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Centaur D1-A Systems in a Nutshell

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Andrew L. Gordan
Lewis Research Center
Cleveland, Ohio

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CENTAUR D1-A SYSTEMS IN A NUTSHELL

Andrew L. Gordan
National Aeronautics and Space Administration
Lewis Research Center
Cleveland, Ohio 44135

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SUMMARY

This report identifies the unique aspects of the Centaur D1-A systems and subsystems. Centaur performance is described in terms of optimality (propellant usage), flexibility, and airborne computer requirements. Major systems are described narratively with some numerical data given where it may be useful.

INTRODUCTION

The Centaur D1-A launch vehicle continues to be a key element in the Nation's space program. The Atlas/Centaur and Titan/Centaur combinations have boosted into orbit a variety of spacecraft on scientific, lunar, and planetary exploration missions and Earth orbit missions. These versatile, reliable, and accurate space booster systems will contribute to many significant space programs well into the shuttle era.

Centaur D1-A is the latest version of the Nation's first high-energy cryogenic launch vehicle. Major improvements in avionics and payload structure have enhanced mission flexibility and mission success reliability. The liquid hydrogen and liquid oxygen propellants and the pressurized stainless steel structure provide a top-performance vehicle.

Centaur's primary thrust comes from two Pratt & Whitney constant-thrust, turbopump-fed, regeneratively cooled, liquid-fueled rocket engines. Each RL10A-3-3a engine can generate 16 500 lb of thrust, for a total thrust of 33 000 lb. The engines use liquid hydrogen and liquid oxygen as propellants and can make multiple starts after a long period in space. The initial flow of propellants (gaseous) is ignited with a spark ignitor, an integral part of the engine. The engine system and its components are purged with gaseous helium before lift-off to preclude moisture contamination.

The Hamilton-Standard reaction control engines (a total of 12 for both engines) provide 6 lb of thrust each. Thrust is generated by catalytically decomposing (in the catalyst, which is an internal unit of the engine) the monopropellant hydrazine (N_2H_4).

Centaur D1-A is the designation for the model that flies with the Atlas-G first stage. Since the Centaur D1-A became operational in 1973 (with AC-30) it has launched Intelsats, Pioneers, Mariner-Venus, Fleetsatcoms, Comstars, HEAO's, etc. Centaur as the upper stage vehicle for the Titan IIIE booster is designated as Centaur D1-T . This combination was the launch vehicle for the Voyager, Viking, and Helios missions.

The Atlas-G has incorporated the latest improvements in propulsion, tank length, and various subsystems. The Atlas lineage traces back to the Atlas weapon system. These improvements and modifications have updated Atlas to one of today's advanced boosters for Centaur.

Immediate predecessors to Atlas-G/Centaur D1-A were the Atlas SLV-3D/Centaur D1-A and the Atlas SLV-3C/Centaur D. Their achievements include the launches of Surveyor, the Applications Technology Satellite, Orbiting Astronomical Observatories, Mariner Mars '69 and '71, Intelsats, and Pioneer F.

Avionics

The Centaur D1-A avionic system integrates many former hardware functions into the airborne computer software: digital autopilot, maneuvering attitude control, sequencing, telemetry formatting, propellant management, and guidance and navigation. This results in a flexible system that is readily adaptable to mission or vehicle changes. Most of the avionics are located on the forward equipment module.

The primary objective of the Centaur D1-A avionics is to place the spacecraft into its prescribed coordinates while maintaining high reliability in all affected subsystems. The flight-proven hardware from which it is derived has a high level of maturity. The use of existing hardware and procedures reduces the number of critical paths in the development schedule for new missions and minimizes the unknowns associated with integrating a flight-booster stage or payload into the Centaur D1-A systems.

System Effectiveness

The Centaur D1-A system effectiveness objective is total mission success - specifically the elimination of launch scrubs, mission failures, or mission degradation - at the lowest cost. To meet this objective, NASA Lewis management techniques and systems have been adapted to the specific Centaur mission requirements. These techniques concentrate on preserving system safety and high performance margins, as well as the reliability inherent in the Centaur design and associated equipment.

Reliability

The Centaur is uniquely qualified (i.e., it exists, it has been qualified, and it has been space proven many times) and is inherently a reliable high-energy upper stage vehicle. Its extremely high inherent design reliability is the result of the following:

(1) The basic avionic units are built from the highest quality electrical and electronic parts available and under the supervision of NASA Lewis engineering control.

(2) Rigorous failure modes and effects analyses were performed as an integral part of the design process. The basic thrust of this process was to identify failures and to ensure that their probability of occurrence or effect is minimized.

(3) A rigorous and demanding qualification program (component and vehicle level) involving extensive testing has been completed by NASA Lewis.

Any qualification failures were the impetus for hardware and system redesign. High inherent reliability has been, and will continue to be, assured by a detailed and comprehensive failure-tracking system. This system requires that all major and critical failures be reviewed for adequacy of corrective action by both NASA Lewis and the contractor's failure review board.

CENTAUR AVIONICS

The avionics include the electronic and electrical hardware used to perform all computation, signal conditioning, data processing, and software formatting associated with navigation, guidance, control, data management, and propellant management. The avionics also provide the communications between Centaur and the ground stations and control the electric power distribution. Centaur avionics consist of the following subsystems:

(1) Guidance and navigation
(2) Data management
(3) Thrust vector control
(4) Telemetry and instrumentation
(5) C-band tracking
(6) Range safety command
(7) Electric power
(8) Vehicle sequencing control
(9) Propellant/pressurization management and control
(10) Digital computer unit software

Guidance and Navigation Subsystem

Centaur uses an Earth-centered inertial guidance and navigation system to furnish measurements of angular rates, linear accelerations, and other sensor data to the data management subsystem for appropriate processing by the software resident in the digital computer unit (DCU). The Honeywell guidance and navigation subsystem (called the inertial measurement group, IMG) consists of an inertial reference unit (IRU), which contains a four-gimbal, gyrostabilized platform that supports the orthogonal accelerometers, and an electronics unit. The electronics provide conditioned power, gimbal stabilization, gyrotorquing, synchronization, and the necessary computer interfaces for the inertial sensors. The IMG also measures acceleration and provides a time reference to the DCU for navigation computations.

The navigation function is to measure sensed acceleration, compute gravity contributions to vehicle acceleration, determine time, and integrate the net vehicle accelerations in order to maintain continuous values of position and velocity. The referenced inertial coordinate system is maintained in the IRU by gyros mounted on a platform. The platform, the inner gimbal of a four-gimbal assembly, is kept fixed in space by the movement of the outer gimbals with respect to it, each other, and the vehicle. The platform itself has unlimited three-degrees-of-freedom movement. If the platform rotates from the inertial reference, the gyros sense this and put out an error signal. The error signal is then used to drive the platform back to its proper orientation. In responses to disturbances the platform is stabilized by three orthogonally mounted one-degree-of-freedom gyros that drive the appropriate gimbal through resolvers and torque motors. No resolving of the W (inner) gyro output is required since the W axis is fixed in space by the inner middle and outer middle gimbals.

The IMG is calibrated and aligned both in the factory and on the launch pad. The navigation function is initialized at lift-off and integrated in the navigation software to determine the current state vector.

