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REUSABLE CENTAUR STUDY

VOLUME I ♦ EXECUTIVE SUMMARY

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D. A. Heald et al

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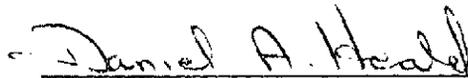
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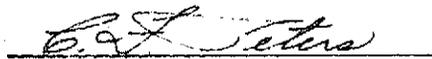
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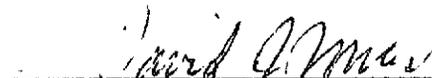
REUSABLE CENTAUR STUDY
Volume I - Executive Summary



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FOREWORD

This final report on the Reusable Centaur Study was prepared by the Convair Aerospace Division of General Dynamics Corporation for the National Aeronautics and Space Administration's George C. Marshall Space Flight Center in accordance with Contract NAS8-30290. The NASA Study Manager was James B. Brewer.

The study results were developed during the period from June to December 1973. Final presentations were made at NASA/MSFC on 17 January 1974 and at SAMSO/Aerospace Corporation on 25 January 1974. This report consists of two volumes:

- | | |
|-----------|-------------------|
| Volume I | Executive Summary |
| Volume II | Final Report |

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SUMMARY

The Space Shuttle will deliver large payloads to low earth orbit. About half of the planned missions require an upper stage to reach higher orbits, such as synchronous, or to escape for planetary probes. Minimum development funding will be available for a new upper stage (Tug) until after 1978 when Shuttle expenditures begin to decline. Therefore existing upper stages, modified for Shuttle compatibility and reuse at minimum cost, are being considered as an initial Orbit-to-Orbit Stage (OOS).

This study developed data for OOS versions based on the current Centaur high energy upper stage. This vehicle has flown 23 operational missions, and has a future mission backlog through 1979. Centaur uses 30,000 pounds of liquid oxygen and liquid hydrogen propellants contained in a pressure-stabilized, stainless steel tank. The liquid oxygen tank is aft, separated from the liquid hydrogen by a double-wall, evacuated intermediate bulkhead. Twin Pratt & Whitney RL10A-3-3 engines provide the main impulse. A hydrogen peroxide auxiliary system provides attitude control during coast as well as turbine drive for the tank-mounted boost pumps. Aluminized Mylar radiation shielding provides thermal protection during mission coast periods, significantly reducing space heating rates. A fully integrated avionics system uses a central digital computer for software control of the vehicle during flight operations.

The D-1T Centaur is the key element in NASA's near future space program. It is scheduled to fly Viking, Helios, and Mariner-Jupiter-Saturn missions.

During the Reusable Centaur and related studies, many configurations were considered, each with advantages, each satisfying different priorities. Configurations studied range from 22 to 35 feet long with 30,000 to 53,000 pounds of propellants. The Reusable Centaur version used in the Government assessment during November and December 1973 is 28 feet long with 47,000 pounds of propellant.

Reusable Centaur is a low risk development since it needs no new technology. Sixty-three percent of the components are flying today on Centaur, 25% are modified existing hardware, and only 12% are new. The Reusable Centaur's main engines are uniquely suitable for OOS application in that they possess a combination of features not found in other engines: (1) multi-flight reuse without any change to the existing RL10A-3-3 qualified configuration, (2) clean, non-toxic propellants, (3) high performance, and (4) minimum turnaround maintenance between flights.

Reusable Centaur has the high performance inherent in a liquid oxygen/liquid hydrogen cryogenic stage: it will place 4600 pounds of payload in synchronous equatorial orbit and return the stage to the Shuttle for reentry and reuse without an expensive, expendable, solid upper stage. This high performance allows multiple payloads to be flown and gives confidence in actually achieving OOS performance and reliability requirements. Centaur has the potential to achieve payload retrieval capability should that eventually be desired.

Centaur is inherently reusable. The Shuttle ascent environment is very similar to Titan's including acoustics and vibration. A review of current Centaur component specifications and qualification test data indicates that most D-1T components have received sufficient life testing to confirm their reusability for 10 to 20 Reusable Centaur missions.

Reusable Centaur is a safe configuration compatible with manned operations in the Shuttle. All Centaur subsystems are at least fail safe, many are first fail operational. The Centaur vehicle can be safed in any flight or ground abort mode. No single failure of any Centaur component will preclude Orbiter abort capability.

Initial development cost, which varies with vehicle capability, is estimated to be \$77.2M for the Reusable Centaur. Thirty-five percent of this is for a dedicated flight test program and ground test program. The investment includes six new vehicles, which will be flown a maximum of 16 times each. The cost of a four-year program to put 112 payloads in orbit is \$212M.

Centaur's high performance and inherent reusability means investment in a small fleet and few expendable kick stages. This means that routine reuse of the Centaur will cost \$800,000 a launch, which is truly low recurring cost. Its low life cycle cost makes Centaur a very cost-effective OOS candidate.

SECTION 1

INTRODUCTION AND BACKGROUND

Under NASA Marshall Space Flight Center Contract NAS8-30290, Convair Aerospace Division of General Dynamics performed an eight-month study of the Reusable Centaur for early use as an initial upper stage with the Space Shuttle. The primary study objective was to provide realistic Centaur capability and cost data to be included in the Government's overall Space Tug program assessment.

The Space Transportation System (STS) includes a propulsive stage, called a Space Tug or Orbit-to-Orbit Stage (OOS), that is carried into low earth orbit in the Space Shuttle Orbiter payload bay. The primary function of this upper stage is to extend the STS operating regime beyond the Shuttle's near earth orbits, including plane changes, higher orbits, geosynchronous orbits, and planetary probes. It is desirable that an upper stage be available at or about Shuttle initial operating capability (IOC) to provide the maximum operational, performance, and cost benefits.

Current resource constraints preclude the coincident development of both the Space Shuttle and an ultimate Space Tug. NASA and DoD are therefore evaluating alternatives for providing an interim, lower cost vehicle. It is logical to consider the use of an existing upper stage to provide much of the desired additional capability at minimum early development cost.

The currently operational Centaur stage, with modification for Orbiter compatibility and for improved performance, represents a cost-effective development solution in the face of present and projected funding constraints. Several Centaur configurations are attractive candidates for the initial upper stage or OOS, depending on mission performance needs and available development funds. This report summarizes the main features of three Reusable Centaur configurations with increasing capability at increasing development cost. All Centaur versions benefit from two key advantages:

- a. Very high performance inherent in the use of cryogenic propellants, which minimizes the need for expendable kick stages and results in low user costs.
- b. Low program risk resulting from (1) maximum use of existing hardware such as the RL10 engine, (2) inherent reusability, and (3) conservative contingencies.

From the overall standpoint of high performance, low risk, and low total program costs, the Reusable Centaur is an excellent OOS candidate.

1.1 STUDY OBJECTIVES

The basic Reusable Centaur study objective was to develop realistic technical and programmatic data to be used in the NASA/DoD program assessment. Key drivers considered in this study were:

- a. Low development costs (especially before 1978).
- b. Safety and manned compatibility.
- c. Low program risks through maximum use of proven hardware.
- d. Low operating costs due to reusability and high performance.
- e. Possible phased development using the building block approach.
- f. Extremely long DoD payloads.
- g. High probability of mission success.

1.2 RELATIONSHIP TO OTHER STUDIES

A preliminary feasibility study of Centaur as an expendable Tug was conducted in 1972 by Convair Aerospace for NASA/LeRC under contract NAS3-14389. The second phase of that work, Centaur/Shuttle Integration Study, was completed in December 1973 under contract NAS3-16786. Much data from that study is directly applicable to a Reusable Centaur.

Data and requirements definition from the Space Tug Systems Study (Cryogenic), NAS8-29676, were integrated into this study, where applicable, particularly in the missions and payload areas. In addition, refurbishment, maintainability, and ground operations data from the KSC-sponsored Space Tug Launch Site Services Study, NAS10-8031, conducted by Convair Aerospace, were used.

This Reusable Centaur study was one of ten Government funded studies directly providing assessment data in late 1973: four Space Tug systems studies (STSS), three related engine studies, and three growth stage studies including this one.

1.3 APPROACH

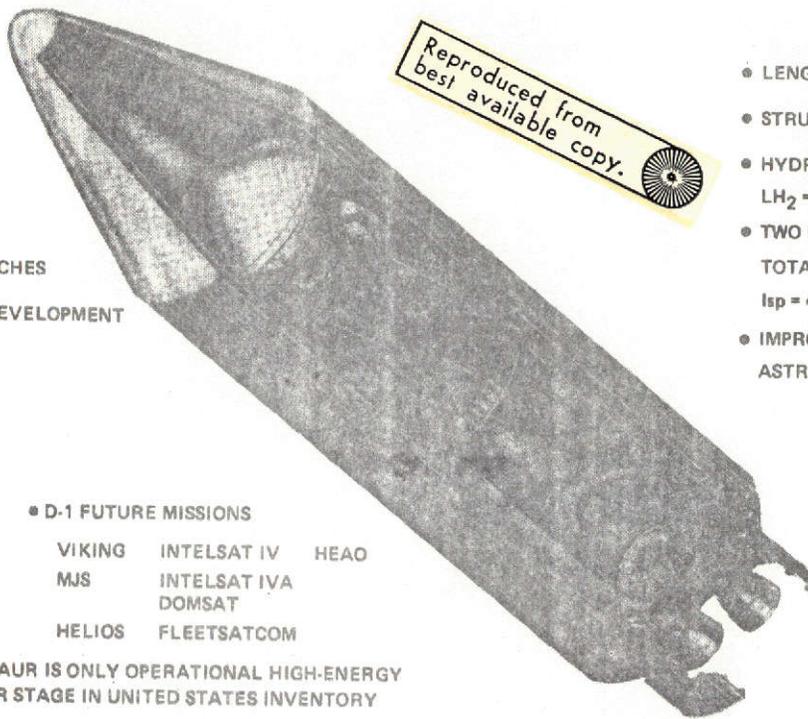
The basic study approach was to build on the current D-1 Centaur program, using weights extrapolated from existing hardware and development costs derived from actuals on the ongoing Centaur-Titan integration contract NAS3-13500. After satisfying Shuttle compatibility requirements, Centaur performance changes were examined to permit placement of more than 3500 pounds in synchronous equatorial orbit with subsequent Centaur return to the Orbiter for reuse. The study focused on cost effective changes with minimum risk. Most of the Program 1 Tug requirements from the

April 1973 MSFC Data Package for the Space Tug System Studies are applicable to a Reusable Centaur. Requirements for very long DoD payloads were also considered. The principal study ground rules and assumptions were:

- a. Reusable Centaur configurations are based on operational D-1A/D-1T programs.
- b. Low development cost is the primary driver.
- c. Basic mission is to deploy 3500 pounds in synchronous equatorial orbit and return to Orbiter.
- d. Payload length is 25 feet maximum, except for a few DoD payloads up to 35 feet long.
- e. Operations for a 4-year program were assumed at ETR only; for 6- and 11-year programs, both ETR and WTR were assumed operational.
- f. Design must be fail-safe so as not to jeopardize the flight or ground crews.
- g. 0.97 probability of mission success is a goal.
- h. Benign payload environment is a goal; acceleration should not exceed 3.6 g.
- i. Payloads can "walk" to their final longitude.
- j. Multiple payload placement is desirable.
- k. Ground tracking for position and velocity update may be considered.
- l. The number of Centaur reuses is to be studied.
- m. Both NASA and DoD communication systems and control centers will be used.

