Ordnance Safety Requirements for Space Launch Vehicles

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Introduction

United Launch Alliance launches Atlas V from Cape Canaveral and Vandenberg Air Force launch facilities. Space launch vehicles such as Atlas V consist of various subsystems like pneumatics, propulsion, ordnance, avionics etc. The ordnance systems play a key role with instant activations to initiate various discrete events such as lift off, stage separations, spacecraft separation and flight termination if needed for public safety. Ordnance function is therefore essential for both mission success and uniquely for public safety. Ordnance hazards are present during prelaunch operations and during flight. Prevention of inadvertent activation and assured functioning are both important for safety. A major requirement is to provide a number of inhibits to prevent inadvertent activation. The number of required minimum inhibits depends on a critical or catastrophic consequence. Adequate qualification testing, lot acceptance testing and service life testing are essential for assured functioning. Operations at the launch ranges are controlled by Range Safety regulations like EWR 127-1 and AFSPCMAN 91-710. A number of military standards such as MIL-STD-1576, MIL-DTL-23659 and MIL-HDBK-1512 provide guidance for design and testing. The Department of Transportation provides requirements for safe ground transportation of ordnance. This paper reviews many of these requirements and their compliance approach.

Atlas V Space Launch Vehicle

Atlas launch vehicle has evolved over many years. Starting with an Atlas A in 1955, the version today is Atlas V. Figure 1 (Reference 1) shows the evolution over the years. Initial launches occurred at Cape Canaveral Complex 36 and Vandenberg Space Launch Complex 3.

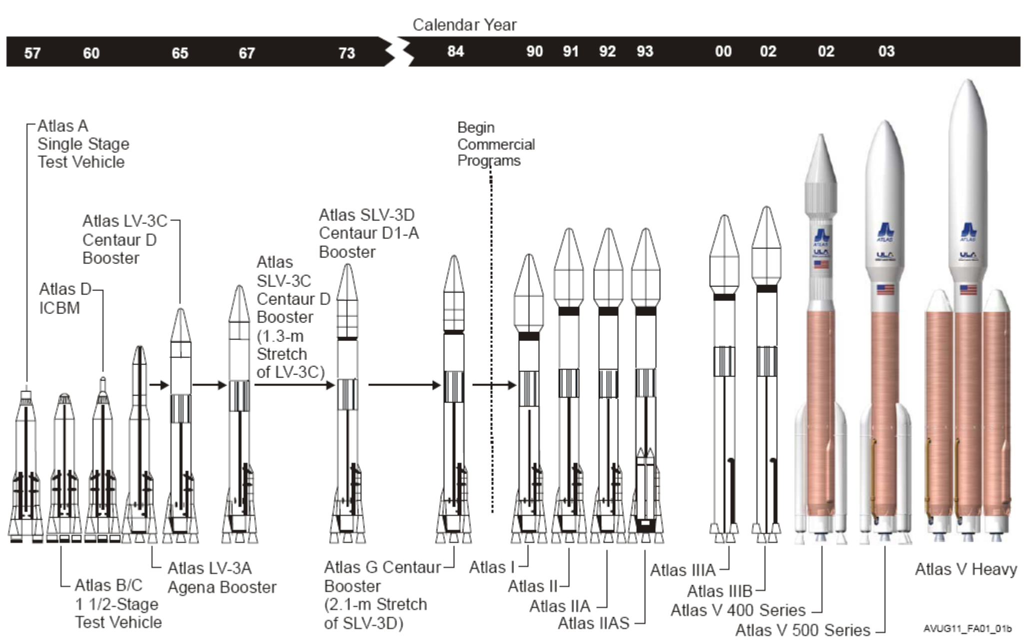

Figure 1 – Atlas Launch Vehicle Evolution

Atlas V launch vehicle is the current version of one of the most successful launch vehicles in operation today. The development of Atlas launch vehicle started with a contract to General Dynamics Corporation, San Diego California, in 1955 and the first launch occurred in 1958. First successful launch of Centaur with Atlas as first stage occurred in 1966. Since then the Atlas and Centaur combination has successfully flown many challenging missions. In 1987, General Dynamics started manufacturing Atlas for commercial launches. The launch vehicle ownership was later transferred to Martin Marietta, then to Lockheed Martin and today it is produced by United Launch Alliance (ULA) located in Denver Colorado. United Launch Alliance is a joint venture of Lockheed Martin and Boeing Corporation.