Centaur uses an explicit guidance algorithm to generate thrust steering commands, engine ignition and shutdown times, and reaction control system (RCS) vernier thrust cutoff times. Before each engine ignition and each RCS vernier thrust cutoff, the vehicle is oriented to a thrust attitude based on nominal performance. During each engine burn the commanded attitude is adjusted to compensate for buildup of position and velocity errors due to off-nominal engine performance (e.g., thrust specific impulse) and uncompensated gyro drifts. This adjustment is based on the current state vector as determined from the navigation function and the desired final drift. Residual errors 3σ resulting from engine burns and shutdowns are compensated for by calculated variations in the injection module heading and the firing time.

Attitude control in response to guidance commands is provided by thrust vector control (TVC) during powered flight and by RCS's during coast. The measured attitude from the guidance and navigation subsystem is compared with the guidance commands to generate error signals. During engine burn these error signals drive the engine servoactuator electronics in the TVC subsystem. The resulting engine deflection produces the desired attitude control torques in pitch, yaw, and roll. Roll control is also maintained by the RCS roll-axis thrusters. During coast flight the error signals are processed in the DCU to generate RCS thruster commands with which to maintain vehicle attitude or to maneuver the vehicle. The coast-phase attitude commands are digital on/off commands sent from the DCU to the sequence control unit (SCU). Sequence is controlled by torques provided by 12 monopropellant N_2H_4 thrusters. The thrusters are fired in short bursts to hold the vehicle in a rate-displacement limit cycle. The SCU relays provide the necessary attitude control switching.

Data Management Subsystem

The data management subsystem (through the DCU) performs the computation, data processing, and signal conditioning associated with guidance, navigation, and control; safe/arming and firing of the pyro devices; controlled venting and pressurization (CCVAPS); propellant utilization (PU); telemetry formatting and data flow between remote sources and the pulse code modulation (PCM) transmitting equipment; and issuance of vehicle events and commands to the SCU for proper switch on/off times. It also issues discretes, including spacecraft discretes of any desired pulse width duration. These discretes can be made two-fault tolerant by selection.

The DCU is a modular, general-purpose digital computer manufactured by Teledyne. It is a 16 384-word, 24-bit random-access core machine. The memory is divided into two distinct types. One type consists of 12K words of non-alterable memory (memory that cannot be altered on the vehicle but can be changed with special test equipment at the factory). This is the portion of memory in which the operational flight software resides. The other type of memory consists of 4K words of alterable random-access memory capable of containing flight and calibration constants that can be changed during the launch operations.

The DCU's high speed is achieved through functional parallism in the central processing unit that allows independent functional units within the DCU to operate on a common register file. Up to five instructions at different stages of execution can be handled simultaneously. For example, the DCU is physically and functionally divided into four sections: the logic section, the core memory module, the analog converter modules, and the power supply. From external sources the logic section receives velocity, ground support equipment data link, and timing data in the form of discretes, serial data, incremental data, and real clock information. The logic section also provides control data and PCM data to external systems in the form of discretes and whole-word data. The core memory module senses, decodes, and stores information provided by the logic module. The analog converter module receives analog data from external units and converts digital data into ac and dc analog data output signals. The input/output (I/O) section handles the signal conversion necessary between the DCU and other system interfaces.

The DCU uses the operational flight software to perform in-flight calculations and to initiate vehicle thrust and attitude functions necessary to guide the Centaur payload through a predetermined flightpath to final orbit. This stored program, including data known as the onboard data load, is loaded into the DCU's nonalterable memory at the factory, verified through various flight acceleration system tests, and checked out at the factory and during software-acceptance runs.

Thrust Vector Control Subsystem

The thrust vector control (TVC) subsystem is the interface between the Centaur guidance and navigation subsystem and the Centaur main-engine gimbaled platforms for powered-flight attitude control.

Centaur main-engine TVC is based on analog vehicle attitude errors received by the DCU from the IMG. These errors are generated by the digital autopilot software in the DCU, which accepts the IMG attitude errors and differentiates them to obtain vehicle rates and the desired engine actuator commands. The analog engine commands are sent from the DCU to the servoinverter unit (SIU), where they are power amplified. These commands send control signals to servovalves of the hydraulic actuator assemblies, which control the flow of hydraulic fluid to the actuator. Feedback transducers close the servoloop (back to the DCU) and furnish position instrumentation.

The TVC hydraulic system is composed of two identical and completely independent servoactuator assemblies (one mounted on each main engine). These assemblies provide the force and velocity required to gimbal the main engine during Centaur powered flight in accordance with flight control commands. After Centaur separation the hydraulic recirculation motors are turned on to supply the hydraulic pressure to preposition the main engines before engine start. After main-engine cutoff (MECO) and after payload separation the hydraulic recirculation pumps (low pressure) are used to gimbal the engines so that thrust from residual propellants flowing through the engines can aid in the retromaneuver.

Telemetry and Instrumentation Subsystem

The PCM telemetry subsystem is used to gather vehicle performance information and transmit these data to the ground monitoring stations. The major telemetry components are the PCM encoder (in the DCU), an S-band phase-modulated transmitter (2200 to 2300 MHz), a ring coupler, two antennas, interconnecting harnesses, and transmission lines.

The central control unit, part of the DCU, gathers digital signals from the DCU and the remote multiplexer unit (RMU). These signals are combined serially to form the PCM digital pulse train, which modulates the S-band transmitter and is hard wired (land line) in parallel to the PCM ground station. The central control unit commands the RMU to sample the measurement signals at a predetermined sequence and rate. It determines the format (sequence of measurement addresses) by reading and interpreting a segment of the DCU memory. Measurements are put on the PCM bit stream by the central control unit in the order of the format addresses. The PCM bit stream goes directly to the transmitter and before launch by land line to the PCM ground station.

The ring coupler accepts the output of the S-band transmitter and divides the power equally to the two antennas. The ring coupler is located on the equipment module. Thus with the power being split and feeding both antennas, ground coverage is excellent.

The antennas accept the radiofrequency (RF) energy and radiate it in an omnidirectional pattern. Both antennas are mounted on the vehicle's stub adapter.

The instrumentation and telemetry function can be configured to match the vehicle or mission. As many as 1536 measurements can be individually addressed. DCU internal data can also be addressed. Each PCM data word has eight bits. Analog signals are converted to digital by eight-bit converters that cover the signal range being serviced (low, medium, or high). The signal conditioners rescale signals not lying reasonably within one of these ranges to match a range. Events are grouped in clusters of eight, all of which are reported when that group is addressed.

Formatting, or the sequencing of PCM addresses, is done by programming a dedicated area of DCU memory. Up to four formats can be stored, and the one in use at any time is selected by the DCU program being executed. The maximum selectable bit rate is 267K bits per second. This non-return-to-zero PCM signal has 240 eight-bit words per frame containing guidance, navigation, and control parameters handled by the DCU. The parameters are sampled at various rates. Additionally the PCM eight-bit word frames (24 frames to a data cycle) contain the analog outputs and bilevel status sampled from different equipment and transducers (located throughout the vehicle) at various rates.

