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ANTARES: A LOW COST MODULAR LAUNCH VEHICLE FOR THE FUTURE

UNIVERSITY OF WASHINGTON

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The single-stage-to-orbit launch vehicle Antares is a revolutionary concept based on identical modular units, enabling the Antares to efficiently launch communications satellites, as well as heavy payloads, into Earth orbit and beyond. The basic unit of the modular system, a single Antares vehicle, is aimed at launching approximately 10,000 kg (22,000 lb) into low Earth orbit (LEO). When coupled with a standard Centaur upper stage it is capable of placing 4000 kg (8800 lb) into geosynchronous Earth orbit (GEO). The Antares incorporates a reusable engine, the Dual Mixture Ratio Engine (DMRE), as its propulsive device. This enables Antares to compete and excel in the satellite launch market by dramatically reducing launch costs. Antares' projected launch costs are $1340/kg ($610/lb) to LEO, which offers a tremendous savings over launch vehicles available today.

Inherent in the design is the capability to attach several of these vehicles together to provide heavy lift capability. Any number of these vehicles can be attached depending on the payload and mission requirements. With a seven-vehicle configuration, the Antares' modular concept provides a heavy lift capability of approximately 70,000 kg (154,000 lb) to LEO. This expandability allows for a wide range of payload options, such as large Earth satellites, Space Station *Freedom* materiél, and interplanetary spacecraft, and also offers a significant cost savings over a mixed fleet based on different launch vehicles.

INTRODUCTION

The expanding applications of communications and military satellites over the last decade have increased the demand for reliable, low-cost launch vehicles. Recent projections made by the Office of Commercial Space Transportation (OCST) indicate that the average number of payloads launched per year will continue to increase(1). NASA has estimated that 11-14 shuttle flights per year are needed to construct and supply the proposed Space Station *Freedom*(2). Other analysis done by NASA, the Air Force's Space Systems Division, and the NASP program reveal that a vehicle able to lift 9000 kg (20,000 lb) into low earth orbit (LEO) could carry 80% of NASA's civil payloads, 60% of the Defense Department's payloads, and nearly all commercial payloads(3). With a backlog of payloads waiting to be launched and a projected increase in the number of launches needed in the future, the current U.S. launch fleet, composed of reusable space shuttle orbiters and expendable launch vehicles (ELVs), will not be able to adequately meet these demands.

The space shuttle, initially hailed as America's dependable, low-cost, all-purpose launch vehicle, has encountered numerous technical problems, causing delays to scheduled launches. Originally, in the early 1970s, NASA projected that a reusable shuttle would deliver payloads to orbit for one-tenth the cost of any expendable launch vehicle available at that time(4). However, in order to achieve these cost savings, the shuttle had to be flown frequently, allowing the operations costs to be spread out over many missions. As late as 1981, NASA's Office of Space Transportation System Operations was predicting that the shuttle could achieve a flight rate of 40 missions per year(4), but unexpected delays to scheduled launches have severely reduced this number, resulting in the current high cost of launching payloads on the orbiters. Being a man-rated vehicle, the shuttle requires multiple redundant systems to ensure the safe launch and return of the crew. This causes increased system complexity and can reduce efficiency. This has required NASA to create a "standing army" of engineers and technicians to keep the space shuttle orbiters in operation and on schedule. The man hours involved significantly increase the shuttle's launch costs, making it less attractive to potential launch customers. The reduction in the number of launches per year caused by delays, and the increased cost to consistently maintain the space shuttle reduces its effectiveness as a reliable vehicle for launching satellites and space probes.

With the delays of the shuttle reducing the number of launches available, commercial and military satellite launch customers have had to rely on expendable launch vehicles, such as the Atlas, Delta, and Titan(4). However, the ELVs, originally developed in the 1960s as intermediate range ballistic missiles (IRBMs), and intercontinental ballistic missiles (ICBMs), impose mass and size restrictions that limit their payload capacities. These restrictions have created a gap in the payload range to geosynchronous Earth orbit (GEO) between 1500 kg (3300 lb) and 4000 kg (8800 lb). Arianespace, a consortium of European aerospace companies and banks, predicts that satellites heavier than 1200 kg, particularly in the 2000- to 3000-kg range, will dominate the future(5). Without an American expendable launch vehicle that is able to compete in the 1500-kg to 4000-kg payload range, and with the uncertainty of space shuttle launches, U.S. companies have turned to Arianespace for their launch needs(2). To date, Arianespace has effectively captured a 50% share of the satellite launch market(5).

The high cost of launching a satellite on the shuttle or an ELV places another constraint on satellite manufacturers. It currently costs from $50,000 to $120,000/kg ($22,700 to $54,500/lb) to launch a payloads into GEO(6). To reach LEO, the cost range is from $6,600 to $26,450/kg ($3,000 to $12,000/lb)(7).

The mass and size restrictions and high launch costs of the current mixed fleet of space shuttle orbiters and ELVs have severely hindered America's ability to compete in the satellite launch market. It is apparent that a new, flexible and cost-effective launch vehicle must be developed to ensure America's continued presence as a leader in the commercial launch market. Current vehicles under consideration, such as the Advanced Launch Development Program (ALDP), formerly the Advanced Launch System (ALS)$^{(8)}$, and the fly back single-stage-to-orbit (SSTO) manned vehicle$^{(9)}$, do not meet the above mentioned criteria. The ALDP is designed as a heavy lift launch vehicle, thus limiting its effectiveness for launching payloads into orbit to a small percentage of the market. The totally reusable manned SSTO requires many additional systems that not only increase the overall cost of the vehicle, but make it more complex. As evident from the problems experienced by the shuttle, very complex vehicles tend to encounter more technical problems, which in turn increase launch costs.

Antares, the new launch vehicle proposed in this report, is the flexible and cost-effective launch system that will be able to meet the nation's growing launch needs both in the near and long term. Antares is a single-stage-to-orbit launch vehicle that can deliver a wide range of payloads. The basic Antares vehicle for LEO and GEO missions uses a single advanced reusable liquid hydrogen and liquid oxygen engine, the Dual Mixture Ratio Engine (DMRE), as its main engine$^{(10)}$. The DMRE is retrieved for reuse in future missions via the Engine Return Unit (ERU), resulting in a substantial reduction of the launch costs. For LEO missions, the Antares vehicle has the capability to be clustered together to provide heavy lift. The LEO mission vehicles (see Fig. 1), which are identical modular units, can be combined to form various modular configurations, from a two-booster configuration (Antares II), up to a seven-booster configuration (Antares VII), as illustrated in Fig. 2. This modular concept reduces cost on the basis that a large, heavy lift vehicle is a cluster of simple, generic boosters, thus giving Antares an unprecedented advantage over any other existing or proposed launch vehicle. The Antares vehicle used for GEO missions is basically the same as the LEO mission vehicle (see Fig. 3). It executes a suborbital trajectory and uses a Centaur upper stage to deliver the payload into GEO. With a reusable engine and the concept of simple modular systems, Antares provides a low-cost, reliable alternative to the existing fleet of launch vehicles.

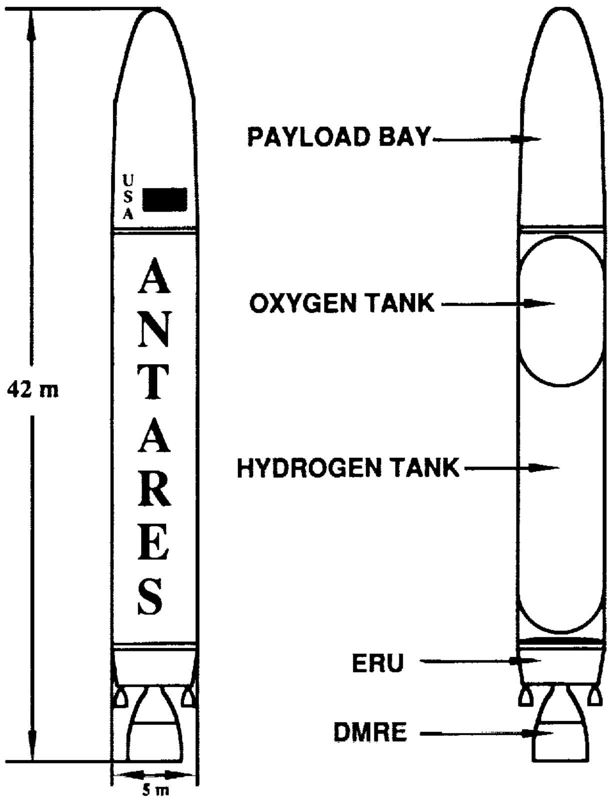


Fig. 1. Antares I configured for LEO missions.