Significant developments have occurred over a period of time as shown in the Figure 1 with the launch vehicle becoming larger and more powerful. The quantities of propellants have increased significantly. Currently the Atlas V version with solid Rocket Motors is in routine flight. The design of HLV version is complete and is available to build when a need arises for a heavy spacecraft or a unique mission.

Today, Atlas V launches from Cape Canaveral Complex 41 in Florida and Vandenberg Complex SLC-3E in California. Figure 2 is an expanded view of an Atlas V configuration.

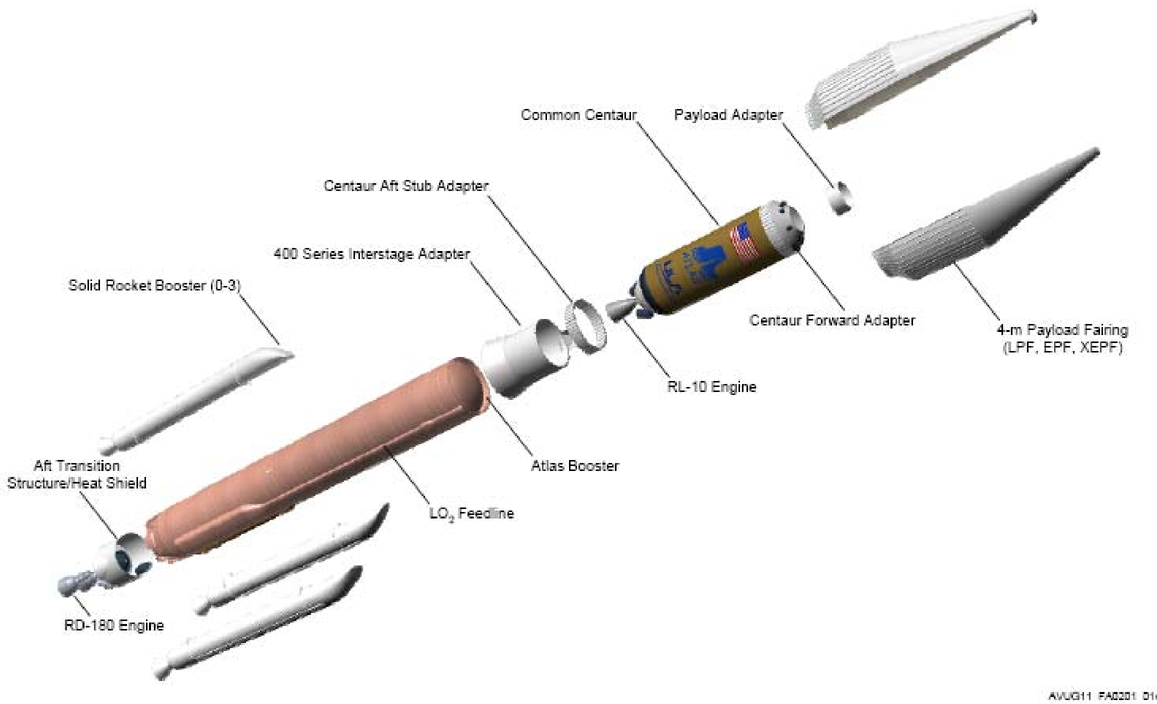

Figure 2 – Atlas V Launch Vehicle expanded view

Atlas Booster is a combination of two tanks to hold RP-1 fuel and Liquid Oxygen. RD-180 engine burns the propellants to create the thrust for lift off and initial flight phase. The Centaur upper stage has Liquid hydrogen fuel and Liquid Oxygen. RL-10 engine provides the thrust for the second phase of the flight that releases the spacecraft on a path to its final destination.

Atlas V is a reliable and versatile launch system capable of delivering Spacecraft (SC) to a wide range of elliptical orbits, low circular orbits, high circular orbits, and Earth-escape trajectories. All Atlas V launch vehicles are capable of launching a single large SC or multiple SC populating low and medium earth orbit constellations. The Atlas V 400 series consists of an Atlas booster combined with zero to three SRBs, a Centaur, and a 4-m diameter PLF. The Atlas V 500 series consists of an Atlas booster combined with zero to five SRBs, a Centaur, and a 5-m diameter PLF.