1.3.1 EXISTING D-1 CENTAUR. The Centaur high-energy upper stage has flown 24 operational missions, and currently has a future mission backlog through 1979. The improved Centaur vehicle, which is designated the D-1A ("A" for Atlas), was successfully launched for the Pioneer 11 mission with a spin-stabilized kick stage. This Centaur incorporates a fully integrated avionics system using a central digital computer for software control of vehicle and flight operations. The D-1T Centaur is configured for launch on the Titan. The proof flight of this vehicle is scheduled for February 1974. In addition to the integrated avionics system, the D-1T incorporates a space radiation shield insulation system, and subsystem modifications to improve vehicle reliability. The proof flight of the D-1T will accomplish several mission objectives of particular interest relative to eventual Centaur/Shuttle use: a four-burn mission and a coast duration of 5.25 hours.

Figure 1-1 shows the general arrangement of the existing D-1T, which is 31.1 feet long and 10 feet in diameter, with a mass fraction of 0.88. The Centaur stage carries 30,000 pounds of liquid hydrogen and oxygen in pressure-stabilized stainless steel tanks. Oxygen is aft, separated from the hydrogen by a double-wall, evacuated intermediate bulkhead. Two Pratt & Whitney RL10A-3-3 engines produce 30,000 pounds



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• 32 CENTAUR LAUNCHES

8 RESEARCH & DEVELOPMENT

7 SURVEYOR

2 ATS

3 OAO

5 MARINER

5 INTELSAT IV

2 PIONEER

• D-1 FUTURE MISSIONS

VIKING	INTELSAT IV	HEAD
MJS	INTELSAT IVA	DOMSAT
HELIOS	FLEETSATCOM	

CENTAUR IS ONLY OPERATIONAL HIGH-ENERGY
UPPER STAGE IN UNITED STATES INVENTORY

- LENGTH 31.5 FT., DIAMETER 10 FT.
- STRUCTURAL WEIGHT 4,028 LB.
- HYDROGEN/OXYGEN PROPELLANTS
LH₂ = 5,000 LB., LO₂ = 25,000 LB.
- TWO RL-10 ENGINES
TOTAL THRUST = 30,000 LB.
Isp = 444 SEC.
- IMPROVED COMPUTER CONTROLLED
ASTRONICS SYSTEM

Figure 1-1. Current D-1 Centaur

of thrust at a nominal specific impulse of 444 seconds. The current operational stage uses hydrogen peroxide monopropellant for propellant settling and attitude control motors. Propellant heating in space is reduced by radiation shields on the liquid hydrogen sidewall and liquid oxygen tank aft bulkhead, a vacuum intermediate bulkhead, and multi-layered insulation blankets on the forward liquid hydrogen dome. An advanced feature of the Centaur D-1 is the use of an onboard digital computer unit (DCU) for navigation, guidance, control, sequencing, propellant utilization, tank pressurization and venting control, and telemetry. This permits many functions to be done by software, eliminating some hardware components. Pulse code modulated (PCM) telemetry data is downlinked by S-Band. The navigation function is done onboard with an inertial reference. The power supply is a 150 ampere-hour battery with a servo inverter unit to provide 400 Hz to the propellant utilization, gyros, and engine position indicators. Testing of the Centaur D-1 astronics is controlled and monitored by a ground computer-controlled launch set (CCLS) that includes a XDS930 computer.

SECTION 2

SUMMARY OF SIGNIFICANT RESULTS

This Executive Summary is a review of the significant findings of the study. The paragraph numbering here correlates with that in the Final Report (Volume II); i.e., paragraph 2.3 here is Astrionics, which is Section 3 in the Final Report.

2.1 COMPARISON OF CENTAUR VERSIONS

This study used the current D-1T Centaur as the basis to develop a range of concepts for an initial upper stage for Shuttle. An optimum solution depends on funding available and the mission model, taking into account the buildup in Shuttle flights and transition from expendable launch vehicles. Table 2-1 compares the three principal configurations resulting from this study with the existing D-1T Centaur. The D-1S(R) ("S" for Shuttle, "R" for reusable) is most like the D-1T and therefore has the lowest development costs. It usually requires a solid rocket motor (SRM), however.

The Reusable Centaur (RC) configuration is only 28 feet long to accommodate long DoD payloads. (Versions as short as 22 feet long can be built without the cylindrical section of the tanks.) Propellant capacity is 50% greater by increasing the hydrogen tank diameter to 14.5 feet, so that no SRM is required except on outer planet missions. Changing the tank geometry is actually a simple task because there is no outer shell, only thin stainless steel sheetmetal is involved. A fuel cell is a logical power supply on a cryogenic stage and development will be mostly paid for by the Orbiter.

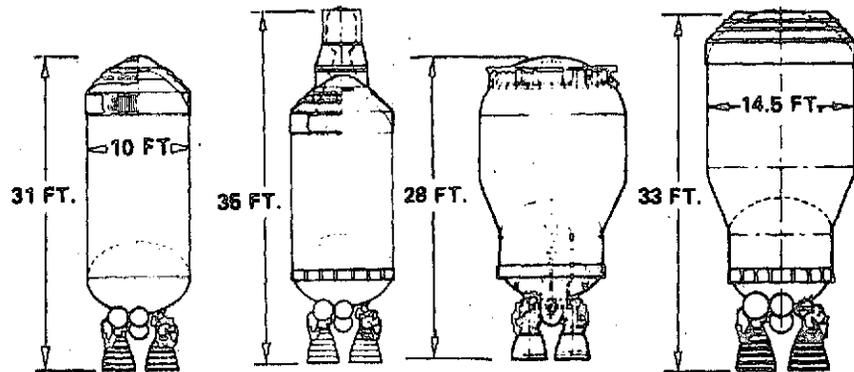
The Reusable Large Tank Centaur (RLTC) is a more sophisticated, autonomous version with greater capability but higher development cost. The most significant feature is the redundant astrionics system, including triple computers for improved reliability over longer missions. Further changes are feasible, such as a single engine arrangement, which could lead to growth versions of Centaur with payload retrieval capability.

These Centaur versions all employ the existing twin RL10A-3-3 main engines, the existing liquid oxygen tank aft bulkhead with thrust structure, and twin-member intermediate bulkhead. The computer-controlled astrionics system just recently developed for D-1T is kept essentially intact. Many components are used as is from the current propulsion subsystems. This leads to low risk concepts. The Centaur is inherently reusable, probably more than ten flights. Long life has already been demonstrated on the main engines.

High performance inherent in hydrogen-oxygen propulsion systems enables all three versions to exceed the requirement of placing 3500 pounds of payload in synchronous equatorial orbit and returning the stage to the Shuttle for reuse. Multiple payloads can therefore be flown on many missions. The RC and RLTC versions use very few

solid rocket motors. The high performance, low risk, and inherent reusability contribute to low recurring and low user costs which make the Reusable Centaur an attractive OOS candidate.

Table 2-1. Comparison of Centaur Versions



	D-1T	D-1S(R)	RC	RLTC
Total Dry Weight, lb	4,028	5,018	4,995	5,510
Liftoff Weight, lb	43,776	46,287	59,731	65,000
Installed Length, ft	31	35*	28**	33
Max Diameter, in.	126	126	176	174
Payload to Sync Eq, lb	7,400	4,096*	4,581	4,500
Nominal Solo Flight, hr	6.9	24	30	36
Number of Burns	4	5	5	6
Percentage Existing Hardware	100	85	69	50
Propellant Capacity, lb	30,000	29,000	47,000	52,000
Mixture Ratio	5.0:1	5.8:1	5.8:1	5.0:1
I_{sp} , sec	444	439.8	439.8	444
Boiloff Vented, lb	187	298	468	661
Pressurization, lb Helium	14	18 amb	15 amb	28 cryo
Chilldown and Start Losses,				
lb O_2 & H_2	415	175	188	210
ACPS Propellants, lb	482 H_2O_2	626 H_2O_2	482 H_2O_2	690 N_2H_4
Computer Memory, k bits	18	24	24	48 (triple)
Guidance Update	N. A.	Ground	Ground	Autonomous
Electrical Power	Batteries	Batteries	Fuel Cell	Fuel Cell
Reliability	0.984 solo	0.951*	0.97 Solo	0.9751
Development Cost, M\$	75	63.3	77.2**	122
Production Unit Cost, M\$	5.2	8.1	8.5	11.9
Launch (Turnaround), M\$	1.1	1.7	0.9	1.2

* A 22-foot version is included for 35-foot payloads

** With Kick Stage

2.2 CONFIGURATIONS

2.2.1 D-1S(R). Figure 2-1 shows the general configuration of D-1S(R) that is closest to the existing D-1T vehicle. It is nearly identical to the expendable D-1S, with features added for return to the Orbiter. The main engines are P&W RL10A-3-3. The structure is the existing pressure-stabilized 301 stainless steel tank with modified aluminum and titanium skin stringer adapters. An SRM such as a Thiokol TE 364-4 is required for most missions due to the performance demands of return flight. To keep the total length including SRM below 35 feet, the D-1S(R) hydrogen tank is shortened 30 inches, which drives the optimum mixture ratio to 5.8:1. The attitude control propulsion system (ACPS) is hydrogen peroxide monopropellant with helium pressurized bladder tanks. Sixteen peroxide thrusters are mounted on the aft adapter in clusters of four to provide all axis maneuver capability. The H_2O_2 also provides power for the liquid hydrogen and liquid oxygen boost pumps, which have an added slow speed to reduce chilldown losses. The existing hydraulic thrust vector control and in-tank capacitance probe propellant utilization systems are used as is.

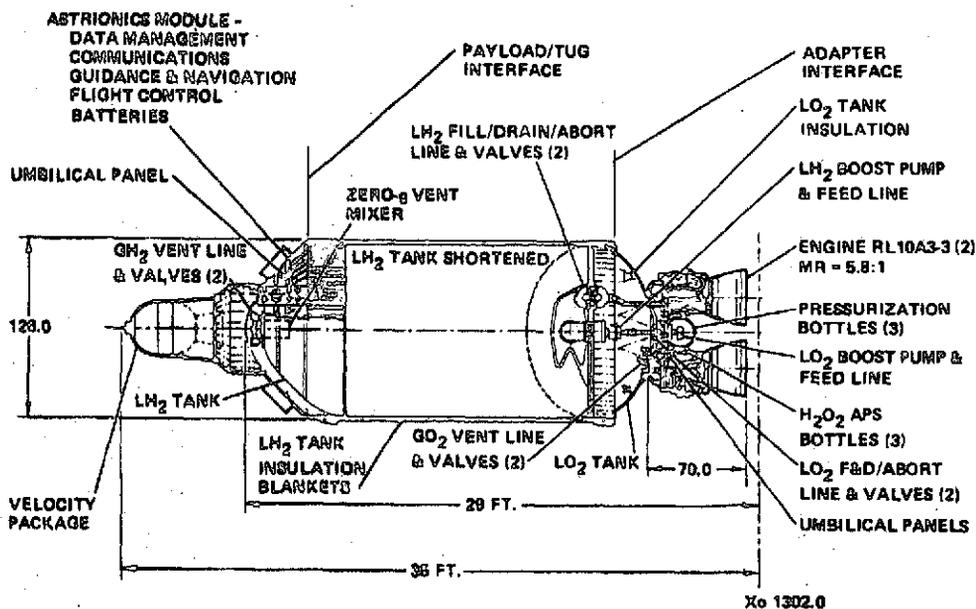


Figure 2-1. D-1S(R) Configuration

The current propellant tank pressurization system raises tank pressures prior to each engine start with ambient temperature helium. The tank vent system uses both ground vent valves and zero-g vent mixers. The fill and drain system also provides inflight propellant dump capability in the event of an abort. The tank insulation system uses multilayer goldized Kapton blankets for ground hold and three-layer radiation shielding for deep space. The D-1S(R) flight support equipment includes a flight pallet for handling and deploying the vehicle. It is possible to build a version with a very short hydrogen tank which could place a 4000-pound payload, 40 feet long, in a 12-hour elliptical orbit.