The PCM telemetry characterizes the instrumentation function on Centaur. Measurements that are not digital are converted to digital representations before transmission. Measurements of several types are accommodated by signal conditioners that convert measurements to voltages usable by the PCM formatting hardware in the DCU. The instrumentation and telemetry function collects, digitizes, and sends to the ground measurements made on the airborne systems in order to establish the flight readiness of the onboard Centaur systems during prelaunch operations and for postflight analysis.

Measurements, made directly or by transducers, are collected by the RMU. Analog signals are scaled by the signal conditioners before reaching the RMU's, where they are digitized. Event signals go directly to the RMU's. The RMU's identify signals by addresses and when addressed by the DCU (or CCU) send these measurements to the DCU (or CCU).

The RMU is tailored to its requirement by the inclusion or omission of circuit boards that service the various types of signals. The RMU contains analog-to-digital (A/D) converters, registers, logic, and power supplies. Additional measurements can be accommodated by adding circuit boards of RMU's and extra signal conditioners and by including these measurements in the PCM format.

The PCM signal conditioners transform a variety of signals into standard signals required by the RMU and supply electric power or excitation to the transducers, as required. The signal conditioners have a complement of conditioning components capable of satisfying local transducer excitation and measurement transformation (i.e., attenuation, discrimination, and presampling filtering). Transducer excitation is provided so that an overload in one transducer will not adversely affect the excitation of the other. The signal conditioners, like the RMU, are tailored to their specific tasks. They contain the circuitry to convert measurements to signal voltages compatible with the analog ranges available in the DCU.

Transducers (such as crystals and diaphragms) sense physical phenomena changes (such as pressure, temperature, and strain) in Centaur's behavior by converting this energy into an electrical signal. The transducers activate electrical circuits to which they are coupled, causing a change in the circuit's output signal. The change in electrical signal is on a one-to-one basis for the particular parameter being monitored. Transducers are selected from a standard list to convert physical measurements into corresponding voltages.

During checkout and launch the PCM elements of the instrumentation and telemetry systems are checked out by the computer-controlled launch set (CCLS) through the PCM data station (using the land-line link to the DCU) and the PCM downlink. Radiofrequency telemetry signal radiation to local ground stations is required to verify flight readiness of the telemetry system and vehicle.

Electric Power Subsystem

The Centaur vehicle electric power system consists primarily of a 28-V dc main vehicle battery and its associated power distribution system. Three separate buses distribute power from the main vehicle battery through the electrical harnesses to the various vehicle loads. The SCU is the focal point of electrical busing and distribution. This unit controls most of the Centaur switched loads by providing relay contact closure upon commands by the DCU.

Switching requirements are fulfilled by the power changeover and arm/safe switches of the SCU. The power changeover switch distributes uninterrupted dc power from the ground power supply to the vehicle. The arm/safe switch isolates vehicle functions that require safety (i.e., pyrotechnic and engine start).

The main vehicle battery, a manually activated silver oxide/zinc battery, is located on the equipment module. It supplies power to the three separate buses in order to isolate equipment that tends to generate electromagnetic interference from equipment that may be sensitive to electromagnetic interference. For example, loads on bus 1 and bus 2 are primarily loads that tend to be sensitive to electromagnetic interference. Bus 3 supplies power to switching loads such as solenoids, relays, and motors. This bus carries loads that tend to generate electromagnetic interference. Because the positive buses are common only at the battery and the ground power supply (the vehicle ground point is internal to the SCU), the need for a filter is minimized.

The single-phase inverter in the SIU provides the 400 Hz, 26 V ac needed to supply power to the instrumentation, the rate gyro unit, and the propellant utilization servopositioners. The inverter also supplies 115 V ac for use by the PU servopositioners.

Before flight the vehicle power is supplied by a ground source. The power changeover switch (located in the SCU) is activated before launch and connects the internal power source (main vehicle battery) to the power distribution system. The power changeover switch features a make-before-break contact arrangement to ensure uninterrupted power to the loads during power changeover. The main vehicle battery then continues to supply power throughout the remainder of the mission.

Centaur's electric power system employs a single-point ground. For individual system usage the current is monitored at the single-point ground bus in the SCU.

Vehicle Sequencing Control Subsystem

The SCU contains the logic to decode DCU sequencing commands (22-bit parallel word command) and 96 magnetic latching relays. It is also the interface between the DCU output registers and the vehicle systems requiring switch or timed commands. The SCU transmits all sequencing commands to the vehicle systems and, if so desired, 16 discrete commands to the spacecraft.

The SCU together with the DCU performs the necessary timed sequencing functions after Centaur lift-off. The SCU receives data from the DCU as a 22-bit parallel output word and decodes the word to operate output switches in groups of 16 each time it receives an execute command. Six sequential input-word strobe commands are required to change the state of all 96 output switches. This DCU/SCU interface consists of a 22-bit register and strobe. The SCU requires both the zero-through-21-bit command and a strobe to interpret the switch register command. Each input line voltage is compared with a reference to verify its proper magnitude. The output relays are arranged in a 6x16 matrix with the set or reset coil at the cross points of the row and column lines. They constitute the basic SCU memory capability. All lines exiting the package, except for direct ac and dc relay output lines, are isolated so that an external short to ground or an open circuit will not overstress any package component.

The mix of output (ac and dc) contact closure is designed to run the Centaur vehicle and to furnish sufficient spares to accommodate reasonable mission-peculiar changes. In addition, the SCU performs airborne-to-ground power changeover and arm/safe functions on critical outputs through multipole motor-driven switches. The arm/safe switches permit selection of either the safe mode for ground test and operation or the arm mode for ground test and flight for Centaur safety functions. The switches are remotely operated by ground control. The arm/safe switches are single-pole, double-throw break-before-make contacts, plus a set of motor control and monitor contacts. Diode suppression is employed in the arm/safe and relay outputs. A separate system is required to separate the spacecraft from the Centaur at a predetermined time. Signals for the start of spacecraft separation are supplied by the SCU through a pyrotechnic control unit to the spacecraft in-flight separation plane. Power to begin spacecraft separation is supplied by the Centaur main battery. This system is part of the mission-peculiar (mission dependent) requirements.

The SCU is checked out and calibrated at the factory with special test equipment at the unit level. Functional testing is performed by the CCLS at both the factory and the Eastern Test Range (ETR).

C-Band Tracking Subsystem

The C-band tracking subsystem determines the Centaur D1-A real-time position and velocity. The system is compatible with the ETR ground system and provides data to support the range safety requirements (i.e., Atlas/Centaur vehicle position and velocity). These data are used to describe vehicle performance and to provide real-time predictions to support range safety flight requirements. When coded double RF pulses (interrogations) from the participating ground radar are received by the C-band transponder system, an RF pulse (reply) on a different frequency is transmitted after a short, fixed delay time. The interrogation signal is received at the vehicle by one or both of two antennas mounted on opposite sides of the Centaur tank. The transponder output signal, after division by the power divider, is radiated from the same antennas to the radar ground station (or stations). The time delay between transmission of the interrogating radar and receipt of the C-band transponder reply is a measure of the vehicle range. All radar ground stations within range of the vehicle can interrogate the vehicle transponder continuously by using a synchronized, rapid, sequential time-sharing technique. The round-trip transit time of the pulsed signal (compensated for beacon delay) is measured and used by the radar computer to determine the vehicle range. The elevation and azimuth angles of the returning signal are transferred to the radar computers and recorders directly from elevation and azimuth shaft encoders to determine the vehicle location.