The LV is held down during booster engine start and a portion of booster start-up. A vehicle health check is performed before achieving full throttle. After passing the health check, the vehicle is released, SRB ignitions occur (if applicable), and booster start-up is completed. Ordnance is used to separate the Centaur stage from Atlas. At some point in flight, the payload fairing halves separate prior to spacecraft separation.

Figure 3 is a typical launch profile. Ordnance is used to initiate the launch. After a few minutes into flight, Centaur separates from Atlas booster stage using ordnance and then the spacecraft separates from Centaur using ordnance.

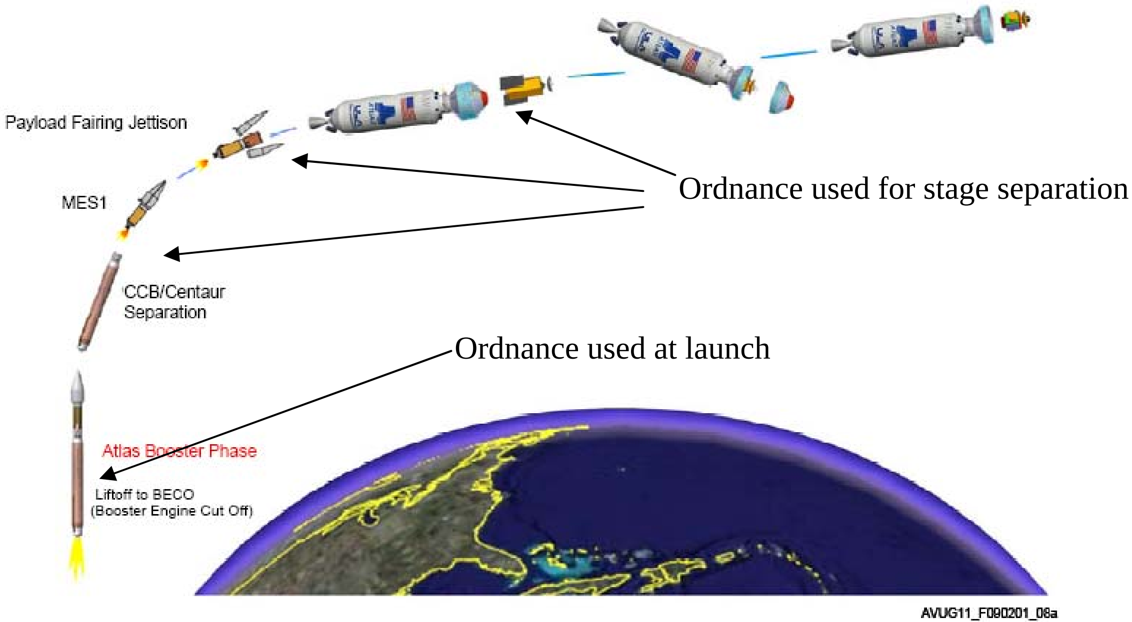

Figure 3 – Typical launch with ordnance initiated events

<u>Operational Ordnance and Flight Termination System Ordnance</u>

The launch vehicle consists of a number of systems that present hazards and ordnance is one of them (Reference 2). The Ordnance on a launch vehicle is broadly categorized as Operational Ordnance and Flight Termination System Ordnance.

Operational ordnance items are required for a normal successful launch of a spacecraft. Operational ordnance items are required to release the rocket from ground holding as well as various ground connections for fuel and booms that carry the ground interfaces. There are ordnance items on ground support systems. The launch vehicle requires ordnance items for engine ignition and stage separation. The launch vehicle also uses a number of pyrotechnic valves for controlling the flow of commodities. The safety concern for operational ordnance is inadvertent activation.

Flight Termination System Ordnance is required to destruct the vehicle if there is an anomaly and the vehicle steers off course and could result in a danger to public. The safety concerns for Flight Termination System Ordnance are failure to activate and inadvertent functioning.

