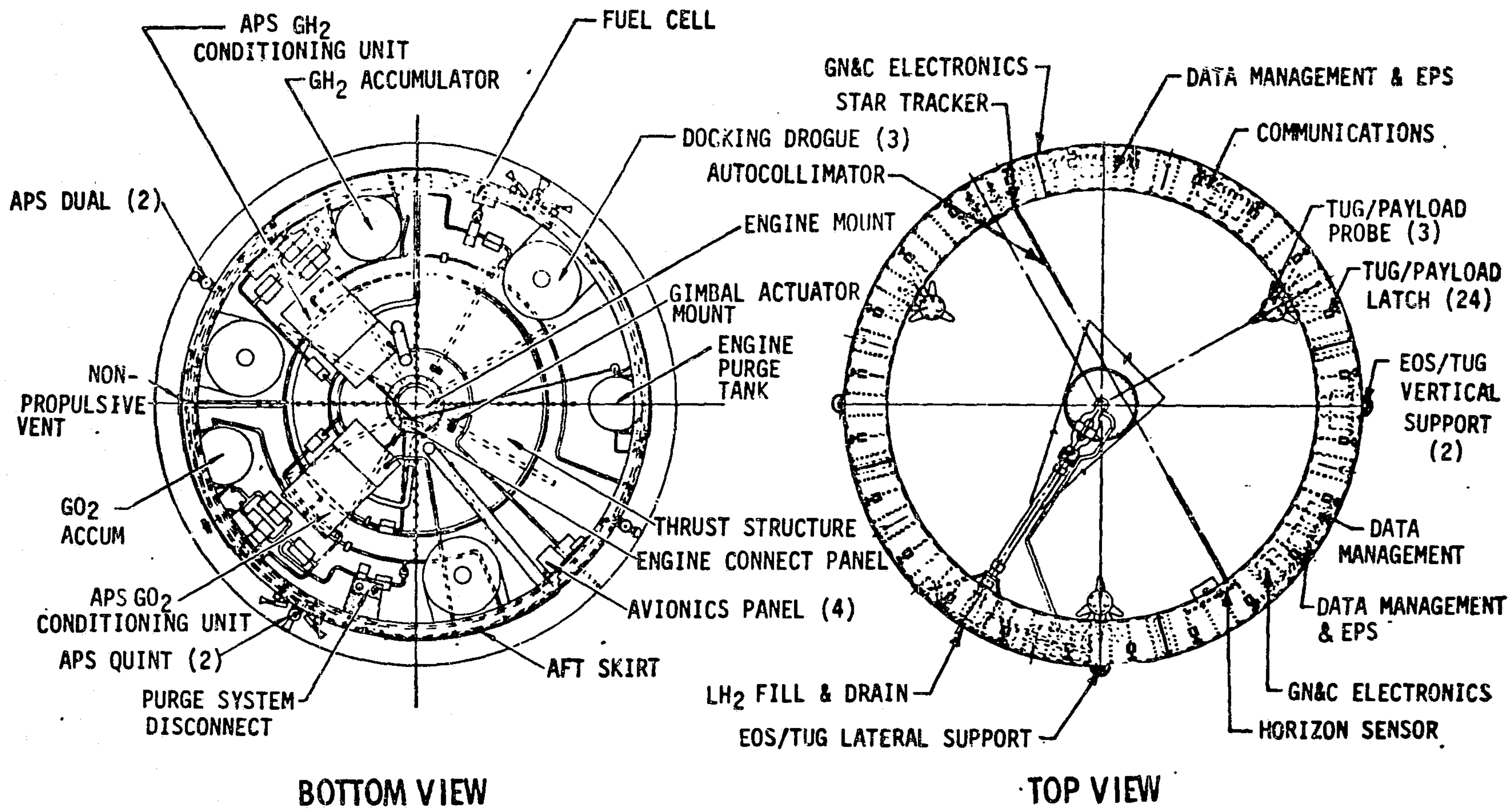


Figure 3.1-2 Tug Point Design Inboard Profile (Cont)

the vehicle, the equipment is mounted outside of the purge bag/meteoroid shield to facilitate maintenance during ground operations.

Two five-engine (quints) and two two-engine (duads) APS modules are mounted on the outer surface of the aft skirt between the radiator panels. The two quints positioned 180 degrees apart are located on the Tug Z-Z axis and the duads are located on the Y-Y axis. On the vicinity of the APS thrusters and attached to the thrust structure are the required propellant conditioning units and GOX and GH_2 accumulators which feed the APS, fuel cell, and are also used for main tanks prepressurization. The LOX and LH_2 for these functions is drawn from refillable auxiliary tanks installed on the aft bulkheads of the respective main tanks.

The Tug is attached to the Shuttle orbiter by a cylindrical shell which supports the Tug plus payload in an inverted position from the orbiter cargo bay forward bulkhead. This adapter provides the main structural attachment to the cargo bay, and in addition incorporates a deployment mechanism and docking system. The adapter also houses eight 6-cubic feet helium tanks for main tanks safing and insulation repressurization. For deployment of the Tug out of the orbiter cargo bay, an actuator driven pin system is used. Prior to deployment, the vehicle with its payload is released from the six orbiter-attach fittings. Following this, the actuator driven pin system is engaged at two places near the top of the Shuttle/Tug adapter. These pins provide the pivot point for rotational deployment. During the boost phase of the mission, the pivot pins are disengaged to avoid inducing loads into the structure and providing an intermittant load path. After release of the Shuttle/Tug forward umbilicals, the orbiter supplied deployment mechanism is actuated rotating the Tug approximately 90 degrees as shown in Figure 3.1-3.

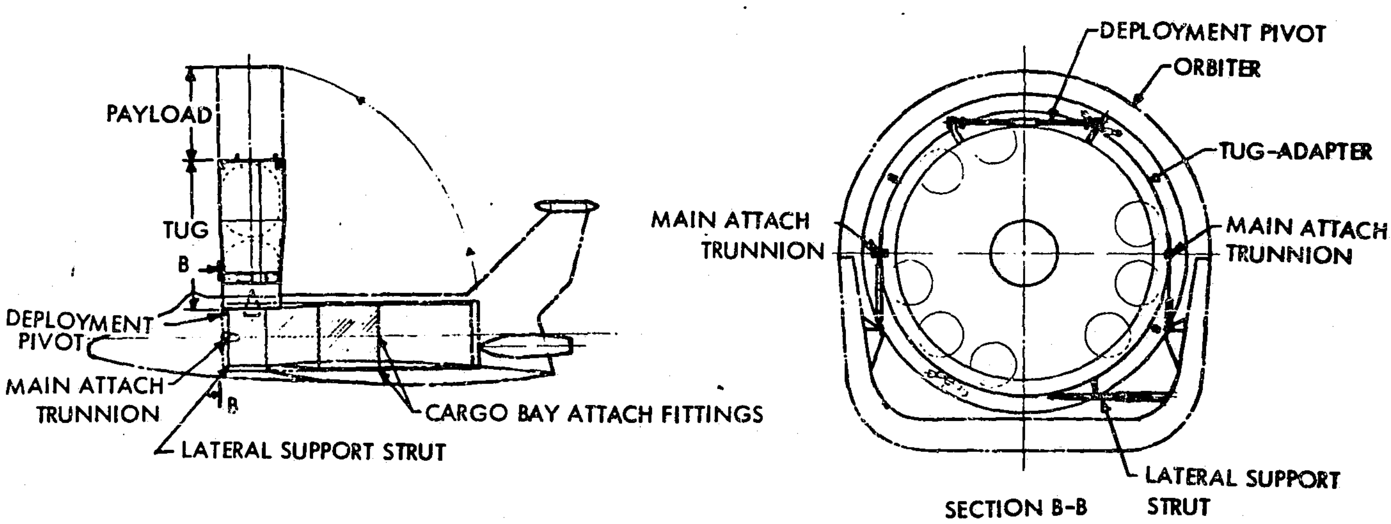


Figure 3.1-3 Tug Deployment Concept

Outer Shell and Shuttle Tug Adapter

The outer shell is a honeycomb sandwich structure comprised of a forward skirt, an intertank assembly, and an aft skirt. The aft adapter is of similar construction and provides for attachment of the Tug to the Shuttle orbiter.

Forward Skirt Assembly

The forward skirt assembly as shown in Figure 3.1-4 is a sandwich shell with an outer mold-line radius of 90 inches and a length of 147.5 in. Three stabilizing frames, a cargo bay frame (Station 452), and a docking support frame stabilize the shell. Attachment to the adjacent intertank shell is accomplished by using mechanical fasteners in a field joint of the shell at the LH_2 tank support frame (Station 304.5). Payload attachment is provided by 24 equally spaced latches located on the web of cargo bay attach frame. Three payload docking probes are also provided. Lateral support for the forward end of vehicle when attached to the Shuttle is accomplished by three fittings located on the outer surface of the shell at Station 452.

The primary function of the shell is to react body loads and moments. Secondary functions include purge bag support, micrometeoroid protection for the LH_2 tank and internal system hardware and equipment support.

The sandwich shell consists of two high strength graphite epoxy face sheets secondarily bonded to 3/8 inch thick 2.2 lb/ft^3 density aluminum honeycomb. These face sheets are laminates of four layers of material oriented to

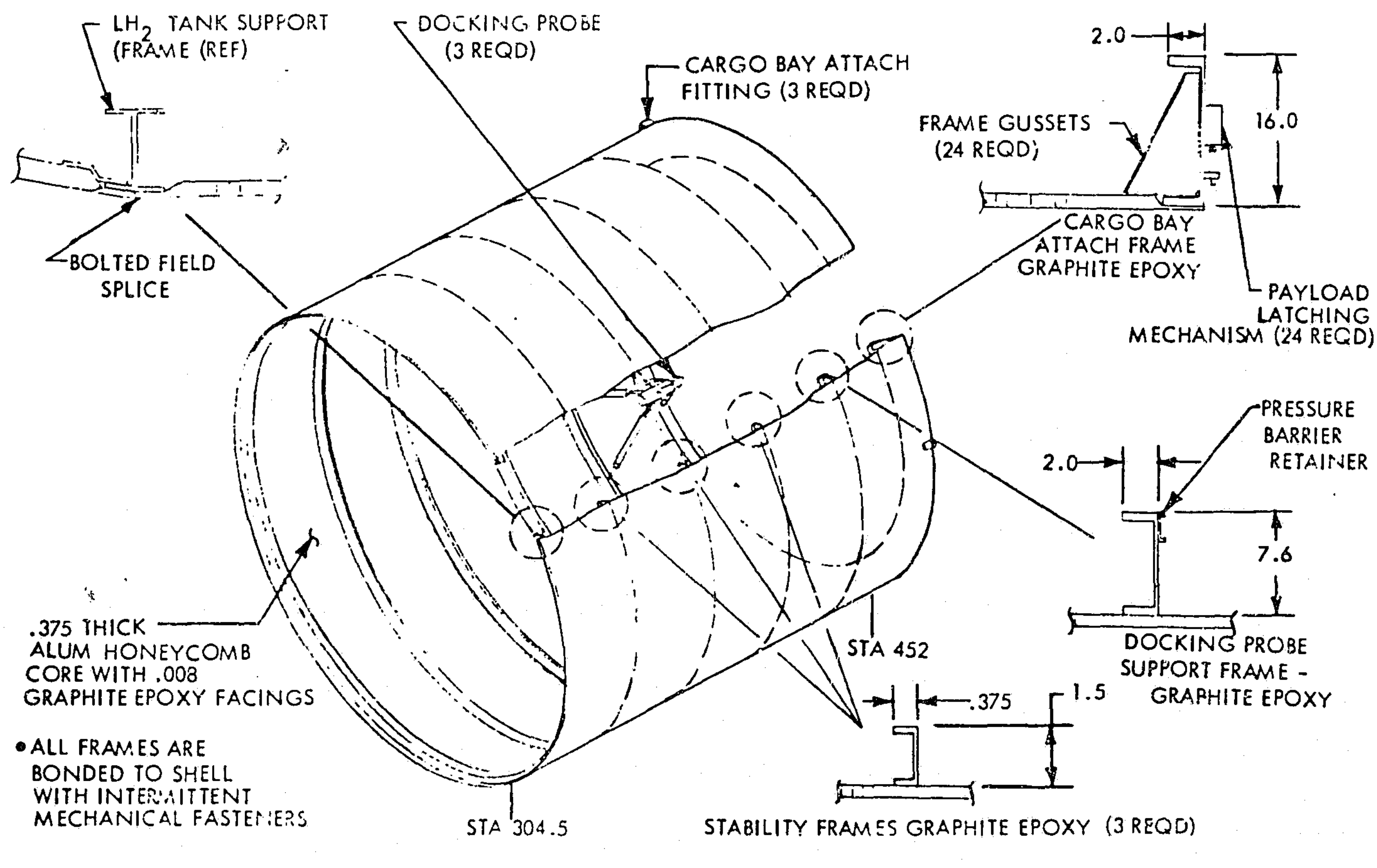


Figure 3.1-4 Forward Skirt Assembly

provide isotropic properties. This pattern produces the shear and circumferential stiffnesses needed for compressive load reaction, as well as the longitudinal shell rigidity. A minimum gage graphite epoxy material of 2 mil/ply is used. Thus, the design employs 8-mil thick face sheets.

All frames are laminates of graphite epoxy for minimum weight and thermal compatibility with the shell. Webs and caps are integrally cured to produce the required section. Web composite material is arranged at 45 degree angles to the frame axis for maximum shear rigidity and strength. Cap composite layers are positioned in the axis direction for maximum frame flexural modulus. The frames are formed in sections and secondarily bonded to the shell sectors. Mechanical fasteners are also used to attach the frame to the shell in order to eliminate peel.

Cutouts in the honeycomb panels are provided for antennas, an umbilical connection, and for the star tracker, horizon tracker, and laser installations. Reinforcement around the cutouts is provided by adding extra plies to the facing honeycomb sheets and, for the larger cutouts, channel shaped intercostals on each side running between frames.

Avionics equipment is mounted on 8 rectangular, aluminum honeycomb panels which are supported in the forward skirt between the two forwardmost ring frames.

To contain purge gas inside the structural shell around the LH_2 and LOX tanks a spherically contoured diaphragm of rubber impregnated glass cloth is attached near the inboard cap of the second aft ring frame. This diaphragm also serves as a meteoroid barrier. The LH_2 fill and drain line passes through a sealed, elliptical cutout in the diaphragm.

All equipment is located forward of the pressure barrier and access is from the open, forward end of the Tug. An umbilical connection of the Tug to the orbiter cargo bay is located in the forward skirt for the LH_2 fill and drain line and pressurization and electrical lines.

Intertank Assembly

The intertank assembly as shown in Figure 3.1-5 is a 148.5-in. long cone frustrum that spans between the 90-in. radius forward skirt and the 81-in. radius aft skirt. The shell is a sandwich with graphite epoxy face sheets and 0.7-inch thick aluminum honeycomb core. It has three stabilizing frames and a major frame at each end. The aft and forward end frames support the LOX and LH_2 tanks, respectively. They also supply a flange for the splice of the intertank shell to adjacent shell components. A 30 x 30 inch, non-structural door provides access to the interior of the shell. The intertank shell reacts body loads, acts as purge bag, and provides micro-meteoroid protection for the two cryogenic tanks.

The sandwich shell has two 8-mil thick high strength, graphite epoxy face sheets. These face sheets are four-layer laminates of composite, arranged in an isotropic pattern. Isotropic composite doublers are used in close-out

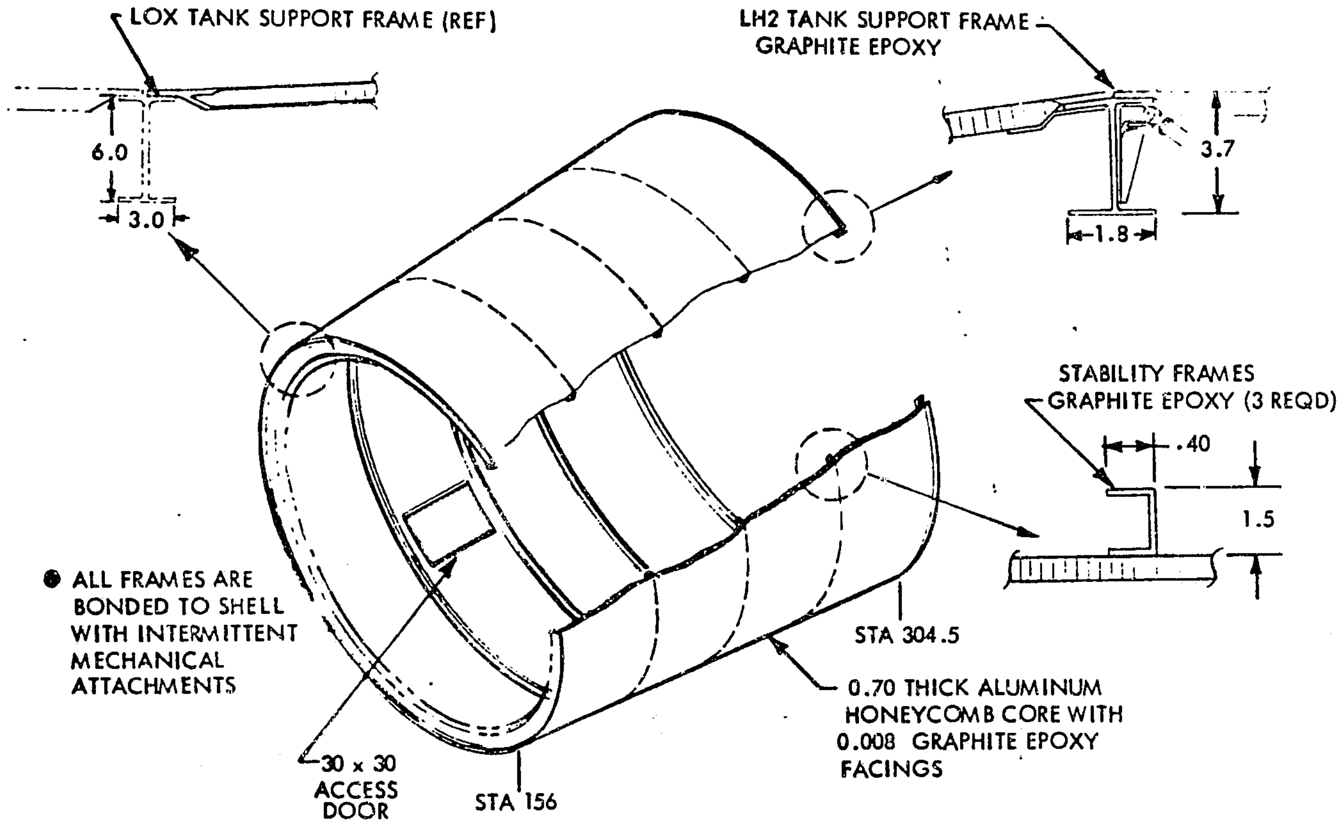


Figure 3.1-5 Intertank Shell

positions for performance in areas of discontinuity and for bolt bearing. Aluminum honeycomb (2.2 lb/ft^3 density) is secondarily bonded to the face sheets.

Stability frames were sized by shell support requirements and the tank support frame dimensions were defined by tank strut loads. All frames employ graphite epoxy for weight minimization and thermal compatibility with the shell. The web and caps are integrally cured to produce the required section.

A 30 by 30 inch door is provided in the shell structure for inspection access and installation of systems. The opening in the shell is reinforced by a close out channel and a graphite epoxy angle around the entire cut out.

Aft Skirt Assembly

The aft skirt assembly as shown in Figure 3.1-6 is a short cylinder - 81 inch radius and 30 inch long. This cylinder reacts body loads in the shell from the Tug and the Shuttle adapter interface (Station 126) to the LOX tank support frame (Station 156). The shell is joined to the LOX tank support frame and the intertank shell by a field joint. A series of 24 latches are provided at the aft end for coupling to the Shuttle Tug adapter. These latch mechanisms have been recessed into the honeycomb sandwich shell to minimize discontinuity bending moments.

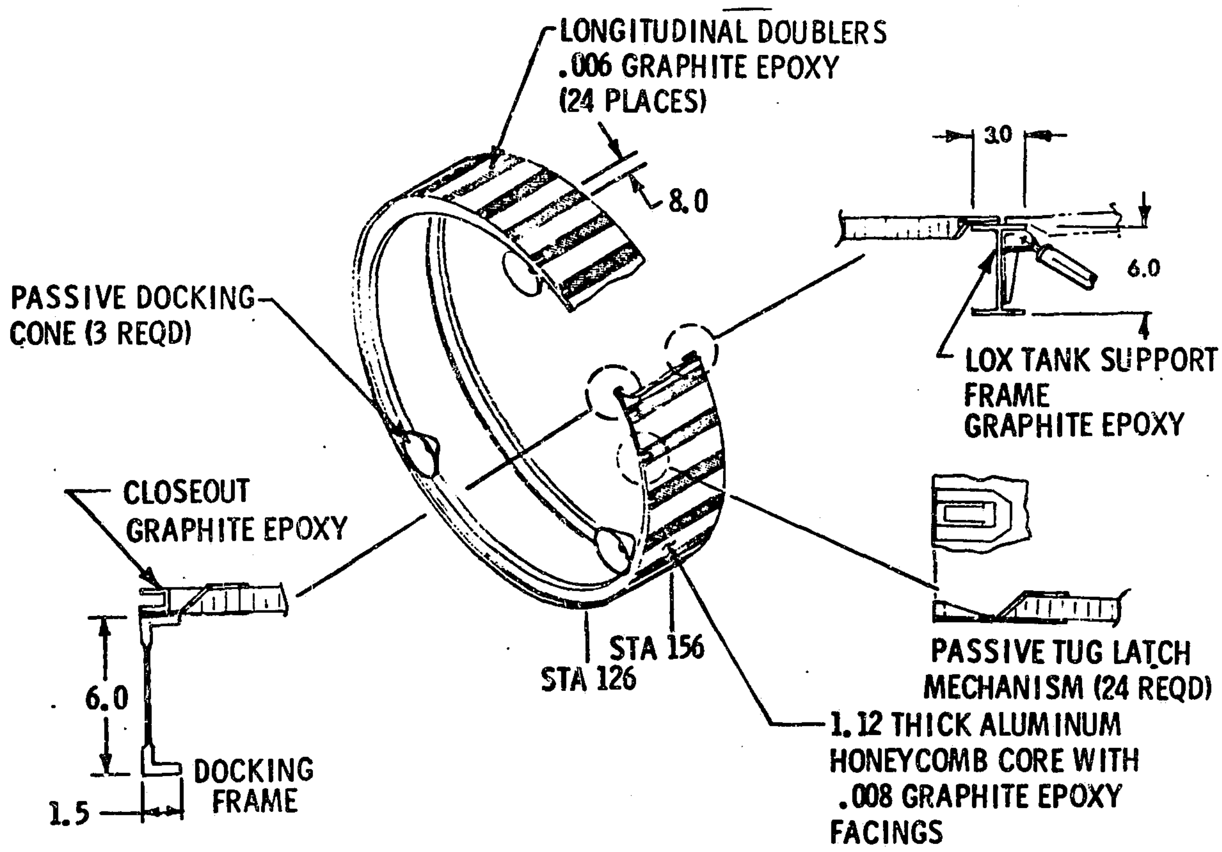


Figure 3.1-6 AFT Skirt Assembly

The cylindrical shell is of a sandwich construction with graphite epoxy skins and 1.12 in. thick aluminum honeycomb core (2.2 lb/ft^3 density). The four layers next to the honeycomb are uniformly distributed over the total area of the shell. They are arranged in an isotropic pattern to provide off-axis rigidity. Local thickened longitudinal areas that act as longerons, provide a direct load path between the 24 latches and the 24 LOX tank support points. The honeycomb is pinched close at the field joint and is closed out by a graphite epoxy "C" channel at the docking end.

The docking frame was sized by the latch moments. It is fabricated from graphite epoxy material. This frame also supports aft mounted equipment such as docking cone and radiators.

Shuttle/Tug Adapter

The Shuttle/Tug adapter assembly provides for attachment of the aft end of the Space Tug to the Shuttle. The adapter as shown in Figure 3.1-7 incorporates two major fittings for the total axial support of the Tug and lateral support in one direction. A third fitting reacts the lateral loads in the second direction. Concentrated loads are sheared into the shell from titanium longerons to 24, equally spaced support ring-to-Tug latches. Load redundancy is minimized in this support approach by the use of load equalizers on the aft trunion fittings. The 81 inch radius, 81 inch long cylindrical shell is a honeycomb sandwich structure with internal frames. Bottles for the storage of helium purge gases are located within the shell supported by glass/epoxy struts. Docking probe housings are supported at Sta's 99 and 126 by glass/epoxy struts and aluminum shear web gussets.

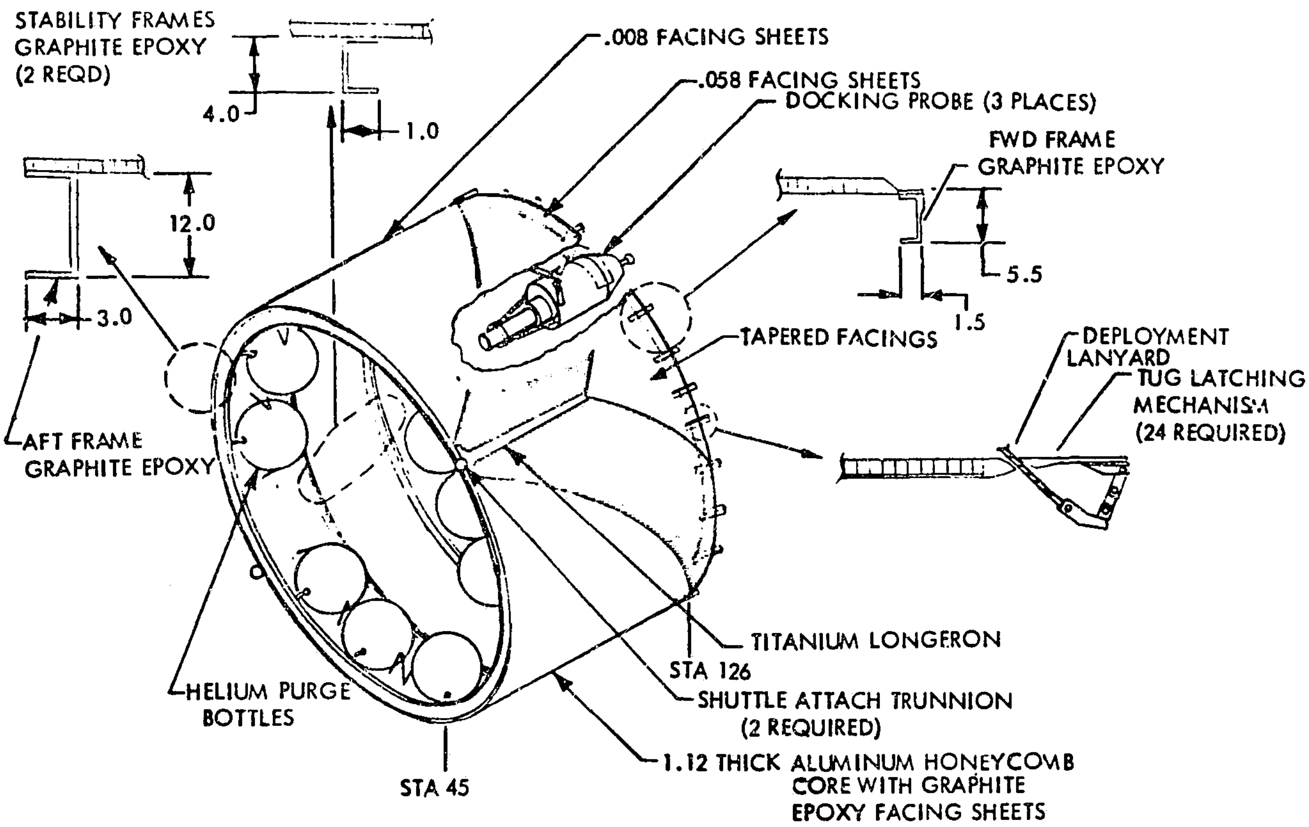


Figure 3.1-7 Shuttle/Tug Adapter

Graphite epoxy laminates are used for the face sheets of the sandwich shell. These face sheets are divided into three areas - an area of high shear rigidity for local distribution, and minimum shear rigidity for minimization of internal loads, and an area for transition from the high shear area to the latch station. The first area contains layers of composite arranged in patterns at 45 degrees to the cylinder axis. These layers are bonded to the titanium longerons in step-lap joints. The thickness of each face sheet in this area is 0.058 in. The second area uses isotropic face sheets of minimum gage graphite epoxy (8 mil per face sheet). The third area thickness tapers in a longitudinal direction from 0.058 in. to 0.010 in. Aluminum honeycomb 1.12 in. thick is used for the sandwich core.

