History of the Titan Centaur Launch Vehicle

The Centaur program began in 1958 with its first successful flight on 27 November 1963. The unique Centaur design is the first liquid oxygen and liquid hydrogen upper stage; which is used on top of launch vehicles to boost spacecraft into higher orbits, lunar trajectories and injection into orbits for planetary missions. Centaur was flown on Atlas for NASA in the 1960s, and then modified with improved avionics into the D-1A (Atlas) and D-1T (Titan) configurations during the 1970s. The D-1T configuration was built to fly longer park orbit coasts for inter-planetary missions and was launched on the Titan III E (numbered TC-1 through 7). The Titan IV program began in 1985 as a back up to the Space Shuttle to launch the Centaur upper stage. In the 1980s, development began on a wide body Centaur, which was integrated into the Shuttle as shown in Figure A. However, the program was canceled following the Challenger accident in 1986. The work that had begun in 1985 to modify the larger Shuttle/Centaur design to fly on the Titan IV launch vehicle continued. A fleet of 16 Titan/Centaur vehicles (numbered TC-8 through TC-23) was produced for the U. S. Air Force, with one of these vehicles launching the NASA Cassini Interplanetary mission to Saturn. All of these Titan/Centaurs were flown between February 7, 1994 and September 9, 2003. There have been over 170 Centaur upper stages launched between the Titan and Atlas boosters by April 2004.

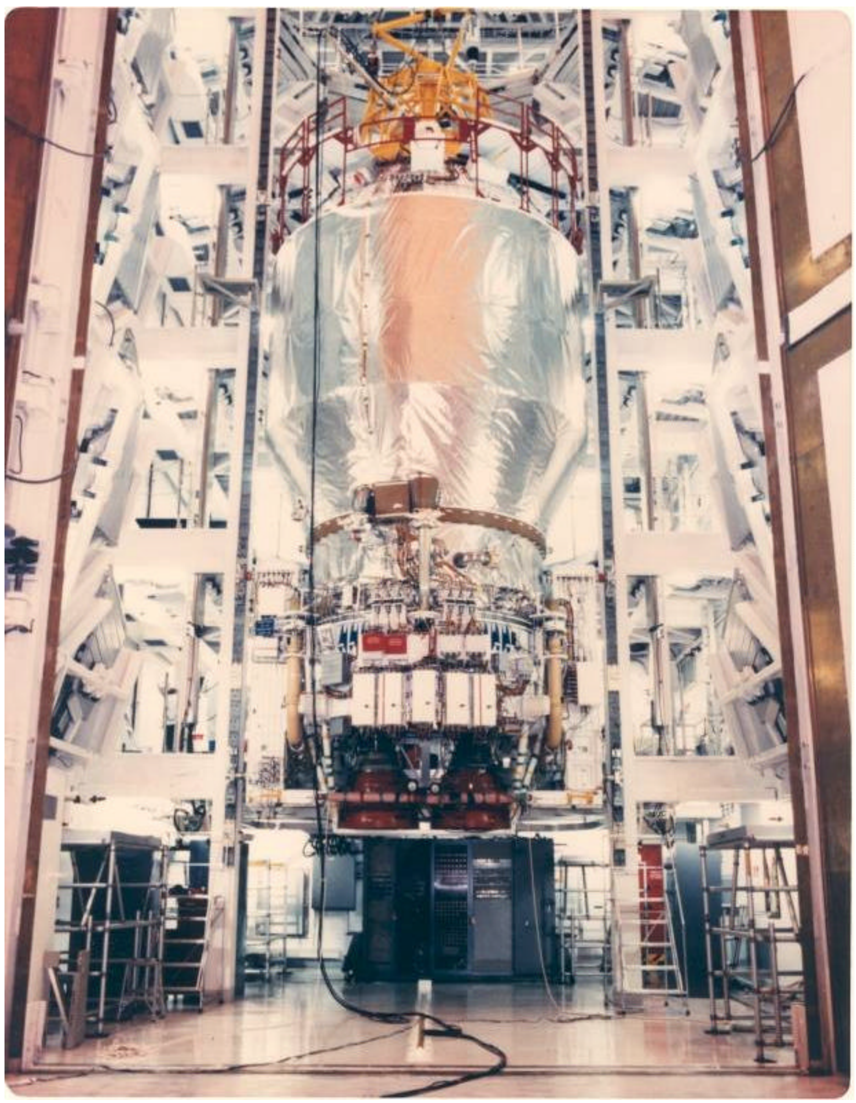

Figure A. Shuttle Centaur in the Shuttle Spacecraft Processing Facility (SSPF)