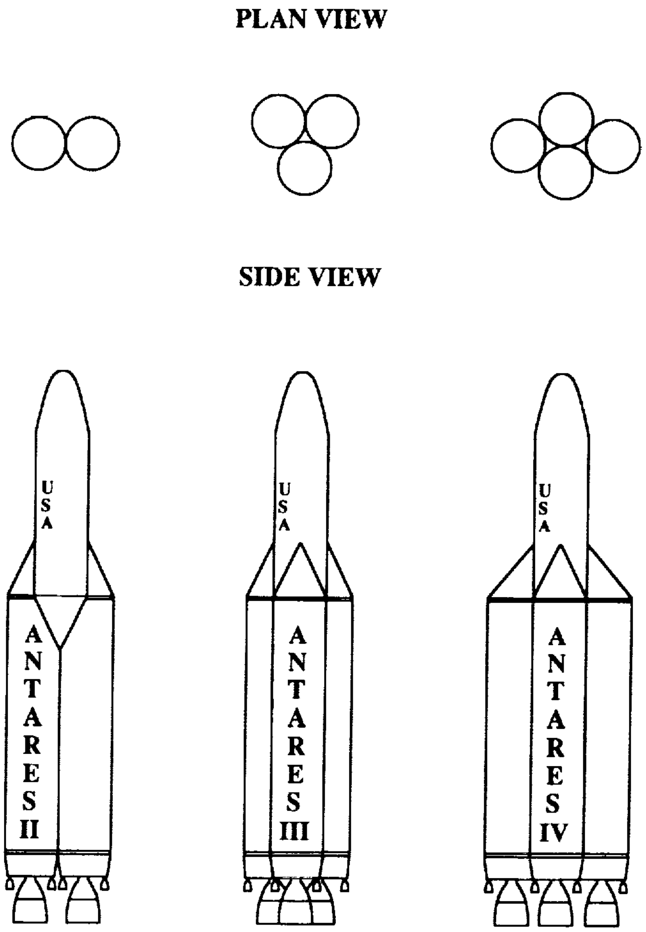


Fig. 2a. Antares modular configurations.

For Antares to be successful, it must recapture a large portion of the U.S. satellite market that has been lost to Arianespace. One Antares vehicle can place a payload of 4000 kg (8800 lb) into GEO, thus allowing it to effectively compete against Arianespace for launch customers. Antares' modular capability provides another distinct advantage over other launch vehicles and is instrumental in making the Antares a potentially dominant player in the commercial launch market. The ability to attach several vehicles together provides launch customers with a wide range of payloads to LEO, from 10,000 kg (22,000 lb) with Antares I to 70,000 kg (154,000 lb) with Antares VII. The low launch costs of the Antares vehicle, $1340/kg ($610/lb) to LEO and

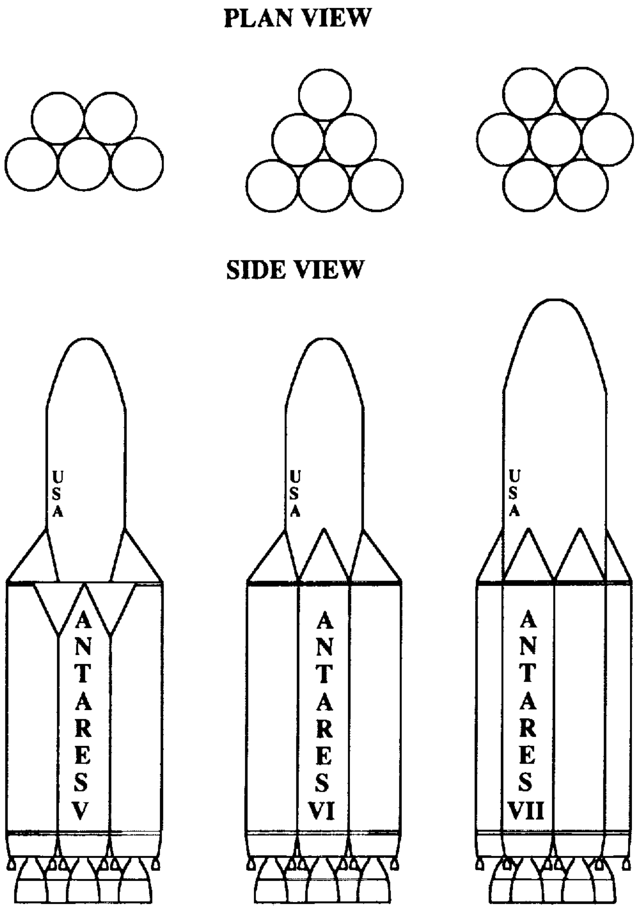


Fig. 2b. Antares modular configurations.

$16,200/kg ($7350/lb) to GEO, cannot be matched by any existing launch vehicles. Antares' unique ability to deliver a variety of payloads into LEO and GEO and its low launch costs, allow it to effectively compete not only against Arianespace, but other foreign competitors such as China and Japan. The concept of modularity and the cost savings attributed to reusable engines makes Antares a reliable, inexpensive, and flexible launch vehicle.

This report provides a summary of the design of the Antares vehicle. It includes LEO and GEO mission profiles, the Antares' main systems: ERU, propellant tanks, structural connectors, and fairings, and the benefits of modular configurations. An evaluation of the cost per unit mass to launch payloads into orbit concludes the report.

MISSION PROFILES

All mission scenarios, whether destined for LEO or GEO, begin in the flight integration building. In an effort to maintain a high launch rate it is essential to reduce the length of time that a launch vehicle spends on the launch pad. With the exception of the space shuttle, all current U.S. launch vehicles are integrated in an upright position on the launch pad. This often requires an extended length of time during which the pad cannot be used for other missions. The approach offered with the Antares vehicle will reduce the time required on the launch pad by performing vehicle integration in a horizontal position at a site located away from the launch pad. The major components of the Antares and its payload can be joined and checked out in the protection and safety of a climate-controlled facility. When engineers and customers are satisfied with the integration, the vehicle will travel to the launch site horizontally on a railed vehicle specifically designed to hold the Antares during integration and transportation. The Antares will be translated to an upright position at the launch site by the transport vehicle. The transport vehicle will then retreat to a safe distance when the operation is complete. By performing only final checkout and fueling procedures on the launch pad, significant savings in pad occupancy time can be attained. This system is very similar to the Soviet approach to launch vehicle integration and it holds potential improvements in ground operation efficiency and hence launch costs.

