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A High Energy Stage for the National Space Transportation System

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A HIGH ENERGY STAGE FOR THE NATIONAL SPACE TRANSPORTATION SYSTEM

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Abstract

The Shuttle/Centaur is an expendable hydrogen/oxygen cryogenic upper stage for use with the National Space Transportation System. It is a modification of the existing Atlas/Centaur which has been used by NASA since 1966 to launch interplanetary and Earth orbital payloads for numerous organizations. Two configurations of the Shuttle/Centaur are being developed. Vehicle capability includes placing approximately 4500 kg (10,000 lb) in geostationary orbit, and initial applications will be for the interplanetary Galileo and Ulysses Missions in 1986. This paper discusses the Shuttle/Centaur development program, describes the configurations and performance, and indicates the unique integration and operations requirements related to the Shuttle. Design changes to the current Atlas/Centaur required for Shuttle operation are described here, and include those related to Orbiter cargo bay dimensions, environment, and safety considerations.

Introduction

Since the presentation of reference 1 at last year's 34th IAF Congress, there has been significant progress in the development, testing, and production of the Centaur upper stage for the National Space Transportation System (NSTS) (Figure 1). This paper will report on that progress, describe the configuration and performance of the two basic vehicles being developed, and discuss the unique integration and operations requirements related to the Shuttle.

The Centaur is an expendable high energy upper stage, using liquid hydrogen and oxygen propellants. It has been utilized for more than 20 years with Atlas and Titan boosters, and has launched 12 of the 15 successful planetary spacecraft for the United States, including all missions since 1962. Centaur has an overall operational reliability of 98% since 1971. Development of the Shuttle/Centaur capability was initiated in 1982 as a requirement for the Galileo and Ulysses (i.e., formerly International Solar Polar) Missions. The principal contractor is the General Dynamics Convair Division. Major contributions are provided by Honeywell, Teledyne, and Pratt & Whitney Aircraft. Project management is provided by the NASA Lewis Research Center.

First application of Shuttle/Centaur will be to launch the European Space Agency's Ulysses Spacecraft in May 1986 to Jupiter, where that planet's gravitational field will alter the spacecraft trajectory such that it will pass over the solar poles, exploring the out-of-ecliptic regions of the Sun for the first time. A few days later, the Jet Propulsion Laboratory's Galileo spacecraft will be launched on a less energetic trajectory to subsequently orbit and probe the atmosphere of Jupiter, and investigate its satellites.

Both of these initial missions will utilize the G-Prime version of the Shuttle/Centaur upper stage that fills about half of the Orbiter's 18.3 m (60 ft) cargo bay length (Figure 2). The second or G version of Shuttle/Centaur is about 3.0 m (10 ft) shorter, thus providing as much as 12.2 m (40 ft) for the payload length. Capability of the G vehicle is approximately 4500 kg (10,000 lb) to geostationary orbit. However, initial NASA planning for this upper stage also includes an interplanetary mission, the Venus Radar Mapper to be launched in 1988.

Performance

As developed for the Galileo mission, the Shuttle/Centaur G-Prime vehicle can inject a 2405-kg (5302-lb) payload into an Earth-escape hyperbolic trajectory with a single burn of the upper stage's main engines providing a C_3 energy of 80 km^2/sec^2 ($6.9x10^{10}/ft^2/sec^2$). This is to be accomplished for launch from the Eastern Launch Site using a 241-km (130-nmi) circular, 28.5° inclined parking orbit provided by the Shuttle. The single Centaur burn is to occur no earlier than 45 min after separation from the Orbiter.

The principal option is a geostationary mission to be launched with a G vehicle from the same parking orbit. This mission profile results in a current spacecraft system weight capability of 4170 kg (9413 lb) to geostationary orbit with a zero degree inclination. Deployment from the Orbiter is assumed to be within 8 hr after liftoff, but separation can be delayed up to 84 hr after liftoff with corresponding performance degradation. The geostationary mission incorporates two burns of the Centaur main engines, as illustrated in Figure 3. The first burn occurs nominally 45 min after separation from the Orbiter. The second Centaur burn occurs after a 5-1/4-hr Hohmann transfer coast. Following spacecraft separation, the Centaur will execute a collision/contamination avoidance maneuver.

The 4270-kg (9413-lb) geostationary capability is based on the development status of the G vehicle at the March 1984 Preliminary Design Review (PDR). This weight includes a launch vehicle reserve of 85 kg (188 lb) for design maturity, which is equivalent to an additional 136 kg (300 lb) of spacecraft system weight. Since the PDR, launch vehicle system weights have decreased, improving payload capability.

In reference 1, mass and performance data were presented for the Shuttle/Centaur G-Prime, which has a propellant capacity of about 20,850 kg (46,000 lb). Performance data for the Centaur G (which has a propellant capacity of about 13,600 kg (30,000 lb)), were not presented. The Centaur G is appropriate for longer, heavier payloads requiring lower energies.

Table 1 provides current G-Prime vehicle mass summaries for the Galileo mission and for a more representative baseline mission with a characteristic velocity of 14.85 km/sec (48,710 ft/sec). For both of the missions shown, the current Shuttle lift capability precludes fully loading the Centaur tanks. The Shuttle/Centaur Galileo mission is a special case due to the commitment and preparation of a specific Orbiter to meet the Galileo requirements. Centaur masses and expendables for the Galileo mission are based on mission groundrules peculiar to that mission. The total loaded mass for the Galileo mission is 29,484 kg (65,000 lb) rather than the standard 27,442 kg (60,500 lb). The groundrules for the G-Prime baseline mission are as below.

Figure 4 shows Shuttle/Centaur G-Prime performance capability as a function of characteristic velocity. These data are also an update of the data of reference 1. The Centaur and CISS masses and groundrules are consistent with current Galileo parameters, but the Shuttle data are based on the current NASA standard Shuttle capability groundrules: (1) Shuttle cargo lift capability to a 241-km (130-nmi) circular orbit with a 28.5° inclination is 27,442 kg (60,500 lb) and (2) Shuttle chargeable weight is 1202 kg (2650 lb). The Shuttle chargeable weight consists of the Shuttle-supplied hardware which is necessary to fly the Centaur. The Centaur tanks must be offloaded when the total loaded mass, including spacecraft, exceeds 27,442 kg (60,500 lb).

Table 2 provides Centaur G vehicle mass summaries for the geostationary orbit mission and for a representative mission with a characteristic velocity of 11.85 km/sec (38,880 ft/sec). The Centaur tanks are fully loaded in these cases. Figure 5 shows the Shuttle/Centaur-G performance capability as a function of characteristic velocity. The Shuttle cargo groundrules are the same as for the Centaur G-Prime.