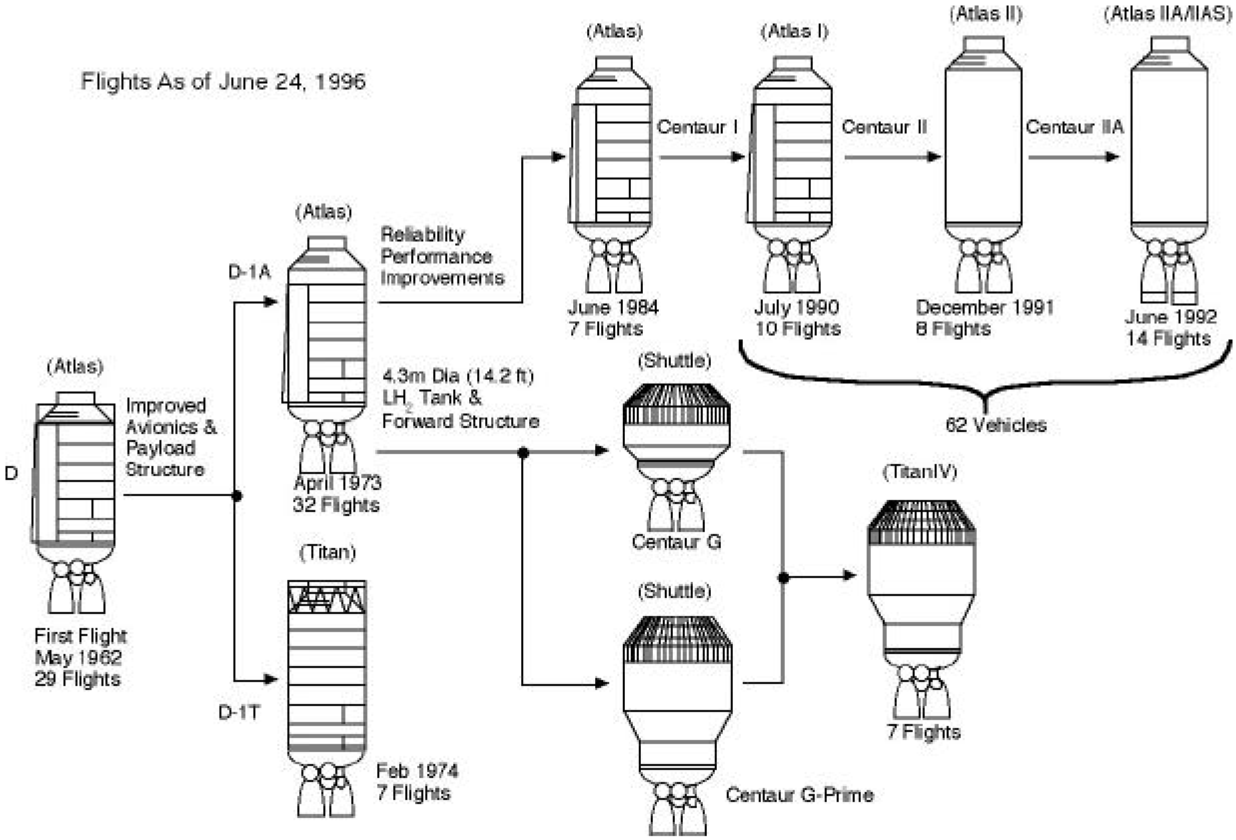

Figure B. Evolution of the Centaur Upper Stage from the Atlas Centaur to the Titan IV Launch Vehicle

The evolution of the Centaur upper stage at the time of the Titan IV vehicle is shown in Figure B. The TIII E-7 Centaur launching the Voyager spacecraft is shown in Figure C. Two configurations of the Atlas Centaur Launch are shown in Figure D.