The transponder operates in a frequency band of 5400 to 5900 MHz. The power divider is a tee device that connects the signals from the two antennas and provides the interconnections to the transponder. Each antenna can receive the interrogating signals from ground radar and radiate the replying signals from the transponder. The antennas provide an omnidirectional RF radiation pattern about the vehicle in flight.

System-level tests are performed after the individual dual components are installed on the vehicle. Testing is performed both at the General Dynamics Space Systems Division factory in San Diego and at the ETR to demonstrate proper operation. Open-loop testing is performed at the ETR with ground radar before launch to ascertain compatibility and to ensure that the systems will perform their intended functions.

Range Safety Command Subsystem

The range safety command (RSC) subsystem terminates the flight of the Centaur D1-A on command from the ground (i.e., if continued flight would endanger life, property, or the interests of the Government. The RSC system is compatible with the ETR ground system and is completely redundant except in the antenna/hybrid junction combination and the explosive tank destructor.

The RSC system comprises the RSC batteries, two antennas, a power control unit, two command destruct receivers, a hybrid junction, an arm/safe initiator, an explosive destruct charge, and a mild detonating fuse assembly.

The RSC system receives and decodes range safety commands from the ETR command ground transmitters. The command-code tone modulation frequency, carrier frequency, and operation sequences are established by the ETR. Command-code tones are used in various combinations to establish a MECO, a destruct, or an RF disable as follows:

(1) MECO: This command cuts off the Centaur D1-A main engines in response to an RF command (MECO) thus imposing a condition of zero thrust or preventing the starting of the Centaur main engines.

(2) Destruct: Provided that the MECO command has been received, this command activates the arm/safe initiator and explodes the explosive destruct charge through the mild detonating fuse assembly. The charge is designed to rupture the liquid hydrogen and liquid oxygen tank structures, dispersing the propellant and destroying the vehicle.

(3) RF disable: This command disables the RSC system in flight by removing operating power from the two command receivers.

As the Centaur vehicle follows its prescribed flightpath, the RSC RF carrier is transmitted from successive ETR ground transmitting stations. The carrier is picked up by one or both of the two antennas. The signal is conducted from the antennas to the input parts of the hybrid junction. The two output parts of the hybrid junction are connected to the two command receivers.

Where the carrier is modulated with command tones (destruct), the tones are demodulated within the receivers and converted to 28-V dc commands as described previously. The three commands are routed from the receivers into the power control unit, where they are conveyed by relay switching circuits to their respective destinations: (1) the MECO command to the engine prestart circuits (via the SCU), (2) the destruct command to the destructor, and (3) the RF disable command to the power changeover switches (within the RSC power control unit) to remove power from the RSC system. The power is supplied by two identical batteries. One battery supplies each redundant half of the system. Circuit isolation makes each battery and its associated equipment completely independent of any single failure of the other battery and its associated circuitry.

System-level tests are performed after the individual components are installed on the vehicle to ascertain that the system will operate properly and perform its intended function. The tests are performed both at General Dynamics San Diego and at the ETR. An inert destructor is used in these tests before the final countdown at ETR. On launch minus 1 day the live destructor is installed, and from that point on the system is tested with the live unit.

PROPELLANT/PRESSURIZATION MANAGEMENT AND CONTROL

Propellant Utilization System

To realize optimum performance in a liquid-fueled bipropellant space vehicle, it is necessary to control both propellants so as to deplete them simultaneously. Such a simultaneous depletion both minimizes vehicle burnout weight (by not allowing any unusable amounts of one propellant or the other to remain in the tanks) and maximizes the mission total impulse (by using all available propellant mass in engine reaction).

Two major factors influence simultaneous propellant depletion. The first is accurate calibration of engine mixture ratios, flow rates, and total thrust under flight conditions. The second is the inability to predict the relative propellant masses to be loaded at lift-off. Even if such a prediction were possible, uncertainties in determining what has actually been loaded onboard provide the second large error source. As an example, for the Centaur two-burn vehicle, these errors would result in a maximum error in mass ratio 3σ of approximately 350 lb at burnout, resulting in a loss of 350 lb of payload capability from a mission requiring propellant depletion. Clearly then, one way to improve total payload capability is to provide some sort of in-flight system for propellant management.

For Centaur the first function of such a system for proper propellant utilization (PU) is to measure accurately the ratio of propellants in the vehicle tanks during the entire powered flight portion of the mission. Centaur has a contoured concentric-cylinder capacitance probe installed in each tank. The space provided between the inner and outer plates is open to allow liquid hydrogen or liquid oxygen to fill the probe. When the space is empty of liquid, the capacitors display a higher dielectric constant since they are of the air dielectric types. Propellant displaces the gas and increases the element capacitance. Probe shaping (to compensate for tank area variance) makes the increase in capacitance directly proportional to the increase in propellant mass. Therefore exciting the probe from an ac source produces an output current proportional to the empty (dry) capacitance plus the increase in capacitance due to propellant mass (i.e., the change in capacitance per unit probe length is proportional to the tank area (shaping), and hence the integrated change is proportional to the propellant mass).

The second basic function of the PU system is to control the flow of propellant through the engines to adapt the ratio of hydrogen and oxygen to the amounts remaining in the tanks.

In operation the PU probes are excited from an ac source provided by the SIU. Currents from the PU probes are rectified and summed at the input to an operational amplifier to produce an error signal proportional to the error in the in-tank propellant mixture ratio. The probe excitation is designed to provide an equal change in current for the liquid oxygen and liquid hydrogen probes from full to empty conditions.

If the ratio is not correct and an error signal is produced, it is detected by the DCU through one of its A/D converters. The DCU in turn generates opening and closing commands to the PU servopositioners by commanding SCU switches through the normal DCU/SCU interface. The servopositioners are installed on the oxidizer flow-control valves for each engine and are motor driven. A change in the liquid oxygen flow-control valve modifies the engine inlet conditions such that the engine controller adjusts both liquid oxygen and liquid hydrogen flows to the new desired mixture ratio. The PU servopositioner angles are measured and sent back to the DCU to close the servoloop. In practice, the error signal at the desired mixture ratio is not always zero volts; the DCU establishes the initial zero value and uses that for the system baseline. Mission-related biases (such as error bias and coast bias) are also loaded in the DCU software (PU flight constants) and are added or subtracted as required by the mission status. Additionally included within the DCU software are failure tests for excessive amplitude error signal as well as tests for failed servopositioner feedback signal. The constants also define other system requirements, such as the time to activate the system and the time to deactivate the system, to allow final guidance computation without PU valve (thrust) motion.

Propellant Pressurization and Vent Control

General. - The propellant feed and main-engine system provides the Centaur vehicle with thrust by burning liquid hydrogen and liquid oxygen propellants. The net positive suction pressure (NPSP) required by the engine turbopumps is produced by pressurizing the propellant tanks.

The propellants are delivered to the main-engine turbopumps through feed ducts from the vehicle tanks. The feed systems consist of individual duct assemblies and pneumatically actuated prevalves. The prevalves, located at the tank outlets, together with the engine inlet shutoff valves constitute the two independent in-series propellant shutoff devices. A multilayered radiation blanket covers the entire feed delivery system to control thermal radiation.