System Description

To meet cost, reliability, and schedule requirements, integration of the Centaur with the Shuttle is being accomplished with minimum modifications to the current upper stage vehicle and Orbiter. To a large extent, this is possible because of the Centaur Integrated Support System (CISS) (Figure 1). The CISS is to be installed in the Orbiter cargo bay and will provide compatible mechanical, electrical, and fluid interfaces between the Centaur and Orbiter. It will be returned to the launch site by the Orbiter for reuse. Installation and removal of the CISS from the Orbiter will have minimal impact on Shuttle schedules and weight. Weight permanently added to Orbiters Challenger and Atlantis to support Centaur is to be only 122 kg (268 lb).

Because the Shuttle is a manned vehicle, safety requirements are more stringent than for previous Centaur applications. Numerous redundant electronic and fluid system components are required on the Centaur and CISS. To minimize upper stage vehicle weight, these redundant computers, valves, and other components are to be mounted on the CISS where feasible, rather than on the Centaur. From lift-off to deployment from the Orbiter, the Centaur will be in a relatively quiescent state, with the CISS monitoring and controlling active Centaur systems required for Shuttle safety. Although the CISS weight increases the total Shuttle lift requirement, its use reduces the Centaur stage dry weight which increases mission payload capability. Also, since the CISS is to be returned with the Orbiter for reuse, recurring costs will be reduced.

Centaur Structure for G-Prime Vehicle

The Centaur tank structure is pressure stabilized using the weight effective thin stainless steel tank technology developed initially by General Dynamics Convair Division. The Centaur tank consists of a liquid hydrogen and liquid oxygen tank joined by a common intermediate bulkhead. The liquid hydrogen tank is at the forward end of the vehicle and consists of a 4.32-m (170-in.) diameter cylindrical section closed by an ellipsoidal forward bulkhead and a 24° conical aft transition section that attaches to the LO_2 tank at its forward bulkhead/cylindrical section joint.

The liquid oxygen tank is formed by two ellipsoidal bulkheads of 3 m (120 in.) major diameter and 2.2 m (87 in.) minor diameter with a 78.75-m (31-in.) cylinder inserted between the bulkheads. The tanks will hold about 21,000 kg (46,000 lb) of propellants. The relative size of the tanks is determined by the desired engine burn mixture ratio of 5/1 (oxygen/hydrogen mass ratio).

The Centaur stage avionics are mounted on the forward adapter which consists of conical and cylindrical sections (Figure 2). The 33° conical section is a skin stringer aluminum alloy structure which is 119 cm (47 in.) long with a 4.32-m (170-in.) diameter at the base and a 2.7-m (108-in.) diameter at the forward end. The cylindrical section is 63.5 cm (25 in.) long and bolts to the liquid hydrogean tank forward ring. The cylindrical section skin is graphite-epoxy composite material.

At the rear of the Centaur, an aft adapter distributes CISS support loads into the Centaur oxygen tank. This is a 3-m (10-ft) cylindrical graphite/epoxy skin structure 28 cm (11.2 in.) long, which bolts to the liquid oxygen tank ring on the forward end and to the separation ring at the aft end.

The liquid hydrogen tank requires insulation that is effective in the atmosphere as well as in space. The liquid hydrogen tank forward bulkhead is insulated by a two-layer foam blanket under a three-layer radiation shield. The area between the forward bulkhead and the forward adapter is purged with helium during atmospheric operations to prevent condensation on the cold hydrogen tank walls. The same foam insulation is used on the liquid hydrogen tank sidewalls for prelaunch thermal control. Three radiation shields surround the foam insulation blanket on the sidewalls with the innermost shield acting as a sealed membrane to contain the helium purge. All other radiation shields are vented so they can be easily evacuated during ascent.

The liquid oxygen tank sidewall insulation is an extension of the liquid hydrogen radiation shield assembly, except all three shields are vented. The helium-purged foam blanket is not required for prelaunch insulation of the oxygen tank sidewalls and is omitted. The oxygen tank aft bulkhead is insulated by four vented radiation shields. All shield surfaces exposed to the Sun have a teflon surface with an under layer of vacuum deposited aluminum to achieve a low solar absorptance-to-emittance ratio for thermal control. A twin-skin vacuum intermediate bulkhead separates the two tanks. This is the same system that has been employed on all Centaur vehicles and yields very low heat transfer across the bulkhead.

The Centaur vehicle structural components will be designed to provide ultimate factors of safety greater than or equal to 1.40 while in the Orbiter bay and 1.25 after deployment.

CISS Structure for G-Prime Vehicle

The aft adapter on the Centaur stage mates to the deployment adapter on the CISS through the Lockheed Super*Zip separation ring, which is a dual pyrotechnic system. When the Super*Zip is fired, the ring is severed and a spring system thrusts the Centaur from the Orbiter at a velocity of 1/3 m/sec (1 ft/sec).

The deployment adapter transfers Centaur loads to the Centaur support structure during flight within the Orbiter and includes the rotation mechanism and the separation spring system. The basic structure of the 3-m (10-ft) diameter, 1.1-m (44-in.) high adapter is conventional aluminum skin-stringer construction. Just prior to deployment, the adapter rotates 45° around the two Centaur support structure trunnion pins. The deployment adapter supports the two fluid umbilical panels, the electrical umbilical panels, valve panels, deployment actuator fittings, and an avionics mounting shelf. It also provides a structure which helps support the two Centaur engines during Shuttle flight.

Centaur/Orbiter Structural Interfaces for G-Prime Vehicle

The Centaur vehicle and CISS attach structurally to the Orbiter at 8 points. Two aft retention pins on the CISS share the aft vertical load, and two forward retention pins on the CISS share the vertical load with the aft pins, and react all axial loads from the Centaur with its payload. CISS keel pins on the forward adapter share the lateral loads. Two sill pins on the forward adapter share the vertical loads with the CISS pins.

G-Vehicle Differences for Centaur and CISS Structures

The Centaur tanks and CISS for the G vehicle are basically the same construction as for G-Prime. The G tanks are smaller holding 13,500 kg (29,600 lb) of propellant for a 6/1 mixture ratio. The overall vehicle is 6.1 m (20 ft) long vs. 9.0 m (29.6 ft) for G-Prime (Figure 2). The CISS is shorter to be compatible with the shorter G vehicle.

Propulsion Systems

The Shuttle/Centaur main propulsion system consists of two Pratt & Whitney RL-10 regeneratively cooled hydrogen/oxygen engines using an expander cycle. The Shuttle/Centaur G-Prime utilizes RL-10-3-3A engines operating at a 5/1 nominal mixture ratio and 73,400 N (16,500 lb) nominal thrust each with a specific impulse of 446.4 sec. The Shuttle/Centaur G uses RL-10-3-3B engines at 6/1 mixture ratio, 66,700 N (15,000 lb) thrust each with 440.4 sec specific impulse. The engines operate at constant thrust and are capable of multiple starts after long coast periods in space, as demonstrated in previous missions. Each engine contains a hydraulic gimbal actuation system which is powered by the turbopump assembly.