2.2.2 REUSABLE CENTAUR FOR LONG DoD PAYLOADS. The general RC configuration is shown in Figure 2-2. Long payloads were a prime consideration. Almost 70% of the hardware and components selected for RC are existing Centaur or off-the-shelf hardware. The remainder is well within the current state-of-the-art technology including fuel cells of the type now being developed for the Orbiter. While the propellant tanks are enlarged so that the RC looks like an RLTC, most of the subsystems are like those on the D-1S(R), which minimizes development risk.

The engines are existing P&W RL10A-3-3 operating at 5.8:1 mixture ratio with the cooldown valves adjusted to minimize propellant chilldown losses. The boost pumps are also D-1T hardware with an idle mode added to conserve chilldown propellants. The auxiliary propulsion system is the D-1T hydrogen peroxide system with forward facing thrusters. The tanks are pressure stabilized 301 CRES (like D-1T) with an enlarged diameter liquid hydrogen tank and lengthened liquid oxygen tank to provide greater propellant capacity. The tank insulation system (similar to the blanket and radiation shield designs for D-1T) has multilayer goldized Kapton blankets for ground operations, and three-layer radiation shielding for deep space protection. Tank vent systems use D-1T hardware plus new zero-g thermodynamic vent/mixers. The adapters are of aluminum and titanium skin-stringer construction. The propellant tank pressurization system uses D-1T hardware and stores helium at ambient temperature. Simplex avionics makes maximum use of existing units.

This RC is 28 feet long installed in the Orbiter payload bay. This length will satisfy all but one of the NASA and DoD payloads currently reported. A short RC, built without cylindrical sections in both tanks, can place a 38-foot long payload of more than 17,000 pounds in a 12-hour elliptical orbit.

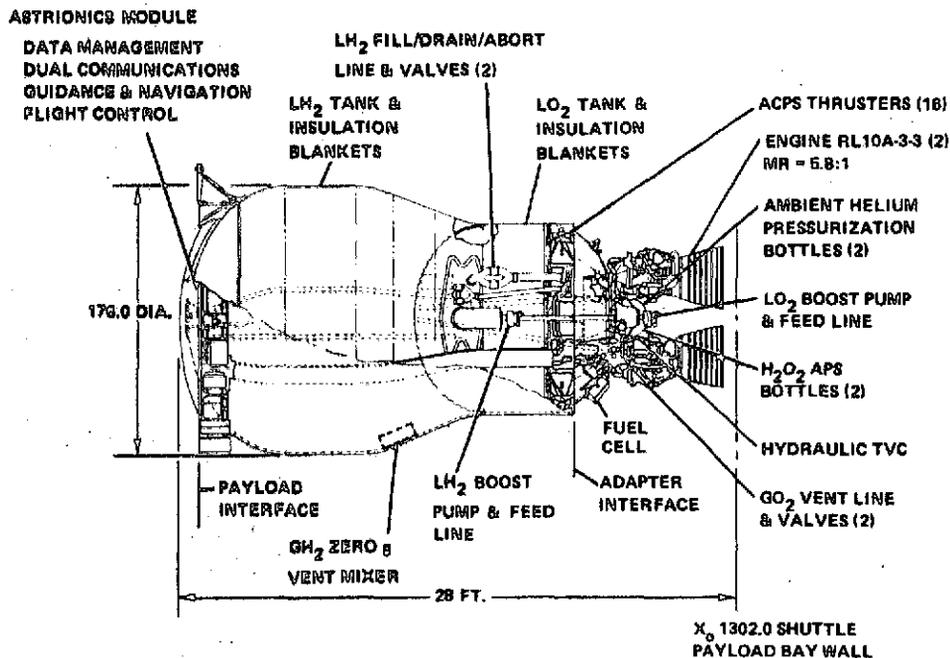
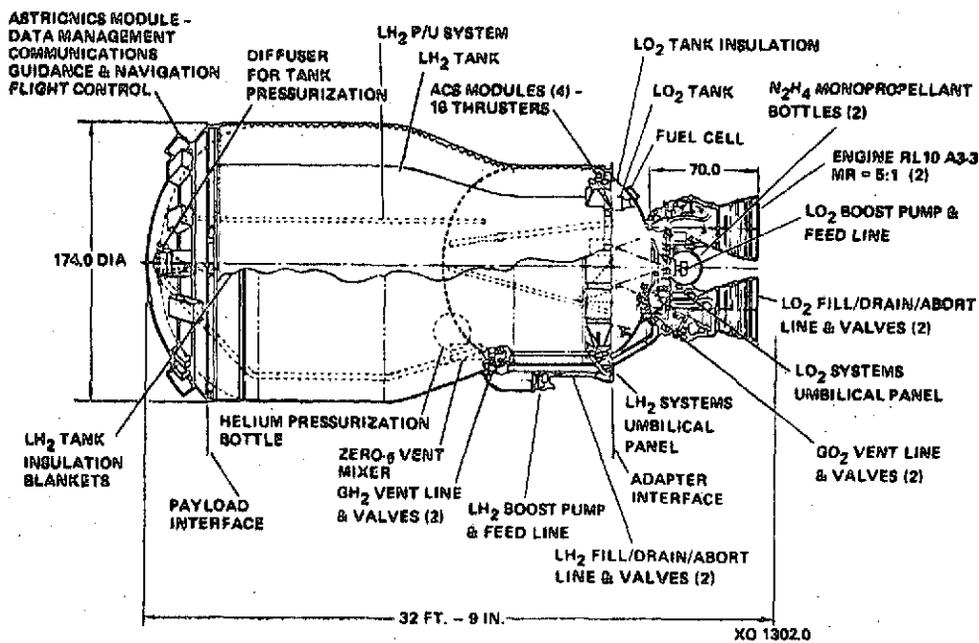


Figure 2-2. Reusable Centaur Configuration

2.2.3 REUSABLE LARGE TANK CENTAUR. The RLTC, shown in Figure 2-3, provides increased propellant capacity to make full use of the Space Shuttle boost capability to launch 65,000-pound payloads. Increased capability includes triple computers for increased reliability and a sixth burn for final payload placement. These improvements are achieved while still using many existing operational subsystems. The main engine is the proven P&W RL10A-3-3 operating with a 5.0:1 mixture ratio and with cooldown valves adjusted to reduce losses. The existing thrust vector control (TVC) system and reshaped capacitance propellant utilization probes are used. While the tanks are enlarged, existing aft and twin intermediate bulkheads are used. The forward and aft adapters are new designs using epoxy graphite composite sandwich construction. Hydrazine monopropellant is used for the ACPS, adapting Transtage thrusters and bottles. There is a large monopropellant supply for extra maneuvers and velocity changes including a 50 feet per second midcourse correction. Hydrazine also provides power for the liquid hydrogen and liquid oxygen boost pumps. Helium for tank pressurization is stored cryogenically within the liquid hydrogen tank and warmed prior to use by a heat exchanger. The tank vent system utilizes both ground vent valves and zero-g vent mixers. The fill and drain system also provides in-flight propellant dump capability in the event of an abort. The tank insulation system uses multilayer goldized Kapton blankets for ground hold and three-layer radiation shielding for deep space conditions. The RLTC flight support equipment includes a deployment adapter; the large diameter precludes the use of a full length pallet.



RLTC VERSION HAS GREATEST CAPABILITY

Figure 2-3. Reusable Large Tank Centaur

2.2.4 PROPULSION SYSTEM. All Centaur versions use the existing Pratt & Whitney RL10A-3-3 engines (Figure 2-4). Only one 15,000-pound-thrust engine is required for the OOS/Tug mission, but the existing Centaur twin engine installation is maintained so that no development costs are incurred in redesigning. Cryogenic propellants (hydrogen and oxygen) inherently have 50% more performance than earth storable propellants (hydrazine or MMH and nitrogen tetroxide or nitric acid). The existing Centaur has a specific impulse (pounds of thrust per pounds of propellants consumed per second) of 444 seconds compared to about 300 for earth storables. These clean, non-corrosive cryogenic propellants allow Centaur to be inherently reusable for a minimum of ten missions, based on test data developed during the past ten years. The critical element is the main propulsion engines for which the existing specification guarantees 4000 seconds of operational life. Test experience gives very high confidence that actual life far exceeds the specification value.

RL10 main engines for RC are uniquely suitable for OOS/Tug application in that they possess a combination of features not found in other engine candidates:

a. Multi-flight reuse without any change to the qualified configuration. The existing specification guarantees the equivalent of 6 to 8 missions while tests have demonstrated more than 20-mission life.



Figure 2-4. RL10A-3-3 Engine

- b. Clean propellants with no problems resulting from residue, no toxicity hazards, and no clogging due to formation of sludges or propellant gums.
- c. High performance. The current engine has an I_{sp} of 444 seconds, which is lowered slightly to 439.8 at a 5.8:1 mixture ratio.
- d. Minimum turnaround refurbishment between flights with no scheduled component replacement (such as ablative chambers). Maintenance is less than 7 hours of visual inspection and flight data evaluation.

Design margins in the current RL10A-3-3 are more than adequate to support operations at a 5.8:1 mixture ratio with no change to the engine design. Engine thermal cycle life far exceeds 10 OOS missions even though the mixture ratio change decreases thrust chamber life slightly. Mixture ratio is changed by merely adjusting the existing thrust controller. Pratt & Whitney has already demonstrated the ability of the engine to run at mixture ratios up to 7:1.



A slow chilldown is planned for the Reusable Centaur to significantly reduce the amount of propellants dumped overboard. The current rapid start sequence is not required for Shuttle missions. The only hardware changes are reorificing the engine chilldown valves and adding a slow speed feed solenoid to the boost pump to recirculate initial flow through the ducts. The slow chilldown arrives at the same engine inlet conditions after almost 3 minutes as the current rapid start does in 28 seconds, but with only 1/6 of the current propellant losses.

Hydrogen peroxide is used to provide hot-gas drive for the boost pump turbines and to provide auxiliary propulsion for attitude control, propellant settling, and orbital velocity corrections including outbound and return mid-course corrections and payload separation. The basic system components are identical to those used on Centaur D-1T, including existing 6-pound-thrust engines and H₂O₂ bottles with a heater blanket for longer coast thermal control. Four forward facing thrusters have been added to provide the capability to back away from payloads and to apply pure moments for attitude control when docking with the Orbiter. Engine clusters are relocated on tripods outboard of the aft adapter barrel which doubles the thruster moment arm. Cluster isolation valves allow shutoff of a failed-open thruster to maintain safe operational capability when the Centaur is in the vicinity of the Orbiter. Hydrazine as proposed on the RLTC is a higher performance system and may prove to be a cost effective change using existing Transtage bottles and thrusters.