The propellant feed and main-engine system interfaces with the pneumatic system at the propellant prevalve panel assembly. This assembly supplies regulated gaseous helium to open the liquid hydrogen and liquid oxygen prevalves and to control engine-valve pressure for prechill, prestart, and engine operation. The propellant feed and main-engine system pressurizes the liquid hydrogen tank during Centaur flight by bleeding off gaseous hydrogen from each engine feed injector manifold (autogenous pressurization). Flow is directed through flexible lines to accommodate engine gimbaling.

The flight operations control interface for the main engine is provided by the DCU, the SCU, the SIU, and the DCU guidance software. The engine fuel prestart, oxidizer prestart, and start solenoids and ignition systems are operated by the SCU switches through DCU commands. Individual SCU switches are required for each function; however, a single SCU switch is provided to control the same function for each engine so that they can be switched on and off simultaneously.

Pressurization, purging, and intermediate bulkhead vacuum maintenance are among the functions of the pneumatic system. The vent system, in conjunction with the pneumatic system, maintains pressure in the main propellant tank. Purging with gaseous helium prevents moisture from entering cryogenic systems and causing icing. Many vehicle systems and components are purged both before and during flight.

Pressurization comes from two sources. With no propellant in the tank pressure is furnished by a gaseous helium system. After propellants are loaded, propellant boiloff pressurizes the tank. During flight the airborne helium system provides supplementary pressure when necessary. The same system also furnishes pressure for the N_2H_4 and engine control systems.

The tank pressurization system controls the flow of helium from the helium supply system into the main propellant tanks. During engine burn it also controls the flow of gaseous helium from the engine into the hydrogen tank. The system consists of valve modules, orifices, filters, check valves, and control pressure transducers. The liquid oxygen tank is pressurized with helium during engine burn, and the liquid hydrogen tank is pressurized by autogenous pressurization. Check valves are used in the autogenous pressurization system to prevent hydrogen from backflowing in the engine chamber (or chambers).

<u>Computer-controlled venting and pressurization system</u>. - The computer-controlled venting and pressurization system (CCVAPS) was originally developed for Titan/Centaur and was later introduced on the Atlas/Centaur vehicle. Titan/Centaurs 1 to 7 and Atlas/Centaurs 36 to the present used the same basic software design; however, modifications were made to accommodate mission-peculiar requirements and other engineering changes.

Centaur vehicles used with Atlas boosters were redesigned beginning with vehicle AC-62 by removing the hydrogen and oxygen boost pumps. Pressurization of the liquid hydrogen and liquid oxygen tanks must therefore satisfy the main-engine requirements rather than the boost pump requirements. Pressurization of the hydrogen and oxygen tanks was changed to accommodate this pressure-fed system as follows:

(1) By increasing the pressure in both tanks to satisfy engine start and operating requirements

(2) By pressurizing the oxygen tank with helium during engine burn. Vehicles with an oxygen boost pump required no pressurization during engine burn.

(3) By pressurizing the hydrogen tank with gaseous hydrogen supplied by the main engines during engine burn. Vehicles with a hydrogen boost pump required no pressurization during engine burn.

The major changes, as of this date, are as follows:

(1) Propellant tank ullage pressures at Atlas/Centaur separation were lowered to pre-AC-62 levels to reduce the magnitude of pressure-induced stresses in the propellant tanks during separation.

(2) Propellant tank ullage pressures were lowered for main-engine start (MES) and engine burn on the basis of the following criteria:

(a) Tanks are not pressurized to levels sufficient to provide specification-required NPSP under single-failure conditions but provide the minimum required NPSP under worst-case nonfailure conditions.

(b) On the basis of testing for shuttle/Centaur the main-engine specification has been revised by expanding the regions in which the engine pump operates at inlet conditions. The new minimum pump inlet requirements allow tank pressures to be reduced. This reduction causes a corresponding reduction in helium usage for the mission.

(3) Pressure in both tanks was stepped to an intermediate level for Atlas/Centaur separation. Postseparation pressurization for MES1 will begin 0.2 sec after the SCU command for separation, to allow sufficient time for the shock induced by firing the separation charge to damp out.

(4) Post-MECO2 liquid hydrogen tank venting, including settling motor operation, was increased from 10 to 30 sec to guard against a increase in rapid liquid hydrogen tank pressure due to unsettled liquid hydrogen at MECO2.

System description: The major components and subsystems that make up the tank pressurization control system are three CCVAPS pressure transducers for each tank, a hydrogen-tank primary vent valve, a hydrogen-tank secondary vent valve, an oxygen-tank vent valve, a helium pressurization system, a hydrogen pressurization system, the DCU, the SCU, and the RCS settling motors.

The three CCVAPS transducers are used to monitor the pressure in each tank. These analog data are supplied to the DCU, where they are converted to digital information for use by the DCU. Transducers 2 and 3 share a common DCU A/D channel. They are switched out and in, respectively, by the SCU. Two parallel SCU switches control each transducer (2 and 3) to provide single-failure tolerance for switching transducers.

When unlocked by CCVAPS the hydrogen-tank vent valves and the oxygen-tank vent valve open and relieve tank pressure when the valve cracking pressure is exceeded. Venting ceases when the tank pressure drops below the valve reseat pressure or when the valve is locked by CCVAPS. The cracking and reset pressures are higher for the hydrogen-tank secondary vent valve than for the primary valve. Each vent valve can be locked to prevent venting by energizing the locking solenoid, which is controlled through an SCU switch.

The helium pressurization system allows helium gas to enter the hydrogen or oxygen tank according to which valves are opened. The system for each tank contains a primary and a backup pressurization valve. A pressurization control valve is located upstream of both primary pressurization valves and is common to both tanks. It must be open when either the hydrogen or oxygen tank is pressurized with the primary valves and is part of the primary pressurization system. Each valve is controlled through a separate SCU switch.

The hydrogen pressurization system, which has three branches, is active only when the main engines are running. Gaseous hydrogen is generated by the engines and flows continuously to the hydrogen tank through branch 1. Branches 2 and 3 each contain two valves in series. Branch 2 contains the primary set of valves and branch 3 contains the backup. Each valve is controlled through an SCU switch.

The RCS settling motors each contain two solenoid valves in series. A separate SCU switch is connected to each solenoid; thus two SCU switches must be set to operate one settling motor. Thrust from these motors is directed forward to achieve propellant settling. When only two motors (four total) are operated together, one is from quadrant II and the other from quadrant IV to produce a balanced moment about the vehicle center of gravity.

CCVAPS software: The CCVAPS software monitors hydrogen and oxygen tank pressures separately but concurrently throughout the Centaur mission. This software uses only data from transducer 1, which are continually checked for accuracy by comparison with transducer 2 data. When either transducer 1 or 2 fails, by exceeding the allowable bandwidth, CCVAPS software sends commands to switch out transducer 2 and switch in transducer 3. CCVAPS software then conducts a reasonableness test on the data to determine which of the three transducers to use.