Prior to engine ignition, the propellants must be settled to the bottom of the tanks to provide the liquid propellants at the sumps for engine operation. The settling thrust is provided by the auxiliary propulsion system. After the propellants are settled, the propellant turbopumps are chilled and primed before each engine operation to prevent pump cavitation during the engine start transient. Hydrogen and oxygen are flowed concurrently through the appropriate pumps during the prestart cycle prior to each engine ignition to chill them to their required temperatures.

The auxiliary propulsion system for attitude control during coast phases and for settling the propellants prior to the main burn consists of twelve 27 N (6 lb) hydrazine monopropellant thrusters. Four thrusters are oriented axially and provide settling thrust. The other eight thrusters provide pitch, yaw, and roll control. The thrusters are fed from a positive expulsion bottle capable of holding up to 77 kg (170 lb) of hydrazine. An additional bottle may be added as required. The hydrazine thrusters are manufactured by Hamilton Standard.

Fluid Systems

The Shuttle/Centaur fluid systems include the main engine propellant supply, the cryogenic vent fill/dump, hydrazine, reaction control, hydraulic, and pneumatic systems. The fluids include liquid hydrogen, liquid oxygen, gaseous hydrogen, helium, hydrazine, and hydraulic fluid.

The main engine propellant supply system provides propellants to the engine (as described earlier) with the net positive suction head (NPSH) required by the engine turbopumps. The required NPSH is provided prior to engine start by pressurizing the vehicle propellant tanks with helium. During a burn the oxygen tank is also pressurized with helium. In the case of the hydrogen tank, gaseous hydrogen from the main engines is bled back into the hydrogen tank to maintain pressure and conserve helium. Flexible insulated feed ducts deliver propellants from the tanks to the engine turbopumps. To prevent inadvertent opening of the propellant inlet shutoff valves, a parallel set of pyro valves and solenoid valves upstream of the pneumatically actuated control solenoid valves provides the two-failure-tolerance dictated by Shuttle safety requirements. The pyro valves will be fired open shortly before the first main engine burn.

The main propellant tanks are filled through the CISS after the Centaur and spacecraft are installed in the Orbiter prior to launch. Unlike a solid fueled stage, the Centaur propellant tanks can be dumped in case of a Shuttle abort after launch. For compatibility with all Shuttle abort modes, the fill/dump system has been sized to provide single-failure-tolerant propellant dump capability within 250 sec. Propellant dump is performed by using pressurized helium stored in bottles on the CISS and the Centaur to force the hydrogen and oxygen from the tanks overboard through the CISS. After the propellants are dumped, the tanks are purged with helium. Capability for abort dumping with the Centaur will allow the Orbiter to land with about 10,000 kg (22,000 lb) in the cargo bay rather than the 29,500 kg (65,000 lb) that otherwise would be in the bay with a fully loaded Centaur.

To prevent large outages (residuals) of either hydrogen or oxygen at the end of flight, Centaur has an active propellant utilization system. The system takes propellant level data obtained from capacitance probes in the propellant tanks and adjusts engine mixture ratio during a burn to maintain the nominal propellant mixture ratio in the tank. Since the main impulse propellants are cryogenic, heat leaks into the tanks cause the propellants to boil and the tank pressures to rise. A vent system is required to control pressure in the tanks. For each propellant tank, pressure is controlled by a parallel set of valves, one mechanical self-regulating vent valve with solenoid lockup capability and one solenoid operated valve. During the time the Centaur is in the Orbiter bay, propellants are vented overboard through the CISS at various locations on the Orbiter sidewalls and aft section.

The liquid hydrogen tank has a thermodynamic vent system for control in a zero-g environment. The thermodynamic vent system has an electrically driven pump to circulate hydrogen over heat exchanger coils and mix the bulk hydrogen. The oxygen tank is not expected to require venting in orbit providing the bulk fluid is well mixed. A pneumatically operated jet pulse mixer assures that the liquid oxygen is well mixed.

For the G-Prime Centaur, two helium bottles on the Centaur and 18 on the CISS contain the helium necessary to meet the pressurization, dump, purge, and pneumatic valve operation requirements. The helium bottles are Kevlar-overwrapped metal-lined spheres. The Centaur bottles are 66 cm (26 in.) in diameter and the CISS bottles are 56 cm (22 in.) in diameter. The G version of the vehicle has an additional 56 cm helium sphere on the Centaur and 12 spheres of 56 cm diameter on the CISS.

The auxiliary propulsion system consists of the twelve 27 N (6 lb) thrusters mentioned earlier. The tank is a positive expulsion type with a 77-kg (170-lb) capacity. The feedlines from the tank to the motors are heated to prevent freezing due to their proximity to cryogenic propellants and exposure to space conditions. The feedline joints are welded to ensure an absolutely leak-proof contamination-free system. For safety reasons, there are pyro valves in the hydrazine tank inlet and outlet lines to provide positive isolation of the hydrazine tank. A downstream set of parallel pyro valves and solenoid valves provides two-failure-tolerance against inadvertent thruster operation. Like the pyro valves in the main propulsion system, the pyro valves in the auxiliary control system will not be fired until the Centaur has reached a safe distance from the Orbiter, about one hundred meters (300 ft).

Thrust vector control is provided during main burns by gimbaling the RL-10 engines using hydraulic actuators. Each engine is driven by two closed-loop, servo controlled actuators. The systems on each engine are independent with an engine-driven main hydraulic pump and an electric-motor-driven recirculation pump. The hydraulic system is inactive in the Orbiter bay except for operation of the recirculation pump during lift-off and abort landing, and intermittent operation on orbit for thermal conditioning of the hydraulic system components.

Avionics and Electrical Systems

The avionics system on the Shuttle/Centaur/CISS performs or controls the guidance and navigation, control, sequencing, propellant utilization, vent and pressurization, instrumentation, and telemetry functions. The system on the Shuttle/Centaur is very similar to that currently used on the Atlas/Centaur, and includes the Teledyne Systems Company digital computer unit (DCU), a Honeywell Inc. inertial measurement group (IMG), a sequence control unit (SCU), a servo inverter unit (SIU), a dual-failure-tolerant arm/safe sequencer (DUFTAS), and other avionics equipment.

The DCU is a 16,384-word, 24-bit, random-access, core memory computer. The IMG provides the DCU with a measurement of vehicle accelerations, using a four-gimbal, gyro-stabilized platform which supports three orthogonal, pulse-rebalanced accelerometers. The guidance and navigation function for the Centaur is performed by the DCU, which takes the vehicle accelerations, integrates them appropriately, computes position and velocity, and generates required steering signals from the guidance algorithm.