Figure C. Titan III E Centaur **Figure D. Atlas IIA AC-122 (Left) Atlas V AV-003 (Right)**

A cut-away of the Titan IV launch vehicle is shown in Figure E with the SRMU, Core vehicle, and the Centaur inside the Payload Fairing. The Centaur upper stage in the San Diego Thermal Acoustic Test Facility is shown on the right.

Figure E. Titan IVB Centaur Launch Vehicle Configuration

Centaur - The Titan IV Centaur, shown in Figure F, consists of a 576 cubic foot aft liquid oxygen tank that shares a common intermediate bulkhead with the 1890 cubic foot forward liquid hydrogen fuel tank. To reduce overall length, the LH2 tank diameter was increased to 14 ft. compared to the 10 ft. diameter Atlas Centaur tank, taking advantage of the 16 ft. diameter Titan IV Payload Fairing (PLF). A conical transition section joins the LH2 tank with the 10 ft. diameter LO2 tank, which attaches to the Titan Forward Skirt Extension (FSE). This transition ring maintains the successful 10 ft diameter common bulkhead, which reduced development cost and risk.

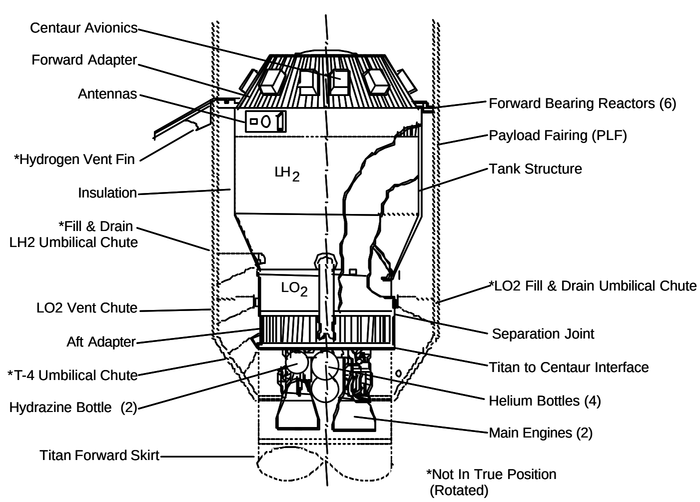

Figure F. Titan IV Centaur Upper Stage

Increasing the LH2 tank diameter increases fuel capacity while maximizing the length available for the payload. Using PLF as long as 86 ft with the Centaur upper stage accommodates the same payload volume as the original Shuttle/Centaur G Design. The stainless steel thin-walled propellant tanks are pressure stabilized, and give Centaur an excellent energy to weight ratio. The vehicle depends on additional pressure to provide the required strength to react to bending and vibration loads on ascent and throughout the mission. Production of the Titan Centaur tank can be seen in Figure G.