Reusable Centaur propulsion subsystems are the same as those on the D-1T, except they are modified only for compatibility with Shuttle interfaces or performance increases to allow return for reuse. Many components are off the shelf from existing propellant utilization, TVC, pressurization, vent, purge, and feed subsystems. This significantly reduces propulsion development costs and reduces program risks.

2.2.5 STRUCTURE AND INSULATION. All Reusable Centaur versions use the unique pressure-stabilized thin stainless steel tanks first used on the Atlas program. There have been more than 440 Atlas and Centaur flights without a tankage structure failure. Analysis of cryogenic stress cycle test data on welded specimens of each Centaur tank built indicates this type of tank should have a fatigue life of more than 45 OOS missions. The existing D-1T Centaur liquid oxygen tank aft bulkhead, thrust structure, and the existing dual member intermediate bulkhead will be used as is, significantly reducing development risk and cost.

To accommodate very long payloads (approaching 40 feet long), vehicles with shortened tanks can be built. The hydrogen propellant utilization probe has to be reshaped and several lines, cables, and the insulation blankets shortened. The dynamic analysis, including sloshing, of the short stage is within the general program requirements which include a range of payload lengths and off-loaded

conditions. This is a minor task, based on experience with several Atlas versions with tank length and forward bulkhead contour variations.

The structural adapters are designed to enable introduction of the four-point loads for mounting in the Orbiter payload bay for both vertical launch and horizontal landing. Titanium and aluminum skin stringer construction based on existing D-1T designs or epoxy graphite composites can be used. The Reusable Centaur candidates are designed to meet manned safety factors including crash landing loads. Modifications are required for relocation of fluid disconnects from the present expendable launch vehicle arrangements to ones compatible with the Orbiter.

Insulation around the main cryogenic propellant tanks is derived from current D-1T Centaur designs. Ground hold insulation is provided by helium purged multilayer blankets on both the sidewalls and forward bulkhead of the hydrogen tank, like those currently used on D-1T forward bulkhead. The outer layer of each blanket is sealed so that the helium purge can be collected and vented overboard to isolate any possible hydrogen leaks. For space insulation, the hydrogen tank sidewalls employ radiation shields based on those just developed for D-1T. Kapton will be used instead of Mylar because it is more fire resistant. It is planned to goldize the flat sheets in the "Dimplar" type blankets for improved life. The result is an existing type relatively low performance multilayer insulation with about half the total heat leak into the hydrogen tank coming through the existing vacuum intermediate bulkhead.

2.2.6 ORBITER INTERFACES. A deployment adapter provides physical interfaces between the Orbiter and the OOS. As shown in Figure 2-5, it is a short barrel structure around the Centaur engines. A full length truss structure pallet is added with 10-foot-diameter versions.

The nine fluid connections, including 2.5-inch vents and up to 6-inch fill and dump lines, are routed to the Orbiter interface panels at the rear of the payload bay and aft to the liftoff disconnects. The Reusable Centaur can use the same four-point non-redundant structural support system proposed for the Tug. The vehicle attached to the deployment adapter rotates 45 degrees out of the payload bay for deployment.

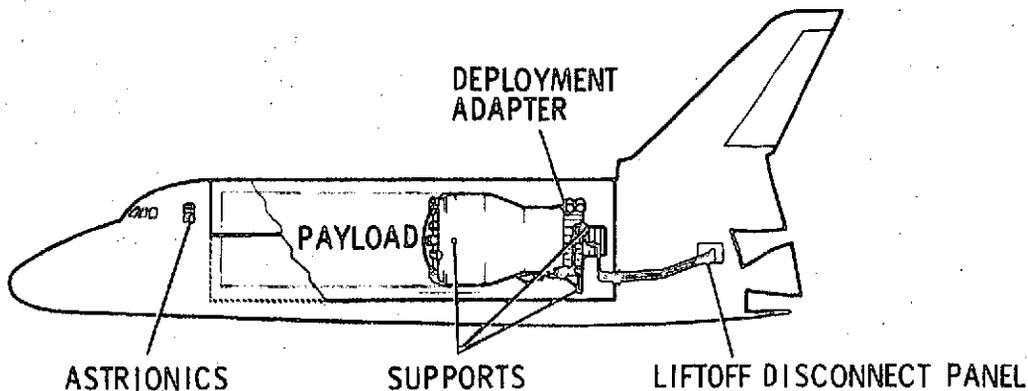


Figure 2-5. Reusable Centaur - Orbiter Interfaces

The adapter includes ample helium to purge the insulation and propellant tanks after return and also for fast propellant dump if required after inflight abort. Astrionics interfaces go not only to ground, but also to Orbiter monitor and control panels including a dedicated computer. Orbiter interfaces including environment, operations, and inflight abort require further study and coordination with Rockwell International.

2.3 ASTRIONICS SYSTEMS

Evolution of the astrionics for the Reusable Centaur has as its base the current operational D-1 Centaur. Recently a redesign has been completed of the D-1A/D-1T astrionics with a large capacity central digital computer, reprogrammable, which provides the starting point for increased capability upper stages. Verification of the improved astrionic and vehicle design has been accomplished with successful operational flights during the past year. Where possible, consistent with the mission and reusability objectives, the existing D-1T Centaur designs for electronic equipment and the same type of electrical interface have been used for Reusable Centaur to minimize risk and to avoid non-essential development costs.

OOS/Tug mission requirements involve extended durations beyond the D-1 flights which are less than 7 hours and this has necessitated increased attention to the reliability of the system design. The Orbiter man-rated safety requirement necessitates arm-safing provisions of the Centaur interface plus functional redundancy applied to potential critical areas. Figure 2-6 shows that the OOS/Tug requirements have modified Centaur D-1T astrionics design as follows:

Data Management — Increased guidance/navigation, communications, and man-rated safety require expanded computer capacity (8,000 words of additional main memory over the D-1T computer have been provided). A tape recorder has been added for engine history and maintenance purposes. The basic control interfaces from the digital computer unit through the sequence control unit to propulsion and flight control functions are kept intact.

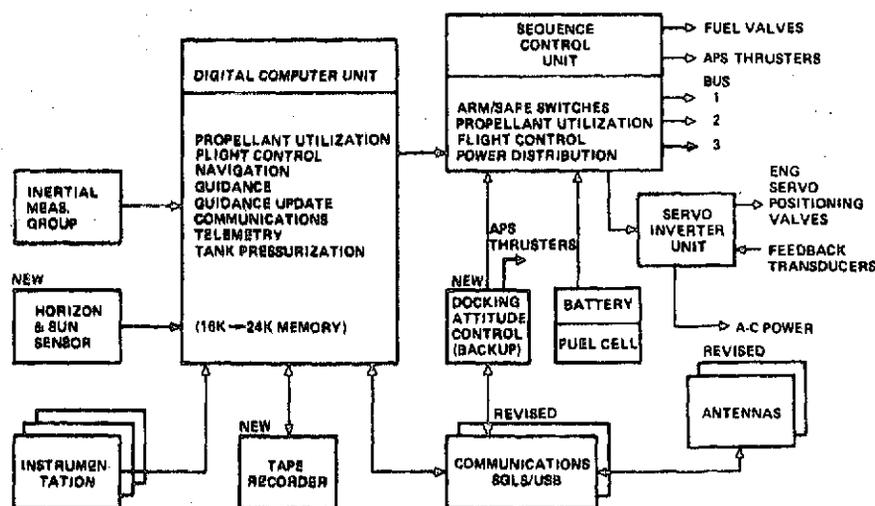


Figure 2-6. Basic Reusable Centaur Astrionics System

Guidance and Navigation — Guidance update is necessary for the new and longer mission durations. State vector update (position and velocity) is accomplished via RF link from the ground and three-axis attitude update is derived from the inputs of onboard horizon and sun sensors. The current Honeywell inertial reference unit can be utilized or dual Delta inertial guidance system strapdown units as an alternative.

Safety — Critical elements are dual redundant, or have functional backup. Dual NASA unified S-Band or DoD space-ground links system (SGLS) communications plus the Orbiter-located Centaur monitor and control system (CMACS) furnish safety control. A 40-pound backup docking control system includes additional attitude sensing gyros and control logic so that the Mission Specialist can provide backup stabilization and attitude control to ensure docking safety. Safety critical outputs are interlocked by arm/safe switches. The Orbiter crew has override control of these functions.

Software — The approach uses the Centaur computer-controlled launch set (CCLS) at ETR and the dedicated CMACS computer in the Orbiter. Close examination of the existing software library indicates that more than half could be used on the OOS onboard computer and 90% of existing checkout software can be used. Sharing an Orbiter computer or changing the interface and/or language increases software costs.

Power Supply — Batteries can be used on the 24-hour D-1S(R) mission to minimize development costs. A combination of Agena lightweight and Centaur rapid drain type batteries is required. On longer missions battery weight becomes critical. A fuel cell of the modified Shuttle Orbiter type has been defined to handle the increased power consumption. Requirements are in the 1 to 2 kilowatt range, so the 7-1/2 kilowatt Orbiter unit has to be scaled down. Reactants can be drawn from the main propellant tanks, using an occasional purge to remove contaminants like helium which may collect in the cells. Continued development of the lightweight fuel cell may make it a more cost-effective solution.

Redundancy — The D-1S(R) and RC versions employ redundant astronics only where required for Orbiter safety: dual communications, triple tank pressure transducers, backup battery, and backup docking attitude control. It would be desirable for safety and reliability to increase astronics redundancy if program funding permits. The RLTC has such an advanced astronics system, with triple computers each with 48k memory. Voting of the three computers avoids the complexity of the software program logic that would be required with only dual computers. The "masking" and coverage limitations (typically 0.9) plus many of the involved problems of redundancy management within the computer are thereby avoided. The RLTC also uses autonomous, three-axis guidance update furnished with horizon and star sensors onboard. A dual strapdown inertial measurement unit with inertial platforms developed and flight proven for the delta inertial guidance system serves as the inertial reference. This system can operate completely independent of the ground, which is Level I autonomy. Greater vehicle capability reduces operations support requirements; for instance, state vector update via RF uplink is no longer required.

2.4 MISSION PERFORMANCE

Reusable Centaurs achieve high performance due to the high impulse inherent in cryogenic propulsion, without requiring advanced technology systems to save weight. The D-1S(R) performance on the baseline mission is 4,096 pounds to synchronous equatorial orbit using a three-axis stabilized kick stage with a TE 364-4 solid rocket motor (SRM). The payload increases to 4,349 pounds with a spin-stabilized SRM, and decreases to 3,925 pounds if a 10% weight contingency is applied to the entire stage instead of 2% on existing hardware and 10% on new designs.

The RLTC can place 4,501 pounds in synchronous equatorial orbit without a kick stage, assuming a 10% weight contingency on the whole stage and very large attitude control propulsion system (ACPS) propellant supply and a sixth burn for final payload placement. The payload would increase to 5,416 pounds using 2% and 10% weight contingency, 50 feet per second total ACPS ΔV , and five burns.

Table 2-2 shows that the 28-foot long Reusable Centaur weighs about 25% more than the existing D-1T, including a large contingency. This results in a mass fraction of 0.87.