To help compare the Antares with other U.S. launch vehicles, sample mission profiles are performed with launches originating at the Kennedy Space Center (KSC). This provides for a launch

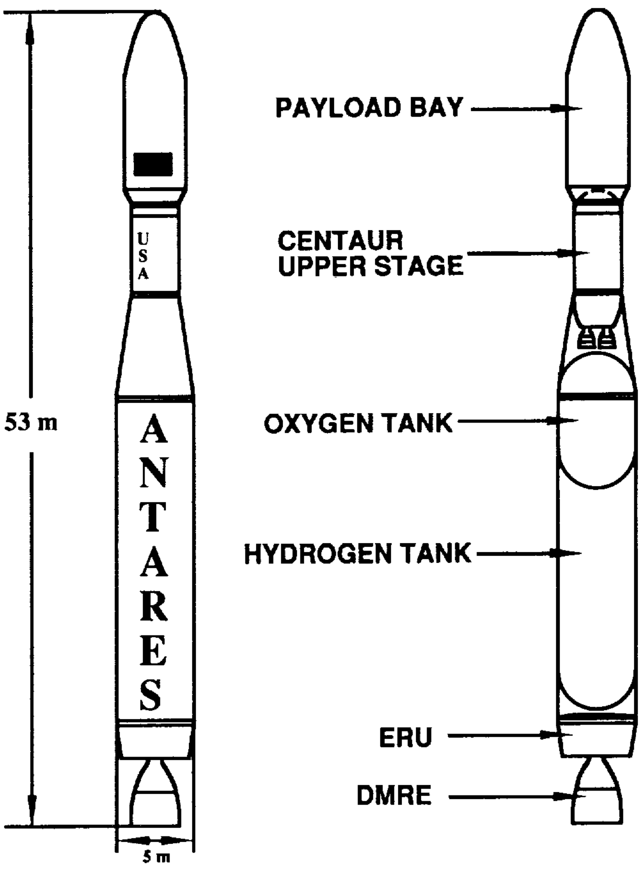


Fig. 3. Antares I configured for GEO missions.

latitude similar to many other vehicles. KSC is located at 28.5° N, and an east launch from here provides for insertion into an orbit of 28.5° inclination.

LEO Mission

At rollout, the dry mass of the LEO Antares is 23,000 kg (50,600 lb). Payload mass for LEO missions makes up 10,000 kg (22,000 lb) of this, while the other 13,000 kg (28,600 lb) is components of the vehicle. They consist of the Engine Return Unit (ERU), the propellant tank structure, and the payload fairing. An illustration of the LEO launch sequence is shown in Fig. 4.

The Antares is designed to use a DMRE. It is a staged combustion cycle engine concept studied by Pratt and Whitney Co.[(10)] specifically for SSTO applications, which require high thrust at liftoff and high I_{sp} at altitude. It burns liquid oxygen and hydrogen and operates at a high oxidizer-to-fuel ratio (12:1) early in the flight, providing for high thrust levels during the boost phase of the mission. High thrust is critical at takeoff when the mass of the vehicle is greatest. Later in the flight the oxidizer-to-fuel ratio is reduced to 6:1. This sustainer phase lowers the engine's thrust but increases the specific impulse. The gross liftoff mass of the vehicle is 197,600 kg (435,500 lb). At takeoff the DMRE produces 2460 kN (553,000 lb) of thrust at an I_{sp} of 333 s. This gives the Antares an initial thrust-to-weight ratio of 1.27. The DMRE has a translatable nozzle that allows the expansion ratio to be changed during flight. At an altitude of 12 km (40,000 ft) the nozzle extension is lowered, increasing the area ratio from 40:1 to 150:1. This adds approximately 28,000 lb to the vacuum thrust and 18 s to the vacuum I_{sp}. At an altitude of 27 km (88,000 ft) the mass of the Antares has been reduced to approximately half of its original value. At this point in the flight the oxidizer-to-fuel mixture ratio is reduced to 6:1, the thrust drops to 417,000 lb, and the I_{sp} is increased to 467 s.

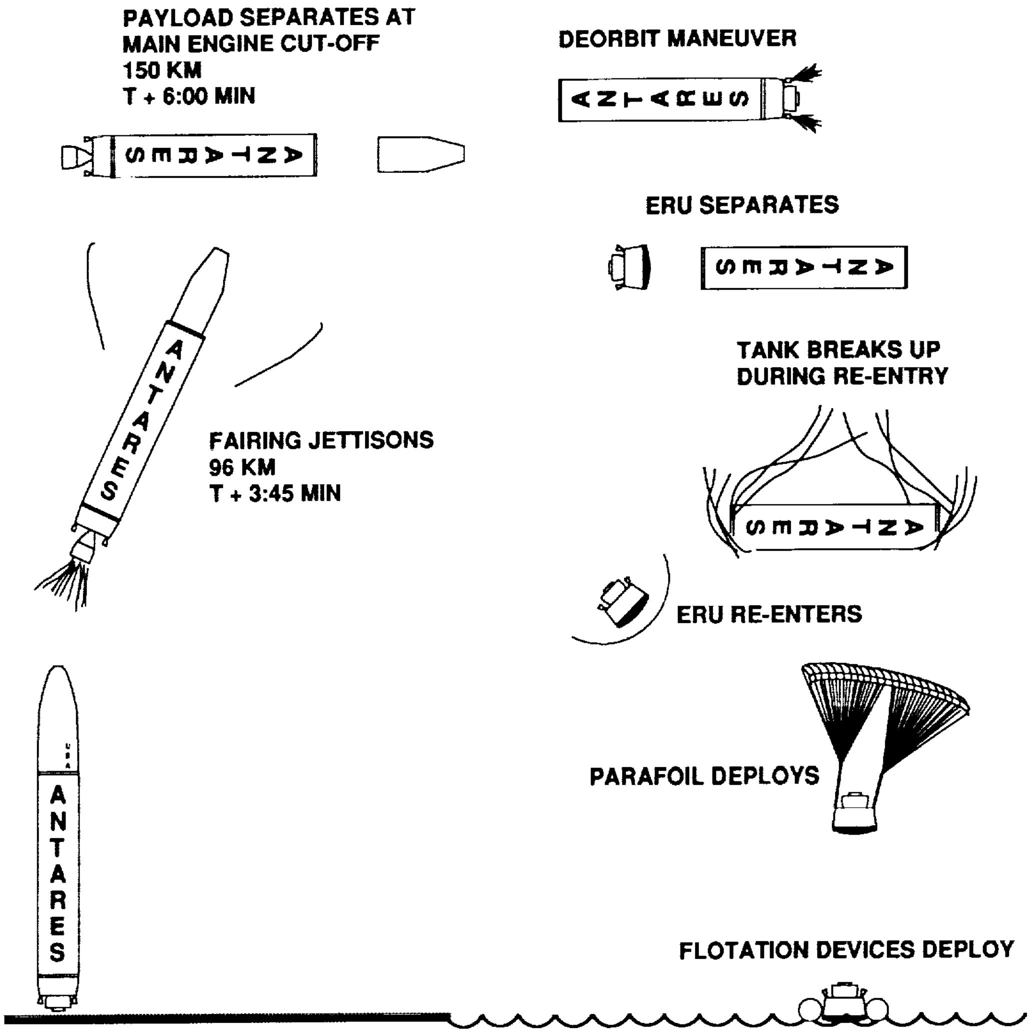


Fig. 4. LEO mission profile.

When the Antares reaches the upper atmosphere, the drag and frictional heating experienced at the payload fairing become negligible. This allows for the fairing to be jettisoned, as it is no longer required to protect the payload. The payload fairing is deployed at an altitude of 96 km (317,000 ft), and decreases the mass of the vehicle by 1400 kg (3090 lb).

Burnout is achieved six minutes after liftoff with the completion of orbital insertion into a 150-km × 300-km elliptical orbit of 28.5° inclination. This orbit was chosen for the sample profile analysis, as it provides the satellite with a wide range of final orbital altitudes which require minimal ΔV from the satellite. The total ΔV required for this LEO mission profile is 9.3 km/s.

After orbital insertion is achieved, the Antares separates itself from the payload and orients itself for a reentry maneuver. The Antares is capable of remaining in the 150 × 300-km parking orbit for several days as it waits for the proper reentry window. At the appropriate time, the DMRE's nozzle retracts and the ERU performs a deorbit burn. The ERU and the tanks separate so that they reenter at different locations. This is desirable, as the ERU is to be retrieved, while the tanks are to be discarded so that they burn up in the atmosphere. Small solid rocket motors push the tanks into a long shallow trajectory that will cause them to be destroyed by atmospheric heating. Any pieces that survive the flight will land harmlessly, far out to sea. The ERU maneuvers into a steep descent that allows it to splash down relatively close to the Florida coast, where it can be retrieved by ship. Once the ERU is retrieved, maintenance is performed on its components and it is integrated into another Antares vehicle for further service.

