Quarterly Report Topic

The Anatomy of a Launch Vehicle

INTRODUCTION

Conceptually, a rocket is a simple machine. Following Newton's law that every force has an equal and opposite reaction, a rocket pushes mass in one direction and moves in the other. However, a modern space launch vehicle is a finely tuned and very complex device. This report discusses the basic details of expendable launch vehicles and explores their function and operations.

LAUNCH VEHICLE ELEMENTS

A launch vehicle is composed of a number of separable sections called stages. Each stage contains fuel tankage, propulsion systems, and control systems. As each stage exhausts its fuel (the largest part of its mass), it is discarded to reduce the amount of mass that the next stage must propel. As each stage is discarded the total vehicle mass is reduced, also reducing the amount of energy required to lift the remaining vehicle mass.

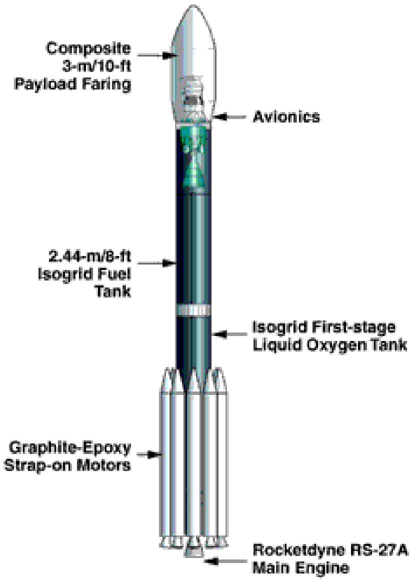

Figure Q1. Delta 2 Launch Vehicle Structure

Each stage of a vehicle is made up of four basic subsystems. These are as follows:

- Propulsion
- Structure
- Tankage
- Guidance and control

In addition to the components that make up each vehicle stage, the vehicle as a whole must also have a payload fairing in which to carry its payload. See Figure Q1 for a representative breakdown of the Delta 2 launch vehicle.

Propulsion

There are two basic types of rocket fuel, solid and liquid. Both types of fuel are used by commercial launch vehicles, but generally solid fuel is used as a primary propellant by smaller vehicles such as the Taurus and Pegasus. In the case of larger launch vehicles, solid rocket motors are generally used in the form of strap-on boosters. Strap-on boosters are attached to the side of a launch vehicle and burn in parallel with the vehicle's main engines. This allows the thrust of the vehicle's main engine to be supplemented by that of the strap-on booster without replacing the stage to be supplemented.

Solid rocket engines can not be throttled and often provide a more stressful launch environment than liquid fueled systems. However, they are more robust, cheaper to design and build, and can be stored for long periods. Liquid fueled systems offer better control and possibly more energy, but they are more fragile and cannot be held on the pad for as long a period as a solid fueled vehicle.

As mentioned above, strap-on boosters are used to increase the lift capacity of a launch vehicle without redesigning the entire vehicle system. The Ariane 4 family is an example of a single common core vehicle that can be tailored for different payload masses by the addition of different types of strap-ons. In the case of the Ariane 4, the strap-on boosters can be either liquid or solid fueled (or some of each) according to the specific vehicle characteristics desired. In the case of the Titan 4, the strap-ons are solid fueled and only come in one version. It this case, the vehicle is tailored by the use of different upper stages.

The term “upper stage” is generally used to describe the final stage of a vehicle. The upper stage is the portion of the launch vehicle that places the vehicle’s payload in a higher orbit than the vehicle itself reaches. Most launch vehicles place their payloads into a transfer orbit from which the upper stage (or in some cases a small device attached to the payload called a kick motor) takes the payload to a final higher orbit.

Another function of an upper stage is to inject a number of payloads into differing orbits from the same launch vehicle. A restartable upper stage was used on the Delta 2 to place each of five different Iridium satellites into different orbits.

Upper stages are generally liquid fueled, but in some cases they use solid rocket motors. The Block-DM used on the Proton and the Centaur upper stage used on the Atlas and Titan 4 are liquid fueled: Block-DM uses liquid oxygen (LOX) and kerosene as a fuel and the Centaur uses LOX/liquid hydrogen (LH_2). However, the Inertial Upper Stage (used with the Titan 4 and Space Shuttle) is a two-stage solid fueled design.