The reasonableness test consists of storing data from the last valid pressure reading of transducers 1 and 2. The most recent data from transducer 3 are then compared with the average pressure of transducers 1 and 2 (plus or minus the maximum rise or decay rate times the maximum elapsed time for the last valid pressure reading). If the transducer reading is within this pressure band, it is considered valid data and transducer 3 is used to monitor tank pressures. If transducer 3 data are outside the band, the software will not use this transducer but will instead check transducer 1 data for reasonableness. If neither transducer 3 nor 1 has valid data, CCVAPS commands transducer 3 to switch out and switches in transducer 2. The reasonableness test, if required, is conducted only once during the mission. The transducer found to be valid by the test is used for the remainder of the mission.

Venting control is active during the boost phase and all coast phases. During the boost phase tank pressure is controlled at the cracking and reseat pressures of the vent valves. For the hydrogen tank the initial boost-phase pressure is controlled by the secondary vent valve. The primary valve is locked. CCVAPS controls the primary valve in a backup mode to vent the hydrogen tank in case the secondary vent valve fails to crack open. During the latter part of the boost phase the hydrogen-tank primary vent valve is also unlocked to control the tank pressure at a lower level. The oxygen-tank vent valve is continuously unlocked during the boost phase. As a backup mode for all vent valves, CCVAPS monitors the vent valves for failure to reseat and then commands the failed valve to lock in an attempt to close it.

During all coast phases, except the post-MECO liquid hydrogen vents, the vent valves are maintained locked. When tank pressure rises, usually because of heating, to a predetermined value, CCVAPS initiates the vent sequence. This sequence comprises a series of timed settling motor operations followed by actual tank venting. Propellant settling may be required prior to venting to ensure that liquid hydrogen and liquid oxygen are absent from the vent valves when venting occurs. Initial settling is performed with two settling motors on. Venting is inhibited during this initial settling period. When the initial settling period ends, all four settling motors may be turned on to coincide with actual venting. Venting is begun (i.e., the vent valve is unlocked) when CCVAPS determines that the tank pressure exceeds a predetermined value.

When tank pressure drops to a lower predetermined value, CCVAPS commands the vent valve to lock and venting ceases. The vent valve will cycle between the vent (unlocked) position and the no-vent (locked) position according to fluctuations in tank pressure as monitored by CCVAPS software until the end of the vent period. For zero-g coasts settling motor operation is controlled by CCVAPS; for settled coasts at least two settling motors are already on, and CCVAPS does not control the settling motors, except to turn on all four for venting as required.

Venting is also provided for structural (safety) protection of the propellant tanks and intermediate bulkhead during the venting mode. When tank pressures are near the structural limits of the tank or the intermediate bulkhead, CCVAPS begins venting independent of the normal vent mode and settling motor operation.

CCVAPS controls the propellant tank pressures during periods other than venting control. Pressurization is required during those periods to provide NPSP and total pressure for the main-engine pumps for engine start and steady-state operation. Before the first MES both tanks are pressurized to predetermined intermediate levels for Atlas/Centaur separation. Pressurization of both tanks is begun by CCVAPS before each engine start to allow time for the pressure to rise to predetermined levels. The tanks are also pressurized before Atlas/Centaur separation to bring them to the proper pressures for separation.

The helium pressurization system is used to pressurize both tanks until approximately 4 sec after MES. The pressurization control valve is opened by CCVAPS commands when pressurization of the tank is first required and remains open until MES + 4 sec. When CCVAPS determines that the tank pressure is below a predetermined level, the primary pressurization valve is opened. When the proper pressure exists in the tank (or tanks), the valve is closed.

CCVAPS continuously monitors for failure of the primary valve to open or close, except during most of the engine burn, when no fail-to-close pressures are monitored. When either tank pressure is excessively low or excessively high, CCVAPS interprets this as a failure of the primary pressurization system and switches to the backup system for both tanks. Failure of either the hydrogen or oxygen primary system causes both tanks to switch to the backup system because of the common pressurization control valve. CCVAPS maintains proper tank pressures by controlling the backup valves for the remainder of the mission in the same manner that it controlled the primary valve.

During engine burn the helium system is used to pressurize the oxygen tank, and gaseous hydrogen bled from the main engines is used to pressurize the hydrogen tank. CCVAPS monitors oxygen-tank pressure and begins or ends pressurization when deficient or excessive pressures occur. The pressurization control valve and the primary pressurization valve are operated together for each pressurization cycle, providing single-failure tolerance for overpressurization and eliminating the need for fail-to-close logic during burn. Note that failure of the oxygen primary system during engine burn (backup in use) will not affect the gaseous hydrogen pressurization system, which is operating during engine burn.

The safety of the intermediate bulkhead is preserved by controlling the hydrogen-tank primary vent valve and the oxygen-tank vent valve during the venting modes and by controlling the active pressurization system during the pressurization modes. CCVAPS monitors the differential pressure ΔP across the intermediate bulkhead with respect to predetermined high and low ΔP safety values and vents or terminates pressurization in the oxygen or hydrogen tanks to maintain the intermediate bulkhead ΔP in the safe range. For intermediate bulkhead protection during venting the safety logic will lock the vent valve on one tank when venting the other tank. This prevents the ΔP across the intermediate bulkhead from worsening.

DIGITAL COMPUTER UNIT SOFTWARE

The Centaur D1-A software was designed to satisfy specific objectives in the areas of cost, reliability, launch simplicity, response, and resiliency. The following procedures were followed:

(1) To minimize cost, many of the mission- and vehicle-peculiar changes formerly requiring hardware are now implemented via software.

(2) To realize high reliability, the software was designed to simplify checkout and to ensure an error-free flight program.

(3) To achieve launch simplicity, the software was designed to allow reasonable last-minute changes in applicable areas and test philosophies.

(4) For quick response, or to reduce lead time, the software was constructed in modular fashion. Thus one module can be checked and changed without disturbing the configuration of other modules.

(5) To provide resiliency, the software was designed to remain intact and functioning in the unforeseen event of failures in the external system hardware. Its task is to achieve maximum flight success in spite of system failures.

Modularity

A modular software concept fulfills the requirement for a cost-effective and flexible system. The concept classifies software into two categories: an executive system that remains unchanged through all missions, and a set of mission- or vehicle-peculiar task modules that can be selected from a library and adapted for the current mission. The test modules are flexible: they can be scheduled by the executive at different frequencies during flight, turned off or reactivated for different phases of flight, and interrupted at any time during their operation. Since the modules do not communicate directly with each other, but only through the executive, they are assured of consistent sets of data. The system is also readily changeable.

Assuming that memory and duty cycle are available, new modules can be added or mission-peculiar modules interchanged. Change flexibility is enhanced by subdividing the task modules into subroutine blocks whenever possible. Program changes are inserted at the module (or subroutine) level and checked at the module and integrated program levels (all task modules operating together as a system).

Both real-time and vehicle telemetry interrupts will occur during a flight. By design an interrupt will cause the program to suspend whatever it is doing and force it to a preset address in order to execute the interrupt subroutine. Upon completion of the interrupt subroutine the program returns to the interrupted address and resumes whatever it was doing.

The Centaur software is designed so that any combination of two or more modules can be in a simultaneous state of interrupt; furthermore the interrupt is allowed at any location in the program. Thus the modular task programs are completely independent of the interrupts, and each one can be coded as if it were the only module in the computer.