The frames are graphite epoxy laminates. These frames consist of two stability frames, a 12 inch deep frame at Station 45 and a 6.0 in. deep frame at Station 126. The frame at Station 45 was sized by the shell rigidity requirements. The other major frame was sized by latch kick loads.

Docking Subsystems

The docking subsystems must be developed to operate within guidance and control parameters and must accommodate desired docking situations with low probability of damage. The two docking subsystems shown in Figures 3.1-8 are of the probe-drogue type.

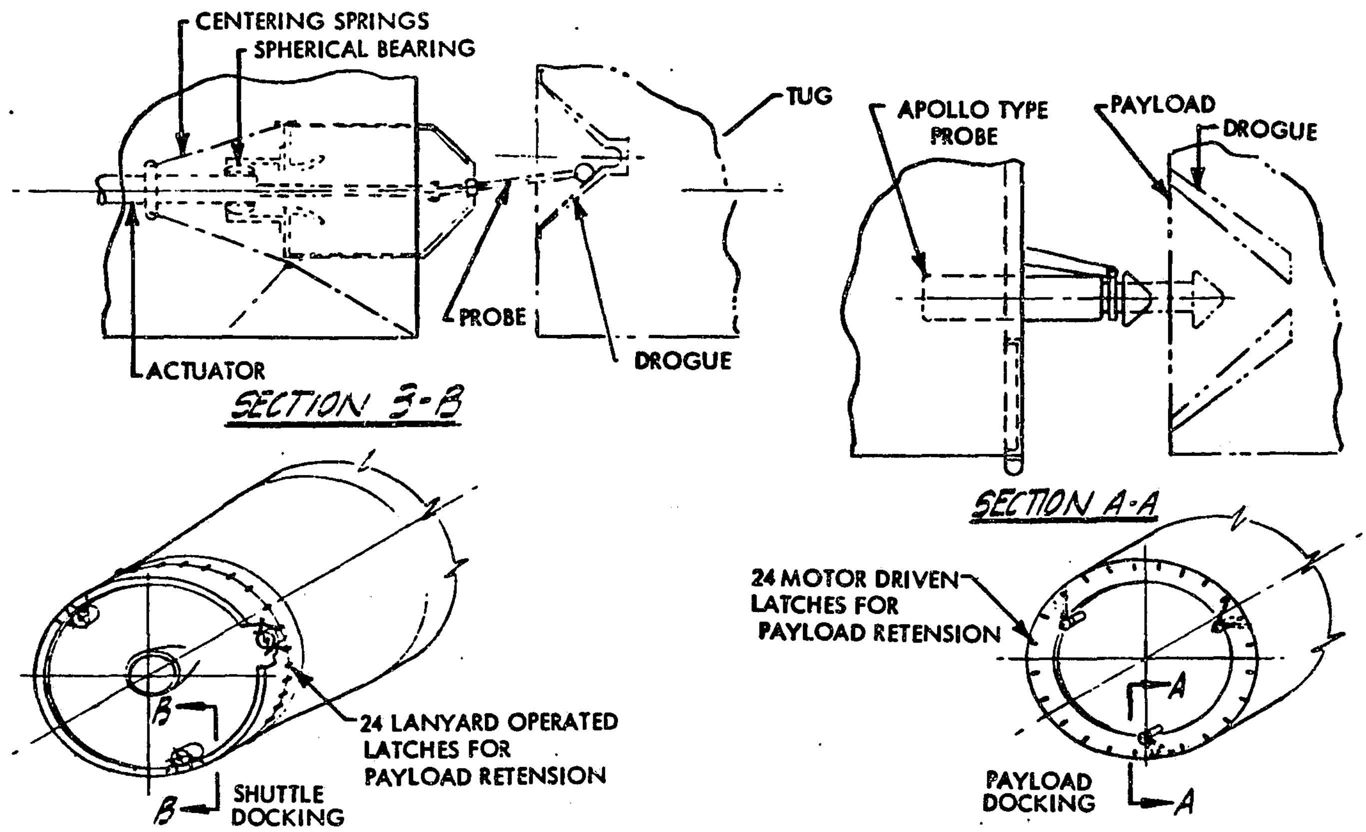


Figure 3.1-8 Docking Subsystems

For the Tug/payload docking, three Apollo type probes are extended to engage payload mounted drogues. Retraction of the probes draws the two interfaces together. Final latching is accomplished with the latching mechanisms spaced around the periphery of the forward interface. A latch is located at each 15° interval to assure uniform distribution of loading. The latching fingers are translated by gearing and are electrically actuated. Redundancy could be obtained by use of dual, parallel drive motors or by use of override pyrotechnic devices.

For Tug/Shuttle docking, three actuated probes extend from the Shuttle-mounted adapter to engage drogue type recessed fittings mounted on the aft skirt of the Tug. When extended the probe arm is free to deflect laterally under slight pressure and to be guided into the drogue latch socket. As the three probes are retracted they are guided into a parallel axial alignment, orienting the Tug about all three axes. The final movement is parallel to the body centerline, snubbing the interface surface together. Twenty four latches are located externally around the perimeter of the interface. Sixteen of the 24 latches are folded away after initial deployment, leaving only eight independently-actuated latches for use in redocking and reentry with a dry Tug and payload. The Shuttle-mounted adapter system with the jointed probe allows initial engagement without translation of the vehicle mass. Alignment and mating of the interface surfaces is controlled by the probe mechanism. The Apollo type probe, while simpler and lighter in weight, requires proper alignment before the probes will engage.

Tankage and Supports

The main propellant tanks are monocoque construction and are supported from the outer shell by tubular struts. The thrust structure is attached to the LOX tank aft bulkhead.

The design ullage pressure for the LH_2 tank is 24 psia, which occurs during both Shuttle boost and Tug operation. Advantage is taken of the dual mode vent valve setting in the LOX tank during boost. The low mode setting of 16 psia during boost results in a lower total design pressure on the forward bulkhead and hence a lighter structure. The design ullage pressure for the LOX tank during orbital operation is 24 psia.

The design load factors reach a maximum at the Shuttle end boost condition and establish the critical loading for the forward bulkheads and tanks support structure. The fracture mechanics analytical procedure employed in the analysis include the combined effects on flaw growth taking into consideration temperature, material thickness, and stress level range over a 20 mission life. A cryogenic proof test is required to permit higher stress levels and thereby minimize the size of flaw that could remain in the tankage.

LH_2 Tank and Support System

The LH_2 tank as shown in Figure 3.1-9 is a cylindrical, 2014-T651 aluminum alloy tank 168 inches in diameter with hemispherical bulkheads at each end. Its volume is 1904 cubic feet with a capacity of 8056 pounds of LH_2 with 4 percent ullage. The end bulkheads consist of six preformed gores and a circular central section all butt-welded together. The main cylindrical section is made up of three sheets butt-welded together to form a cylinder which is then chem-milled to a thickness of 0.045 inches between weldlands. A heavier ring segment is welded between the aft bulkhead and the cylindrical section. This ring provides the thickness necessary to attach the strut support fitting. This heavy section also serves to distribute the loads introduced by the support struts. The end bulkheads are chem-milled to a thickness of 0.020 inches between weldlands. In certain areas, heavier bosses are welded to provide attach points for propellant feedlines, etc. The forward bulkhead has an access door located in the center of the circular section. The aft bulkhead has an identical size circular section with structural bosses. The refillable APS tank is mounted inside the LH_2 tank. It is located three inches off the tank center line and is supported one inch above the bottom of the tank on six pairs of legs welded on the inside of the gore weldlands.

The LH_2 tank is supported within the Tug shell structure by a series of 48 "S" glass filament wound composite tubular struts. The struts are attached to the LH_2 tank by fittings bolted to the heavy ring section at 15 degree intervals.

LOX Tank and Support System

The LOX tank as shown in Figure 3.1-10 is an ellipsoidal shaped structure consisting of welded 2014-T651 aluminum alloy bulkheads. The volume is 707 cubic feet with a capacity of 48,338 pounds with 4 percent ullage. Each

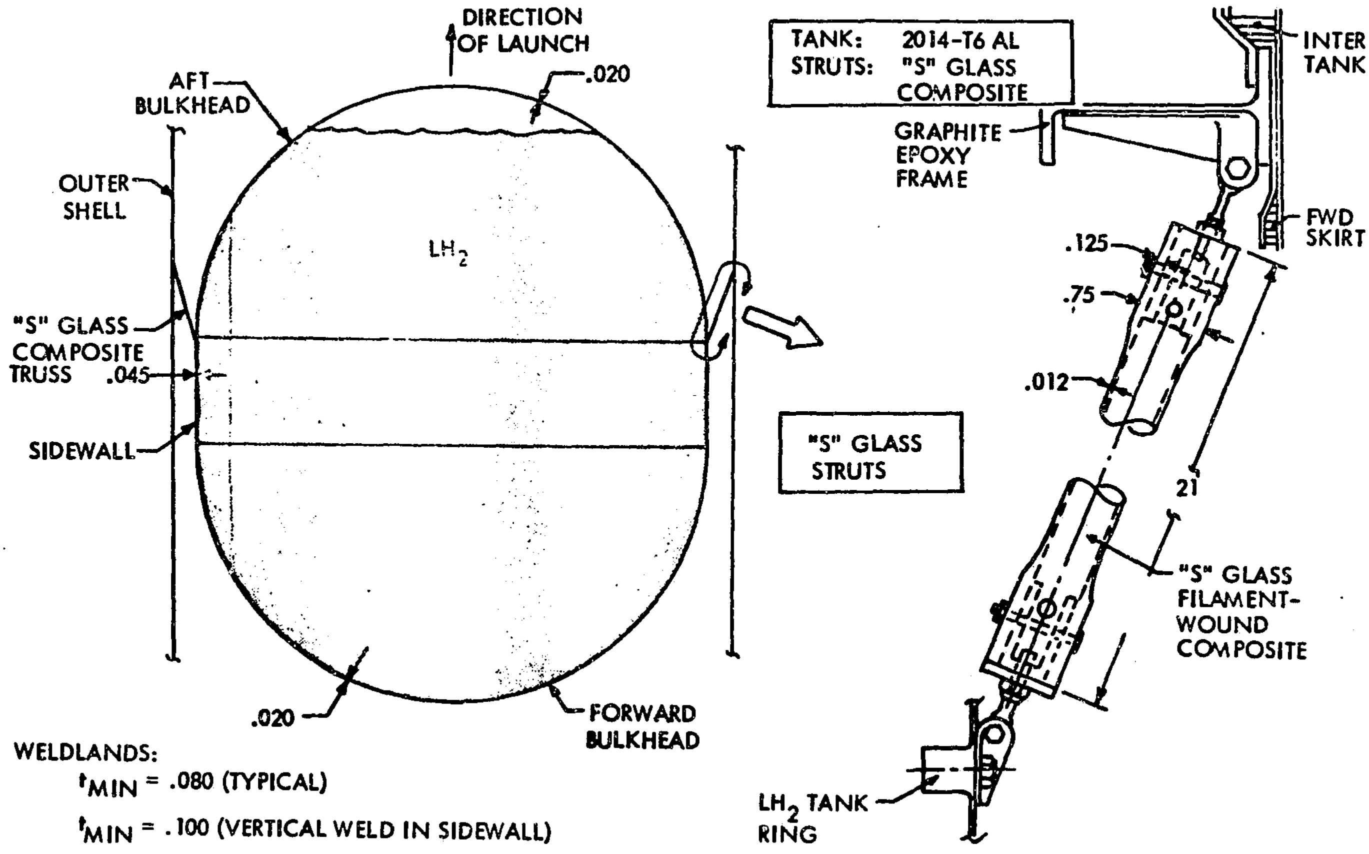


Figure 3.1-9 LH_2 Tank and Support Subsystem

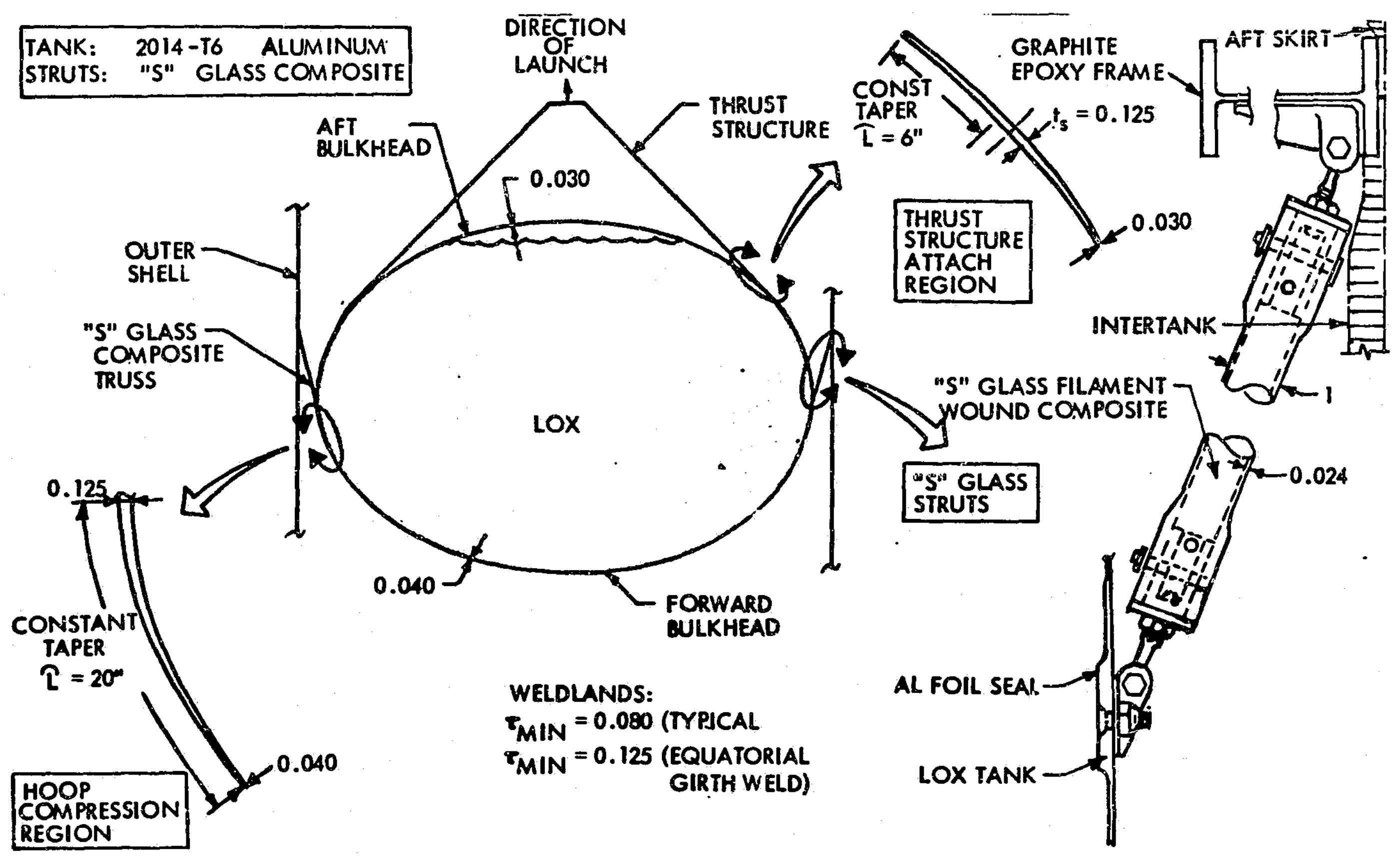


Figure 3.1-10 LOX Tank and Support Subsystem

bulkhead is manufactured from six preformed gores butt-welded together and joined at the apex by a circular section which is also butt-welded to the gores. The systems ports are incorporated into circular sections that are butt-welded into the apex circular section and individual gores. The forward and aft bulkheads are chem-milled to basic thicknesses of 0.040 and 0.030 respectively, between weldlands. A heavier section at the girth is required for hoop stability and stresses induced into the tank wall by the tank support struts. A heavier section, that bands the aft bulkhead, is required to distribute loads induced into the bulkhead by the thrust structure attachment. A 20 inch diameter access door is located in the forward bulkhead off center and 30 degrees off the Z-Z axis. This door provides access into the LOX tank for installation of equipment. Baffles are supported in the tank by lugs welded to the longitudinal weldlands at 12 locations. The refillable APS tank is mounted inside the LOX tank and is supported by six integral bosses which are machined into the aft bulkhead dollar weldland.

The LOX tank is supported within the Tug shell structure by a series of 48 "S" glass filament-wound composite, tubular struts. The struts are attached to the tank by fittings bolted to the heavy ring section at 15 degree intervals.

Thrust Structure Assembly

The thrust structure as shown in Figure 3.1-11 is a conical arrangement of frame-and skin-stabilized tubular struts attached to the LOX tank aft bulkhead. Its primary function is to react engine thrust loads. The struts are circular in cross-section with flats on the inboard and outboard sides for skin and frame attachment. Constructed of longitudinal boron and hoop graphite fiber reinforced epoxies, the struts utilize the high modulus and low thermal conductivity characteristics of the constituent materials. Glass reinforced epoxy end fittings bonded to each end further minimize heat transfer and provide for attachment to the LOX bulkhead and the aluminum thrust block fitting. Graphite epoxy frames are sized to support externally attached systems and to preclude general cone instability prior to local or general instability of the individual struts. Both frames are attached perpendicular to the cone surface for maximum efficiency. The forward frame is external to the structure due to proximity to the LOX tank bulkhead.

The maximum strut load is -2040 pounds (ultimate), and results from a 7 degree engine gimbal position. Because of its low stiffness, as compared to that of the struts, the skin carries less than 1% of the axial load. The skin is not considered effective when computing strut loads or strut column capabilities. It provides torsional stability to the structure and reacts the 0.28 psi (ultimate) design purge gas differential pressure, and acts as a meteoroid bumper.

The thrust cone struts and intermediate frames also provide back-up structure for engine systems equipment mounted on the cone. Equipment mounted on the structure includes two APS modules containing turbo-pumps, heat exchangers and gas generators, engine feedlines and engine actuators.

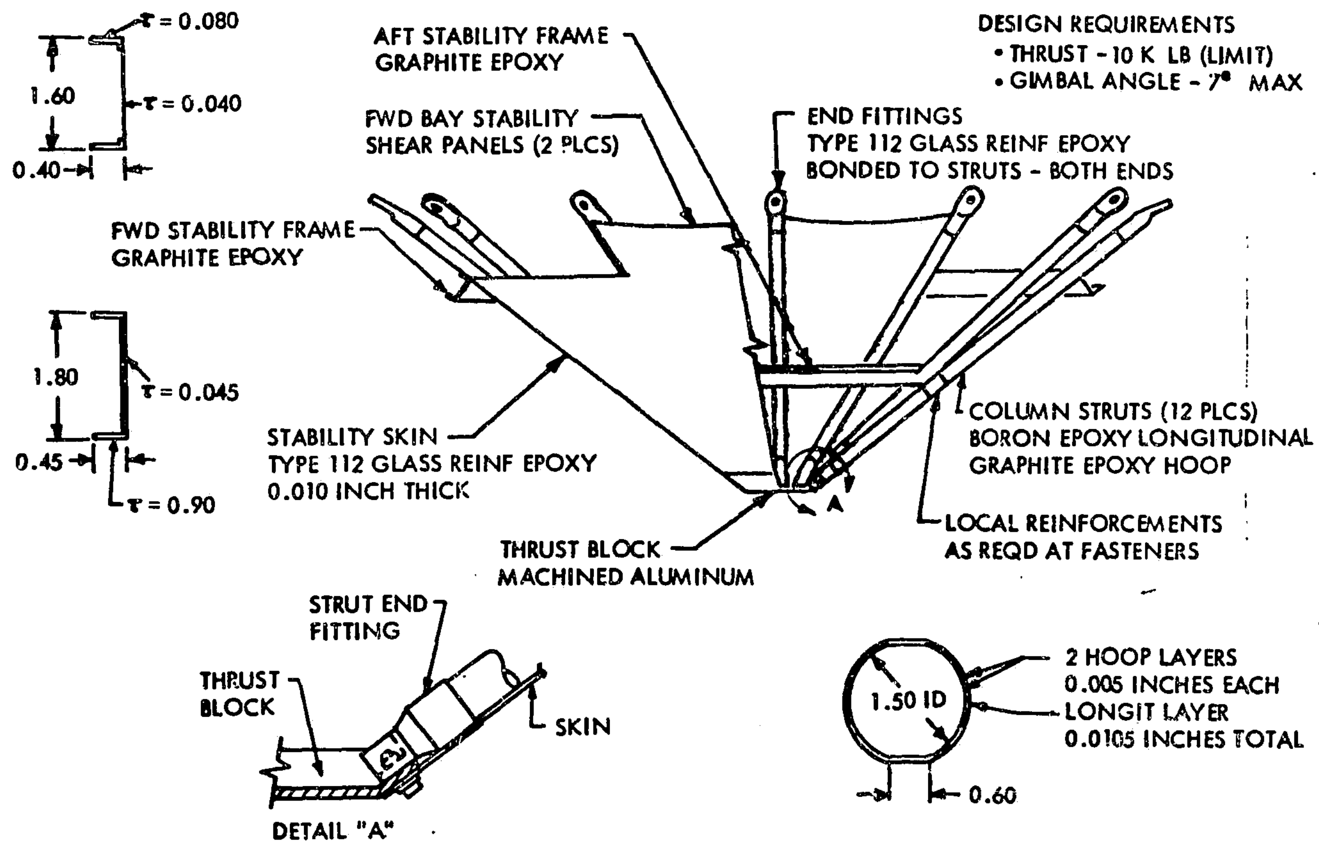


Figure 3.1-11 Thrust Structure Assembly

Detail "A" shows attachment of thrust structure to the thrust block. Bath tub type fittings are utilized to tie the struts to the thrust block. These bath tub fittings are required to provide local stability for the thrust block.

Thermal Protection

Heat transfer analyses were performed for the Tug while in the Shuttle cargo bay and in orbit. While in the cargo bay, the wall was assumed at temperatures specified in the Study Guidelines and heat transfer to the Tug is by convection and radiation. During the orbital mission the heating environment was applied directly to the Tug structural wall. Heat transfer to the propellant tanks is through the basic insulation system including support posts and penetration such as tank supports, fill and drain lines, and thrust structure. The engine feed lines are designed with thermodynamic vents to cool the lines and to preclude heat transfer between the lines and the tanks. The boiloff rates during ground hold satisfy the requirements of 10% per hour for LH_2 and 6% per hour for LOX. During boost the heat input into the tanks is absorbed in the propellant bulk. For the orbital mission, which includes the period between Tug ignition and redocking with the Shuttle, the equivalent boiloff rates resulting from heat leaks through the insulation, tank supports, fill and drain lines, and thrust structure are 1.27 pounds per hour including a 5% contingency factor.

Insulation Subsystem

A purged multi-layer insulation (MLI) system as depicted in Figure 3.1-12 was selected as the baseline for insulating the LH_2 and LOX tanks and the associated feedlines. The natural layup concept, which is under development by NR, was chosen on the basis of low installed weight and simplicity of manufacture and installation. Kapton was selected for the shield film due to its ability to withstand cargo bay temperatures during reentry. The shields are aluminized on one side to a thickness of approximately 300 angstroms, with a total hemispherical emissivity of 0.045 (max) to obtain the desired thermal properties. The shields are embossed to provide proper separation, and perforated to permit evacuation of entrapped gases. Each shield is 0.25 mil thick.

The design concept is the natural lay configuration, which allows the shields to drape smoothly over multi-contoured surfaces without external loads being induced at the attachments. The MLI is handled and installed in modules of five shields each. The total MLI thickness is 0.50 inch, consisting of 30 shields. A 1.0 inch purge plenum between the tank and the MLI affords even distribution of the purge gas flow. Aluminum wire mesh is used for the inner support of the MLI since it exhibits the same thermal contraction properties as the tanks. An outer support membrane, which restraints the MLI during purge, is made from "Nomex" fabric due to its high temperature resistance and excellent elongation properties.

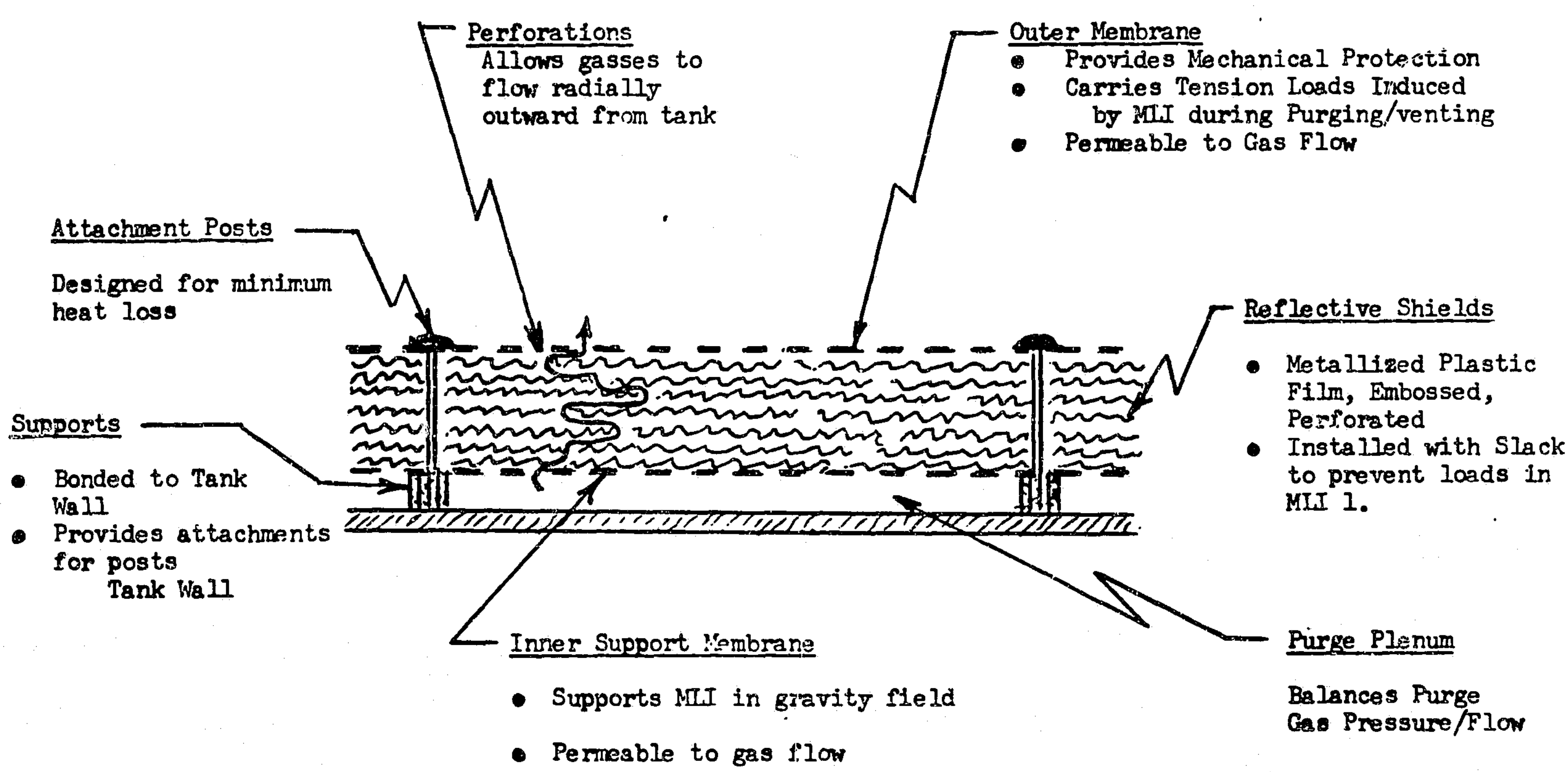


Figure 3.1-12 Multi-Layer Insulation Concept

Auxiliary systems will be provided on the ground to isolate the MLI from atmospheric contaminates such as moisture, chemicals, and condensable gases, and to remove moisture in the event of accidental intrusion.