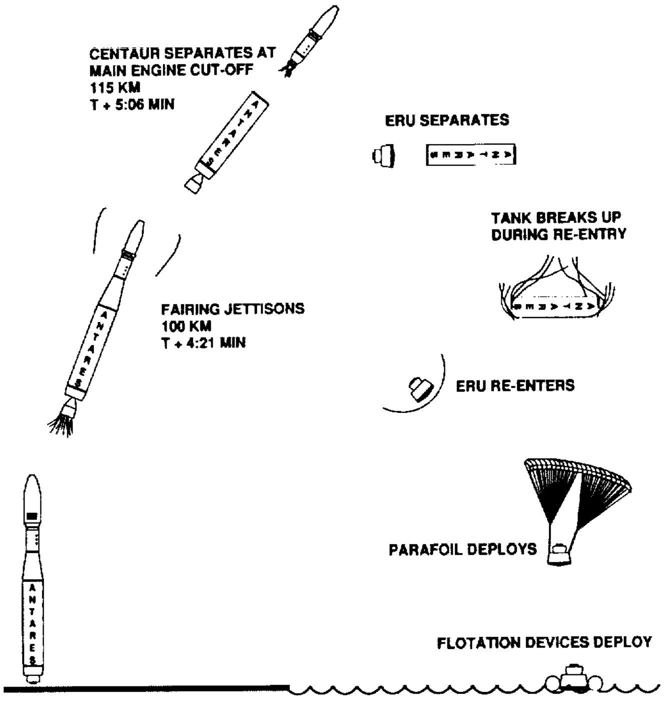


Fig. 5. GEO mission profile.

GEO Mission

The mission to GEO also begins at KSC, but the final destination of the payload is in a much higher orbit that is equatorial rather than inclined. Both the LEO and GEO missions involve initial insertion into a 150 × 300-km parking orbit. The GEO mission, however, performs this mission as a two-stage vehicle. In place of a LEO payload, a Centaur upper stage and GEO payload ride atop the Antares booster. The Centaur upper stage performs insertion into the parking orbit, the transfer to a Geosynchronous Transfer Orbit (GTO), and final insertion of the payload into GEO.

At liftoff, an optimum thrust-to-weight ratio of 1.27 is desired. Since a fueled Centaur and payload have a greater weight than a LEO payload, this is achieved by only partially filling the Antares propellant tanks. This results in a fueled Antares booster of 175,300 kg (383,800 lb), topped with a Centaur of 18,400 kg (40,600 lb) and a payload of 4000 kg (8,800 lb). The launch characteristics for the GEO mission profile (Fig. 5) are very similar to those of the LEO mission. The area ratio and oxidizer/fuel ratio change at altitudes corresponding to the LEO mission and have the same effects described above. The payload fairing is also deployed at altitude, reducing the mass of the vehicle by 1200 kg (2650 lb). Burnout of the Antares booster is achieved five minutes after liftoff, when the Centaur separates and begins its burn. The Antares booster begins to fall back to earth in a suborbital, ballistic trajectory. The ERU separates from the tanks for reentry and is recovered by ship approximately 2100 km east of KSC. The tanks are allowed to burn up on reentry, and are not reused.

The Centaur burns approximately half of its propellant in achieving insertion into the parking orbit. The remaining propellant is required for insertion of the payload into GEO. The Centaur waits in the parking orbit until the proper transition time. At the perigee of the parking orbit, the Centaur performs a burn to accelerate it into GTO. The optimum transfer involves a plane change at both the perigee and apogee of the GTO. The perigee plane change is from an inclination of 28.5° to 26.4°. The apogee of the GTO is at GEO, where the final plane change is performed and the satellite is released into a circular orbit of 0° inclination. Once separation of satellite and Centaur is complete, the Centaur places itself into a circular orbit 1000 km lower than the satellite. The ΔVs for this mission are 9.17 km/s from launch to LEO and 4.24 km/s from LEO to GEO.

Analysis of the Antares' mission profile, in both LEO and GEO configurations, was performed with a trajectory optimization program called OPGUID, provided by NASA's Marshal Space Flight Center(11). It performs a three-dimensional vector analysis of the rocket's trajectory, based on the initial and final conditions and the vehicle operating parameters. A separate program was used to determine the characteristics of both the deorbit and suborbital reentry of the ERU. Worst-case dynamic stability analysis was performed on the LEO Antares based on the flight characteristics predicted by OPGUID.

ENGINE RETURN UNIT

The Engine Return Unit (ERU), shown in Figs. 6-8, is the key element for the reusability concept of the Antares launch vehicle. It houses the DMRE, secondary propulsion, and avionics, which are the most expensive components of the vehicle. The ERU is designed to return these components to Earth, so that they may be reused on subsequent missions. The ERU makes up 5800 kg (12,800 lb) of the vehicle's 13,000 kg (26,600 lb) dry mass.

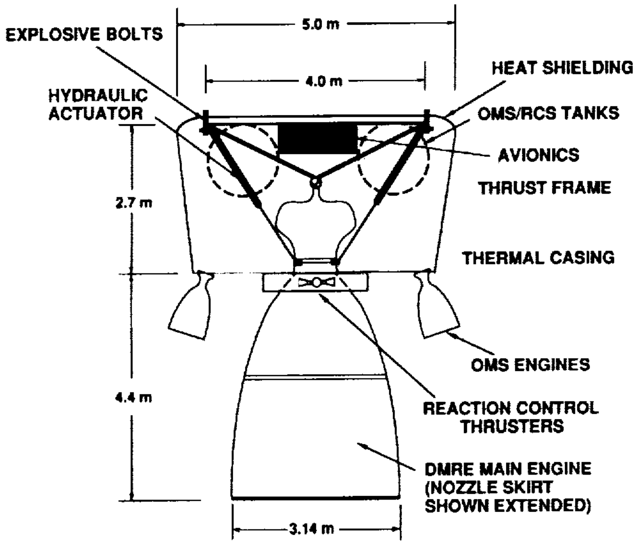


Fig. 6. Schematic cutaway view of Engine Return Unit (ERU): LEO configuration.

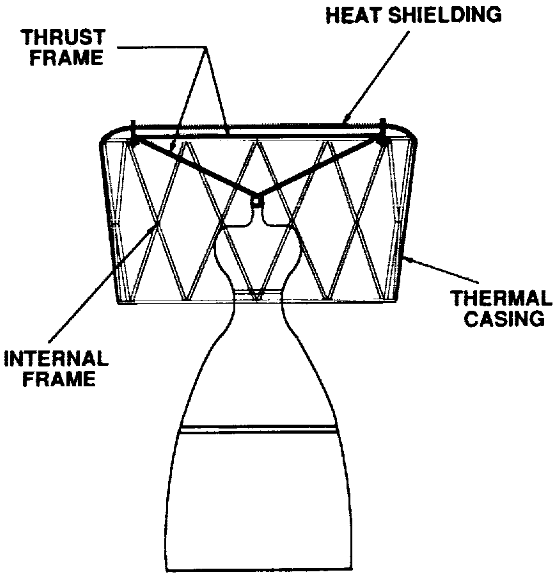
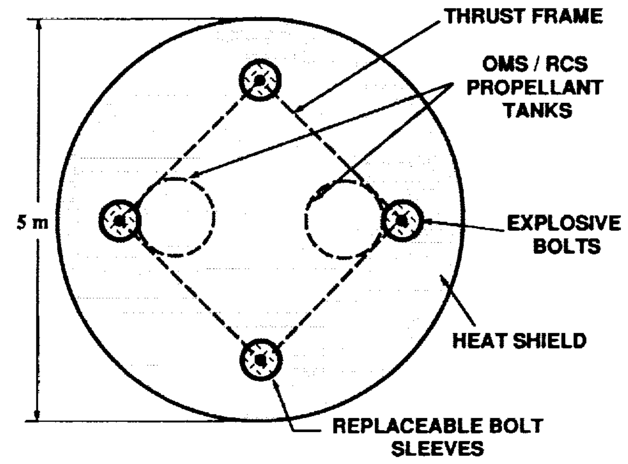
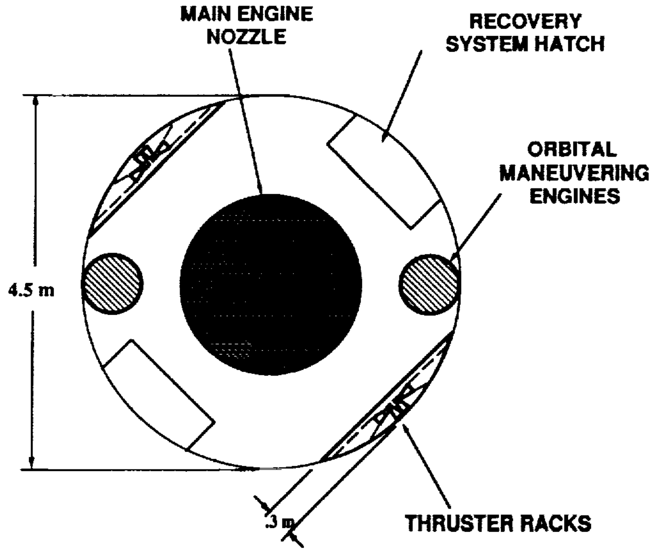