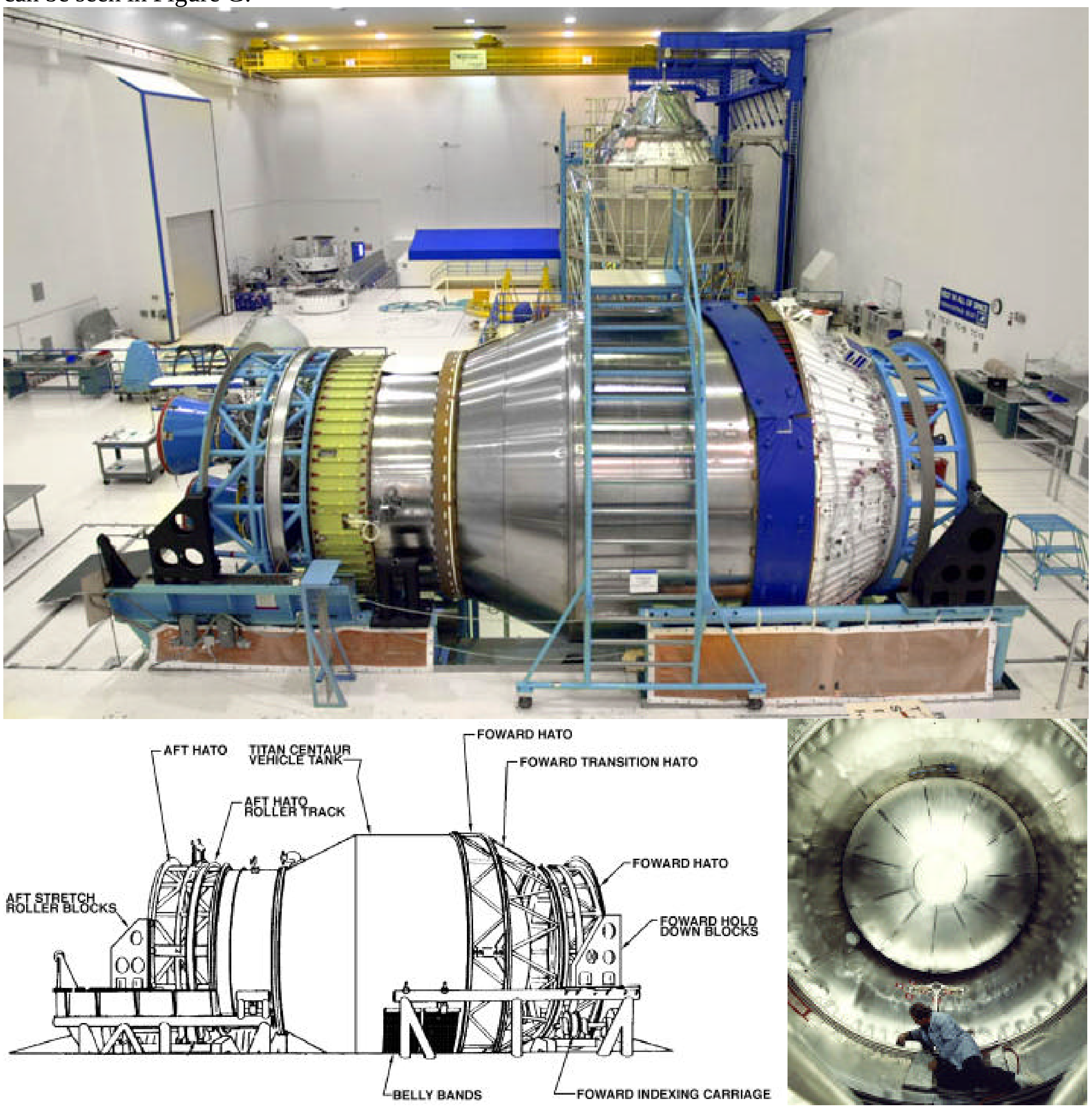

Figure G. Titan IV Centaur Large Diameter Hydrogen Tank During Manufacture

Using the lightweight design requires a fluids system that is capable of maintaining the required pressure levels for all phases of flight as well as on the ground. The fluid and propulsion systems consist of a helium supply system, a pressurization system, a vent system, a hydraulic system, two main engines, a reaction control system, and a computer control system. The long TIV missions require radiation shields on the LO2 and LH2 tank. In addition, the LH2 tank uses foam purged on the ground with helium. The insulation system can be seen in Figure H. The D-1T did not use foam; the hydrogen tank compartment was purged with helium.

Helium Supply and Pressurization System

Helium is used for tank pressurization. The helium is stored in four high pressure graphite/epoxy composite overwrap helium bottles mounted on the aft bulkhead. These bottles are charged to 4000 psia prior to liftoff.

Figure H. Titan Centaur in the Thermal Acoustic Facility in San Diego

The bottles are connected to two pressurization valve modules, one for each propellant tank. The LO2 pressurization line enters the LO2 tank through the aft bulkhead. The LH2 pressurization line enters the tank through the forward bulkhead. Helium is used for tank pressurization prior to engine burns. A gaseous hydrogen autogenous system bleeds gaseous hydrogen off the engines and is used for pressurization during the engine burns. A valve module identical to those used for helium pressurization provides control.

Vent System

The LO2 vent system consists of a self-regulating vent valve with a solenoid-locking feature, which is mounted on the sidewall of the tank. The LO2 valve remains locked until after stage 0 separation and then vents the tank to the self-regulating range. The LH2 tank vent system consists of two (primary and secondary) self-regulating vent valves with a solenoid-locking feature. The valves are locked to allow pressurization. The secondary valve with an orifice is used during the controlled vent-down on ascent by cycling the solenoid. The primary valve has no orifice and is used later on ascent.