Centaur main engine thrust vector control and coast phase attitude control are performed based on vehicle attitude errors received by the DCU from the IMG. The DCU computes desired engine actuator commands which are then sent from the DCU to the servo inverter unit. The SIU differences the command from a position signal from the engine actuator feedback transducer. This difference is power amplified and applied to the engine actuator servo valve. During a coast phase, attitude control signals are generated by DCU computations, again using input from the IMG. The sequence control unit receives input from the DCU which activates relays in the SCU which cause the appropriate attitude control thrusters to fire. Until the deployment is complete and Centaur is a safe distance from the Orbiter, a timing mechanism (DUFTAS) provides dual-failure-tolerance against inadvertent initiation of all Centaur hazardous functions, including both main engine and attitude control engine firings.

In addition to controlling the attitude control thruster firings, the DCU provides all sequencing commands to vehicle systems and required discrete commands to a spacecraft. These commands are routed to the SCU which activates relays implementing the discretes. Logic in the DCU minimizes main impulse propellant residuals by actively controlling engine mixture ratio. As mentioned earlier, capacitance probes in the propellant tanks sense propellant levels. These data are used by the DCU to determine the proper engine mixture ratio to minimize residuals. The DCU also monitors and controls the pressurization of the Centaur main propellant tanks according to a predetermined schedule, minimizes helium usage, and provides failure detection and corrective action for the redundant tank pressurization components. In addition to the above functions, the DCU with ancillary equipment manages the instrumentation/telemetry function to provide a data stream through the Orbiter while the Centaur is in the bay or in Orbiter proximity. After deployment and separation, the Centaur switches to the Tracking and Data Relay Satellite (TDRS) link which transmits data to the White Sands Ground Tracking Station.

CISS avionics provide the dual-failure-tolerant capability to meet Orbiter safety requirements. Five identical control units (computers), with majority voting, provide the redundancy to meet these requirements. All electrical interfaces between the Centaur and the Orbiter are provided by the CISS. The CISS also provides computer control prior to separation for operational sequencing of all systems requiring multi-failure-tolerance, propellant tank vent and pressurization control, electrical and power control, instrumentation and telemetry pyrotechnic control for Centaur separation from the CISS, and Centaur propellant-level tanking indications. The system is designed to minimize the Centaur avionic interfaces with the Orbiter.

Electrical power for the Centaur is provided by a silver-zinc battery of 150 amp-hr, which is switched on just prior to Centaur deployment. Additional batteries can be provided for longer missions. Backup CISS electrical power is provided by two 375 amp-hr silver-zinc batteries, redundant with Orbiter power to provide two-failure-tolerant power to the CISS/Centaur in the Orbiter-attached mode.

Software System

The software system includes Centaur vehicle software, CISS software, and extensive ground computer software. The Centaur and CISS software is modularized such that each module performs a unique and manageable segment of instructions which are individually coded, checked, and documented. This modular concept has been successfully used in the Atlas/Centaur program and provides the necessary flexibility and reliability for the rapid assembly of the software required to fly a wide variety of missions. The vehicle DCU software includes not only the software required to perform the functions described in the avionics section, but also software which supports ground checkout and launch operations. The flight software uses backups that are as forgiving as possible of hardware failures.

The CISS software supports ground testing, ground and launch support operations including tanking, predeployment testing and operations of the Centaur and the CISS, and prelanding and postlanding operations, including Shuttle abort. As stated earlier, the major purpose of the CISS software is to control in a one-or-two-failure-tolerant system all safety related functions while the Centaur vehicle is attached to the Orbiter. The CISS software is designed to relieve the burden which would otherwise be placed on the Centaur vehicle avionics or the Shuttle crew to control all safety related functions in a two-failure-tolerant mode. The ground computer software includes extensive capability for ground testing of the Centaur and CISS systems, the tanking operation, and prelaunch and launch operations.

Development Program

Test Program

Ongoing development, qualification, and validation tests, together with previous experience with cryogenic Atlas and Centaur vehicles, will result in a low-risk program. Development testing for Shuttle/Centaur is planned to provide early solutions to design problems and to identify key characteristics of hardware and software. Component and/or subsystems will be tested in progressive stages to ensure earliest recognition of possible problem areas.

A limited amount of structural development testing will be necessary for Shuttle/Centaur. These development tests will consist initially of material elements and welding tests, separation tests, tank insulation tests, Centaur support structure load tests, and tests due to the new launch and landing environment. These new environmental tests include acoustics, vibration, Centaur loads, and modal surveys. Fluids and mechanisms systems for Shuttle/Centaur are based on Atlas/Centaur (i.e., Centaur D-1A) technology except where Shuttle imposes additional requirements. The development test will cover mechanisms to deploy the Centaur from the Orbiter, propellant dump capabilities, and fluid interfaces with the CISS.

Avionics and software on the Shuttle/Centaur also evolved from the Atlas/Centaur systems with all changes required because of the additional Shuttle requirements, such as safety, operations sequence, different-shaped vehicle, and platform torquing functions. Although most ground avionics will be the same as used on Atlas/Centaur, a few additional items of test equipment or test sets will be required to test the Centaur avionics and software. A functional integration test will verify that the vehicle with the CISS will meet vehicle-level performance requirements. The initial phase of functional integration consists of tests on each functional subsystem using the other systems as necessary to support the tests. These individual subsystem tests will concentrate on detailed performance and margins of each individual subsystem.

Factory testing of the Shuttle/Centaur first article will be similar to current practice. New tasks include checkout of redundant systems, vehicle-to-CISS interfaces, and combined Centaur/CISS system tests. Since the CISS is a new item, the test philosophy will be similar to Centaur testing using a CISS simulator. Early qualification testing will reduce cost and increase reliability. Component qualification testing for Shuttle/Centaur is expected to identify any design problems before system and subsystem-level testing. All components will have successfully completed functional checkout and acceptance testing including burn-in (if required) before qualification testing. Environmental qualification test requirements will comply with specifications. All newly designed components will be qualified to ensure full compliance with Shuttle requirements. Validation tests on the Centaur and CISS will increase reliability. These tests will be performed at the launch site.

Upon completion of the developmental phase of the test program, the structural test Centaur/CISS will be refurbished and used as a Pathfinder test vehicle. This Pathfinder test vehicle will be delivered to Florida for use at the Eastern Launch Site (Cape Canaveral Air Force Station and NASA Kennedy Space Center) to accomplish physical fit checks, along with handling and facility processing procedure checkouts. These Pathfinder test vehicle operations will be performed prior to the flight Centaur vehicle operations in each of the Eastern Launch Site facilities. The physical fit check with an actual Shuttle orbiter vehicle will be accomplished with the actual flight Centaur scheduled to perform the Galileo mission.