Table 2-2. Twenty-eight Foot Reusable Centaur Weight Summary

Subsystem	D-1T	RC	Comments
Fuel & Oxidizer Tanks	781	1,160	Enlarge volume 50%
Insulation	354	488	Larger tanks, ground hold insulation on sidewalls
Structures	632	563	Remove forward truss adapter, add aft adapter
Main Engines Install'n	732	734	Unchanged
Attitude Control	185	195	Longer mission, reduced settling
Pressurization	176	265	Five burns, larger tank, 1.5 psi H ₂ prestart pressure.
Propellant Systems	407	523	Add zero-G vent, rearrange disconnects, add large dump lines
Power Supply & Wiring	291	281	Modified Orbiter fuel cell
Astrionics	470	506	Add guidance update & communications
Contingency	0	280	2% existing, 10% new
Total Dry Weight	4,028	4,995	Liftoff weight 60,000 lb

The baseline mission is a five-burn flight, allowing the payload to "walk" to final position. Reusable Centaur is solo about 30 hours and total time from liftoff to landing is less than 48 hours. Only the 10-foot-diameter D-1S(R) version normally uses a kick stage. Figure 2-7 shows that the Reusable Centaur has a large performance margin. The 28-foot-long vehicle can deploy 4,581 pounds in geosynchronous equatorial orbit without any velocity package. For two very high energy NASA missions, it is necessary to expend the vehicle. A 22-foot-long version constructed without straight sections in the fuel and oxidizer tanks can far exceed requirements for payload placement in a 12-hour elliptical orbit.

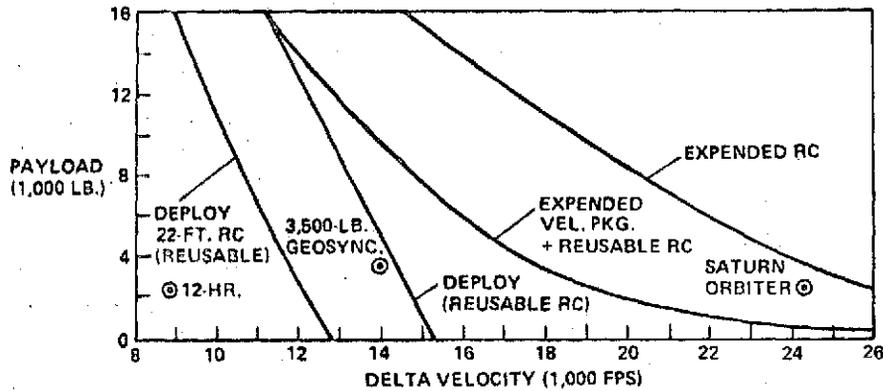


Figure 2-7. Reusable Centaur Performance

OOS/Tug mission requirements are not yet firm, especially considering the transition period with requirements for backup. Figure 2-8 is based on the NASA-MSFC NASA/Non-NASA Mission Model of September 1973, and DoD Space Mission Model of 16 August 1973, Revision 1. Polar and near-polar payloads normally launched from WTR are assumed to be launched from ETR. This can be a significant program consideration when planning the substantial Shuttle activation costs at WTR.

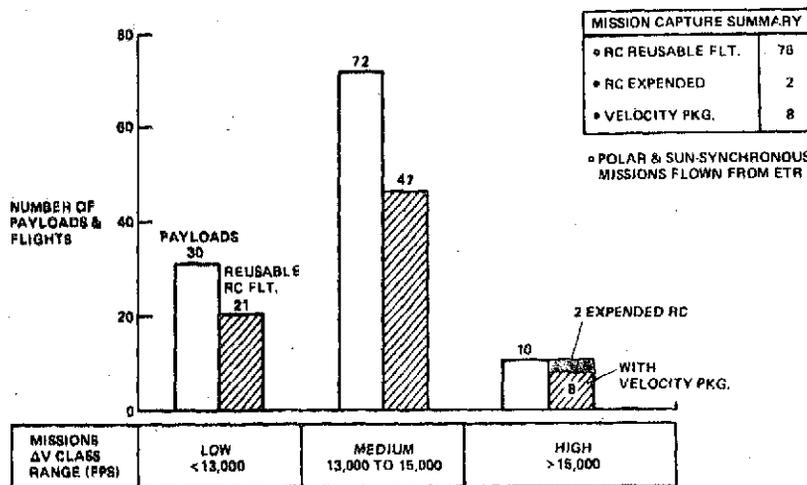


Figure 2-8. Initial OOS Missions 1980-1984

Most of the payloads are less than 25 feet long and require relatively high delta-velocities. Only 5 out of 112 are longer than 25 feet, and only two longer than 32 feet. Most payloads require delta-velocities in the geosynchronous level and higher, up to 27,500 fps for some planetary missions. Reusable Centaur can accommodate the long payloads and still provide the maximum delta-velocities required, with very few velocity packages required. High performance makes it possible to launch multiple payloads on many flights, which means much lower user costs. All 112 missions shown can be done in 78 flights, 91% in completely reusable mode.

2.5 FLIGHT OPERATIONS

Flight operations include deployment from and retrieval by the Orbiter, which leads to the recommended backup docking control system. The proposed CMACS provides to the Mission Specialist in the Orbiter status information, caution and warning functions, override control, and checkout capability. In case of a return-to-launch-site abort, provisions have been made for the Centaur to dump propellants in flight. Dumping only above 220,000 feet, as shown in Figure 2-9, precludes any possible hydrogen ignition because the lower concentration limit of hydrogen combustion in the atmosphere requires pressures of more than 0.1 psia for a hot surface ignition source. Additionally, any dumped hydrogen ingested into the payload bay at these altitudes will be too diluted to later form a combustible mixture. Helium pressurant supply is provided in the deployment adapter (or pallet) which, in conjunction with the large dump lines, allows propellant dump within 250 seconds. In no case is there a requirement or a condition where the Centaur will return with fully loaded propellant tanks. The use of redundant dump valves and the techniques shown are designed to always provide the inflight dump capability under all abort modes.

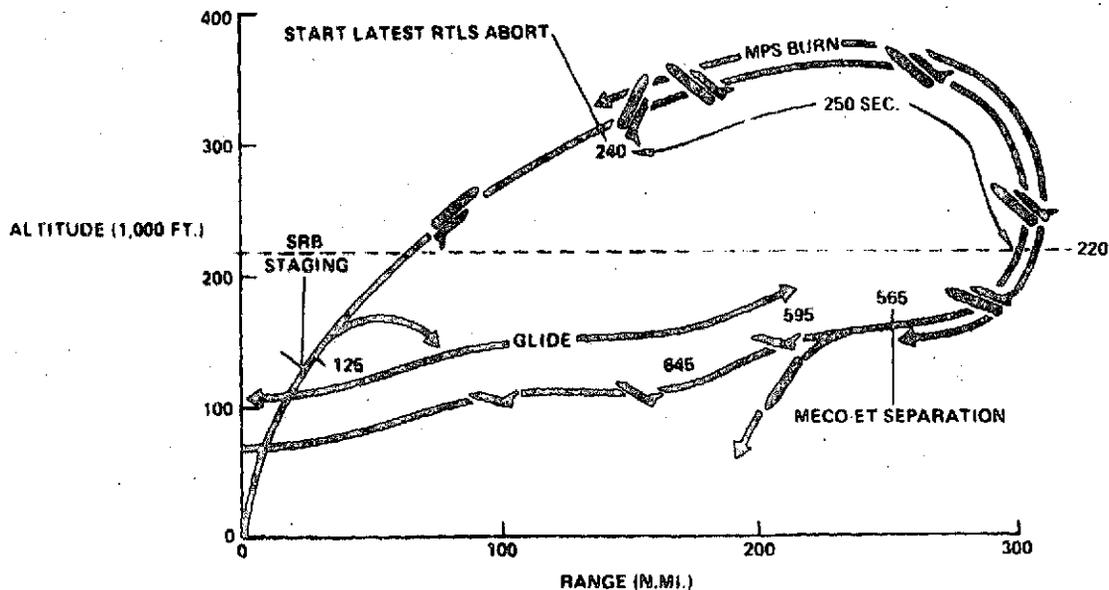


Figure 2-9. Abort Propellant Dump Profile

Solo flight operations are simplified by the lack of drop tanks, tandem stages, and usually no kick stages. Only payload(s) deployment is required by the mission model; however, it is feasible to grow to payload service and/or retrieval capability. The Reusable Centaur delivers a synchronous satellite to orbit, but allows the payload to "walk" or drift to its final position as is current practice. The RLTC delivers payloads directly to their orbital positions by using an additional burn.

Control and communications in flight are different for DoD and NASA payloads. DoD flight operations are controlled from the Satellite Test Center, Sunnyvale, California, using the Air Force Satellite Control Facility (AFSCF) with seven ground stations, and encrypted SGLS compatible communications. NASA may use a five-ground-station space tracking and data network (STDN) plus the tracking and data relay satellite with the Operations Management Center in Houston using unified S-band communications. Since the D-1S(R) and RC are not fully autonomous, ground tracking is required to provide position and velocity update information during flight. The Centaur flight controller and support personnel will provide commands when required.

2.6 SAFETY AND RELIABILITY

Safety is a major consideration for any payload flown in the Shuttle. The Centaur must be essentially fail-safe from the time the stage is installed in the Shuttle until it has separated a sufficient distance from the Orbiter to preclude any possibility of its imposing a safety hazard. The safety features designed into the Centaur were not considered tradeable and more than 200 pounds of associated weight penalties are included. The result is a Centaur design that is considered to be fully compatible with manned Shuttle operations.

One of the most important of these design features is the complete control of any cryogenic propellant leaks while in the Orbiter by using tank isolation valves and a vented purge bag concept. As shown in Figure 2-10, each of the main propellant tanks and its outlet valve, is individually enclosed in a purge bag. The purge bags are purged with helium and are individually vented external to the Orbiter. If a leak should develop in a propellant tank, the leaking propellant will be safely carried overboard. Tank isolation valves are used to maintain the propellant lines in an empty condition during the entire time that the Centaur is in the Orbiter payload bay, thus eliminating the chance of a propellant leak from lines and fittings during Orbiter flight. The dual vent valves and dual dump valves installed on each tank are backed up by parallel redundant valves on the adapter.