CCVAPS

The Computer Controlled Vent and Pressurization System (CCVAPS) is the flight software that provides the instruction to the computer and controls the systems that maintain the required tank pressures throughout the mission. A redundant measurement system is used to measure pressure in each tank. The output of these transducers is provided to the flight computer system contained in the Inertial Navigation Unit (INU), which commands pressurization and vent valves per the CCVAPS software to maintain the proper pressure level. A primary pressurization level can be set providing on-off control of the pressurization valves. If tank pressure drops below the pressure level CCVAPS will command the primary pressurization branch open until tank pressure rises above the level. Backup levels can also be set in case tank pressure does not respond rapidly enough. CCVAPS controls the vent system in a similar manner.

Tank pressure must be maintained at minimum required levels to prevent the tanks from buckling and maximum levels to avoid bursting the tank. These two limits create a narrow band of allowable pressure during the early ascent phase as the atmospheric pressure decays. The highest tank pressure occurs during the first minute of ascent when the vehicle undergoes maximum air loads. The intermediate bulkhead creates an additional requirement. The LO2 tank pressure must always be greater than LH2 tank pressure to prevent the bulkhead from collapsing but low enough to prevent bursting the bulkhead. The pressurization and vent systems are also used to provide the proper propellant conditions at the engine inlets for engine burns.

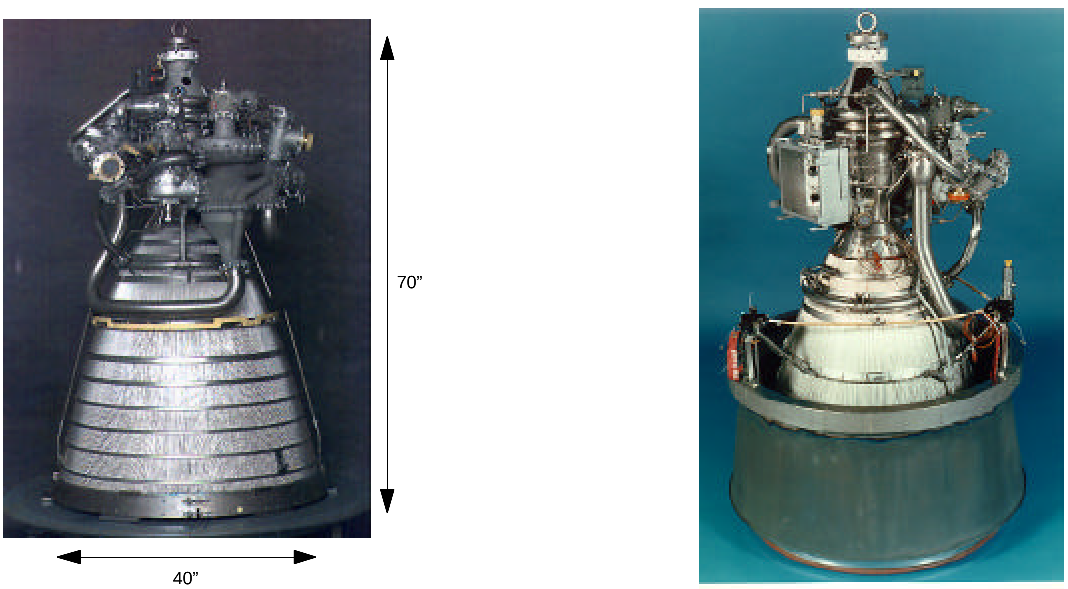

Figure I. TIV Centaur Pratt & Whitney Engines, RL10A-3-3A (left) & RL10A-4-1 (right)

Propulsion System

The Centaur used the Pratt & Whitney engines shown in Figure I. The Centaur propulsion system used two RL10A-3-3A (left) or two RL10A-4-1A (right, but without the extendable nozzle). This series of engines has been used successfully since 1963 on the Saturn and Atlas/Centaur vehicles. There have been 335 RL10 launched on Centaur as of April 2004.