The insulation installation on the LH_2 tank is divided into four sections: the forward access door segment; the aft dollar weld segment; the aft bulkhead segment which extends to the tank support struts; and the forward bulkhead and cylindrical section. The bulkheads and cylindrical sections are made up of 24 gores which are staggered when installed. The MLI is spaced 1 inch from the tank wall by foam filled honeycomb pads which are bonded directly to the tank wall. The LOX tank is also covered with MLI and is installed in the same manner as for the LH_2 tank.

The MLI system is protected from intruding atmospheric contaminates such as moisture, dust and chemicals by a ground supplied purge system. This system flows dry nitrogen or air into the Tug structure at a rate (estimated 10 SCFM) that will maintain positive internal pressure up to 0.1 maximum. Prior to loading cryogens the condensible nitrogen or air is flushed from the MLI by a helium purge. This purge is introduced into the plenum between the tank wall and the MLI and flows radially outward through the perforations in the reflective shields. The helium purge is continued throughout all cryogenic operations on the ground. Flow is channeled into the purged volume and into the plenum chamber by means of selector and isolation valves.

During boost the orbiter compartment pressure was assumed equivalent to ambient pressure for the flight altitude. Evacuation of residual purge gas to preclude overpressurization of the Tug structure is accomplished by vent valves. An aperture diameter of 5 inches has been computed for accomplishing this venting. Valves are left open during orbit operations to facilitate outgassing of materials. Two valves are included for redundancy. These valves are also interlocked by pressure switches to ensure the structure is not overpressurized and that the cryogenic tanks are not subjected to collapsing pressures.

During re-entry the Tug purge bag is repressurized with helium to match re-entry profile pressure. This precludes intrusion of atmospheric contaminates and also serves as a thermal short within the MLI to transfer heat from the outer reflective shields to the tank wall, thus minimizing shield temperature.

Incorporation of the purge plenum under the MLI provides a means for preconditioning the MLI or removing moisture. Tests at NR indicate that preconditioning will not be required if the system is protected in accordance with demonstrated specifications.

APS Impingement Thermal Protection Requirements

The location of the APS engine clusters on the aft skirt result in direct plume impingement on the graphite epoxy composite structural body of the Tug. The exhaust plumes from both the forward firing axial thrusters and side firing roll thrusters impinge on the Tug body. Also the plume from the aft facing thrusters impinges on the main engine. Plume impingement heating rates were predicted for the forward axial, roll, and aft thrusters. The heating rates along the forward axial thruster plume centerline are shown in the upper left of Figure 3.1-13. These rates represent the worst heating on the Tug structural wall. A temperature analysis was made for the uninsulated Tug wall to determine the areas where the allowable temperature of 350°F for the graphite epoxy wall would be exceeded. The areas which require protection are shown in the figure, and total about 46 square feet. Thermal protection requirements were determined from a thermal analysis conducted for an external insulation system utilizing dynaflex. Dynaflex was selected because it has a relatively low density with good insulating properties to approximately 2800°F. An analysis of the area of maximum heating indicated that a dynaflex thickness of 0.25 inches is required to maintain a maximum graphite epoxy wall temperature of 350°F. This thickness was assumed for all areas requiring protection. The temperature histories for this configuration are also shown in the figure.

A maximum temperature of 690°F was calculated for the main engine nozzle when exposed to the maximum APS plume impingement heat rate of one Btu/Ft^2-Sec. Current engine studies propose the use inconel or a similar steel material with dump cooling through axial channels. Such a design and material is predicted to tolerate temperatures to 750°F, and any resulting circumferential differential heating.

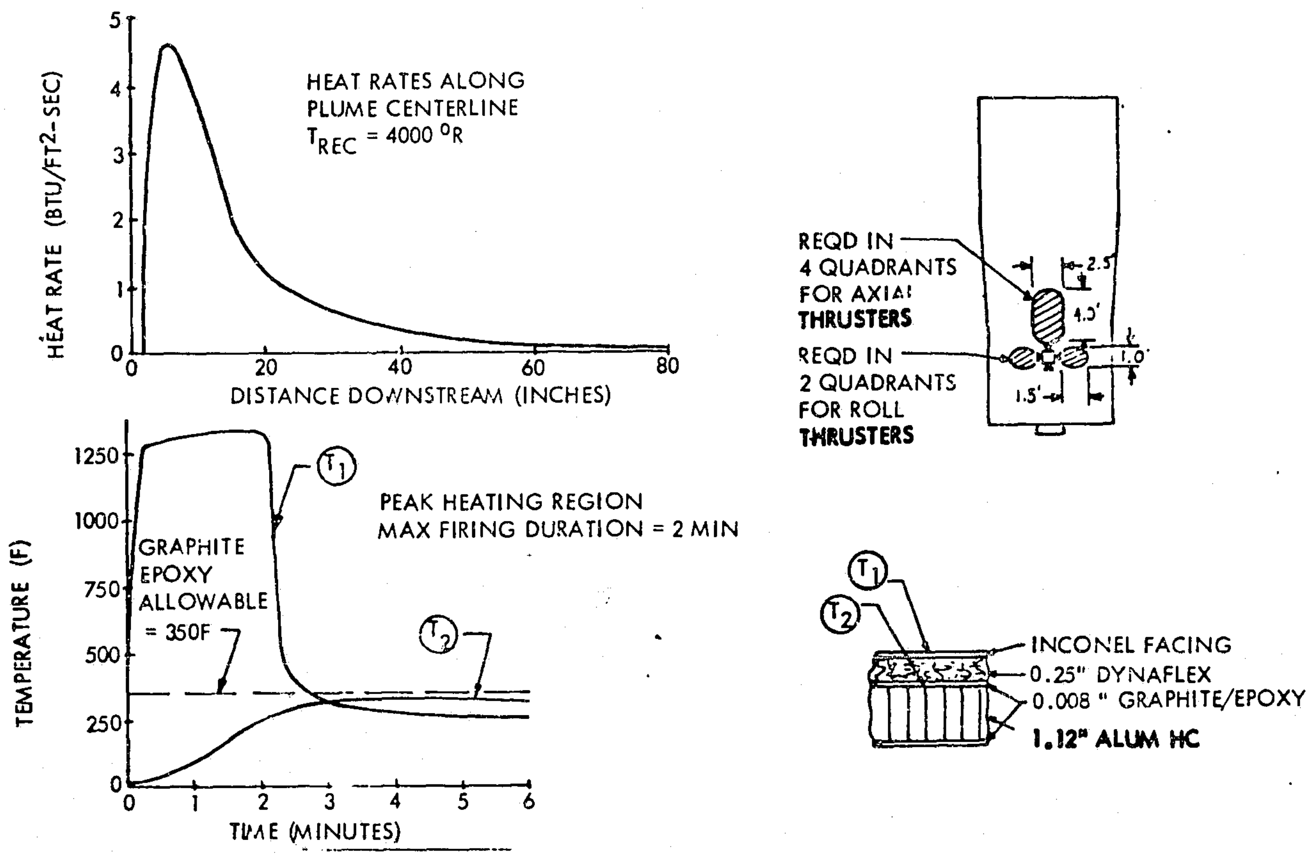


Figure 3.1-13 APS Impingement Thermal Protection Requirements

Meteoroid Protection

Current MSFC environment criteria for advanced spacecraft were used for the Tug meteoroid protection study. The properties of particles included a density of 0.5 gm/cc with velocities of 20 KM/Sec, representing cometary, average yearly flux. A design life of twenty 6.4-day round-trip geosynchronous missions was employed in the analysis. During each mission, 1.3 days were spent at 100 n mi and 5.1 days at 19,300 n mi.

Only failures due to tank damage were considered in the study. The design probability of no tank failure during its operating life was set at a minimum of 0.95. Twenty-five percent penetration of the tank wall was assumed acceptable. This value has been previously used in Apollo Service Module studies, where impact tests on pressurized tank sections have confirmed that greater damage is required to cause failure. This was confirmed by the fracture mechanic analysis performed for the Tug tankage design.

Earlier analyses by NR of Tug meteoroid protection concepts have indicated that only minimal protection is necessary to meet the design requirements, and that a single bumper shield will result in the minimum weight. To further minimize weight without compromising the system safety requirements, the approach taken was to utilize the outer shell and the insulation purge bag as a bumper, and to adjust the density and/or thickness of the thermal insulation to limit meteoroid penetration into the tanks. The damage resulting from meteoroid impact was then computed using a Discrete Particle Analysis computer program, which is based on discrete particle modeling of the impact process. Shielding characteristics were determined as follows: 1. The nominal design meteoroid corresponding to the criteria and the Tug surface area was computed. 2. The bumper thickness was determined so that the mass removed was at least 80 percent of the meteoroid mass. 3. Insulation was sized to satisfy the required survival probability. In the last step, the tanks were divided into several separate areas to account for variations in wall thickness.

The results of the analyses as shown in Figure 3.1-14 demonstrated that the insulation required for thermal protection together with the outer shell and the allowable penetration to the tank (without failure during the life of the vehicle) more than satisfy the design survival probability required for 20 missions.

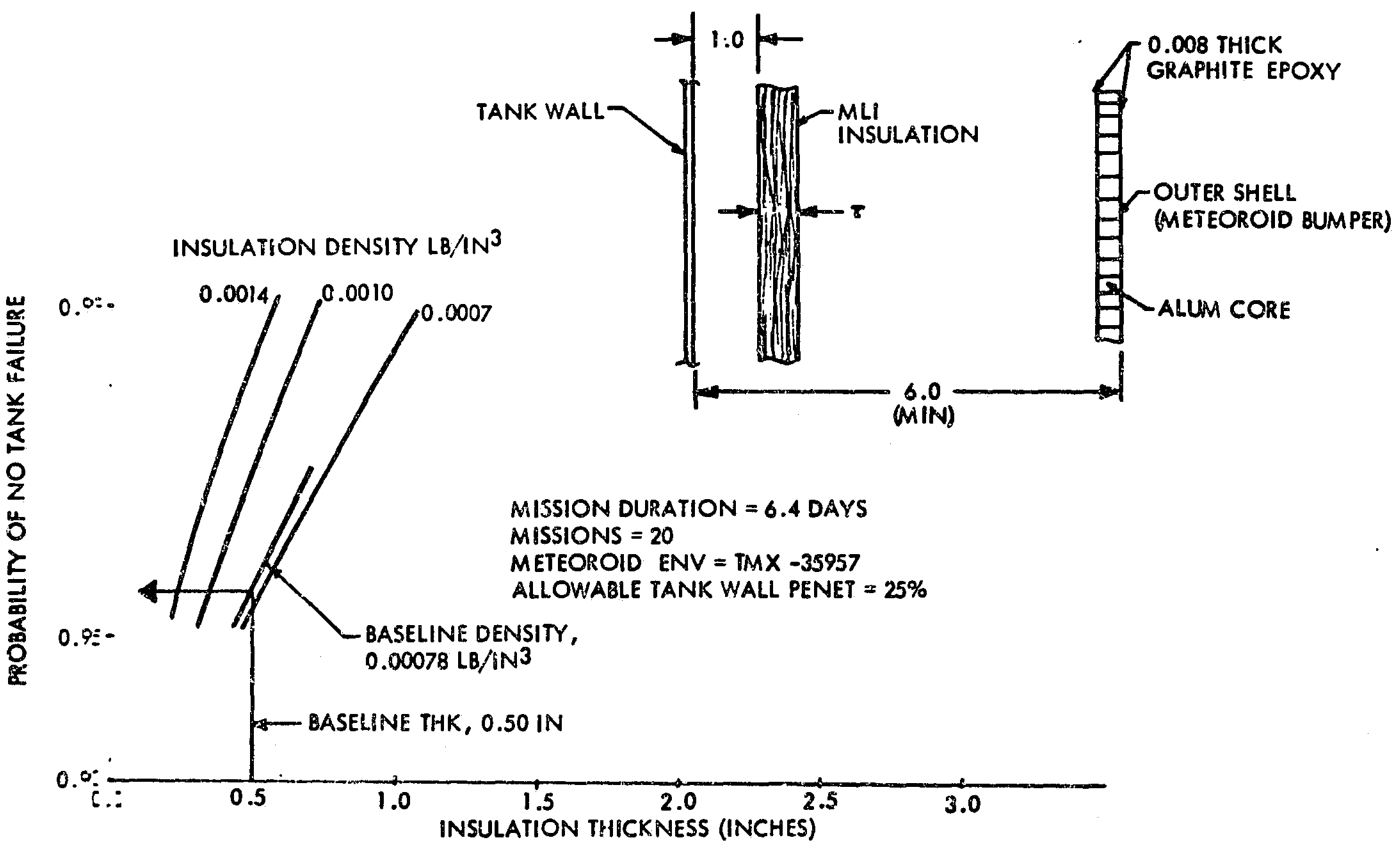


Figure 3.1-14 Insulation Sizing for Meteoroid Protection

Propulsion and Mechanical Subsystems

The propulsion and mechanical subsystems include propellant feed, fill and drain; safing and venting; pressurization; propellant acquisition; propellant management; main propulsion; thrust vector control; and auxiliary propulsion. The individual requirements for these subsystems as well as the fuel cell, which is discussed in the Avionics section, have been integrated where practical. This has been accomplished to minimize weight without compromising the design, reliability or operational simplicity of the subsystems. Figure 3.1-15 shows schematically how this has been accomplished.

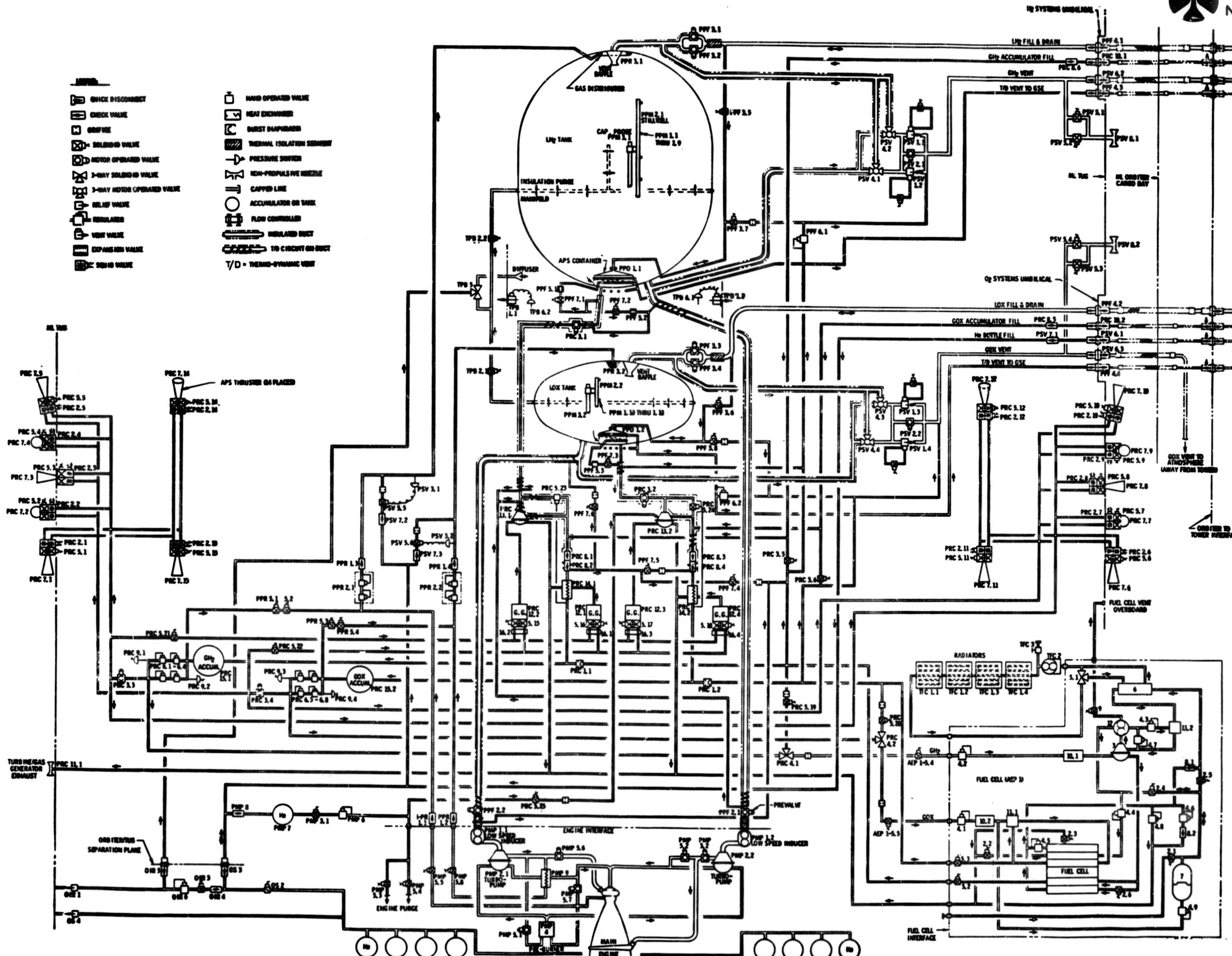
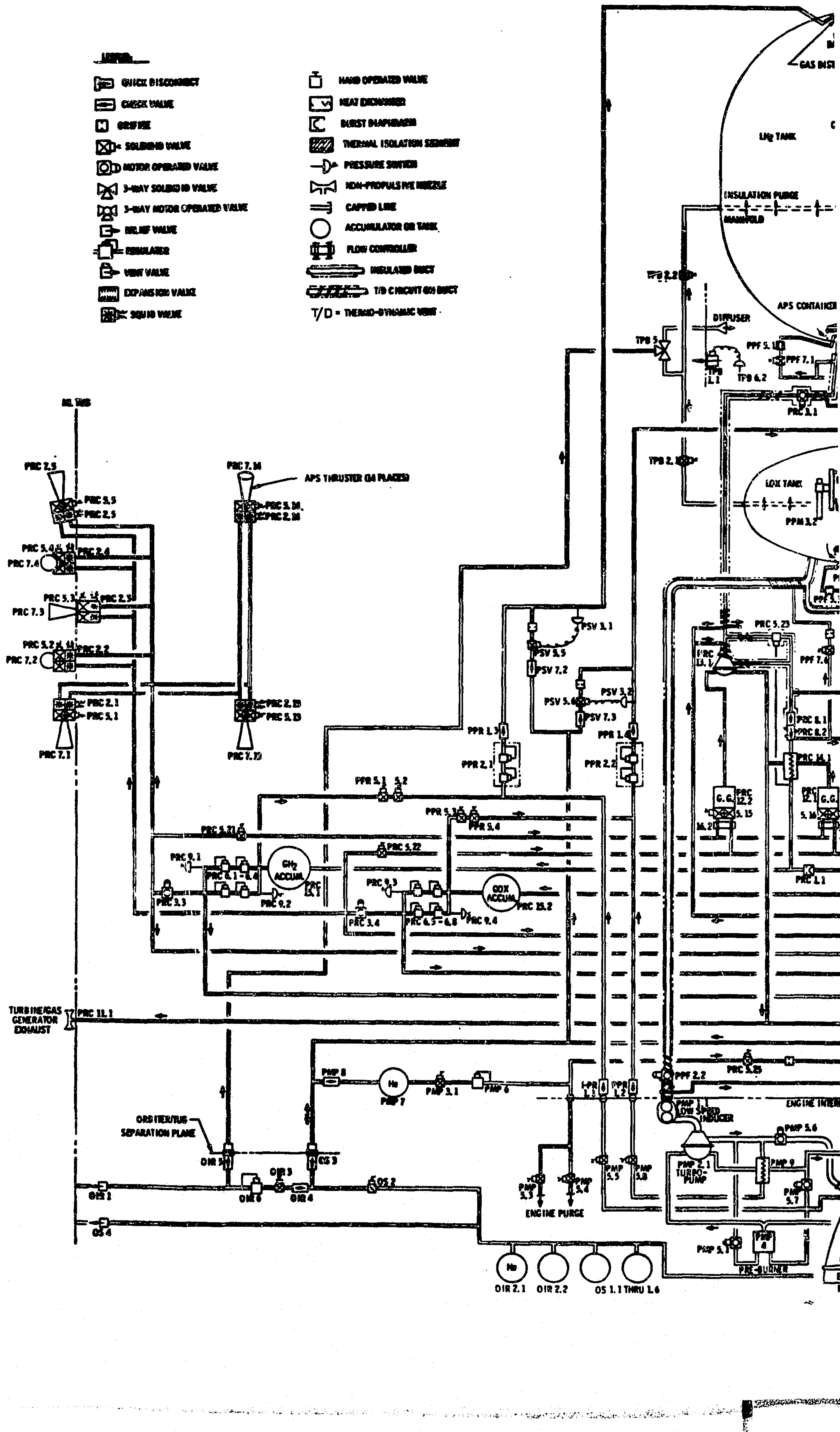


Figure 3.1-15 Propulsion and Mechanical Subsystem Integrated Schematic


LEGEND
QUICK DISCONNECT
CHECK VALVE
ORIFICE
SOLENOID VALVE
MOTOR OPERATED VALVE
3-WAY SOLENOID VALVE
3-WAY MOTOR OPERATED VALVE
RELIEF VALVE
REGULATOR
VENT VALVE
EXPANSION VALVE
SQUIB VALVE
HAND OPERATED VALVE
HEAT EXCHANGER
BURST DIAPHRAGM
THERMAL ISOLATION SEGMENT
PRESSURE SWITCH
NON-PROPULSIVE NOZZLE
CAPPED LINE
ACCUMULATOR OR TANK
FLOW CONTROLLER
INSULATED DUCT
T/D CIRCUIT ON DUCT
T/D = THERMO-DYNAMIC VENT
LH2 TANK
INSULATION PURGE MANIFOLD
LOX TANK
APS CONTAINER
DIFFUSER
APS THRUSTER (24 PLACES)
GH2 ACCUM.
GOX ACCUM.
TURBINE/GAS GENERATOR EXHAUST
ORBITER/TUG SEPARATION PLANE
ENGINE PURGE
LOW SPEED INDUCER
TURBO-PUMP
PRE-BURNER
OIR 2.1
OIR 2.2
OS 1.1 THRU 1.6

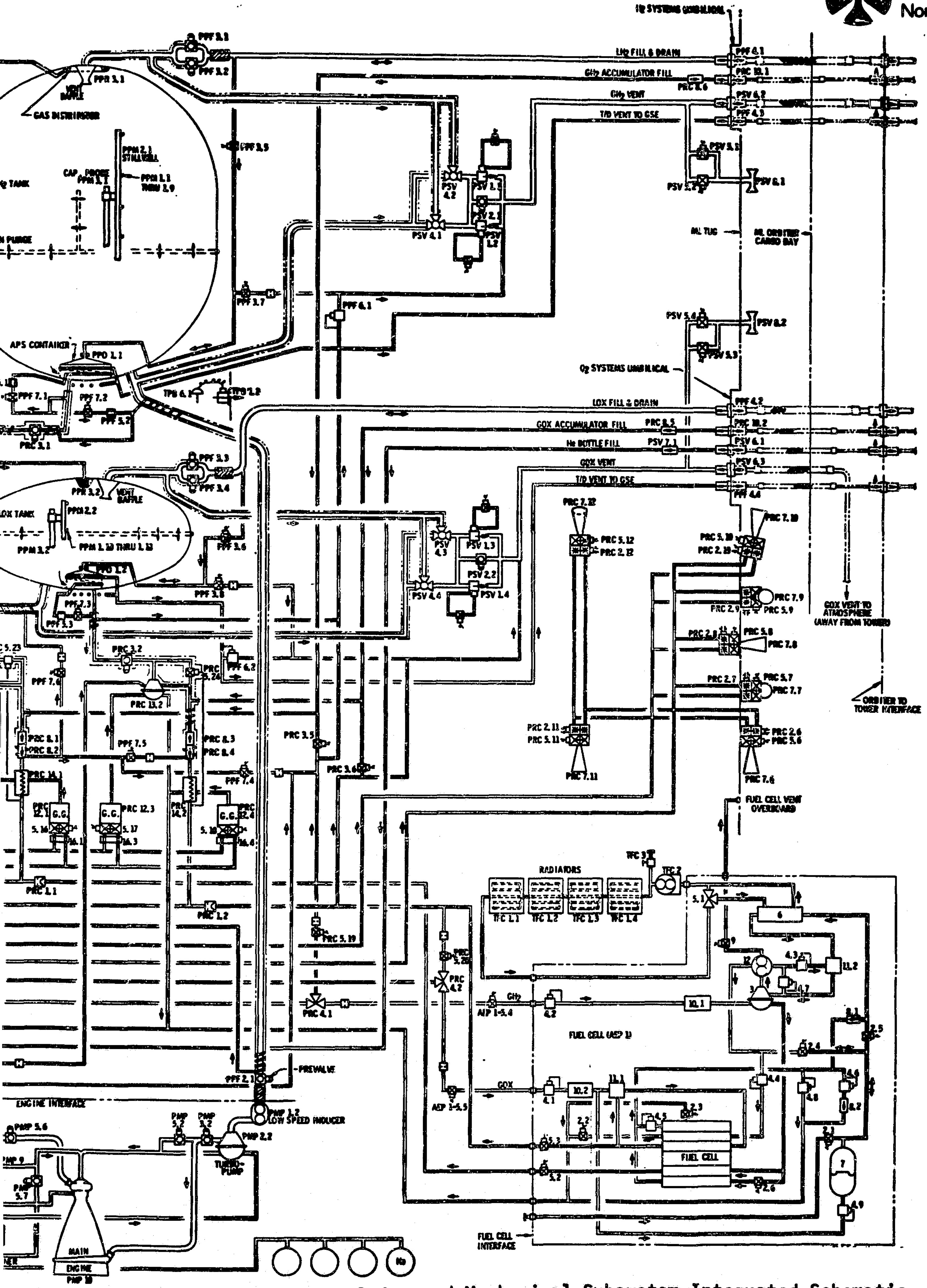


Figure 3.1-15 Propulsion and Mechanical Subsystem Integrated Schematic

3-21 3-22
Vol I

Feed, Fill, Drain, Safing and Vent Subsystem

Figure 3.1-16 shows the integrated feed, fill, drain, safing and vent subsystems schematic. Propellants are delivered to the main engines through insulated 2.5 inch feedlines and prevalves, which are the optimum size from a stage weight standpoint. The entire feed system is wrapped inside MLI with small diameter (1/8 inch) tubing which is part of an LH_2 thermodynamic vent cooling system. Use of this system plus the insulation will minimize boiloff when the MPS is not operating and will minimize system childown time and propellant losses during each main engine start.

For ground operations, each main propellant tank is filled through a 3-inch line with two parallel 2-inch fill and drain valves located at the top of the tank. This same system will be used for in-flight propellant dump since it takes place with the Tug in the cargo bay and with the propellants settled by thrust from the orbiter. Parallel fill valves are required to provide redundancy and the 3-inch line is required to drain the propellants in 27 minutes.

After propellant dump operation, the tank will be safed by use of two cycles (dump-vent-pressurize-vent-pressurize) with helium gas which has been stored in the Shuttle/Tug adapter in the cargo bay. The first safing cycle and the final pressurization for re-entry will be to 17 psia (pressure switch setting).