To conclude verification of designs, some first article flight hardware will also be utilized. An acoustics test will be conducted on the flight forward adapter with simulated avionics packages. A rotation/separation test will be conducted using the flight Centaur Support Structure (CSS), flight deployment adapter, separation ring, and the aft flight adapter.

Systems Integration Laboratory (SIL)

To support the integration of the Centaur vehicle as a high energy upper stage vehicle for the Shuttle program, a system to simulate and emulate the Shuttle/Centaur avionic flight system and its supporting ground control and checkout equipment has been developed. This system has been designated the Systems Integration Laboratory (SIL)[2]. The SIL is composed of integrated simulators that form a composite control system complement to the Centaur airborne and avionic support equipment. It provides an off-line capability to verify the system design of the Centaur airborne support equipment and the Centaur avionic flight systems. In addition, it provides a realistic medium for the development and integration of ground checkout and airborne control software programs.

Each simulator is composed of prototype hardware, where feasible, to maximize configuration likeness. Where emulated flight or ground hardware is used, it provides physical characteristics (loads, signals, etc.) equivalent to those of the flight hardware. The SIL is so designed that after it is used for integrated laboratory testing of the Centaur it will be transported to Kennedy Space Center, Florida, to verify the operational readiness of the Shuttle/Centaur prelaunch and launch complexes. The individual simulators will be mounted on a structure for handling purposes. This combination simulator will be utilized at the Eastern Launch Site for electrical and electronic functional checkouts of the facilities. These checkouts will be completed prior to use of the facilities by the first flight Shuttle/Centaur vehicles.

Manufacturing Status

The status of the G-Prime hardware, as of July 1984, will be described here. As of this date, fabrication of hardware for the G vehicle has not started. In both instances the first vehicle fabricated and assembled will be dedicated as a test vehicle with the remaining vehicles destined to support the space missions.

Fabrication and assembly of the test CSS started in February 1984 and was completed in July. The test tank fabrication/major weld started in January 1984 and was completed in May. This included installation of internal mechanical hardware. Following this, the test tank underwent a high pressure leak check in June 1984. The test tank was then moved to the final assembly buildup area. The fabrication and assembly of the test forward and aft adapters started in February of 1984 and were also completed in July. The forward and aft test adapters will be installed on the test tank at the final buildup area in August 1984. The test deployment adapter assembly started in May of 1984 and was completed in mid-July. This adapter was then shipped to NASA's Goddard Space Flight Center via a Super Guppy aircraft to support a 3-wk acoustic test in late July/early August.

As stated above, this first article hardware was fabricated to be used in support of structural verification testing followed by a Pathfinder program. The Structural Test Program will start in August 1984 and is scheduled to be completed in March 1985. The tests will consist of the following: A CSS stiffness test, insulation/helium purge test, static load test, cargo modal survey test, and ending with a tank modal survey test. Following completion of the Structural Test Program the test hardware will be shipped to NASA's Kennedy Space Center (KSC) to verify interfaces between the test vehicle and the KSC facilities such as Complex 36A, Vertical Processing Facility (VPF), and Launch Complex 39. In addition, personnel not familiar with handling thin-walled pressure stabilized vehicles will be provided the opportunity to familiarize themselves prior to actual handling of the flight vehicles.

National Space Transportation System Operations

Ground Processing

The Shuttle/Centaur vehicles will be checked out during ground processing (Figure 6) at the Eastern Launch Site (ELS) in Florida prior to the launch of each vehicle in the Shuttle. Each Centaur and CISS will arrive at ELS on the NASA Super Guppy aircraft. The Centaur and CISS are to be transported to Hangar J for general inspection. The CISS will be transported to Complex 36A where it is to be installed and subjected to subsystem functional checkouts. The Centaur vehicle is then to be transported from Hangar J and installed on the CISS. Additional checkout and verification tests will be performed on the Centaur/CISS assembly prior to an actual cryogenic tanking which will be accomplished during a Terminal Countdown Demonstration Test. Upon completion of that test, the vehicle tanks are to be drained and purged. Finally, reaction control system propellants will be loaded into the Centaur hydrazine tanks.

The Centaur/CISS Assembly is to be transported from Complex 36A to either the Vertical Processing Facility (VPF) or the Shuttle Payload Integration Facility (SPIF). The operations at either of these integration facilities will involve mating a spacecraft to the Centaur and verifying interfaces between the Centaur/Spacecraft and the Centaur/Orbiter. The Centaur-to-Orbiter electrical interface is to be verified using the Cargo Integration Test Equipment at either of the two integration facilities (VPF or SPIF). The final integrated test prior to transport to the launch pad will be the Centaur Cargo Element (Centaur, CISS, and Spacecraft) End-to-End Test. This test encompasses all of the control and monitoring centers and is a test of the telemetry and command links.

The Centaur Cargo Element will be installed in the Multi-use Mission Support Equipment (MMSE) canister and transported to Launch Complex 39 where it is to be transferred to the Rotating Service Structure. After the Orbiter is mounted on the launch pad, the Rotating Service Structure will be rotated to the Orbiter for cargo installation. The Centaur Cargo Element is then to be installed into the cargo bay and all connections, leak checks, and functional tests finalized. A test will be performed to verify the interfaces between the Orbiter and the Centaur Cargo Element. An end-to-end test will also be performed to verify the communication links between the Orbiter and the control and command centers; and a dry and wet countdown demonstration test completed to verify cryogenic loading and mission readiness. The final countdown, concluding in the launch of the Shuttle, includes cryogenic tanking.

The Shuttle Orbiter, of course, is to return to ELS after successful deployment of the Centaur and Spacecraft. The Orbiter will be rolled into the Orbiter Processing Facility (OPF) where the payload bay doors are to be opened and the CISS removed. The CISS is then to be returned to Hangar J for refurbishment and support of a subsequent Shuttle/Centaur mission.

Flight Operations

During ascent and Orbiter-attached operations, primary flight operations control will rest with Johnson Space Center's Houston Mission Control Center (MCC-H). The Centaur Payload Operations Control Center (CPOCC) located at the ELS will monitor Centaur systems and provide appropriate GO/NO GO decisions for Centaur deployment phases to MCC-H. After separation, when the Orbiter has maneuvered out of the zone of safety around Centaur, CPOCC will continue to monitor Centaur. CPOCC monitoring continues through Centaur burns, spacecraft separation, and Centaur post-separation maneuvers. Actual CPOCC "control" of Centaur prior to separation from the Orbiter is limited to initiation of pre-programmed system checks, initiation of navigation updates, GO/NO GO decisions for rotation and separation from the Orbiter, data monitoring and recording, and evaluation of anomalies. Since there is no uplink to Centaur after separation from the Orbiter, during that period CPOCC is limited to data monitoring and recording, and evaluation of anomalies.