Fig. 7. ERU structural components. (For clarity OMS structure is not shown).



a) Top view



b) Bottom view

Fig. 8. End views of ERU.

The Antares uses the DMRE as its main engine because it is designed specifically for single-stage-to-orbit operations. The DMRE provides high thrust for the boost phase, which accelerates the vehicle quickly through the atmosphere. This is accomplished with a high mixture ratio of 12:1, and a low nozzle expansion ratio of 40:1. For the sustainer phase of the launch, the mixture ratio is reduced to 6:1 and the nozzle expansion ratio is increased to 150:1 to give a maximum specific impulse (see Table 1). The engine also has the ability to throttle to keep the vehicle's acceleration within the 4-g limit.

The ERU structure (see Fig. 7) is divided into three parts: the main thrust frame, the internal frame, and the outer heat shield. The thrust frame is designed to transfer the thrust of the DMRE through the fasteners that connect the ERU to the propellant tank. The frame members consist of titanium tubes for maximum material strength per unit mass. The internal framing is a Kevlar composite structure that supports the ERU's outer casing and is strong enough to withstand the loads experienced during splashdown, which can be as high as 1400 kPa (~200 psi). Extra titanium frame structure is required to support the two orbital maneuvering engines used in conjunction with the LEO configurations. This structure is attached to the main thrust frame. A carbon-carbon ablating heat shield is mounted on the forward face of the ERU to absorb the heat of reentry.

TABLE 1. DMRE Performance Characteristics.

	Boost Phase	Sustainer Phase
Thrust (kN), (lb_f)	2460 (553,000)	2670 (417,000)
I_{sp} (sec)	334	467
Mixture ratio (O/F)	12:1	6:1
Expansion ratio	40:1	150:1
Chamber Pressure (MPa)	27.6	18.6

The avionics housed in the ERU are controlled by a distributed command and data handling system (C&DH). The guidance, navigation, and control system (GN&C) consists of an inertial navigation system (INS) and two horizon sensors. The communications subsystem uses a transponder that is compatible with the Space-Ground Link System (SGLS) on the S-band. The avionics themselves use approximately 100 W of power for both LEO and GEO missions. The ERU power supply consists of primary batteries as well as secondary rechargeable batteries for the longer term LEO missions. The total avionics mass is 500 kg.

For LEO missions, the Antares requires orbital maneuvering and deorbiting capability and an attitude control system. These are provided by an independent propulsion system integrated into the structure of the ERU (see Figs. 6 and 8). This secondary propulsion system becomes active after the payload has been deployed. The vehicle's attitude is maintained by a reaction control system (RCS) while it coasts in the parking orbit. The orbital maneuvering system (OMS) engines then decelerate the vehicle at the appropriate time, initiating the vehicle's deorbit trajectory. GEO missions do not require this additional hardware, as the Antares vehicle performs a suborbital flight.

Rocketdyne XLR-132 orbital maneuvering engines, which each produce 16.68 kN of thrust, are mounted on the ERU to carry out orbital maneuvers and perform the deorbit burn. Marquardt R-1E thrusters, which produce 110 N of thrust, provide reaction control for the Antares. They are housed in thruster racks, which are mounted onto the bottom of the ERU (see Figs. 6 and 8). This makes the thruster racks easily accessible and allows them to be reconfigured for modular Antares vehicles (see Fig. 9). Both the XLR-132 engines and the R-1E thrusters burn monomethyl hydrazine (MMH) and nitrogen tetroxide (N_2O_4). These propellants are stored in spherical tanks that are mounted in the ERU as shown in Figs. 6 and 8. A high-pressure helium tank is located upstream of the propellant tanks, and pressure regulators are used to adjust the pressure to the required engine manifold inlet pressure.

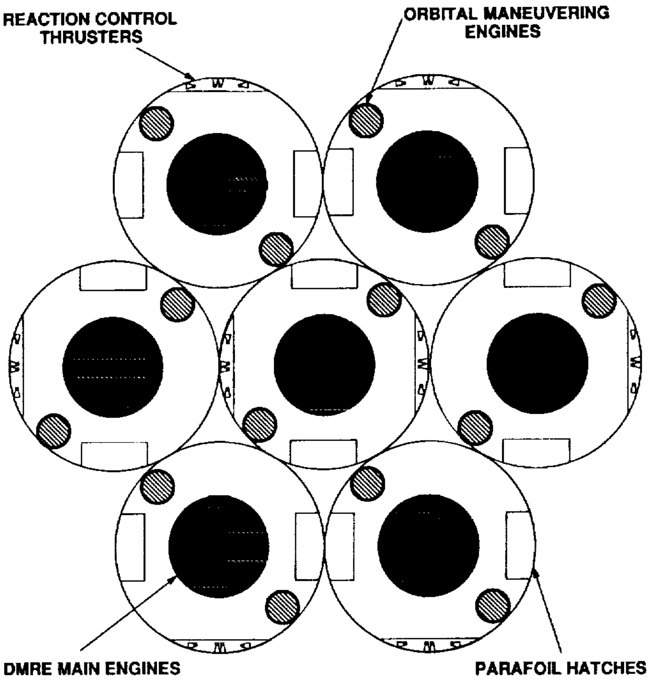


Fig. 9. Antares VII propulsion system configuration.

The separation system disconnects the ERU from the tank structure before reentry by means of explosive bolts extending from the thrust frame of the ERU. At the proper time, the bolts explode and expanding springs push the ERU and tank safely apart. No retractable doors are necessary to seal off the ERU to avoid sinking after a water landing because there is no pathway for water through the separation system components and into the ERU. This feature minimizes mass and reduces system complexity.

After separation from the tank, the ERU reenters the atmosphere, where it experiences a very high thermal load. The ERU is protected from this through the use of an ablating heat shield on the blunt forward surface. Blunt bodies dissipate a large fraction of the energy of reentry to the atmosphere, thus reducing the heat transferred to the vehicle. The ablator's function is to absorb the heat that is imparted to the vehicle. The material vaporizes, jettisoning the heat from the vehicle. A carbon-carbon composite is used as this material because of its high heat of vaporization.

A parafoil is deployed for the final phase of deorbit. This parafoil slows the vehicle so that it safely splashes down into the ocean, and allows some maneuvering capability just prior to splashdown. An inflatable flotation ring is deployed to give the ERU additional buoyancy and stability in the water. The ERU is recovered by ship and returned for refurbishment and reuse.