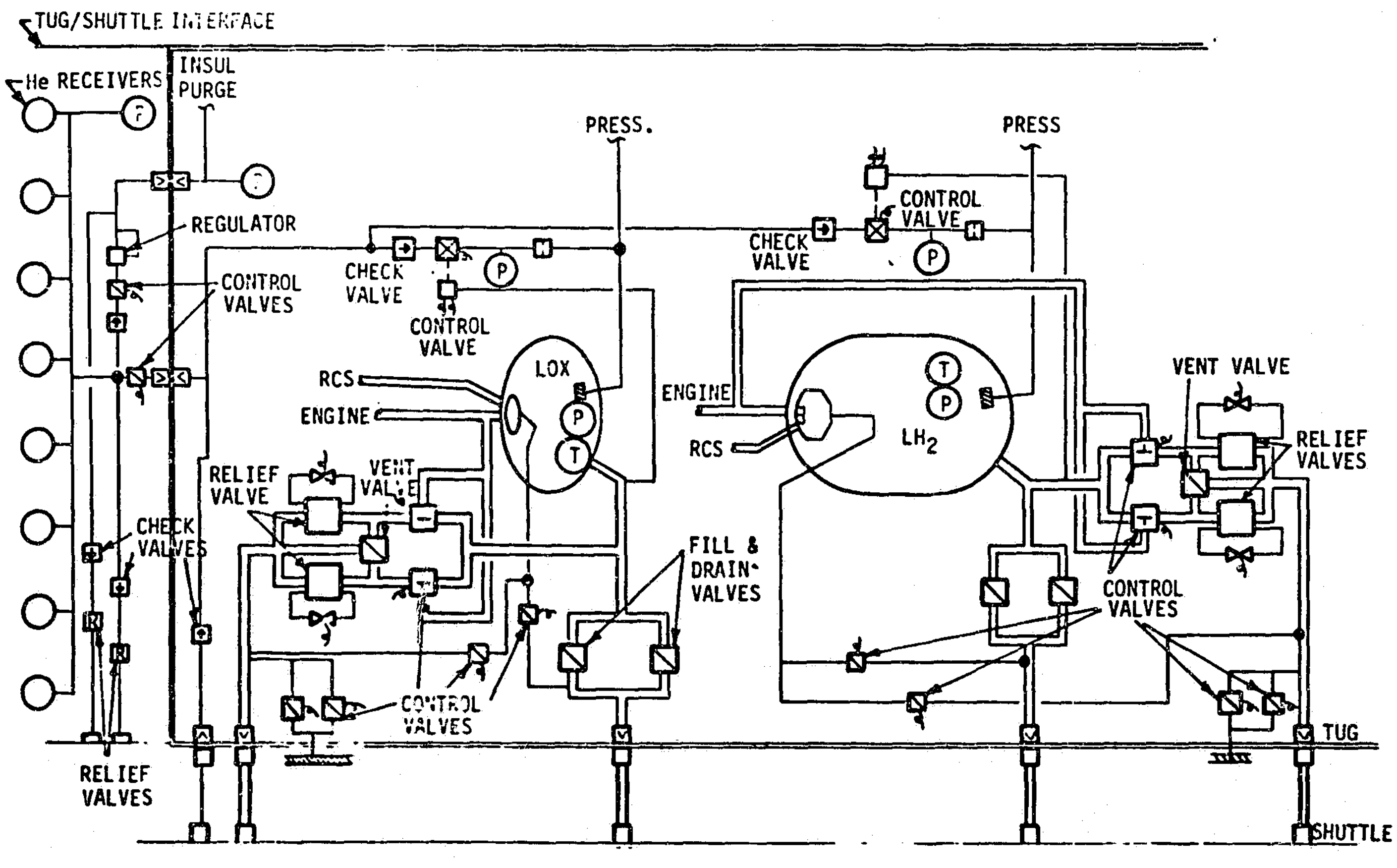


Figure 3.1-16 Feed, Fill, Drain, Safing and Vent Subsystems

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An alternate to the ground rule of safing both the LOX and LH_2 tank using 2 cycles of helium is not to safe the LOX tank but use the helium for a third cycle for the LH_2 tank. The total quantity of helium required to safe the LOX tank is 17.62 pounds, a third cycle for the LH_2 tank would require 15.15 pounds and would reduce the LH_2 concentration from 24.2 percent to less than 5 percent. After dumping LOX the tank pressure would be 13 psia but the tank could be allowed to self pressurize to the 16 psia (LOX relief valve low mode) required for reentry.

It is of importance to note that the choice of 6 ft^3 receivers for helium storage for safing and insulation repressurization is based primarily on installation considerations. The relatively small size receivers facilitate location in the Shuttle/Tug adapter and reduces mounting problems associated with larger bottles.

Ground fill and drain of the APS auxiliary tanks is accomplished during the main tank filling operation by tapping off the main fill line through a single auxiliary tank fill valve. In-flight refill of these tanks occurs only during periods of positive thrust (APS or MPS) by opening the APS auxiliary tank vent valve and dumping the ullage gas overboard through the non-propulsive vent system. Both tanks use thermodynamic vent cooling coils to reduce their heat input, both on the ground (using GSE vacuum) and inflight.

During ground operations the propellant tanks are vented through the main engine feedline and a single (one for each tank) electrically operated vent valve. Overpressurization of the tanks is prevented by the low mode (LOX 15-16 psia, LH_2 16-17 psia) of the two (for each tank) parallel mounted dual mode relief valves. Structural and system operations requirements dictate dual mode relief valves. The high mode setting for both the LOX and LH_2 valves is a result of a summation of vapor pressure, NPSH, head, feed line pressure drop, regulator band, relief valve band and margin. The low mode setting for the LOX valve is dictated by the maximum limit loading on the forward bulkhead during high "g" Shuttle boost and by the requirement to lower the vapor pressure of the LOX for engine start. This same requirement for low vapor pressure at engine start sets the low mode for the LH_2 valve.

During boost to orbit the LOX relief valves will be in the low mode and the LH_2 valves in the high mode. All controlled or programmed venting while the Tug is in the cargo bay is accomplished by using the vent valve. From Tug deployment through re-entry, the propellant tanks are protected against over-pressurization by the high mode (23-24 psia for both tanks) of the relief valves. While the Tug is deployed, venting of the ullage gas will be through the non-propulsive vent system.

No venting during "zero g" conditions will be done to preclude loss of liquid propellant. The only venting anticipated during Tug operations is just prior to the main engine burn after the potentially long coast period. For this case and any others that may arise the APS will be used to settle the propellants. If, during any coast period, either propellant tank pressure should rise to 21 psia, the APS will be used to settle the propellants and the respective relief valves will be switched to their low mode.

Pressurization Subsystem

The pressurization subsystem schematic is shown in Figure 3.1-17. Pre-pressurization of the propellant tanks on the ground will be accomplished by closing the vent valves after loading and allowing the tanks to self-pressurize to the low mode setting (LOX 15-16 psia, LH_2 16-17 psia) of the relief valves.

Pre-pressurization prior to each main engine burn will be controlled to 21-22 psia by a single, two-stage regulator for each tank using gases from the APS accumulators. The gases from the accumulators will be at 375 psia. Temperatures are 200°R for the GH_2 and 400°R for the GOX. Proper ullage pressure during main engine burn will be maintained by the same regulators using evaporated propellants from the engines. GH_2 will be extracted from between the engine jacket cooling coils and pre-burner (2000-2500 psia and 260°R), and GOX will be extracted from the engine supplied GOX heat exchanger (3000-3500 psia and 600°R).

Engine isolation check valves are required in each system to prevent the engine from being pressurized during the pressurization sequence. The total pressurant required is 249 pounds for the LOX tank, and 244.5 pounds for the LH_2 tank. The ullage mass at cutoff is 236.2 pounds for the LOX, and 187.3 pounds for the LH_2.

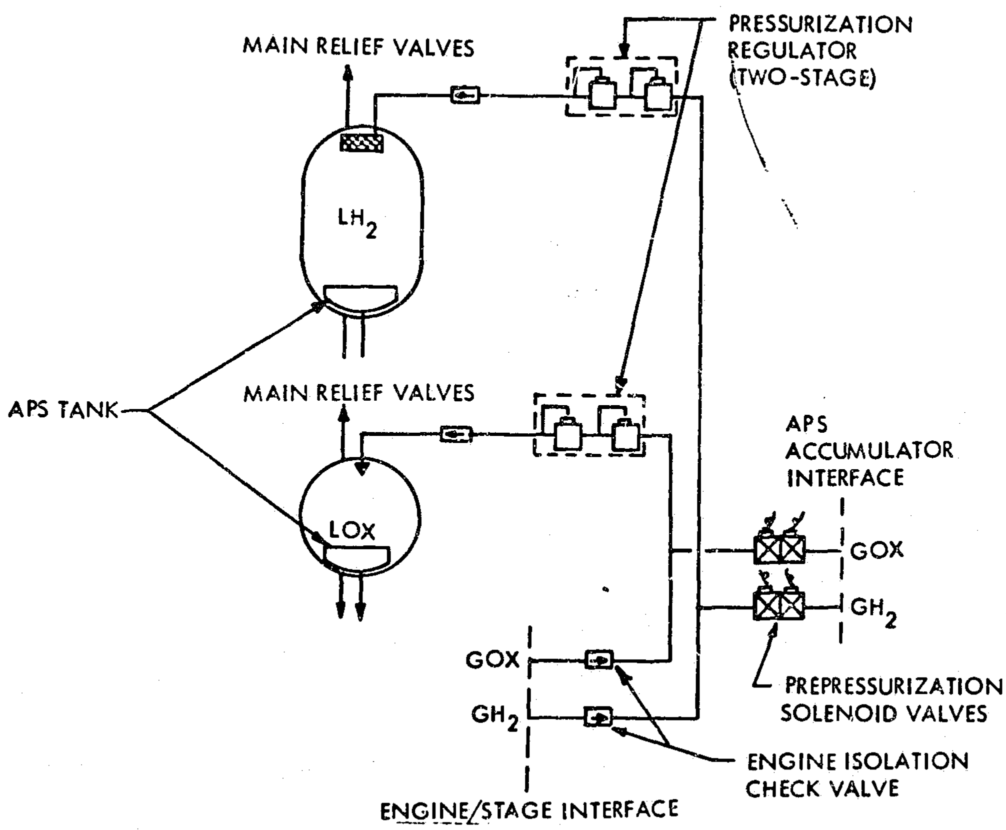


Figure 3.1-17 Pressurization Subsystem Schematic

Propellant Acquisition

To insure the availability of propellant at the inlet to the APS and MPS under all conditions of Tug operation a system of baffles in conjunction with an auxiliary propellant tank for the APS is required. A refillable tank with screened inlet was selected as the concept to be used for the auxiliary tank. It has the principle advantages of mission flexibility, low weight (LH_2 18 lb, LOX 9 lb) and is operationally simple.

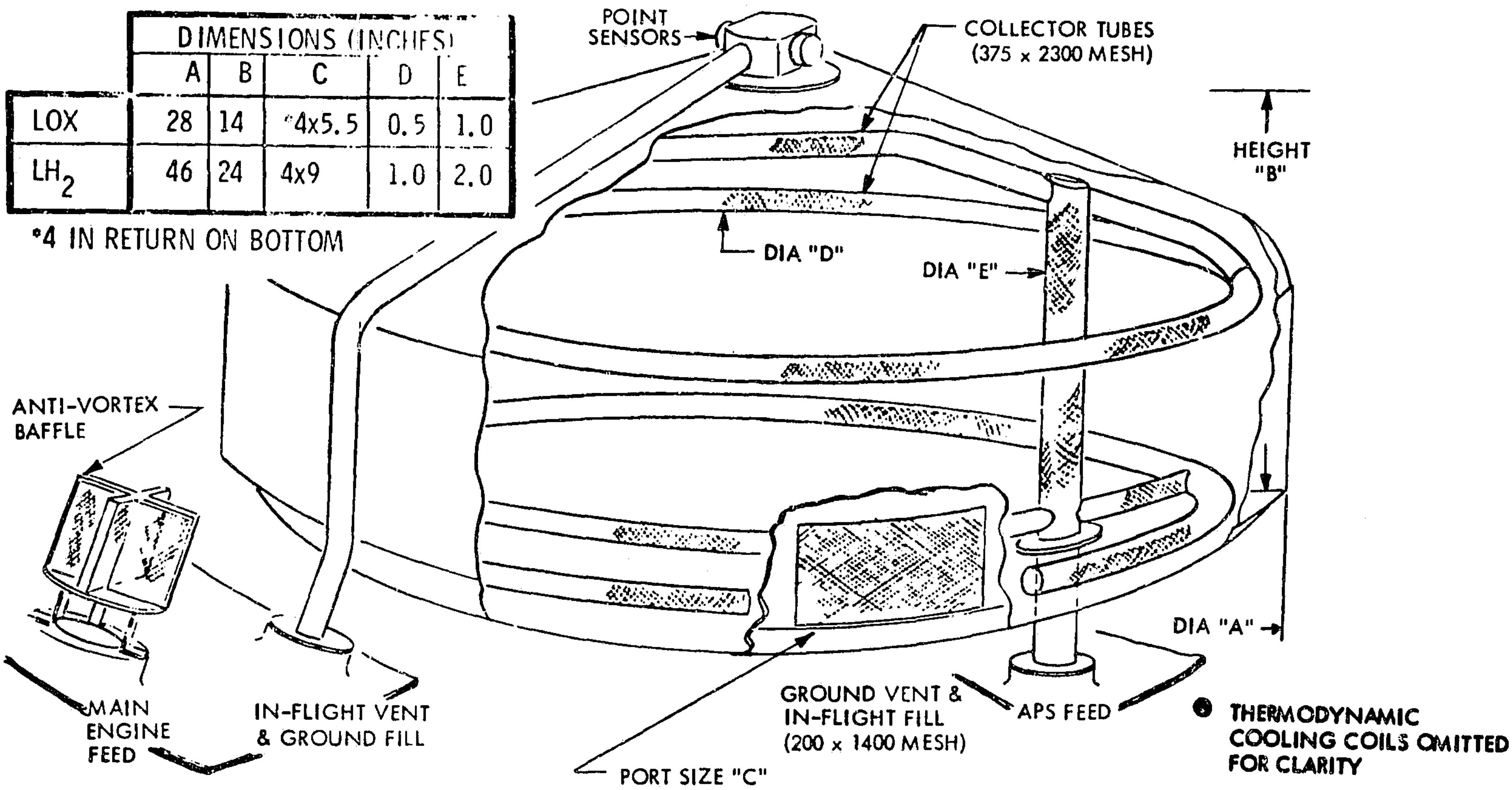
The main engine feed outlet is directly from the main tank. All main engine starts are preceeded by APS settling maneuvers (25 sec max) and MPS propellant acquisition devices are thereby obviated. This simple start concept is also efficient since APS specific impulse is relatively high (380 sec) and the refillable APS acquisition system incurs no weight penalty for such usage regardless of the number of starts.

Main engine outlet feed is enhanced by a system of small baffles on the bottom of each main tank. One set of four baffles 1.5 inch high, 40% perforated, and assymetrically located around the outlet expedite the settling process. They decrease rebound, direct the flow of bubble free liquid over the outlet and function as low level slosh baffles. The other baffle provision is an anti-vortex cruciform baffle 7 inches high by 5 inches wide located over the outlet.

The refillable auxiliary tank (shown in Figure 3.1-18) is ground filled. Propellant has direct access during refill via an unvalved screened (dutch twill) port. The shape of the port (two to three times as wide as it is high) is based upon anticipated launch acceleration which is two to three times as great in the longitudinal direction as in the lateral direction. The pressure drop across the screened inlet is expected to be less than 0.2 psi. The calculated minimum refill rates are 0.5 lb/sec LH_2 and 1.5 lb/sec LOX.

For both launch and space flight phases, the contents are cooled by a thermodynamic vent cooling circuit supplied with propellant expanded through a Joule Thompson valve. A tubular collection system within the auxiliary tanks, also constructed of dutch twill screen material permits acquisition of propellant at APS flow rates from any portion of the container. The system is made up of a torus at the top and bottom of each tank. Each torus has a single tube connecting opposite sides (on a diameter). These two connecting tubes are in turn connected by a vertical tube which exits the tank bottom as the APS feed line. The fluid is sub cooled with respect to the contents of the main tank and therefore is under a suppression head. Anticipated development of APS pumps by 1976 permits a design requirement to supply only zero NPSP fluid.

Refilling is accomplished after settling during either MPS or APS positive ΔV maneuvers by opening the overboard vapor vent. Loss of liquid by venting past the fill point (overfilling) is avoided with redundant liquid point sensors contained in the vent outlet. The top of the tanks are tilted at 15 degrees to facilitate bubble rise to the top.



	DIMENSIONS (INCHES)				
	A	B	C	D	E
LOX	28	14	*4x5.5	0.5	1.0
LH_2	46	24	4x9	1.0	2.0

*4 IN RETURN ON BOTTOM

Figure 3.1-18 Auxiliary Propellant Tank

Propellant Management

Propellant loading will be measured by capacitance probes (selected for mission flexibility) extending from the 50 percent to the 100 percent level to permit off-loaded missions. The loading accuracy is 0.6 percent and 1.25 percent for LOX and LH_2 respectively. The loaded MPS propellant mixture ratio is 6.0, which represents an LH_2 bias with respect to the engine mixture ratio control range. A maximum (including tolerances) engine operating mixture ratio requirement of 6.34 results from this loading and is beneficial in reducing the engine operating temperature and maintaining performance when compared to the engine maximum capability of 6.5.

Loading of the auxiliary tank is a time phased operation since any overfill spills into the main tank through the in-flight refill port.

The propellant consumption is controlled by a three position (5.5/6.0/6.22 $\pm$0.12) engine mixture ratio control valve. Valve position and timing is determined by point sensor gaging systems in conjunction with control computer electronics. The resulting 3 sigma worst case outage residual is 64 pounds.

Other candidate propellant utilization concepts are not considered competitive at the present time. There is no need for continuous propellant measurement as provided by a capacitance probe. Such probes are operationally less accurate and reliable than point sensors, and have extremely low physical sensitivity. Elimination of the gaging system in favor of the use of a precalibrated/computed engine consumption technique is a potential improvement. The reuse of the same engine on successive flights should enhance the accuracy of this method.

Main Propulsion Subsystem (MPS)

The main engine start sequence is preceeded with a settling maneuver by the APS. This assures nearly simultaneous presence of liquid at the engine inlets. The pressure fed idle initiates the start sequence in order to chill the engine and provide useful impulse. During chill idle the tanks are also pressurized by the APS system. The engine is then sequenced to buildup thrust to the 100 percent throttle setting. During the buildup transient (one or two seconds after start) pressurization gas bleed from the engine to the main tanks is initiated. A study of losses involved in start and shutdown of the main engine revealed that it is more efficient to use the APS for maneuvers requiring 29,000 lb sec impulse or less. Except as part of the normal start chill period and thrust buildup transient, pressure fed and pumped idle modes are not useful - either the APS or the main engine full thrust mode is superior in performance.

The alternative of selecting an engine thrust rating in the range of 12,000 to 14,000 pound instead of 10,000 lb is worth further consideration. It would simplify engine design and development and allow for growth. No decrease in stage performance would result but the larger nozzle would add 6 to 8 inches to stage length.

A retractable nozzle would reduce stage length 37 inches but this does not appear necessary or desirable. A weight increase of 30 pound and less reliability would result.

The use of two engines could add reliability at some penalty in stage performance. Evaluation of this advantage depends on a thorough design study and failure mode effects analysis to determine the extent of redundancy achievable.

Thrust Vector Control Subsystem

During main propulsion system (MPS) engine thrusting, vehicle attitude control will be maintained by commands from the guidance computer. The pitch and yaw control system operates with dual action of the gimballed engine. The requirements per actuator were determined to be ±7 degrees deflection (square pattern), 8 degrees/second rate, and 12 degrees/sec/sec gimbal acceleration. These requirements can be met by state of the art hardware design.

The vehicle roll attitude is controlled using four APS thrusters which are members of the two quints located diametrically opposite on the stage perimeter. These roll thrusters also provide roll control during APS operation, and were therefore sized to satisfy both MPS and APS operation requirements. The recommended twenty pound thrusters were found adequate during MPS operation to provide control authority and to counter roll moment disturbances due to main engine thrust cross-coupling effects.

The selected gimballing concept is a conventional hydraulic system utilizing an electric motor-driven pump as the source of power. All system components are housed within the actuators to minimize surface area and heat loss. One actuator will contain the pump and motor. The reservoir and accumulator are housed in the other actuator. Both actuators and interconnecting pressure and return lines are insulated. The actuator piston position is controlled by servovalves incorporating mechanical feedback of piston position.

Auxiliary Propulsion Subsystem (APS)

The APS provides supplementary attitude and translation control for the Tug during periods of main propulsion inactivity. Pre-injection burn orientations, small midcourse trajectory corrections, rendezvous and docking maneuvers, coast period attitude stabilization, and main propulsion roll control are among the operations performed by the APS. Design groundrules include fail-safe operation, minimum weight, delta-V corrections up to 100 ft/sec, gaseous oxygen and hydrogen propellant, and requirements for alignment accuracy and relative velocity at docking contact. Fail-safe in this case permits passive docking after a single thruster failure.

A 14-thruster configuration was selected for minimum weight. Installation simplicity is achieved by mounting the thrusters at a single body station (approximately station 146.5 inches) near the propellant supply. With a single thrusters inoperative the APS can stabilize attitude and translation disturbance accelerations within passive docking limits. Retro and roll thrusters are canted 20 degrees to minimize plume impingement heating on the vehicle, without significantly compromising system performance. The four aft facing thrusters are not canted, but are located so that the skirt ends at the exit plane, which also minimizes heating.

Thruster thrust levels were determined by considering compromises between control resolution for docking, response for midcourse corrections and large attitude maneuvers, and propellant efficiency. The capability to meet docking requirements was analyzed using an Apollo handling qualities model, which accounts for differences in mass properties, geometry, thruster characteristics, and docking accuracies. Thrust is principally constrained by angular rate docking requirements. Pitch and yaw thrusters are also used for axial translation; where pulses of 2.5 minutes duration, using two thrusters, duplicates a minimum main engine pulse. These constraints led to the thrust level selections of 20 pounds for roll thrusters and 70 pounds for all other thrusters, which allow for reasonable variations in vehicle mass properties.

The APS is integrated into Main Propulsion System by utilizing propellants stored in the main tanks. This is accomplished by employing refillable auxiliary tanks which in addition provide pressurants for prepressurization and venting through the main propellant tank vent system. LOX/LH_2 are supplied to zero NPSP turbopumps. These pumps eliminate need for NPSP through use of inducers.

Turbopump and heat exchangers have separate gas generators due to different mixture ratios and need for independent operation. Turbopump gas generator mixture ratio of 0.97:1 is required due to turbine temperature limitation. However, heat exchanger gas generator are less sensitive to temperature of the combustants and provides greater efficiency due to higher combustion temperatures at mixture ratio of 3:1. Independent operation enables the control system to sequence operations to avoid damage or flow of liquid propellants into accumulators. Linked bi-propellant valves for the gas generators and thrusters minimize weight and assure proper operating sequence.

The accumulators are sized (GH_2 2.4 ft^3, GOX 1.5 ft^3) for 3 seconds of maximum gas withdrawal while the propellant conditioning units respond to meet the demand and repressurize before the pressures drop to 575 psia. The conditioning units produce 0.5 lb/sec GH_2 and 1.5 lb/sec GOX. Maximum demand is 0.333 lb/sec GH_2 and 1.258 lb/sec GOX leaving 0.167 lb/sec GH_2 and 0.242 lb/sec GOX for repressurization. If abort mode occurs at minimum accumulator pressure of 575 psia, accumulators contain sufficient gas for one-half hour attitude hold before reaching 475 psia (minimum regulator inlet pressure without degrading thruster performance).

Maximum gas demand is based on the following simultaneous operations: Attitude control with four 70 lb_F and two 20 lb_F thrusters. The conditioning units dead band, 1050-1250 psia for GOX, allows 4 hours of fuel cell operation at 1 KW before accumulator repressurization is required.

Prior to liftoff, the accumulators are chilled and charged by the GSE through orbiter interfaces with GOX and GH_2 to 1250 psia. The accumulator gas temperatures are 400 ± 25°R for GOX and 200 ± 25°R for GH_2, and are protected by MLI and sunshields to minimize environmental influences in space. The motor operated isolation valves are opened, and the system is operationally checked after the Tug is deployed in orbit, but prior to physical separation (no ignition) from the orbiter. The propellant conditioning systems (turbopump, heat exchanger, gas generator) are activated to repress the accumulators when gas usage reduces the pressures from 1250 psia to 1050 psia for GH_2 and 925 psia for GOX. The pressure switch controlled relief system limits the accumulators to 1450 psia and downstream of regulators to 500 psia. Figure 3.1-19 shows the system schematic.

Avionics Subsystems

The Tug utilizes an integrated avionics system to perform the functions of: data management, guidance, navigation and control; communications; instrumentation; rendezvous and docking; and electrical power generation, conversion and distribution. The integration of subsystems to perform these functions is depicted in Figure 3.1-20.

Control of the vehicle electrical, electronic, electro-optical, electromechanical, and electro-chemical components in the operational modes necessary to perform the Tug mission is provided by a data management subsystem utilizing a single centralized general purpose digital computer and remotely positioned digital multiplexing input/output terminals.

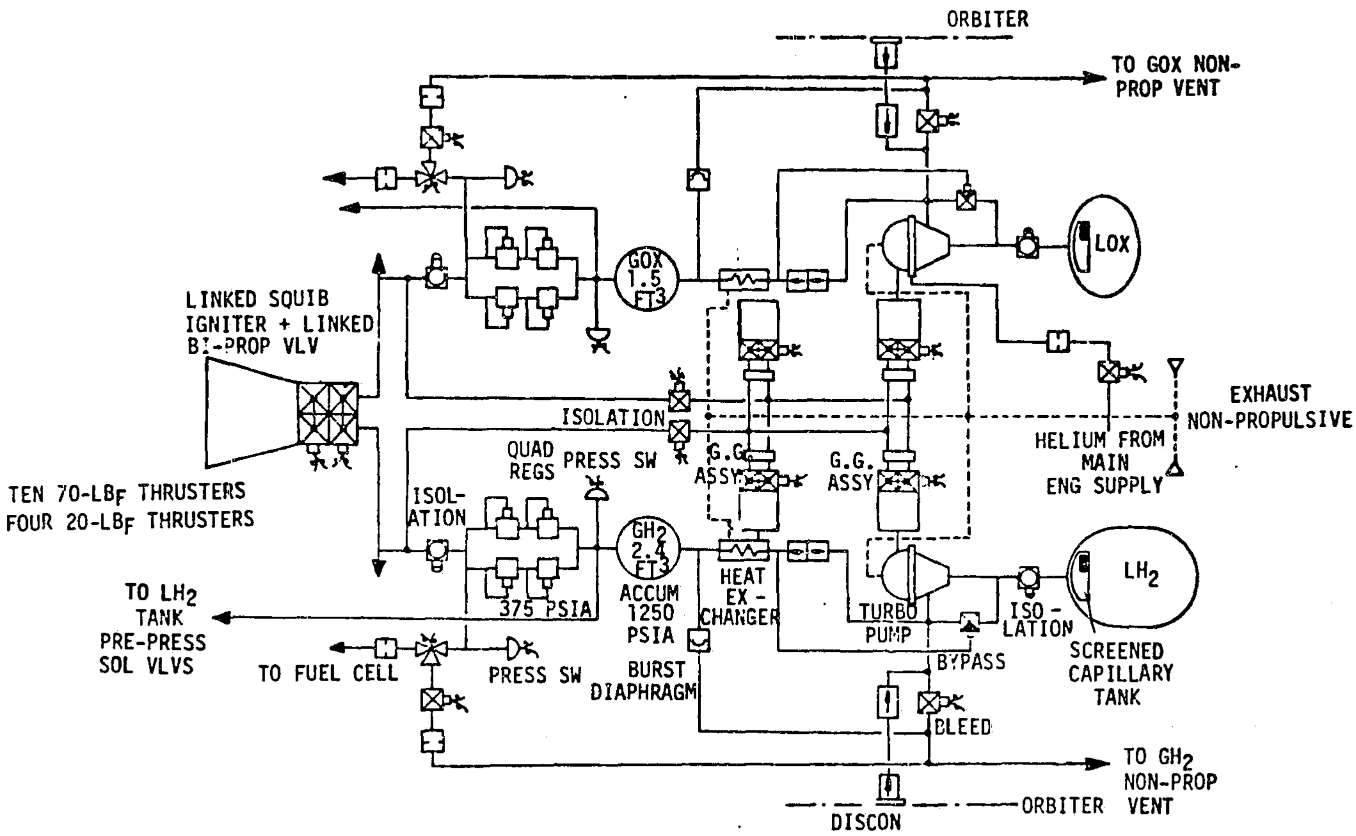


Figure 3.1-19 APS Schematic

The avionics subsystems design reflects a simplex (non-redundant components) concept resulting in virtually no redundancy management capability. This approach is consistent with study plan guidelines.