Structure

Structures of launch vehicles vary; in some cases there is a separate skin and structure that surrounds the tanks and engines (Soyuz is an example), and in other cases the skin of the stage is actually the outside of the fuel tanks (as with the Delta 2). In other cases (Atlas 2 and Atlas 3), only the pressure of the fuel on the skin/tank provides the strength that keeps the skin from buckling under the weight of the vehicle and payload.

Tankage

Launch vehicles using liquid fuel must use vessels and plumbing to contain and direct the liquid fuel. These vessels differ according to the fuel for which they are used. In a Titan 2, the fuel is hypergolic (it burns when it is mixed) and the vehicle hardware must resist its particularly corrosive effects. With cryogenic (super cold) fuels like LOX, or the much colder LH_2, the greatest design challenge is to deal with the effects of extreme cold on vehicle hardware. The easiest fuels to use are those at room temperature such as hydrogen peroxide and kerosene.

A common compromise between the demands for an energetic fuel and one that is easy to handle is the LOX/kerosene combination used by the first stages of the Delta 2 and Delta 3. However, even vehicles that use this combination in lower stages may use a fully cryogenically fueled upper stage.

Guidance and control

The final element of a launch vehicle is the guidance and control system. This is the seat of a launch vehicle’s intelligence. The system tells the engines when to fire and for how long, initiates stage separation, can sense a fatal problem with the launch, and can initiate a self-destruct sequence.

Guidance and control systems are the final resort when some other sub-system fails. A sufficiently capable guidance and control system may be able to compensate for a failed system elsewhere in the vehicle. An example of this occurred in the launch of two European Cluster II scientific satellites. When main engine cut-off occurred prematurely, the control system of the Soyuz launch vehicle's Fregat upper stage kept the upper stage engines firing for longer than planned to achieve the correct final orbit.

Table Q1. Atlas Component Suppliers*

Supplier	**Component**
BF Goodrich	Digital acquisition system.
Boeing Rocketdyne	MA-5/5A propulsion system.
CASA	Conical interstage adapters on the Atlas 5.
Contraves Space	Expanded payload fairing for the Atlas 5.
GenCorp Aerojet	Strap-on solid rocket boosters for Atlas 5.
Honeywell Space Systems	Inertial Navigation Unit (INU).
RD AMROSS	RD-180 propulsion system.
Saab Ericsson Space	Payload separation systems for Atlas 3 and Atlas 5.
Thiokol Propulsion	Castor 4A solid rocket boosters.
United Technologies Pratt & Whitney	RL10 rocket engines for the Centaur upper stage.

*Data from International Launch Services http://www.ilslaunch.com/atlas/majorsupplier/

LAUNCH VEHICLE MANUFACTURING

Launch vehicle manufacturers generally do not produce all components of an entire vehicle on their own. Instead they assemble parts made all over the country or even in other countries.

In the case of a large, new integrated production facility like the Boeing Delta 4 plant in Decatur, Alabama, major portions of the vehicle come from other Boeing facilities or different companies altogether. In the case of the Delta 4, the main engines are designed and built by Rocketdyne. Alliant Techsystems builds the rocket's strap-ons and L3 Communications Space & Navigation builds the Redundant Inertial Flight Control Assembly. In the cases of Lockheed Martin's Atlas 3 and Atlas 5, Khrunichev in Russia manufactures the engines. For a list of primary component suppliers for Atlas vehicles see Table Q1.

This is not a paradigm limited to launch vehicles. The same conditions hold true in the aviation, automotive, and electronics industries. For even the largest launch vehicle manufacturer, the role of integrating components from other manufacturers is at least as important as that of producing components in house.

VEHICLE CONFIGURATIONS AND VARIANTS

Different launch vehicle variants are optimized for different tasks. A vehicle designed to carry a payload into low earth orbit (LEO) is generally not a good choice to place a satellite into geosynchronous orbit (GEO). This is true because the energy requirement and profile required to put a payload into LEO differs greatly from that needed for GEO. Because of these considerations, launch vehicles are generally produced in a number of different variations and are optimized for different flight profiles. For a representative list of Delta 2 variants see Figure Q2.

In the case of the Proton launch vehicle, a version known in the West as the SL-13 is traditionally used to place large payloads into LEO. This is the vehicle that placed the major components of the Russian space station Mir into orbit. The version of the Proton used for launches to GEO is called the SL-12 and differs from the SL-13 by the addition of the Block-DM upper stage. Without this upper stage, the Proton cannot launch payloads to GEO.