PROPELLANT TANKS

The design of the Antares propellant tanks (Fig. 10) is based on the relationship between the forces and moments that are imposed on the oxidizer and fuel tanks and the ability of the

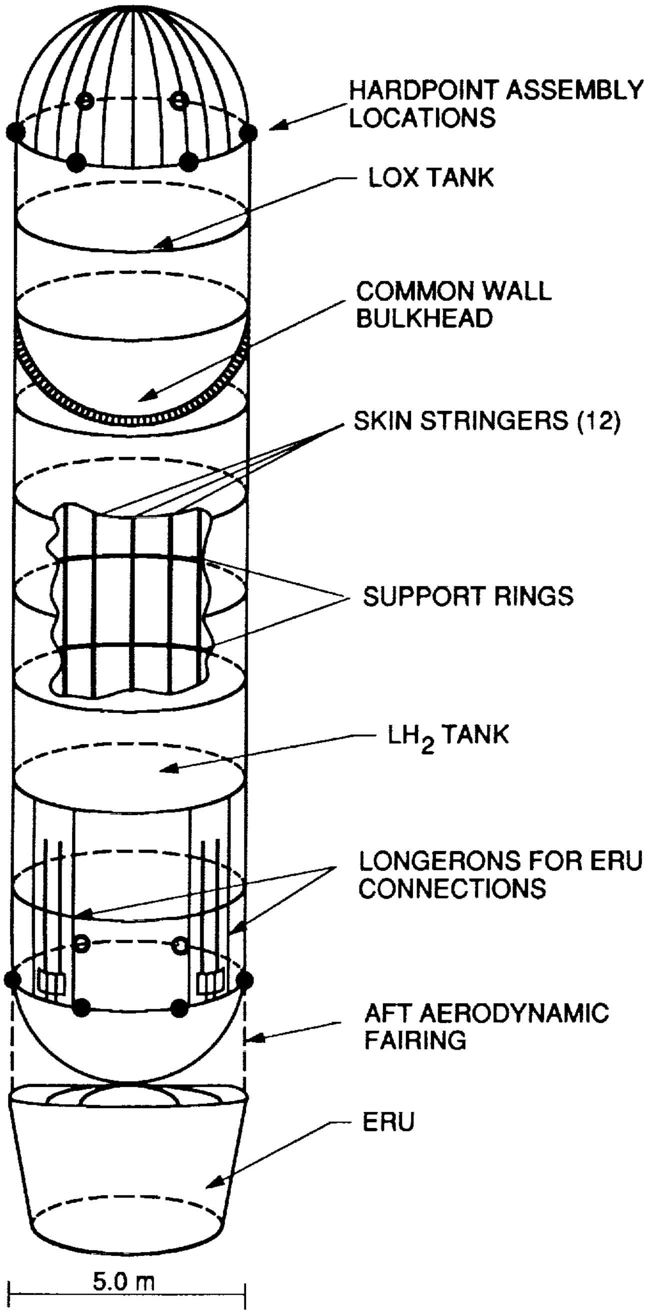


Fig. 10. Antares propellant tank.

tanks to withstand these loads. This relationship limits the minimum dimensions of the propellant tanks and corresponds to a minimum dry mass of the tank structure. The Antares encounters various combinations of axial, lateral, and shear forces prior to launch and during ascent, and is designed to withstand worst-case loading situations.

The lightweight propellant tanks are designed with the liquid hydrogen tank (292.4 m^3) below the liquid oxygen tank (140.3 m^3). A common wall bulkhead separates the two tanks. The oxidizer and the fuel tanks are semimonocoque structures constructed of aluminum alloy 2219 and have a wall thickness of 2 and 2.2 mm respectively. The propellant tank structure is 23.5 m long, and has a constant diameter of 5 m. Through the use of supporting rings and stringers the tanks are self-supporting and do not require internal pressurization to maintain structural integrity. One of the key features of the Antares propellant tank structure is the common wall bulkhead that separates the fuel and oxidizer tanks. It is an aluminum 2219 honeycomb structure with an evacuated core to minimize the heat flux between the propellants. The tanks are externally insulated with polyurethane foam that is 10 mm thick for the liquid hydrogen tank and 5 mm for the liquid oxygen tank. The fuel and oxidizer are transferred to the ERU via 10-cm-I.D. external lines, constructed of Inconel 718. The mass of the complete tank system, including an estimation for slosh baffles, is 4200 kg. An inventory of the mass of each tank component is listed in Table 2.

TABLE 2. Tank Component Structural Masses.

Component	Mass (kg)
Liquid Oxygen Tank	
• Cylinder	335
• End Closure	220
• Support Rings	100
• Stringers	70
Liquid Hydrogen Tank	
• Cylinder	1440
• End Closure	440
• Support Rings	440
• Stringers	280
Common Wall Bulkhead	550
Propellant Lines	200
Insulation	125
Total Tank Structural Mass	4200

CONNECTIONS

There is one connection device that is common to all Antares configurations. This is the ERU to tank connection (Fig. 11). The bottom of the liquid hydrogen tank is connected to the ERU via four struts. These connect to the four corners of the ERU's main thrust structure and attach to the sides of the liquid hydrogen tank via longerons, which extend up the tank walls. The total mass of the ERU-to-tank connection, including the aft aerodynamic skirt, is 1000 kg. Another major connection device is the inter-stage adapter (ISA) used on GEO missions. The ISA connects the liquid oxygen tank to the Centaur upper stage and transfers axial loads to the propellant tank walls. The ISA has a total mass of 1200 kg. A modified ISA is used as support for payloads on LEO missions. The ISA for the LEO Antares has a mass of 600 kg.

PAYLOAD FAIRINGS

The design of the lightweight payload fairings is based on payload envelopes that are attractive to potential users of the Antares. The fairing shape minimizes aerodynamic loads while

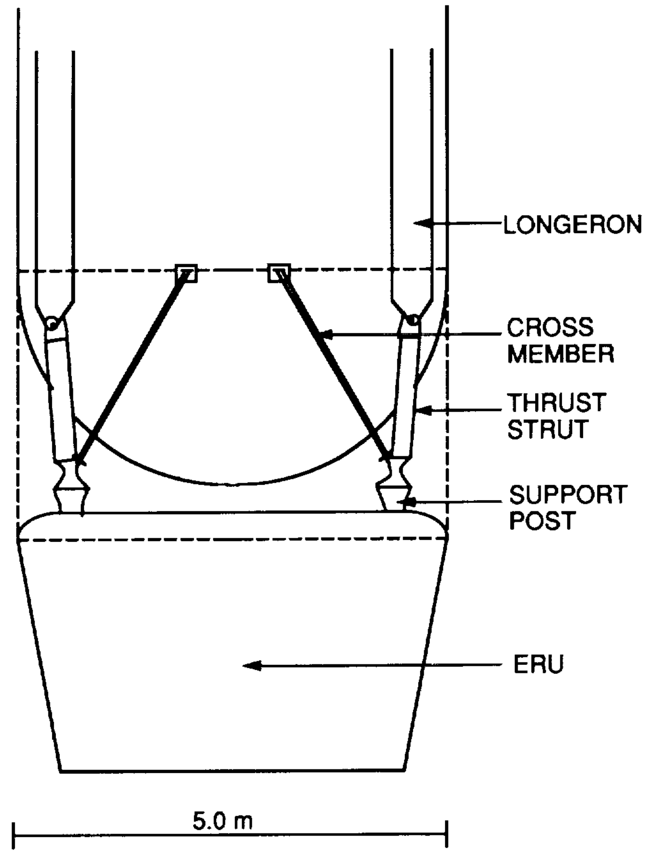


Fig. 11. ERU to tank connection.

maximizing the structural integrity. The sizes of Antares payload envelopes are in accordance with current and projected payload dimensions that can utilize the full payload capacity of Antares. Geostationary communications satellites have progressed toward increased circuit capacity and a longer life span. The more capable spacecraft are larger and heavier than their predecessors. Indications are that future communications satellites will be even larger still. The Antares GEO payload fairing accommodates today's communications satellites and the larger spacecraft of the future (see Fig. 12).