Ground subsystem checkout is performed under on board computer control to optimize checkout requirement implementation. The unmanned aspect of the Tug vehicle strongly influenced the design in this area.

The level of detail reflected in each subsystem design resulted from a philosophy in approach that dictated the definition of each subsystem to the depth required to establish Tug mission performance capability and minimum weight objective achievement credibility. With such an approach, the level of subsystem design detail is directly related to the inherent complexity of the subsystem design (i.e., more detail is required as complexity increases).

Data Management

The data management subsystem provides the means of integrating, managing and controlling the various systems of the highly autonomous Tug vehicle. The subsystem design uses three major elements: (1) data management computer, (2) data bus distribution components, and (3) software.

The data management computer provides the centralized vehicle intelligence for control of subsystems and associated data. The data bus elements provide the communication link between the central computer and the vehicle subsystems, the EOS crew status and control panel, and ground via telemetry.

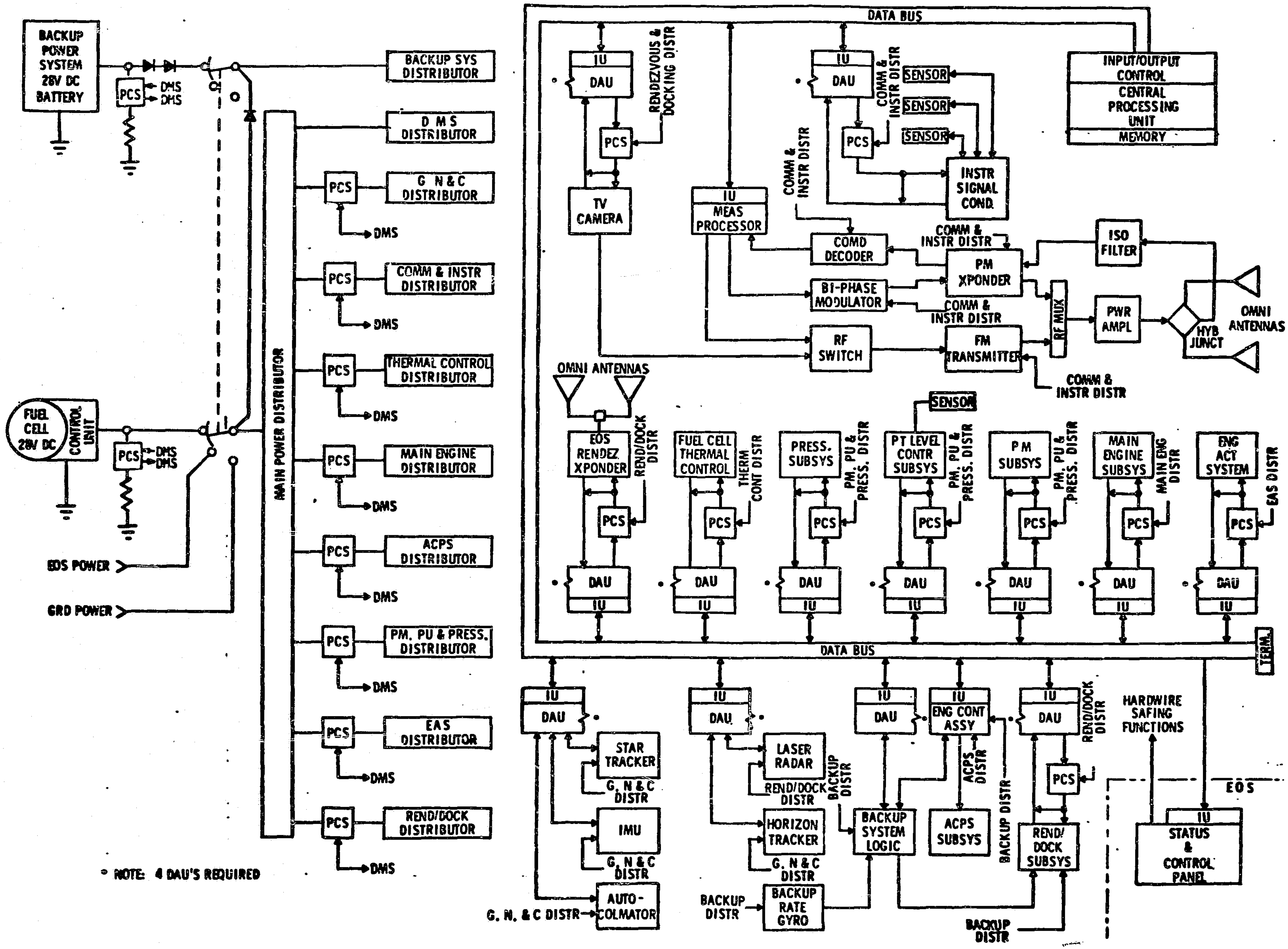


Figure 3.1-20 Avionics Subsystems Integrated Block Diagram

The data bus elements consist of a twisted shielded pair transmission line, data acquisition units, interface units, and measurement processor. The software element includes all computer programs for on board checkout and flight sequencing of the vehicle subsystems

The computer performs vehicle operational control in accordance with the programs contained in protected memory. In transmitting commands to the vehicle subsystems, the computer central processing unit identifies data to be transmitted and initiates the outputting of data. The computer input/output processor outputs data to the data bus independently once the operation has been initiated. Data is placed on the data bus in a serial pulse code at a one MHZ rate. The first word of the data transmission contains the address of the interface unit desired to receive the instructions contained in the message. If the command message requests data, the data acquisition unit routes the desired subsystem back to the computer via the interface unit and data bus. When the command message is an instruction to issue a subsystem control stimuli, the interface unit processes the data through to the data acquisition unit where it is decoded and the appropriate stimuli issued. At the time the stimuli is issued, it is selftested and the GO/NO GO status fed back to the computer. The computer continues to monitor the function's operational parameters to verify proper system response to the command. If the desired response does not occur, action is to determine the cause and perform those actions required to continue subsystem operation.

The subsystem provides the information and control necessary for the communications subsystem to transmit data to the ground. The measurement processor is loaded with the addresses of the desired data which is then retrieved each time it appears on the data bus. Continual and automatic update is provided to transmit current status to the ground upon preprogrammed command or as requested by the uplink.

The subsystem includes a status and control panel installed on the EOS to be utilized prior to Tug electrical demating for transmitting Tug status to the EOS crew, to transfer navigation state vector information, and to control critical Tug subsystems.

An onboard tape recorder is included in the subsystem to record the data stream from the main engine instrumentation system during main engine burns.

Guidance, Navigation and Control (GN&C)

The primary GN&C subsystem is comprised of a strapdown 3-axis inertial measurement unit (rate gyros, accelerometers, and associated electronics), a gimballed star tracker, a horizon edge tracker, an autocollimator, and an engine control assembly (APS drivers and main engine gimbal servo electronics).

The GN&C subsystem receives a state vector handoff from the EOS prior to electrical demating. From that point the subsystem elements provide navigation and guidance data to the central computer through appropriate data acquisition units in the data management subsystem. The computer uses this data to determine vehicle position, attitude, and velocity. Based on this state vector determination and programmed mission timeline requirements, the computer generates main engine thrust commands, steering commands, and APS stabilization and control commands. The commands are delivered to the appropriate components through the data acquisition units and engine control assembly. The GN&C subsystem and data management subsystem work in conjunction to provide autonomous control for performance of the Tug mission. Autonomy is relinquished in the normal mode only for man controlled Tug/payload docking. For abnormal modes, the subsystem design provides for a ground override capability to interrupt autonomous operation.

Included in the GN&C subsystem is an autocollimator to determine relative structural alignment between the star tracker and horizon tracker mounting bases. The alignment data is fed to the central computer where it is used to reduce the bias error between the star tracker and horizon tracker and hence improve star/horizon navigation accuracy.

To provide backup vehicle rate stabilization in the event of a primary GN&C subsystem or data management subsystem failure, a completely analog separate rate stabilization system is incorporated in the subsystem design. The backup system operates independent of the data management subsystem. It consists of a rate gyro triad and associated logic package wired directly to the APS subsystem.

Rendezvous & Docking

The rendezvous and docking subsystem is composed of components which operate in conjunction with the data management and communications subsystems to accomplish automatic rendezvous and man controlled docking. The subsystem is designed to be supported by a ground control facility (with a ground operator for docking), and by visual and laser aids included on the target vehicle.

A modified version of the "YAG" scanning laser radar being developed by ITT is chosen for the baseline design to perform the function of target acquisition. Self-test, payload rendezvous and docking, and EOS rendezvous with the payload attached to the Tug is accommodated by the addition of a three-position mirror and test reflector to the basic unit. For close range, high scan rate capability, the basic unit will be modified to permit the rapid field of view scan necessary for smooth display of data at the pilot console and stable range feedback information.

The television camera used in the subsystem design is a black and white version of the unit developed for the Apollo program to transmit video signals from the lunar surface. The camera is controlled by the data management subsystem and its output is transmitted to the ground station via the communications subsystem FM transmitter and antenna system. To provide adequate illumination of the payload mounted visual aids used in docking, a lighting system is included in the design configuration. The subsystem design rigidly mounts the television camera and provides for a fixed field of view. Performance and operational requirements are satisifed by this approach and savings in weight and improvement in reliability are gained.

A TACAN transponder system is included in the subsystem to provide ranging information during EOS/Tug rendezvous and docking.

Communications

The communications subsystem utilizes unified S-band equipment (USBE) and analog video processing equipment to establish the interfaces shown in Figure 3.1-21. Antenna, RF/IF, and baseband subsystem components make up the total system.

Antenna Subsystem - To minimize weight and complexity, an omni-directional antenna configuration is used throughout all mission phases. A high power amplifier is used to offset the effects of the low-gain antennas. Video and USBE transmission share the antenna subsystem.

RF/IF Subsystem - A pulse modulated transponder including transmitter and receiver is used for the basic USBE link. The transponder receives the MSFN uplink carrier signal, demodulates the ranging code and coherently remodulates it on a downlink carrier. In addition, it demodulates the uplink data subcarrier and routes it to a command decoder. The transponder transmitter simultaneously transmits the ranging code along with a pulse code modulation (PCM) subcarrier (telemetry data). Both signals are phase modulated directly on the downlink PM carrier.

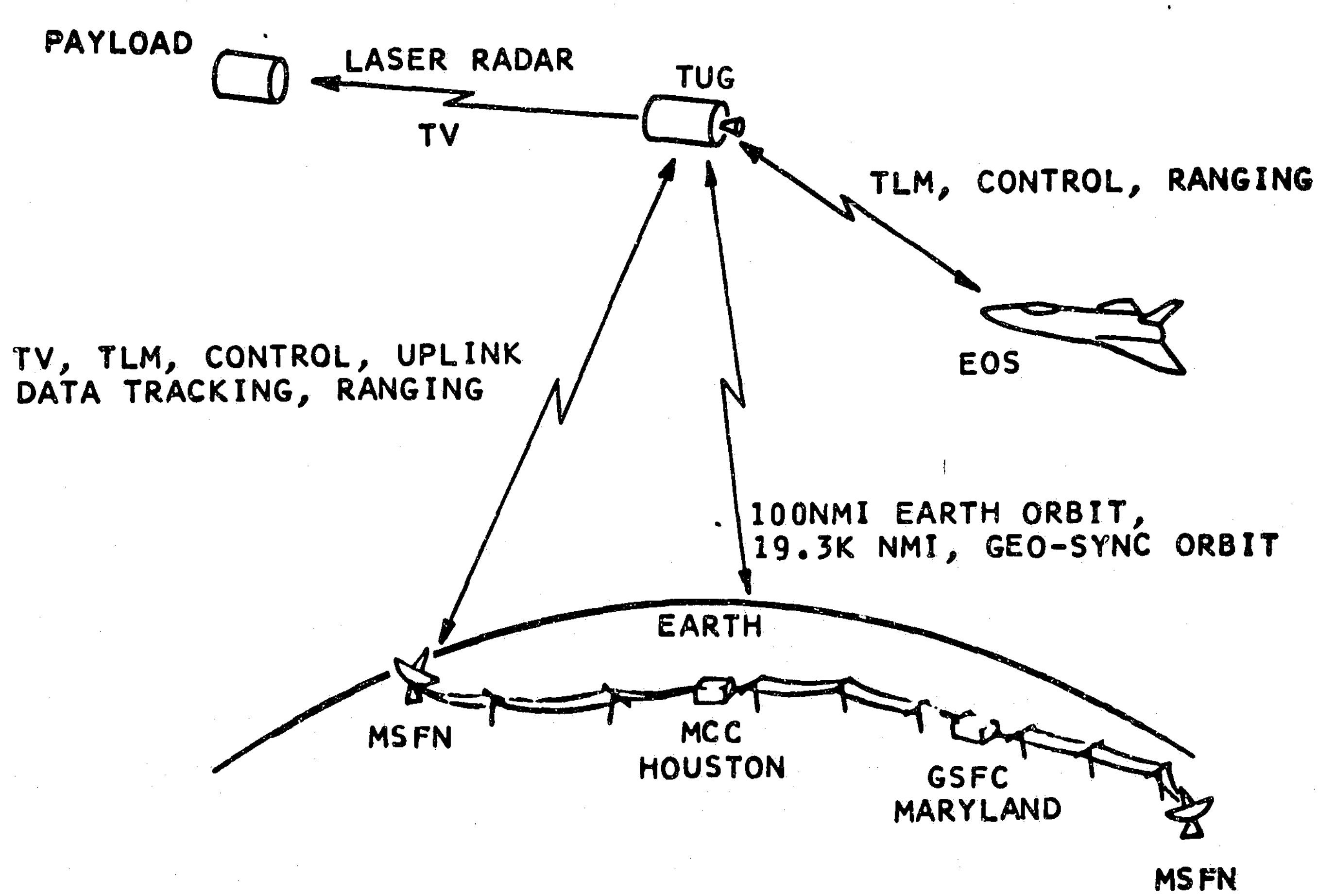


Figure 3.1-21 Communications Subsystem Interfaces

An FM transmitter provides the wideband transmission capability required for television. The video signal is frequency modulated directly on the FM carrier. The FM transmitter is also utilized to transmit limited telemetry to the EOS to indicate Tug status prior to docking.

Baseband Subsystem - The baseband subsystem consists of a bi-phase modulator and a command decoder. The modulator takes a PCM serial bit stream from the data management subsystem and bi-phase modulates it on to an internally generated subcarrier. The modulated signal is then routed to the transponder for phase modulation onto the carrier.

The decoder accepts a demodulated bit stream from the transponder receiver, detects the command word bits and subsequently decodes and distributes command words to the data management subsystem. In addition, the decoder provides a limited capability for commands independent of the data management subsystem.

Instrumentation

The instrumentation subsystem is composed of transducers and signal conditioning equipment in the variety and quantity necessary to satisfy the vehicle systems measurement requirements as identified in Table 3.1-1. To obtain high accuracy and reliability in the measurement of the most numerous parameters, strain gage pressure transducers and platinum wire resistance temperature transducers are used. Dedicated, remotely located signal conditioning modules provide sensor excitation and output amplification to a 0-5VDC level for data management subsystem input compatibility. Measurement of position parameters is made with potentiometric transducers excited to provide a 0.5-VDC output. Voltage and current measurements are made using a sensor, electronic package combination to provide a 0.5-VDC output. The measurement of fluid flow is made using a turbine type flowmeter that provides a pulse output at a level compatible with the data management subsystem input requirements. The liquid level point sensors provide a discrete output to the data management subsystem.

No multiplexing of measurement channels is performed in the instrumentation subsystem. All channels are individually routed to the data management subsystem data acquisition units where multiplexing is accomplished as a normal subsystem function.

For the measurement of main engine parameters (not identified in Table 3.1-1), the main engine control package provides self contained signal conditioning and pulse code modulation circuitry to perform internal processing that outputs data at the engine/stage interface in a serial digital wavetrain format. The output is routed to a data acquisition unit where the data becomes available for use by the data management subsystem computer.

Table 3.1-1 Operational Measurement Summary

SUBSYSTEM	PRESSURE	TEMPERATURE	POSITION	VOLTAGE	CURRENT	FLOW	POINT SENSORS*	TOTAL
THRUST VECTOR CONTROL	2	2	3	-	-	-	-	7
FUEL CELL AND THERMAL CONTROL SYSTEM	2	10	-	-	-	1	-	13
POWER GENERATION SYSTEM	-	1	-	3	3	-	-	7
FEED, FILL, DRAIN AND VENT SYSTEM	-	-	-	-	-	-	22	22
PRESSURIZATION SYSTEM	8	12	4	-	-	-	-	24
APS SYSTEM	32	6	-	-	-	-	-	38
SAFING/VENT SYSTEM	8	11	-	-	-	-	-	19
TOTAL	52	42	7	3	3	1	22	130

* MAIN ENGINE MEASUREMENTS ARE MADE AVAILABLE TO THE DMS IN SERIAL DIGITAL FORMAT BY THE ENGINE CONTROL PACKAGE AND ARE NOT IDENTIFIED IN THIS SUMMARY

Electrical Power Generation, Conversion and Distribution

The electrical power generation for the Tug primary systems is achieved through the use of a single high performance, H_2/O_2 reactant fuel cell. The fuel cell is rated at 28 VDC, 200-3000 watts to satisfy the vehicle power requirements shown in Figure 3.1-22. The cell selected for the subsystem is a Pratt & Whitney unit requiring development effort for use in the Tug IOC time frame. An active coolant loop provides thermal control for the fuel cell.

A single primary battery is included in the electrical power generation subsystem for the specific purpose of providing a minimum of 30 minutes backup power to the Tug backup stabilization system in the event of primary power failures.

The electrical power conversion and distribution subsystem converts, through the use of a static inverter, DC power to AC power for specialized loads and distributes power to all using components on the vehicle. The distribution of power to the various loads is through the use of solid state switches controlled and statused by the data management subsystem.

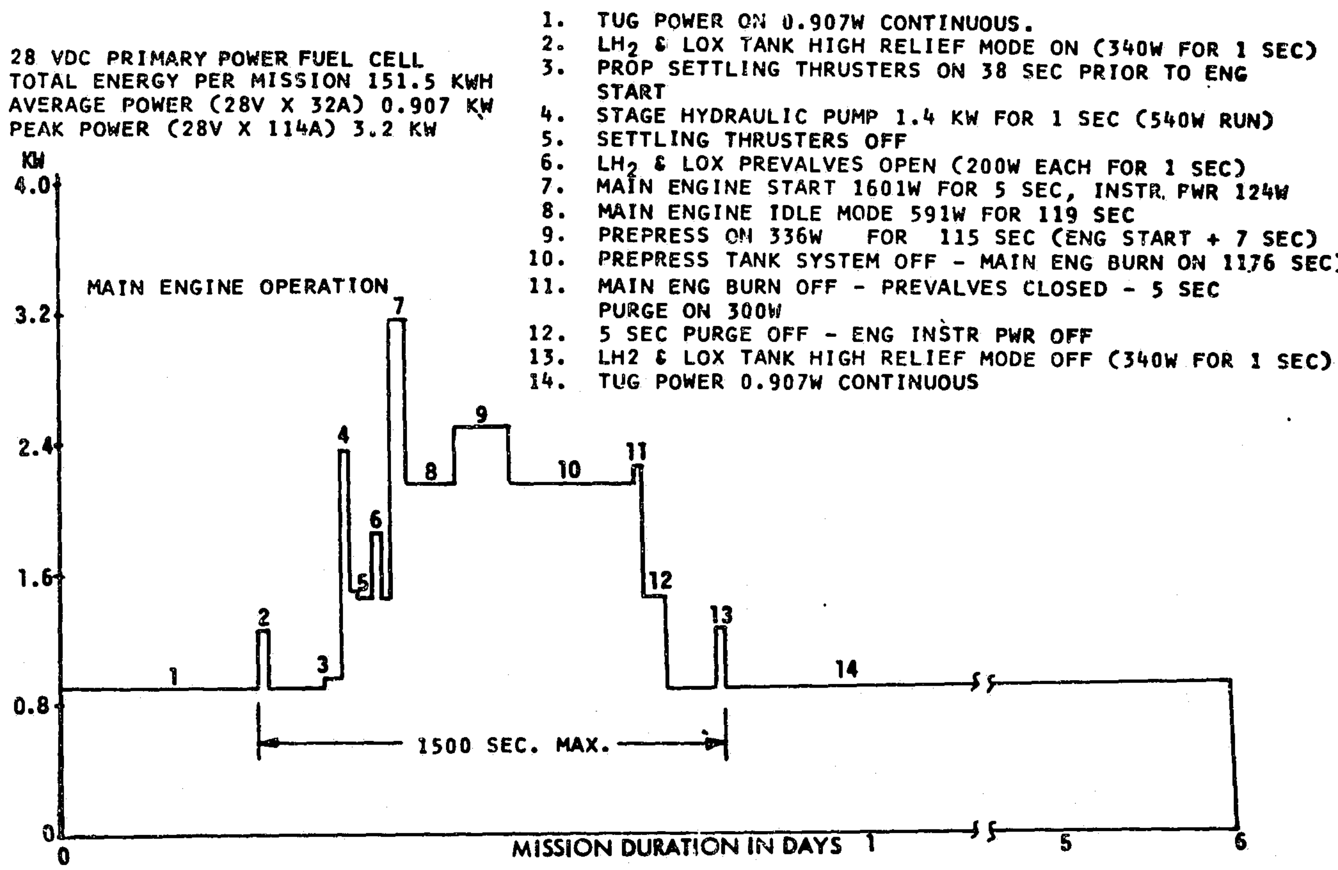


Figure 3.1-22 Main Engine Burn Electrical Power Profile

Thermal Control

The fuel cell thermal control system is shown graphically in Figure 3.1-23. The basic requirement of the system is to remove the excess heat generated during operation of the cell. During peak loads the system is augmented by the open cycle operating mode of the cell. In this mode stored water is taken into the cell, evaporated and dumped overboard as steam.

The use of radiators equally spaced around the circumference of the Tug eliminates the need for selective orientation for satisfactory operation of the fuel cell thermal control system. The fuel cell condenser outlet temperature is maintained at the proper temperature by a sensor located downstream of the condenser outlet. The sensor positions the temperature control valve to route coolant fluid as required through the condenser or to bypass the condenser and return to the freon pump inlet. The freon pump operates continuously to circulate coolant through the radiator system.

Subsystems Installation

The avionics subsystem components are installed on open panels mounted in the forward and aft skirt areas of the vehicle as shown in Figure 3.1-24. Data Management, primary GN&C, Communications, and Rendezvous and Docking components are installed in the forward skirt. Power generation and backup rate stabilization components are located in the aft skirt. Instrumentation, power distribution, and data management data acquisition units are installed

- REQUIREMENTS
  - FUEL CELL VENT REJECTION RATE AT 1.1 KW = 2500 BTU/HR
  - CONDENSER WATER IN AT 180 F MAX, OUT AT 140 F MAX

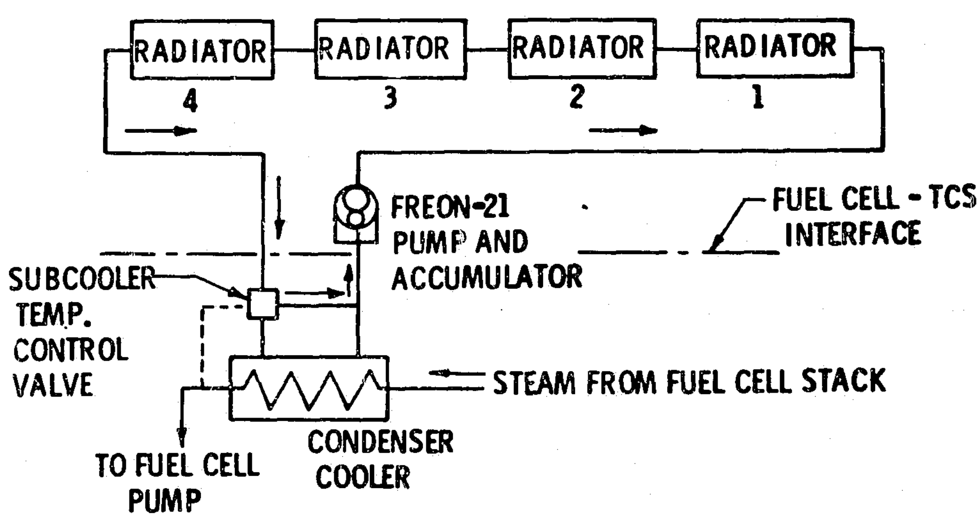


Figure 3.1-23 Fuel Cell Thermal Control

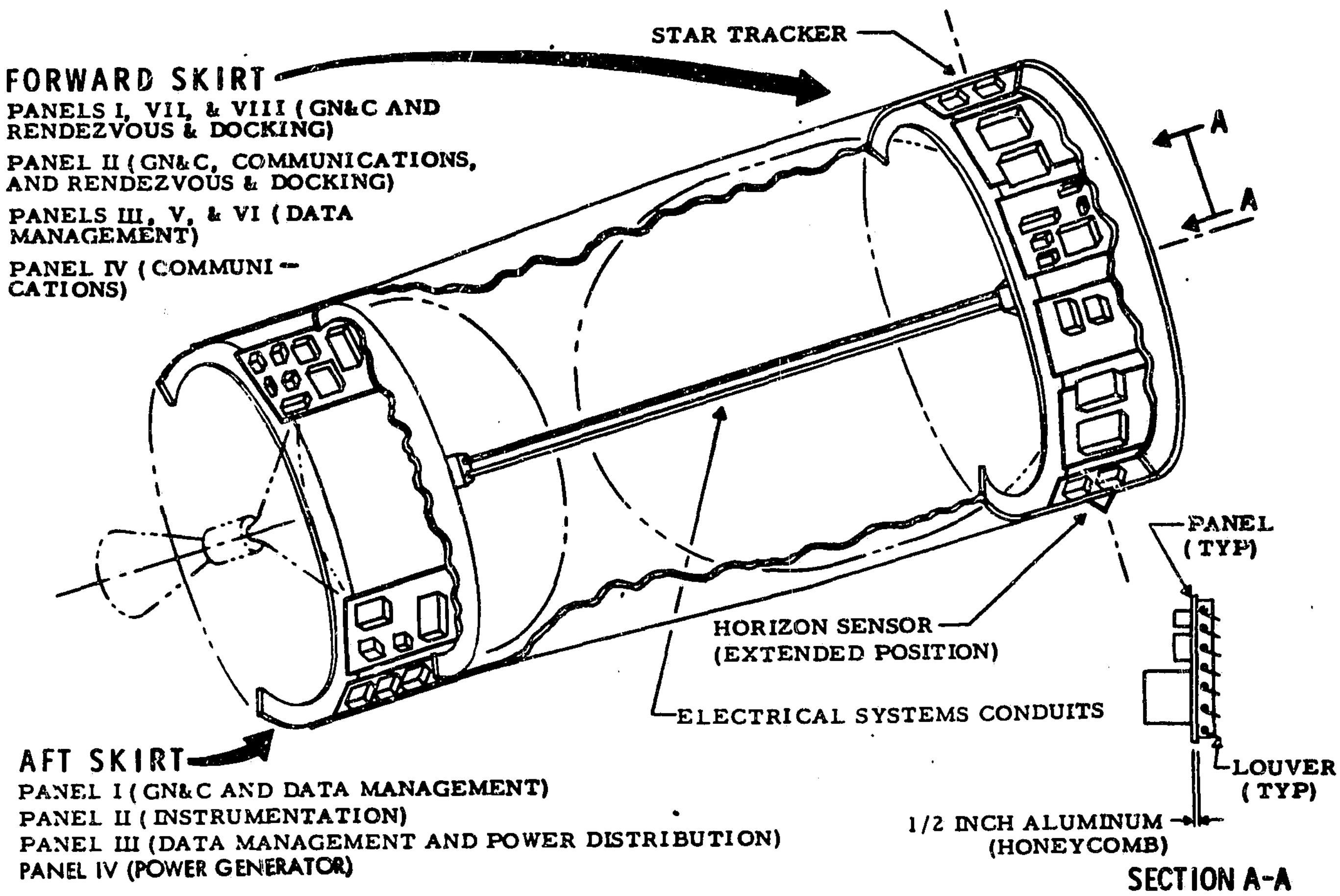


Figure 3.1-24 Avionics Subsystems Installation

in both forward and aft areas in close proximity to the components they service. Power and signal transmission between forward and aft located components is via cabling installed in two electrical conduit runs.