Each RL10A-3-3A produced 16,500 lbf of thrust, a 444.4 sec nominal Specific Impulse (Isp or pounds of thrust per mass flow of propellant) at a 5.0:1 propellant mixture ratio and a nozzle area ratio of 61:1. All the RL10 engine series use an expander cycle, where all of the hydrogen fuel is burned in the combustion chamber, except for a small amount used for autogenous pressurization (later models) and pump bearing cooling/gear box pressurization. The working fluid, which runs the engine's turbine, is the supercritical hydrogen heated in the regeneratively cooled thrust chamber. Solenoid valves which control the flow of vehicle helium to pressure actuated valves provide engine control for pump chilldown, engine start and engine shutdown. The use of the super-cold propellants requires that the pumps be chilled down prior to engine start. LH2 is used to cool the fuel pump, which is then exhausted to space though two valves. The LO2 used in the oxidizer pump chilldown flows through the engine and out the thrust chamber to space. The chilldown times are pre-programmed in the Inertial Navigation Unit (INU), which provides all the valve sequencing. The ignition system uses a spark plug embedded in the center of the injector. The fuel and oxygen near the spark provide the initial ignition to light the chamber at the low pressure, cold conditions of space. The INU determines how long the engine is required to run for each of the three burns to achieve the proper orbital velocities and orientation.

During steady state, the vehicle Propellant Utilization (PU) system provides commands to the engine valves to control the mixture ratio of the fuel and oxidizer so they burn at the right proportions. Engine gimballing is provided by pitch and yaw actuators powered by a hydraulic power unit mounted on the RL10A-3-3A LO2 pump shaft. Electrical recirculation motors powered by batteries on the Centaur provide low pressure operation in the hydraulic system when the engine is not running. These motors remain on during vehicle ascent, are cycled during the coasts periods in space to keep the hydraulic fluid warm, and are turned off during each engine start.

Reaction Control System

A hydrazine reaction control system (RCS) provides the impulse to perform vehicle control, thermal roll maneuvers and propellant settling. The RCS stores hydrazine in two bladder tanks with a pressure regulated feed system supplying 12, 6 lbf thrusters in two 2-thruster modules and two 4-thruster modules. A redundant pyrovalve isolates the thruster loop from the bottles. Redundant pyrovalves also isolate the pressure side of the bottles from the regulator in the vehicle helium system. The system is pressurized during vehicle ascent after the solid motors are jettisoned by firing all the pyrovalves.

Figure J. Launch Complex 40 used to Launch Titan IV Centaur

Launch Operations

The Titan Centaur was launched from both Launch Complex (LC) 40 & 41. LC-40 is shown in Figure J. A Centaur is shown being stacked onto the Core vehicle at LC 40 in Figure K. The countdown on launch day typically starts at L-750 mins for a TIVB Centaur. The primary activities include facility preparation for the air conditioning systems preparing for GN2 change-over within the PLF, range safety system preparation and checks, pressurizing the Core vehicle tanks, installing lanyards for umbilical retract, securing the vehicle and facility for retracting the Mobile Service Tower (MST), propulsion performance monitoring, cryogenic operations and Centaur loading, SRMU TVC heater power application, prevalve open and engine bleed-in, and TVC GHPU start, which can not be shutdown. SRMU ignition and thrust to weight exceeding 1.0 lift the vehicle off the launch mount heads; there is no hold down system or explosive bolts.