NASA's needs and industry projections dictated the initial LEO payload envelope dimensions. The *Civil Needs Data Base*(12), maintained by NASA, contains several hundred entries describing NASA's current and projected payloads for delivery to LEO. A majority of these payloads have widths suited for delivery by the space shuttle (4.57 m) and are under 9000 kg. Such payload widths are accommodated by Antares' standard LEO fairing, shown in Fig. 12. The fairing base diameter is dictated by Antares I's single booster diameter (5.0 m). The standard LEO payload fairing will service more than 75% of NASA's LEO payloads. A larger payload envelope is provided for modular versions of the Antares (Fig. 2). The Antares III fairing has the same diameter as the Antares I, but has a length comparable to that of the shuttle's payload bay.

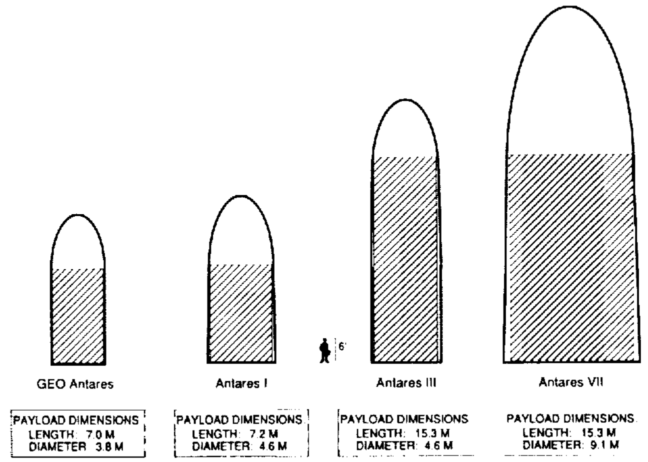


Fig. 12. Antares payload fairings.

The fairing of the Antares VII (Figs. 2b and 12) provides a payload envelope that is unique among current or planned U.S. launch vehicles. The envelope's diameter is approximately twice that of the Titan IV, while its length corresponds to the lengths of many larger payloads listed in the *Civil Needs Data Base*.

All fairings use a parabolic nose geometry with a length-to-diameter ratio of 1.2. This geometry allows a sizeable portion of the payload to be stowed inside the nose section, thus resulting in an overall reduction in length and mass of the cylindrical portion of the payload fairing. In addition, the continually curved shape resists collapse or buckling loads, thereby requiring less structural support in the nose cone shell.

The Antares' nose cone shell structural support is modeled in a manner similar to McDonnell Douglas' Titan IV nose cone (an isogrid arrangement). The benefit of using an isogrid is that the outer skin of the nose cone can be made less massive, due to the forces being transmitted through the isogrid truss. The nose cone tip's skin will be made from a carbon-carbon composite to withstand the high temperatures experienced during the maximum Q region of flight. The remaining skin will consist of Cycom NCG nickel-coated graphite fiber composite. This composite is specially designed to dissipate electrical charge, should a lightning strike to the nose occur. Acoustic blankets are inserted between the composite beams of the isogrid in the inner fairing wall to prevent excessive vibration transmission to the payload envelope.

The payload fairing is jettisoned from the vehicle at a prescribed altitude (~100 km). To perform this separation two rails that sandwich an explosive charge are used. When detonated, the explosive charge splits the fairing along its axis into two or more segments. Once split the segments rotate back on hinges until they reach an unhinging point and fall off.

CONFIGURATIONS

One of the key features of the Antares is the ability to combine the boosters to provide expanded payload capabilities. The Antares is capable of attaching from two to seven boosters to form its family of vehicles called the Antares II through the Antares VII. In the modular configurations the Antares units are attached using hard points that are a part of the propellant tanks. Two of the tanks' stiffening rings, one forward and one aft, contain six hard point attachment assemblies that allow up to six boosters to be attached to a central booster (see Fig. 10).

The modular configurations of Antares allow for expanded payload capabilities. Since each booster is identical to the Antares I, the payload capabilities are just multiples of the Antares I. The Antares family has a payload range of 10,000 kg (22,000 lb) for the Antares I to 70,000 kg (154,000 lb) for the Antares VII. This wide range of payloads gives the Antares an advantage over existing launch vehicles by providing the space launch market a fleet of vehicles with only one vehicle design.

An issue that must be addressed in the modular configurations is that of engine failure. If one of the engines were to fail in a modular configuration launch, the mission's success would be dependent upon when the failure occurred. If the failure occurs too early in the ascending phase of the mission, there is no alternative but to abort the mission. Beyond a certain point during ascent, the Antares can still complete its mission, in spite of an engine failure, by using an Emergency Propellant Communication System (EPCS).

The EPCS allows for the propellant from the booster with the failed engine to be shared with the engines that are still firing. This is done by interconnecting the propellant lines of the boosters that are joined together. This gives each ERU access to another unit's propellant. If there is an engine failure, the appropriate valves open, so that all the propellant is consumed and the mission is salvaged.

COST ANALYSIS

For the Antares vehicle to establish itself as the dominant launch vehicle in the 21st century it must be cost effective. To achieve this goal the Antares uses many cost saving techniques. One idea used to reduce cost was to design the Antares as a single-stage-to-orbit vehicle. Although this design is less efficient than multi-stage vehicles it lowers the cost by reducing the complexity of the vehicle and the costs of operation and support. Another technique is using the ERU to retrieve the DMRE and the avionics, which together can account for up to 70% of total vehicle cost. The savings achieved by reusing the expensive components of the Antares translate directly to a much lower cost per unit payload mass to the customer.

To determine the cost per unit payload mass for Antares, the Life Cycle Cost (LCC) had to be taken into consideration. The LCC consists of three basic costs: Research, Development, Test, and Evaluation (RDT&E) cost, the production cost which is a function of the Theoretical First Unit (TFU) cost, and the Operations and Support (O&S) cost. The RDT&E cost includes all of the design, analysis and testing of the Antares vehicle. The TFU cost indicates the production cost for one Antares vehicle and is the basis for computing the cost for multiple units in production. The O&S cost consists of the necessary operations for preparing the Antares for a launch and supplying personnel for these launches. Other factors that are added to the O&S cost are the recovery and the refurbishment costs for the ERU, and total propellant costs for the vehicle. All of these costs are necessary to determine the expenditures required to put the Antares on line, and to calculate the cost per unit payload mass.

Before the LCC could be computed, the number of launches had to be estimated. The Antares mission model shows how many launches per year will be flown over the projected life span of 40 years. The mission model (see Fig. 13) proposes a maximum launch rate of 30 per year, and a total of approximately 900 launches over the program's anticipated life span.

For the cost analysis the Antares vehicle was separated into eight categories. These categories are the structure, thermal control, avionics, power, main propulsion, secondary propulsion, recovery system, and staging/ordnance (Table 3). Cost per kilogram values for the eight categories were used to determine the TFU and the RDT&E for the vehicle(12). This was done simply by summing the masses of the components that fit into a specific category and multiplying the result by its respective cost per kilogram value. The results are shown in Fig. 14. RDT&E and TFU cost per kilogram values differ for ERU and tank components due to the differing complexity of these two systems. To compensate for this the category masses were separated into ERU and tank values. To determine the total production costs the TFU costs must be adjusted using a learning curve, which accounts for productivity improvements as more units are produced. The O&S cost is calculated using a linear slope approximation. It follows that the O&S cost increases as more flights are made but the average cost per flight decreases (see Fig. 15).

TABLE 3. Categories for Life Cycle Costs.