The basic Atlas/Centaur pressure-stabilized tank design concept was "man-rated" on the Mercury program. There have been no tank structural failures in more than 440 Atlas and Centaur flights. The spotwelded, tough, stainless steel construction leaks before failing, allowing detection of impending problems. Pressure stability of the Centaur is assured by (1) redundant pressure control systems, (2) redundant pressurization systems, and (3) series/parallel vent valves. In the event of

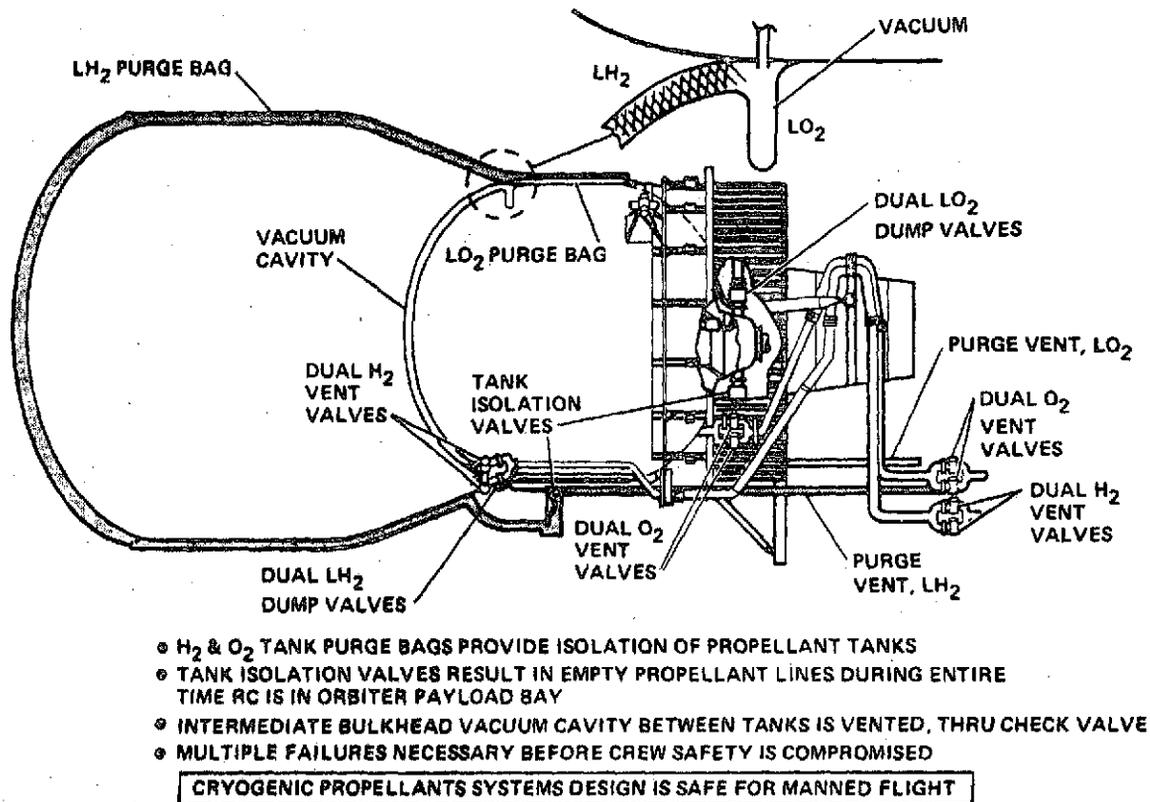


Figure 2-10. Propellant Safety Features

multiple failures of pressurization control, crew override capability (via CMACS) can be used to maintain pressure stability. Normal boiloff of the cryogenic propellants will also automatically maintain pressurization. In the worst case (the series redundant oxygen vent valves both failing open during launch), the pressure decay in the oxygen tank will be less than 2 psi in the first 100 seconds. This will allow sufficient time for the crew to initiate hydrogen dump, which will preclude bulkhead reversal. The intermediate bulkheads are dual: a leak across either bulkhead will not result in propellant mixing. The vacuum cavity is vented overboard.

In achieving the safety levels required for manned operations, all Centaur subsystems are designed to be at least fail safe. Most of the subsystems in fact are designed to be fail operational. The ACPS subsystem was designed to be fail operational/fail-safe to satisfy program reliability requirements as well as safety requirements. Two arm/safe switches are used to interlock astronics subsystem outputs such that premature initiation of potentially catastrophic events (such as main engine ignition) cannot occur. Additionally, events that must occur to ensure safe vehicle operations (such as propellant venting) are backed up by crew override controls via CMACS. The Centaur vehicle can be safed in any flight or ground abort mode. No single failure of any Centaur component will preclude Orbiter abort capability.

The foundation for Reusable Centaur reliability was established by the D-1T reliability improvement study which added redundant tank pressurization/pneumatic

system valves, prime/reference/backup tank pressure sensing, improved vent valves, and jet pipe hydraulic servo valves. In addition to these features, changes were made in the Reusable Centaur subsystem designs to assure manned compatibility with the Space Shuttle. Several of these changes, such as fail-operational/fail-safe ACPS and redundant vent valves, contribute to vehicle reliability as well as to vehicle safety. The resulting reliability for the RC is 0.970 for 30-hour missions (out of payload bay only). For kick stage missions, the mission reliability is the product of the kick stage reliability (0.984) and the vehicle reliability. If funding were available, by using triple computers and dual redundancy for all avionics components in addition to the aforementioned redundancies, vehicle reliability would increase to 0.975 for a 47 hour mission. The high performance of the Centaur will allow the associated weight penalties of redundant avionics to be incurred without a compromise of Centaur capability to deliver all identified payloads to their prescribed orbits.

2.7 GROUND OPERATIONS

Results from the Space Tug Launch Site Service Interface Study, Contract NAS10-8031, were revised to suit an initial Reusable Centaur program. The focus was on turnaround costs, considering manpower and vehicle reusability. Ground operations covers the time span from initial delivery of the new vehicle to the launch range through test and checkout, spacecraft mating, Orbiter mating and checkout, pre-launch operations, launch, landing, safing, removal from the Orbiter, maintenance and refurbishment, and storage or preparation for the next mission. Most turnaround manhours are spent on maintenance and refurbishment, which can conveniently be done in a horizontal dock as shown in Figure 2-11. Space Transportation System ground rules were followed to assure upper stage compatibility with Shuttle operations and turnaround timelines.

Prior to installation, tanking, and launch in an Orbiter for the first time, each new Centaur upper stage vehicle will undergo pre-first flight test and checkout at existing Centaur Launch Complex 36A at Cape Kennedy. A payload bay simulator will be mounted directly on the existing launcher, with service lines tapped off existing service lines at the base of the umbilical mast, to permit propellant loading of Centaur within the payload bay simulator, and control by the existing CCLS. The simulator will duplicate the Orbiter payload bay physical interfaces and thermal characteristics. The first flight article will receive additional testing in this Orbiter simulator to verify safety, compatibility with payload bay nitrogen purge, and the resulting temperatures under prelaunch and hold conditions.

Two-hundred-and-eighty hours are required for turnaround from the time the Centaur lands in one Orbiter until it is launched in another (3-1/2 weeks based on a 5-day week, 2 shifts per day). More than half of this time is constrained by Orbiter activities. This turnaround time allows up to 14 flights per year with one Centaur, if necessary. The active fleet size is not driven by ground operations.

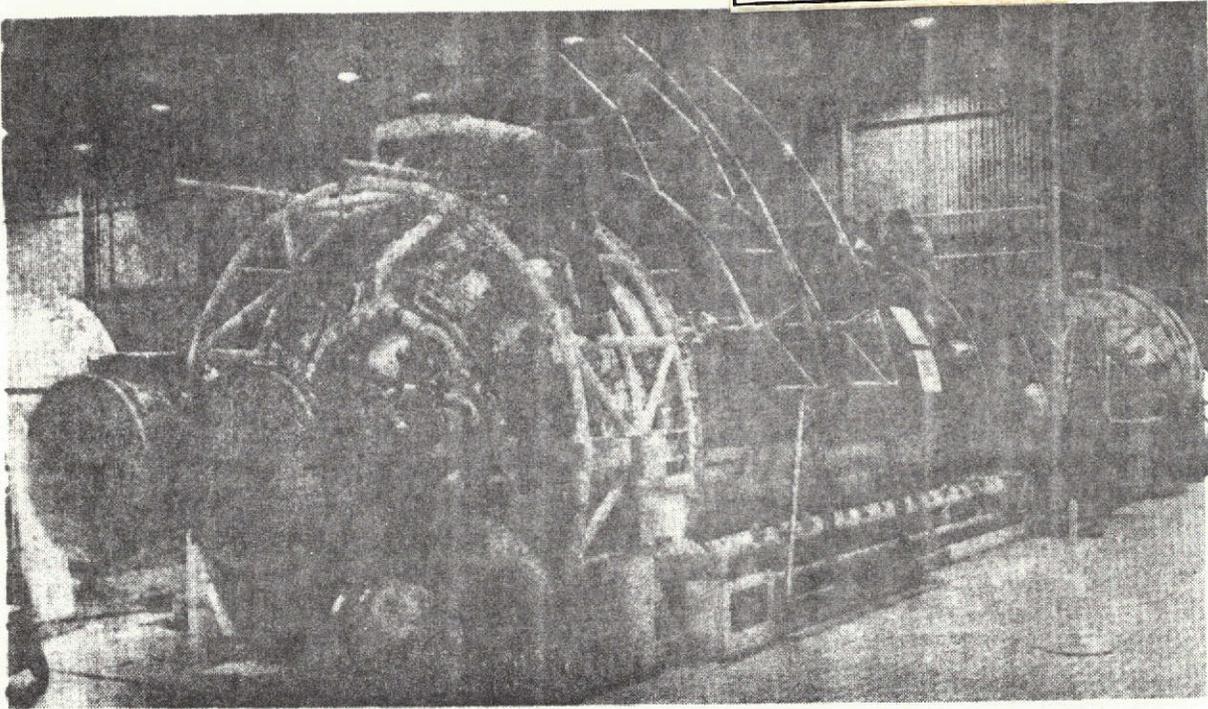


Figure 2-11. Centaur in Maintenance Dock

Existing Centaur facilities at Cape Kennedy can be used with minor modification, deferring the initial investment cost associated with a new Tug maintenance facility until Tug is phased in at a later date. Existing Hangar J will be used for Centaur maintenance and refurbishment; Centaur launch complex 36 will be used for pre-first flight test and checkout of each fleet vehicle before installation in an Orbiter. While a major portion of existing Centaur ground support equipment (GSE) will be utilized for the Reusable Centaur program, ample allowance has been made for new GSE required for test and checkout, maintenance, handling, and storage.

Ground operations studies contributed to the manned compatibility/safety analysis. During preflight operations, cryogenic propellants are loaded on the launch pad via remote controls. The payload bay will be continuously purged with nitrogen to provide an inert environment in case of a propellant leak. Hydrogen and oxygen leak detectors are used to sense any leaks that may develop.

If for any reason rapid defueling of the vehicle should be necessary, Centaur is capable of being drained of all main propellants within 5 minutes. This will also expedite payload changeout at the pad. Postflight safing requires facilities or mobile GSE near the runway for venting residual hydrogen vapors and purging propellant and propulsion systems. Postflight handling is simplified by the fact that the propellants are not toxic or corrosive.

2.7.1 REUSABILITY. The existing Centaur is inherently reusable. Most of the subsystem components (>62%) on the Reusable Centaur are the same as D-1T. Environment in the Shuttle is no more severe than on the Titan booster. The Centaur has been subjected to repeated ground and altitude cycles at San Diego and NASA/LeRC. Review of current Centaur component specifications and qualification test data indicates that in most cases D-1T components have received sufficient life testing to confirm their reusability for 10 to 20 RC missions in terms of operational cycles, thermal and pressure cycles, acceleration, and shock. Component fatigue life testing (vibration) will require demonstration in some cases. New or modified components will be tested to demonstrate life exceeding 10 missions. The propellants used by Centaur are clean and non corrosive, so reuse of the propellant tanks is limited only by fatigue. Welded specimens of each production Centaur tank have been fatigue tested more than 200 cycles to maximum stress at liquid hydrogen temperature. Analyzing this data for OOS flight indicates this type of tank should have an operational life exceeding 45 flights. A fatigue test to demonstrate this reuse is included in the development cost. The tanks and lines are not coated, so inspection and refurbishment is greatly simplified. The RL10A-3-3 main engines are currently qualified for 4000 seconds of firing (six to eight average flights) and have demonstrated a service life of 4 hours (>20 missions). The engines are regeneratively cooled and do not have ablative nozzles that require replacement after each flight.