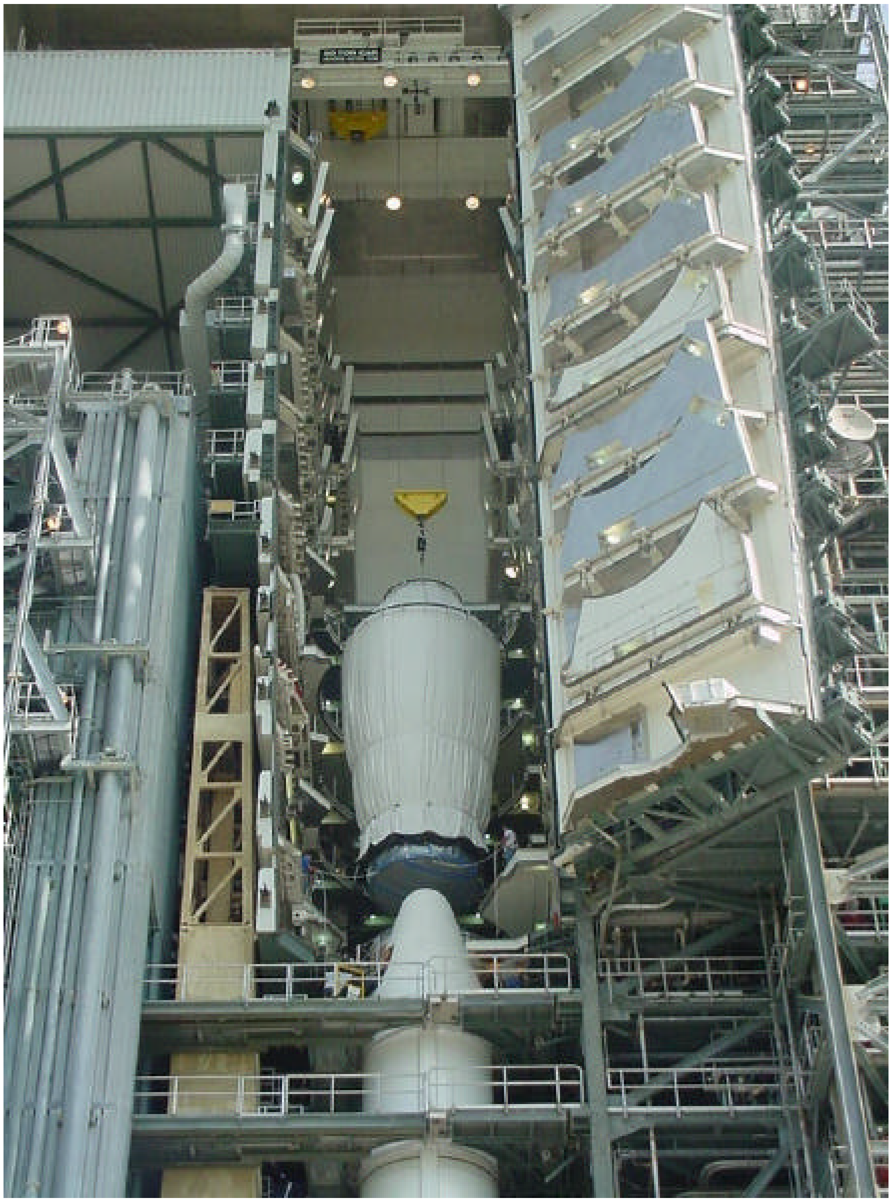

Figure K. Titan Centaur TC-23 being installed on the Core Vehicle TIVB-35 at LC-40

The primary propulsion activity during the terminal count of a T-IV Centaur is the cryogenic operations of the Centaur, which begins at T-180 mins and counting. The Titan Centaur launch countdown operations were derived from the operations used in the 1970s with the Titan IIIE/Centaur D-1T launch vehicle. Figure L illustrates the critical timelines in the cryogenic systems starting with the Engine Chilldown operation at T-170 minutes. Soon after ground engine chilldown is initiated, the LO2 and LH2 loading operations begin. The use of the same cryogenic hardware designs or, in many cases, the refurbishment and reuse of the same hardware (dewar and vacuum-jacketed lines) as that used at Launch Complex 41 in the 1970s extends the timeline because of the larger Centaur tanks.