<u>Ordnance safety concerns and safety regulations</u>

Ordnance is an explosive device which functions with a sudden release of energy that may be used to perform an action such as stage separation or destroy a stage that is out of control. The two concerns with ordnance are:

1. Inadvertent activation
2. Failure to initiate

Inadvertent activation during ground operations can result in injury to personnel or destruction of equipment. Inadvertent activation during flight can result in loss of mission. Failure to initiate of operational ordnance during flight could result in loss of mission and failure to initiate of flight termination ordnance could endanger public safety. To mitigate these concerns, Air Force has issued Range Safety Regulations that must be complied with to ensure safety during ground operations and flight phases. AFSPCMAN 91-710 (Reference 3) is issued by US Air Force Space Command for regulating safety at Eastern and Western Ranges. Eastern Range is located at Cape Canaveral in Florida and Western Range is located at Vandenberg in California. Chapter 13 of Volume 3 and chapter 13 of volume 6 provide the safety requirements for all ordnance. Volume 4 provides the additional requirements for Flight Termination System Ordnance. Several military standards such as MIL-STD-1576, MIL-HDBK-83578, MIL-DTL-23659E and MIL-HDBK-1512 (References 4 to 7) are also available for specifying and guidance.

Hazardous and Non-hazardous Ordnance

Broadly there are two ordnance categories. Category A is hazardous and Category B is nonhazardous. Ordnance activation may result in fragments, high temperature, overpressure or flame. Some ordnance can be categorized as non-hazardous by testing. If it cannot be screened out as non-hazardous then it is classified as hazardous. Some ordnance items such as those used for pyrotechnic valves may be classified as Category B if in the assembled condition the results of activation are safety contained within. The safety requirements in AFSPCMAN 91-710 are applicable only to Category-A ordnance. On a launch vehicle, Category-A ordnance include initiator, FCDC and conical shaped charge.

DOT Ordnance Classification

To ensure an appropriate approach for storing, transportation and handling, AFSPCMAN 91-710 requires all ordnance to have a classification in accordance with DOD or DOT regulations. Typically, the ordnance suppliers obtain these classifications by performing tests or other data acceptable to the agency providing the certification. This ensures an initial level of screening for safety. When a supplier submits an application and it is approved, DOT approves it with an exemption number. This authorizes the safe transport of ordnance and acceptance by Range Safety for use at the Range. Code of Federal Regulations (CFR) 49 section 173.50 provides a definition of explosive classifications.

(1) Division 1.1 consists of explosives that have a mass explosion hazard.

(2) Division 1.2 consists of explosives that have a projection hazard but not a mass explosion hazard.

(3) Division 1.3 consists of explosives that have a fire hazard and either a minor blast hazard or a minor projection hazard or both, but not a mass explosion hazard.

(4) Division 1.4 consists of explosives that present a minor explosion hazard. The explosive effects are largely confined to the package and no projection of fragments of appreciable size or range is to be expected. An external fire must not cause virtually instantaneous explosion of almost the entire contents of the package.

(5) Division 1.5 consists of very insensitive explosives. This division is comprised of substances which have a mass explosion hazard but are so insensitive that there is very little probability of initiation or of transition from burning to detonation under normal conditions of transport.

(6) Division 1.6 consists of extremely insensitive articles which do not have a mass explosive hazard.

For a typical launch vehicle, most of the ordnance items are 1.4, some 1.3 and some 1.1 classifications where an explosion is required, such as for flight termination.

Ordnance System Design Requirements from AFSPCMAN 91-710

An ordnance system includes the following subsystems

Power Source
Firing Circuit
Control Circuit
Monitoring Circuit

Initiating Device
Receptor Ordnance

In the Flight Termination System figure 4 (reference 1), the battery is the power source. The receiver is the firing circuit. A separate control circuit controls the state of the Safe/Arm Device. There are monitoring circuits to monitor the states of the Safe/Arm device and receiver. The ordnance initiating device is part of the Safe/Arm device. The receptor ordnance includes the explosive transfer system (FCDC and manifolds) and the Conical Shaped Charge.