Decentralized, Parallel Design and Checkout

Functional tasks are designed as separate software modules and are developed and checked out in parallel. The checkout of the software is subdivided into the task level and the integrated level. The software system structure is designed to be general enough so that revised or new modules can be incorporated after the first integrated checkout with minimum effort. After a revised module is completely checked out, it is added to the modular library. The decentralized checkout concept minimizes the reaction time of the software to changes and promotes maximum reliability by providing detailed engineering visibility at the task and integrated levels.

Contingency Software

In the event of certain external equipment failures (e.g., unscheduled thrust termination or failure to start a stage) the software can be used to select reasonable alternative strategies.

The software senses nonstandard environments (such as a large-state drop in thrust level) and makes appropriate adjustments to the trajectory. The recovery techniques are designed so that the mission is achieved within the performance capability of the launch vehicle.

Flexible Ground/Computer Interface

The DCU operates in conjunction with the ground computer-controlled launch set (CCLS) to perform many preflight vehicle and avionic systems tests. A modular DCU software concept is again used; only now the modules are called tenants. The tenant programs are loaded from the CCLS to the DCU. The

DCU tenant program, operating in conjunction with its corresponding ground CCLS tenant, services each vehicle or avionic system test.

The tenant regions are sectors of temporary storage (in the DCU) allocated to the test programs. Flexibility is such that any test program can be loaded into any tenant region of the DCU. The tenants work in conjunction with the resident software control system, which starts and stops each tenant based on priority. Thus the tenants have the same independence from the interrupts as described previously.

The communications link between the CCLS and the DCU also allows flexibility. A common format is used to communicate data, programs, or special requests from the CCLS to the DCU. The downlink, or telemetry channel, is formatted so that any word desired can be communicated from the DCU to the CCLS.

Documentation

The management and engineering interface aid developed for Centaur D1 software has been a flexible, decentralized documentation system. A document defines the design requirements for each software function, and after the module has been developed and checked out, a document provides a thorough functional description.

Executive System

The Centaur D1 flight program consists of subprograms in two basic categories: system routines and functional tasks. System routines comprise the executive system control program execution, manage data flow between tasks, and service the computer I/O functions. The modular functional tasks, such as navigation and guidance, perform the computations that satisfy the computer's responsibility with respect to its external world.

Clock pulses, which occur at 20-msec intervals, generate a real-time interrupt. The task currently in progress is stopped and program control given to the executive. The executive first services the DCU I/O functions, then solves all 50-Hz tasks, and finally routes the program execution to the lower frequency task.

Interrupts

Two types of interrupts will normally occur during flight: real time and telemetry. An interrupt causes a transfer to the interrupt processor. The interrupt processor saves the variables that were being calculated by the interrupted program. A real-time interrupt (also known and functions as the software clock) occurs at precisely a 50-Hz rate; a telemetry interrupt occurs at approximately a 1000-Hz rate.

"Power off" followed by "power on" are two other interrupts that conceivably could occur during flight for some unplanned reasons. If these unexpected interrupts occur, the software is designed to continue functioning in a reasonable manner.

If a telemetry interrupt occurs, the program executes a subroutine that results in the emission of a telemetry word. For the real-time interrupt the program executes the real-time interrupt program, a system program that provides I/O servicing and scheduling of task programs.

Task Schedule/Task Table

The task schedule scans the task table, which contains three entries for each task:

(1) Normal task entry address
(2) Required task solution period
(3) Task start time

The task schedule uses this information to execute all software task programs at their required frequency and within the required time interval. Interrupted tasks have the highest priority.

Task Organization

A "tree" structure is used to organize the tasks. The tasks are grouped according to executive priority. Each task on the tree must appear as an entry in the task table. A 50-Hz drive is used to control the execution of the 50-Hz tasks in order to save duty cycle. Thus only one call to the 50-Hz tasks appears on the task table.

Adaption to Real Time

If time is required by a software task to any resolution finer than 20 msec, an instruction count is required or the countdown register may be implemented. With the countdown register discretes can be issued to a time resolution of 1.25 msec.

Since the task programs are coded to be invulnerable to random interrupts and since they are minimally sensitive to changes in start time, the task programs can be coded separately as if there were no time constraints. The term "insensitive to time changes" means that if a task execution is skipped because of a temporary overload, the task will continue to function properly. The task schedules will compare actual start time with desired start time and recalculate a new start time if a temporary overload occurs.

Input/Output Servicing

The input/output servicing subroutine is executed every time a real-time interrupt occurs; it interfaces DCU software with the I/O devices. Since the task program interface with the I/O servicing software is fixed, the functional task software reads the attitude signals from the resolver chain and the most recent 20-msec accumulation of velocity pulses. The output software stores the desired attitude vectors into the resolver chain input locations and issues the discrete register bit pattern to external equipment.

Telemetry Formatting

A PCM telemetry system is used that results in the DCU words being intermingled with all other vehicle telemetry data. The DCU data consume approximately 10 percent of the PCM channel capacity, assuming that approximately 1000 24-bit DCU words are telemetered per second.

The "fast" portion of the formatter establishes the frame marker and counter, approximately 16 out of the 18 data words. This fast portion is actually performed as part of the real-time interrupt service subroutine (I/O service). The fast formatter supplements the I/O service by assigning words to the remaining slots. To do this, it selects words from the lower frequency task buffers. The slow formatter moves the low-frequency task data from the current to the previous buffer, thus preparing these buffer tables for use by the fast formatter. Data from each task are moved at a different frequency; this means that the slow formatter need only be executed at the highest non-50-Hz task frequencies.

Data Communication

Intermodule data communication is through the data management module, a subroutine with multiple entry points. Its basic function is to load the task's input or output buffer with the appropriate dynamic data. These data are defined in the I/O requirements of the task's documentation.

The buffer fill operation is protected by disarming the real-time interrupt during this vulnerable phase. Since the disarm/arm sequences occur under the control of the executing task, a coherent set of the latest available I/O data is always guaranteed. Furthermore these buffers remain static throughout the execution period of the task (i.e., until the executing task requests the data management module to refresh them again on the subsequent cycle).

Task Table Modifications

During a flight it is sometimes necessary to enable or disable certain tasks, such as enabling the powered guidance task just after booster engine cutoff. Tasks can be enable or disabled by modifying the task start time. The frequency with which a task is executed is changed in flight by modifying that number on the task table. Also, a different portion of the task can be enabled by changing the task entry address. In general, task turnon, turnoff, or frequency change can be achieved by task table modification. Thus appropriate use of the task table can facilitate this requirement and obviate the need for extra branches and flags.