The sensors for star/horizon navigation are mounted on opposite sides of the vehicle. A recess is provided in the vehicle outer mold line to accommodate the star tracker field of view. The horizon tracker is mounted on a panel that is deployed beyond the vehicle outer mold line to provide the necessary field of view.

The component mounting panels serve the dual purposes of providing an installation base and acting as heat sinks for passive thermal control. Louvers installed on the vehicle outboard side of the panels provide heat rejection capability.

3.2 SHUTTLE/TUG INTERFACES

For ground operations outside of the Shuttle orbiter the interface panels located on the Tug skin provide the means of checking out and servicing the vehicle in the maintenance and refurbishment areas. For ground operations with the Tug inside the cargo bay the interface with GSE will be at the orbiter moldline. All electric and fluid interfaces with the orbiter have been combined into three panels including a LOX panel, an LH_2 panel, and an aft panel located at the interface of the Tug with the Shuttle/Tug adapter assembly. Figure 3.2-1 shows the details of the panel as well as the location and orientation of the panels in relation to the orbiter.

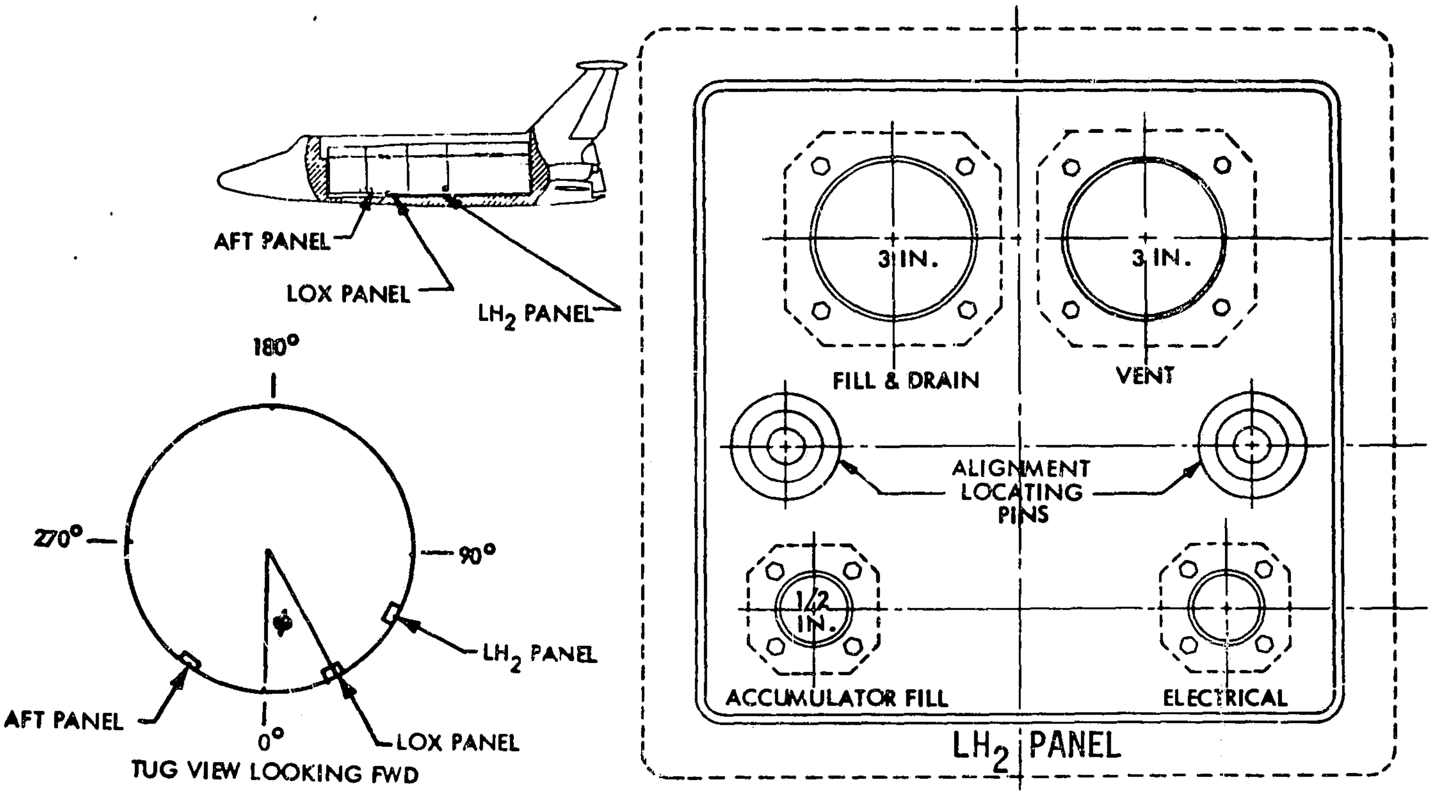


Figure 3.2-1 Shuttle/Tug Interfaces

The LH_2 panel is parallel to the vehicle moldline and recessed into the skin. It is approximately 18.5 inches by 18 inches and located at Station 443.5 with ϕ = 30 degrees. It has three fluid and one electrical connections as indicated in Table 3.2-1. The details of the umbilical mechanism are shown in Figure 3.2-2.

Table 3.2-1. LH_2 Panel Details

LH_2 Fill and Drain - 3 in. - 24 psia
LH_2 Vent - 3 in. - 24 psia
LH_2 Thermodynamic Vent - 0.5 in. - 2 psia
APS LH_2 Accumulator Fill - 0.5 in. - 1250 psia
Electrical Connector - 24 shell size

The LOX panel is also parallel to the vehicle moldline and recessed into the skin. It is approximately 18 inches by 25 inches and located at Station 246 with ϕ = 8 degrees. The panel is composed of five fluid and one electrical connection as indicated below in Table 3.2-2.

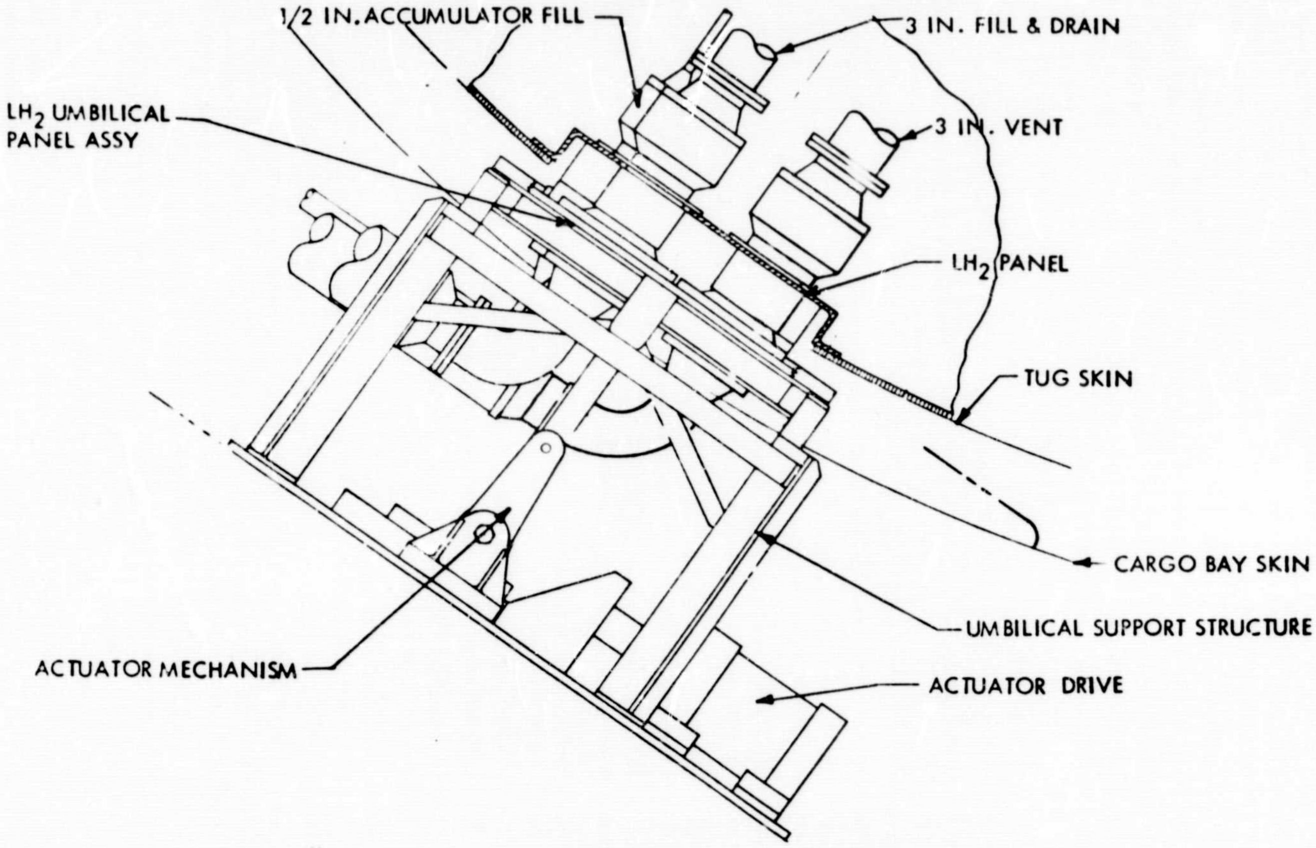


Figure 3.2-2 LH_2 Interface Panel Details

Table 3.2-2. LOX Panel Details

LOX Fill and Drain - 3 in. - 24 psia
LOX Vent - 2 in. - 24 psia
APS LOX Accumulator Fill - 0.5 in. - 1250 psia
Thermodynamic Vent - 0.5 in. - 2 psia
Helium Fill - 1 in - 3000 psia
Electrical Connector - 24 shell size

The aft panel is in the plane of the Shuttle/Tug adapter interface (Station 130.5). It is facing aft at a radius of 66 inches and with an angle of ϕ = 345 degrees. It has three disconnects as shown below in Table 3.2-3.

Panels similar in layout and size to the LOX and LH_2 panels will also be required on the orbiter skin for connection to the GSE when the Tug is within the cargo bay.

Table 3.2-3. Aft Panel Details

Helium Purge - 1 inch - 3000 PSIA
Insulation Repressurization - 0.5 inch - 15 PSIA
Electrical Connector - 24 Shell Size

Prior to deploying or removing the Tug from the cargo bay, the LOX and LH_2 mating umbilicals of the Orbiter will be withdrawn (perpendicular to Tug) from the panel at the Tug skin by means of an electrically driven screw and cam arrangement as shown in Figure 3.2-2. This mechanism is outside the cargo bay but within the framework of the Orbiter. The reverse operation is used when the Tug is returned to the cargo bay.

The disconnects on the aft panel are mated or demated with the matching disconnects on the support structure as the Tug is either attached or separated from the orbiter.

3.3 WEIGHTS

Table 3.3-1 shows the Tug weight breakdown for the baseline roundtrip geosynchronous mission. Also presented in the table are the "bogey" weight breakdown furnished by NASA-MSFC as part of the Study Guidelines.

The weights shown are the result of detailed drawing analysis as well as data received from mechanical and astrionic equipment manufacturers.

Tug structural elements, the meteoroid shield, tanks, insulation and mechanisms reflect nominal gages established from stress analyses and include the effects of manufacturing tolerances. The weights also account for all identified cutouts, weld lands and bosses. In addition, support provisions for all equipment are included. Astrionics weights are composed of the specified equipment and the associated wiring. Harness layouts were constructed to aid in assessing wire and connector weights.

A similar procedure was followed for the propulsion system equipment. Although the engine weight was provided by the Study Guidelines, all other weights result from detailed analyses. Tubing, unions, elbows, gimbals and bellows, as well as all plumbing and lines, were assessed from routing drawings and specifications.

The fluids and gases weights including consumables and non-consumables are based on performance and components duty cycle analyses following the mission profile.

The resulting weight breakdown has the confidence level commensurate with the analytical depth performed in the point design study. In addition, it incorporates the necessary allowances to preclude any significant variations should the development of the vehicle be continued with the established criteria and mission requirements.

Table 3.3-1 Tug Weight Statement

ITEM	WEIGHT (LB) MSFC BOGEY	NR POINT DESIGN
STRUCTURE	(2552)	(1769)
FUEL TANK (INCL. SCREENS, BAFFLES, ETC.)		373
OXIDIZER TANK (INCL. SCREENS, BAFFLES, ETC.)		319
FUEL TANK SUPPORTS		16
OXIDIZER TANK SUPPORTS		28
OUTER SHELL		742
METEOROID SHIELD		46
THRUST STRUCTURE		[illegible]
TUG/PAYLOAD DOCKING MECH.		70
TUG/EOS DOCKING MECH.		30
UMBILICALS		15
SUBSYSTEM MOUNTING HARDWARE		100
THERMAL CONTROL SYSTEM	(476)	(275)
FUEL TANK INSULATION		83
OXIDIZER TANK INSULATION		60
PURGE BAG VALVES AND LINES		79
THERMAL CONTROL SYSTEM		53
ASTRIONICS	(1011)	(869)
DATA MANAGEMENT		120
GUIDANCE, NAVIGATION, AND CONTROL		133
COMMUNICATIONS		55
INSTRUMENTATION		122
ELECTRICAL POWER		166
POWER CONVERSION AND DIST.		198
RENDEZVOUS AND DOCKING		75
PROPULSION	(1057)	(924)
MAIN ENGINE		230
PRESSURIZATION SYSTEM		59
FEED, FILL, DRAIN & VENT SYSTEMS		200
GIMBAL AND ACTUATION SYSTEM		40
ATTITUDE CONTROL SYSTEM (THRUSTERS, LINES, VALVES, TANKS)		360
PROPELLANT UTILIZATION SYSTEM		35
DRY WEIGHT	5096	3837
CONTINGENCY 10% DRY WEIGHT	510	383
DRY WEIGHT + CONTINGENCY	5606	4220
NON USABLE FLUIDS	(842)	(1068)
TRAPPED PROPELLANTS AND GASSES	492	295
PRESSURANT		423
MAIN ENGINE RESERVES (2% OF ΔV)	350	350
THERMAL CONTROL FLUIDS		
BURNOUT WEIGHT	6448	5288
*USABLE MAIN ENGINE PROPELLANT	55148	54027
USABLE ACS PROPELLANT	404	153
START/STOP LOSSES		85
VENTED PROPELLANTS		151
FUEL CELL REACTANTS		125
CHILLDOWN LOSSES		
*GROSS TUG WEIGHT AT TUG/EOS SEPARATION	62000	59829
PAYLOAD CHARGEABLE INTERFACE PROVISIONS		492
FORWARD SUPPORT RING AND DOCKING MECH.		100
PAYLOAD AND TUG SNUBBER AND DAMPER SYSTEMS		794
PURGE SYSTEMS (INCL. TANKS, LINES, FLUIDS)		65
EOS/TUG SERVICE SYSTEMS		
PAYLOAD WEIGHT	3000	3720
GROSS PAYLOAD WEIGHT AT EOS LIFTOFF	65,000	
*TUG $\lambda = \frac{\text{USABLE MAIN ENGINE PROPELLANT}}{\text{GROSS TUG WEIGHT AT TUG/EOS SEPARATION}} = .903$		

Presented in Table 3.3-2 and Figure 3.3-1 are the sequenced mass properties variation following the baseline mission profile.

Table 3.3-2 Sequence Mass Properties Statement

CONFIGURATION: 3720 LB PAYLOAD TO GEOSYNCHRONOUS ORBIT AND RETURN							
MISSION EVENT	WEIGHT LB	CENTER OF GRAVITY			MOMENT OF INERTIA		
		INCHES			SLUG FT^2		
		X	Y	Z	I_{x-x}	I_{y-y}	I_{z-z}
GROSS IN EOS CARGO BAY (ASCENT)	65,000	223.8	0.2	0.3	8,728	227,406	227,144
TUG SUPPORT AND INTERFACE SYS.	- 1,451						
SEPARATION PROPELLANT	- 67						
IGNITION	63,482	227.1	0.2	0.3	7,660	218,436	218,174
PROPELLANT	- 27,287						
ORBIT INSERTION (100 x SYNC)	36,195	231.7	0.3	0.5	7,659	181,730	181,469
PROPELLANT	- 11,721						
CIRCULARIZED ORBIT (GEOSYNCHRONOUS)	24,474	251.0	0.5	0.8	7,657	163,267	163,006
PROPELLANT	- 198						
DEPLOY PAYLOAD	- 3,720						
PHASE FOR RENDEZVOUS 2ND PAYLOAD	20,556	187.1	0.6	1.0	4,409	36,721	36,461
PROPELLANT	- 534						
PAYLOAD	+ 3,720						
PHASE FOR RETURN TO SHUTTLE	23,742	252.5	0.5	0.8	7,657	161,990	161,729
PROPELLANT	- 7,540						
ORBIT INSERTION (270 CIRCULAR)	16,202	288.7	0.7	1.2	7,655	141,128	140,868
PROPELLANT	- 6,426						
ORBIT INSERTION (100 CIRCULAR)	9,776	373.5	1.2	2.0	7,650	98,308	98,050
PROPELLANT	- 768						
DOCK TO SHUTTLE	9,008	391.0	1.3	2.2	7,649	90,080	89,823
VENT PROPELLANT	- 1,068						
PURGE GAS	+ 72						
TUG SUPPORT & INTERFACE SYS.	+ 1,379						
GROSS IN EOS CARGO BAY (RETURN)	9,391	367.1	1.3	2.1	8,662	109,142	108,899

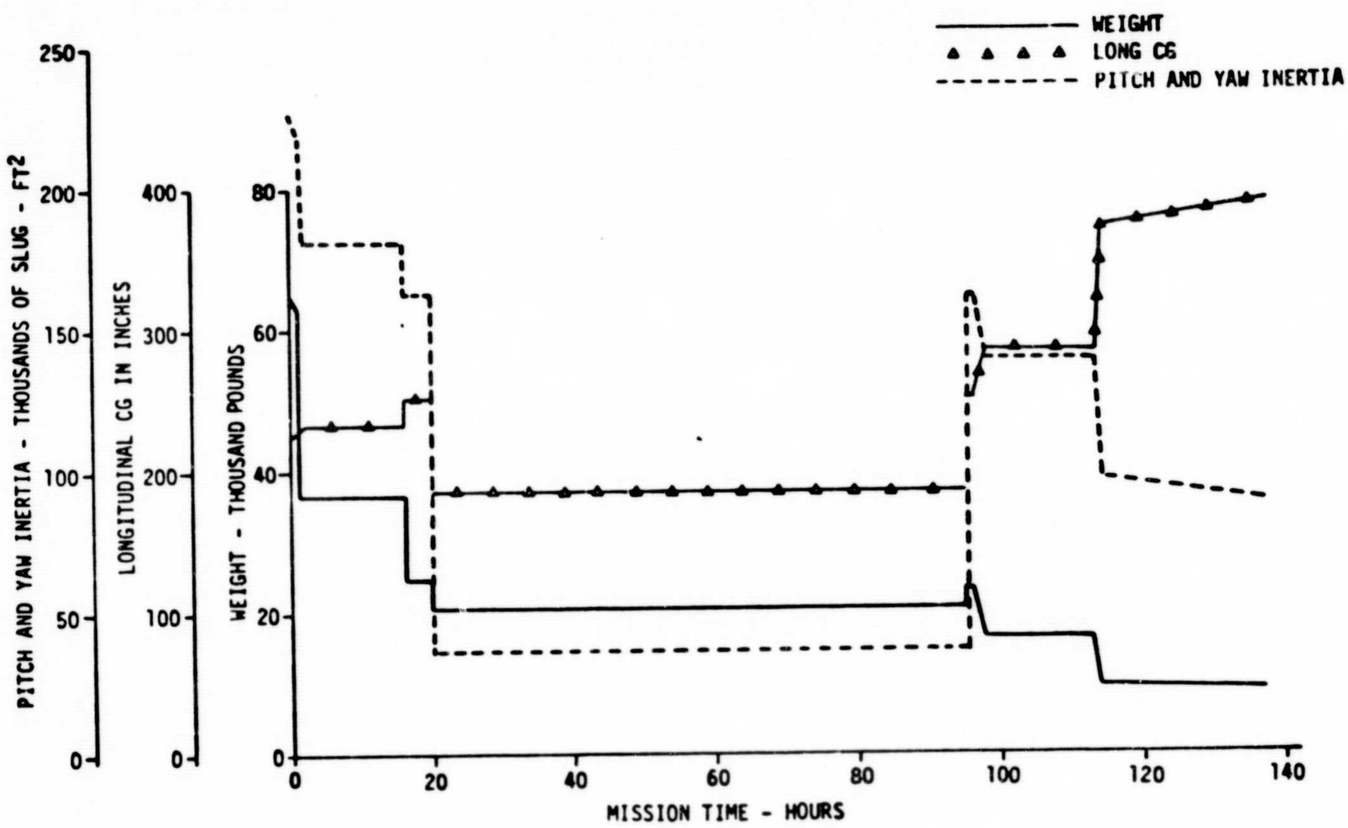


Figure 3.3-1 Mass Properties Variation with Mission Time
3720 lb Payload to Geosynchronous Orbit and Return

3.4 PERFORMANCE

In accordance with the performance groundrules summarized in Table 3.4-1 a Shuttle with an assumed 65,000 pound payload capability is used to fly the Tug from the ground into a 100 nautical mile parking orbit. Throughout the 6 day mission, the Shuttle awaits the return of the Tug and returns it to ground base.

The baseline mission calls for the Tug to fly from the 100 nautical mile parking orbit into an equatorial geosynchronous orbit. Once there, the Tug separates the outbound payload and picks up a second payload which it returns to the Shuttle bay for transit back to the earth. The same Tug is also required to fly the alternate missions listed. Note that the first alternate mission is a payload placement whereas the second alternate mission is a retrieval mission. Since the alternate missions call for the handling one-way payloads only, that portion of their ΔV budgets assigned to phasing and rendezvous is lower than the baseline mission ΔV budget by 215 ft/sec.

The NASA-furnished ΔV budget for the payload outbound/inbound mission is shown in Table 3.4-2. For comparison purposes, the equivalent ΔV increments as simulated by NR computer programs are also listed. The maximum deviation between any two corresponding entries is less than 10 feet per second.

Table 3.4-1 Flight Performance Groundrules

- GROUND BASED TUG
- MISSION TIME: 6 DAYS ON ORBIT
  1 DAY IN SHUTTLE BAY
- BURNING MIXTURE RATIO = 6:1
- ENGINE CHARACTERISTICS:

ENGINE	THRUST (LB)	SPECIFIC IMPULSE (SEC)	PROPELLANTS
MAIN ENGINE	10,000	470	LOX/LH_2
MAIN ENGINE THROTTLED TO 20% THRUST	2,000	461	LOX/LH_2
RCS	TBD	380	GOX/GH_2

- MISSIONS ASSIGNED:

MISSION	OUTBOUND PAYLOAD (LB)	INBOUND PAYLOAD (LB)
BASELINE	3,000	3,000
ALTERNATE MISSION NO. 1	8060	0
ALTERNATE MISSION NO. 2	0	4160

Table 3.4-2 Delta V Budget Allocation

EVENT	MAIN ENGINE		20% THROTTLED *		APS	
	NASA	NR	NASA	NR	NASA	NR *
SEPARATE FROM SHUTTLE AT 100 nmi					10	10
PERIGEE BURN	8136	8130				
GRAVITY LOSS	310	310				
MID COURSE CORRECTION					50	50
APOGEE BURN	5883	5887				
GRAVITY LOSS	10	10				
STATION KEEPING					30	30
DEPLOY PAYLOAD					10	10
INJECT INTO PHASING ORBIT TO RETRIEVE PAYLOAD			100			100**
RETRIEVE PAYLOAD			100		15	115**
DE-ORBIT	5814	5818				
GRAVITY LOSS	7	7				
MID-COURSE CORRECTION					50	50
CIRCULARIZE IN 270 nmi	7842	7836				
GRAVITY LOSS	25	25				
TRANSFER TO SHUTTLE ORBIT 100 nmi	592	592				
TERMINAL RENDEZVOUS			100		15	115**
DOCK WITH SHUTTLE AT 100 nmi					10	10
CONTINGENCY (2 PERCENT)	572	572				
TOTAL	29,191	29,187	300	0	190	490

* MAIN ENGINE THROTTLED TO 20 PERCENT
** MORE THAN ONE BURN

The three 100 ft/sec ΔV's that are used to achieve phasing, retrieval, and rendezvous have been transferred from the throttled mode column to the APS column. This allocation was made because the phasing, retrieval, and rendezvous maneuvers will, in practice, be broken into two or more smaller burns. For burns of small magnitude, the APS engines are advantageous in that their burning intervals are more realistic and their start/stop losses are negligibly small.

Figure 3.4-1 summarizes the Tug's significant performance parameters in order to pinpoint the vehicle's performance capabilities. The horizontal and vertical scales correspond respectively to the Tug's ignition weight and its allowable burnout weight. Each of the slanting lines, in turn, denotes a specific budget of non propulsive consumables (i.e., fluids on board the vehicle which do not provide any propulsive energy). The non propulsive consumables include boiloff losses, start/stop losses, fuel cell reactants, and attitude control propellants.

The baseline ignition and burnout weights of 60,549 and 4938 pounds respectively are depicted on the plot with the total weight of the non-propulsive consumables (514 pounds). As shown in the figure, the current burnout weight of the Tug could increase by 720 pounds still satisfying the baseline mission requirements. For example, if 7075-T6 aluminum is employed on the outer shell in lieu of the baseline graphite composite the resulting weight increase would be approximately 430 pounds. However, as shown in the figure, the Tug would still be more than able to satisfy the baseline mission requirements. On the other hand, holding the propellant mass fraction at its present value would result in a Tug baseline mission capability of 3720 pounds.