The astronics equipment is designed for repetitive use and quality of Centaur components is such that life expectancy exceeds 29 flights for the overall system. The mean time between failures for the digital and inertial units are projected at 3500 hours or more. It is expected that preflight checkout of astronics units will be reduced to 100 hours or less between operational OOS flights.

2.8 PROGRAMMATICS

OOS is currently expected to be operational in July 1980. The Reusable Centaur development plan requires about four years as shown in Figure 2-12. The pacing item is flight software including validation and integration with the Orbiter ground control centers, and launch site (an area still unsettled concerning language and interfaces); therefore, program go-ahead is needed approximately mid 1976.

2.8.1 DEVELOPMENT TESTS. More than one third of the Reusable Centaur development effort involves the major system tests listed in Table 2-3. Propulsion system testing is required to demonstrate that slow shutdown satisfies the new Shuttle mission thermal environment and 5.8:1 nominal mixture ratio. Since engine inlet conditions are to be the same as for current Centaurs, extensive development tests are not required as they would have been for a Cat I program (an RL10 version being considered for the single engine Tug).

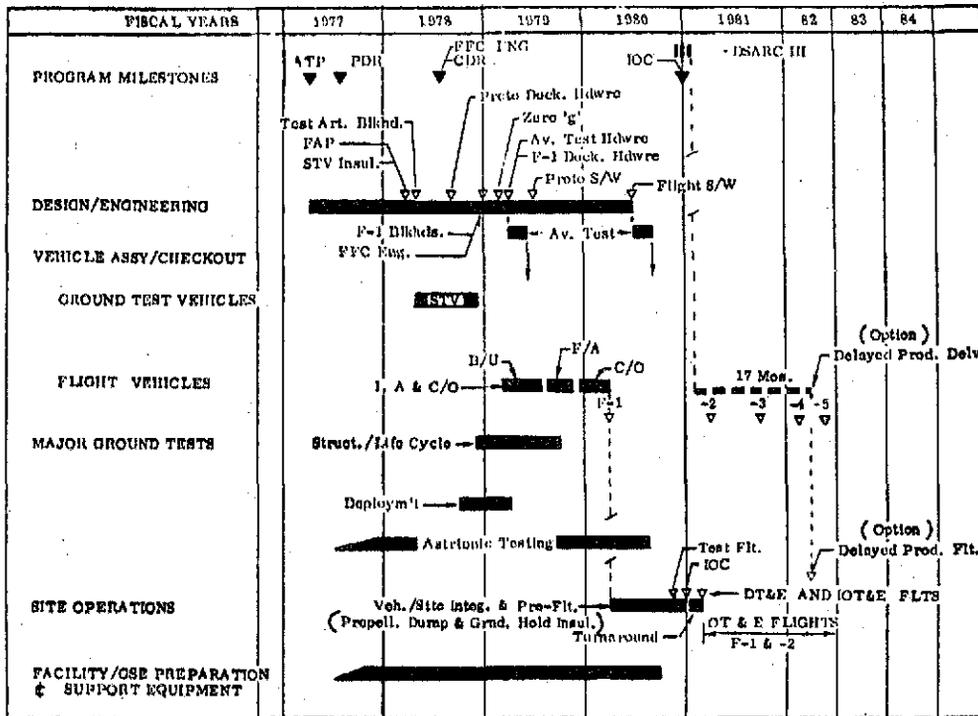


Figure 2-12. Reusable Centaur Program Schedule

Table 2-3. Development Test Summary

TEST ACTIVITY	TEST SITE	TEST ARTICLE	TEST PROGRAM COSTS (\$M)			
			TEST ART.	FACILITY & MATL.	TEST OPS.	TOTAL COST
COMPONENT QUALIFICATION	CONVAIR & VENDORS LABS	PREPRODUCTION COMPONENTS				3.50
ENGINE SYSTEMS	P&W E-5	ENGINE AND FEED SYSTEM HARDWARE	(FEED SYSTEM HARDWARE INCLUDED)			4.76
STRUCT. LOADS & CRYO/PRESS. CYCLES	M&FC S-2	STRUCTURAL TEST VEHICLE	2.23	1.09	1.34	4.66
DEPLOYMENT ADAPTER SYSTEMS TEST	CONVAIR	DEPLOYMENT ADAPTER TEST ARTICLE	0.97	0.02	0.30	1.29
ASTRIONICS SYSTEMS INTEGRATION	CONVAIR, JSC, AND ETR	ASTRIONICS SYSTEM MODULE	4.05	0.02	0.37	4.44
SITE VALIDATION	ALL ETR R/C FACILITY	AGE, FACILITIES & FLIGHT TEST VEHICLE	-	0.08	0.42	0.50
CRYO TANKING, FLOWS & GROUND HOLD VERIFICATION	ETR CX 36	FLIGHT TEST VEHICLE & CARGO BAY SIMULATOR	-	0.05	0.35	0.40
FLIGHT TEST	ETR CX 39	FLIGHT TEST VEHICLE	5.31	-	1.34	6.65
TOTAL TEST PROGRAM COST (\$M)						28.20

One dedicated structural test vehicle will be subjected to static load tests for strength and deflection to qualify the redesigned fuel/oxidizer tank structure, combined cryo-pressure cycles to obtain reusability data, and dynamic testing for vibrational loads if desired. A large cryogenic test stand, such as the MSFC S-2, or TAPER facility of AFRPL is required. The deployment test is an ambient functional evaluation of the deployment and docking mechanisms.

Astrionics units will be installed on the astrionics module in a flight configuration and hardware interfaces, procedures, and computer control software will be finalized and demonstrated during subsystem level tests. The Centaur astrionics module with associated GSE will be tested for compatibility with the Shuttle astrionics systems and associated GSE in the Shuttle Vehicle Systems Integration Lab at NASA/JSC and integrated with the operational flight site at KSC, as part of the flight test vehicle.

The flight test vehicle will be delivered to the test site some seven months prior to initial flight to verify vehicle compatibility with all operational facilities, support equipment, and procedures. During vehicle-site integration, it will be used at Pad 36, an existing Centaur launch site, for thermal evaluation of the vehicle ground-hold insulation system and for demonstration of the propellant rapid-dump system capabilities. The flight test will precede IOC by two months, allowing two months for vehicle turnaround activity tests.

Flight tests are basically to verify Orbiter-Centaur interfaces, operations, and safety. As part of the flight test, it is most cost-effective and technically feasible to carry a relatively low-cost operational payload, placing it in a low-energy operational orbit at relatively low risk.

Following completion of the flight test mission, R&D instrumentation and test equipment will be removed and Centaur readied for operational service. Test flight costs can be minimized by use of refurbished test engines, astrionics test module, and support systems from structural test articles. As applicable to the procuring agency, the test flight cost can be allocated directly to DDT&E with payload placement as a secondary objective, or it can be assigned to the operations phase of the program with testing as the secondary objective.

2.8.2 FLEET SIZE. The Reusable Centaur has a performance capability which permits 100% capture of the 112 payloads in the four-year mission model, with 78 flights. Multiple payload delivery is used on many missions, velocity packages are used on eight flights, and Centaur itself is expended on two outer planet missions. Consideration of all programmatic factors indicates a recommended buy for the four-year program of seven vehicles and one spare tank: six "standard" 28-foot vehicles including the flight test article, one "short" 25-foot vehicle, and a short tank spare for buildup in event of loss of the short tank vehicle. The short vehicle delivers single payloads only, including long DoD payloads which can only be flown on the short vehicle.

As indicated in Table 2-4, the seven-vehicle fleet provides for two expended vehicles, one vehicle lost through attrition, and four vehicles left in inventory at the end of the four-year program. The four inventory vehicles provide for contingency capability, scheduling flexibility, uneven launch center scheduling, unexpected early attrition, assurance of mission model completion, and a reusability factor which will permit program extension during Tug phase-in, if required. No vehicle will be required to fly more than seven times per year, with an average for all vehicles of four to five flights per year. With normal attrition, the maximum life requirement for any vehicle will be 16 flights, or 17 in the case of early attrition. In most cases, vehicles are Agency-dedicated, although some sharing of missions is scheduled to equalize usage.

Table 2-4. Reusable Centaur Fleet Utilization Schedule

Active Fleet (7 Vehicles)				Annual Traffic				Total Flights
Vehicle No.	Delivery Date	Need Date	Disposition	80	81	82	83	
NASA-1 FT	Apr 79	Nov 79	Expen.	3 Δ				3
NASA-2	Jan 80	Jan 80	Expen.	7	4 Δ			11
NASA-3	Sep 80	Jan 81	Attri.		5	3*		8
NASA-4	Jan 81	Jan 81	Inven.		5	4	7	16
DoD-1	Sep 79	Jan 80	Inven.	(4)	(5)	(5)	(1)	(15)
DoD-2(S)	May 80	May 80	Inven.	1+(1)	3+(2)	(1)	(2)	4+(6)
DoD-3	May 81	May 81	Inven.		(3)	1+(5)	3+(3)	4+(11)
NASA Flights				11	17	8	10	46
DoD Flights				(5)	(10)	(11)	(6)	(32)
Total Flights				16	27	19	16	78
Active Fleet, Including Attrition				4	6	5	4	

FT: Flight Test Article

(): DoD flights

* : Attrition loss assumed

Δ : Vehicle expended on outer planet mission

(S): Short stage

2.9 PROGRAM COST ESTIMATES

Cost data from D-1A and D-1T development and Titan/Centaur integration, which commenced in mid 1969 and will conclude with the Titan/Centaur proof flight in February 1974, provides a comprehensive and relevant cost data base from which to estimate the Reusable Centaur and Shuttle/Centaur integration costs. D-1A/D-1T development costs total \$75M including General Dynamics, associate contractors like Teledyne, and site integration costs at ETR. Costs presented are for budgetary

planning purposes only. They represent estimated total program cost to the government at program completion and as such include allowances for cost growth over the program life cycle which are not normally included in bid type estimates. Costs are expressed in constant year dollars at 1973 values and exclude prime contractor fee/profit. An allowance for typical payload and mission-peculiar costs is included, but costs associated solely with the spacecraft and/or the Space Shuttle are excluded. Costs of GFE and associate contractor items such as engines, guidance, and propellants are included. The Reusable Centaur program is an adjunct to an ongoing Centaur production, minimizing program start-up costs. Overall costs associated with the three configurations for Reusable Centaur are presented in Table 2-5.

Table 2-5. Program Cost Comparison

	D-1S(R)	RC	RLTC
DDT&E	\$63.3M	\$77.2M	\$122.2M
Unit Production	8.1	8.5	11.9
Unit Operations	1.7	0.9	1.2

The RC vehicle configuration resembles the D-1S(R) configuration with the exception that the main propellant tanks are larger like the RLTC tanks; hence, the development costs of RC correspond more closely with D-1S(R) than RLTC. For example, the RC does not incorporate the triple redundant guidance computers and other complex astrionics associated with Level I autonomy as does the RLTC. Additionally the RLTC incorporates a new hydrazine ACS and composite structures while the RC retains the existing hydrogen peroxide ACS and conventional aluminum and titanium structures. Although the RC appears to more closely approximate the RLTC configuration, in fact it is a D-1S(R) with a lengthened liquid oxygen tank, widened liquid hydrogen tank, and modified Shuttle fuel cell in lieu of batteries.