Category	Example of Components in Category
Structure	Propellant tanks, fairings, ERU thrust frame
Thermal Control	Insulation, heat shield, thermal casing
Avionics	On-board computers, accelerometers
Power	Batteries
Main Propulsion	DMRE engine, piping for the main vehicle
Secondary Propulsion	OMS, RCS
Recovery Systems	Parafoils, flotation devices
Staging Ordnance	Explosive bolts, range safety devices

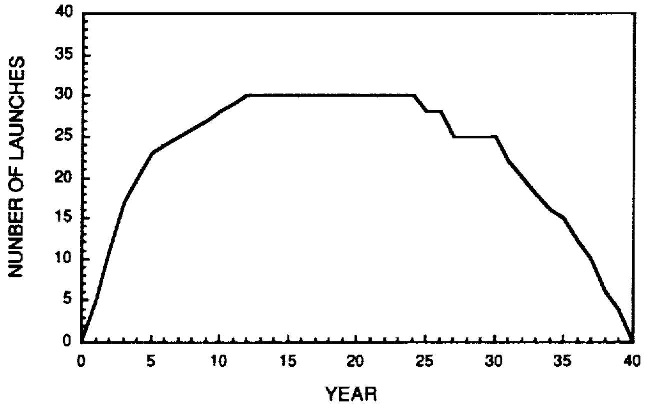
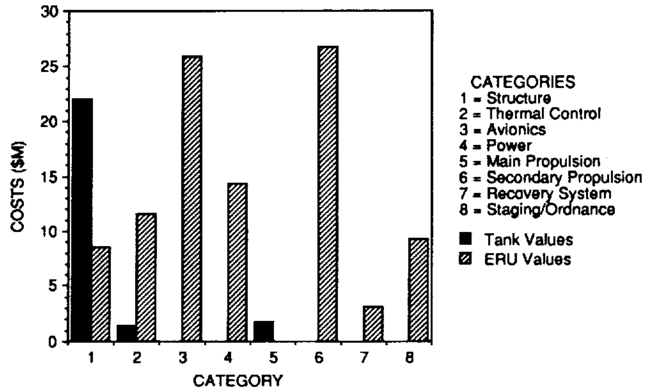
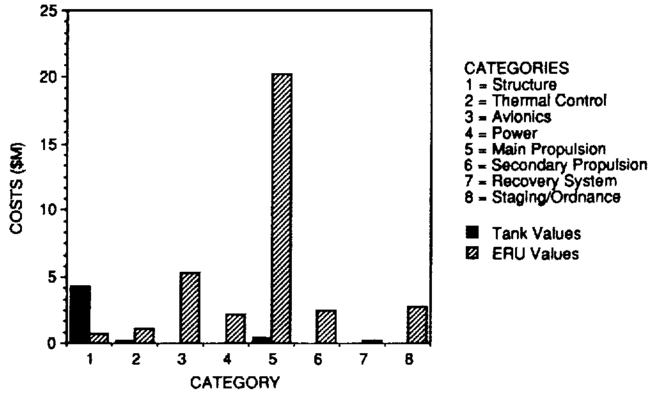


Fig. 13. Antares mission model.



a) Research, Development, Test & Evaluation costs.



b) Theoretical First Unit costs.

Fig. 14. Costs for tank and ERU components (in millions of 1991 dollars).

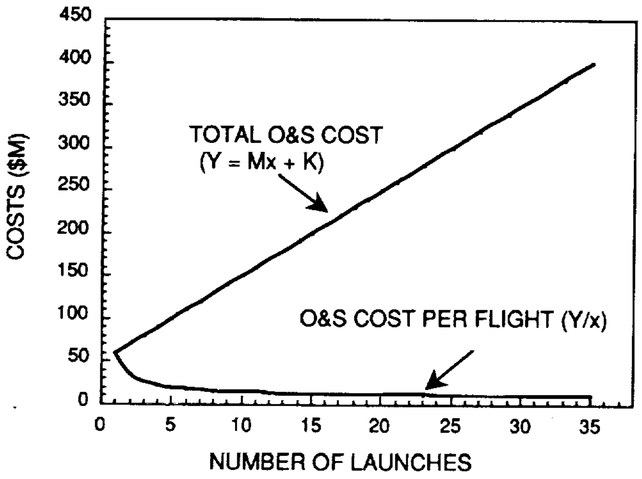


Fig. 15. Operations and Support cost per launch (in millions of 1991 dollars).

To determine the cost per unit payload mass for the Antares all of the previous data must be taken into account. The RDT&E costs are spread out over the 900 flights contained in the mission model. A model year is chosen to determine the average cost per unit payload mass. For our analysis the fifteenth year of service is chosen. In this year of service thirty launches are scheduled. The values obtained for production and O&S costs are averaged for the thirty launches to determine the launch cost for one vehicle. The cost per unit payload mass is obtained by simply dividing the average launch cost by the maximum payload delivered to LEO. The cost per unit payload mass to LEO for the Antares is $1340/kg ($610/lb).

The cost per unit payload mass to GEO is a direct function of the total LEO launch cost. To calculate the cost per unit payload mass to GEO, there are a few other factors that need to be addressed. These factors are the cost of the Centaur, which is the cost for the vehicle and all O&S necessary to launch it, and the additional components, mostly structure, necessary to attach the Centaur to the Antares. These costs are added directly to the total (RDT&E, TFU, and O&S) launch cost obtained in the LEO analysis. From this the GEO cost per unit payload mass is determined by simply dividing the total GEO launch cost by the Antares payload capabilities to GEO. The cost per unit payload mass to GEO is $16,200/kg ($7350/lb).

From the above data it is evident that the Antares vehicle is capable of providing launch services at a cost unmatched by any existing launch vehicle. The cost per unit payload mass to LEO for the Antares is approximately one-tenth that of the space shuttle and one-sixth of the current industry leader, the Ariane IV. For these reasons alone, it is evident that the Antares launch vehicle is prepared to make space affordable and to open this market to the world.

CONCLUSION

The Antares is a single-stage-to-orbit launch vehicle, designed for versatility and low cost. To achieve these goals a modular system based on single identical units is proposed. The basic unit of the modular system, a single Antares vehicle, is aimed at launching approximately 10,000 kg (22,000 lb) into LEO. When using the Centaur upper stage it is capable of placing 4000 kg (8,800 lb) into GEO. The Antares incorporates a reusable engine, DMRE, as its propulsive device. This enables Antares to compete and excel in the satellite launch market by dramatically reducing launch costs. Antares' projected launch costs are $1340/kg ($610/lb) to LEO, which offers a tremendous savings over launch vehicles available today.

The most cost-effective aspect of the Antares is its ability to return the main engine and reuse it in future launches. Since the engine accounts for the majority of the total vehicle cost, returning it results in a considerable savings, which can be returned to the customer in the form of a low cost per unit payload mass. Engine reusability is assuredly the wave of the future, if launching is ever to become economical. The Antares will pioneer the way to developing this new technology.

Antares' modular configurations accommodate a payload range of 10,000-70,000 kg to LEO, which is unmatched by any other launch vehicle. The ability to launch multiple booster configurations makes the Antares in itself a family of launch vehicles.

Thus the launch cost is greatly reduced because only one vehicle is developed to serve this large range of payload masses. Another cost reducing factor is that the Antares is conducive to inexpensive, large-scale production because the main booster is identical in all the modular configurations. This straightforward approach to production, similar to the commercial airplane industry, also assures a high level of reliability in that specific manufacturing methods, unique to the Antares vehicle, can be implemented because of its inherent long term usefulness as a competitive launch vehicle.

Another feature of the Antares that enables it to achieve its design goal is its ability to expand and meet the growing needs of the satellite market. The Antares' modular concept makes this expansion possible. Satellites are no longer bound to the small payload capacities of existing launch vehicles. In addition to an increased payload mass, the modular concept also accommodates an increased volumetric capacity. In effect, the Antares is an all-purpose vehicle ready to expand to future needs.

Antares' innovative design makes it an inexpensive and reliable launch vehicle, and because of Antares' unique features it is capable of encouraging expansion in the satellite industry. By making the one-time dream of low-cost vehicles a reality, Antares could help the U.S. regain its dominance in the commercial launch market.

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