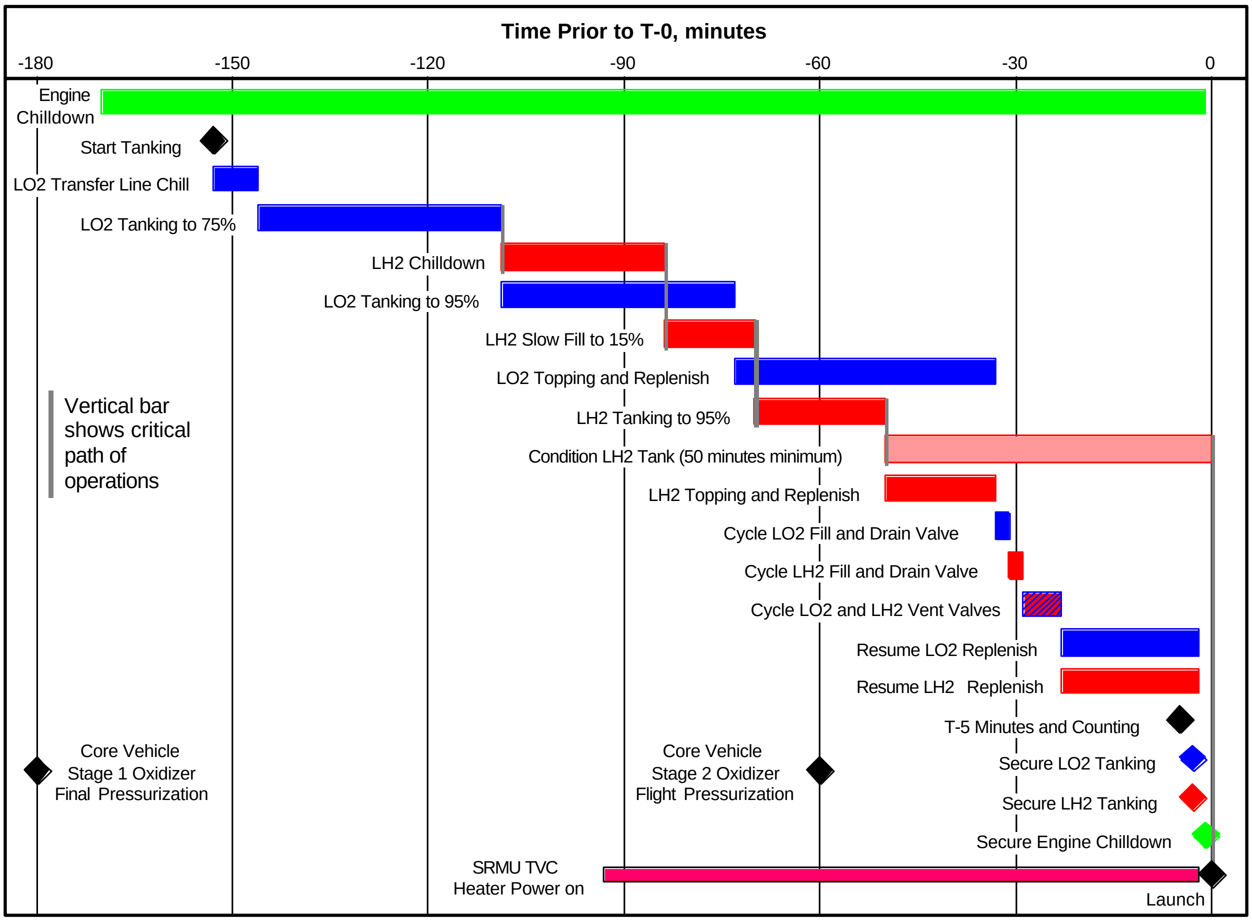

Figure L. Titan/Centaur Cryogenic Launch Countdown Operations Timeline

The engines are chilled on the ground to reduce the first burn chilldown time and therefore performance loss due to use of main impulse propellant and the loss of velocity due to gravity. Helium is supplied to the engine from the facility LHe/GHe mixer system through an umbilical that is ejected at T-4 sec, aluminum tubing and to the engine's redundant prelaunch cooldown pyrovalves. After cooling the LH2 pump directly, the helium flows through the engine, then through the line from the Centaur to the Core vehicle, where it finally exits the vehicle below the payload faring at two places. The LO2 pump is cooled by conduction and the gearbox coolant flow. The pyrovalves are fired with the signal that commands the T-4 panel ejection. Helium purges are supplied to the engines during ground operations and ascent to prevent moisture intrusion.

One of the major improvements to the launch countdown operations has been the use of the Centaur Ground Computer System to automate all of the pneumatics and the cryogenic pre-launch operations. Nearly all fluid system operations are automated including facility chilldown, LO2 and LH2 Fast Fill to the 95% level, and topping to flight level; requiring a keyboard operator only to initiate operations. After T-5 minutes and counting, even the keyboard operations are unnecessary as the Ground Computer System automatically controls, secures, and, following launch, safes each of the fluid systems. Another enhancement that has been introduced successfully on Titan Centaur is the Fluids Monitor System. This system, an adaptation of the Fluids Monitor program developed for the Shuttle Centaur, is software that monitors all of the critical temperatures and pressures in the fluid systems to verify that they are within tolerances. If the tolerances are violated, then the system is automatically safed by the ground software. This system has identified anomalous conditions and prevented unsafe operations. TIVB-41 is shown in Figure M just as the SRMU ignites on LC-40.

Figure M. Launch of TIVB-41 with TC-22