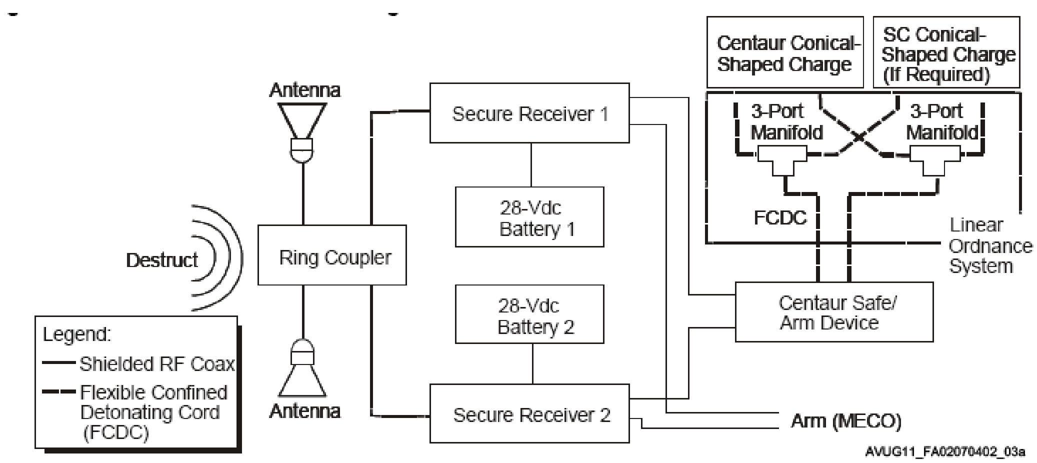

Figure 4 – Flight Termination System and Ordnance items

If a launch vehicle is on an errant trajectory, Range Safety Officer can send a destruct command from a ground station. The command is received by the antenna and an electrical input is provided to the Safe/Arm device. This results in the activation of an ordnance train consisting of FCDC (Flexible Contained Detonating Fuse), manifolds and conical shaped charge. The conical shaped charge destructs the launch vehicle before it becomes a danger to the public. The safety concern with the flight termination ordnance is activation when required and prevention of inadvertent activation.

An operational ordnance system would be similar but a safe/Arm device or a complex ordnance train may not be required. The safety concern is inadvertent activation.

For both Operational and Flight Termination Ordnance, major safety concern is inadvertent firing. There are a number of requirements to mitigate this concern but the two most important requirements are,

1. Ordnance items in general and initiators in particular, should be installed as late in the process as possible. This will minimize the period over which the risk exists.
2. Ordnance system must include inhibits so that there is a safe period during which other operations can occur in the vicinity of installed ordnance.

Ordnance Initiating Devices

In the ordnance train, the initiating device is the most sensitive element and is a significant concern for safety. AFSPCMAN 91-710 lists the following types of initiating devices.
Low voltage EEDs
High Voltage Exploding Bridgewires
Laser Initiated Devices
Percussion Activated Devices
Non-Explosive initiators

Among these, Low voltage EEDs (Electro Explosive Device) is widely used in the space industry A number of designs exist but most are based on the NASA Standard Initiator (NSI) as shown in figure 5 (Reference 8). The Apollo Standard Initiator (ASI) was originally developed for Apollo program. Electrical sensitivity problems with the double-bridgewire design were discovered. In response, the Single-Bridgewire Apollo Standard Initiator (SBASI) was developed in 1966 as the initiating element for all electrically-initiated pyrotechnic devices. The SBASI is a two-pin, electrically-activated, hot wire, electro explosive – translates an electrical stimulus into a pyrotechnic action or “train”. The SBASI was adopted and used as the NASA Standard Initiator (NSI) on the Space Shuttle, Shuttle payloads, & other NASA programs (Reference 9).