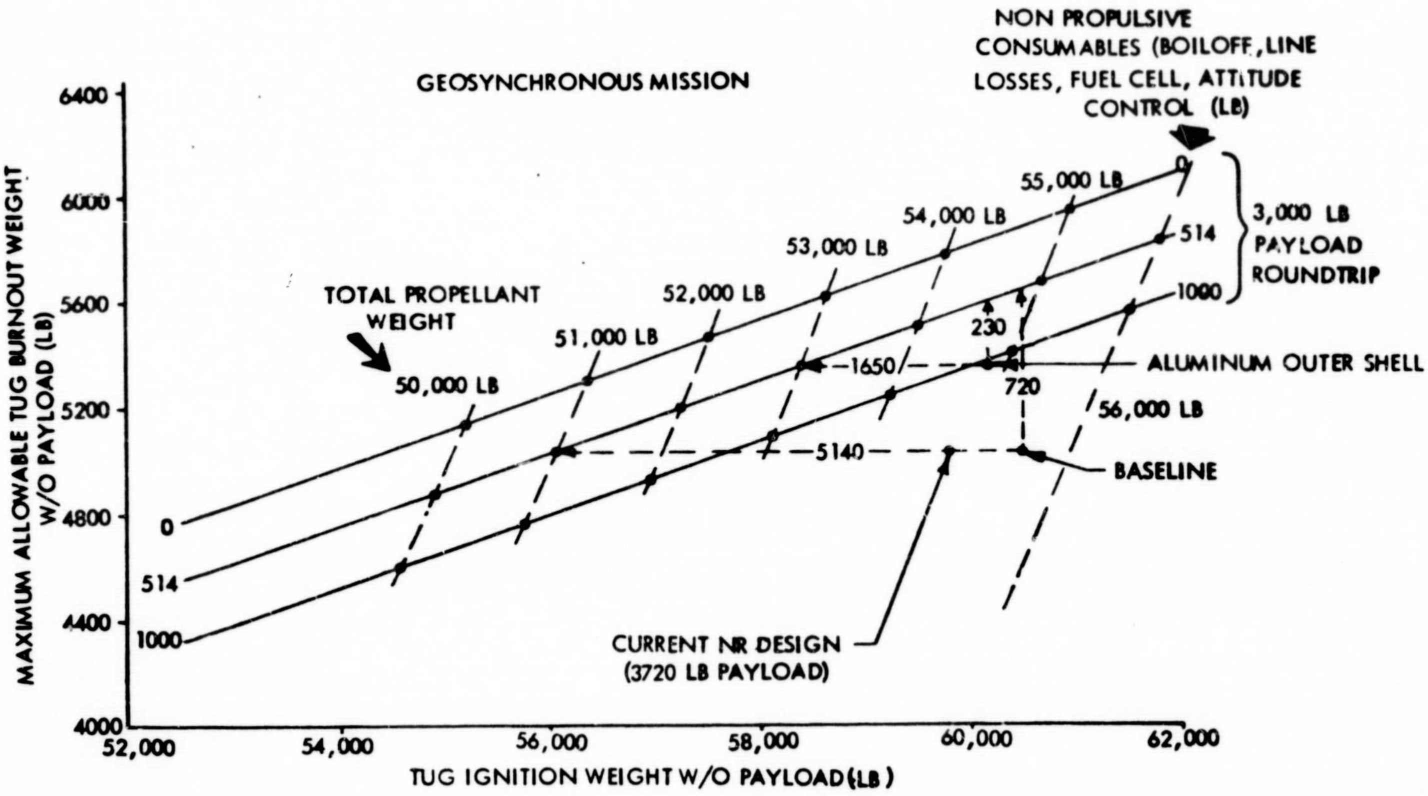


Figure 3.4-2 Tug Baseline Payload Performance Summary

The horizontal line segment of 5140 pounds can be interpreted as an allowable reduction in the Shuttle payload capability. That is, holding the Tug at its present **propellant** ass fraction will allow a Shuttle payload degradation of 5140 pounds, and still satisfy the Tug 3,000 pounds payload mission. It is important to note that the quoted burnout weight does not include the 350 pounds of reserve propellant. However, they are included in the ΔV budget to satisfy the mission.

The results of the point design Tug study has shown that the vehicle can satisfy the established mission requirements with performance to spare. The round-trip geosynchronous mission payload capability is 3720 pounds; 720 pounds above the specified requirements. Further payload increase can be achieved by implementing various performance enhancement techniques. These include employing an optimum thrust engine. The main engine was groundruled at 10,000 pound thrust. However, a 12,500 pound thrust engine would provide the vehicle with approximately 50 pounds of additional payload capability. This gain results from the reduction of the vehicle's 310 ft/sec gravity losses by the higher thrust-to-weight ratio. At still higher thrust levels, the gravity loss continues to decline but the extra gains are more than offset by the increased engine weight. However, a thrust level slightly higher than 12,500 pounds would be advantageous in that it would make the vehicle less sensitive to statistical performance variations and payload weight increases.

According to the point-design mission groundrules, the Tug must return from its orbit at the geosynchronous altitude via a 270 nautical mile circular phasing orbit. The use of circular phasing orbits is somewhat inefficient because the vehicle must make its circularization burn at an unnecessarily high altitude and thus some of the potential energy intrinsic to its propellant supply is wasted. The lower the altitude of the burn, the more of the potential energy that can be salvaged. The altitude of the burn can be lowered by utilizing elliptical phasing orbits thereby accruing a net performance saving of approximately 220 ft/sec.

Adjustments in the average phasing rate can be made by varying the apogee altitude of the phasing orbit. Investigations show that the apogee altitude can be raised at a cost of only 2 ft/sec per 100 nautical miles.

Another technique that would result in performance improvement to the Tug is the usage of multiorbit injection. In boosting upward toward the geosynchronous altitude, the Tug sustains a nominal gravity loss of 310 ft/sec. This loss stems from the fact that during its burn, the vehicle swings outward away from the center of the earth and hence its engines expend unnecessary energy in carrying the propellants upward against the pull of gravity. The multiorbit injection technique can be used to reduce the gravity losses at a cost of slightly increased mission complexity. Essentially, the vehicle's burning program is broken into a series of shorter burns each of which straddles the perigee of a set of ever elongating transition ellipses. This technique effectively constrains the vehicle to a relatively low altitude throughout its entire burning profile. Optimal vehicle performance is provided by a four-burn maneuver sequence. In comparison with a single-burn insertion, the four-burn sequence yields a gain of 124 pounds of allowable burnout weight but increases the mission duration by about 10 hours.

The improvements briefly outlined above would provide another 200 to 300 pounds of extra payload capability to the Tug. In summary, the results of the study have shown that the baseline Tug can meet the mission requirements established by NASA-MSFC.

3.5 RELIABILITY AND SAFETY

The MSFC study plan for the Tug Point Design did not specify a reliability goal. However, based upon Apollo and Saturn II experience, factoring in growth with the use of 1976 technology, an apportionment goal for mission success probability was developed which exceeded 0.9. Design criteria as specified in the study plan stated a requirement for fail safe performance.

A comprehensive Failure Mode Effect Analysis (FMEA) was performed on all Tug subsystems to identify single failure points and the resultant effect on the Shuttle crew and Tug mission objectives. The results of this FMEA indicated no critical single failure points involving functional equipment. Eight helium receivers and two APS accumulators were identified as critical to Shuttle crew should rupture of the vessels occur. These failures are of low probability of occurrence.

A preliminary hazard analysis disclosed several areas that warrant further study. These include suborbital abort, hydrogen leakage into the cargo bay, Tug deployment failure to release, and avionics equipment malfunction. The

Tug deployment failure to release would require an emergency release system which could be accommodated at a small weight increase. Fail-safe redundancy has been provided for crew safety in the power and attitude control subsystems to satisfy design requirements. The suborbital abort and hydrogen leakage into the bay were given further consideration and the results are presented below under the appropriate headings.

Tug Reliability Prediction

The fail safe criterion defines a single string component series for operation. Following this criterion, the baseline point design success logic for the Tug system with projected 1976 hi-reliability components was assessed at 0.8097 as shown in Figure 3.5-1. Two options which can potentially raise this success probability were formulated and investigated. The first option introduces a single standby Data Acquisition Unit and Interface Unit into the Data Management Subsystem for transmitting only critical and mandatory vehicle commands and data. This would be used in a degraded operational mode wherein some vehicle status loss and some loss of trajectory precision, navigation updates, etc. would occur. A weight penalty of 16.8 pounds is incurred while raising the Tug success probability to 0.9117 as shown in the figure.

The second option introduces a second computer unit into the DMS in addition to the configuration of the first option. The total weight penalty is now 42.8 pounds and Tug success probability is elevated to 0.9138. This again is a degraded operational mode, although better than the first option. This principle may be extended to other subsystems and components to achieve further reliability gains at minimal weight penalty.

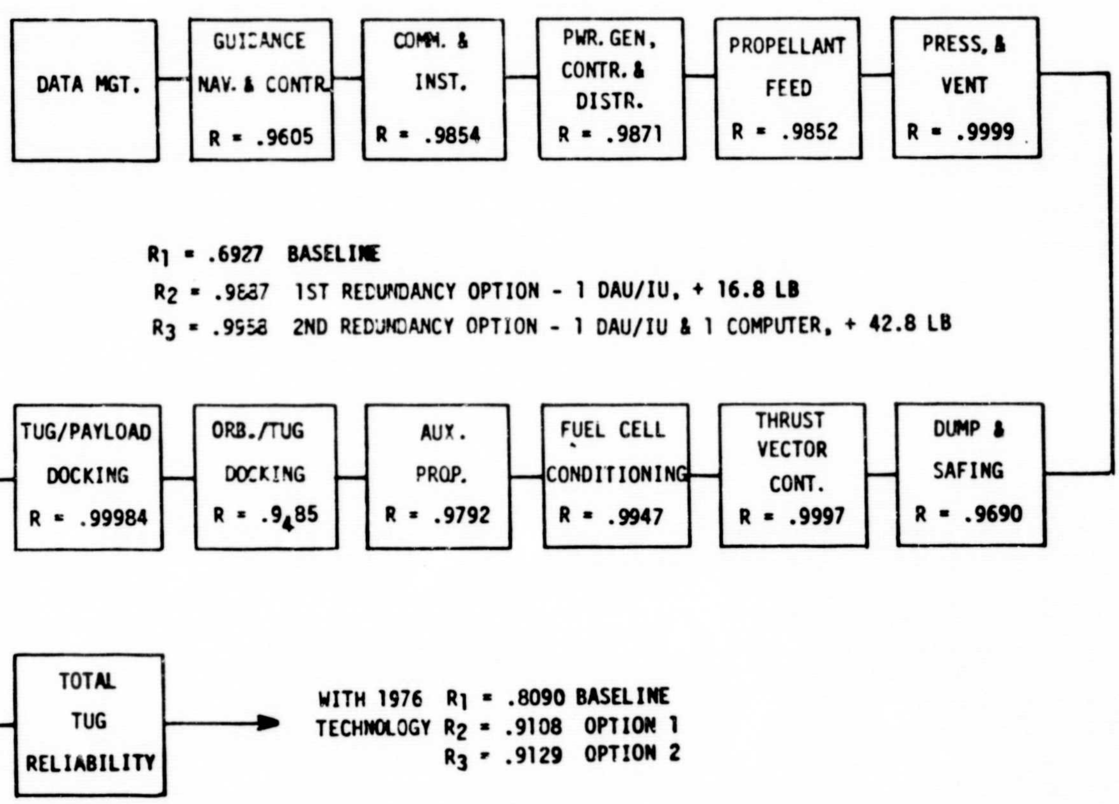


Figure 3.5-1 Tug Reliability Prediction

Hydrogen Leakage Into Cargo Bay On Re-Entry

The Tug design contains approximately 230 joints or interfaces that would be exposed to hydrogen under pressure. Assuming all joints to be 2.5 inch diameter flanged joints, for which the leakage rate is 10^{-2} scc/day/inch of seal, the total leakage would be 0.25 scfh. This rate, expanding into the free cargo bay volume where the pressure is 2 mm Hg when reactions are first possible, would give a concentration of 0.38 percent H_2. This is less than 1/10 of the hydrogen concentration necessary to support a reaction. Thus, it is not necessary to inert the Tug hydrogen tank to protect against normal H_2 leakage.

The above discussion pertained to distributed leakage, molecular diffusion and intimate mixing of escaping gases. If the leakage occurs at a point source the escaping jet of gases must be examined separately.

Preconditions:

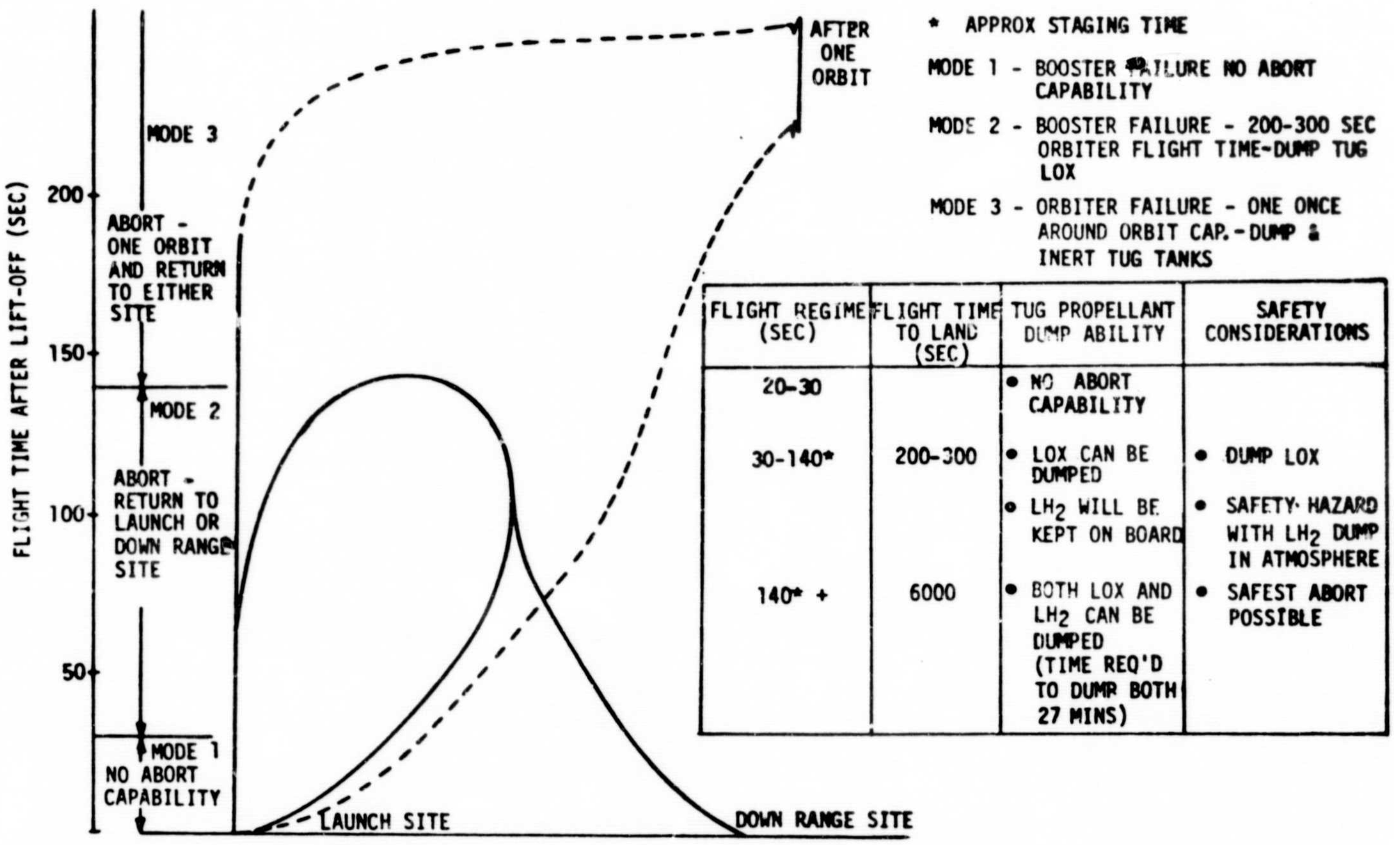
- H_2 - O_2 reactions are possible with a minimum of 2 percent oxygen and 4 percent hydrogen.
- The oxygen will be available from the air that diffuses into the cargo bay on re-entry.
- Reactions can occur at cargo bay pressures of 2 mm Hg or greater.
- H_2 - O_2 reactions will occur in the interface region where the escaping gas and the air mix.

A delta volume of the interface must contain 2 percent O_2, but since air contains 20 percent oxygen, 5 x 2 percent or 10 percent of the delta volume must be air, the remaining 90 percent or 0.9 of the mixture must contain enough H_2 to bring the hydrogen content to 4 percent. Therefore 4 percent/0.9 = 4.5 percent in the jet is required.

If the Shuttle is to be protected against point source or blowing leaks from the Tug by inerting the H_2 tank, then the H_2 content must be 4.5 percent or less. This can be essentially attained without a weight increase by precluding inerting of the LOX tank and increasing the number of helium inerting cycles to three in the LH_2 tank from the baselined two cycles.

Shuttle Abort Envelope

The Shuttle abort envelope at the present time can be divided into 3 modes. Mode 1 is indicative of a booster failure. During this mode, there is no abort capability as shown in Figure 3.5-2. Mode 1 is the time span from 20-30 seconds after lift-off. Mode 2 is also indicative of a booster failure. There are two abort plans for this mode which are also shown in the figure. The orbiter is capable of separating from the booster and flying to either the launch site or a down range site. Flight time to land is approximately 200-300 seconds which is enough time to use up the orbiter main engine propellants and sets the time limits for dumping the liquid oxygen from the Tug. LOX is the safer to dump



FLIGHT REGIME (SEC)	FLIGHT TIME TO LAND (SEC)	TUG PROPELLANT DUMP ABILITY	SAFETY CONSIDERATIONS
20-30		• NO ABORT CAPABILITY	
30-140*	200-300	• LOX CAN BE DUMPED • LH_2 WILL BE KEPT ON BOARD	• DUMP LOX • SAFETY HAZARD WITH LH_2 DUMP IN ATMOSPHERE
140* +	6000	• BOTH LOX AND LH_2 CAN BE DUMPED (TIME REQ'D TO DUMP BOTH 27 MINS)	• SAFEST ABORT POSSIBLE

Figure 3.5-2 Shuttle Abort Envelope

due to combustion potential of atmospheric oxygen and the liquid hydrogen. Mode 2 is the time span from 30 to 140 seconds (approximate time of staging) after lift-off.

Mode 3 is indicative of an orbiter failure. The orbiter has capability to achieve one earth orbit and then de-orbit and land at either site. During orbit time (approximately 90 minutes), the Tug can dump all propellants and inert tanks as necessary.

This information was obtained from an analysis performed by the NR Shuttle program on the sub-orbital abort capabilities of the Shuttle orbiter. The analysis was adapted to the Tug study for that phase of the mission where the Tug is in the Shuttle orbiter cargo bay.

3.6 PROGRAM REQUIREMENTS

The program requirements including manufacturing, test operations, facilties, quality assurance, technology, and scheduling were developed to ascertain the producibility and schedule requirements of the baseline design including maintenance and refurbishment. In addition, these requirements aided in the cost analyses which include development, first unit cost, supporting research and technology, and refurbishment.

Two plans were requested by NASA-MSFC as output of the effort, i.e., a Maintenance and Refurbishment Plan and a Supporting Research and Technology Plan, and consequently these areas were highlighted in the study.

Maintenance and Refurbishment

The Space Tug maintenance and refurbishment (M&R) plan utilizes an "on-condition" maintenance concept essentially similar to that currently used by commercial airlines and military operations, and planned for the Space Shuttle system use. Under this concept, the need for specific maintenance action is determined on the basis of measurement, observation, or performance analysis. Maintenance is performed when a red-line condition is indicated, or an item fails, rather than on a pre-determined or repetitive time interval except for those components with short lifetimes requiring periodic replacement. The "on-condition" concept reduces the potential of maintenance-induced errors, and in addition, serves to decrease the support required for the traditional specified maintenance intervals.

The goal of maintenance planning under this concept is to provide a proper balance between preventive and corrective maintenance. Preventive maintenance is that performed to retain an item in an operational condition through systematic inspection, adjustment, calibration, cleaning, replacement, checkout, etc., at established intervals. The preventive maintenance approach will be applied to items that exhibit a wear-out mode of failure. Corrective maintenance is that performed to restore an item to an operational condition after a premature malfunction occurs.

The "on-condition" maintenance approach, including the flow of repair or replace items under preventive or corrective maintenance, is represented by the top level M&R cycle shown in Figure 3.6-1. Turnaround time for the Tug, as

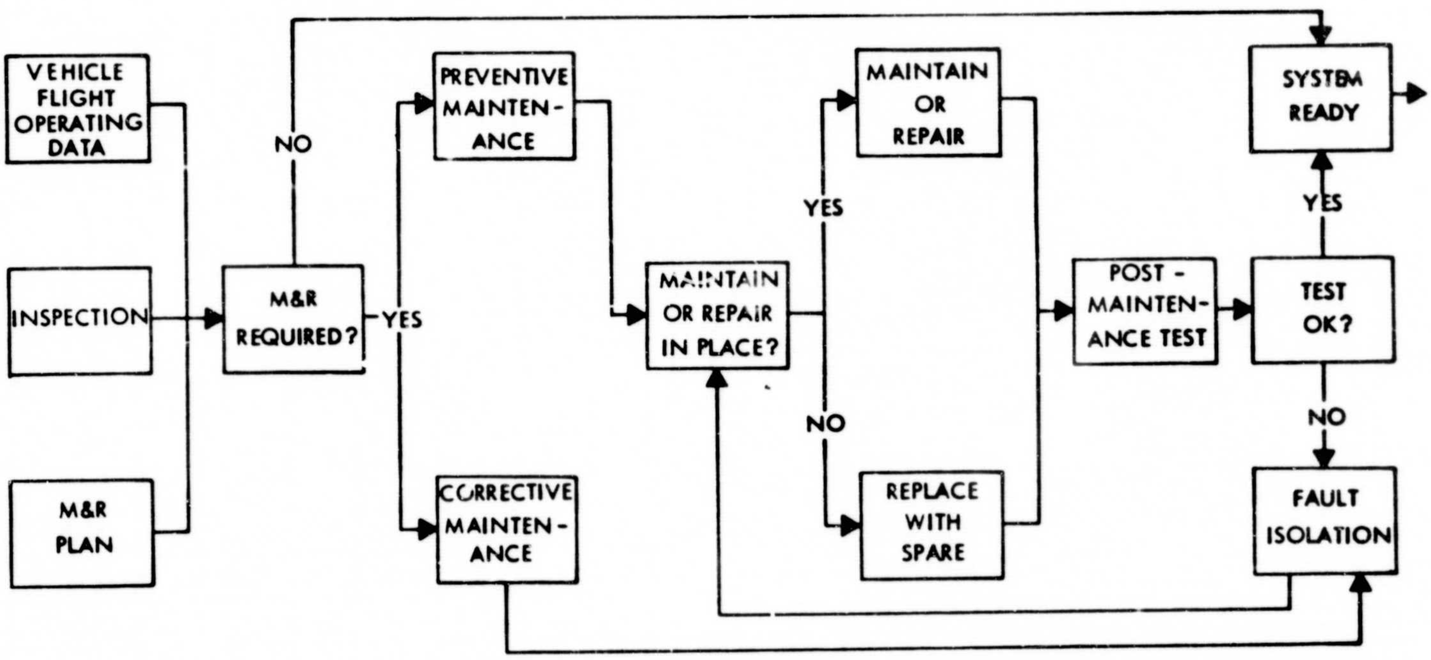


Figure 3.6-1 Maintenance & Refurbishment Cycle

shown in the timeline (Figure 3.6-2), is five and one-quarter days, based on a two-shift operation. Maintenance times were developed from task analyses conducted for each subsystem and component. The separate estimates for each task were then combined in sequence to establish a maintenance operations envelope. In addition to the two working days provided for post-landing operations and the 10 hours alloted to post-maintenance testing, fifty-four working hours have been provided for basic maintenance starting with the time the Tug is delivered to the maintenance facility. This time includes the "look and fix" functions of maintenance and is considered to be the maximum turnaround time necessary during the operational phase.

Supporting Research and Technology

From the point design and previous Tug/OOS design studies, the 1976 baseline technology requirements have been identified in all relevant areas (Figure 3.6-3). Several kinds of supporting research and technology (SR&T) effort can be utilized in the Tug development program as shown in the figure. In a number of cases the technology can be provided from other programs or on-going research effort having appropriate system/subsystem philosophies and technology levels, (i.e., B-1, Skylab, Shuttle, USAF/RPL and LeRC/MSFC engine development, etc.). Such utilization has the obvious advantage of minimizing development costs chargeable to the Tug. However, it must be noted that there are a number of currently-funded efforts (such as the high performance engine research being sponsored by AFRPL, the APS studies supported by LeRC and MSFC, and the MSFC laser rendezvous radar) which need to be oriented toward Tug application.

GUIDELINES:
- SPACE SHUTTLE GROUND OPERATIONS TIMELINE
- PREVIOUS STUDY FINDINGS
- ESTIMATE OF MANHOURS REQUIRED PER TASK BASED ON COMPANY AND INDUSTRY EXPERIENCE

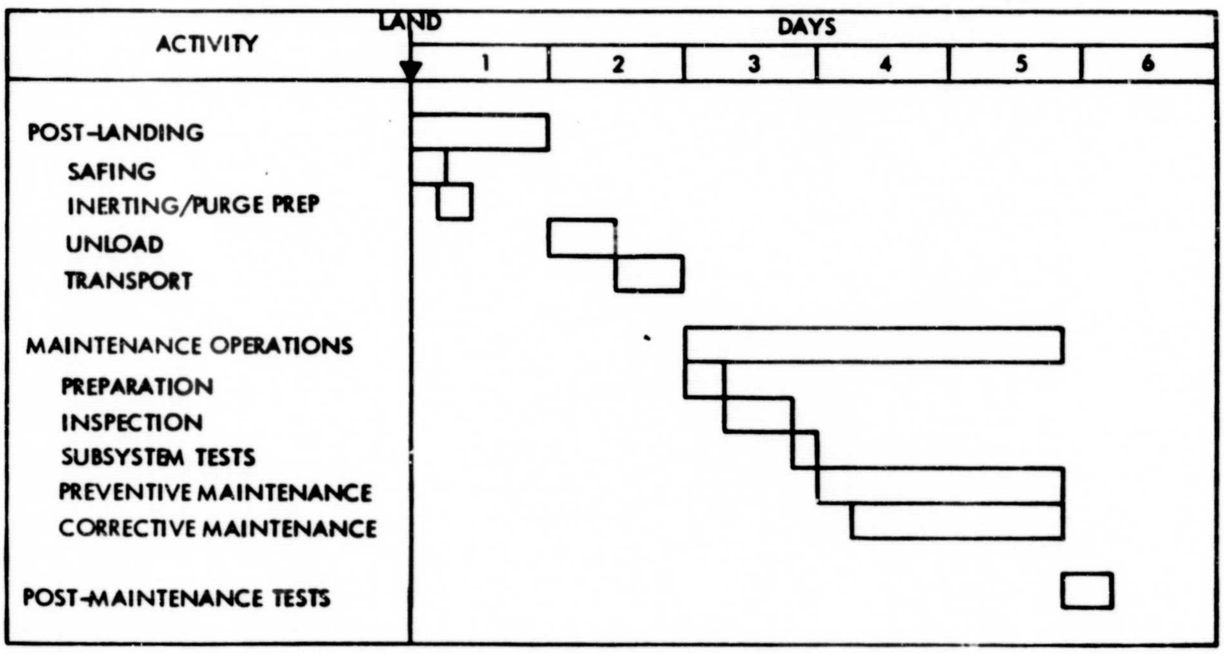


Figure 3.6-2 Maintenance Timeline

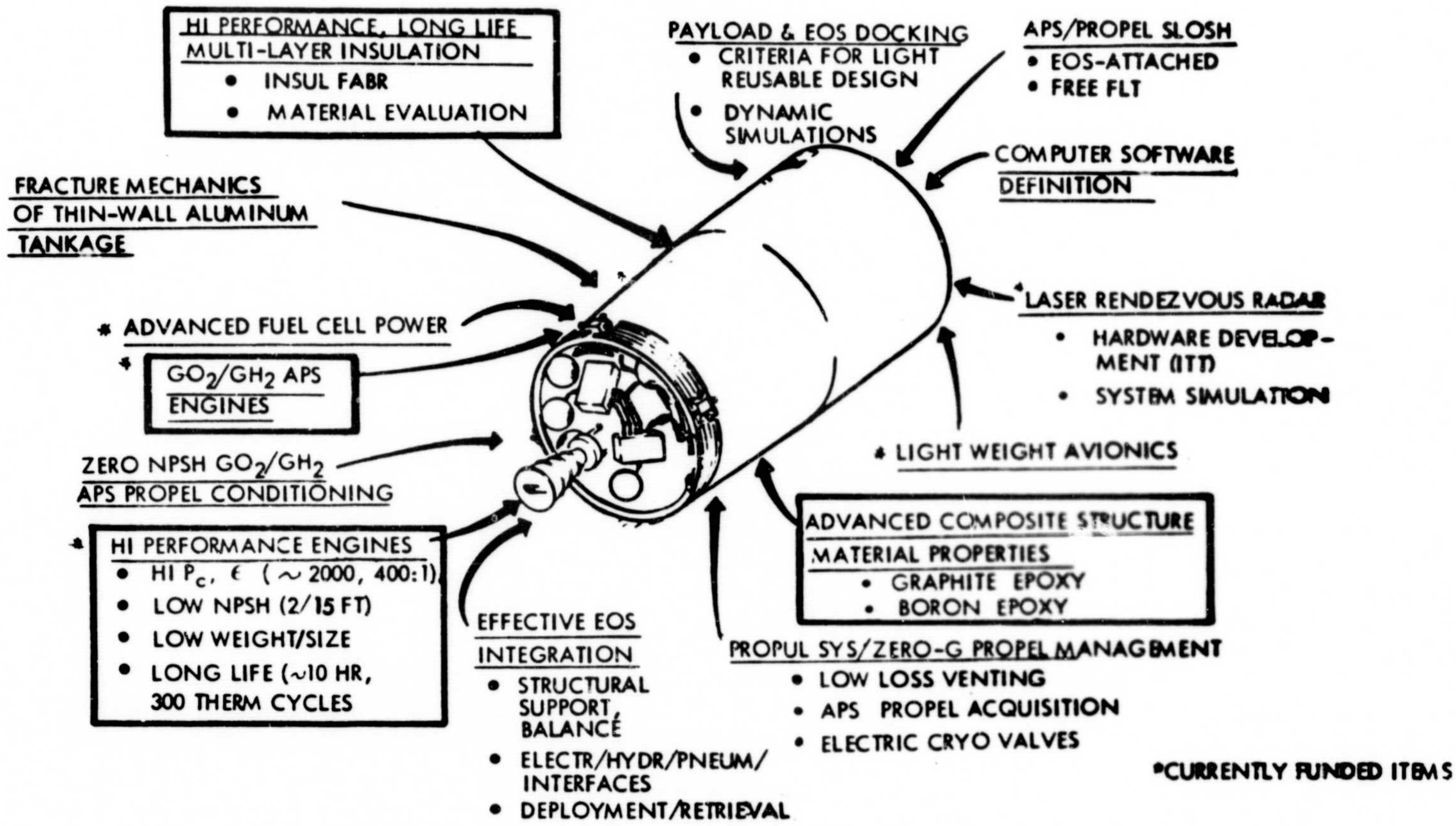


Figure 3.6-3 Research & Technology Areas

This is particularly true for those hardware items which were undertaken to meet requirements of other major programs which have been since changed, thus jeopardizing further support for technologies key to the Tug support.