Functional Tasks

The functional tasks performed by the DCU are coded in program modules. These modules are listed in the task table from which they are called by the executive for operation at the proper time to ensure correct module frequency. Some of the modules (e.g., navigation) operate throughout the flight; others (e.g., powered autopilot) are scheduled for only certain phases. The modules do not interface with each other. Date flow is controlled by the data management portion of the executive. A brief description of some of the modules follows:

Navigation

Functions	To furnish position, velocity, and acceleration data to guidance
Method	Integrate in the true initial coordinate system, having previously converted for known platform drifts

Guidance

Functions	To determine the steering coefficient data for optimizing the trajectory and to furnish the engine cutoff time to the sequencer
Method	Assume a near-optimum linear-target steering law in pitch and a calculus-of-variation steering law in yaw

Steering

Function	To furnish the desired vehicle attitude to the platform resolver chain
Method	Compute the desired vehicle attitude from the guidance-supplied steering coefficients

Altitude rate

Function	To furnish rate information to the powered- and coast-phase autopilots
Method	Compute the time derivative of the attitude error signal

Powered-phase autopilot

Functions	To maintain control stability during main-engine firings and to control the vehicle axes to the desired attitude
Method	Compute engine gimbal output commands by using attitude errors and error rates as inputs to control laws

Coast-phase autopilot

Function	To control the vehicle attitude during coast-phase maneuvers
Method	Command the N_2H_4 attitude control engines in the on/off mode

Booster steering

Function	To steer the booster in pitch, yaw, and roll in an open-loop manner during ascent through the atmosphere

Method	Use polynomials in attitude to generate attitude as a function of altitude

Postinjection

Function	To provide steering coefficients to point the vehicle for separation and retromaneuver
Method	Output roll and pitch axes pointing vectors to the resolver chain

Sequencer

Function	To generate discretes for sequencing of all flight events
Method	Perform various tests to determine the time to issue event discretes or to accept output from selected modules for module-dependent discretes

Computer-controlled venting and pressurization system

Function	To maintain proper liquid oxygen and liquid hydrogen tank pressure
Method	Monitor tank pressures and command venting and pressurization valves to function via SCU switch commands

Propellant utilization

Function	To maintain a proper ratio of liquid hydrogen and liquid oxygen in the tanks to preclude a premature depletion of one or the other
Method	Monitor the propellant ratio error signal and command the PU valves to a position that will null the error

Queue

Function	To resolve any potential conflict of simultaneous requests for switch action
Method	Assign priorities to switch requests and command switches according to the priorities

Flight Program Validation

The validation of the DCU software ensures an error-free program. Validation checks that the software meets the design requirements, that the software and hardware interfaces are correct, that an adequate duty-cycle margin exists, and that the software is forgiving in the event of large hardware dispersions.

The validation procedure consists of two testing phases: a design evaluation test and a design acceptance test. The design evaluation test is primarily a search for weaknesses in the design. The software is severely stressed to determine the limits and to verify an adequate design margin. This is accomplished by simulating and inputting data representing failed or severely dispersed hardware systems into the software.

The second validation test, the design acceptance test, is a formal procedure that verifies that the program is error free and qualified for release. The input data are generally the limits of the acceptable flight environment (i.e., 3σ dispersion or combinations of dispersions). This test verifies that the logic is coded correctly and that the program meets the design requirements.

The validation of the DCU software is a multilevel function. It first takes place at the module level, where it results in a library of validated modules. Modules may then be combined into subsystems for an initial check of the module interfaces. This subsystem level is not part of the formal validation procedure but serves as an interim between the formal module and program validation. Validation of the integrated flight program is then performed. Finally a verification is made using the targeted trajectories.

Systems Management

Centaur D1-A software is subject to controls from module inception through flight. These controls ensure that the management of the software will be thorough and complete. The Software Review Board monitors all DCU and CCLS software from inception on. This board is made up of NASA Lewis, NASA Kennedy, General Dynamics, and Honeywell personnel.

The change requirement system is a formalized procedure for initiating, approving, and recording changes to modules or programs. Change approval is required from the Software Review Board chair.

When a DCU model has been validated, it has a unique check number assigned to it. This number is generated by the support software and will change with any change made to the module.

Similarly when modules are assembled into a program, a unique check number is calculated for that program configuration. This number is sensitive not only to the modules in the program but also to the order in which they are assembled into the program.

The resources control process is a continual review by NASA Lewis and General Dynamics management of new DCU software requirements that would use more storage or duty-cycle resources. The gains achieved by implementing these requests are weighed against the ever-increasing load on the DCU. This review helps ensure that the DCU resources are used only for total D1 system improvements.

CONCLUDING REMARKS

The Centaur vehicle provides the operational advantages of a high-energy, liquid-fueled upper stage, namely high specific impulse, multiple burns, and a propellant load that can be varied to match mission requirements. Other advantages are that it can be flown with or without a booster guidance system (as done on today's Atlas/Centaur) and features fault-tolerant designs and redundancy of critical functions.

Centaur's design approach makes maximum use of space-qualified hardware. The piece-part levels for this program were likewise established to provide cost-effective, yet reliable, space-proven components. The system environment and operating requirements are thoroughly analyzed and are integrated into our reliability analysis. Reliability analyses include a failure modes and effects analysis and numerical assessments. Selected redundancy, as discussed in the appropriate subsystem design sections, was implemented to meet reliability requirements.

Achievement of a high level of mission success depends on a full complement of requirements and controls provided by a comprehensive test and product assurance program. These programs were developed and implemented starting with the Titan/Centaur programs and now embrace all disciplines involved in the life cycle of the Centaur system. Our mission success program has supported both the Atlas and the Atlas/Centaur programs. This common system approach ensures that all program elements affecting, or having the potential to affect, readiness to launch or mission success are identified, analyzed, and remedied through appropriate corrective action. It ensures sharing of lessons learned, program visibility, and a single focal point for program and problem communication.

Centaur's mission success organization consists of three elements: corrective action, hardware review, and audit and vendor surveillance. The corrective action element of the organization provides the project with rapid identification of problems; a strong, effective followup to closure, with high visibility of problems requiring management attention; and the ability to establish the status of total program hardware problems before an event. The corrective action element is responsible for discussing program problems with the division, the project, and major contractors and subcontractors. The hardware review element establishes the pedigree of related hardware and vehicle assemblies through mandatory independent review of documentation associated with building and testing. Anomalies are resolved for the hardware or article before it is permitted to proceed into inventory use. The audit element evaluates the degree of compliance with NASA Lewis' program policies, procedures, and applicable technical requirements for processing, testing, and acceptance. Both the audit and vendor surveillance elements report deficiencies to the Centaur management to ensure that effective corrective actions are implemented. The corrective action and hardware review elements also report to the Atlas/Centaur manager.

Within the framework of system maturity changes are continually evaluated to improve Centaur's capability and performance. Two factors drive the continual upgrading of Centaur's hardware and software:

(1) New technology accounts for improved electronic parts, components, and techniques.

(2) New mission requirements demand increased capability - from more computation capacity to greater accuracy.

In summary, it has been the purpose of this report to identify and describe the unique aspects of the Centaur D1-A system and to provide a qualitative feeling for the different levels of effort involved.

APPENDIX - GLOSSARY OF ACRONYMS AND ABBREVIATIONS

AC	Atlas/Centaur (usually followed by vehicle number)
A/D	analog to digital
CCLS	computer-controlled launch set
CCVAPS	computer-controlled venting and pressurization system
DCU	digital computer unit
IMG	inertial measurement group
I/O	input/output
IRU	inertial reference unit
NPSP	net positive suction pressure
MECO	main-engine cutoff
MES	main-engine start
PCM	pulse code modulation
PU	propellant utilization
RCS	reaction control system
RF	radiofrequency
RMU	remote multiplexer unit
RSC	range safety command
SCU	sequence control unit
SIU	servoinverter unit

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16. Abstract

This report identifies the unique aspects of the Centaur D1-A systems and subsystems. Centaur performance is described in terms of optimality (propellant usage), flexibility, and airborne computer requirements. Major systems are described narratively with some numerical data given where it may be useful.

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