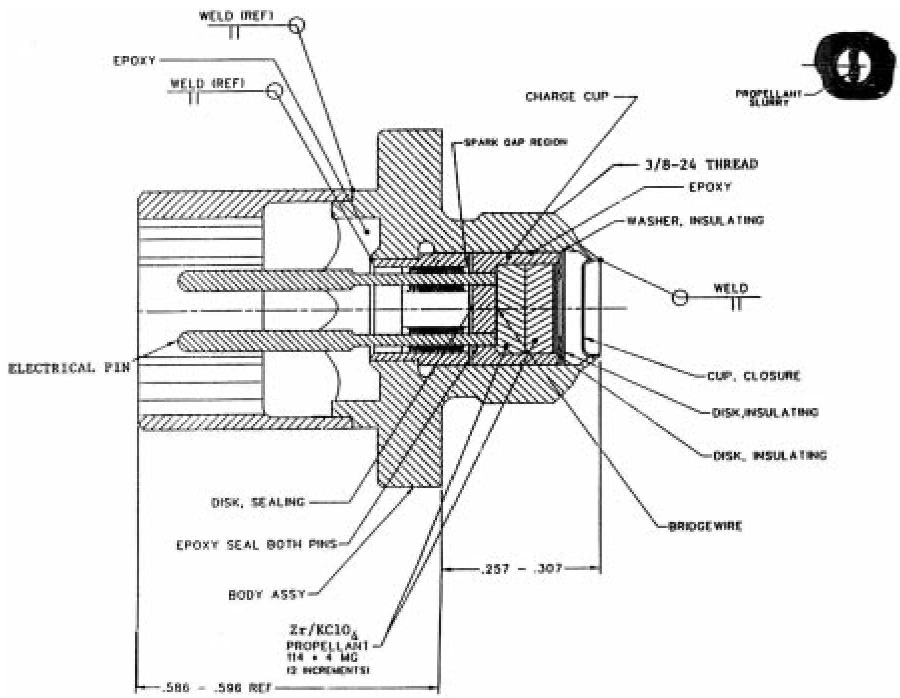

Figure 5 – Cross sectional view of NASA Standard Initiator (NSI)

NSI has an excellent safety record. Inadvertent activation is prevented by its 1-amp/1-watt 5 minute no-fire capability and high resistance to stray energy (transients, radio frequency, electromagnetic) as well as electrostatic discharges. NSIs and its derivatives are used as initiating devices for both operating ordnance and flight termination system ordnance.

Inhibit requirements from AFSPCMAN 91-710

AFSPCMAN 91-710 specifies that all solid rocket motor ignition circuits and other high hazard ordnance systems using low voltage initiators like NSI shall provide an electromechanical Safe/Arm device. The primary function of the S/A device is to prevent premature electrical or mechanical activation. EED ordnance systems for other ordnance systems shall provide 2 independent circuit interrupts such as enable and fire switches in the power side of the initiator and one safe plug that interrupts both the power and the return side.

High hazard applications are typically solid rocket motor ignitions and flight termination ordnance systems. The non-high hazard applications are typically stage separations and other operational ordnance items.

RF Margin requirement from AFSPCMAN 91-710

A significant safety concern is the effect of high RF energy on the low voltage initiators. AFSPCMAN 91-710 specifies that the system circuitry shall be designed and/or located to limit RF power at each EED (produced by range and/or vehicle transmitter) to a level at least 20 dB below the pin-pin DC no-fire power of the EED.

<u>Flight termination Ordnance Requirements from AFSPCMAN 91-710</u>

The requirements for flight termination system ordnance items are more stringent than for operational ordnance due to significant hazard potential for both launch site personnel and public during flight. For this reason, volume 4 of AFSPCMAN 91-710 is dedicated to the flight termination system. There are specific qualification and acceptance test procedures for Safe/Arm devices, EEDs and all the items of ordnance train. Age surveillance (shelf life) testing is also required to ensure performance after storage.

<u>MIL-HDBK-83578</u>

MIL-HDBK-83578 combines the elements of DoD-E-83578 and MIL-STD-1576 which have established the best practices for ordnance for space applications. DoD-E-83578 was issued in 1979 (now superseded) and MIL-STD-1576 was issued in 1984 (still active). This handbook is the best resource for qualification, acceptance and age surveillance testing of ordnance for space applications.

<u>Summary</u>

In summary (Figure 6), this paper reviews the ordnance application on typical space launch vehicles. The ordnance items are hazardous to launch personnel and public. Safety is assured by the imposition of Range Safety requirements such as AFSPCMAN 91-710. The requirements cover design, test, transportation and installation. Design safety requirements are provided in volume 3 and operation safety requirements are in volume 6. Additional stringent requirements for flight termination system ordnance are provided in volume 4. Several military standards such as MIL-STD-1576 have contributed to establish stringent design and test practices to assure safety.