Average unit operations cost for RC is lower than D-1S(R) and RLTC and reflects the fact that the larger vehicles require fewer kick stages to perform the mission model: (D-1S(R) =44, RLTC =2, RC=8). Additionally the RLTC with its larger triply redundant computers requires more flight control software which partially accounts for the higher average RLTC operations costs.

Nonrecurring costs of \$77.2M for the 28-foot Reusable Centaur development are summarized in Figure 2-13. Total stage DDT&E cost is \$28.8M and includes development and component qualification of all new hardware. Included in the propulsion and fluid system development is engine testing required to demonstrate the changes associated with engine chilldown conditioning and mixture ratio. Astrionics and electrical power changes include the addition of sun and horizon sensors, DoD and NASA communications systems, and a modified Shuttle fuel cell unit. The Orbiter interface equipment includes the deployment adapter and associated mechanical and fluid systems as well as the interfacing astrionics identified as CMACS (Centaur

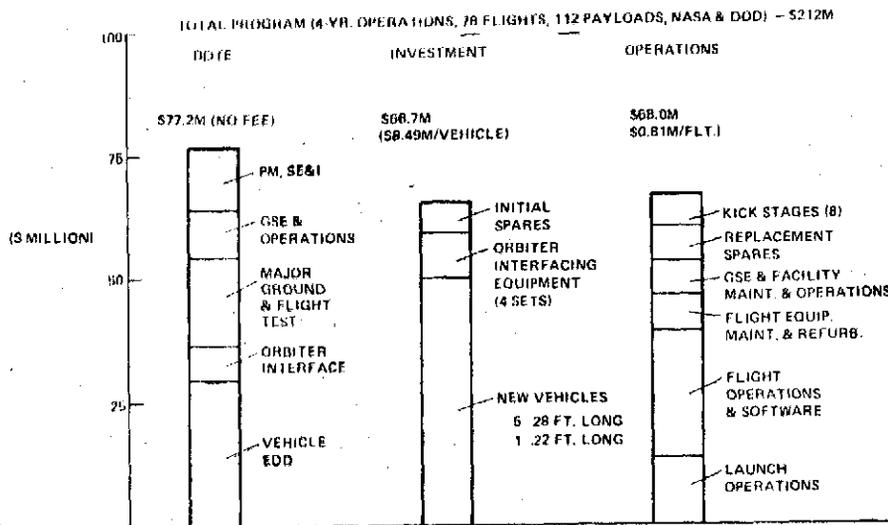


Figure 2-13. Reusable Centaur Program Costs

monitor and control system). Unlike the D-1S(R) and RLTC programs, the RC development costs include a dedicated flight test. GSE and Operations includes development and production of necessary GSE to support factory production and flight operations program phases. Also included is ETR site buildup, integration and activation. Systems engineering and integration (SE&I) includes integration and interface control between the Centaur stage and its payload and the Shuttle Orbiter and Centaur stage. Necessary additional software for the Centaur computer, CMACS computer, and GSE are also included. Cost estimates are based upon current actual experience of interface costs with Titan and payloads.

Investment for a 4-year program launching 112 payloads from ETR includes six new vehicles at \$8.49M each (which is 60% greater than current Centaur unit cost). Operations costs are only \$0.8M per flight because the Centaur is entirely recovered except for 8 kick stages, and it is inherently reusable. In addition to the maintenance and launch crew at ETR, a large team is assumed to be preparing mission peculiar software. The average OOS-dedicated manpower on site and off site is approximately 250. Note that spares are included in investment (initial) and operations (replacement). The low operating cost and multiple payload capability quickly amortize the added development costs, making reusability definitely worthwhile and show that the Reusable Centaur is the least-cost approach to achieving initial upper stage capability.

SECTION 3

CONCLUSIONS & RECOMMENDATIONS

This study used the current D-1T Centaur as a basis to develop several concepts for an initial upper stage for Shuttle. Basic drivers were: (1) low development cost, (2) safety and reliability, (3) reusability and low user cost, and (4) high performance. The D-1S(R) configuration has the lowest development cost. RC has the lowest operating costs. RLTC has the highest reliability and performance. There could be an evolution from one configuration to another. Each Centaur version satisfies different priorities. An optimum solution depends on the mission model taking into account the buildup in Shuttle flights and the transition from expendable launch vehicles. A national mission model must define a backup position, WTR activation for Shuttle operations, whether or not sortie/roundtrip/servicing or retrieval is required, maximum length of special DoD payloads, and the date the ultimate Tug will be available. All of these questions have funding implications. The mission model, OOS requirements, and funding levels are all interdependent, necessitating a complex cost versus capability trade.

3.1 SUPPORTING RESEARCH AND TECHNOLOGY REQUIREMENTS

While the Reusable Centaur programs do not depend on technology breakthroughs, there are areas requiring further development. There are backout positions for each item, and with the inherent Centaur performance margin, alternates can be used. These technology and development areas should be better defined during the next major program phase (Phase B or Validation) to further reduce uncertainties and risk. The identified items are not really technical breakthroughs as much as they are advances or specializations of the current state of the art. Many of them are the subject of ongoing technology contracts which need only to include Shuttle requirements.

- a. Zero-G thermodynamic vent devices, particularly liquid oxygen, including optimum sizing and electric drive system design, culminating in a flight demonstration.
- b. Lightweight advanced fuel cell, such as Pratt & Whitney is developing under USAF (Wright-Patterson) and NASA (LeRC) sponsorship. This should evolve to better suit the OOS/Tug than a modified Orbiter fuel cell.
- c. Composite materials (like epoxy graphite), particularly thin gage face sheets, considering acoustics and meteoroid impacts, compatibility with hydrogen temperatures, and lower costs.
- d. Guidance update accuracy including horizon sensor performance over a wider range of altitudes. Improved techniques need further definition for non-optical alignment on the launch pad, update from the Orbiter, and autonomous or ground assist in flight.

- e. Slow burn kick motor the size of an existing Thiokol TE-M-364-4 but with thrust reduced 1/2 so that planetary probes are not accelerated more than 3.6 g.
- f. Postflight checkout techniques, such as:
 1. Propellant tank leaks/cracks detection including meteoroid impact,
 2. Metalized insulation deterioration measurement,
 3. Self-checking maintenance support instrumentation, and
 4. Checkout isolation of redundant hardware.

3.2 SUGGESTED ADDITIONAL EFFORT

In addition to continuing these technology programs and further defining OOS program requirements, specific studies should be continued. NASA/LeRC should continue the Centaur improvement program to reduce production costs, increase reliability, and improve performance of the Centaur, the RL10 engine, Teledyne computer, etc. Phasing in improvements can benefit both expendable and reusable programs.

3.2.1 OOS TO ORBITER INTERFACES. The Centaur/Orbiter interface requirements have been documented during two previous expendable Centaur integration studies and now the data has been modified for use on the Reusable Centaur. Several aspects of the interface can impact the Orbiter, the Centaur/OOS, and ground operations. The most important areas currently not firm involve operations such as abort and docking. Physical, environmental, operational, and safety interfaces between the Orbiter and Centaur need continued study by both sides to support the Orbiter program review in December 1974. Specific interface areas to be firmed up are:

- a. Structural support arrangements, loads, and deflections in the Centaur and its payload.
- b. Single and multiple payload support and release concepts.
- c. Fluid and mechanical interfaces, including a hydrogen vent on the Orbiter fin tip.
- d. Abort propellant dump operations. The Centaur provisions for complete inflight dump may be unnecessarily conservative.
- e. Payload bay environment, including prelaunch chilling after tanking (thermal model).
- f. Non-optical guidance alignment techniques, for prelaunch and predeployment.
- g. Software development plan covering onboard software for Centaur, Orbiter support equipment software, and ground (flight operations) support software. Recommend format and language which is NASA Shuttle and DoD compatible and still allows maximum utilization of the existing Centaur program library.

3.2.2 FLIGHT AND GROUND OPERATIONS. The major objective of the whole Space Transportation System program is lower uses costs. Yet there are many important features of OOS/Tug operations not clearly defined. Basic questions arise such as: Is the added expense of vehicle autonomy justified by reduced ground operations costs? Are the expense of design improvements and life demonstration tests justified by reduced maintenance and spares costs? Listed below are some of the areas to be covered in an operations study:

- a. Trade autonomy level against hardware, software, communications, and operations costs and ground operations complexity, including fault isolation and system testing.
- b. Maintenance requirements considering Centaur component life expectancy, available test techniques, and learning curve on condition monitored maintenance. Consider life testing during the operational phase to extend service life.
- c. ACPS requirements considering payload requirements, guidance accuracy, rendezvous envelope, etc.
- d. Multipayload combinations considering operations and hardware.
- e. Inflight abort propellant dump.
- f. Postflight safing requirements, routine and post abort.
- g. Utilization of slack time for ground crews.

3.2.3 CONTINUED REUSABLE CENTAUR STUDIES. The basic goal of near term studies, until better mission requirements can be defined, should be to develop cost versus capability data for a range of possible Centaur subsystems. This data would be useful in outlining a possible evolution from expendable to reusable and growth to payload retrieval. Some details of such studies would include:

- a. Trade reliability redundancy versus cost and weight, also defining redundancy management.
- b. Compare hydrazine versus peroxide ACPS operational cost effectiveness.
- c. Compare aluminum/titanium to epoxy graphite structures.
- d. Minimize chilldown and engine start losses.
- e. Compare fuel cells versus batteries; include Orbiter type and advanced fuel cell.
- f. Compare cryogenic helium storage using fuel cell heat exchanger to ambient helium.
- g. Optimize ground insulation and radiation shields; including goldizing.
- h. Propellant utilization versus nominal mixture ratio.

- l. Refine development and qualification test requirements and costs including flight test.
- j. Refine software tasks and costs, considering language and word size to satisfy any revised ground rules.
- k. Refine operating costs for payload and mission peculiar support, ground support during flight, maintenance, and spares.

3.3 CONCLUSIONS

This study has shown that a Reusable Centaur can meet current requirements for an Initial Upper Stage or Orbit-to-Orbit Stage for Shuttle. The major points established are:

- a. Existing D-1T Centaur is an advanced upper stage with computer controlled astronics, and recent reliability improvements.
- b. Centaur has very high performance: 4,580 pounds to synchronous equatorial orbit and more than 4,000 pounds to 12 hour orbit in the reusable mode. This provides margin for future contingencies and growth.
- c. Hardware is inherently reusable, probably more than 10 missions without major overhaul. Long life has been demonstrated in ground test programs.
- d. Safety and reliability have been designed in. Atlas/Centaur tank concept is flight proven including Mercury program.
- e. Program risk is low, not dependent on new technology. Propulsion and computer-controlled astronics can be used essentially as is.
- f. Development cost estimates of \$77.2M are realistic since they are based on recent similar size D-1A/D-1T programs.
- g. User costs and recurring costs are low at \$0.9M per flight due to multiple payloads, minimum expended kick stages, and small fleet size.

Therefore we conclude, from the overall standpoint of low risk, high performance, and low total program cost, Reusable Centaur is the best OOS candidate.