The sequence for rotation and separation of Centaur from the Orbiter requires several discrete actions by the Orbiter crew. After reorienting the Orbiter, inhibiting its primary maneuvering system, and receiving a "GO" for rotation, the mission specialist engages the rotation system clutches, releases the payload latches, and initiates the "ROTATE" sequence. Following successful rotation, initiation of the "COMMIT" sequence switches Centaur to internal power, activates a telemetry transmitter check, and configures the fluids systems for separation. Upon receipt of the "GO" for separation from the ground, Orbiter maneuvering is again inhibited, and the mission specialist arms and fires the separation system.

Centaur's maneuvering system is inhibited until 5 min after Orbiter separation. The main engine system is inhibited until 45 min have elapsed after separation. Depending upon mission requirements, Centaur performs one or two main engine "burns" to achieve spacecraft trajectory and positioning. Following spacecraft separation, Centaur performs a deflection maneuver, vents residual propellants, and terminates operations.

Abort Operations

Orbiter malfunctions early in the ascent may dictate Return to Launch Site (RTLS) or Trans-Atlantic Abort Landing (TAL) abort modes. In these events, Centaur propellants are to be dumped according to an Orbiter-programmed sequence activated by a switch on the Orbiter's abort panel. Centaur propellant dumps for TAL Avoidance (TALA) and Abort Once Around (AOA) modes are initiated by mission specialist program execution from the Orbiter keyboard. An Abort To Orbit (ATO) situation may not require a Centaur propellant dump and may allow deployment of Centaur from a lower Earth orbit. If a Centaur dump is necessary, the mission specialist controls it from the keyboard as in the TALA and AOA modes.

An Abort From Orbit (AFO) that occurs with Centaur still on board the Orbiter will require an Orbiter maneuver to settle Centaur's propellants before the mission specialist initiates the dump cycle from the keyboard. For all abort modes except RTLS, residual Centaur propellants (remaining after the dump cycle) can be dumped during an Orbiter propellant settling maneuver or during the Orbiter's re-entry burn.

Conclusions

The new Shuttle/Centaur cryogenic stage will provide a capability, not currently available with solid rockets, to place large spacecraft into Earth orbit and high energy trajectories to the planets. With as much as 12.2 M (40 ft) of Orbiter cargo bay length available for spacecraft and a projected capability of 4500 kg (10,000 lb) to geostationary orbit, the addition of the Centaur to the fleet of Shuttle upper stages offers attractive mission possibilities. Shuttle/Centaur development is based on modification of the reliable Centaur D-1A currently used with Atlas boosters, and is progressing satisfactorily towards initial 1986 launch availability.

References

1. Spurlock, Omer F.; "Shuttle/Centaur - More Capability for the 1980's," IAF Paper 83-18, October 1983.

2. Gordan, Andrew L.; "Role of Simulation and Emulation in Development of Shuttle-Centaur," NASA TM-83326, July 1983.

TABLE 1

SHUTTLE/CENTAUR G-PRIME VEHICLE MASS SUMMARY (KG)

	BASELINE*	GALILEO
TOTAL LOADED MASS	27,442	29,484
TOTAL SUPPORT MASS	4,162	4,343
TOTAL VEHICLE MASS	23,281	25,141
SPACECRAFT SYSTEM MASS	1,357	2,561
CENTAUR TANKED MASS	21,924	22,580
CENTAUR JETTISON MASS	3,125	3,119
CENTAUR DRY MASS	2,605	2,605
CENTAUR RESIDUALS	277	277
FLIGHT PERFORMANCE RESERVE	81	99
LAUNCH VEHICLE CONTINGENCY	162	138
CENTAUR EXPENDABLES	18,799	19,461
PROPELLANTS	18,776	19,438
MAIN IMPULSE	18,549	19,211
OTHER	227	227
HYDRAZINE	22	22
HELIUM	1	1

*14.85 KM/SEC (48,710 FT/SEC) CHARACTERISTIC VELOCITY.

TABLE 2

SHUTTLE/CENTAUR G VEHICLE MASS SUMMARY

	BASELINE*	GEO
TOTAL LOADED MASS	25,919	25,422
TOTAL SUPPORT MASS	4,139	4,139
TOTAL VEHICLE MASS	21,780	21,283
SPACECRAFT SYSTEM MASS	4,811	4,266
CENTAUR TANKED MASS	16,969	17,017
CENTAUR JETTISON MASS	3,537	3,642
CENTAUR DRY MASS	3,098	3,097
CENTAUR RESIDUALS	235	357
FLIGHT PERFORMANCE RESERVE	120	103
LAUNCH VEHICLE CONTINGENCY	84	85
CENTAUR EXPENDABLES	13,432	13,375
PROPELLANTS	13,410	13,319
MAIN IMPULSE	13,229	13,151
OTHER	181	168
HYDRAZINE	21	54
HELIUM	1	2

*11.85 KM/SEC (38,880 FT/SEC) CHARACTERISTIC VELOCITY.