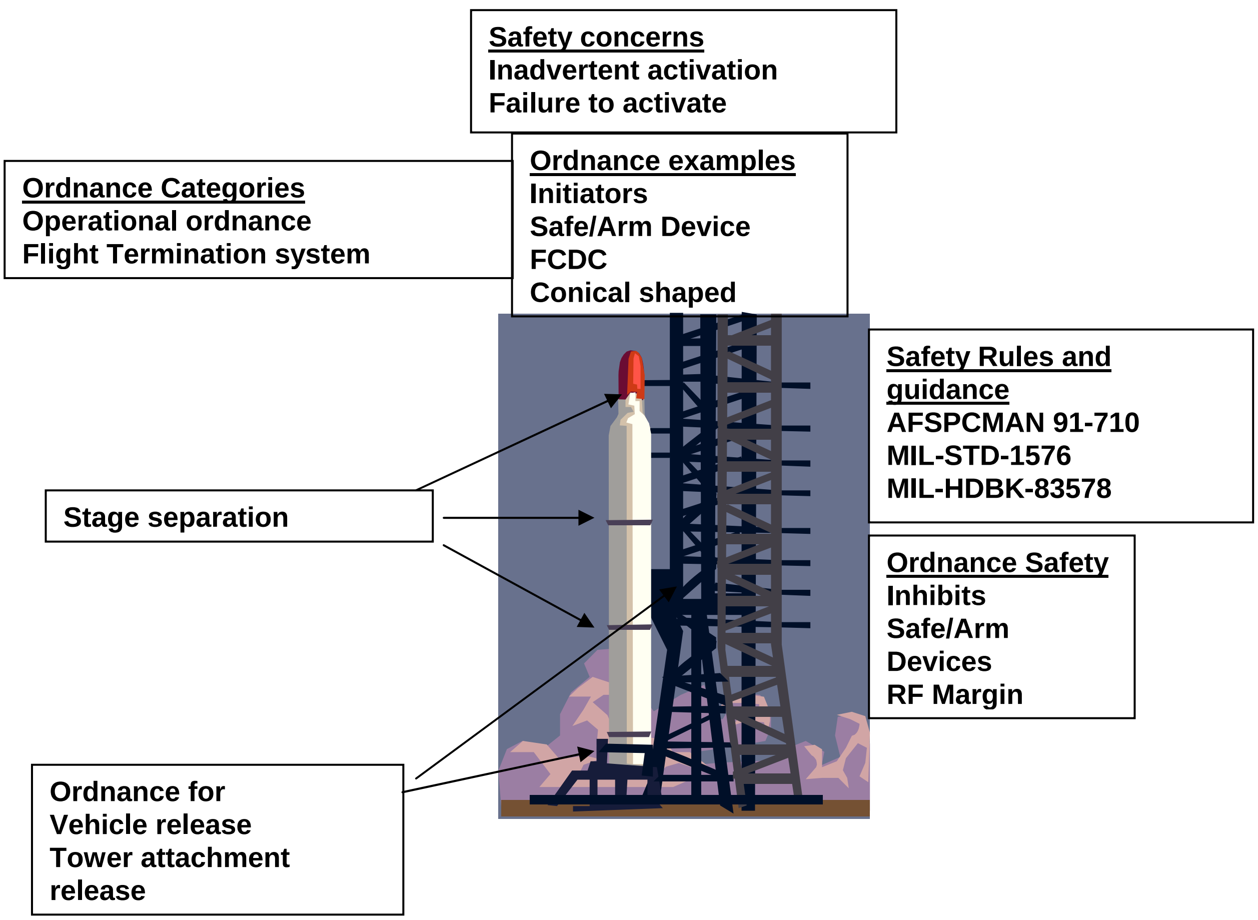

Figure 6 – Ordnance on Space Launch Vehicles

At United Launch Alliance, system safety engineers and design engineers work closely with ordnance suppliers during design, development and testing to ensure proper component selection, testing and compliance to all safety requirements. At launch sites, safety engineers closely monitor the procedures to install ordnance and system testing.

Acknowledgements

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Biography

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Mr. Sri Iyengar is the Lead Launch Vehicle System Safety Engineer at United Launch Alliance located in Littleton, Colorado USA. He has worked on Titan and Atlas launch vehicle programs since 1988. From 1999 to 2002, Sri served as the Lead System Safety Engineer for the Atlas V development program. Prior to that, Sri was involved in the development of Titan Centaur launch vehicle and the development of launch sites at Cape Canaveral and Vandenberg. From 1978 to 1988, Sri worked as a Principal Design Engineer at Air Products Inc on the design of cryogenic tanks for transporting liquid helium and liquid hydrogen. Sri holds a Master of Science degree in Mechanical Engineering from Northeastern University, Boston and is a Registered Professional Engineer. He is a member of American Society of Mechanical Engineers.