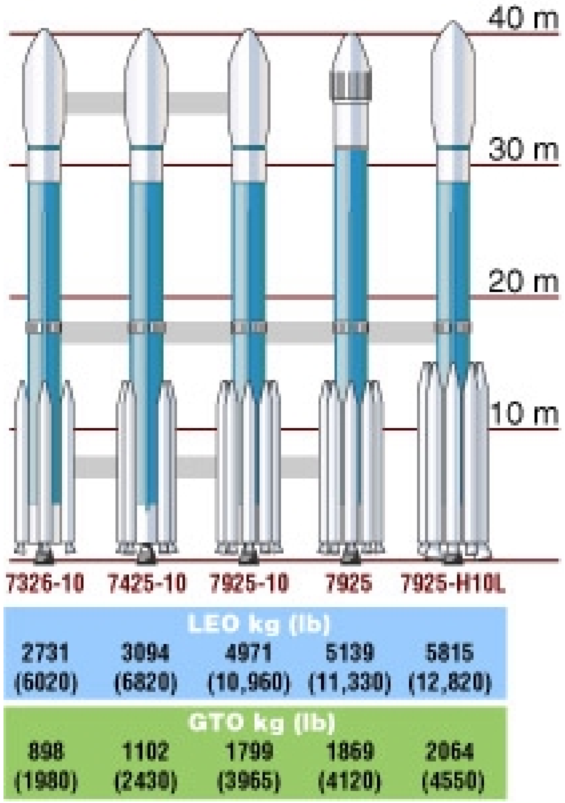

Figure Q2. Delta 2 Launch Vehicle Family

An exception to this rule is the case of multiple satellites being placed into different LEO orbits. In this case, the upper stage provides the energy to place each payload in a different orbit after the launch vehicle has reached LEO. This is why the GEO-capable SL-12 version of the Proton was used to launch seven Iridium satellites to LEO simultaneously while the SL-13 version is used for single large space station components going to a similar LEO location.

VEHICLE CAPACITY

Launch vehicles come in all sizes. The smallest may only be able to place a few hundred pounds into LEO, while the Apollo program's Saturn 5 could lift close to 300,000 pounds (136,363 kilograms) to that altitude and send an entire crewed spacecraft to the moon. The FAA divides launch vehicles into a series of different mass classes based on the mass of the payload that they can place in a LEO equatorial orbit. For a list of these definitions see Table Q2.

Table Q2. FAA Vehicle Classes

Suborbital	Not capable of putting any mass in orbit.
Small	Maximum mass capacity 5,000 lbs. (2,273 kg) to LEO.
Medium	Mass capacity is in the range of 5,001 (2,274 kg) to 12,000 lbs. (5,454 kg) to LEO.
Intermediate	Mass capacity is in the range of 12,001 (5,455 kg) to 25,000 lbs. (11,363 kg) to LEO.
Heavy	Mass capacity is greater than 25,000 lbs. (11,364 kg) to LEO.

An important factor in determining vehicle capacity is the location of the vehicle's launch site. Sites closer to the equator are more efficient for launches into GEO because they are aided by the Earth's rotational speed. This means that a vehicle launched from the equator could carry more to GEO than the same vehicle launched from a site closer to the Earth's poles.

Table Q3 shows how the capacity of a vehicle changes from differing launch sites. A vehicle with a capacity of 1,000 pounds (455 kilograms) at the equator would have its capacity reduced to the values in Table Q3 for the given launch site.

Table Q3. Vehicle Capacity from Different Launch Sites

Site	Payload to GEO (lbs.)	Payload to GEO (kg)
Equator	1,000	455
CCAFS	883	401
Baikonur	731	332

Beyond the pure physics of launch efficiency, there are other factors that affect vehicle flight path. Vehicles are often launched on paths that are less than optimal because of safety and political concerns. Some launch paths are chosen to keep the vehicles over uninhabited areas so that a failure does not result in casualties or property damage. Even in the Pacific Ocean, Sea Launch has added “dog legs” to some of their flight paths to ensure that vehicles will avoid inhabited islands. In Japan, the Tanegashima launch site is only used for part of the year because of agreements with the local fishermen’s union. Perhaps the most extreme example of the effects of political considerations on launch paths is the policy at the Israeli launch site at Palmachim Air Force Base. In order to keep rockets from passing over their neighbors, the Israelis make all launches in a westward, or retrograde, direction, against the direction of the Earth’s rotation (the most inefficient direction possible).