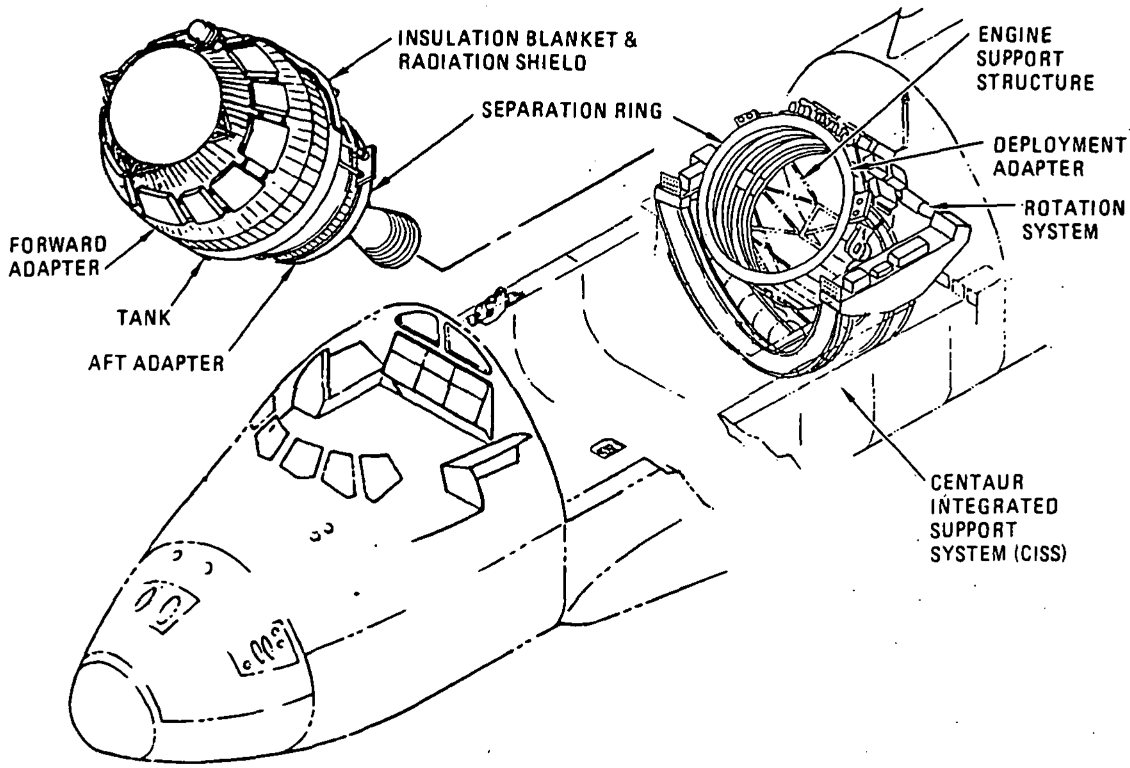

Figure 1. - Shuttle/Centaur system.

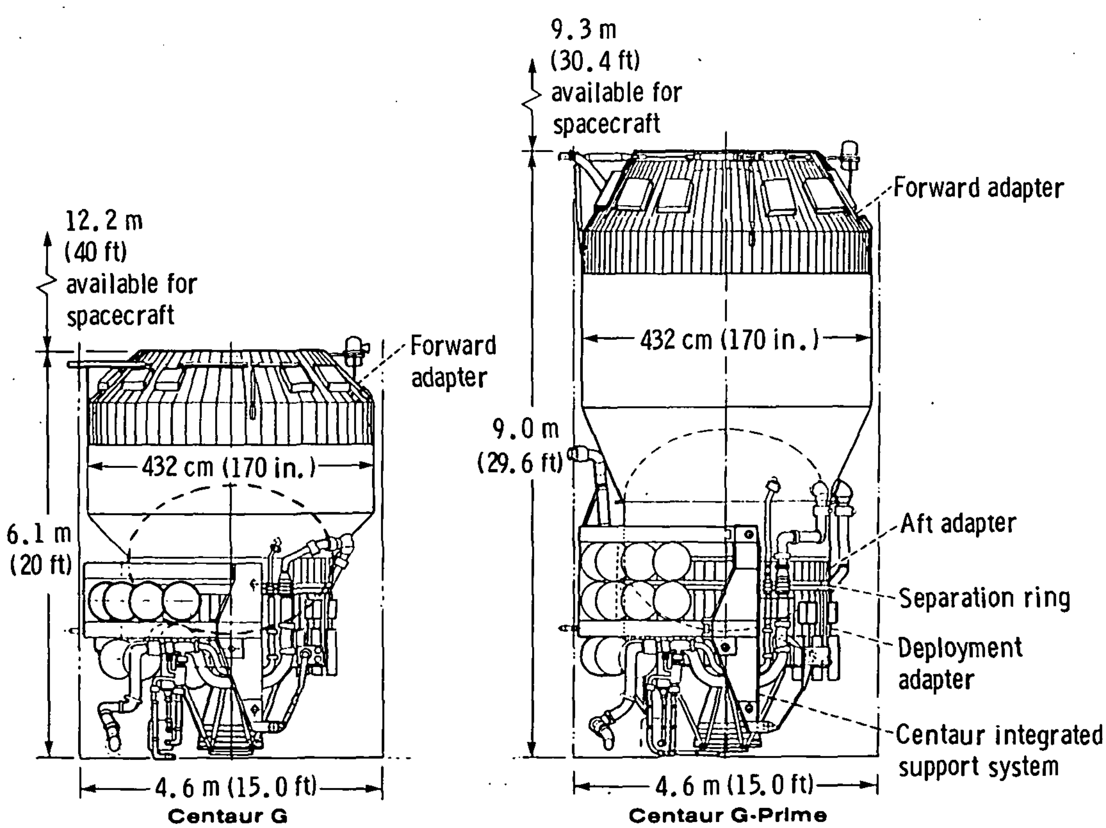

Figure 2. - Shuttle/Centaur configurations.

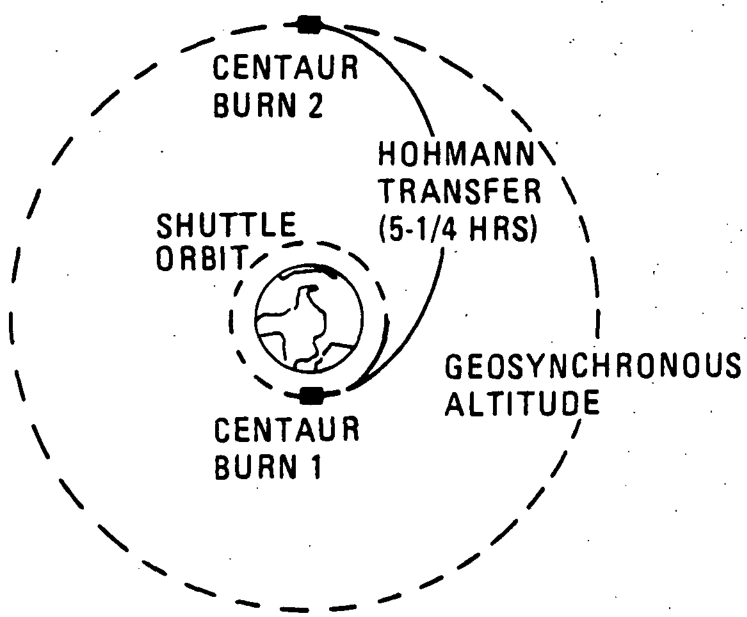

Figure 3. - Geosynchronous mission.