The other prime source of baseline technology is that which is Tug-unique and must therefore be developed under Tug-sponsored SR&T funding. Especially noteworthy is research on aluminized Kapton (metalizing films, embossing techniques, small scale tank tests, etc.), fracture mechanics of thin-walled aluminum propellant tanks, and tests on advanced composite structure (particularly graphite epoxy to obtain data at low temperatures). Figure 3.6-4 shows a recommended schedule and ROM funding estimates for the key SR&T activities defined in this point-design study.

Another class of possibly desirable technology items are those leading to post-1976 application. For example, further experience with advanced engines should be reasonably expected to yield some additional performance improvement by 1985. This increase is likely to be on the order of 1 second of specific impulse since additional improvement beyond that would undoubtedbly require costly redevelopment of turbo machinery along with higher chamber pressure. Slight weight reduction is likely as well as potentially lower allowable pump NPSP values.

Multi-layer insulation materials and design improvements should enable design of MLI systems able to withstand corrosion and eliminate repressurization

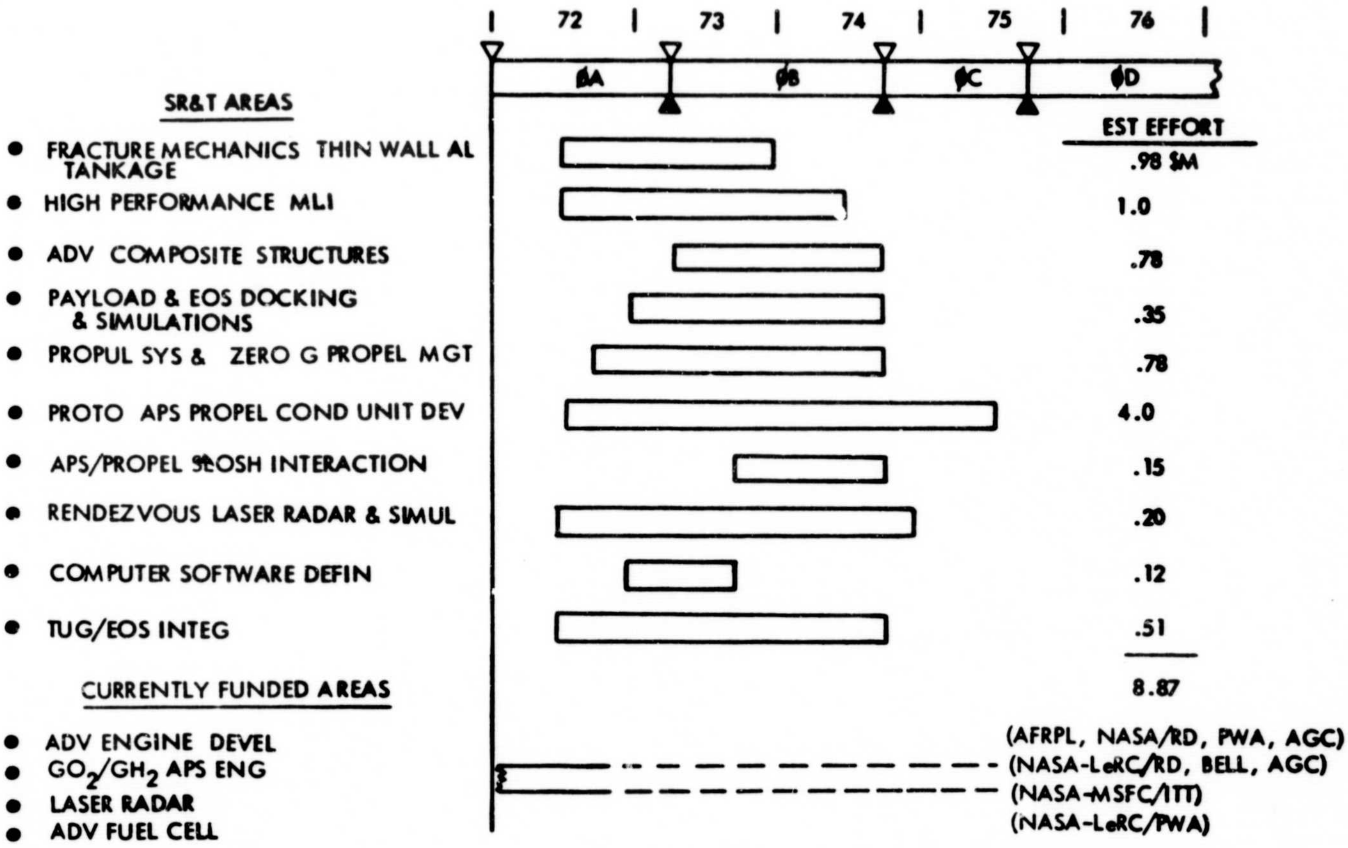


Figure 3.6-4 Point Design Tug SR&T Schedule

requirements thereby providing increase design confidence and weight reduction. Also, improvements in electrical power distribution equipment such as connectors, switches, relays, terminals should result in some further weight reduction.

In avionics, some general decrease in electronic components weights should also be expected with time. A new horizon sensor design which does not require deployment for adequate field of view could simplify vehicle design. A small separate dedicated guidance and navigation computer would simplify software and thus save costs.

Manufacturing

As previously stated the manufacturing study was conducted primarily to verify the producibility of the Tug baseline concept and to provide information necessary for estimating program costs. The preliminary requirements identified during the study will serve as the basis for development of a supporting manufacturing plan during subsequent phases of the program.

The Manufacturing Flow Schedule shown in Figure 3.6-5 was developed based on manufacturing estimates and previous experience with vehicles of similar design and construction. The bars on the flow schedule representing the six major structural components of the Space Tug are not detailed, but are intended to include all the activities necessary for production of the item from material procurement through detail fabrication, panel fabrication, welding, insulation, mating and assembly. Production time for a single vehicle based on a single

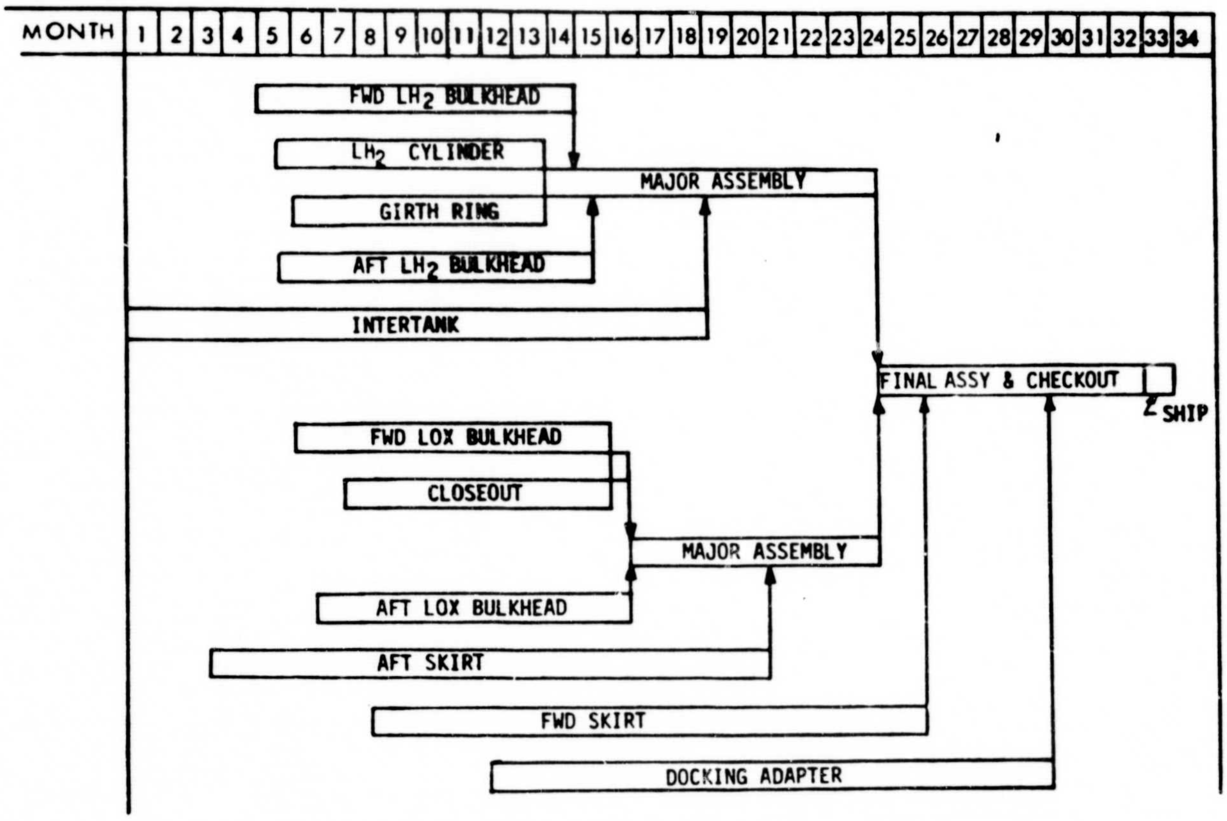


Figure 3.6-5 Manufacturing Flow Schedule

shift operation is 33 months. This is a "nominal" production schedule and is not intended to represent either a minimum or maximum time requirement.

In-house experience with aluminized mylar provides a solid base for the use of aluminized Kapton insulation proposed for the Space Tug. The fabrication of structural components from graphite epoxy is considered current technology from the manufacturing standpoint, although tooling development is believed necessary to reduce dependence upon manual layup methods and to assure uniform reproducibility of graphite epoxy tubes, struts, frames, and sheets.

Test Operations

The objectives of the test planning accomplished in support of the Space Tug were to define test requirements and identify the test hardware necessary to accomplish the test program. The planning resulted in a test program which includes testing from development through qualification, design verification, acceptance and flight test. The purpose of the test program is to evaluate and verify materials and processes, evaluate design concepts and system performance and verify the vehicle manufacture and assembly process. Test hardware requirements include a complete outer shell, an engine thrust structure, an LH_2 tank, a LOX tank/thrust structure combination, a "battleship," and one flight test vehicle.

Both the tanks and the shell of the battleship vehicle will be constructed of heavy gage aluminum. The objectives of the battleship program are to supply design information, demonstrate systems adequacy and evaluate systems performance under simulated operational requirements. Data generated from static firing of the battleship provide valuable early data prior to static firing tests on the flight test vehicle. Additionally, flight type components and subsystems installed for support of the battleship test program will be utilized for support and evaluation of the operational software system.

The flight test vehicle will undergo two cycles of thermal vacuum testing - one at the MSC facility utilizing a pressure of 10^{-4} Torr, and a second at KSC at a pressure of 10^{-2} Torr. Operational vehicles will subsequently be subjected to the latter cycle only for acceptance requirements.

Preliminary test planning indicates one flight test vehicle to be sufficient for the test program considering the early static firing data support from the battleship program and the early availability of an operational vehicle to serve as a backup flight test vehicle if required. This position is preliminary, however, and will be subject to change as test requirements are more carefully defined during subsequent program phases.

Facilities

Facilities planning was conducted to verify that there would be no serious facilities-related problems which could affect future Tug support requirements.

In facilities planning, there were three primary considerations: 1) maximum utilization of existing facilities, 2) testing to be as close as possible to the base of operations, and 3) operational compatibility with Shuttle facilities requirements.

The facilities survey confirmed that no new facilities would be required to support the Tug Program, and that there were no facilities problems which might be expected to impact program support in the future.

Figures 3.6-6 and 3.6-7 provide a list of the development test and program facilities requirements for the Tug Program, and the preliminary sites selected to support each requirement.

Quality Assurance

The Quality Assurance approach to the Tug concept concentrated on the coordination required with design engineering to insure inspectability and verification of the engineering design intent. Engineering personnel responsible for structures, avionics, propulsion and thermal design concepts have been exposed to demonstrations of non-destructive testing (NDT) and current techniques which can be used for inspection of the interior and exterior sections of tanks, lines, etc. Early design determination of defect criteria and accessibility provisions for NDT equipment will permit inspections that previously required man-entrance. Any one or a combination of NDT applications may be required during the manufacturing, test or maintenance cycles. The NDT techniques, including fiber optics, ultrasonics, microwave, acoustic emission, thermography, infra red and ultra violet photography, and radiometrics are either current or expected to be available to support Tug technology requirements.

		NR DOWNEY	NR OFF-SITE	MSFC	MSC	KSC	
STATIC TEST	OUTER SHELL	X					
	THRUST STRUCTURE	X					
	LOX TANK/THRUST STRUCTURE		X				SANTA SUSANA
	LH_2 TANK		X				ALT. EDWARDS
DYNAMIC TEST	ACOUSTIC						
	THRUST STRUCTURE			X			
	LOX TANK--THRUST STRUCT-AFT SHELL			X			
	LH_2 TANK--FWD SHELL SEGMENT			X			
	COMPONENTS	X					
	ELECTRO-MECHANICAL COMPONENTS	X					
"BATTLESHIP" PROP SYS.	COLD FLOW/HOT FIRING		X				SANTA SUSANA; ALT--EDWARDS
FLIGHT TEST VEHICLE	POST-MANUFACTURING C/O (INTEGRATED)	X					
	COLD FLOW & STATIC FIRING			X			ALT: MTF
	THERMAL VACUUM				X	X	
	POST-DELIVERY C/O & P/L INTEGRATION					X	O&C BLDG.
	EMI/RFI COMPATIBILITY					X	O&C BLDG.
	SHUTTLE CARGO BAY INSERTION					X	VAB
	MAINT/REFURBISHMENT CYCLE VERIFICATION					X	SAFING PAD + O&C
	SHUTTLE ERECTION					X	VAB
	PAD INTERFACE VERIFICATION & REMOVAL					X	L/C 39 PAD
	FLIGHT TEST					X	L/C 39, MSFN, DSN

Figure 3.6-6 Development Test Facilities

		NR DOWNEY	NR OFF-SITE	KSC	OTHER	
MANUFACTURING	STRUCTURE	X				
	CRYOGENIC PROOF PRESSURE TEST		X			
	FUNCTIONAL SUBSYSTEMS	X			X	CONTR & VENDORS
	ASSEMBLY, SYSTEMS INSTALLATION & C/O	X				
	POST-MANUFACTURING CHECKOUT	X				
OPERATIONS	POST-DELIVERY C/O & PAYLOAD INTEGRATION			X		O&C BLDG
	SHUTTLE ORBITER INTERFACE			X		VAB
	LAUNCH			X		L/C 39
	FLIGHT			X		L/C 39, MSFN, DSN
MAINTENANCE & REFURBISH. CYCLE	SAFING			X		L/C 39 SAFING PAD
	LEVEL I & II M&R			X		O&C BLDG
	LEVEL III M&R	X			X	CONTRACTOR & VENDORS
	SUPPORTING RESEARCH & TECHNOL	X			X	CONTRACTOR & SUBCONTRACTORS

Figure 3.6-7 Program Facilities

Preliminary Program Development Schedule

The Preliminary Program Development Schedule (Figure 3.6-8) summarizes the major program milestones and activities necessary for the design, development, production, and test, of an operational Tug. The schedule is in consonance with the individual manufacturing and test schedules that were developed for this study. It was constructed employing techniques developed by NR during previous programs with changes appropriate to Tug requirements. The schedule represents an orderly evolution of events leading to and supporting a Space Tug Program.

Major program phasing depicted in the schedule includes approximately ten months for Phase A (Analysis) followed by eighteen months for Phase B (Definition) and twelve months for Phase C (Design) prior to Phase D (Development/Operations) go-ahead. Phase D activities reflect in more detail the logical sequence of events leading to an operational posture approximately five years from Phase D go-ahead.

The schedule reflects the requirements for one static firing vehicle (battleship of heavy gage aluminum), four structural test articles, and one space flight test/operational vehicle. Two mission-equivalent flight tests are planned prior to IOC. The first dedicated operational vehicle will serve as a backup to the flight test program until initial operational capability is certified. Major tests include static firing, structural testing, vibro-acoustic testing, vibration pogo testing, thermal vacuum testing, and flight testing.

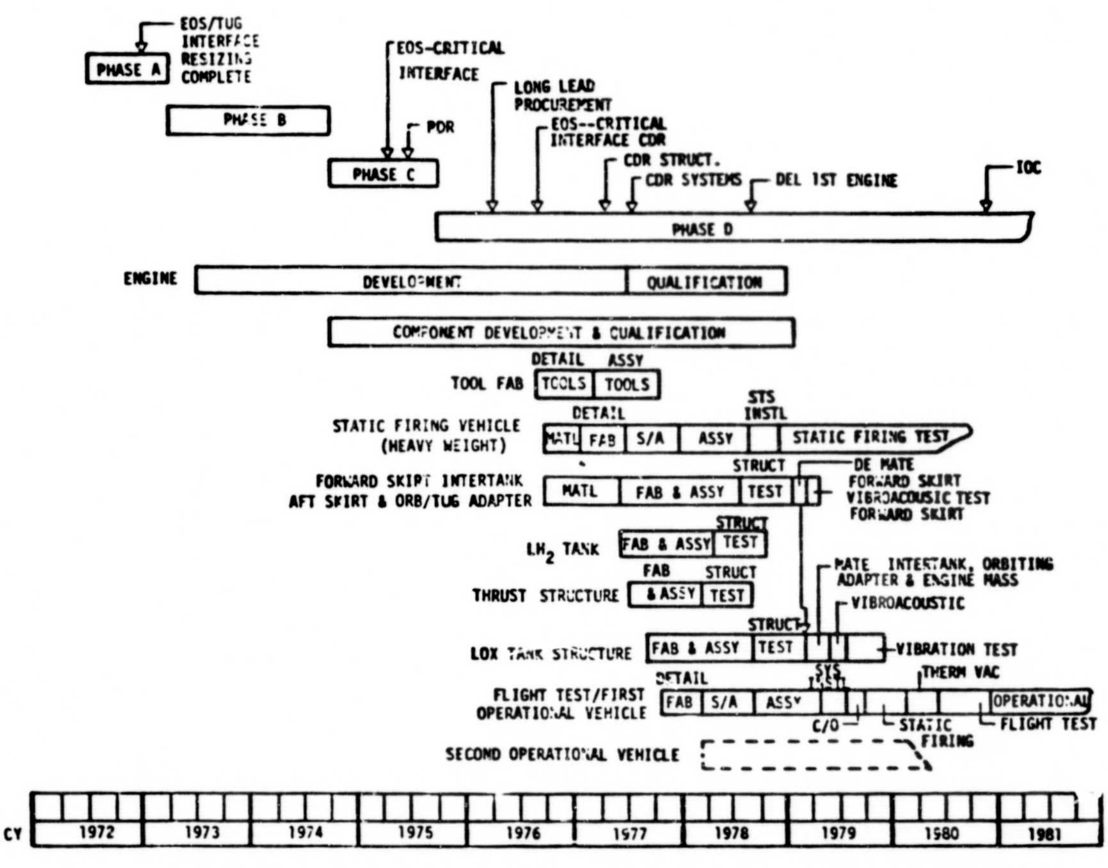


Figure 3.6-8 Preliminary Tug Program Development Schedule

The Program Development Schedule is based on a production rate of three operational vehicles per year, which was determined to be the optimum manufacturing rate considering facilities, tooling, and man-loading requirements.

IOC in late 1980 is approximately a year later than the target of end-of-1979 contained in the study guidelines. If desirable, an earlier date could be accommodated by employing a two- or three-shift manufacturing operation and accelerated testing. It should be noted that the first flight of the Tug occurs about mid-1980. Further studies may indicate the acceptability of carrying a useful payload on this flight.

Space Tug Vehicle Cost

The cost data cover five major categories:

Design, Development, Test and Evaluation (DDT&E)	$505.7M
First Unit Production	25.5M
Technological Advancement	8.9M
Average Flight Maintenance and Refurbishment (M&R)	0.7M
Flight Test Vehicles Refurbishment	3.1M

The DDT&E cost includes all non-recurring effort performed during Phase D excluding facilities, government management, and integrating contractor management. In addition to normal vehicle development cost, the costs of main and auxiliary engine development are included as are two flight test articles and the launch cost of four Shuttle flights.

First unit production cost includes that portion of the recurring Phase D activity associated with producing the first Space Tug vehicle required for the operational phase of the program. It excludes all operational costs.

The total technological advancement cost includes those efforts outlined earlier to insure the 1976 materials and concepts base is attained excluding currently-funded research. They are primarily in the areas of fracture mechanics for thin wall tanks, high performance insulation, composite materials, and APS propellant conditioning.

M&R flight cost represents the average cost over twenty flights to perform scheduled and unscheduled maintenance and refurbishment of the Space Tug duration operations. Flight test vehicle refurbishment cost is for the effort required to convert the two flight test vehicles to operational status.

4.0 CONCLUSIONS AND RECOMMENDATIONS

The study results have clearly shown that the Tug can be designed to meet the target performance goals employing the baseline design concept, and the flight mode and study guidelines described earlier (including use of a 65000 lb. Shuttle delivery capability). The depth of design analysis, supported by programmatic considerations such as producibility confirms that use of advanced materials and concepts affords a sufficient payload margin to permit consideration of greater redundancy for improved reliability. It would also allow reduction in SR&T and development requirements thereby lowering costs and risk. Furthermore, preliminary investigations indicate a number of potentially attractive flight mode and design alternatives warranting further consideration.

The concept of employing the primary load-carrying outer shell as a multi-function element integrating the meteoroid shield and insulation purge bag requirements is feasible and enhances design simplicity. In addition, allowing moderate meteoroid penetration to the tank walls yields light-weight structural elements without compromising the vehicle safety criterion. Also, the use of a dual-mode pressure schedule during boost to orbit when applied loads are highest minimizes LOX tank weight as well as vent losses. These combined with an integrated gaseous O_2/H_2 APS for stability and control, main tanks prepressurization, and fuel cell usage yield a minimum weight and operationally simple system. In the avionics area, it was established that the system capability requirements can be met utilizing technology available by 1976 including hardware adapted from the B-1 program.

Reliability and safety analyses showed that no single failure of a component will result in a critical or non-safe condition. This was accomplished employing redundancy as required, notably in propulsion subsystems valving and attitude control components. However, while satisfying the guideline of a fail-safe system, the Tug design yielded a mission success probability of only 0.81 - a low value by today's standards (S-II has a reliability of 0.95). Although, preliminary analyses indicated that a value of over 0.91 can be achieved by moderate redundancy in avionics at a small weight penalty, a more comprehensive study is required to establish a realistic goal without jeopardizing performance objectives.

Although the study ground-ruled abort from orbit, a brief analysis of suborbital abort was conducted to provide insight on critical areas for future studies. Questions like the impact on design of abort during Shuttle ascent with a Tug and an 8,000 pound payload require further analysis. Definition of a realistic abort envelope and the effects on Shuttle and Tug design must be made. Hazards such as hydrogen leakage require additional study to establish acceptable inerting and contingency action criteria. In addition, maintenance requirements and timelines need to be more firmly developed and the implications of applying an airline-type approach to M&R explored in terms of component reliability apportionment, development cost, and overall Tug design.

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Tug performance is extremely weight-sensitive. Therefore, a strong SR&T program is necessary to assure that the predicated 1976 technology base will in fact be realized. Continued emphasis should be given to such critical items as the LOX/LH_2 main engine (470-sec I_{SP}) and APS (380-sec I_{SP}, zero NPSP), MLI (aluminized or goldized Kapton), composite structures, and others identified in the SR&T section. If the 1976 capabilities of these hardware items is substantially below expectations (particularly engine I_{SP}), it could seriously impact Tug feasibility or necessitate a substantial increase in Shuttle payload-carrying capability, Tug orbital fueling, or separate Tug payload delivery to orbit.

The point design study, as previously mentioned, had an important but limited objective. As such, no attempt was made to define or develop an optimum compromise of the many pertinent program factors important in future system planning. Thus, no effort was made to minimize cost or even determine its sensitivity to design. Although the costs defined for the point design are believed to be realistic and show a reasonable correlation with results from OOS and other studies, they are primarily based on a CER-type approach. This is standard practice for a Phase A study. However, the depth of design detail now available should permit use of a "grass roots" approach in a future study to develop Tug cost prediction confidence to the same level as design.

The lack of more definitive interface and characteristics information on Shuttle and Tug payloads for this study represents an important deficiency. While not necessarily impacting Tug feasibility, this lack of definition raises questions of Tug flexibility and interface compatibility which could require substantial design changes to the concept developed in this study. Future efforts need to trade off design, performance, operations, safety, reliability, and cost in the presence of definitive Shuttle and payload interfaces to achieve an acceptable Tug design representing an "optimum" compromise between key Space Transportation System (STS) and program factors.