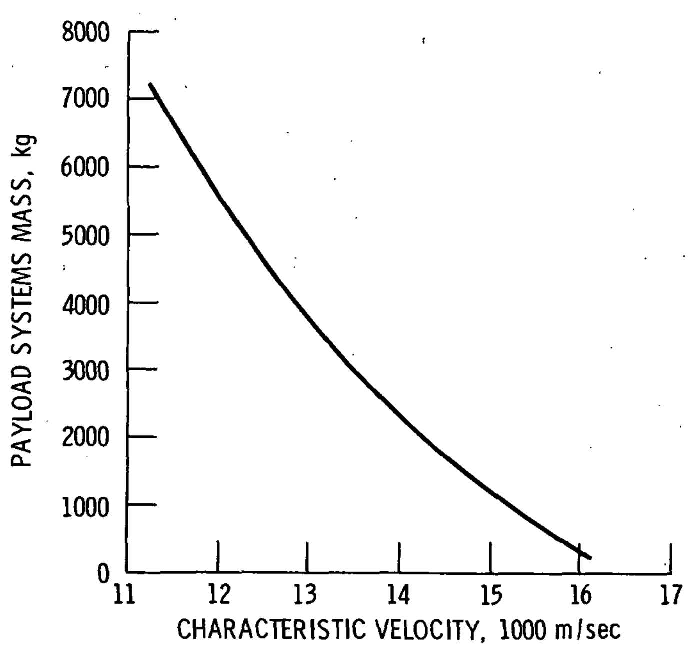

Figure 4. - Payload capability of Centaur G-Prime.

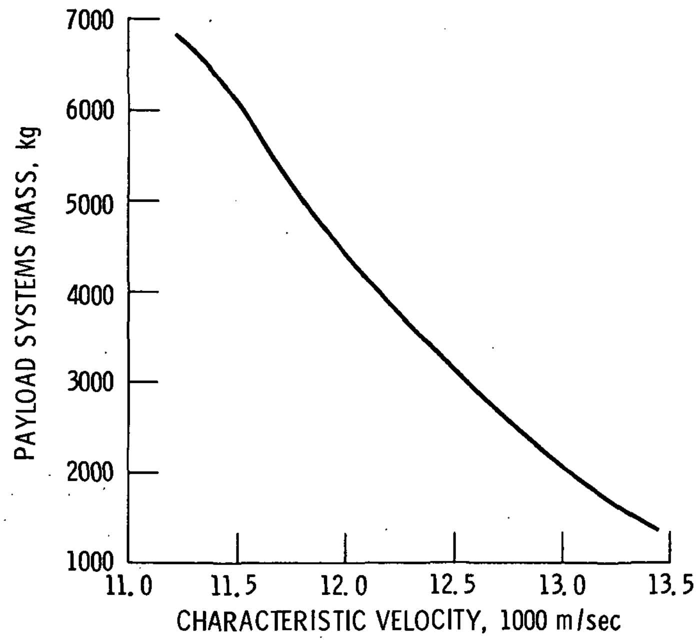

Figure 5. - Payload capability of Centaur G.

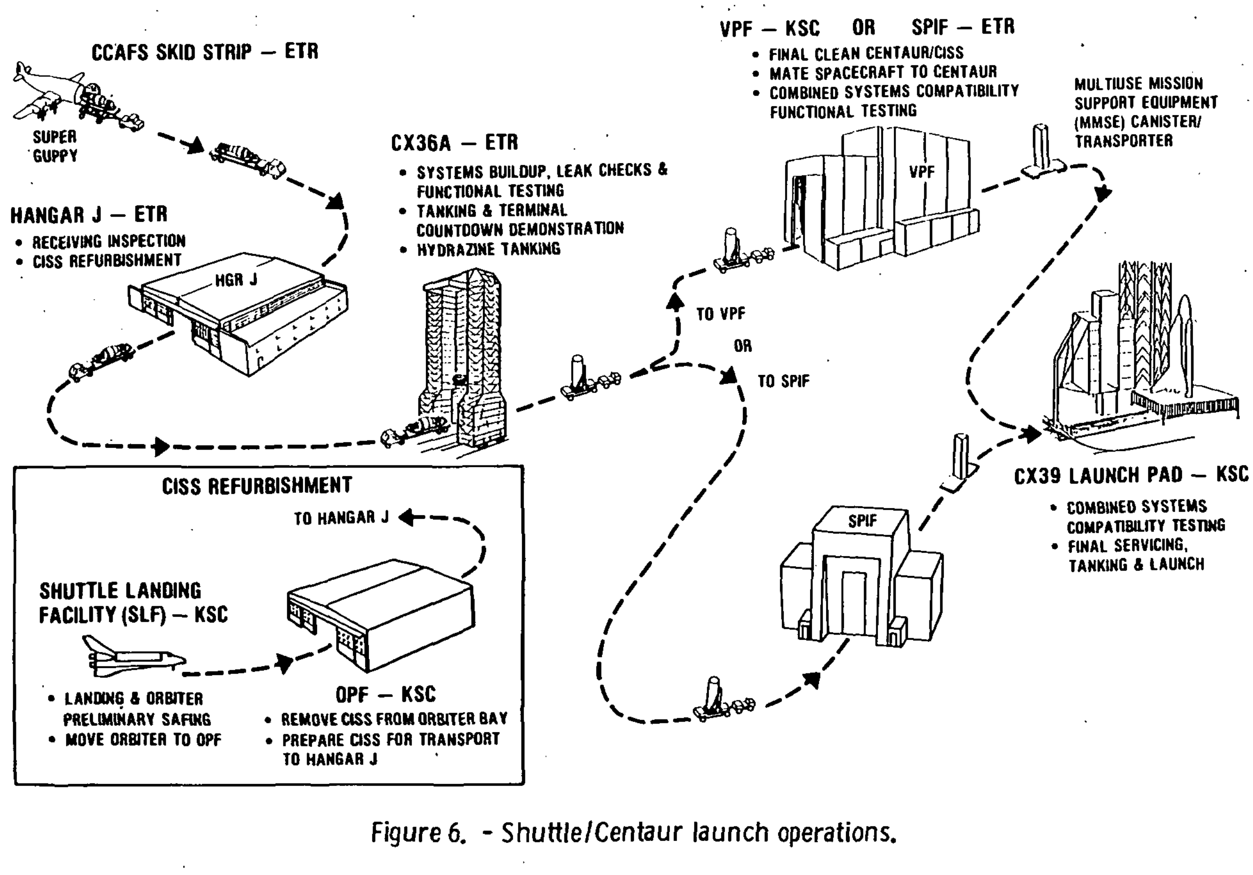

Figure 6. - Shuttle/Centaur launch operations.

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16. Abstract
The Shuttle/Centaur is an expendable hydrogen/oxygen cryogenic upper stage for use with the National Space Transportation System. It is a modification of the existing Atlas/Centaur which has been used by NASA since 1966 to launch interplanetary and Earth orbital payloads for numerous organizations. Two configurations of the Shuttle/Centaur are being developed. Vehicle capability includes placing approximately 4500 kg (10 000 lb) in geostationary orbit, and initial applications will be for the interplanetary Galileo and Ulysses Missions in 1986. This paper discusses the Shuttle/Centaur development program, describes the configurations and performance, and indicates the unique integration and operations requirements related to the Shuttle. Design changes to the current Atlas/Centaur required for Shuttle operation are described here, and include those related to Orbiter cargo bay dimensions, environment, and safety considerations.

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